Whole Lithospheric Folding as a Mechanism of Basin Formation and Tectonic Implications for Gondwana Evolution: Evidence from the Palmyride Trough, Syria*

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Abstract

Data from the Palmyride Trough of Syria do not support a rift origin of this intra-plate basin. The trough has filled with six successor basins since the late Paleozoic, each basin sequence consisting of low energy, shallow water sediments recording cyclical drowning and drying. Late cycle and inter-cycle regional erosion and volcanism suggest a tectonic influence on cycle termination and basin renewal. New isocore maps show a narrowing of nested troughs through time, increasing structural segmentation and regional counterclockwise rotation.

Lithospheric folding is proposed for trough initiation in the late Palaeozoic with subsequent cyclical deposition, exposure and deformation occurring as a reaction to a naturally occurring decrease in the underlying fold wavelength and regional rotation. Shortening across the basin since the late Paleozoic has been minor, probably less than 20-30 kilometres. Basin longevity, stratigraphic history and limited shortening preclude the view that formation and deformation of the Palmyride trough occurred solely during Tertiary left-lateral movement on the Levant Fracture. An alternate mechanism is needed.

Although not often considered contiguous, Egypt and Syria share a common late Paleozoic and Mesozoic structural and sedimentary history. It is proposed that this greater Eastern Mediterranean Basin formed as a lithospheric, compressional downwarp during the disintegration of Gondwana and a single, constant, unidirectional, far-field force from the southeast best explains the compression and subsequent narrowing and counter clockwise rotation of successor basins. There is no need to introduce constantly changing stress fields through time to account for local and regional patterns. Independent support for this new tectonic model comes from the rotational history of Afro-Arabia derived from the study of magnetic stripping of the surrounding Mesozoic oceans which matches that derived from the rotation of Palmyride Trough successor basins.

Gondwana partitioning by northwest oriented rifting, sedimentation in plate-scale northeast oriented compressional downwarps and a history of continental scale counter clockwise rotation, all driven by a constant, far-field, northwest oriented force, fits regional geologic and structural patterns across the present day African and Arabian plates. Understanding regional deformation through time allows for prediction of sedimentation patterns from tectonic to local scale.

Rethinking Palmyride Basin Geology

The Palmyride Mountains of west central Syria are topographically separate from the Anti-Lebanon Mountains. These highlands consist of a series of individual north-northeast elongated ranges, rising to 1000-1200 m and resting on a broad elevated mass oriented east-northeast. Middle Cretaceous rocks crop out on the crestal areas while the flanks expose a succession of upper Cretaceous to Miocene rocks. Very attenuated lower Mesozoic and upper Palaeozoic successions scarcely outcrop and therefore can only be investigated using seismic and well data.

The surface expression of the Palmyride Mountains belies the full extent of the underlying Palmyride Trough (Figure 1) that consists in the subsurface of a Central Uplift and two flanking catchments, the Addaw and Homs depressions. The Homs Depression to the northwest is a 30-40 km wide flat plain covered in Miocene marls and younger gravels. The emergence of Paleocene rocks further northwest is evidence of the thinning of the underlying sedimentary section onto the Aleppo High and well data such as Khanaser-1 further northeast, with a strongly attenuated Mesozoic section, solidifies the concept. The Addaw Depression to the southeast, effectively a perched valley elevated some 200-300 m above the Rutbah High further southeast, like its counterpart to the northwest, is a broad flat plain of young gravels.

Unlike the subtle northwest margin of the Homs Depression, the Southern Palmyride Mountains mark the boundary between the Addaw Depression and the Rutbah High. They encompass a series of left-stepping, elongated ridges extending from southwest of Damascus to Palmyra where they converge on the Central Uplift. As in the Central Uplift, middle Cretaceous carbonates outcrop on the crests of each ridge with the underlying Mesozoic and upper Palaeozoic showing, on seismic, strong attenuation toward the southeast. Individual ridges, rising from 800-900 m, are box-folded structures cored with Triassic evaporites, the flanks of which show complicated small-scale thrusting with either limb overturned (Searle, 1994). Their formation related to detachment along an underlying evaporitic surface can generally be confirmed, however the timing and mechanism of structuring have been the subject of discussion (Seber et al., 1993). Further southeast, the Rutbah High is an area of very thin Mesozoic and upper Paleozoic.

The Palmyride Trough and related structures form part of a linear belt, the Syrian Arc (Krenkel, 1924), extending from central Egypt into northeast Syria. The continuity of this extensive intraplate system was broken by the north-northeast oriented, left-lateral strikeslip Levant Fault System in the Miocene. Movement since has critically altered the configuration of the arc through the region of the Lebanese and Anti-Lebanon Mountains, but to what extent has been a long-standing open discussion (Walley, 1998).

The intent of this paper is three fold. First, to describe the structural and stratigraphic development of the intraplate Palmyride Trough itself, second, to build a tectonic model for the intraplate deformation of the north west Arabian Plate, and third, to extend the model to plate-scale deformation.

A thorough examination of data from in excess of 90 wells and 3000+ km of high quality seismic resulted in the construction of several isocore maps of selected stratigraphic intervals and palaeogeographic maps of these same intervals allows for an in-depth look at the development of the Palmyride Trough through time. While it is beyond the scope of this abstract to present all the findings, enough will be presented to justify the conclusions. The geology indicates that the trough is not and never has been a rift and this opens the discussion as to how it formed and what the implications are for regional tectonics.

Observations

Figure 2 and Figure 3 demonstrate the stratigraphic fill of the trough and offer a two dimensional view of the basic components and construction of the trough. The construction of the stratigraphic column demonstrates the presence of unconformities of very long duration separating the trough into six stacked basins (Cycles I–VI) equivalent to second-order cycles of the Tethyan Super Cycle. These inter-basin unconformities are confirmed by seismic and paleontological data.

Each sediment package (basin) is composed entirely of low energy deposits. Sediment type distribution demonstrates that basins are not erratic erosional remnants as deeper water deposits coincide with maximum thickness contours of isocore maps of individual units.

Further, dating of regional volcanic activity (Figure 4) confirms the inter-basin time gaps were coincident with volcanism in the immediate and peripheral regions suggesting episodic periods of upheaval separated by deposition of low energy and shallow water sediments (Wilson et al., 1998),

Structurally, no trough parallel, marginal, down-to-the-basin normal faulting occurred at any time during the sediment expanding smoothly into a simple syncline. These observations contradict most of the literature on the origin of the Palmyride Trough, that the basin has been an intracratonic rift since perhaps as long ago as the early Paleozoic (Litak et al., 1997), and begged a deeper review.

Rethinking Basin Genesis

To investigate a compression model of deformation, geological cross sections of individual basins were constructed; shortening is clear as is basin scale folding, with younger folding appearing to display progressively higher frequency, i.e., a shorter wave-train across the basin (approximately 50 to 70 kms during the Jurassic). Most striking is the migration of basin depocentres toward the northwest coincident with uplift of the southeast flank (the Rutbah High).

Lateral compression is very clear on seismic (Figure 6) where internal box folding has compensated for severe shortening in a northwest by southeast direction. Basin crowding and space deprivation fit with compression on a tectonic scale. Timing of folding can be well controlled by noting on-lap sequences on seismic (Chaimov et al., 1992). When their claim is compared to stratigraphic evidence that similar uplifts (folds?) are developing as far away as northern Egypt (Figure 7; Kuss et al., 2000; Wood, 1998), the regional aspect of basin formation begins to emerge.

That each cycle of basin formation and filling was followed by destruction coincident with trough narrowing and internal structuring prior to filling successor basins, suggests the formation of the basin has been derived in compression not extension. Implicit is trough formation by compressional folding of the entire substratum and, considering the full basin width of 250-300 kms represents one wavelength, was probably of lithospheric proportion.

To test the idea, a series of flattened trough-wide geological sections were constructed then simplified into a two-dimensional deformation model (Figure 8). The northwest migration of the nested basins of the trough suggest that a northwest force was active much further back in time than the Alpine Orogeny, the timing most often cited as the only time of compression of northwest Arabia (Litak et al., 1997). Basin crowding (shortening) also infers that there was resistance to plate migration to the northwest throughout the formation of the Palmyride Trough, further inferring a massive "backstop" lay to the northwest, probably the Eurasian landmass. For the model of the Palmyride Trough, however, it is inferred here that this "backstop" was immovable and therefore the "pin-point" for the cross sections is placed in northwest Syria against the border with Turkey.

The model starts with documented uplift of the region in the late upper Palaeozoic (Gvirtzman et al., 1984), coincident with the collision of Gondwana and Laurasia. As Upper Silurian, Devonian or lowest Carboniferous sediments are generally absent in Syria, the timing of the uplift cannot be placed precisely dated, however it is clear that this time gap and uplift coincide with the Afro-Arabian Hercynian Unconformity (Kohn et al., 1992). The Palmyride Trough appears to initiate as a crestal collapse or refolding of a massive, elongated uplift extending from northeast Syria more than 1500 kms into northwest Sudan (Wood, 2001). Since that time, the trough has slowly closed with successor basins forming and deforming in very regular and repeating cycles.

Missing to this point has been the third dimension, the areal configuration of the basins and the fourth dimension to understand the episodic filling, inversion and internal buckling of stacked basins and basin shape through time. Each basin is also segmented laterally into sub-basins by seismically and stratigraphically definable, northwest oriented, cross-trough fractures, adding a new element to the development of the trough not recognized before.

Detailed isocore and seismic mapping provide a new three-dimensional view of the trough and individual sub-basins. Basins were found to be not simple, elongate depressions as per earlier outlines (Laws et al., 1997) but rather are segmented into sub-basins by cross-basin, northwest oriented elements (Figure 9 and Figure 10). Each sub-basin retained its simple synclinal cross sectional configuration, yet individual depositional axes were equally but separately rotated counterclockwise as much as 20° to the trend of the entire trough complex. Figure 9 shows this rotation and basin segmentation using the Triassic and Jurassic isocore maps. Referencing back to Figure 5, the basin narrowing is better demonstrated.

Further, the depositional axes of successively older sub-basins were rotated sequentially further counterclockwise, with the Triassic sub-basins rotated up to 30° away from the present stress direction of approximately N25°W. As episodes of tectonic activity (inversion, volcanism and rotation) within the Palmyride Trough were coincident not only with regional tectonic activity, but also coincided with activity throughout Europe and Africa, the linkage of local intraplate deformation, plate margin structuring and other plate-scale tectonism is evident.

Figure 11 is a model for northern Arabian deformation showing how, under a constant northwest oriented stress, plate scale fracturing and folding appears to give way to intraplate rotation and rifting.

Rethinking Regional Tectonics

To this point, the integration of stratigraphic and structural information suggests that the Palmyride Trough developed under a continuous northwest directed stress field since the late Paleozoic, and the scale of folding with a wavelength of 250-300 km is consistent with lithospheric scale structuring. The coincidence of episodic magmatism and structural activity within the Palmyride region with similar episodic activity throughout the Afro/Arabian Plate offers the real possibility that the entire region deformed under a common stress regime since the separation of Gondwana from Pangaea in the late Paleozoic (Figure 12). To test this idea, successively larger areas of investigation were included in review of regional tectonic activity.

First, the areas of the Gulf of Suez and Red Sea were examined in light of a little cited World Bank, eight country, study (Beydoun et al., 1992) that refuted the earlier McKenzie (1970) pull-apart models or the lithospheric shear models of Wernicke (1985). Key to both older models was the belief that rift parallel faults began life as normal extension faults. This independent studies demonstrated that rifting initiated along vertical northwest trending fractures in the Eocene and that later compartmentalisation related directly to movement on N-S to N10°E "Aqaba" parallel vertical fractures. Folding parallel to the Palmyride Trough was common to the entire region and completed a picture of strain identical to that documented for western Syria (Figure 13).

Mapping of Mesozoic basin sequences in Egypt equivalent to those found in the Palmyride Trough confirmed the extension of these units and inter-basin hiatuses into Egypt, forming single continental scale troughs within the interior of the then contiguous Afro/Arabian Plate. Figure 14 is an isopach map of the Jurassic basin of Egypt based on the database of Marathon Egypt (Morsi et al., 1996) combined with the isocore of the same unit in Syria and for the first time offers an image of a greater Eastern Mediterranean Basin formed under northwest compression, not extension. Further, when the isopachs of the Cretaceous, the Jurassic and the Paleozoic are superimposed, counterclockwise rotation of the basins through time is demonstrated (Figure 15).

That northern Afro-Arabia was probably deformed by lithospheric folding from as early as the late Paleozoic, and that this deformation coincided with the breakup of Pangaea and the following disintegration of Gondwana, a causal relationship is suggested. Further, should this relationship hold true, then a major theme developed here, that a constant, northwest oriented, far-field force has been actively influencing the structuring of northeast Afro-Arabia since at least the late Paleozoic, should also hold true. It then stands that independent plates, formed under the influence of this force, then fractured, folded, compressed, inverted and finally rotated away from its direct influence while a new compressional downwarp took shape over the remains of the former basin (Figure 16).

Rethinking Plate Tectonics

To complete the exercise it is necessary to independently verify the model at a continental scale and rotation angles and times of rotation of the Afro/Arabian Plate based on this single stress model were tested against reconstructions based on fitting oceanic magnetic anomalies, transform-fracture systems and continent-ocean boundaries (a kinematic approach). They were also compared with paleo-plate positions based on paleomagnetic information and regional geologic data (the traditional tectonic approach).

Figure 16 shows a comparison of the rotation of the Palmyride Basins against a robust kinematic effort (Dewey, 1989) of the rotation of Africa to Europe. Rotation angles predicted by this new geological technique back to the early Jurassic and the closure of the Atlantic matched those of Dewey within 5°. Encouraged by this match, and to remove the strictly continent-continent relationship, the basins were rotated assuming a constant far-field force through time and the time curve of Dewey for lateral movement. The picture that emerged (right side of Figure 16) is strikingly close to the polar wander curve for Arabia by Besse et al. (1991). Finally, assuming the "Palmyride" rotations and time frames of Dewey could place the Palmyride Trough in its correct tectonic positions, a palinspastic reconstruction of Afro-Arabia was prepared for the late Triassic period (Figure 17). Again, a match of the new map against published reconstructions instilled confidence in the approach.

This map of Africa, rotated to approximately the point of the breakup of Pangaea using the “Palmyride” rotations, shows nine attempts to plot the rotation of Afro-Arabia at this time. There are clearly two groupings with the rotation suggested by the Palmyride study lying within the more recent attempts. This new geological approach therefore suggested a rotation of the Triassic plate much further clockwise than earlier published versions, while offering a rotation compatible with more recent ones.

Rethinking the Driving Force

As Arabia is presently being torn from Africa along the Red Sea Rift, so were the multiple micro-plates of Tethys, and the understanding of the mechanism of these separations is critical to understanding the past. Further, as the history of the Palmyride Trough, lying on the newest member of Tethyan “transit plates”, predates the Red Sea Rift and separation of Arabia, it is an ideal candidate to shed light on the underlying mechanism.

In two dimensions, the Palmyride Trough offers a picture of simple lithospheric folding while in three dimensions, the trough displays folding plus domino-like rotation (Figure 11). Analyses of periods of regional volcanism demonstrate that, despite the incredible volumes of material involved, the times of emplacement were incredibly short and the domino-like rotation of sub-basins, during brittle failure of the crust, probably occurred with like rapidity. Independent evidence of rapid plate reorganisation, coincident with intraplate magmatism and fracturing, within the oceanic realm supports this conclusion.

Data from the oceanic plates document rapid plate reorganizations in the late Jurassic (~An M22), the Barremian (~An M10), the Aptian (~An M0), the early and late Eocene (~An 22 and ~An 13), the late Oligocene (~An 7), and in the late Miocene (~An 5). That rotation also occurred in the intraplate environment at precisely the same instances provides a direct link between intraplate deformation and oceanic deformation.

The forgoing observations lend themselves to a simple but elegant model of intraplate deformation (Figure 18). Constrained by South America and/or squeezed against Europe and unable to freely migrate away from the affecting northwest directed force, Africa disintegrated by fracturing parallel to the stress direction. Under continued constraint, the plate expanded and effectively “rolled” counterclockwise in the only direction possible, to the northeast, an action which induced shearing of the continent along at least the two dominant shear sets, the Central African and the South Africa Karoo systems. A third system probably lay across the Atlas Highlands region completing the fragmentation of Gondwana into elongated slivers, successively with an open east-facing corner. Constant pressure against this corner kept the plate torqued and dynamic.

As the plate expanded and rotated through the maximum stress direction, each strip of continent was momentarily compressed and folded, with folding probably made easier by a thinning of the lithosphere during rifting of the northeast margin. Further rotation carried marginal, compressed strips of continent beyond the maximum stress direction where, free of constriction and turning away from the maximum stress direction, they were driven with increasing speed to the north northeast facilitated by Levant-like, north to north-northeast shear systems. Differential motion between the new platelets and the continent it had just left behind resulted in first the development of a rift comparable with the Red Sea Rift, and ultimately an ocean basin with its own spreading ridge. Arabia is presently passing through the influence of the far-field stress and just beginning to separate from Africa, although the immediate presence of Asia will probably deter the formation of a major Tethyan-like ocean basin between Arabia and Africa.

Conclusions

Horizontal, lithospheric-scale compression of Arabia, under a single, constant, far-field stress field, best explains the local sedimentary and structural history of the Palmyride Trough in central Syria. It also accounts for the coincident and complex array of young and old structures across the northeast Afro/Arabian intraplate region and therefore offers a model for plate scale deformation (Figure 19).

Detailed geological and geophysical mapping of a single basin in northern Arabia has provided an alternative avenue for determinations of former Afro/Arabian plate rotations. Similarly directed endeavors should lead to a better understanding of global-scale deformation, perhaps ultimately revealing the driving force behind plate tectonics.

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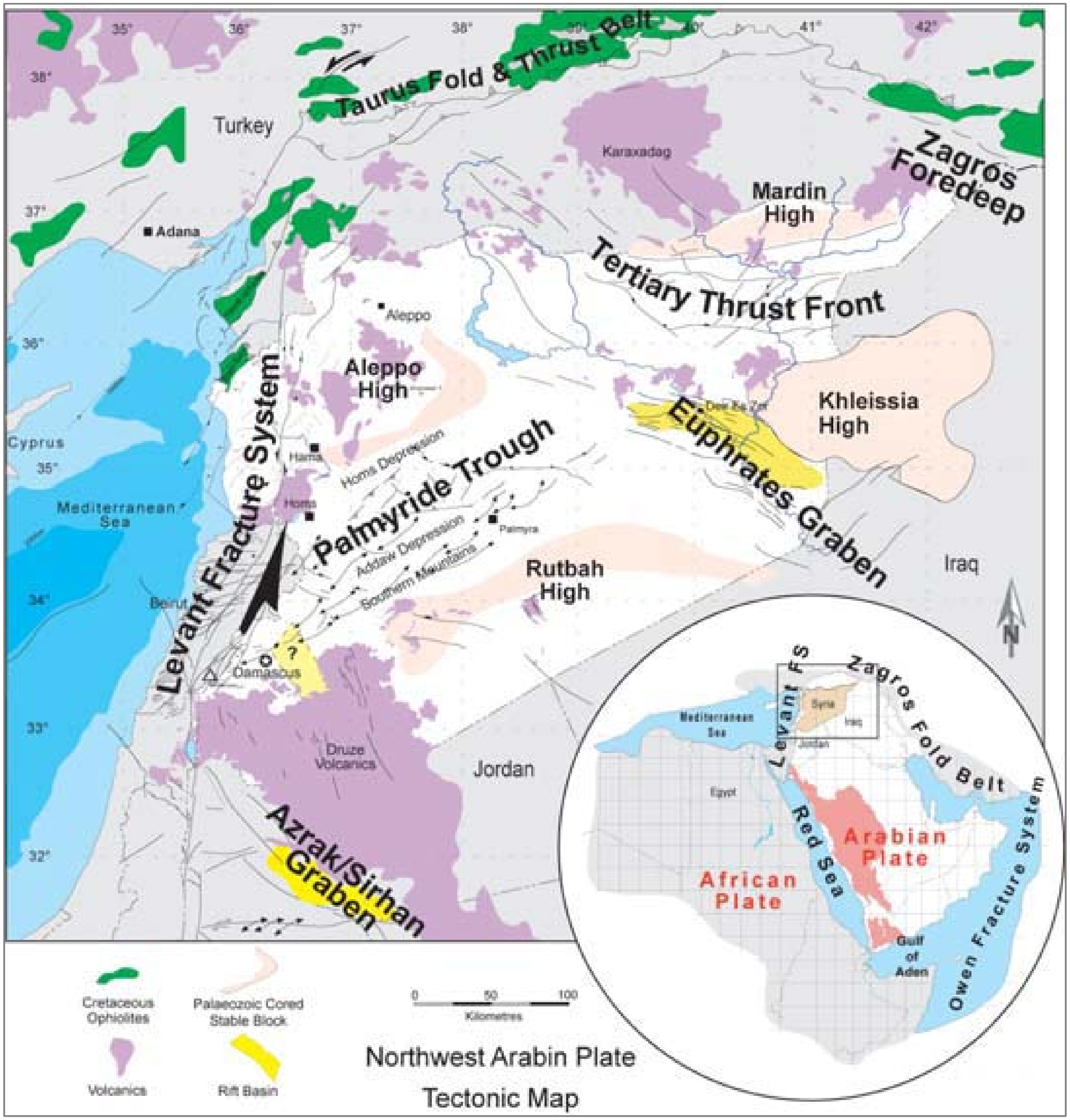
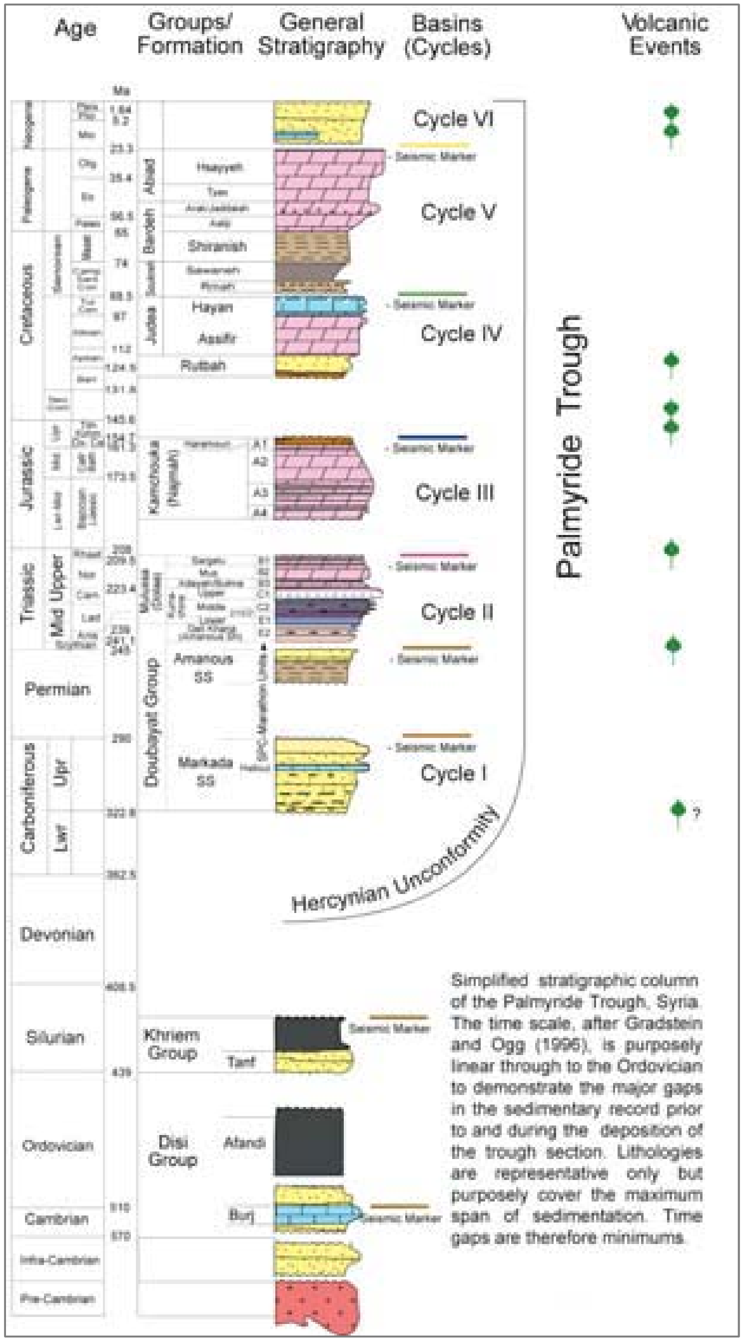


Figure 1. Tectonic map of northwest Arabian Plate.



Simplified stratigraphic column of the Palmyride Trough, Syria. The time scale, after Gradstein and Ogg (1996), is purposely linear through to the Ordovician to demonstrate the major gaps in the sedimentary record prior to and during the deposition of the trough section. Lithologies are representative only but purposely cover the maximum span of sedimentation. Time gaps are therefore minimums.

Figure 2. Stratigraphic column of the Palmyride Trough, Syria.

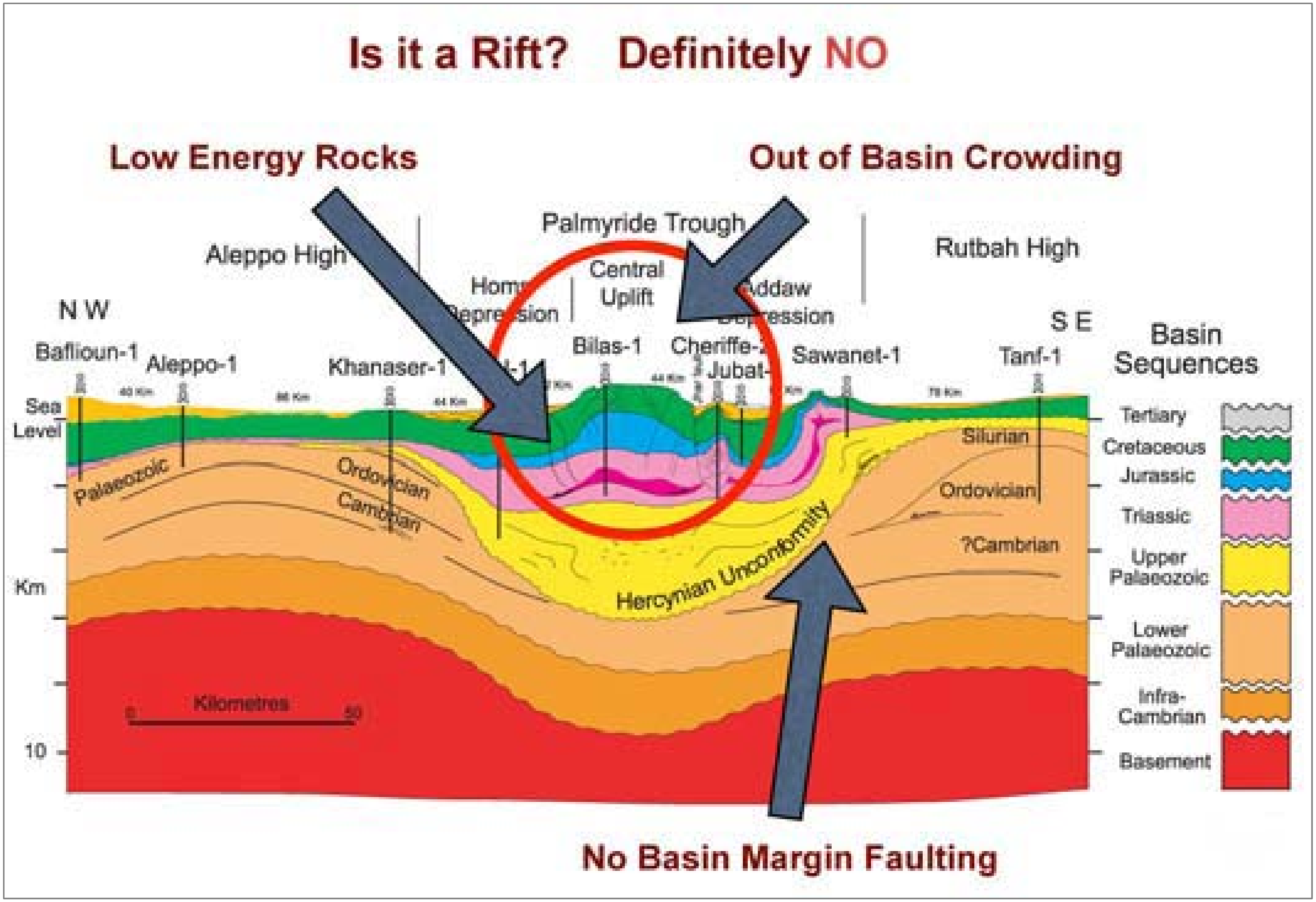


Figure 3. Model of Palmyride Trough formation.

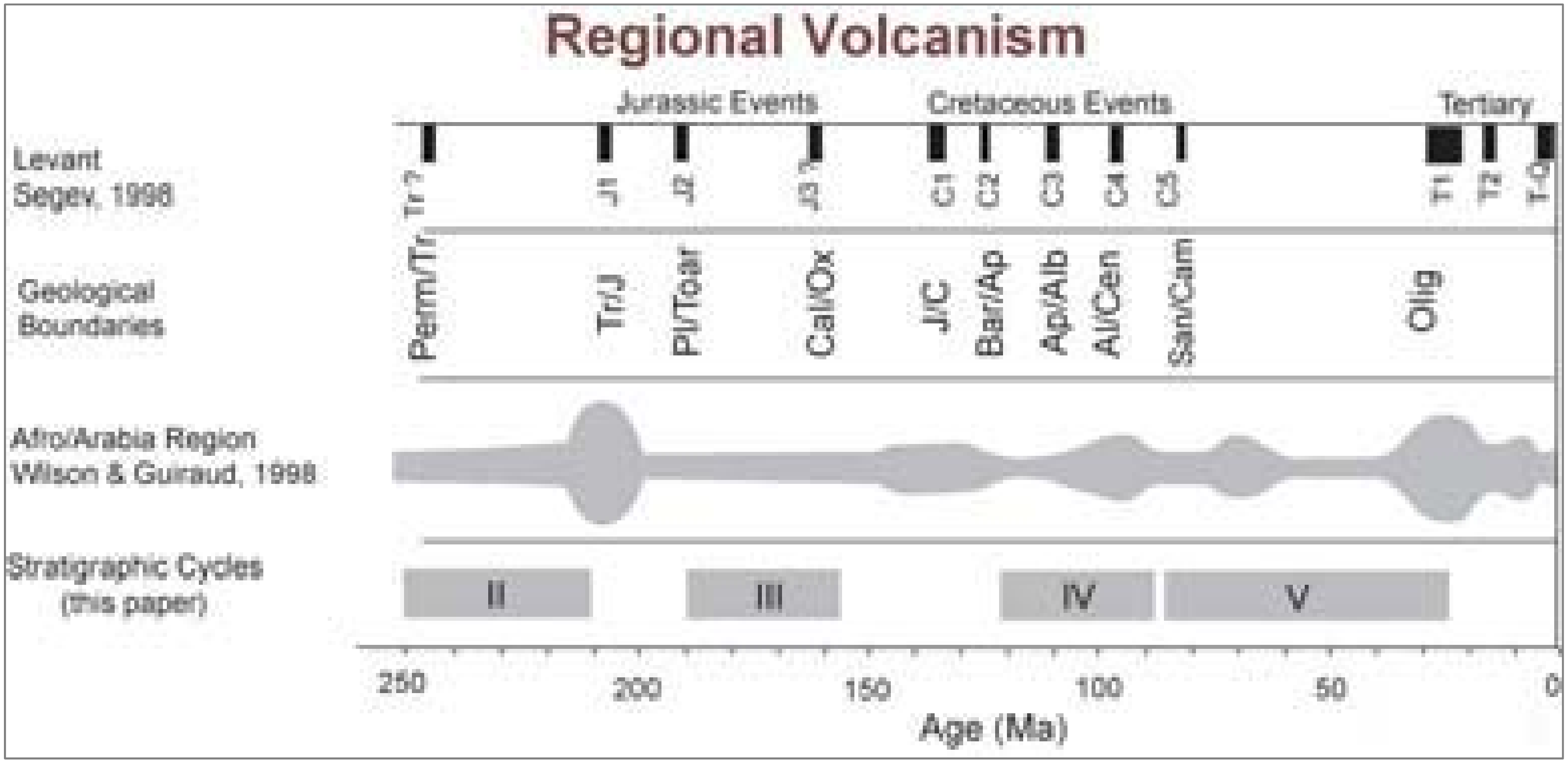


Figure 4. Timing of regional volcanism.

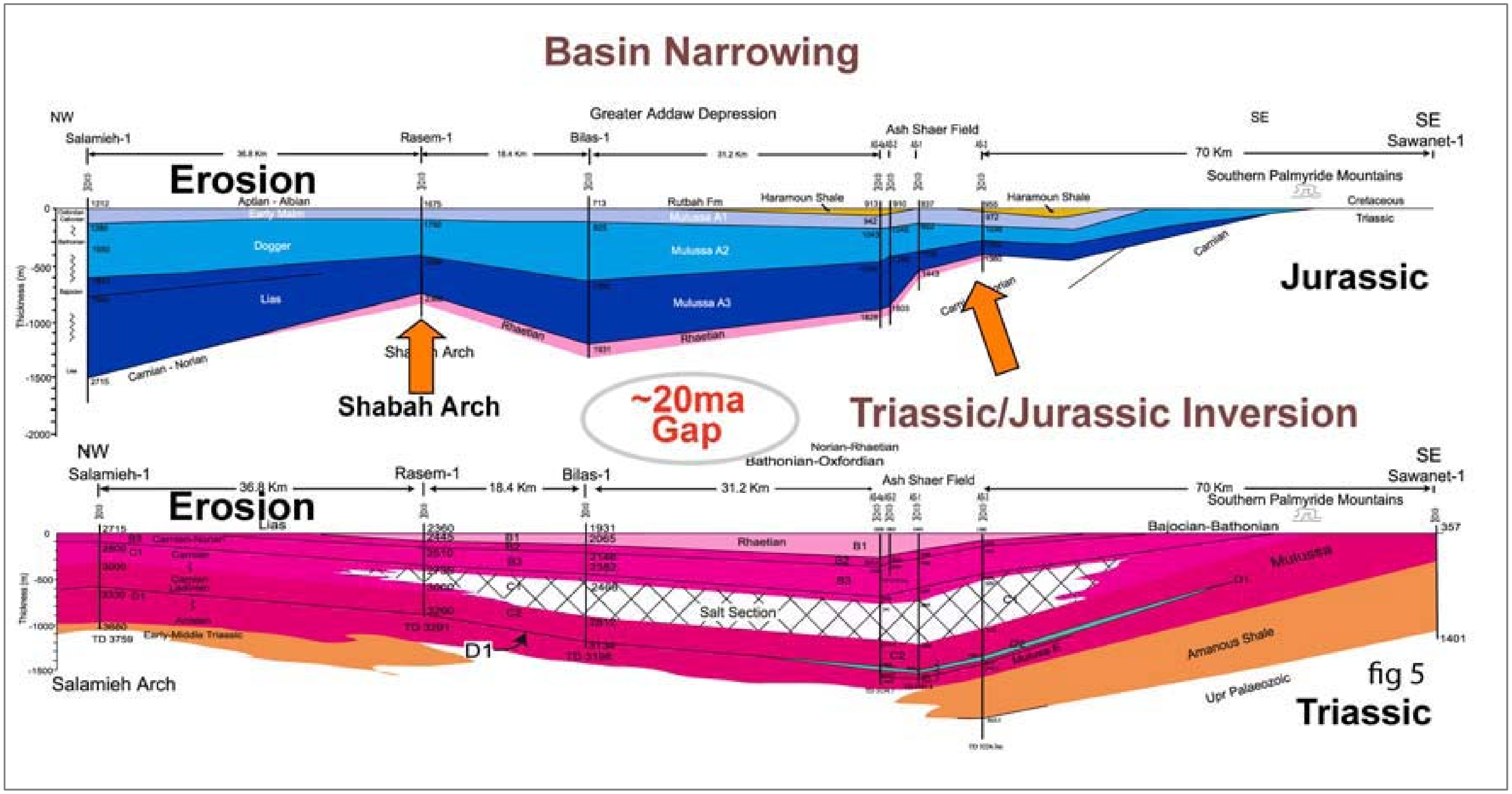


Figure 5. Northwest-Southeast cross sections showing basin narrowing and Triassic/Jurassic inversion.

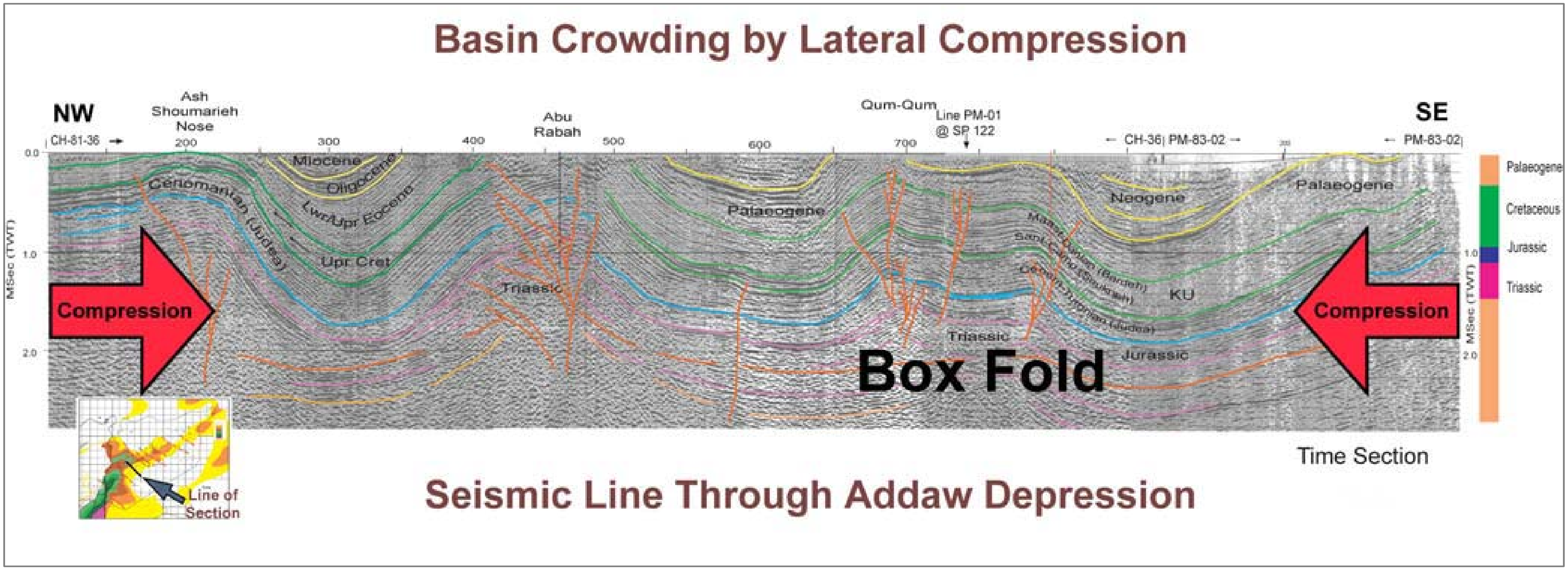
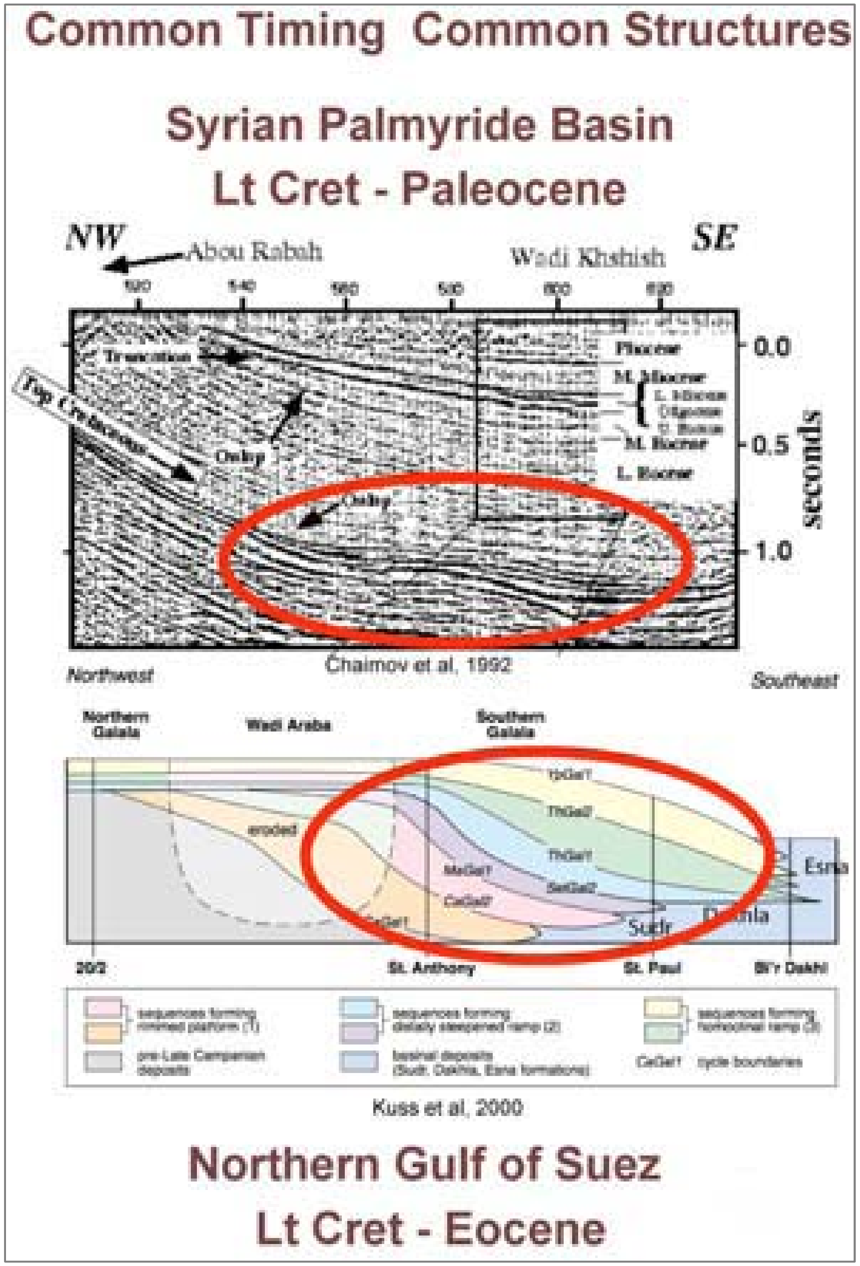


Figure 6. Seismic section through Addaw Depression showing basin crowding by lateral compression.



Common Timing Common Structures

Syrian Palmyride Basin
Lt Cret - Paleocene

Chaimov et al, 1992

Kuss et al, 2000

Northern Gulf of Suez
Lt Cret - Eocene

Figure 7. Common timing and structure of Palmyride Basin and Northern Gulf of Suez.

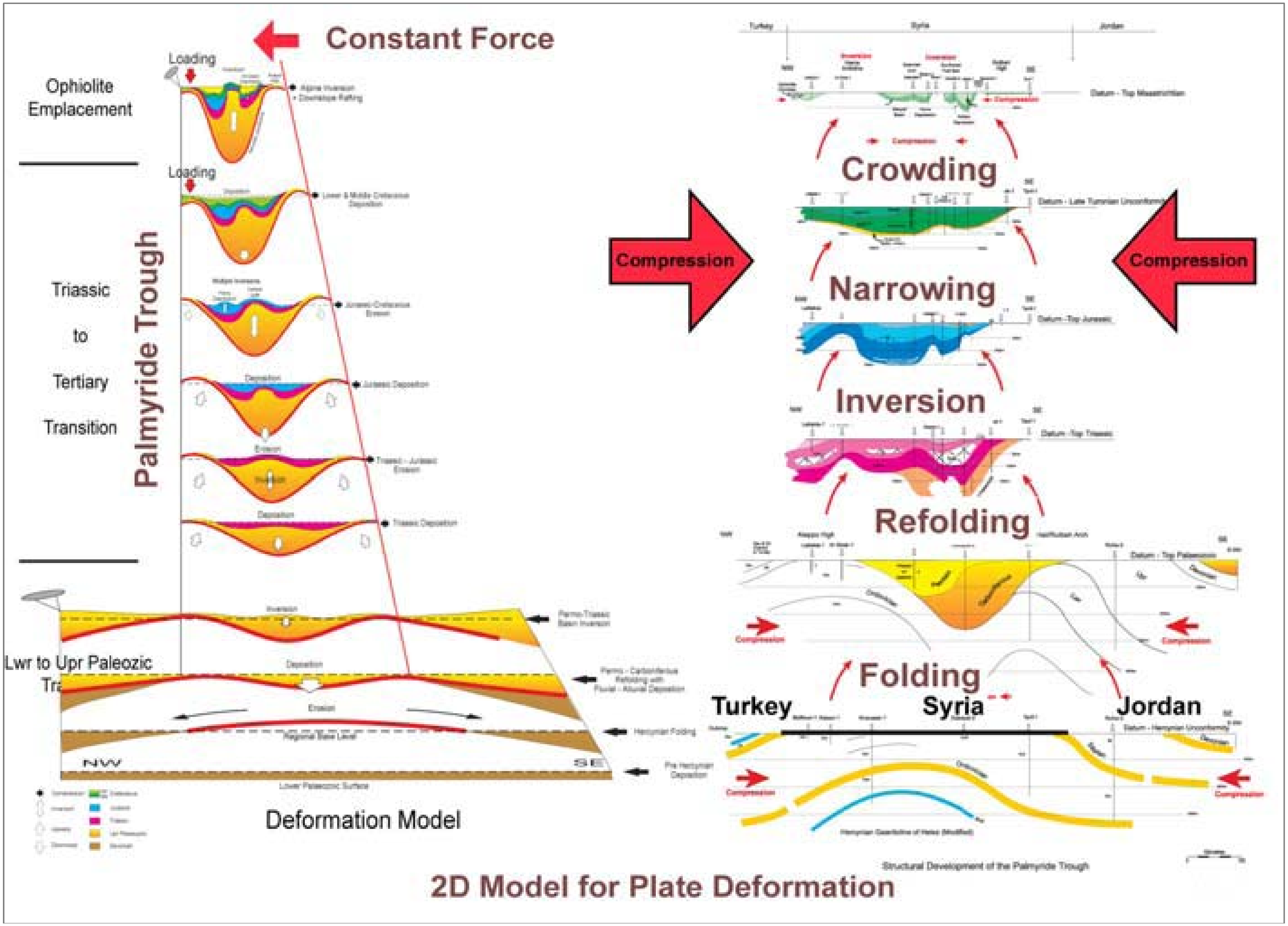


Figure 8. 2D model of plate deformation at Palmyride Trough.

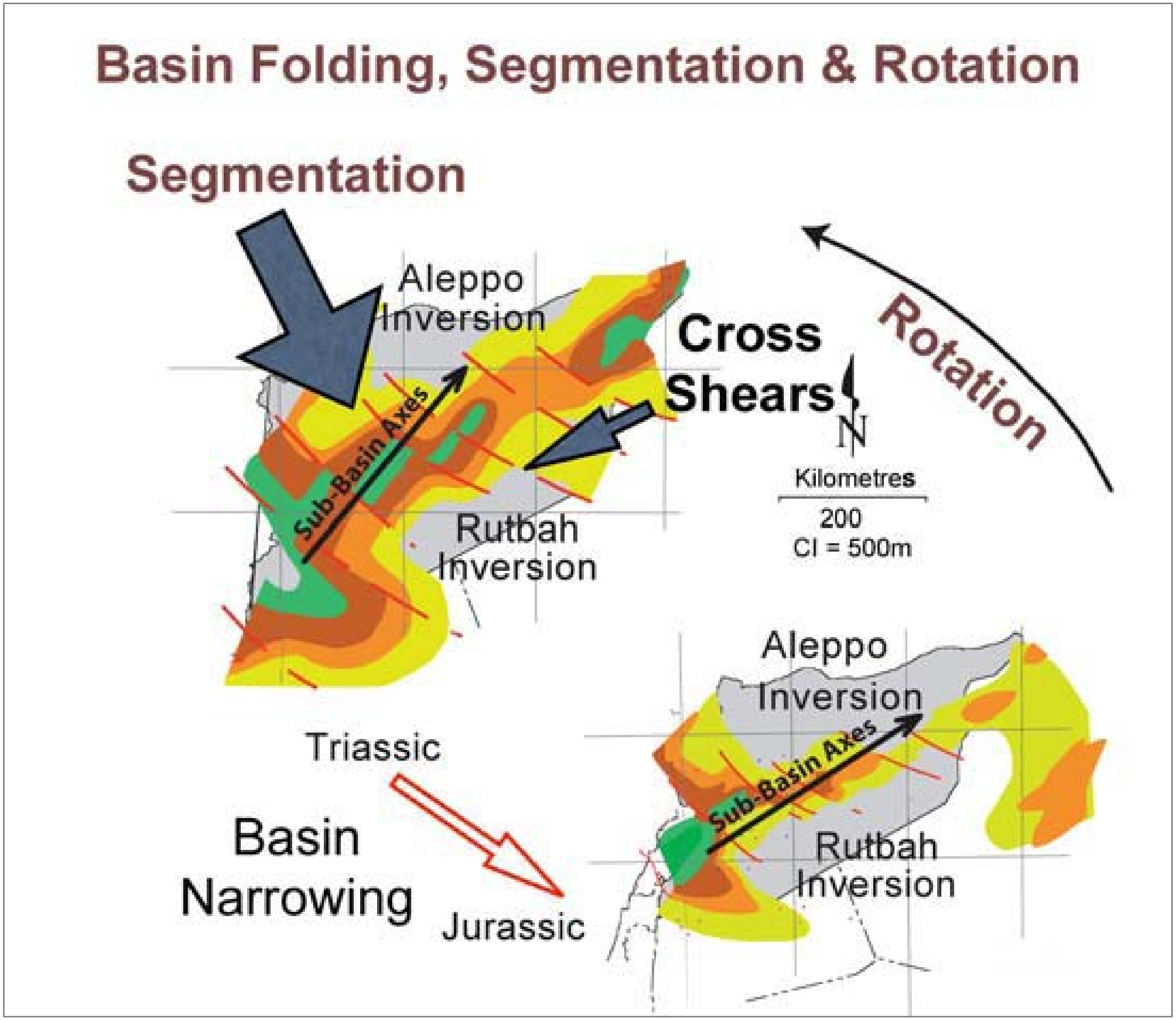


Figure 9. Map showing basin folding, segmentation and rotation.

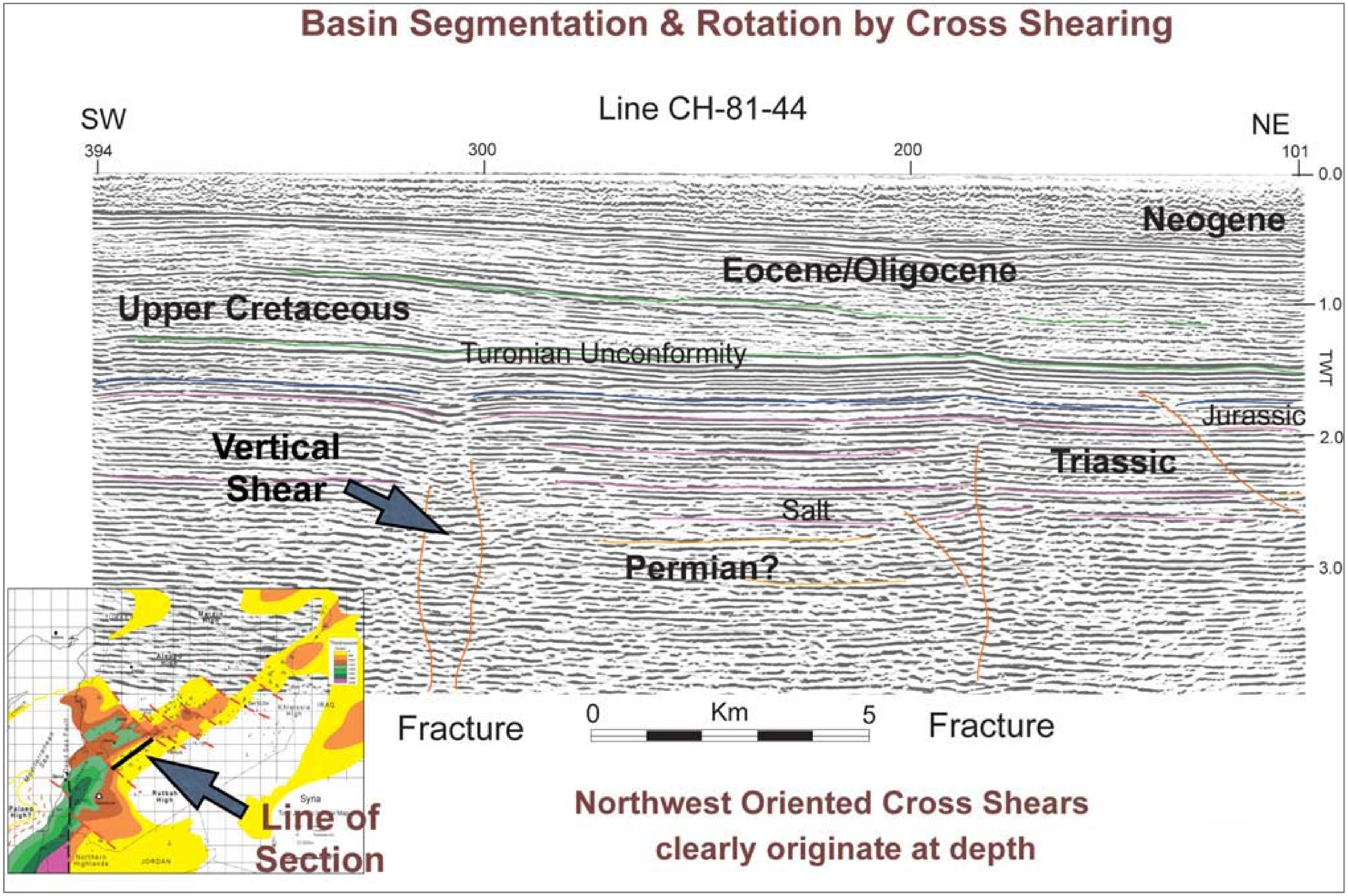


Figure 10. Seismic section showing northwest oriented cross shears.

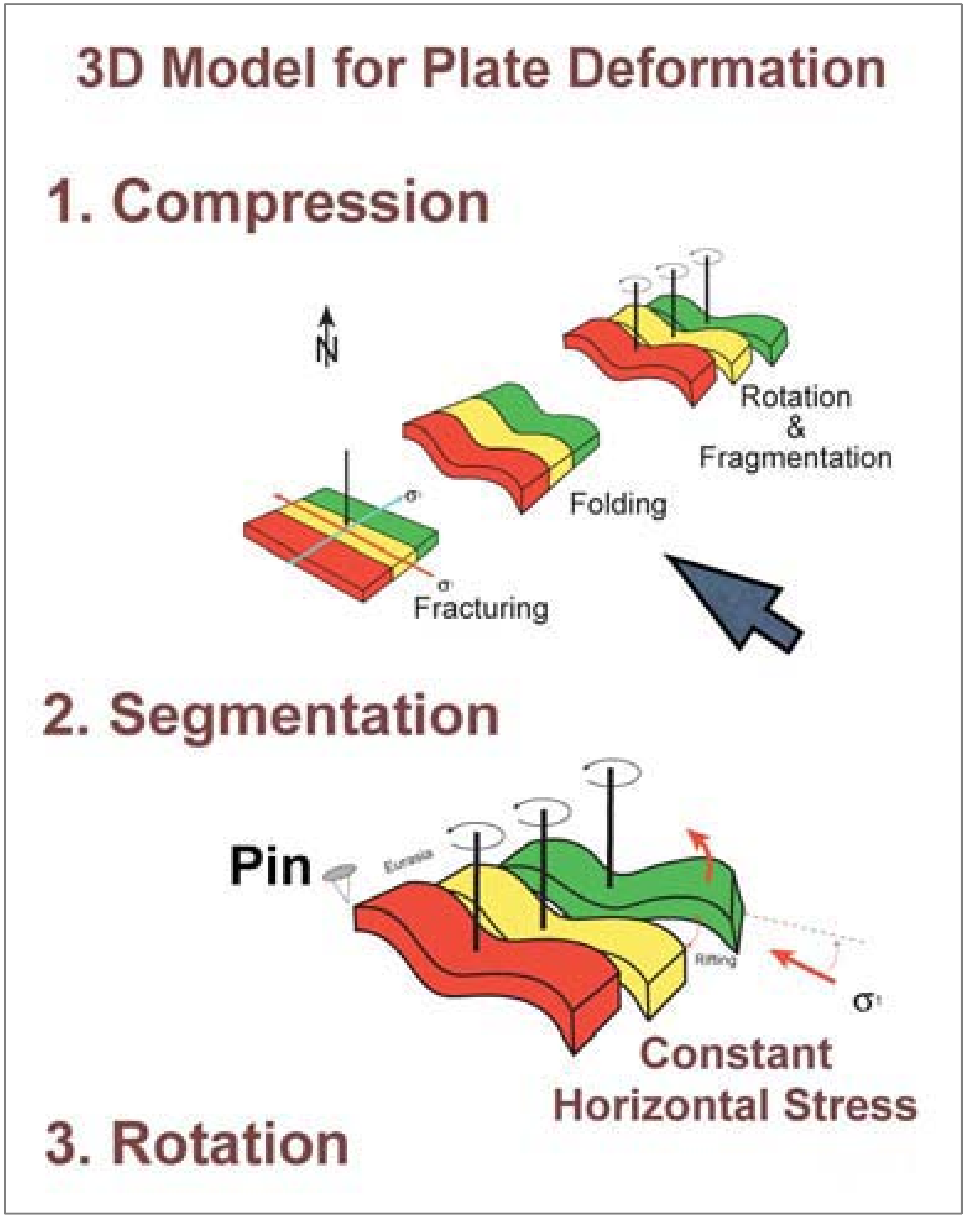


Figure 11. 3D model of plate deformation.

Figure 12. Extension of Palmyride tectonic story into Egypt.

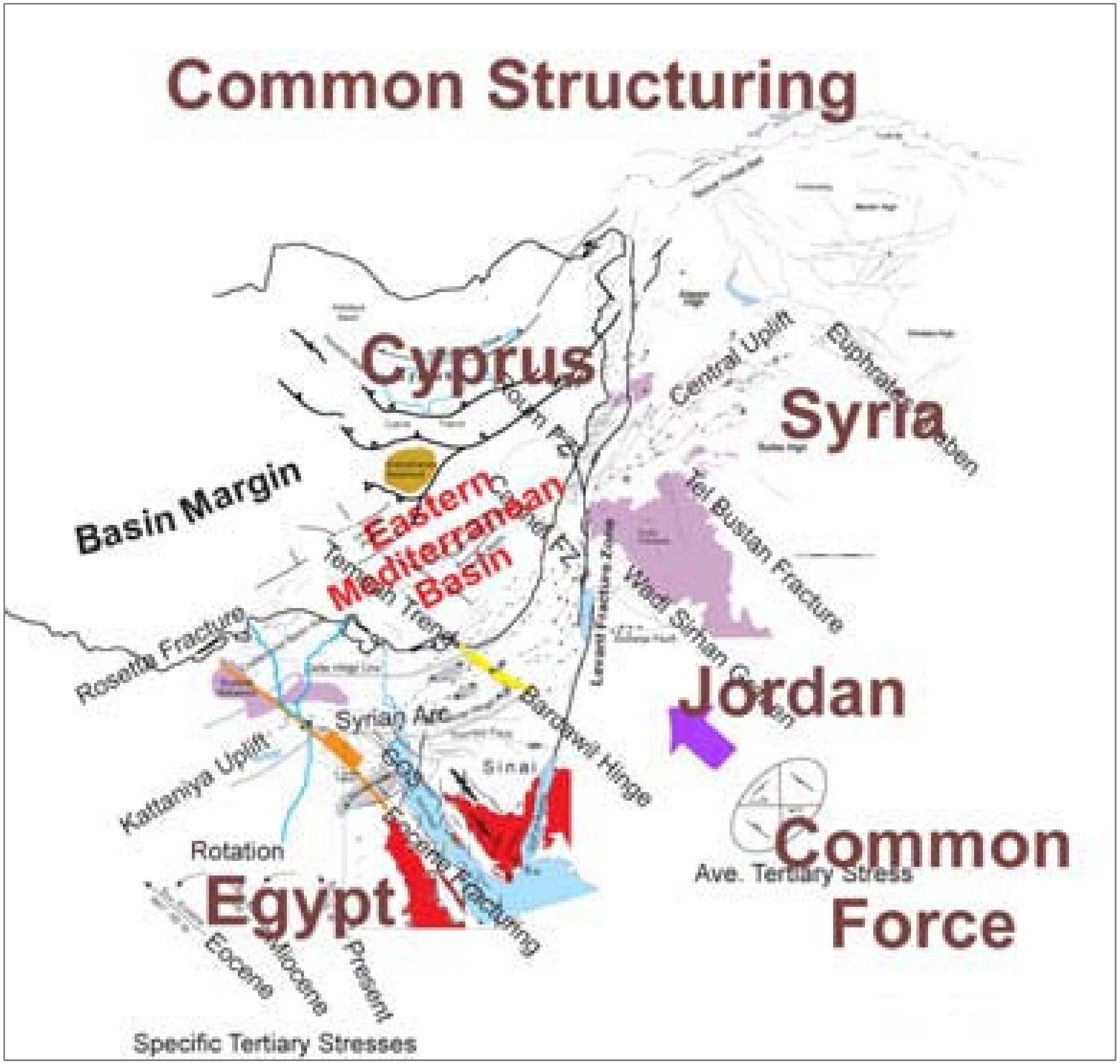


Figure 13. Common structuring in Eastern Mediterranean Basin region.

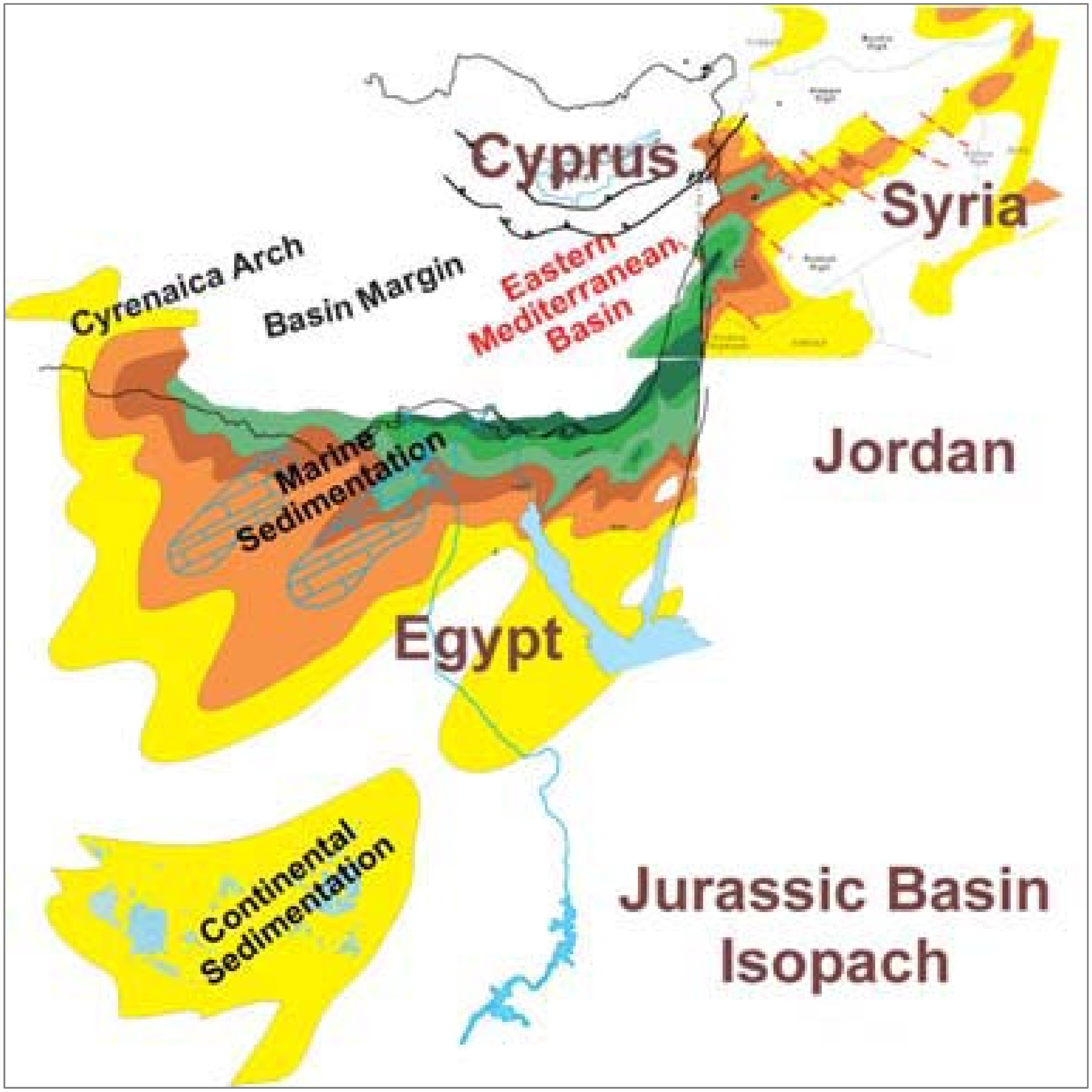


Figure 14. Jurassic Basin isopach map.

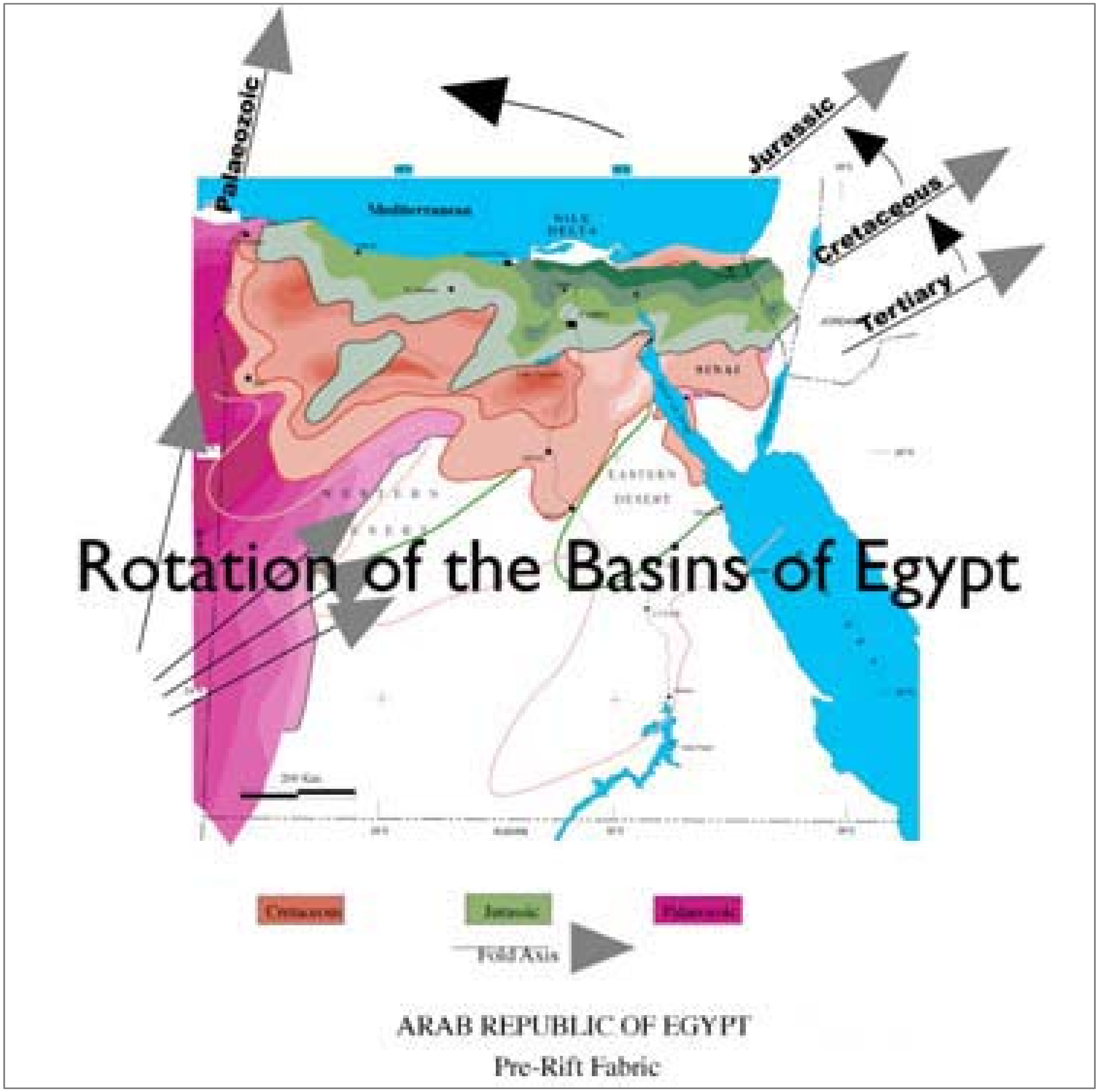
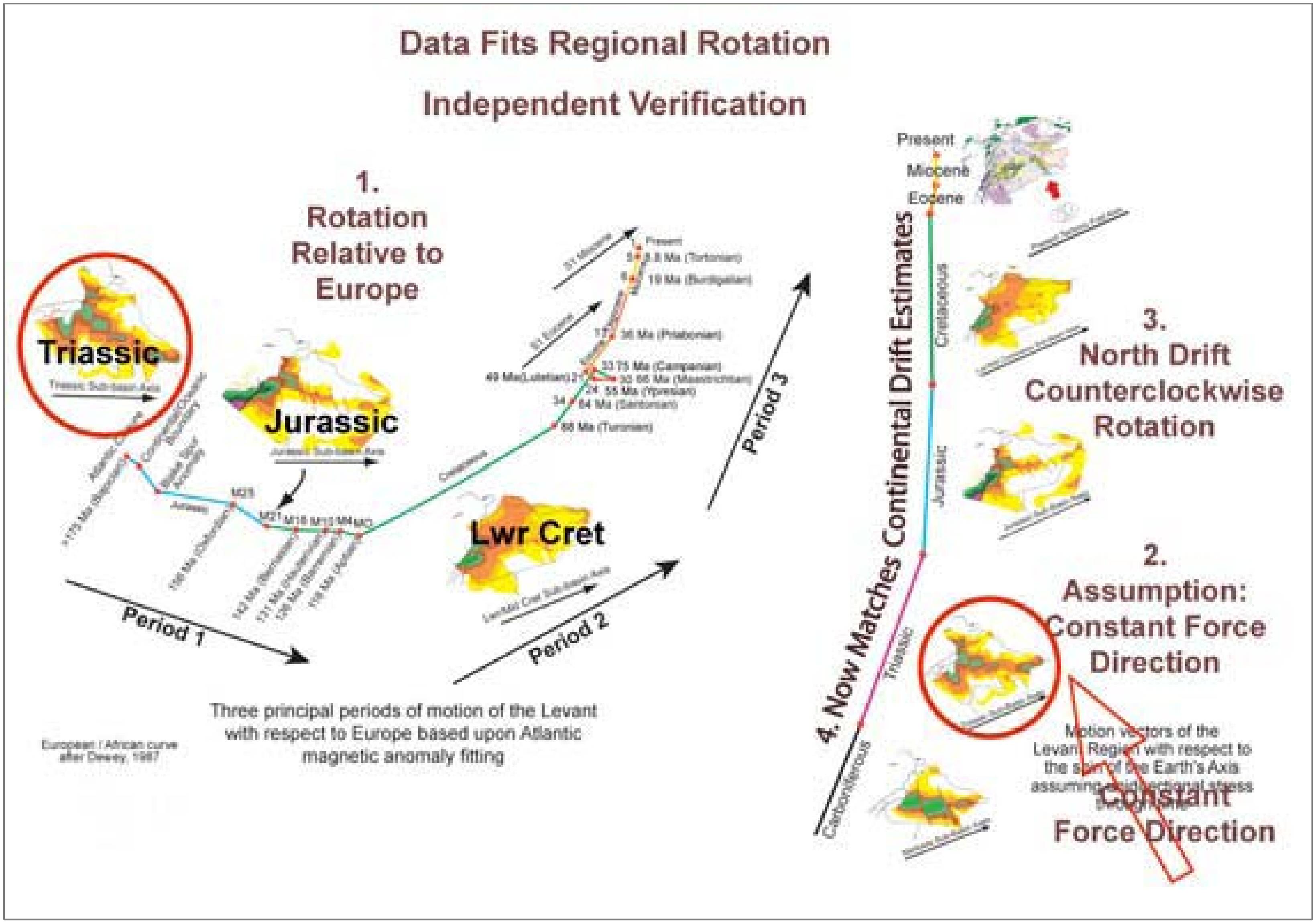


Figure 15. Rotation of basins of Egypt.



Three principal periods of motion of the Levant with respect to Europe based upon Atlantic magnetic anomaly fitting

Motion vectors of the Levant Region with respect to the spin of the Earth's Axis assuming unidirectional stress

Figure 16. Data fits regional rotation.

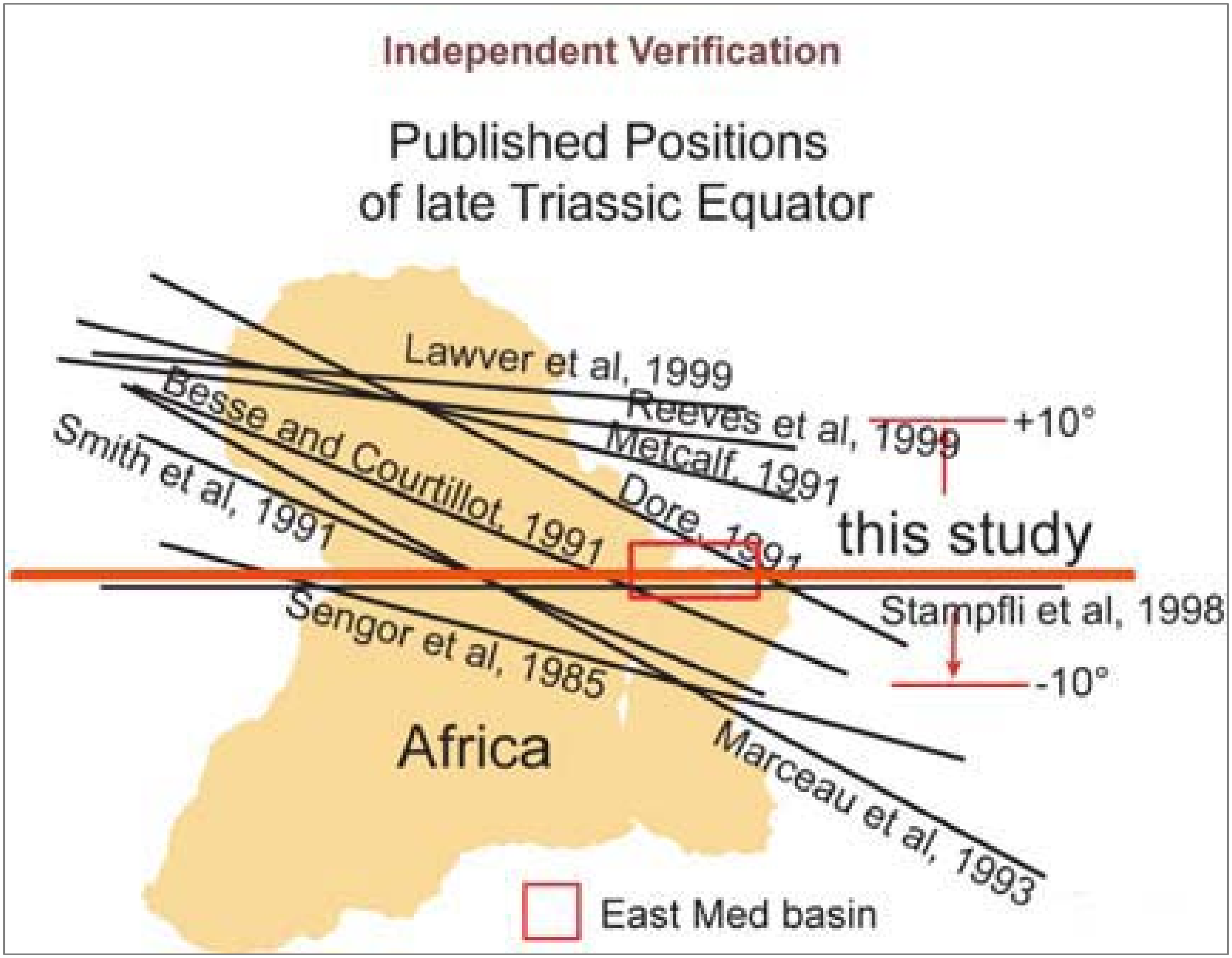
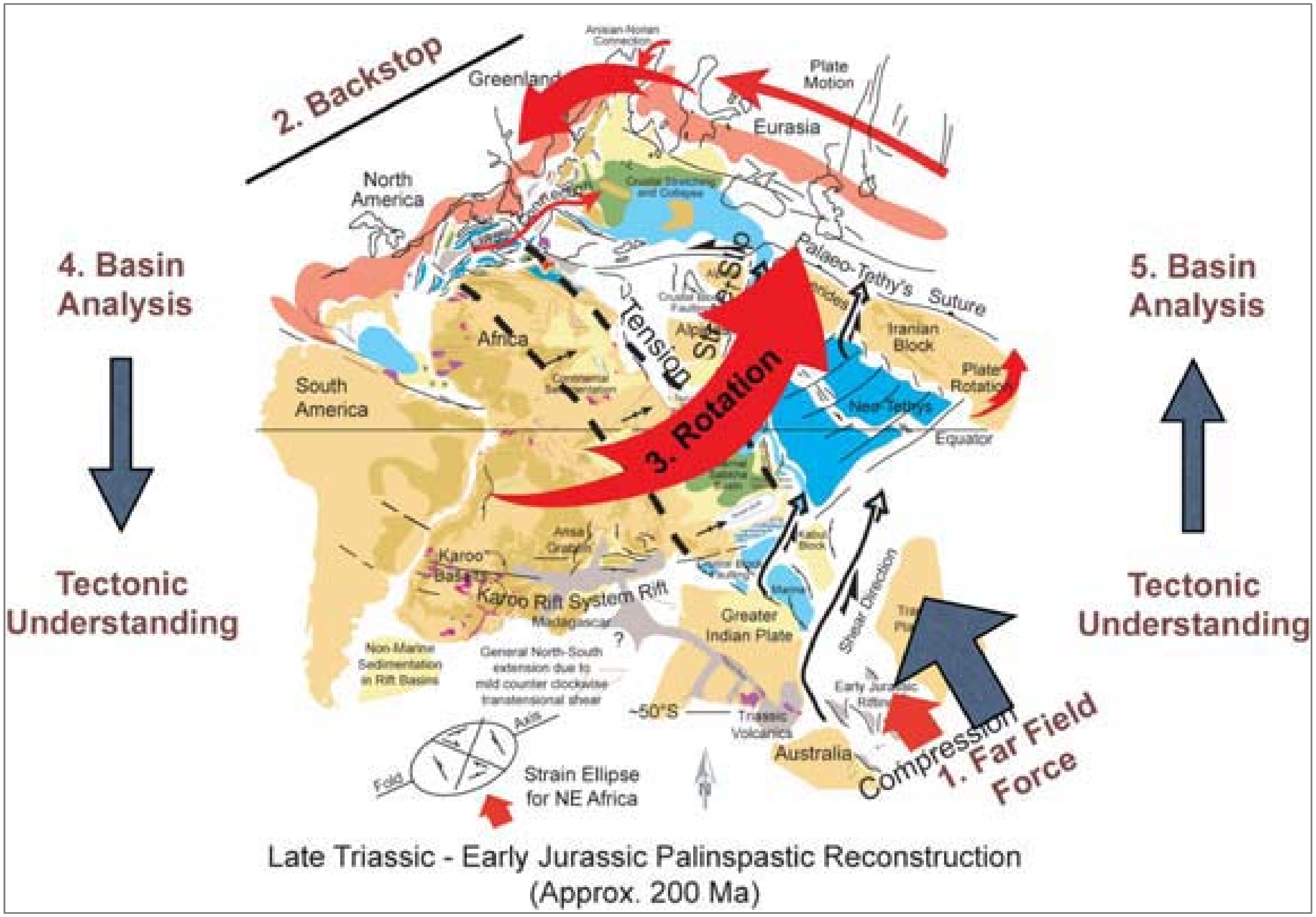


Figure 17. Published positions of Late Triassic equator.



Late Triassic - Early Jurassic Palinspastic Reconstruction
(Approx. 200 Ma)

Figure 18. Late Triassic-Early Jurassic palinspastic reconstruction.

Figure 19. Model of the deformation of Afro/Arabian continent (Gondwana), Triassic to Present.