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TECTONIC EVOLUTION OF THE INTRAPLATE S-SHAPED SYRIAN ARC FOLD-THRUST BELT OF THE MIDDLE EAST REGION IN THE CONTEXT OF PLATE TECTONICS

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ABSTRACT

A system of en-echelon arranged, NE and NNE oriented fold-thrust structures extends in S-shaped belt from Farafra-Bahariya Oases to Abu Roash, Western Desert through Sinai and the Levant into Central Syria. The development of this belt, known as the Syrian Arc System, is controversial and several models have been suggested to explain the mechanism of its formation. Tectonic evolution of the fold-thrust belt seems to have passed through an extensional tectonic style followed by contractional tectonics. The extensional style coincided with the global opening of the Neo-Tethys and comprises Late Permian-Early Triassic initial rift, early Middle Triassic extensional rift, late Middle Triassic quiescent rift, Late Triassic thermal subsidence and Jurassic-Early Cretaceous rejuvenated rift stages. Major angular unconformities separate these stages from each other. The main pattern of the extensional tectonic style is half grabens rotating in a clockwise direction along NE (in Farafra-Sinai and Palmyra) and NNE (in Levant) oriented listric normal faults. This structural framework is responsible for the S-shape of the study belt. The half grabens are transversely broken by NW oriented right-lateral wrench transfer fault zones. The contractional tectonic style coincided with the Late Cretaceous closing of the Neo-Tethys and the convergence of The African-Arabian plate with the Eurasian plate. The new NNW oriented compressive stress led to a reverse rotation of the pre-existing fault blocks along the NE oriented listric faults and to a tectonic inversion of the rift basin. This rotation caused flexuring of the strata forming a number of anticlines with their southeastern limbs much steeper than the northwestern ones. Reverse and/or thrust faults are often associated with the steep limbs of the anticlines. The underlying fault blocks govern the orientation, areal distribution and the size of these structures. The separation of the Arabian plate from Africa that initiated in Oligo-Miocene time through the Red Sea rift enhanced the intensity of folding and thrusting of the study belt. More shortening and left-lateral offset along the almost N-S oriented Dead Sea transform fault began in the Miocene and is still active at present.

1. INTRODUCTION

The Syrian Arc (Krenkel, 1925) forms a conspicuous S-shaped fold-thrust belt composed of structural and topographic highs that extend from the Farafra through Bahariya, Abu Roash in the Western Desert, Sinai to the Levant and central Syria where they vanish close to the NW oriented Euphrates graben (Figs. 1&2). The timing, kinematics and mechanism of formation of these structures have long been a controversial subject. The main target of the present work is to investigate the tectonic evolution of the S-shaped fold-thrust belt and to study the influence of the evolutionary stages on the sedimentary assemblages in a region facing the Eurasian Craton to the north and the African-Arabian continent to the south. The African-Arabian plate experience collision with the Eurasian plate since Late Cretaceous time. The folds of the study belt are NE and NNE oriented elongate doubly plunging asymmetric anticlines aligned in an en echelon arrangement (Fig. 2). They are characterized by gentle northwestern limbs and very steep, vertical or overturned southeastern limbs that are often bounded by major reverse or thrust faults (Fig. 3). The folds of the northern Sinai exhibit northward increase of folding intensity (Shata, 1956). The Palmyra fold-thrust segment in Syria (400 km long and 100 km wide) is bounded by the Aleppo plateau and the Rutbah uplift in the northwest and southeast respectively (Figs. 2&3). The northeastern part of the Palmyra folds displays broad anticlines with reverse faults along their southern flanks whereas the southwestern part of the Palmyra exhibits short-wavelength folds that are associated with south-vergent frontal thrust faults with small intermontane basins (Ponikarov, 1966; Chaimov et al., 1992; Barazangi et al., 1993).

The structures of the S-shaped fold-thrust belt have attracted the attention of many workers such as Krenkle (1925); Shata (1956); Said (1962); Omara (1964); Ponikarov (1967); Youssef (1968); Bartov et al. (1980); Lovelock (1984); Quennell (1984); Abdel Khalek et al. (1989); Moustafa and Khalil (1989,1990); Abdel Aal et al. (1992); Chaimov et al. (1992,1993), Barazangi et al. (1993); Best et al. (1990,1993); Brew et al. (1997); Litak et al. (1997); Ayyad et al. (1998); Kusky and El-Baz (1998,2000), Bosworth et al. (1999); Abd El-Motaal et al. (2001); Sawaf et al. (2001); Walley (2001).

Lithospheric extension has recently become widely accepted as a key process in the evolution of passive continental margins and some intracontinental sedimentary basins. A key feature of this extension is that it induces large fault zones that may penetrate a large fraction of the crust and may be of basin-wide extent (Etheridge et al., 1985). Such structures provide long-lived zones of weakness in the sub-basinal crust that can influence the subsequent structural evolution of the basin.

2. TECTONIC SETTING AND TECTONOSTRATIGRAPHY

convergent, transform and divergent plate boundaries (Fig. 1B). This belt consists of three main segments as the Farafra-Sinai in Egypt, the Levantine in Levant and the Palmyra in Syria. The folds of the Farafra-Sinai and the Palmyra segments are of ENE-WSW to NE-SW trends whereas the Levantine folds are mainly trending NNE-SSW (Fig. 2). The NNE oriented Dead Sea transform fault offsets the S-shaped belt through the Levantine segment and separates the Palmyra segment from the other segments. The S-shaped fold-thrust belt forms conspicuous structural and topographical highs in the northern reaches of the African and Arabian plates.

The deformation of this belt began in Late Cretaceous time (Moustafa and Khalil, 1989; Ayyad et al., 1998, Bosworth et al., 1999; Chaimov et al., 1992, Abd El-Motaal et al, 2001). Late Cretaceous uplift of the Palmyra was coincident with emplacement of ophiolites along the nearby Arabian plate boundaries in southern Turkey and western Iran (Barazangi et al., 1993). The northern margin of the Arabian plate is subducted under the Eurasian plate along the Bitlis suture whereas its northeastern and eastern margins are subducted along the Zagros collision zone in Iraq and Iran (Figs. 1,2). The northeastern African plate subducts under the Eurasian plate along the Cyprus Arc. The left-lateral transform movement along the Dead Sea fault began in the Miocene time and is still seismotectonically active till present. Kusky and El-Baz (2000) suggest neotectonic activity in the northern Sinai area.

The thick Phanerozoic sedimentary cover in the regions of the S-shaped fold-thrust belt can be divided into three main divisions; Pre-rift, syn-rift and post-rift sequences (Fig. 4). This classification is based on the early Mesozoic rift that coincident with the opening of the Neo-Tethys. The thickness of the pre-rift Cambrian, Ordovician and Lower Silurian open marine sandstones and shales is about 5km beneath the present-day Palmyra fold and thrust segment (Sawaf et al., 2001).

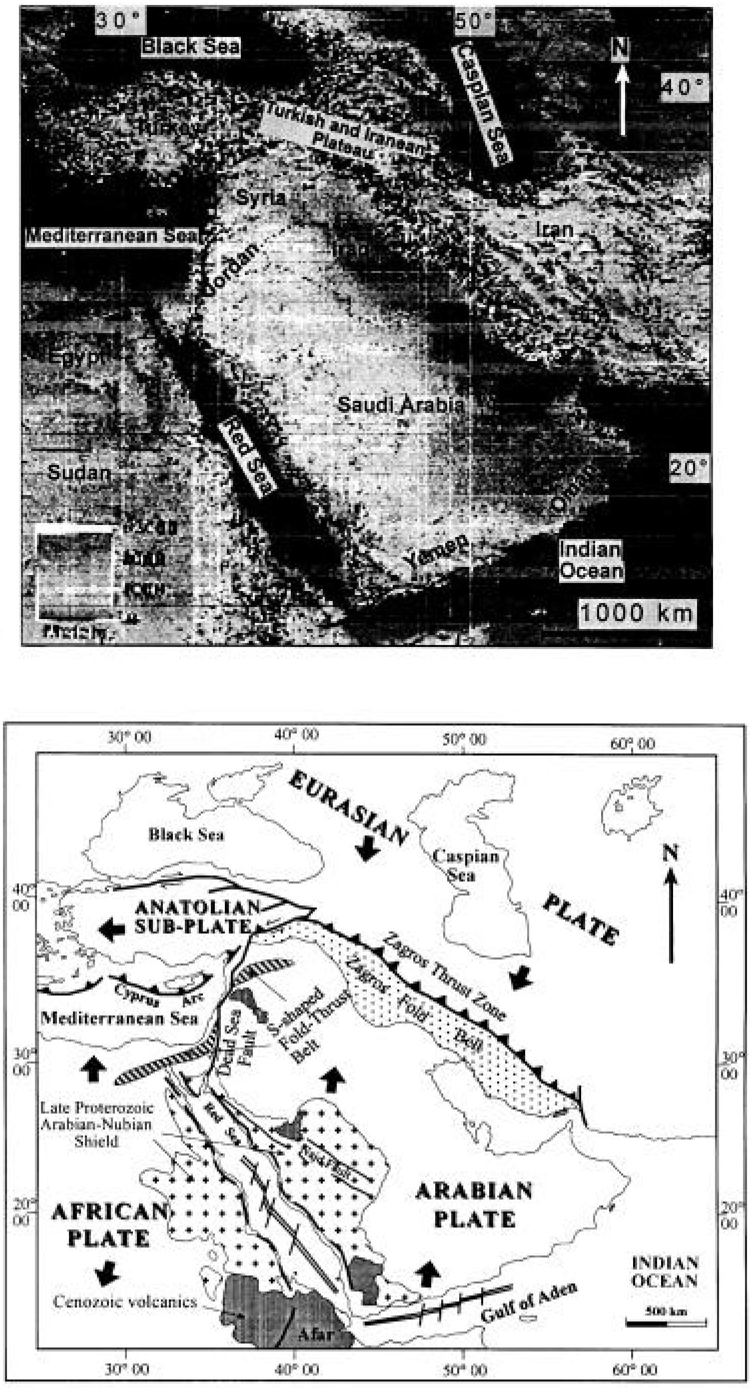

Fig (1): Shaded topographic map for the Middle east (A)and regional tectonic map showing the plate boundaries and the main tectonic elements surrounding the S- shaped fold- thrust belt (B; compiled from various sources).

3. TECTONIC EVOLUTION

The tectonic evolution of the Syrian Arc fold-thrust belt has been markedly influenced by the opening and closing of the Neo-Tethyan Ocean around the margins of the African-Arabian plate. The Opening of the Neo-Tethys, in the Eastern Mediterranean region, started in the Late Permian (Garfunkel and Derin, 1984; De Ruiter et al., 1994; Ricou, 1995; Robertson et al., 1996). The opening of the Neo-Tethys led to the predominance of extensional tectonics in the study area forming a major rifted basin. Isopachs of Phanerozoic successions in Syria

(Sawaf et al., 2001) reveal a persistent linear basin, with thickened Late Paleozoic and Mesozoic rocks sharply confined to the region of the present-day Palmyra fold-thrust segment (Ponikarov, 1966; Lovelock, 1984; McBride et al., 1990; Best, 1991). This regional extension seems to have been aborted and followed by contractional tectonics that started in the Late Cretaceous time coincident with the closing of the Neo-Tethys. This resulted in the inversion of the rift basin and the formation of asymmetric anticlines with reverse or thrust faults along their southern flanks (Fig. 3). McBride et al. (1990) suggest that the Mesozoic and Cenozoic sedimentary rocks of the Palmyra segment were elevated relative to the surrounding stable platforms. However, the Aleppo plateau and the Rutbah uplift are characterized by the absence of substantial internal deformation (Al-Saad et al., 1992). The seismic reflection data clearly show that the deformation is thick-skinned and affects the whole Phanerozoic section; i.e. no local or regional detachment is apparent in the Mesozoic section of the Palmyra fold-thrust segment (Al-Saad et al., 1992). The tectonic evolution of the S-shaped fold-thrust belt seems to have passed through the following stages (Figs. 4, 6-9):

3.1. Pre-Tethys rift stage

The Early Paleozoic sequence in the northern Egypt including Sinai is represented by coarse clastics of probable earliest Cambrian age overlain conformably by dominantly terrigenous formations. They correspond to the oldest marine transgression across the eroded post-Pan-African topography along the northern African-Arabian margin (Guiraud et al., 2001). During the latest Ordovician period, a section of white fluvio-glacial sandstones was deposited in Sinai (Issawi and Jux, 1982). According to Ziegler (1989), the Cambro-Ordovician (to Silurian) magmatic activity in the northern Africa accompanied the detachment of continental terranes from its northern margin. The Ordovician tectonic instability is also evidenced by the NE-SW trending Farafra-Bahariya uplifted arch in the Western Desert of Egypt (Keely, 1989; Issawi, 1996). The sequence of Cambrian, Ordovician and Lower Silurian open-marine sandstone and shale is about 5 km beneath the Palmyra fold-thrust segment in central Syria (Sawaf et al., 2001). They were accumulated in the northern passive margin of Gondwana and reflect deepening of the margin to the east-southeast (Best et al., 1993). These deposits are thickest beneath the present-day Rutbah uplift, that was a large depocenter during this time, and thin considerably to the west, indicating uplift along what is now the Levantine margin during Ordovician time (Sawaf et al., 2001). Moreover, a facies change from deep marine to deltaic towards the west indicates a roughly north-south trending, east facing Early Paleozoic margin (Best et al., 1993). Lower Carboniferous marine carbonates containing manganese minerals are exposed in Um Bogma area, western Sinai. The latest Early Carboniferous witnessed some tectonic instability, evidenced by an unconformity in Sinai between the marine carbonates and the overlying thick cross-bedded sandstones (Jenkins, 1990; Issawi, 1996). Carboniferous sandy shale with minor terrigenous carbonates rest on the Lower Paleozoic rocks of central Syria with a low angular unconformity (Sawaf et al., 2001). During the Middle Carboniferous, sea levels rose again and a mixed carbonate-clastic platform fringed the northern African-Arabian margin (Guiraud et al., 2001). Upper Carboniferous sediments are absent in Sinai. In the Levant, the Geanticline of Helez expanded (Gvirtzman and Weissbord, 1984).

3.2. Initial Tethys rift stage

During the early Late Permian, the northeastern Africa and the Levant were composed of a narrow, shallow marine platform, characterized by mixed and carbonate facies (Guiraud et al., 2001). In the continental domain, fluviatile sandstones accumulated in subsiding basins located along the future Dead Sea fault zone (Powel and Khalil Mohamed, 1993). Extensional tectonic activity prevailed during the Permian times. This is evidenced by the magmatic activity as the extrusion of the Mid-Late Permian basalts in the central Sinai (Steinitz et al., 1992). Similar basalts are recorded in the Gulf of Sirt in Libya (Almond, 1991). Along the African continental margin subsidence also affected large domains as evidenced by rifting in the Tunisian-Libyan confines (Stampfli et al., 1991). Isopachs of the Permian shales, sandstones and siltstones show a thickening of these deposits (~800 m) into a northeast trending trough along the present-day Palmyra fold-thrust segment (Sawaf et al., 2001). Little or no Permian rocks are present in the Aleppo plateau and east of the Euphrates River (Best et al., 1993).

The Late Permian initial rift stage seems to have been controlled by NE and NNE oriented listric normal faults that are transversely bounded by orthogonal NW oriented, near vertical right-lateral strike-slip faults (Fig. 6). NE oriented antithetic listric normal faults have formed the boundaries of major half graben basins. NW oriented wrench (transfer) faults terminated the listric normal faults. Transfer faulting is an almost universal result of crustal extension, because of the difficulty of developing continuous normal faults along the whole rift length (Etheridge et al., 1985; Hempton, 1987).

3.3. Extensional Tethys rift stage

During the early Middle Triassic, the study area witnessed drastic structural and sedimentological changes in comparison to Paleozoic conditions. In Halal-1 well in central Sinai, the deposits of this age are mainly made up of biomicrites and micrites indicating a low energy carbonate shelf resulting from a southerly marine transgression with a postulated east-west shoreline (Jenkins, 1990). The early Middle Triassic deposits, in the core of Arief El Naga anticline to the south of the Halal-1 well, show increased clastic sedimentation. They consist of sandstones, variegated siltstones, and shales carrying plant remains (Awad, 1946; Bartov et al., 1980). Paleocurrent analysis of the festoon-bedded sandstones indicates a southeasterly source for the clastics (Jenkins, 1990). In the Palmyra, the early Middle Triassic deposits consist of dolomite with some limestone (Sawaf et al., 2001). The facies variation of the early Middle Triassic deposits reflects more tilting of the initial rift half grabens (Fig. 7) leading to carbonate deposition in the trough of the rift and clastic accumulation in the rift margins. Rifting probably affected the entire margin of the northeastern Africa, as indicated by block tilting and uplift of Mid-Cyrenaica in Libya (Wennekers et al., 1996).

3.4. Quiescent Tethys rift stage

The late Middle Triassic time is characterized by the predominance of evaporites that were deposited under relatively quiescent rift conditions (Fig. 7). Evaporites have been recorded in Arief El Naga area in central Sinai (Bartov et al., 1980) and central parts of the Palmyra are also characterized by a very thick evaporitic Triassic section including more than 400 m of halite, anhydrite and shale (Sawaf et al., 2001).

3.5. Thermal subsidence stage

The quantitative modeling of intracratonic sedimentary basins has been concerened primarily with the isostatic response of the lithosphere to a single extension event (Karner et al., 1987). Such extension predicts two discrete phases of basin development; a rapid subsidence phase related to rifting of the crust and a thinning of the sub-crustal lithosphere (i.e. the active phase), followed by a generally negative exponential subsidence phase associated with the conductive cooling of the lithosphere (i.e. the passive phase). In marked contrast to this simple model prediction, many basins exhibit a polyphase rifting history as characterized by episodes of renewed basin subsidence (Karner et al., 1987). Often, this renewed subsidence is very rapid and is followed by little, if any, thermal subsidence. During extension isotherms within the lithosphere are raised, so that when extension ceases, the stretched portion of the lithosphere cools and subsides (McKenzie, 1978). The Mesozoic is largely a time of thermal subsidence since rifting appears to have ceased in the Early Triassic (Sawaf et al., 2001). During the Late Triassic, basin subsidence began as a thermal consequence of the rifting (Fig. 8). This is

3.6. Rejuvenated Tethys rift stage

The boundary between the Triassic and Jurassic strata displays a significant unconformity. The Jurassic and Cretaceous sedimentation of north and central Sinai was cyclical and was controlled by the clastic supply from the Arabian-Nubian Shield, eustatic sea level, and local and regional tectonics (Jenkins, 1990). Relatively thick Jurassic sediments are preserved in the northern Sinai, where tilted blocks were active throughout the Jurassic (Fig. 8).

The rift rejuvenation is manifested by the northward increase in thickness of the Jurassic deposits in the northern Sinai. Differential subsidence may take place across transfer faults, particularly to accomplish the subsidence variation along the basin axis. Lateral E-W thickness variation of the Jurassic deposits can be attributed to such differential subsidence (Abd El-Motaal et al., 2001). Jurassic carbonates are preserved almost exclusively within the subsiding Palmyra basin (Sawaf et al., 2001). The Aleppo plateau and Rutbah uplift flanking the Palmyra basin to the northwest and southeast respectively were relative highs at that time (Fig. 4). They may form the shoulders of the rift in the Palmyra segment. The Jurassic environments in Sinai range from deep marine to shallow-marginal marine to continental-fluvial. The basal part of the Jurassic succession is made up of fluvial sandstones deposited by northerly-flowing braided streams carrying detritus shed off the Arabian-Nubian Shield. This dominance of continental clastics was probably due to rejuvenation of rift that led to uplift of the southern rift shoulder. Extensional block faulting is evident in Sinai (Guiraud et al., 2001). The clastics are followed by interbedded shallow marine carbonates and nearshore marine clastics.

The Middle Jurassic sediments consist of a lower carbonate unit and an upper clastic unit whereas the Upper Jurassic deposits are dominated by carbonates reflecting more deepening of the basin. Bioherms are locally developed in the Upper Jurassic sediments. These bioherms seem to have been deposited on the crests of the tilted fault blocks. Locally abundant basaltic volcanics are present in the Jurassic and Lower Cretaceous sequence of the Levant (Walley, 2001). The base of the Lower Cretaceous deposits, throughout the S-shaped belt, is marked by a pronounced unconformity (Walley, 2001; Sawaf et al., 2001). The Early Cretaceous was marked by sharply accelerated continental rifting activity as evident by the development of dominantly E-W trending grabens in northern Egypt and northeastern Libya (Guiraud, 1998) and active faulting in the Levant margin (Guiraud et al., 2001). This tectonic activity was associated with magmatic activity as evidenced by the extrusion of basalts in Negev (Gvirtzman et al., 1998). Lower Cretaceous volcanics are recorded throughout much of the Palmyra segment (Mouty et al., 1992).

3.7. Post-Tethys rift depositional stage

The rift tectonics seems to have been terminated by the end of Early Cretaceous time. During the early Late Cretaceous (Cenomanian), the north African margin was widely transgressed with the Neo-Tethys (Dercourt et al., 1993). In central Sinai, Cenomanian sediments are predominantly marls and shales whereas in northern Sinai carbonates become increasingly common. Turonian shales, marls, limestones and sandstones were deposited conformably on the Cenomanian beds. In north and central Sinai, the Senonian deposits are predominated by chalks. The Upper Cretaceous deposits of the Levantine and Palmyra segments consist mainly of marl, carbonates and chalks of the inner shelf and deep marine conditions (Walley, 2001; Sawaf et al., 2001). Lateral thickness variations of the Upper Cretaceous strata are partially controlled by the preexisting structural framework created by the preceding rift tectonics (Fig. 9).

3.8. Compressive tectonic stage

During the Late Cretaceous (Late Santonian-Early Campanian), the tectonic setting of the study area changed from being an extensional block-fault style to a compressive regime, due to closure of the Neo-Tethys and the coincident collision of the African-Arabian and Eurasian plates. Compressive fault blocks preferentially occur at convergent-plate boundaries (Harding and Lowell, 1979). At the time of Tethys closing, the new stress field seems to have been NNW-SSE oriented horizontal compression due to the convergent movement of the African-Arabian plate toward the Eurasian craton. This superimposed a separate generation of structures on the basin sediments, and interrupted the evolution of the basin. Since the larger preexisting extensional structures are faults that penetrate a substantial fraction of the crust, they provided discontinuities and zones of weakness that were reactivated by the new compressive stress field. Reactivation of the preexisting extensional faults in response to this new stress would have led to oblique reverse movement, whereas the transfer faults would have undergone simple wrench movement (Fig. 9). The deformation in the compressive stage could be started by the imposition of a small amount of horizontal shortening before the rejuvenation of the inherited NE and NNE oriented dip-slip and NW oriented wrench faults. Horizontally directed principal compressive stress, generated during the earliest stages of Neo-Tethys closing, affected the inclined surfaces of the preexisting faults in the study region. This stress was resolved into a normal stress (ǒ) perpendicular to the inclined fault planes and a shear stress (ô) acting parallel to these planes. As a result, the preexisting half grabens experienced movement in a reverse direction and the normal dip-slip movements along the NE (the southwest Cairo-Sinai and Palmyra segments) and NNE (the Levantine segment) oriented faults have reversed their directions of slip.

Intraplate contractional structures seem to have witnessed frequent compressive stress since the Late Cretaceous till the present. The consequent inversion and uplift of the Palmyra segment occurred in three distinct time periods (Chaimov et al., 1992). The first occurred at the end of the Cretaceous, the second in the Middle Eocene and the third began in the Miocene. This led to the tectonic inversion of the basin and to the formation of reverse and/or thrust faults whose hanging walls pushed up the sedimentary cover forming anticlinal folds with steeper flanks close to the reverse and/or thrust faults (Fig. 9). The reverse movement along the fault planes began initially at the basement and propagated into the overlying sedimentary rocks. The reverse movement may attenuate upward so that the causal reverse fault plane is seldom seen at the surface. Fault displacements and associated fold amplitudes continued to increase with the progress of the horizontal compressive stress. Faulting is assumed to be the primary deformation mechanism in the basement whereas faulting and folding have deformed the sedimentary rocks. This is due to the fact that the sedimentary rocks are mechanically different from basement rocks in two ways. First, most sedimentary rocks are considerably weaker than basement rocks and thereby more susceptible to failure under the same conditions (Handin and Hager, 1957; Borg and Handin, 1966). Second, the sedimentary rocks exhibit extreme layered anisotropy in the form of bedding (Scheevel, 1983). The second factor plays a large role in the geometry and kinematic development of folds. Wrench reactivation of the NW oriented transfer faults in the compressive stress would have been right-lateral and would have produced an en echelon arrangement of the contractional structures.

The contractional tectonics seem to coincide with a deepening of the southeastern Mediterranean and a shift in marine conditions so phosphatic and cherty chalks became the major regional sediments in the Palmyra and Levant (Walley, 2001). In Campanian to Maastrichtian time, ophiolites were obducted on the northern margin of the Arabian plate (Delaloye and Wagner, 1984).

The areal distribution and facies of Cenozoic sediments have been controlled by the inversion and uplift of the S-shaped Syrian Arc fold-thrust belt. The Paleogene carbonates are thicker in the intermontane basins (Fig. 9). The Red Sea rift, initiated in Oligo-Miocene time, and the Dead Sea transform fault system that initiated in Miocene time led to the separation of the Arabian plate from the African plate. Consequently, the Arabian plate experienced northward movement and anticlockwise rotation and its northern margin was thrust under the Eurasian plate. As a result, the S-shaped Syrian Arc fold-thrust belt experienced additional shortening and the Palmyra segment was separated from the Levantine segment by the Dead Sea left-lateral strike-slip faults. Oligocene and Miocene sediments, in the Palmyra, are composed of shallow marine to continental clastics and are overlain by Pliocene-Recent continental clastics derived mainly from the uplifting anticlines (Sawaf et al., 2001). Neogene and Quaternary basaltic volcanism is widespread in the Rutbah and Aleppo regions, but no surface volcanism exists within the Palmyra segment. Recent uplift of the northern Sinai contractional structures is supported by quantitative indices of active tectonics including values of mountain front sinuosity (Kusky and El-Baz, 2000). Modest seismicity, coupled with geological evidence based on morphotectonic observations, indicates that many of the Palmyra faults are still active (Trifonov et al., 1983; Leonov, 1989). The focal mechanisms of two moderate-size earthquakes that occurred in 1970 and 1987 in the northeast Palmyra segment show right-lateral oblique reverse motion along NW oriented faults (Chaimov et al., 1990).

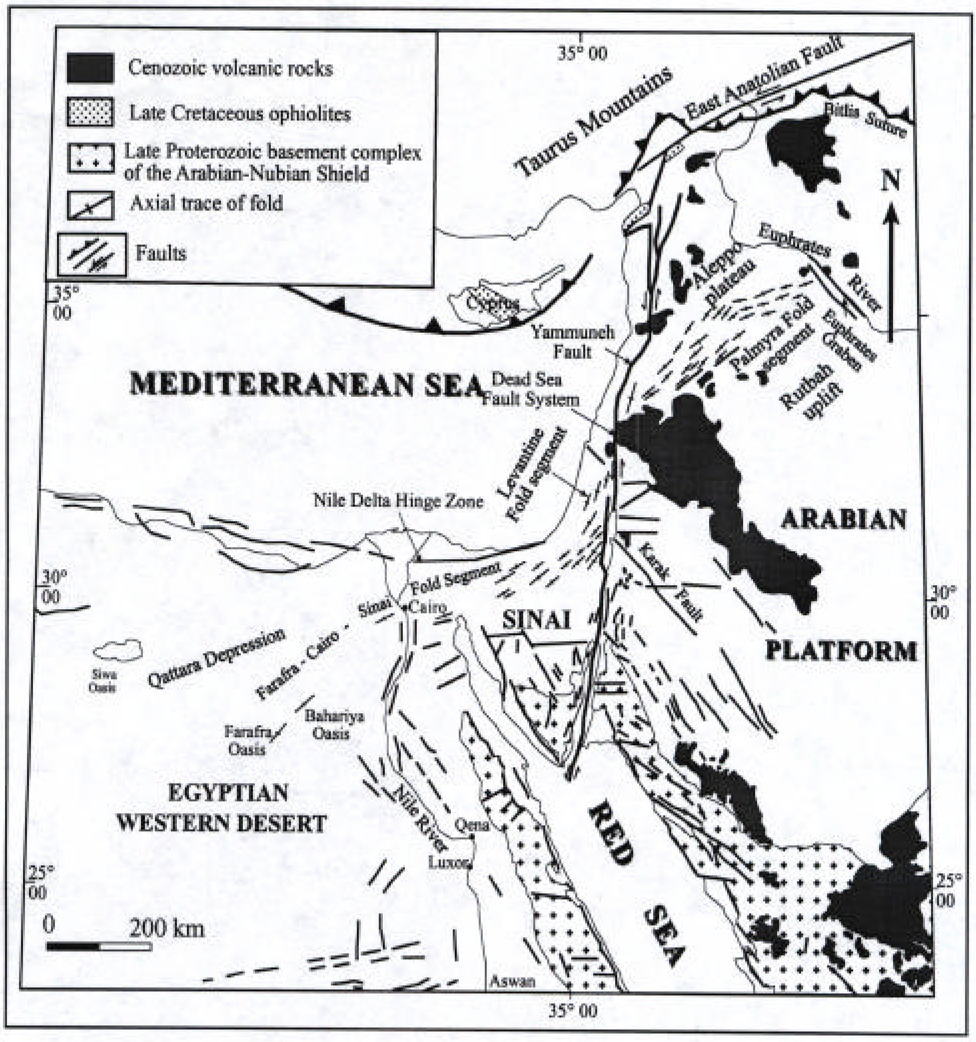

Fig (2): Structural framework of the S- shaped fold- thrust belt and its surroundings (based on UNESCO, 1976; Garfunkel, 1981 ; Sestini, 1984; McBride et al., 1990; Meshref, 1990; Morgan, 1990; Coleman, 1993).

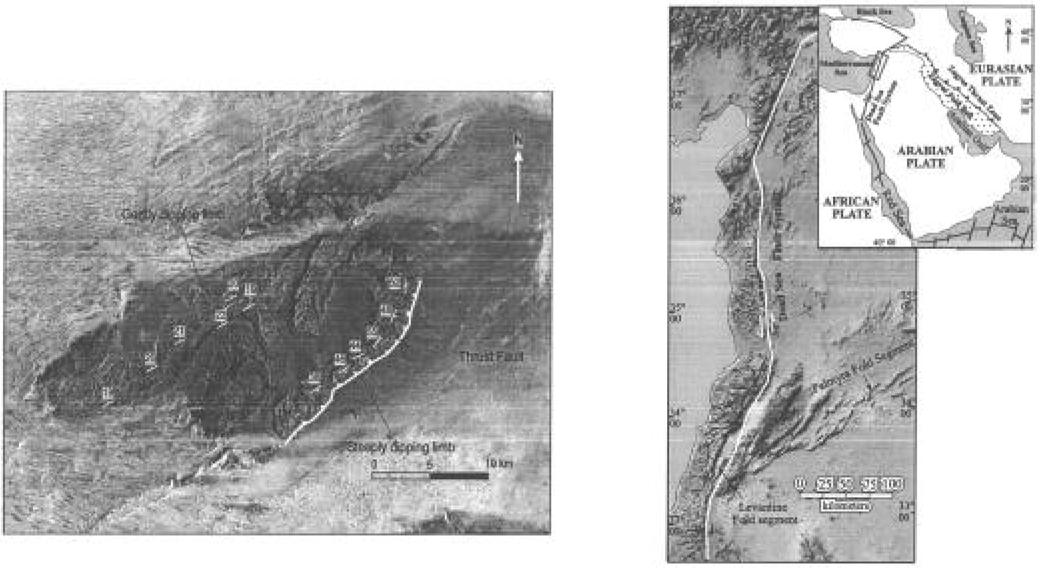

Fig (3): Landsat image showing NE-oriented asymmetric Maghara anticline, north Sinai, Egypt (left)and digital elevation model showing the Levantine and Palmyra fold- thrust segments (right).

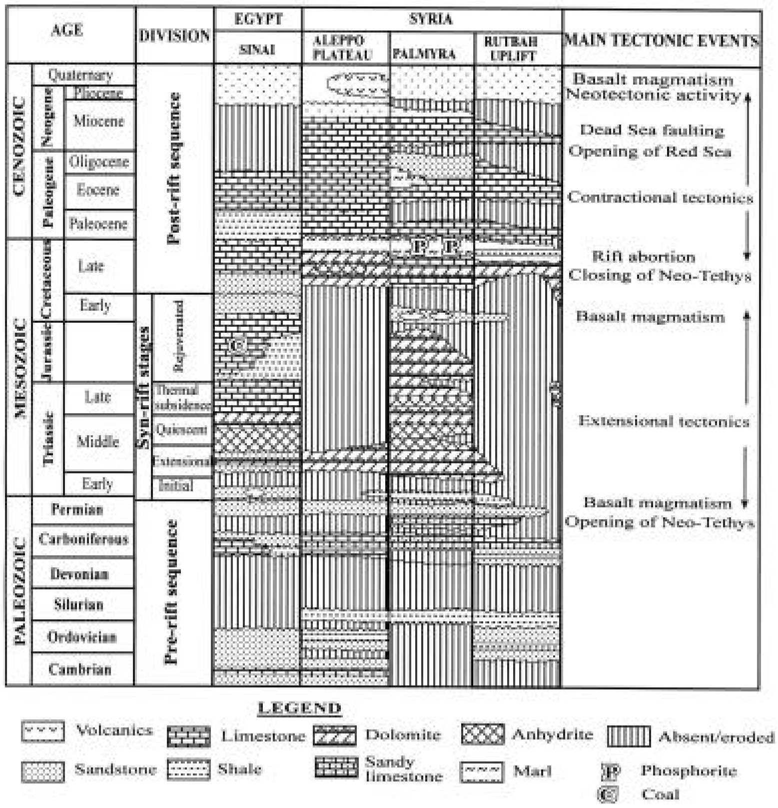

Fig (4): Tectonostratigraphic column of Sinai (Egypt)and Syria showing schematic lithology and the main tectonic events. Data from various sources; see text details.

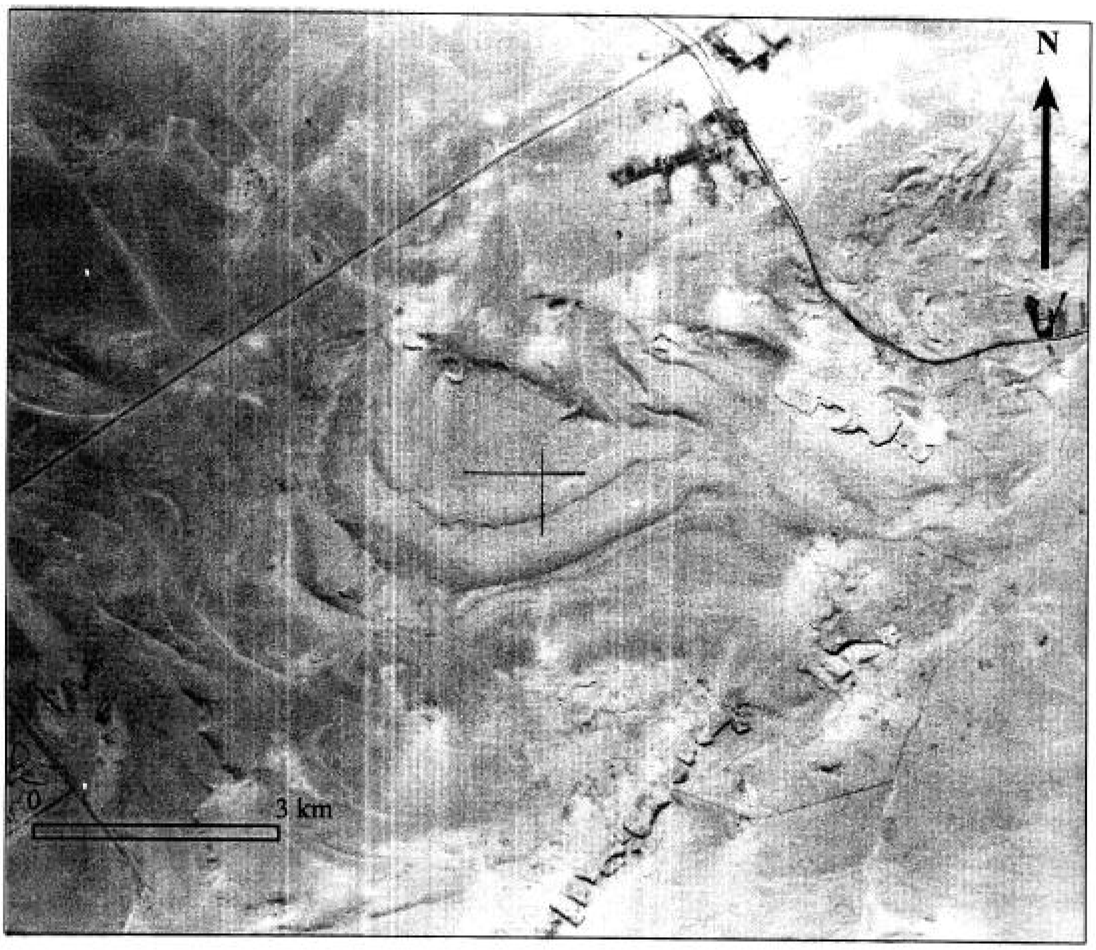

Fig (5): Orthogonal aerial photograph showing NE oriented folding in Abu Roash area about 8 km southwest of Cairo, Egypt.

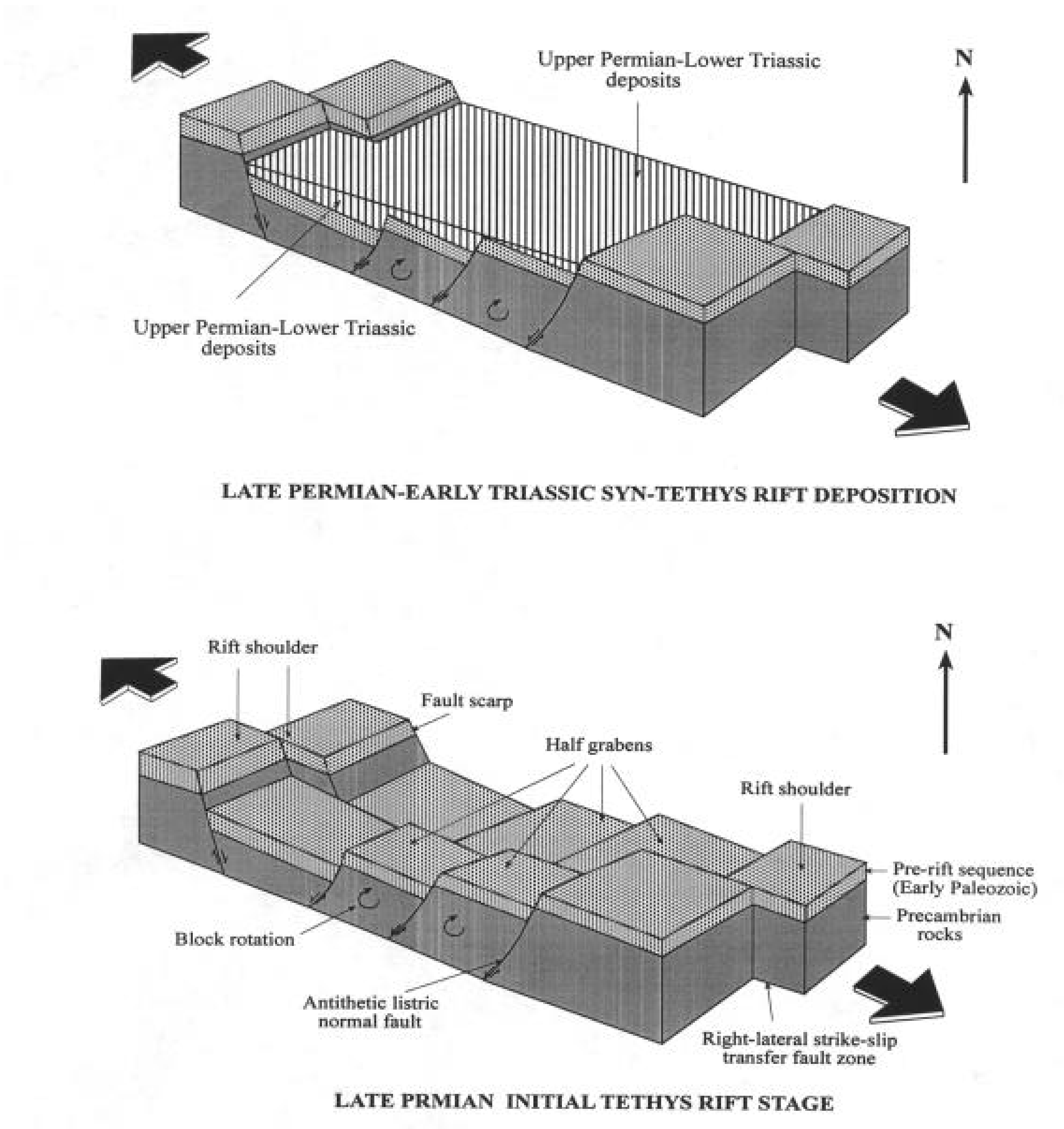

Fig (6): Schematic block diagrams showing the Late permain initial Tethys rift stage (below) and the late permain- Early Triassic syn-Tethys rift deposition (up).

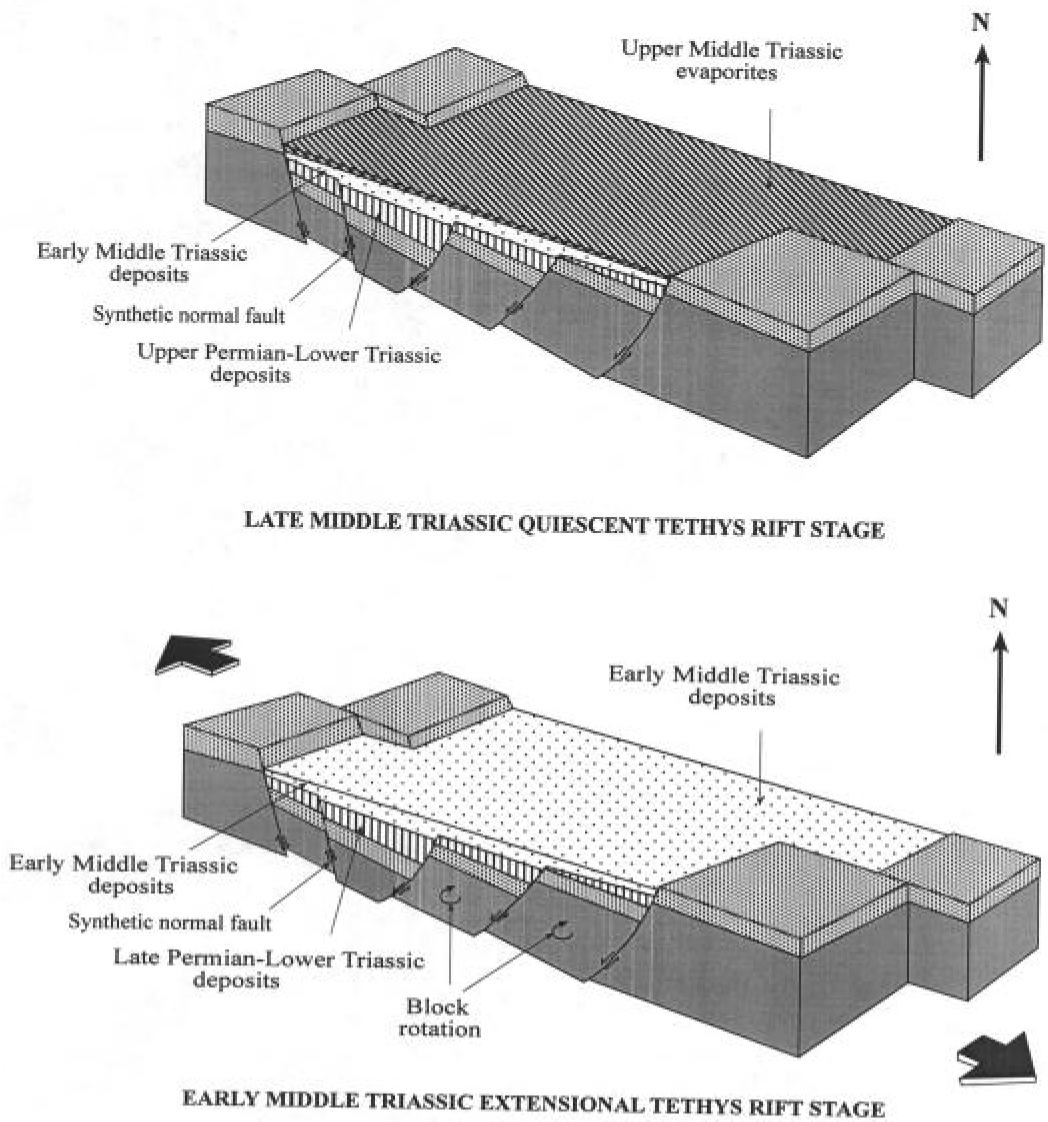

Fig (7):Schematic block diagrams showing early Middle Triassic extensional Tethys rift stage (below)and late Middle Triassic relative quiescent Tethys rift stage (up).

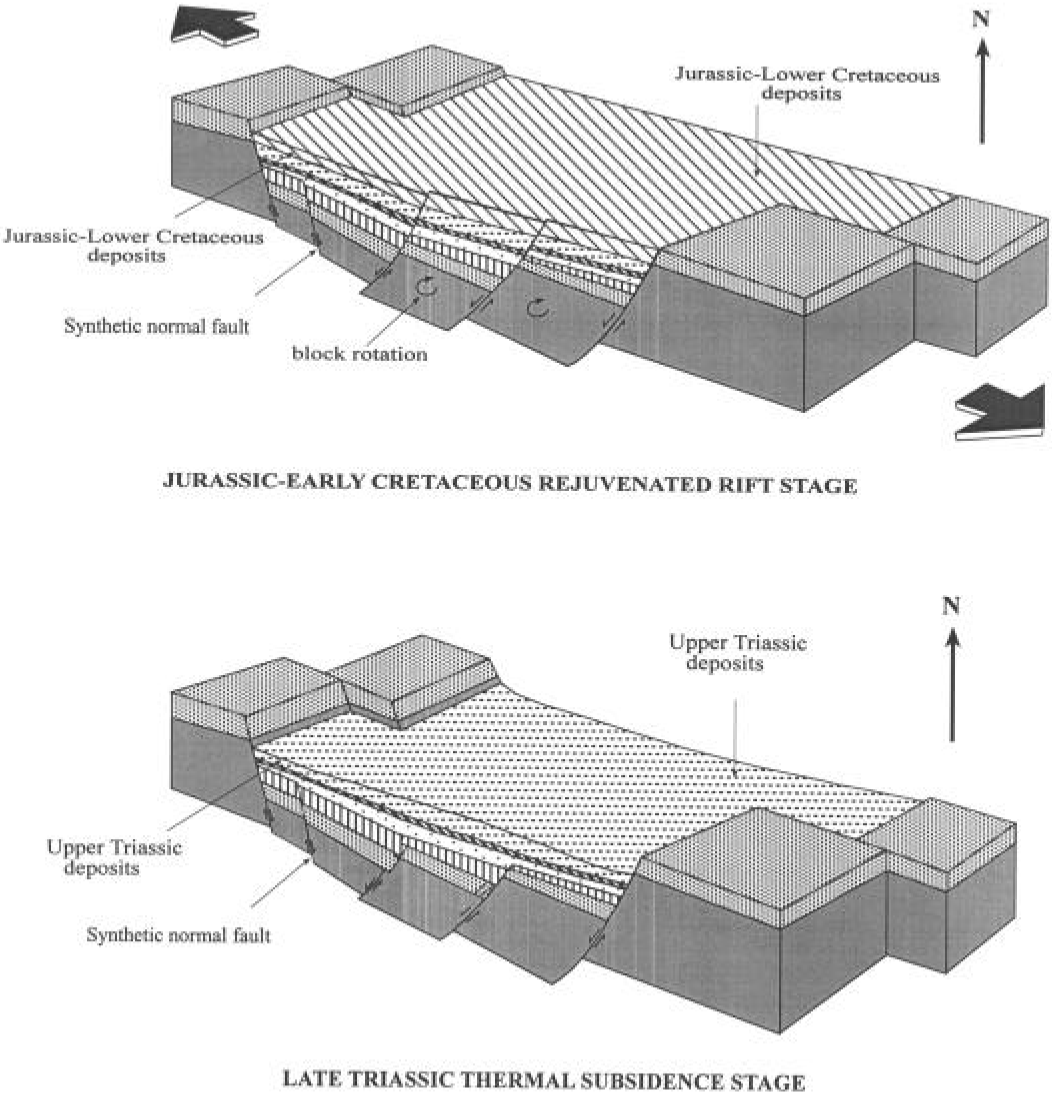

Fig (8): Schematic block diagrams showing the Late Triassic thermal subside nce stage (below) and Jurassic-Early Cretaceous rejuvenated rift stage (up).

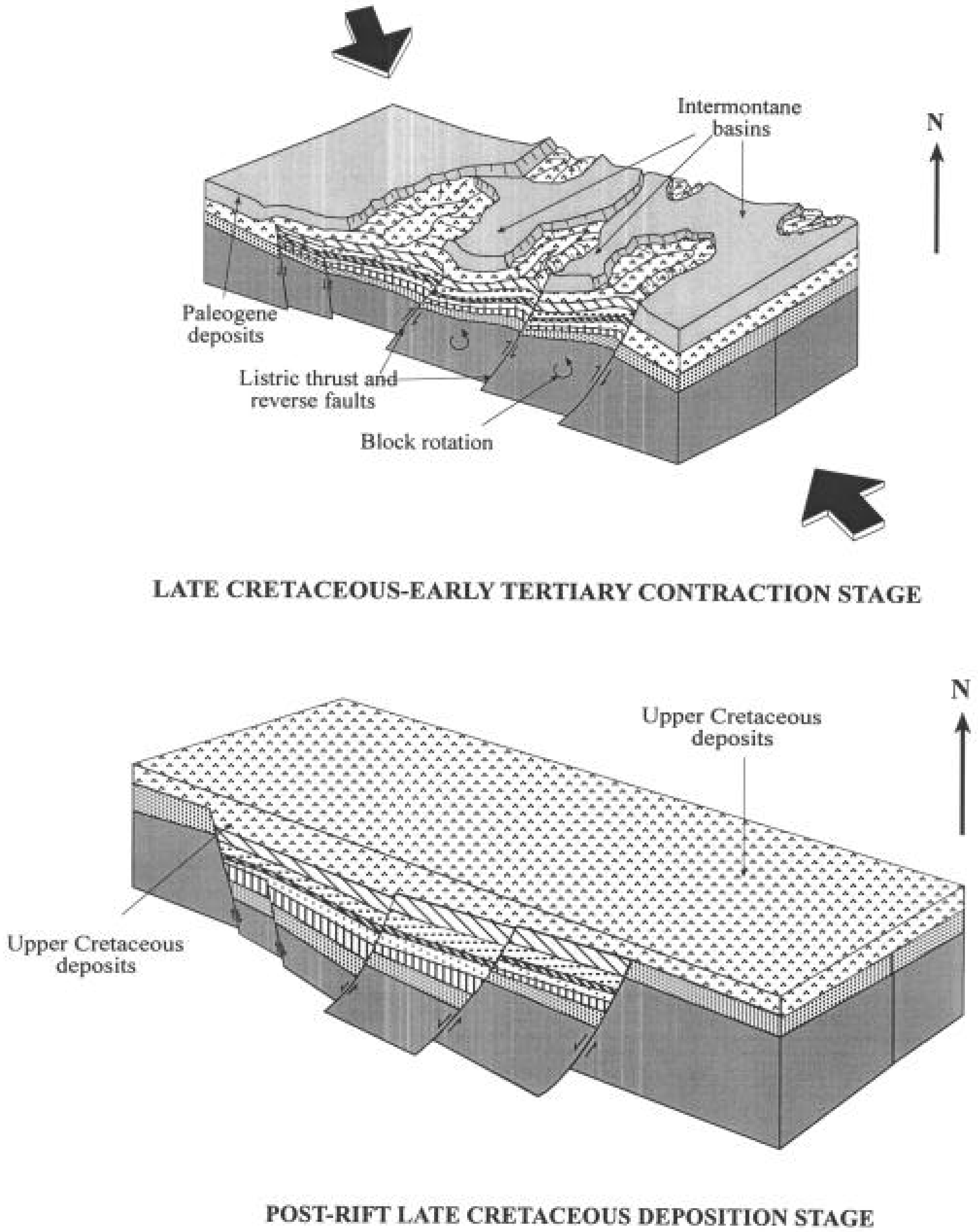

Fig θ): Schematic block diagrams showing the post-rift Cretaceous deposition (below) and the Late Cretaceous- Early Tertiary contractional stage (up). Note the paleogene deposits are thicker in the intermontane basins.

4. SUMMARY AND CONCLUSIONS

The intraplate S-shaped Syrian Arc fold-thrust belt consists of the NE oriented Farafra-Sinai and Palmyra segments and the NNE oriented Levantine segment. This belt evolved as an extensional rift in Late Paleozoic-Mesozoic times followed by contractional tectonics that began to inverse the rift basin in the Late Cretaceous. The tectonic evolution of the belt is governed by the opening and closing of the Neo-Tethys Ocean. Accordingly, the stratigraphic column of the study region is divided into pre- Tethys rift, syn- Tethys rift and post-Tethys rift sequences. Extensional NE and NNE oriented half grabens, formed during the initiation of rift, controlled thickness and facies variations in the study belt. NW oriented right-lateral strike-slip transfer faults bound the half grabens. During the rift process the half grabens experienced subsidence due to frequent rotations about NE and NNE oriented antithetic listric normal faults leading to an extensional block-fault style. Relative quiescent rift and thermal subsidence stages interrupted the rift tectonics during the late Middle Triassic and Late Triassic times respectively.

By Late Cretaceous, the rift tectonics had been aborted by the new NNW oriented horizontal compressive stress due to the closing of the Neo-Tethys and the convergence of Africa-Arabia and Eurasia. This compressive stress led to the initiation of uplift and inversion of the preexisting rift basin. Block-bounding listric normal faults have been rejuvenated into reverse faults in response to the resolution of the compressive stress. The inversion process involved contractional structures represented by folding and reverse/or thrust faulting. Cenozoic sedimentation has been significantly controlled by the occurrence of intermontane basins that received thick Paleogene and Neogene deposits. NW oriented right-lateral strike-slip faults significantly contribute to the structural evolution of the S-shaped fold-thrust belt. They controlled the en echelon arrangement of the contractional structures.

The Neogene-Quaternary structural development of the S-shaped Syrian Arc fold-thrust belt is coincident with intense movements documented along the margins of the African and Arabian plates, including the Red Sea rift system, the Dead Sea transform fault system, the Bitlis suture and the East Anatolian fault, and the Zagros continental collision zone. The intensity of neotectonic activity is well manifested in the northern reaches of the study region. Seismotectonic activities have been recorded in different areas of the belt. Clear knowledge of the structural architecture and evolution is prerequisite for successful exploration of petroleum producing structures in the intraplate S-shaped Syrian Arc fold-thrust belt.

REFERENCES

Abdel Aal, A.; Day, R. and Lelek, J. (1992): Structural evolution and styles of the northern Sinai, Egypt. 11th Explration & Production Conference, Egyptian General Petroleum Corporation, Cairo, Egypt, p. 547-562.

Abdel Khalik, M.L.; El-Sharkawi, M.A.; Darwish, M.; Hagras, M. and Sehim, A. (1989): Structural history of Abu Roash district, Western Desert, Egypt. Journal of African Earth Sciences, v. 9, no. 3, p. 435-443.

Abd El-Motaal, E.; Orabi, A.A.; Tolba, M.E. and El-Sawy, E.K. (2001): Structural development and its influence on the geomorphology of the strongly folded portion in northern Sinai, Egypt. Al-Azhar Bulletin Science, v. 12, no. 2, p. 37-50.

Almond, D.C. (1991): Anorogenic magmatism in northern Africa. In: M.J. Salem and O.S. Hammouda (eds), The geology of Libya. Third symposium on the geology of Libya, Tripoli, 27-30 September 1987, Elsevier, New York; Amsterdam, v. V, p. 2495-2510.

Al-Saad, D.; Sawaf, T.; Gebran, A.; Barazangi, M.; Best, J. and Chaimov, T. (1992): Crustal structure of central Syria: the intracontinental Palmyride Mountain belt. Tectonophysics, 207, p. 345-358.

Awad, G.H. (1946): On the occurrence of marine Triassic deposits in north Sinai. Bull. Inst. Egypt, 27, p. 397-429.

Ayyad, M.H.; Darwish, M. and Sehim, A. (1998): Introducing a new structural model for north Sinai with its significance to petroleum exploration. 14th Exploration & Production Conference, Egyptian General Petroleum Corporation, Cairo, Egypt, p. 101-117.

Barazangi, M.; Serber, D.; Chaimov, T.; Best, J.; Litak, R.; Al-Saad, D. and Sawaf, T. (1993): Tectonic evolution of the northern Arabian plate in western Syria. In: E. Boschi; E. Mantonani and A. Morelli (eds), Recent evolution and seismicity of the Mediterranean region. Kluwer Academic Publication, Dordrecht, p. 117-140.

Bartov, Y.; Lewy, Z.; Steinitz, G. and Zak, I. (1980): Mesozoic and Tertiary stratigraphy, paleogeography and structural history of the Gebel Areif en Naga area, Eastern Sinai. Israel Journal of Earth Sciences, 29, p. 114-139.

Best, J.A. (1991): Crustal evolution of the northern Arabian platform beneath the Syrian Arab rebuplic. Ph.D. Thesis, Cornell University, Ithaca, NY, USA, 152 p.

Best, J.A.; Barazangi, M.; Al-Saad, D.; Sawaf, T. and Gebran, A. (1990): Bouguer gravity trends and crustal structure of the Palmyride Mountain belt and surrounding northern Arabian platform in Syria. Geology, 18 (12), p. 1235-1239.

Best, J.A.; Barazangi, M.; Al-Saad, D.; Sawaf, T. and Gebran, A. (1993): Continental margin evolution of the northern Arabian platform in Syria. American Association of Petroleum Geologists Bulletin, 77 (2), p. 173-193.

Borg, I. and Handin, J. (1966): Experimental deformation of crystalline rocks. Tectonophysics, v. 3, p. 249-268.

Bosworth, W.; Guiraud, R. and Kessler, L.G. (1999): Late Cretaceous (~84 Ma) compressive deformation of the stable platform of NE Africa (Egypt): Far field stress effects of the 'Santonian event' and origin of the Syrian arc deformation belt. Geology, 27 (7), p. 633-636.

Brew, G.E.; Litak, R.K., Seber, D.; Barazangi, M.; Sawaf, T. and Al-Iman, A. (1997): Summary of the geological evolution of Syria through geophysical interpretation: Implication for hydrocarbon exploration. The Leading Edge, p. 1473-1482.

Chaimov, T; Barazangi, M.; Al-Saad, D.; Sawaf, T. and Gebran, A. (1990): Crustal shortening in the Palmyride fold belt, Syria, and implications for movement along the Dead Sea Fault system. Tectonics, 9 (6), p. 1369-1386.

Chaimov, T; Barazangi, M.; Al-Saad, D.; Sawaf, T. and Gebran, A. (1992): Mesozoic and Cenozoic deformation inferred from seismic stratigraphy in the southwestern intracontinental Palmyride fold-thrust belt, Syria. Bulletin Geological Society of America, 104 (6), p. 704-715.

Chaimov, T; Barazangi, M.; Al-Saad, D.; Sawaf, T. and Khaddouri, T. (1993): Seismic fabric and 3-D structure of the southwestern intracontinental Palmyride fold belt, Syria. American Association of Petroleum Geologists Bulletin, 77 (12), p. 2032-2047.

Coleman, R.G. (1993): Geological evolution of the Red Sea. Oxford Monographs Geology Geophysics, 24, 186 p.

Delaloye, M. and Wagner, J. J. (1984): Ophiolites and volcanic activity near the western edge of the Arabian plate. In: J.E. Dixon and A.E.F. Robertson (eds), The geological evolution of the Eastern Mediterranean. Special Publications, Geological Society of London, 17, p. 225-233.

Dercourt, J.; Ricou, L.E. and Vrielynck, B. (1993): Atlas Tethys, palaeoenvironmentalmaps. Gauthier-Villars, Paris, p. 1-307.

De Ruiter, R.S.C.; Lovelock, P.E.R. and Nabulsi, N. (1994): The Euphrates graben, Eastern Syria: a new petroleum province in the Northern Middle East. In: M. Al-Husseini (ed.),Geo 94, Middle East Petroleum Geosciences. Gulf Petrolink, 1, p. 357-368.

Etheridge, M.A.; Branson, J.C. and Stuart-Smith, P.G. (1985): Extensional basin forming structures in Bass Strait and their importance for hydrocarbon exploration. A.P.E.A. Journal, v. 25, p. 344-361.

Garfunkel, Z. (1981): Internal structure of the Dead Sea leaky transform (rift) in relation to plate kinematics. Tectonophysics, 80, p. 81-108.

Garfunkel, Z. and Derin, B. (1984): Permian-early Mesozoic tectonism and continental margin formation in Israel and its implications for the history of the Eastern Mediterranean. In: J.E. Dixon and A.H.F. Robertson (eds), The geological evolution of the Eastern Mediterranean. Special publications, Geological Society of London, 17, p. 187-201.

Guiraud, R.; Issawi, B. and Bosworth, W. (2001): Phanerozoic history of Egypt and surrounding areas. In: P.A. Ziegler; W. Cavazza; A.H.F. Robertson and S. Crasquin-Soleau (eds), Peri-Tethys Memoir 6: Peri-Tethyan rift / wrench basins and passive margi Memoires du national naturelle, 186, p. 469-509.

Gvirtzman, G. and Weissbrod, T. (1984): The Hercynian geanticline of Helez and the Late Paleozoic history of the Levant. In: J.E. Dixon and A.H.F. Robertson (eds), the geological evolution of Eastern Mediterranean. Special Publications, Geological Society of London, 17, p. 117-186.

Gvirtzman, Z.; Garfunkel, Z. and Gvirtzman, G. (1998): Birth and decay of an intracontinental magmatic swell: Early Cretaceous tectonics of southern Israel. Tectonics, 17, p. 441-457.

Handin, J. ad Hager, R.V., JR. (1957): Experimental deformation of sedimentary rocks under confining: test at room temperature on dry samples. American Association of Petroleum Geologists Bulletin, v. 41, p. 1-50.

Harding, T.P. and Lowell, J.D. (1979): Structural styles, their plate-tectonic habitats and hydrocarbon traps in petroleum provinces. American Association of Petroleum Geologists Bulletin, 63, p. 1016-1058.

Hempton, M. R. (1987): Constraints on Arabian plate motion and extensional history of the Red Sea. Tectonics 6, p. 687-705.

Issawi, B. (1996): Tectono-sedimentary synthesis of the Paleozoic basins in Egypt. In: Proceeding of 13th Exploration Conference, Egyptian General Petroleum Corporation, Cairo, v. 1, p. 1-23.

Issawi, B. and Jux, U. (1982): Contribution to the stratigraphy of the Paleozoic rocks in Egypt, Geological Survey of Egypt, paper no. 64, 28 p.

Jenkins, D.A. (1990
Rotterdam, Brookfield, p. 361-380.

Karner, G.D.; Lake, S.D. and Dewey, J.F. (1987): The thermal and mechanical development of the Wessex Basin, southern England. In: M.P. Coward; J.F. Dewey and P.L. Hancock (eds) "Continental Extension Tectonics ", Geological Society Special Publication no. 28, p. 517-536.

Keely, M.L. (1989): The Palaeozoic history of the Western Desert of Egypt. Basin Research, 2, p. 35-48.

Krenkel, F. (1925): Geologie der Erde, Geologie Africas, Bd. Gebruder Borntraeger, Berlin, 461 p.

Kusky, T.M. and El-Baz, F. (1998): Structural and tectonic evolution of the Sinai Peninsula, using Landsat data: Implications for groundwater exploration. Egyptian Journal Remote Sensing Space Sciences I, p. 69-100.

Kusky, T.M. and El-Baz, F. (2000): Neotectonics and fluvial geomorphology of the northern Sinai Peninsula. Journal of African Earth Sciences, v. 31, no. 2, p. 213-235.

Leonov, Y.G. (1989): The tectonic map of Syria, scale 1:500,000, Ministry of Petroleum and Mineral resources of the Syrian Arab Republic and Academy of Sciences of the USSR.

Litak, R.K., Barazangi, M.; Beauchamp, W.; Seber, D.; Brew, G.; Sawaf, T. and Al-Yousef, W. (1997): Mesozoic-Cenozoic evolution of the intraplate Euphrates Fault System, Syria: Implications for regional tectonics. Journal of the Geological Society, London, 154 (4), p. 653-666.

Lovelock, P.E.R. (1984): A review of the tectonics of the northern Middle East region. Geological Magazine, 121 (6), p. 577-587.

McBride, J.H.; Barazangi, M.; Best, J.; Al-Saad, D.; Sawaf, T.; Al Otri, M. and Gebran, A. (1990): Seismic reflection structure of intracratonic Palmyride fold-thrust belt and surrounding Arabian platform in Syria. American Association of Petroleum Geologists Bulletin, 74, p. 238-259.

McKenzie, D.P. (1978): Some remarks on the development of sedimentary basins. Earth and Planetary Letters, 40, p. 25-32.

Meshref, W.M. (1990):Tectonic Framework. In R. Said "Geology of Egypt". A.A.Balkema, Rotterdam, Brookfield, p. 113-155.

Morgan, P. (1990): Egypt in the framework of the global tectonics. In R. Said "Geology of Egypt". A.A. Balkema, Rotterdam, Brookfield, p. 91-111.

Moustafa, A.R. and Khalil, M.H. (1989): North Sinai structures and tectonic evolution. M.E.R.C. Ain Shams University Earth Sciences Series, V. 3, p. 215-231.

Moustafa, A.R. and Khalil, M.H. (1990): Structural characteristics and tectonic evolution of north Sinai fold belts. In R. Said "Geology of Egypt". A.A. Balkema , Rotterd Brookfield, p. 381-389.

Mouty, M.; Delaloye, M.; Fontignie, D.; Piskin, O. and Wagner, J.-J. (1992): The volcanic activity in Syria and Lebanon between Jurassic and actual. Schweitzerische Mineralogische und Petrographische Mitteilungen, 72, p. 91-105.

Omara, S. (1964): Diapiric structures in Egypt and Syria. American Association of Petroleum Geologists Bulletin, v. 48, no. 7, p. 1116-1125.

Ponikarov, V.P. (1966): The geology of Syria, scale 1:100 000. Ministry of Industry, Syrian Arab Republic, Damascus.

Ponikarov, V.P. (1967): The geology of Syria, explanatory notes on the geological map of Syria, scale 1:500 000 part I: stratigraphy, igneous rocks and tectonics. Ministry of Industry, Syrian Arab Republic, Damascus, 229 p.

Powel, J.H. and Khalil Mohamed, B. (1993): Structure and sedimentation of Permo-Triassic and Triassic rocks exposed in small-scale horsts and grabens of pre-Cretaceous age, Dead Sea margin, Jordan. Journal African Earth Sciences, 17, p. 131-143.

Quennell, A.M. (1984): The western Arabian rift system. In: J.E. Dixon and A.H.F. Robertson (eds) The geological evolution of the Eastern Mediterranean, Geol. Soc. London special publication 17, Blackwell scientific publications, Oxford, p. 775-778.

Ricou, L.E. (1995): The plate tectonic history of the past Teyhys Ocean. In: A.E.M. Nairn; L.E. Ricou, B. Vrielynck and J. Dercourt (eds), The ocean basins and margins. v. 8: The Tethys Ocean. Plenum Press, New York, London, p. 3-70.

Robertson, A.H.F.; Dixon, J.E.; Brown, S.; Collins, A.; Morris, A.; Pickett; Sharp, I. and Usta mer, T. (1996): Alternative tectonic models for the Late Palaeozoic-Early Tertiary development of Tethys in the Eastern Mediterranean region. In: A. Morris & D.H. Tarling (eds), Palaeomagnetism and Tectonics of the Mediterranean region. Special Publications, Geological Society of London, 105, p. 239-263.

Said, R. (1962): The geology of Egypt. Elsevier Pub. Co., Amsterdam, 377 p.

Sawaf, T.; Brew, G.; Litak, R. and Barazangi, M. (2001): Geological evolution of the intraplate Palmyride basin and Euphrates fault system, Syria. In: P.A. Ziegler; W. Cavazza; A.H.F. Robertson and S. Crasquin-Soleau (eds), Peri-Tethys Memoir 6: Peri-Tethyan rift / wrench basins and passive margins.Memoire du Museum National d'Hisoire naturelle, 186, p. 441-467.

Scheevel, J.R. (1983): Horizontal compression and a mechanical interpretation of Rocky Mountain foreland deformation. Wyoming Geol. Assoc. 34th Annual Field Association Guidebook: Geology of the Bighorn Basin, p. 53-62.

Sestini, G. (1984): Tectonic and sedimentary history of the NE African margin (Egypt/Libya). In: Dixon, J.E., Robertson, A.H.F. (eds), The geological evolution of the Eastern Mediterranean. Blackwell Scientific Publishers, Oxford, p. 161-175.

Shata, A. (1956): Structural development of the Sinai Peninsula, Egypt. Bull. Soc. Geogr. d'Egypte, 6 (2), p. 65-82.

Stampfli, G.M.; Marcoux, J. and Baud, A. (1991): Tethyan margins in space and time. In: J.E.T. Channel; E.L. Winterer and L.F. Jansa (eds), Paleogeography and paleoceanography of Tethys. Palaeogeography, palaeoclimatology, paleoecology, 87, p. 373-410.

Steinitz, G.; Bartov, Y. and Eyal, M. (1992): K-Ar and Ar-Ar dating of Permo-Triassic magmatism in Sinai and Israel-initial results.Israel Geological Society, Annual Meeting, 147 p.

Trifonov, V.; Youssef, A.; Al-Khair, Y. and Zaza, T. (1983): Using satellite imagery to infer the tectonics and the petroleum geology of Syria. Syrian Petroleum Company, Unpublished reports, Damascus, Syria, 18 p.

UNESCO (1976): Geological World Atlas. UNESCO and commission for the geological maps of the world, Paris, 22 sheets, scale 1:10 000 000.

Walley, C. (2001): The Lebanon passive margin and the evolution of the Levantine Neo-Tethys. In: P.A. Ziegler; W. Cavazza; A.H.F. Robertson and S. Crasquin-Soleau (eds), Peri-Tethys Memoir 6: Peri-Tethyan rift / wrench basins and passive margins. Memoire du Museum national d'Histoire naturelle, 186, p. 407-439.

Wennekers, J.H.N.; Wallace, F.K. and Abugares, Y.I. (1996): The geology and hydrocarbons of the Sirt Basin: a synopsis. In: M.J. Salem; A.J. Mouzughi and O.S. Hammuda (eds), The geology of the Sirt Basin, First Symposium on the sedimentary basins of Libya, Tripoli, 10-13 October 1993, Elsevier, Amestrdam; New York, v. 1, p. 3-58.

Ziegler, P.A. (1989): Evolution of Laurussia. A study on Late Palaeozoic plate tectonics. Kluwer Academic Publication, Dordrecht, p. 1-102.

Youssef, M.I. (1962): Structural pattern of Egypt and its interpretation. AAPG Bulletin, v. 52, p. 601-614.