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The Levant Slumps and the Phoenician Structures: collapse features along the continental margin of the southeastern Mediterranean Sea

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Abstract Two distinct series of slumps deform the upper part of the sedimentary sequence along the continental margin of the Levant. One series is found along the base of the continental slope, where it overlies the disrupted eastern edge of the Messinian evaporites. The second series of slumps transects the continental margin from the shelf break to the Levant Basin. It seemed that the two series were triggered by two unrelated, though contemporaneous, processes. The shore-parallel slumps were initiated by basinwards flow of the Messinian salt, that carried along the overlying Plio-Quaternary sediments. Seawater that percolated along the detachment faults dissolved the underlying salt to form distinctly disrupted structures. The slope-normal slumps are located on top of large canyons that cut into the pre-Messinian sedimentary rocks. A layer of salt is found in the canyons, and the Plio-Quaternary sediments were deposited on that layer. The slumps are bounded by large, NW-trending faults where post-Messinian faulted offset was measured. We presume that the flow of the salt in the canyons also drives the slope-normal slumps. Thus thin-skinned halokynetic processes generated the composite post-Tortonian structural patterns of the Levant margin. The Phoenician Structures are a prime example of the collapse of a distal continental margin due to the dissolution of a massive salt layer.

Keywords Mediterranean geology · Messinian evaporites · Salt dissolution · Levant margin · Collapse structures · Salt flow · Shallow faults · Collapse of continental margin

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Introduction

The Levant Basin is located at the southeastern corner of the Mediterranean Sea, bounded by the continental margin of Egypt and Sinai to the south, of Israel and Lebanon to the east, by Cyprus Arc and Eratosthenes Seamount to the north, and the Nile deep-sea fan to the west (Fig. 1). The Levant Basin and its southeastern continental margin has comprised a divergent continental margin since the Triassic (Garfunkel and Derin 1984; Mart and Ryan 2002), and a sequence of some 12 km of sedimentary rocks has accumulated there since (Ginzburg and Gvirtzman 1979). The present bathymetric depth of the basin is approximately 1,000 m off southern Israel and Sinai, and exceeds 2,500 m north of Eratosthenes Seamount (Hall 1984).

Sediment deposition in the Levant Basin and margin was interrupted in the latest Miocene, when the Mediterranean Sea desiccated during the Messinian stratigraphic stage (6.9–5.4 Ma) (Ryan 1978; Bertoni and Cartwright 2006). During that time-span sea level dropped to depths of nearly 2 km below its present level, so that the deeper parts of the Levant Basin became a series of hypersaline basins, depositing large quantities of gypsum, halite and other evaporitic minerals. Concurrently the Mediterranean continental margin changed from a depositional environment to an erosive continental domain (e.g., Ryan and Cita 1978;

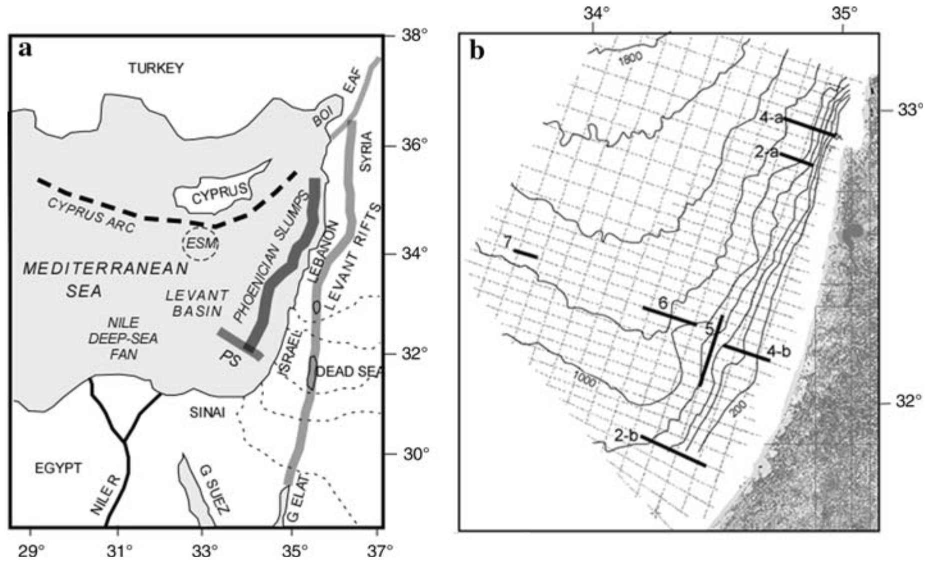

Fig. 1 (**a**) The Levant Basin and surrounding terrains. The divergent margins are the southern and eastern margins of the basin. The tentative pattern of Hazeva fluvial system in the late Miocene is marked by dashed lines; BOI—Bay of Iskanderun, ESM—Eratosthenes Seamount, EAF—East Anatolian Fault, PS—Palmahim Slump. (**b**) Location map of the unmigrated seismic database and numbered heavy lines show the position of the presented seismic profiles. Contour interpolation is based on the seismic database. Contour interval is 200 m

Rouchy et al. 2003; Bertoni and Cartwright 2005; Rouchy and Caruso 2006). The normal marine regime of the eastern Mediterranean was resumed in the early Pliocene, but two features remained in the geological record as evidence of the Messinian desiccation, the thick evaporitic sequence that was deposited in the Basin, and the extensive erosion that shaped its margins (e.g., Ryan 1978).

The thickness of the evaporite deposit indicates that the truncation of the Levant Basin from the Atlantic water supply was not complete. The hydrologic regime was such that the amount of water flowing into the basin was less than the evaporated water, but sufficient to accumulate a 2 km thick layer of evaporitic rocks. The widespread distribution of the Messinian erosional features indicates that the wearing down of rock and the subsequent fluvial transport of clastics during that short stratigraphic stage was extremely intensive, and that fluvial systems extended far into domains occupied by sea previously and subsequently.

The major source of sediments in the eastern Mediterranean since the Messinian is the Nile River. Until the construction of the Aswan High Dam, the river poured large quantities of sands and clays into the sea to form the distal Nile deep-sea fan and the proximal Nile littoral cell (Ross and Uchupi 1977; Goldmith and Golik 1980; Bellaiche and Mart 1995; Loncke et al. 2006). The Nile River was also a major sedimentary contributor to the depositional prism of the Levant margin (Gvirtzman and Buchbinder 1978). However, an additional source of fluvial sediments to the Levant margin existed in the Miocene and the early Pliocene where a large network of rivers drained NW Arabia to the Mediterranean Sea named "Hazeva Fluvial System" (Sneh 1981; Zak and Freund 1981). The Hazeva fluvial system transported sediments from northern Arabia across the Dead Sea Rift and its elevated flanks to the Mediterranean Sea (Horowitz 1979, 2001). The joint sedimentary input of the Nile and the Hazeva led to the accretion of a large sedimentary prism along the distal continental margin off southern and central Israel. However, whereas the sedimentary prism of the Nile delta reaches its maximal thickness under the distal shelf, then it gradually thins seawards (Ross and Uchupi 1977; Tibor et al. 1992; Abdel-Aal et al. 2000; Segev et al. 2006), the Levant prism reaches its maximum thickness along the distal continental slope, then pinches out seawards. The structural development of the Dead Sea Rift truncated the drainage of the Hazeva rivers to the Mediterranean Sea probably in the middle Pliocene (Horowitz 2001) and since then the Nile provides the major contribution to the sedimentary prism off Israel. Consequently we presume that deep canyons of the Hazeva Rivers that transect the coastal plain and continental margin of Israel linked late Miocene drainage with the Messinian desiccation.

The Plio-Quaternary accretion of sedimentary prisms along the distal continental slope are not abundant phenomena, and the Levant prism is characterized also by its occurrence along the eastern edge of the Messinian evaporites as well, and the prism is transected by numerous slumps and faults. These structures can be traced along the base of the continental slope from southern Israel to northern Lebanon (Fig. 1). In the present paper we present a halokynetic account for the slumps and faults along a Plio-Quaternary sedimentary prism off the Levant, and suggest an explanation for the Plio-Quaternary depositional patterns in that region. Furthermore, the Phoenician Structures are an example of the collapse of a distal continental margin due to the dissolution of a massive salt layer.

Methods

We used for our research a series of multichannel seismic reflection profiles that were obtained offshore Israel in 1983 for petroleum exploration purposes, then released to academic research by the Petroleum Commissioner of the Israeli Ministry of National Infrastructures (Fig. 1b). The seismic signal was produce using seven airguns with total capacity of 2,180 cu. in. at pressure of 1,950 p.s.i., and 25 m spacing between shots. Receiving system comprised 120 channels of 30 seismometers each at 25 m spacing. The survey was shot at square-set trending NNE and WNW. Spacing between the NNE trending profiles was 10 km, and between the WNW profiles—5 km along the continental margin and 10 km in the marine basin. The seismic data were processed by the acquisition team, and interpreted using The Kingdom Suite 8.1 interpretation software of Seismic Microtechnologies Inc.

Geological setting

Early geophysical investigations in the Mediterranean Sea recognized two prominent seismic reflectors. A deeper one was encountered under the basinal domains and was termed Reflector N, and an upper one, which was more widespread, was called Reflector M (Ryan et al. 1970). The boreholes of Deep Sea Drilling Project (DSDP) Legs 13 and 42-A showed that these reflectors mark the base and the top of the Messinian evaporitic sequence, respectively (Ryan et al. 1973; Hsü et al. 1978). Most commonly Reflector M extended not only into the marine basins, but along the continental slope and shelf as well, where it covers a wide range of strata. Reflector M, which marks the base of the Pliocene sedimentary series, has two facies—depositional and erosional. Reflector N, which marks the base of the Messinian evaporitic sequence, was encountered only in the Levant Basin. In most places the reflection time to the merging zone between Reflectors M and N is approximately 2.5 s.

Seismic reflection studies along the distal continental margin of Israel encountered a series of irregularly deformed and faulted features buried under Plio-Quaternary sediment slumps at the base of the continental slope (Neev et al. 1976). Neev (1977) attributed the feature to a mega-shear that delimited the Levant Basin. Since the megashear was supposed to extend below the Pelusian arm of the Nile delta, Neev (1977) named it "The Pelusian Line". In subsequent studies Neev et al. (1982, 1985) suggested that their Pelusian Line extended across Africa and even further into the Atlantic Ocean, but that megashear concept was not accepted by the geological community. On the other hand, Garfunkel's (1984) structural analysis of the Levant margin ignores the structures at the base of the continental slope altogether. Tapponnier et al. (2004) encountered these irregular structures in the Messinian and Plio-Quaternary offshore Lebanon, and suggested that they indicate subduction processes, where Mediterranean oceanic crust is being thrust eastwards under Lebanon. Since, in spite of the conflicting views, the irregular structures of the Messinian series along the base of the continental slope off Israel and Lebanon seem real, we suggest that in order to avoid confusion, the term "Phoenician Structures" should be applied to them.

The Phoenician Structures

The Messinian evaporitic sequence in the Levant Basin reaches thicknesses of nearly 2,000 m. It maintains a nearly steady thickness in the Levant Basin (Mart and Ben-Gai 1982), and wedges out towards the Levant continental slope. In many places this pinching-out occurs at seismic reflection two-way time of ~2.5 s (ca. 2,250 m), where coastal terraces and other shore-related features were reported (Bertoni and Cartwright 2006). A different depth estimate presumed that sealevel during the Messinian was 1,300 m below the present level, and that subsequent subsidence brought the stratigraphic marker to its present depth (Ben-Gai et al. 2005) Along large tracts of the continental slope off Israel and Lebanon the pinching-out zone of the Messinian evaporites is distinguished by irregular seismic stratigraphy. Seismic Reflectors N and M do not present continuous reflections. Their elevations vary locally, apparently suggesting faulting and thickness variation of the evaporites (Fig. 2). The width of the disrupted zone is 10–25 km, and it extends for more than 200 km (Fig. 3), from the Palmahim Slump off southern Israel to north of Beirut in Lebanon (Fig. 3). The only place where the Phoenician Structures were noticeably displaced is along the northern fault of the Palmahim Slump, where lateral offsets of 12 km and vertical displacement of 110 m apparently took place (Fig. 3). It should be noted however, that the lateral offset could be partly or entirely apparent, as indicated by evaporite deposition in the morphological trough that preceded the Palmahim Slump. The vertical displacement could be real and not an artifact, and could be attributed to halokynetics.

The Phoenician Structures do not occur south of the Palmahim Slump and the pinching-out zone of the evaporites, where reflectors M and N merge, show regular bedding (Fig. 2b). Some studies have reported on the occurrence of salt diapirs in the Phoenician Structures (e.g., Neev et al. 1976; Garfunkel and Almagor 1985), but we could not verify this observation.

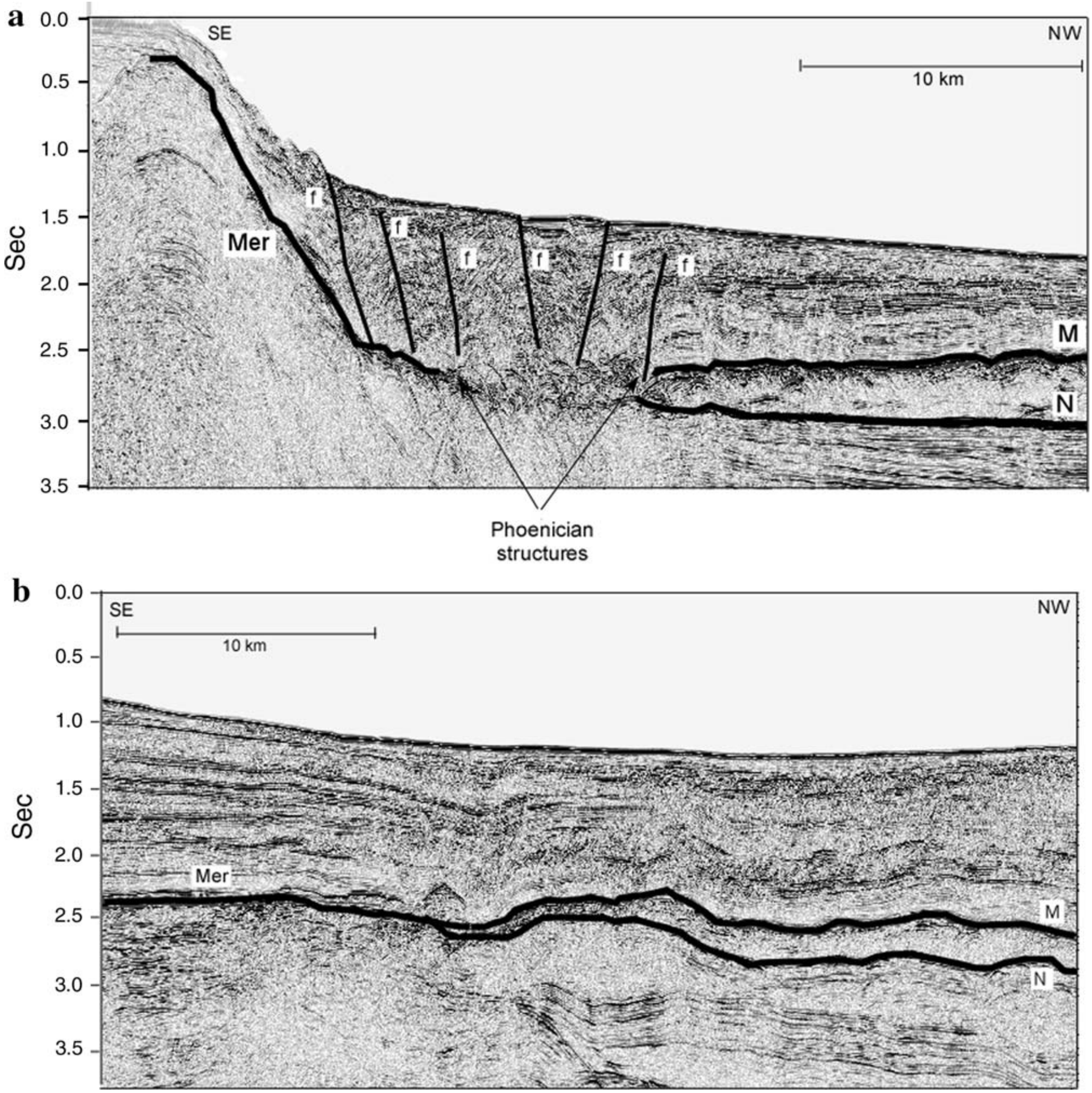

Fig. 2 (**a**) The Phoenician Structures are complex slumps located at the pinching out zone of the Messinian evaporites, where seismic Reflectors N and M merge. Reflector Mer is the erosional facies of Reflector M with depicts base Pliocene. Note that the coherent reflectors above the erosional Reflector M collapse above the merging zone. (**b**) South of the Palmahim Slump the Phoenician Structures are absent, and the merging zone of Reflectors M and N and the overlying Plio-Quaternary sequence are regular. See Fig. 1b for location

The Phoenician slumps

The Phoenician Structures and the disrupted pinching-out zone of the evaporites is overlain by large slumps and thick accumulation of sediments of Plio-Quaternary age. The slumps always have a series of large normal faults that detach slumped blocks from the proximal margin to the east (Fig. 2a). Many of these faults extend laterally for approximately 30–50 km and the faults are set *en échelon*, oriented 5–10° east of the trend of the coastline. In many places the Phoenician Plio-Quaternary slumps are constrained from the west by a conjugate series of normal faults. The throw along these latter faults is less than that of the eastern fault belt, and commonly the offset sediments retain their bedding. The inner texture of the slumps is not uniform. In some places the bedding of the slumped blocks is well preserved, suggesting slow evolution and gradual displacement of the slump, but in others the internal reflections were not preserved, indicating a faster rate of slumping. It is of interest to note that the Plio-Quaternary sediments off the Levant reach their thickest development along the Phoenician slumping zone, and they thin out both upslope and downslope.

The Phoenician Messinian structures and the overlying Plio-Quaternary slumps are independent of the gradient of the continental slope. They occur offshore northern Israel (Fig. 3) where the slope is very steep (Fig. 4), but also off central Israel, where gradients of the continental slope are moderate (Fig. 2). Even the intensity of the deformation of the Messinian layers does not show correlation with the gradient of the continental slope. The only change of depth of the Messinian layers in the Phoenician Structures was encountered south of the northern boundary fault of the Palmahim Slump, where it is probably apparent. The Phoenician structural complex does not extend south of Palmahim Slump.

Transverse slumps

Unlike the Phoenician Structures that are characterized by their steady depth and lack of interference with the gradient of the continental slope, a series of transverse slumps cross the continental slope of the Levant. These slumps show diverse types of structural patterns. Two large slumps developed in the continental margin of Israel, the Palmahim and Dor Slumps (Garfunkel et al. 1979; Mart 1984), and several have also been reported from the Lebanese margin. The Palmahim and Dor Slumps were deposited on top of large and deep canyons that reach depth of 1,000 m and width of 10 km (Fig. 5). The occurrence of the Messinian evaporite sequence in the proximity of the canyon is not uniform, and evaporite layer of thickness of at least 300 m was discerned there. It seems that during the late Messinian the canyon formed a topographically depressed area, where evaporites were deposited while erosional facies prevailed along the elevated shoulders of the canyon. The Phoenician Structures were discerned inside the slump at reflection times of 2.35 s, some 0.15 seconds shallower than the depth of the remainder of the Phoenician

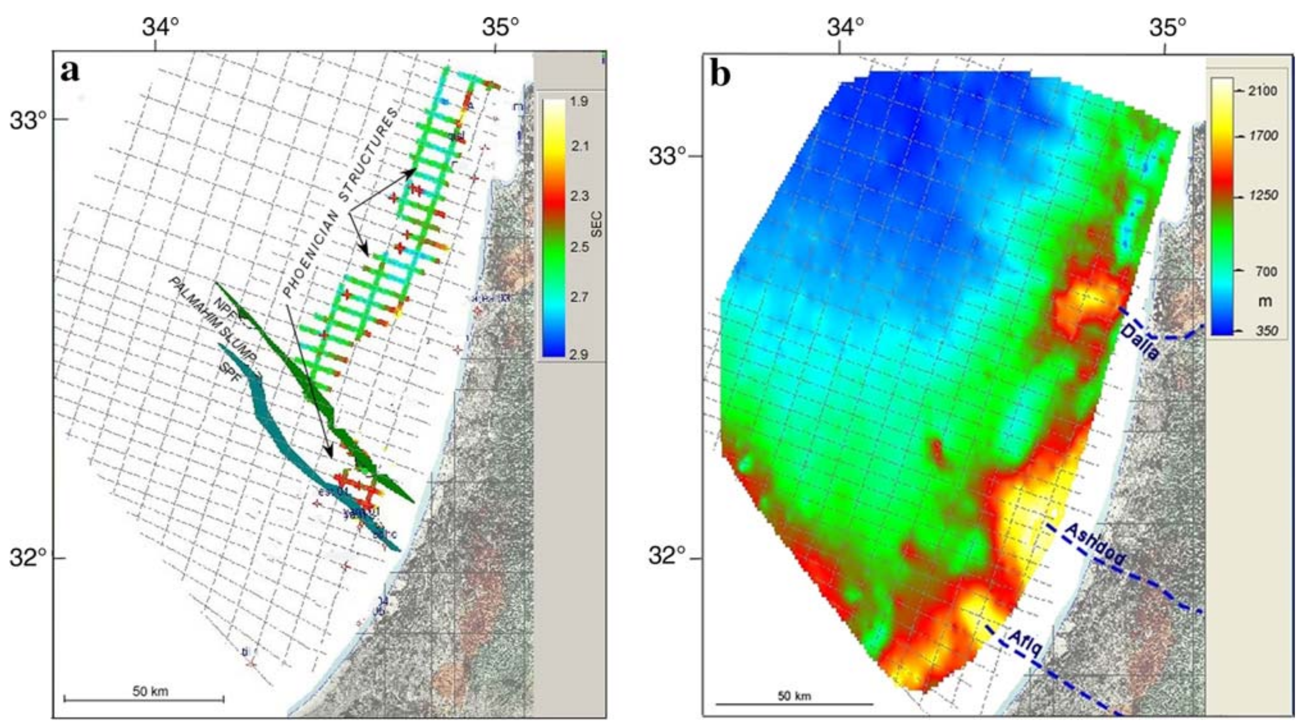

Fig. 3 (**a**) Time-based map of the Phoenician Structures, which are located where the traces of the profiles are colored. Thick green and petrol lines marked NPF and SPF represent the northern and southern boundary faults of Palmahim Slump respectively. The displaced segment of the Phoenician Structures inside the slump is elevated 0.15 s reflection time above the rest of the structures. The area of the Palmahim Slump was a morphological trough during the Messinian, and salt accumulated there, while the areas laterally adjacent to it were eroded. Color bar shows reflection time in seconds. (**b**) Time-based isopach map of base Pliocene to seafloor, thickness in meters. Note the increased thickness of the Plio-Quaternary sedimentary prism off several rivers that cross the coastal plain. Since the mid Pliocene the rivers are short and small, but in the early Pliocene and the Miocene they drained northern Arabia across the Dead Sea rift and its elevated margins. (After Zak and Freund 1981; Mart et al. 2005)

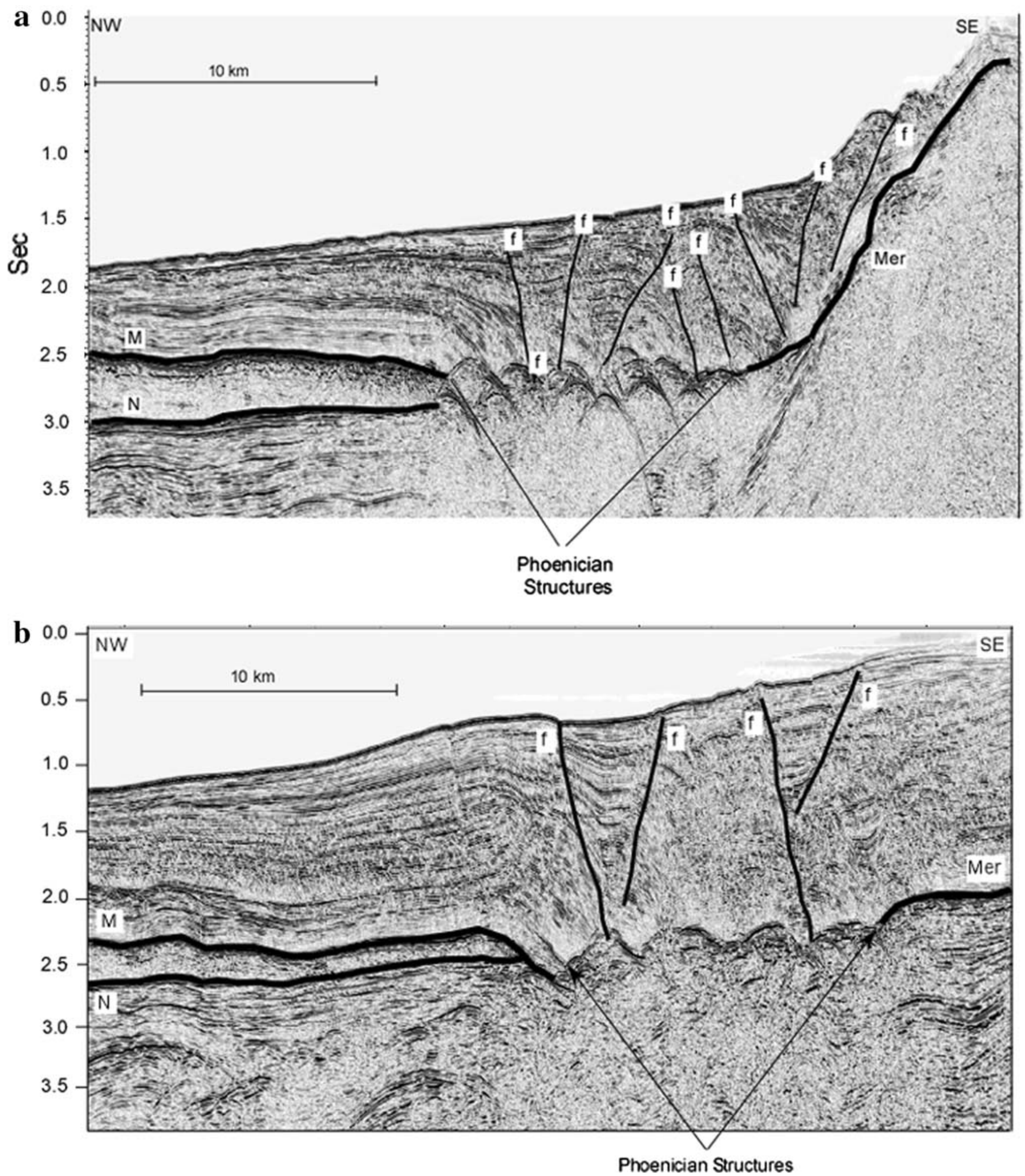

Fig. 4 Phoenician Structures and the overlying Plio-Quaternary slumps are not dependent on the gradient of the continental slope. They were formed off Akko, northern Israel where the bathymetric gradient is steep (**a**) and along the gentle gradients off Ashdod in the southern coastal plain (**b**)

Messinian structures (Fig. 3). The Phoenician complex, both of the Messinian evaporites structures and the Plio-Quaternary slumps, does not extend beyond the Palmahim Slump, and south of that feature the pinching out of the Messinian evaporites and the merging of Reflectors M and N is regular (Fig. 2b).

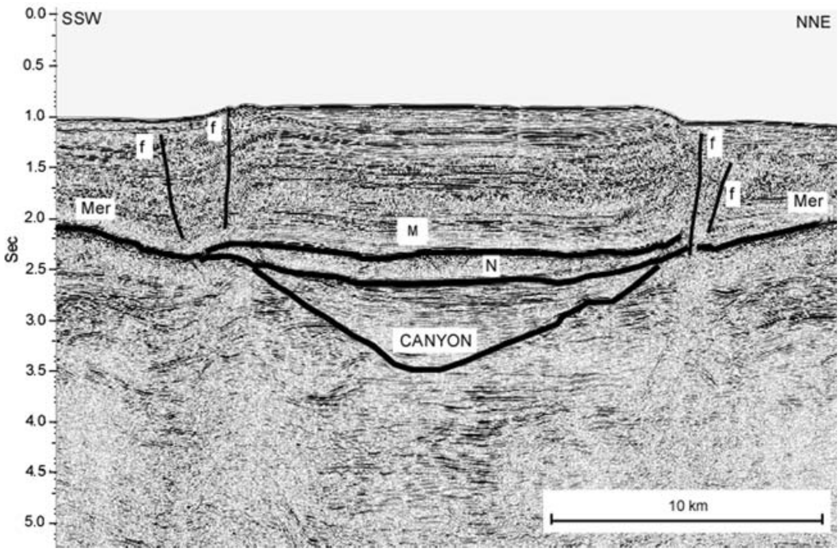

Fig. 5 A few canyons transect the continental slope of Israel and cut into the pre-Messinian sedimentary sequence. Palmahim Canyon is approximately 10 km wide and 1 km deep. The thickness of the Messinian sequence in the canyon reaches 300 m, while it is absent outside. The canyon affects, but does not deform intensively, the overlying Messinian strata. The Messinian sedimentation occurred when the thalweg of the canyon in the latest Miocene was a depositional zone while the shoulders of the canyon were eroded subaerially. The Plio-Quaternary sequence above the canyon is a part of the Palmahim Slump. See Fig. 1b for location. *Mer* marks the erosional facies of Reflector M, which depicts the base of the Pliocene sedimentary series

Reverse faults

The occurrence of numerous small reverse faults in the Levant Basin has been reported only recently (Ryan and Mart 2005; Bertoni and Cartwright 2006). The faults invariably dip landwards, uplifting the block nearer to land, and affecting Reflector M and the overlying Plio-Quaternary sequence. The faults do not displace the lower part of the evaporitic sequence and Reflector N is not offset by them, indicating that the motion can be regarded as a thin-skinned structural phenomenon (Fig. 6). Similar faults and offset patterns were discerned also in the deep-sea fan of the Nile (Loncke et al. 2006). Commonly the overthrust layers are bent to produce a partial fold. The orientation of the faults and the folds is composite. Some strike E-W to NW-SE, while others trend NNE-SSW. The composite

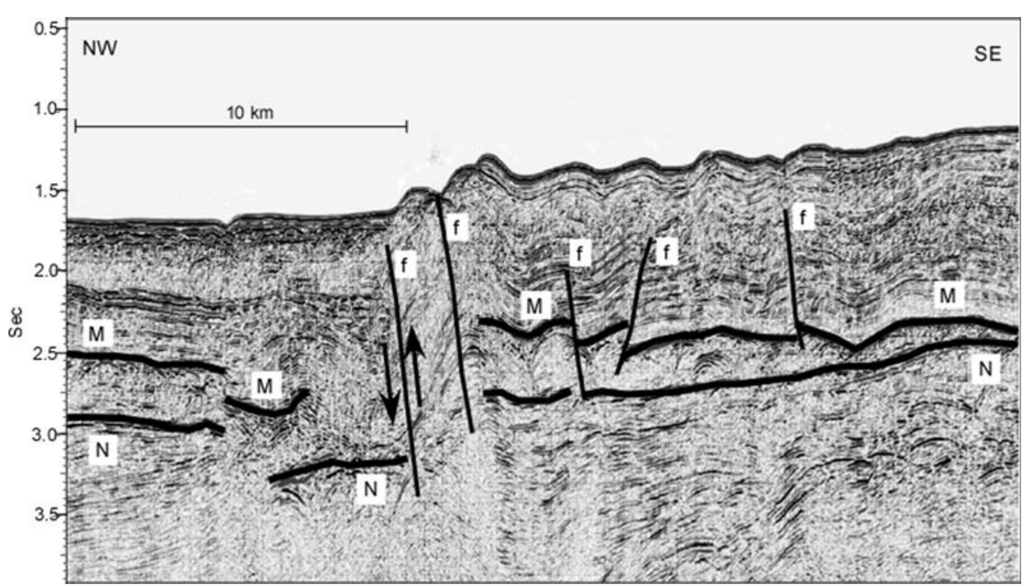

Fig. 6 The western edge of the Palmahim Slump shows local overthrusting of the sedimentary mass that glides downslope. See Fig. 1b for location

orientation of the reverse faults was recently described by Bertoni and Cartwright (2005), who utilized 3D seismic data as their high-resolution tool. These authors showed that the Messinian salt has been flowing since the Pliocene, dragging with it the overlying strata. The cause of that flow could only be speculated upon, and could be linked to the sedimentary load on the salt due to the thick sequence of Plio-Quaternary sediment deposits. That sedimentary load could mobilize the salt and drive it toward the lowest parts of the Levant Basin. Because a critical load is required before the salt would flow, it seems plausible that the motion started sometime during the Pliocene. The deformation pattern of this flow in the Messinian evaporites is such that the top of the series was deformed but the base remained intact. This could indicate that the upper part of the series is built mostly of halite, while more gypsum could be expected at the lower part. Previous suggestions that the flow is restricted to the Plio-Quaternary sequence, and the evaporites acted to reduce the friction between the strata of the sedimentary rocks and thus enhanced the sedimentary motion (Garfunkel and Almagor 1985) are not supported by this study.

Discussion and conclusions

Series of slumps and faults are abundant along the continental margin of the Levant. One series of faulted slumps was discerned along the base of the continental slope, and a second series crosses the slope from the continental shelf to the Levant Basin. The co-occurrence of numerous faults and slumps in the proximity of the continental slope is enigmatic if it is compared with the low rate of repetition of strong earthquakes, which is estimated to be 350 years (Poirier et al. 1980). The tectonic regime of the continental margin of the Levant coastal plain and continental shelf is thus presumed to be mild, even though textual evidence for earthquakes and tsunami in coastal Israel is well known (Amiran et al. 1994).

The patterns of the tectonic regime that could lead to the occurrence of intensive structural deformation in the Levant margin are highly contested and poorly understood. Neev (1977) and Neev et al. (1976, 1982, 1985) suggested that the slumps at the base of the continental slope, as well as the disrupted structures of the Messinian evaporites, are a part of a megashear. That structure apparently extends from the Bay of Iskanderun in southern Anatolia across the eastern Mediterranean, and across the African continent to the Atlantic Equatorial transform faults. Nur and Ben-Avraham (1978) associated the Phoenician Structures with a faulting system that separated the colliding continental Levant from the subducting Levant Basin, while Garfunkel et al. (1979) described the Phoenician slumps as products of sediment gliding from shelf to slope on top of the Messinian salt. Mart (1984) described the Phoenician Structures off central Israel and attributed them to faults of unknown tectonic origin. Recently Tapponnier et al. (2004) attributed the Phoenician Structures at the base of the continental slope off Lebanon to initiation of eastwards subduction of the Mediterranean oceanic crust under the Lebanese mountains.

It seems that the key to the Phoenician Structures at the edge of the Messinian evaporite series and the overlying slumps in the Plio-Quaternary sequence lies with the shallow reverse faults in the Levant Basin (Fig. 7). Interpretation of the seismic data suggests that the faults are the product of flow of the Messinian salt towards the distal parts of the Levant Basin due to the yield of that salt layer to the load of the accumulating sediments (Fig. 8). The flow of the salt of the upper Messinian and the overlying Pliocene and Pleistocene strata led to collapse and detachment in the Plio-Quaternary series above the eastern edge of the Messinian evaporites, where the flowing Messinian salt was depleted and motion stopped. The depletion of the salt led to the collapse and slumping of the overlying Plio-Quaternary sequence (Fig. 8c), which, in turn, enabled excessive sedimentary accumulation above the edge of the Messinian series (Figs. 2a, 4a). The detachment faults in the Plio-Quaternary sedimentary sequence enabled the penetration of seawater that dissolved the eastern edge of the Messinian evaporites (Fig. 8d). Since lithological data from boreholes in the Levant Basin have not been available yet, direct observations of dissolution features in the Messinian salt of the Levant Basin have not been carried out. However, Bertoni and Cartwright (2006) used high-resolution 3D seismic reflection data to suggest dissolution of the top of the Messinian sequence even before the deposition of the Plio-Quaternary sedimentary series. Thus we conclude that the Phoenician Structures in the Messinian evaporites are halokynetic and not tectonic. Motion and dissolution of the salt is the cause of the Phoenician slumps at the base of the continental slope of the Levant.

The processes that developed the transverse slumps that cross the continental slope of the Levant, such as the Palmahim and Dor Slumps (Mart 1984) are also controversial. Already Neev et al. (1976) and Mart et al. (1978) discerned the NW-trending faults that constrain the Palmahim Slump from NE and SW. Subsequently a NW-trending fault was encountered under the Dor Slump (Mart and Eisin 1982). Mart (1984) presumed that the slope-normal structures of the Levant are constrained by NW-trending faults and are therefore tectonic in origin. Alternately Garfunkel et al. (1979), who studies the Palmahim Slump, argued that the Plio-Quaternary sediments glided

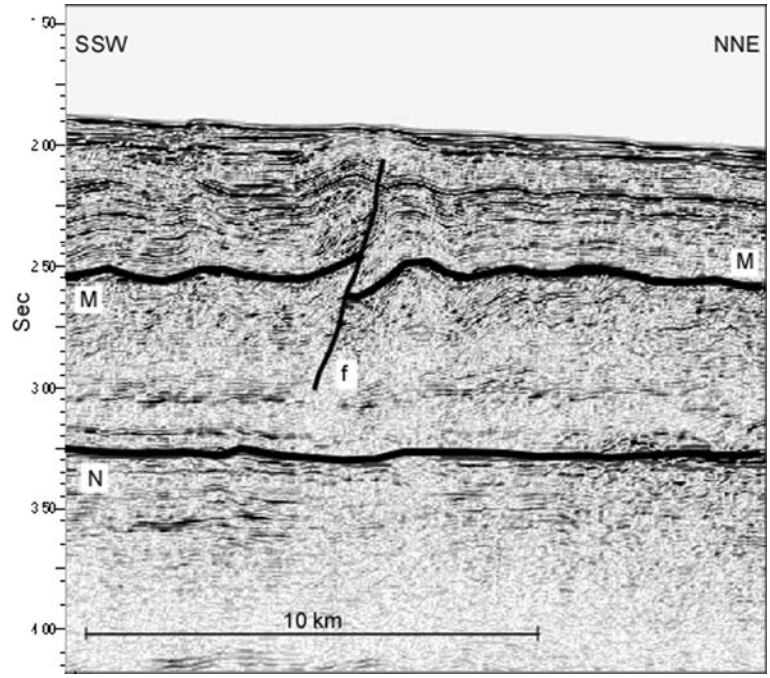

Fig. 7 Seismic reflection profile showing a thrust fault that displaces the Plio-Quaternary sequence and the top of the Messinian evaporites. Such thrust faults are commonplace in the Levant Basin away from the continental margin, and they do not affect the base of the evaporites, and do not offset Reflector N. Seafloor is offset in places, suggesting that the thrusting has been prolonged and is still active. See Fig. 1b for location

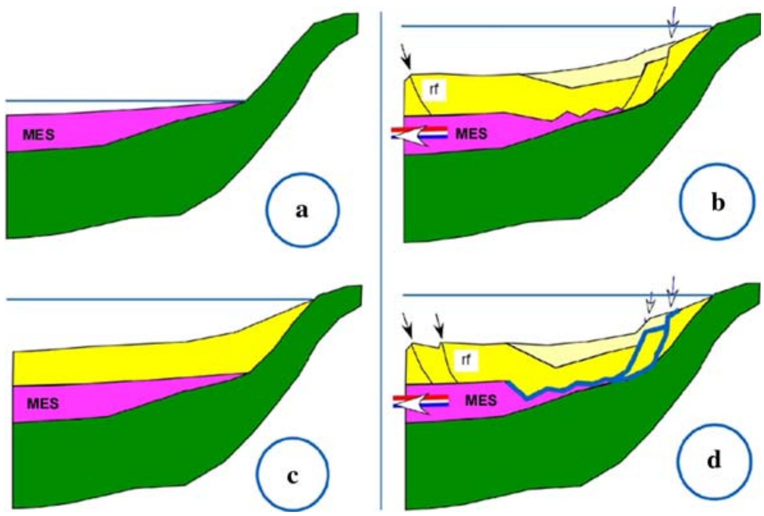

Fig. 8 Cartoon depicting the structural evolution of the Phoenician Structures and slumps. (**a**) As sealevel dropped during the Messinian, a thick series of evaporites was deposited (MES). (**b**) When sealevel returned to the level of world oceans a thick sequence of sediments accumulated along the Levant margin in the Plio-Quaternary. (**c**) The sedimentary load mobilized the Messinian salt, that started to flow towards the deeper part of the Levant Basin, carrying along the Plio-Quaternary sequence. This displacement led to the landwards-dipping reverse faults (rf) in the distal Levant Basin. The Plio-Quaternary sediments were internally detached above the edge of the Messinian salt, where the flow stopped. Normal detachment faults were formed there. (**d**) Seawater (heavy blue line) penetrated along the detachment faults, dissolving the salt and forming the disrupted patterns of the Phoenician Structures

on the Messinian salt and that the large slump is therefore of geotechnical origin.

The presently available data indicate that the geological history of the Palmahim Slump and the Phoenician slumps is shaped by a single geological origin. The setting of the Palmahim Slump begins with the entrenchment of a large canyon across the continental margin of the southern Levant. The southern canyon was approximately 10 km wide and reached depths of more than 1,000 m. It was described along the southern coastal plain of Israel by Druckman et al. (1995), who called it "Afiq Canyon". Druckman et al. encountered Miocene fauna in the cuttings of petroleum exploration wells in the canyon. The fossils were well-preserved (B. Derin, Pers. Comm., 2005), so that

Druckman et al. (1995) suggested that the canyon already existed in the Miocene, and, therefore, had been entrenched in the Oligocene. Bertoni and Cartwright (2006) encountered the western extension of that canyon under Palmahim Slump along the continental slope. They associated the Palmahim Canyon with the Afiq Canyon, and presumed that the erosion of the distal section of the canyon was caused by submarine currents during the early Messinian. We show in the present study that the Messinian evaporites were deposited directly on the shoulders of Palmahim Canyon (Fig. 5), so that the entrenchment of the canyons must have been active until then. Similar depositional setting occurs under Dor Slump as well.

It seems plausible to us to associate the entrenchment of the canyons that transect the coastal plain and the continental margin of Israel to Miocene rivers of the southern Levant known as the Hazeva fluvial system. These large rivers drained northwestern Arabia to the Mediterranean Sea until the structural evolution of the Levant Rift system diverted the drainage of these rivers to the rift (Horowitz 1979, 2001). Our data show that canyon entrenchment ebbed during the early Messinian, because we noticed that only a shallow morphological depression still existed on top of the axis of the canyon in the Messinian. Consequently Messinian evaporites were deposited in a wide and shallow riverbed on top of canyon sediments, while erosion prevailed along the flanks of that canyon (Fig. 5).

The second stage of the structural evolution of the Levant continental margin took place with the deposition of thick salt deposits during the Messinian stage. That deposition was constrained by the configuration of the shore of the Levant hypersaline lake, and the data presented here show that most of the salt pinched out towards a straight coastline, with the exception of a large bay in the Palmahim Canyon (Fig. 3). A smaller inlet might have existed at the site of the Dor Slump. Subsequently, when the load of the Pliocene sediments triggered basinward flow of the Messinian salt, the sediments that overlie the salt moved with it. That motion formed a gap under the Plio-Quaternary sequence that had been located above the edge of the Messinian salt. The collapse of the sediments into that gap would have formed the large slumps in the Plio-Quaternary sediments. Penetration of seawater along the detachment faults of the slumps dissolved some of the salt at the pinch-out zone of the Messinian evaporites, thus forming the Phoenician Structures from the remainder of the salt, and enhanced the collapse of the Plio-Quaternary sequence. It should be noted that the sedimentary slumping started before the dissolution of the salt, which, in turn, enhanced the slumping and led to sediment collapse in some places. Thus the present stratigraphic setting differs from that during the initiation of the slumping.

The westward flow of the Messinian and Plio-Quaternary sedimentary strata was compensated by numerous reverse faults that offset the top of the evaporitic series, the Plio-Quaternary sequence and even the seafloor (Folkman 2006). The base of the evaporites was not affected by that displacement (Fig. 6). It seems that the flow of the salt carries with it the overlying sediments, but does not support the presumption that the Plio-Quaternary sedimentary strata glided on top of the salt, which acted as a lubricant (Garfunkel et al. 1979; Garfunkel 1984). Seafloor deformation by the reverse faults indicates that the processes of salt flow and the consequent slumping and collapse of the overlying sediments are still active.

A unique pattern of slumping was developed along the Miocene canyons, where the flow of the landward protrusions of the salt occurred. When the salt started to flow seawards in the Pliocene, it carried with it a 10 km wide belt of sedimentary rocks. That motion formed the geotechnical detachment faults along the flanks of the slump. These faults trend normal to the continental slope. Thus although some offset along the boundary faults of the Palmahim Slump did take place, most of the offset discerned along the north Palmahim Fault in Fig. 3 is apparent, though some displacement along the faults is evident (Fig. 4).

The available data from the continental margin of the Levant indicate that the processes that led to deformation of the post-Tortonian sedimentary column are controlled by halokynetics, where normal, strike-slip and reverse faults co-occur with synclines and anticlines in the same region, due to gravity-controlled, thin-skinned geological processes. Furthermore, the Phoenician Structures of extensional faulting and slumping present a good example of the structural patterns of the collapse along the distal continental margin due to the dissolution of a massive salt layer.

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