Stratigraphy, fluid dynamics and structural evolution of the Messinian Evaporites in the Levantine Basin, Eastern Mediterranean Sea

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ABSTRACT

The mobile unit (MU) of the Messinian evaporites in the Levantine Basin is up to 2 km thick. It was deposited in a basin of 2-3 km water depth. The Oligocene to Middle Miocene strata beneath the MU was partly eroded. 6 evaporite sequences have been identified in the MU. Four of them are seismically transparent and are characterized by interval velocities of up to 4.6 km/s, which is typical for halite. The other two sequences reveal subparallel internal reflections and interval velocities below 4 km/s, which suggests vertical changes in the evaporite facies, intercalated clastics or trapped fluids. Prior to deposition of the Pliocene-Quaternary overburden, the evaporite sequences were strongly deformed by compressional folds and faults and the top of the MU was eroded or subroded. The syn-depositional deformation of the MU may have resulted from subsidence of the deep basin and uplift of the Levantine hinterland due to the onload of the MU. Both processes would have enhanced the dip angle of the basin floor and caused the salt to creep towards the deepest part of the Levantine Basin. A second thin-tectonic phase (gravity gliding) started contemporaneously with significant mass wasting off Israel during Pliocene times. The sediment load of the more than 3 km thick Nile Fan squeezes the MU in a north-east direction through the bottleneck between the Eratosthenes Seamount and the Levantine margin. The onload of the sediment prism off Israel has only a slight impact on the lateral salt tectonics. Vertical fluid migration through the MU and fluid escape out of the MU is well documented by seismic data. A Dead Sea transform fault related plate-tectonic overprint of the MU by strike-slip tectonics is likely.

1. INTRODUCTION

It is generally accepted that a salt giant, i.e. a tabular salt layer of some 10,000 km^3 volume and up to some km thickness, has a significant impact on the evolution of the hosting basin. Owing to its viscous rheology, salt is capable of decoupling deep-rooted tectonics from the supra-salt response. Salt tectonics controls the formation of complex traps for hydrocarbon or metals. Lateral salt flow may cause subaerial or submarine land slides. Salt diapirs are potential waste repositories. The interaction of fluids and salt may cause subrosion and subsequent surface collapses with a potential impact on civil infrastructures. The impermeability of evaporites controls fluid dynamics and hydrocarbon distribution. However, there is a significant lack of knowledge about the early evolution of juvenile salt giants and their controlling factors.

The Levantine Basin in the south-eastern Mediterranean Sea is a world class site for studying the early evolution of such a salt giant, since the mobile unit (MU) of the Messinian evaporites in the deep basin is comparatively young, the sediment load varies along the basin margin, the evaporites are little tectonically overprinted, and the geometry of the basin and the overburden is well-defined. On a regional scale, the high interest in the analysis of the MU is based on the fact that the so-called Messinian Salinity Crisis (MSC) represented the most significant environmental change in the Mediterranean realm. The reconstruction models are based on the analysis of evaporites in the marginal basin, which led partly to contradictory models (see Rouchy and Caruso, 2006 and the references therein). Finally, the deep biosphere of such an extreme habitat is absolutely unexplored.

During the last few years, new attempts were made to unravel the structural evolution of the MU in Levantine Basin and associated fluid dynamics. Since 2004 several studies have been published in which the evolution of the Levantine basin is discussed by means of academic seismic data. (Loncke *et al*., 2004; Gradmann *et al*., 2005; Loncke *et al*., 2006; Netzeband *et al*., 2006a, b, Hübscher *et al*., 2007; Hübscher and Netzeband, 2007). The release and subsequent publication of industrial 2D and 3D-seismic data led to a giant step forward in the understanding of salt tectonic related processes (Martinez *et al*., 2005; Bertoni and Cartwright, 2005, 2006, 2007a; Gardosh and Druckmann, 2006).

In this paper we will summarize the recent achievements in understanding salt dynamics in the Levantine Basin and point out the ongoing debates. Since most results are based on seismic interpretation it should be noted that due to the limited band width of the seismic wavelet the vertical resolution is quite limited compared to outcrop studies. For instance a 50 Hz seismic wavelet has a wavelength of about 40 m in the Pliocene-Quaternary sediments and about 80 m in halite layers. It follows that vertical resolution is limited to some 10 m. Consequently, all conclusions drawn from seismic interpretation have to be considered under this limitation.

2. GEOLOGICAL FRAMEWORK

The Levantine Basin in the south-eastern Mediterranean Sea is bounded to the south by the Egyptian and to the east by the Levantine coast (Figure 1). The Eratosthenes Seamount in the north-west of the basin is considered to be a continental fragment of the African plate (Makris *et al*., 1983). Between the Eratosthenes Seamount and the Egyptian coast there is the gateway to the

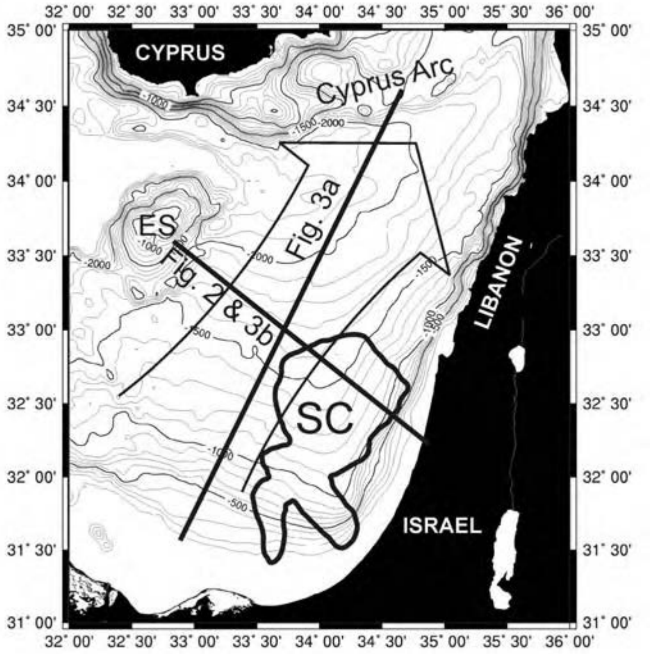

Fig. 1. Map of the Levantine Basin. Black lines show locations of cross-section in Figure 3. The arrow indicates the main gliding direction of the mobile unit (MU) of the Messinian evaporites (after Netzeband *et al.,* 2006a). The MU is squeezed through the bottleneck between Eratosthenes Seamount (ES) and the basin margin to the east. SC: slump complex (after Martinez *et al.,* 2005).

Herodotus Basin to the west. The Levantine Basin includes the northward moving African plate, the postulated Sinai sub-plate (Almagor, 1993; Mascle *et al*., 2000), the N - NW moving Arabian plate, and the westward moving Anatolian plate. The Cyprus Arc, which results from the collision between the African and Eurasian plate represents the northern boundary (e.g., Robertson *et al*., 1998; Vidal *et al*., 2000a).

Recent studies showed that the Levantine Basin is underlain by stretched continental crust (Vidal *et al*., 2000b; Gardosh and Druckman, 2006; Netzeband *et al*., 2006b). The basin-fill deposits reach a thickness of 14-16 km (Netzeband *et al*., 2006b; Gardosh and Druckmann, 2006, Figure 2). The basin is considered to be a relic of the Mesozoic Neo-Tethys Ocean (Robertson and Dixon, 1984; Garfunkel, 2004). The initial rifting occurred in the Middle Triassic in a northwest-southeast direction (Garfunkel, 1998; Robertson, 1998). Inversion and hence contraction pulses started in the Upper Cretaceous and ended in the Miocene. The folding was associated with the closing of the Neo-Tethyan ocean, the so-called Syrian Arc inversion and contraction (Gardosh and Druckmann, 2006). A number of smaller fault zones were interpreted in the Levantine Basin, which were associated with the rifting and contraction phase. Several SW - NE striking shear zones converge towards the north, e.g., the Pelusium Line, the Hinge Line and the Damietta-Latakia Line (Neev, 1975, 1977; Neev *et al*., 1976; Abdel Aal *et al*., 2000). There is some evidence that these faults are still active (Gradmann *et al*., 2005; Netzeband *et al*., 2006a). However, as shown by Gardosh and Druckmann (2006, Figure 2), these faults do not significantly overprint the Miocene to recent succession in the central basin.

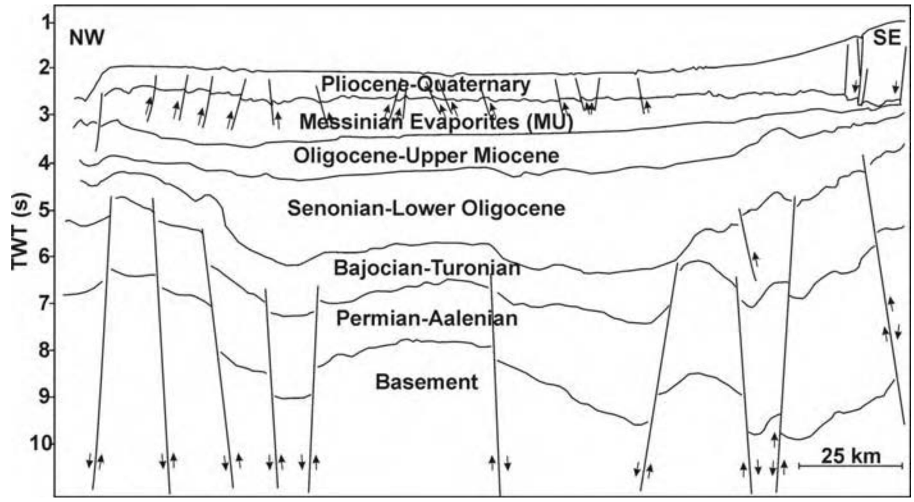

Fig. 2. Line-drawing of a seismic time section between the central Levantine coast and the Eratosthenes seamount (after Gardosh and Druckmann, 2006). See Figure1 for location.

In Late Miocene (5.96 Ma ago) a combination of tectonic uplift, combined with other factors, caused a narrowing of the western connection to the Atlantic Ocean and initiated the Messinian Salinity Crisis (see Executive Summary of this volume). The water shortage and the high evaporation rates in the Mediterranean climate resulted in a sea level drop, an increase in the salt concentration finally lead to precipitation. The first reported increase in salinity took place in Sicily at 6.26 Ma (Blanc-Valleron *et al*., 2002). According to the chronostratigraphic scheme of Clauzon *et al*. (1996) or Krijgsman *et al*. (1999a) the precipitation of the MU started around 5.6 Ma during the middle of the Messinian Salinity Crisis (MSC). The end of the MU formation and the rapidity with which the Mediterranean basin was refilled at the end of the MSC is debated, the given time intervals varying between a few thousand years (Clauzon *et al*., 1996) and about 200,000 years (Krijgsman *et al*., 1999a). Hilgen and Langereis (1993) dated the end of the salinity crisis to 5.33 Ma. The lowered base of erosion during the MSC caused the drainage channels to incise canyons and valleys into the continental shelf (Garfunkel *et al*., 1979; Almagor and Garfunkel, 1979). According to Maillard *et al*. (2006a) and by analogy with the Western Mediterranean we will use the terms Top Erosion Surface (TES) for the upper boundary of the MU and the term Basinal Erosion Surface (BES) for its base. The Marginal Erosion Surface marks the Messinian erosional unconformity where no MU is present.

The Plio-Quaternary deposits overlie the MU unconformably (Almagor, 1984) and consist mainly of Nile derived sediments (Ross and Uchupi, 1977). South of Haifa the continental shelf and slope are formed by a broad and smooth shelf and the easternmost part of the Nile Fan (Almagor, 1984).

3. Structural evolution of the Messinian evaporites

3.1 Overall structure

The evaporites in the Levantine Basin reach a maximum thickness of about 2 km. According to back-stripping analysis of Netzeband *et al*. (2006b) the initial basin depth prior to MU deposition lay between 2 and 3 km. The underlying strata are partly eroded (Bertoni and Cartwright, 2006).

Two cross-sections elucidate the overall structure of Late Miocene to recent deposits (Figure 3). In the east, a series of anticlines of the Syrian Arc fold belt acted as a structural barrier indirectly governing the overall landward extension of the evaporites (Bertoni and Cartwright, 2006; Gardosh and Druckmann, 2006). The load of the Nile Fan pushes the entire evaporites in a NNE direction and parallel to the bathymetric gradient. In front of the lower Nile Fan, the evaporites are thickened due to forebulging (Figure 3a). In the bottleneck between the Eratosthenes Seamount and the Levantine slope the evaporites are squeezed. In the north, the Cyprus Arc acts as a backstop, where compressional folds strike parallel to the arc as it is revealed in bathymetric data (Benkhelil *et al*., 2005).

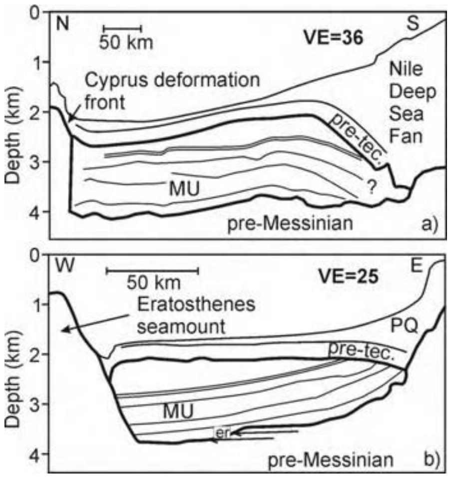

Fig. 3. Simplified line-drawings of pre-stack depth migrated seismic sections showing the mobile unit (MU) of the basinal Messinian evaporites across the entire Levantine Basin (after Netzeband *et al.,* 2006b). The reflections within the MU indicate the geometry and termination, respectively. For location see Figure 1. PQ: Pliocene-Quaternary. Er: Erosion.

The top of the evaporites declines beneath the Nile Fan (Figure 3a) in the south and beneath the sediment prism off the Levantine margin not only because of the lateral displacement (Netzeband *et al*., 2006a). The differential load of the basinward prograding overburden also causes the evaporites to creep towards the basin. The load of the basinward prograding sediment causes differential subsidence which is highest beneath the thickest part of the sediment prism. The resulting down-warping at the basin margins presents rollback folding and thin-skinned extension, respectively, also in areas where no or very little thin-skinned extension occurred.

3.2 Stratigraphy of Messinian evaporites

Six MU sequences labelled ME-I – ME-VI can be traced across the entire Levantine basin (Figures 3, 4) (Hübscher *et al*., 2007). Sequences ME-I, II, IV and VI are seismically transparent and sequences ME-III and ME-V reveal several internal reflections. Since the entire succession of the MU has never been drilled, the interpretation of the sequences has to rely on seismic data. The absence of seismic reflections is typical of salt bodies (Mitchum *et al*., 1977) and so is the interval velocity of up to 4.5 km/s which we recently calculated for ME-VI. Consequently, we suggest to interpret sequences ME-I, II, IV and VI as halite deposits. The interpretation of the layered sequences is more speculative. Some authors consider them as evaporites with intercalated (and presumably overpressurized) clastics (Garfunkel, 1979; Gradmann *et al*., 2005). However, 3D-seismic data analysis proved a high lateral continuity of seismic reflection characters and identified polarity changes which are more indicative of chemical sedimentation processes (Bertoni and Cartwright, 2007a). In this case the acoustic impedance contrasts could result from alternating halite, anhydrite, limestone or potash.

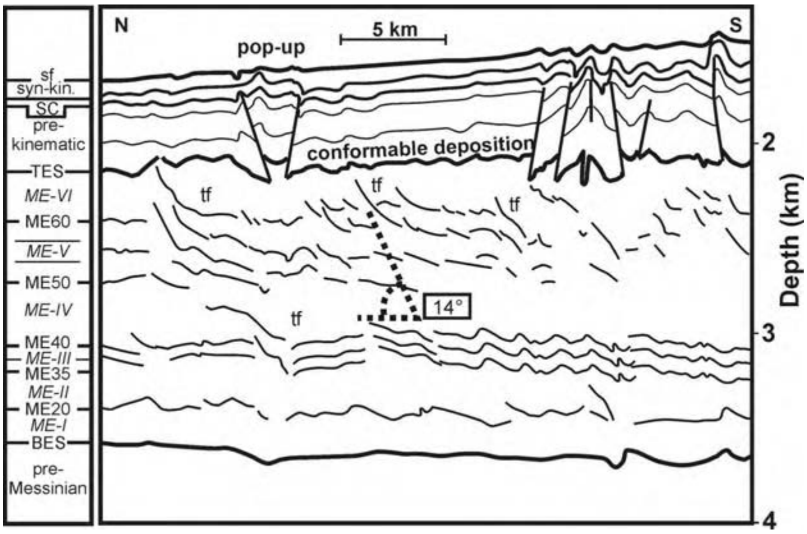

Fig. 4. Line-drawing of pre-stack depth migrated seismic section showing intra-evaporitic sequences labelled ME-I-VI (after Hübscher *et al.,* 2007). Horizon labels ME 20 – 60 according to Bertoni and Cartwrigh (2006, 2007a). BES: Base Erosion Surface. TES: Top Erosion Surface. tf: thrust fault. SC: slump complex.

Chemical depositional processes do not necessarily produce reflection horizons which represent isochrones. For example, a laterally prograding overburden could cause a temporal and lateral increase in overburden thickness and pressure, respectively, which could have resulted in gypsum-anhydrite conversion and, consequently, in acoustic impedance contrasts. In this case internal reflections would represent diachrons and no isochrons.

Submarine canyons represented preferential sites of erosion and deposition of evaporites at the basin margin during the MSC. Seismic geomorphological analysis of 3D seismic data strongly suggests the occurrence of clastic bodies within the basal part of the MU (Bertoni and Cartwright, 2007b). They are composed of two closely spaced channel-mouth lobe deposits and are presumably correlated with a long-lived system of canyons (i.e. the El Arish and Afiq Canyons).

The temporal and stratigraphical relation between marginal and basinal evaporites is still a matter of debate. The same age for the onset of evaporite deposition in the marginal basins and in the deep basin and therefore a correlated stratigraphy is considered by some research groups (Krijgsman *et al*., 1999a, Figure 5a). Other authors assume diachronic deposition (e.g., Clauzon *et al*., 1996; Cornée *et al*., 2002; Butler *et al*., 1995; Riding *et al*., 1998, Figure 5b). Rouchy and Caruso (2006) suggested a progressive but fast deposition of evaporites from the margin to the deep central basin. This question is critical to the understanding of the depositional environment and the reconstruction of the Miocene climatic conditions. It is noteworthy that the vast reconstructions of the Messinian paleo-environment are based on the descriptive and analytical work on the succession preserved in the marginal basins only. The climate archive represented by about 95% of the MU within the deep basins has not been opened yet.

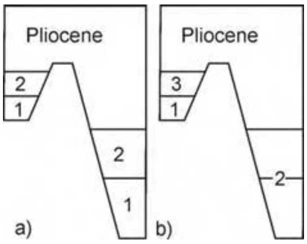

Fig. 5. Endmember models elucidating the ongoing debate regarding the temporal relationship between marginal and basinal evaporite stratigraphy (simplified after Rouchy and Caruso, 2006). Basinal and marginal sequences may have developed contemporaneously (a) or alternating (b).

3.3 Deposition and erosion patterns

Outside the main part of the Nile Fan the internal reflections dip towards northwest. Both the eastern and northern dip component are seen in Figure 3a and b. Different models apply to explain an isochronic deposition of each sequence.

The sequences aggraded within the central basin almost symmetrically if a hinge zone is assumed 40 km west of the eastern termination point (Netzeband *et al*., 2006a, Figure 6). The northwestern tilt of the basin after the deposition of sequence ME-V could have been the consequence of the collision between the Eratosthenes Seamount and Cyprus or, alternatively, of the increasing load due to evaporite deposition. The uplift of the Levantine hinterland results from the flexure of the lithosphere. If no significant tilting and flexural response is assumed, the evaporites in the northwest were deposited in a much deeper water than those in the southeast (Figure 6b). It may be speculated that marine water inflow from the Herodotus basin through the gateway between Eratosthenes Seamount and Cyprus Arc would have caused laterally varying salinity and, consequently, laterally varying deposition rates and facies.

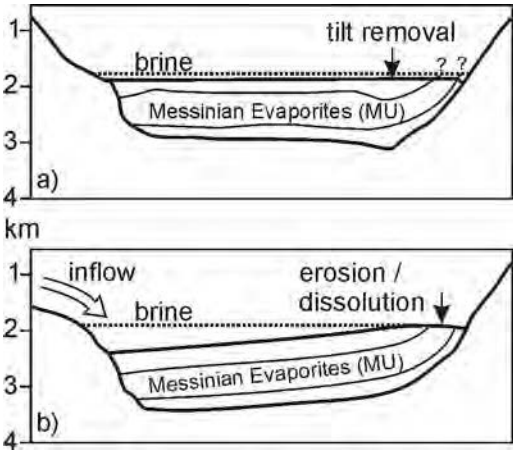

Fig. 6. Endmember models elucidating the growth pattern of the Mobile Unit (MU). a) Evaporites aggradation in an untilted basin. b) Progradation and lateral facies change owing to dipping basin floor and water inflow, which cause a lateral salinity gradient.

Towards the east and south the reflections and sequences, respectively, terminate updip against the TES in different distances to the pinch-out line of the MU (Figure 3a). Thus the termination distance of sequence ME-VI is 40-60 km (Bertoni and Cartwright, 2006). The similar depth levels of the toplap location indicate a simultaneous erosion of the marginal parts of the sequences, likely due to subaerial exposure at the end of the MSC. The abrupt up-dip termination and absence of asymptotic tapering rule out the interpretation of TES as a non-depositional surface. The geometry of the eroded evaporites at the basin margin remains uncertain.

3.4 Syn-depositional deformation

The intra-evaporitic sequences are highly deformed by faults and fault-propagation folds (Figure 4). In many regions, the lower Pliocene deposits overlie the TES concordantly, even if the intra-evaporite sequences are deformed. The time of deformation obviously predates the erosional truncation of the uppermost evaporites. This observation has been published for the first time by Netzeband *et al*. (2006a) who suggested that thin-skinned salt tectonics (compression) already occurred during the deposition phase. Bertoni and Cartwright (2007a) discussed the same process later by analyzing 3D-seismic data. The strongest deformation has been observed for the layered sequences ME-III and ME-V. In Figure 4 the thrust fault planes dip with up to 14°, maximum values of 30° have been observed in the 3D-data.

The most likely driving forces for the syn-depositional deformation are gravity gliding. According to the thin-skinned tectonic concept, the slope of a margin or simply the differential load of a seaward prograding shelf causes the overburden to move basinward, leaving extensional structures such as listric normal faults and rotated blocks along the upper slope. Compression is present at the distal end leading to folds or thrusts. A submarine Nile Fan developed presumably in the Messinian (Barber, 1981; Griffin, 2002). Such a fan squeezing the evaporites basinward during the precipitation phase should interfinger with the MU. The post-Messinian pre-tectonic sequence has a thickness of some 100 meters (see section below), a similar thickness should be assumed for the syn-depositional fan. However, industrial seismic data give no evidence for this (Abdel Aal *et al*., 2000).

We suggest therefore that the basinward creep and thrusting of the individual evaporitic sequences during the deposition phase were driven by gravity gliding above a tilted subsurface and without significant sediment load. The lateral displacement was presumably comparable to modern salt glaciers, e.g., in Iran. Owing to the onload of the deposited MU the basin-floor tilted towards the basin center which may have acted also as a trigger mechanism (Figure 7). Furthermore, we assume that the internal shear strength of the entire salt body was reduced since sequence boundaries acted as detachment layers.

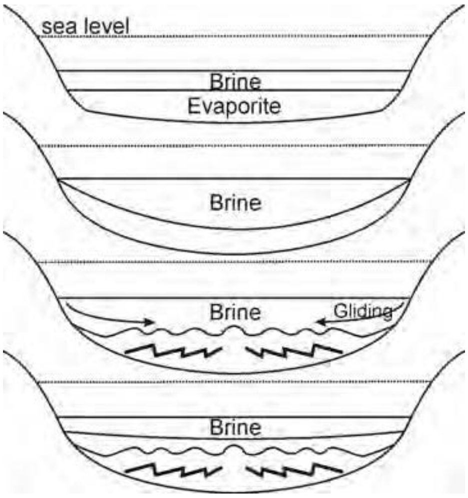

Fig. 7. Model to explain syn-depositional shortening of the MU. The deposition of the evaporites increases the dip angle of the basin margin. The mobile evaporites creep towards the basin center. The subsequent deposited evaporite sequence drapes the folded sequence beneath.

3.5 Post-depositional deformation

There is a clear line of evidence that a second phase of thin-skinned extension started in the later Pliocene (Garfunkel *et al*., 1979; Almagor, 1984; Gradmann, 2005). Extensional faults in the overburden typically include listric and antithetic growth faults, turtle back structures and crestal grabens (Humphris, 1978; Martin, 1978). Some faults pierce the seafloor proving that this phase is still active (Gradmann *et al*., 2005). Salt rollers developed in the extensional domain (Figure 8). Netzeband *et al*. (2006b) showed that the thin-skinned compression at the Cyprus Arc which acted as a buttress for the generally NE-flowing MU ceased in the Quaternary.

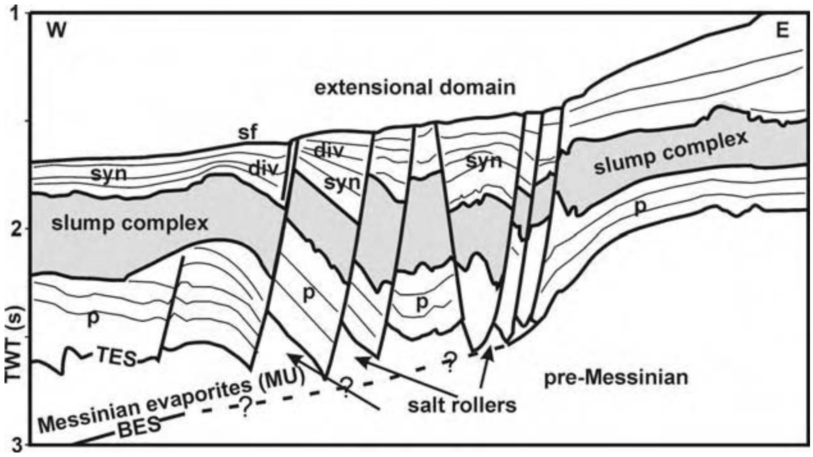

Fig. 8. Thin-skinned salt tectonics in the extensional domain. Pre- and syn-tectonic deposits are separated by a slump complex. p: parallel. div: divergent; syn: syn-tectonic; sf: sea floor. BES: Base Erosion Surface; TES: Top Erosion Surface.

A pre- and syn-tectonic unit can be clearly identified. The pre-tectonic unit is about 300-400 ms TWT or 250-400 m thick and it is characterized by parallel horizons. The syn-tectonic unit includes the sediment prism off the eastern shelf and reveals divergent horizons above the salt rollers. The pre- and syn-tectonic sequences are separated by a late-Pliocene slump complex off the southern Levantine slope (Martinez *et al*., 2005). The slump complex has been mapped by means of 3D-seismic data and the volume was estimated to approx. 1,000 km^3. Several trigger mechanisms are possible, e.g., over-steepening, seismicity, gas migration and initial salt tectonics. A sequence of low seismic reflectivity that is time correlated with the slump can be traced all over the basin separating pre- and syn-tectonic sequences also in the compressional domain (Netzeband *et al*., 2006b).

Near the Eratosthenes Seamount, the situation is different (Netzeband *et al*., 2006a). The BES appears comparatively flat and smooth until it merges into the flank of the seamount, while the TES and the seafloor are strongly distorted (Figure 3b). Hence, the deformation observed there has probably been caused by thin-skinned tectonics. Since there is no significant E–W movement of the evaporites, the E–W contraction observed at the Eratosthenes has probably been caused by the northward creep through the bottleneck between seamount and the Levantine margin. It is remarkable that no salt glaciers or salt tongues escaped from the evaporites into the Nile Scarp.

4. MIGRATION OF FLUIDS AND VOLATILES

Fluid escape structures have been reported from the southern and eastern basin margin. Possible fluid resources may be located beneath and within the MU (Figure 9a). Several factors combine to control fluid release locations. E.g., the MU were considered as a sealing sequence and syn-tectonic faults as conduits (Loncke *et al*., 2004, Figure 9b). However, a mud volcano is located at the lower Nile Fan and above almost undisturbed and 1.5 km thick MU without any evidence for lateral fluid flow (Netzeband *et al*., 2006a). A cone-like feature at the top of the MU directly beneath the mud volcano was interpreted as salt that precipitated from fluids escaping out of the MU (Figure 8b). These fluids remobilized sediments within the overburden that feed the mud volcano.

Buried circular collapse structures within the upper MU strata were recorded by 3D-seismic data on the eastern basin margin (Bertoni and Cartwright, 2005). These structures formed during the Pliocene as the buried MU underwent extensive dissolution in a submarine, deep-water setting. The

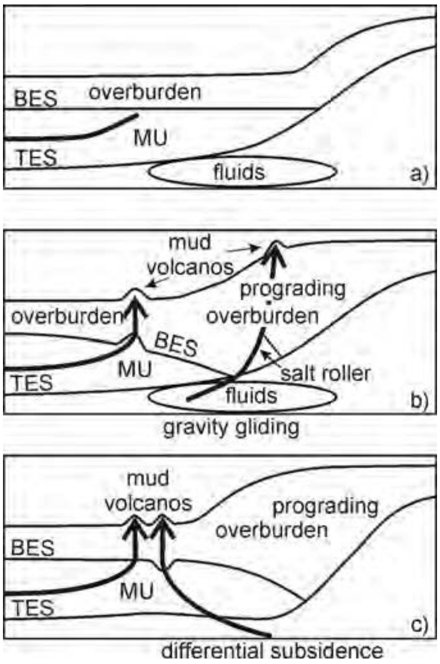

Fig. 9. Endmember models for salt tectonic related fluid dynamics. A) Fluids are present within the evaporites and beneath. B) The differential load of the prograding marginal sequences initiates basinward salt creeping. Extensional faults act as conduits for fluids which migrate upwards where salt has vanished. Fluids escape from the salt and feed mud volcanoes. Precipitated salt form salt cones on top of the main salt body. C) The differential sediment load causes differential subsidence which squeezes fluid through and out of the evaporites.

authors propose that focused vertical fluid flow at the base of the evaporitic series dissolved the more soluble evaporites within the entire MU succession (Figure 9c). Fluid through and outflow from the MU has been also reported. Near vertical faults represent the conduits from the top of the MU to the seafloor, where muddy fluids escape. Possible fluid reservoirs within the MU are intercalated sediments or water that was released from gypsum-anhydrite conversion.

The fluid escape structures at the eastern basin margin are located at the lower slope. This location coincides with the landward termination of the evaporite layer, which is buried under the prograding shelf sediments. Fluids that were trapped within the MU presumably became overpressured, eventually penetrated through the overlying strata and migrated upwards.