Tectonophysics 470 (2009) 173–182

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Salt tectonics and mud volcanism in the Latakia and Cyprus Basins, eastern Mediterranean

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ARTICLE INFO

Article history:
Received 2 July 2007
Received in revised form 26 May 2008
Accepted 20 August 2008
Available online 4 September 2008

Keywords:
Eastern Cyprus Arc
Marine geophysics
Messinian evaporites
Salt tectonics
Mud volcanoes

ABSTRACT

Salt tectonics and mud volcanism in the Latakia and Cyprus Basin, eastern Mediterranean, is investigated by means of swath sounding, reflection seismics and side-scan data as well as by camera and video sledge observations. Both basins are located east of Cyprus and are associated with the collision front between the African and Anatolian plate. The Pliocene–Quaternary sediment succession is underlain by up to 1 km thick Messinian evaporites. Both thick-skinned plate tectonic and thin-skinned salt tectonic control fluid dynamics and associated mud volcanism in the Latakia and Cyprus Basin as well as at the Troodos Latacia Culmination, which separates both basins. An end-member model is proposed which explains the presence of elongated topographic highs and trenches along the Troodos Larnaca Culmination and south of it by gravity gliding of the Messinian evaporites and associated fluid migration. Thin-skinned extension in the Troodos Larnaca Culmination and boudinage, respectively, facilitate fluid flow through and out of the evaporites. The fluid or mud flow dissolutes the salt layer and creates elongated trenches. Mud intrudes into the Pliocene–Quaternary sediments above the trenches. Consequently, the overburden is thickened and forms morphological ridges. South of the culmination the evaporites and overburden are folded due to thin-skinned shortening of the evaporites. In one instance fluid extrusion out of the evaporites is inferred from seismic data interpretation. The outflow caused a volume reduction and collapse of the evaporites. Mud volcanoes and fold anticlines align above deep-rooted transpressional fault systems which are associated with the African–Anatolian collision zone. The faults may act as conduits for rising fluids. In the western part of the survey area, where the Cyprus Arc strikes almost West–East and the collision occurred more frontal and stress was highest, mud volcanoes emerged. Further to the east, where the Cyprus Arc runs SW–NE and sinistral strike-slip has been proposed, fold anticlines evolved. Particular mud volcanoes and folds emerged prior to the deposition of the Messinian evaporites. The undisturbed upper Pleistocene sequences as well as the absence of significant mud outflow on the seafloor strongly suggest that the main fluid dynamic ceased.

1. Introduction

Fluid flow and associated mud volcanism have an important impact on the gas budget as well as geochemical and nutrient cycles in marine basins (e.g., Kopf et al., 2001; Dimitrov, 2002). Many publications deal with mud volcanism in the eastern Mediterranean (Fig. 1), in particular at the Mediterranean Ridge (Cita et al., 1981; Cita and Camerlenghi, 1990; Cita et al., 1995; Robertson and Kopf, 1998; Huguen et al., 2004; Zitter et al., 2005), the Anaximander Mountains and Florence Rise (Woodside et al., 1998, 2002), or the Nile Fan (Loncke and Mascle, 2004). Yet, the role of the widespread Messinian evaporites in the formation and evolution of mud volcanoes in the eastern Mediterranean has been rarely discussed. Evaporites are generally considered to be effective seals in terms of seal capacity and resistance to fracturing (Downey, 1984). Loncke and Mascle (2004) suggested that the fluid reservoirs of mud volcanoes, gas chimneys, hydrothermal pockmarks or hydrocarbon seeps at the Nile Fan are located within the sub-salt strata and that the conduits are restricted to salt welds where the evaporites have vanished due to lateral gliding (thin-skinned tectonic). However, recent publications showed upward directed fluid pathways through or even out of Messinian evaporites (Gradmann et al., 2005; Bertoni and Cartwright, 2005; Netzeband et al., 2006a).

The Cyprus Arc in the eastern Mediterranean and the adjacent basins like the Cyprus and Latakia Basins are part of the collision zone between the African and Anatolian plate (e.g. Robertson, 1998; Aksu et al., 2005). Previous seismic studies revealed a complex fault pattern

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doi:10.1016/j.tecto.2008.08.019

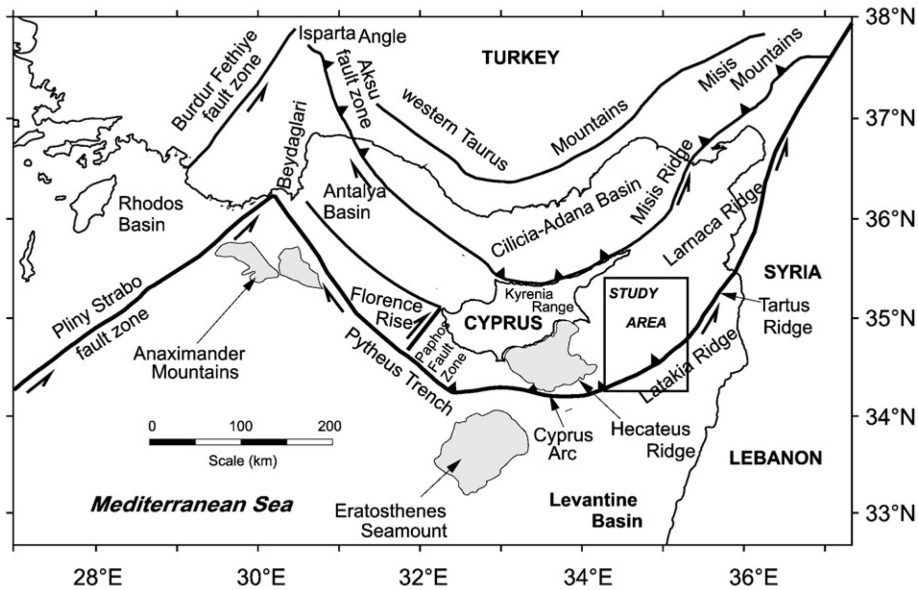

Fig. 1. Overall map of the eastern Mediterranean (Courtesy: J. Hall). The study area of the eastern Cyprus Arc is marked by a rectangle.

that result from the "thick-skinned" plate-tectonic evolution of this intricate realm (Calon et al., 2005). Bathymetric and high-resolution reflection seismic data collected at the eastern Cyprus Arc with *RV LeSuroit* in 2003 (BLAC project; Benkhelil et al., 2005) revealed a complex topography of the Cyprus and Latakia Basins including surficial folds, graben and mud volcanoes suggesting additional processes. In this paper we present new data from a subsequent seismic studies in 2004 with *RV Pelagia* (SAGA project) carried out to better image the Messinian evaporites and the Pliocene–Quaternary overburden. The discussion aims on an advanced understanding of the interaction between thin-skinned salt tectonic, mud volcanism and plate tectonics in these evaporite floored basins.

2. Geological setting

The eastern Mediterranean consists of several larger (Eurasian, African and Arabian Plate) and smaller (Apulian, Aegean, Anatolian and Sinai Plate) lithospheric plates (Fig. 1). Tectonic processes and plate boundaries are still a matter of debate (e.g., Woodside, 1976, 1977; Nur and Ben-Avraham, 1978; Riad et al., 1981; Rotstein and Kafka, 1982; Rotstein and Ben-Avraham, 1985; Kempler and Garfunkel, 1994; Ben-Avraham et al., 1988; Robertson et al., 1990, 1994, 1995; Ben-Avraham et al., 1995; Robertson, 1998; Anastasakis and Kelling, 1991; Woodside, 1991; Ambraseys and Adams, 1993; Oral et al., 1995). Excellent reviews of this topic can be found by Robertson (1998) and Aksu et al. (2005). It is consensus that the Levantine Basin (Figs. 1, 2b) evolved during the Late Triassic. The convergence between the African and Eurasian plates started in the Early Cretaceous simultaneously to the opening of the South-Atlantic. Subsequently, an intra-oceanic subduction zone developed in the Neo-Tethys. The plate-kinematic setting of the eastern Mediterranean changed significantly in the Late Miocene (e.g., Bosworth et al., 2005; Hall et al., 2005) when the Eratosthenes Seamount collided with the Cyprus Arc (Galindo-Zaldivar et al., 2001) and the Arabian Microplate collided with the Eurasian Plate along the Bitlis–Zagros fold-thrust belt. The Anatolian plate started to move westwards along the North- and East Anatolian Transform Faults (Sengör et al., 1985; Dewey et al., 1986). Consequently, the compressional regime along the Cyprus Arc changed into a sinistral, partly transpressional regime (Hall et al., 2005). Sage and Letouzey (1990), Vidal et al. (2000a,b) and Kläschen et al. (2005) showed that the Levantine Basin terminates against the southern flank of the Cyprus Arc. The Levantine Basin of today is floored by highly stretched continental crust (Hirsch et al., 1995; Netzeband et al., 2006b).

During the Messinian Salinity Crisis the Mediterranean was cut off from the water exchange with the Atlantic. Sea-level dropped dramatically due to evaporation and tabular evaporites were deposited in the Mediterranean sub-basins (Hsü et al., 1977; Cita, 1982). In the Levantine Basin the Messinian evaporites reach thicknesses of almost 2 km (Netzeband et al., 2006a). The evaporites reveal a complex internal reflection pattern (Gradmann et al., 2005; Netzeband et al., 2006a; Bertoni and Cartwright, 2006; Hübscher and Netzeband, 2007). Intra-salinar reflections offshore Israel have been previously interpreted as embeddings of over-pressurized clastic sediments between evaporites by Garfunkel and Almagor (1984) and Garfunkel (1984). Gradmann et al. (2005) observed mud flows on the seafloor and above a strong reflection that cuts through the evaporites. Netzeband et al. (2006a) interpreted cone-like features atop the evaporites and an overlying mud volcano at the seafloor as results of fluid outflow from the Messinian evaporites.

The survey area covers the western part of the eastern Cyprus Arc and includes the southward shallowing and 1000 m deep Latakia Basin, the 1500–1600 m deep Cyprus Basin, and the 2000 m deep northernmost Levantine Basin (Fig. 2). The Troodos Larnaca Culmination includes the southern and shallowest part of the Latakia Basin as well as the southern slope which links Latakia and Cyprus Basin. The Cyprus Arc marks the boundary between the Levantine and Cyprus Basin.

Several elongated topographic highs align SW–NE along the Troodos Larnaca Culmination. They are 1–2 km wide and up to 80 m high (Fig. 2). The ridges at the lower slope of the Troodos Larnaca Culmination are more continuous. Several round shaped or elongated topographic highs are present in the Cyprus Basin. They partly align along a bended morphological step of some 10 m height. Compressional folds in the northern most Levantine Basin have been discussed by Netzeband et al. (2006a) and result from the northern creep of the Messinian evaporites caused by the sediment load of the Nile cone. These folds are not discussed in this study.

3. Methods

Bathymetric data from the eastern Cyprus Arc have been gained using the hull-mounted EM300 multi-beam swath sounder system

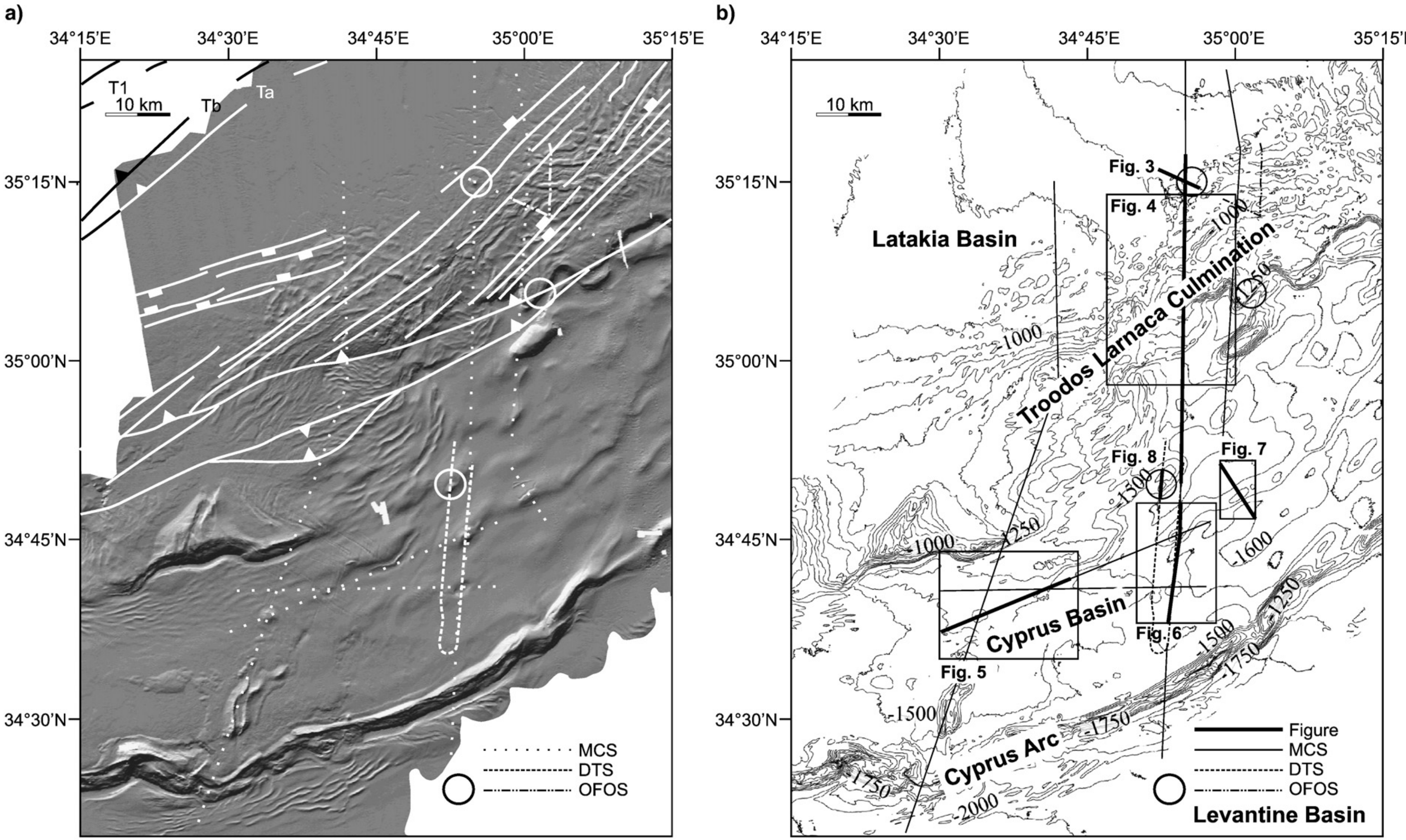

Fig. 2. a) Shaded relief of the study area with available seismic, DTS and OFOS profiles and survey areas. Small scale OFOS surveys are indicated by circles. The tectonic fault system is redrawn from Calon et al., 2005. Small rectangles indicate normal faults with ticks at hanging wall. Thrust and reverse faults are indicated by triangles with ticks at hanging wall. T1 is a fold/thrust belt, Ta and Tb are thrusts. b) Bathymetry of study area showing water depth of the survey area and figure location. MCS: Multi-channel seismic; DTS: Deep-towed side-scan sonar and CHIRP sub-bottom profiler; OFOS: Ocean floor observation system (video and photo).

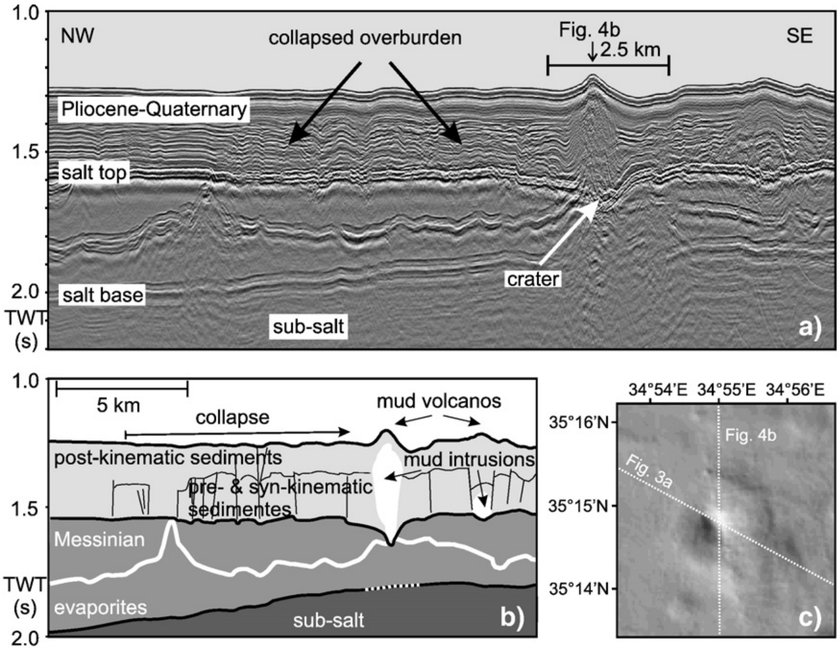

Fig. 3. a) Seismic profile across a mud volcano at the Troodos Larnaca Culmination. b) Line drawing and interpretation. c) Shaded relief of the mud volcanoes. The dotted lines mark the measured seismic profiles. For location see Fig. 2b.

installed on *RV Le Suroit* (Benkhelil et al., 2005). Almost complete coverage has been obtained for a 20,000 km^2 wide area ranging in water depth from 500 to 2000 m. The bathymetric data were gridded with a cell size of 50 × 50 m.

The seismic data presented in Figs. 3–6 were recorded during the SAGA cruise with *RV Pelagia* using a streamer of 600 m active length, 24 channels with a group distance of 25 m and a maximum offset of 700 m. Seismic signals were generated by a GI-Gun cluster (2 × 105/105 in^3) for profiles in Figs. 3 and 5b and a G-Gun cluster (2 × 360 in^3) was used for Figs. 4b and 6b. The shot spacing was 25 m. The recordings were CMP-sorted with a CMP spacing of 12.5 m, then stacked and band-pass filtered with passing frequencies between 10 and 150 Hz. A stacking velocity analysis was carried out on every 50th CMP in super-gathers of 5–9 CMPs. All lines are post-stack time migrated. Owing to the limited offset interval velocities were roughly estimated to 4500 m/s for the Messinian evaporites and 1800 m/s for the sedimentary overburden.

The seismic data of Fig. 7b were collected aboard the *RV Le Suroit*. The multi-channel seismic equipment consisted of two GI-guns (45/105 and 75/105 in^3) as the seismic sources and a 300 m long six-channel streamer. Shots were fired every 12.5 s at a ship velocity of 8 kn, resulting in a shot distance of 50 m. Consequently, the CDP coverage was 3 and the CDP-spacing was 25 m. The data processing included trace editing, CDP sorting, NMO-correction, stacking, frequency filtering and post-stack time migration. Since the maximum streamer offset of 300 m was relatively small compared to the water depth, the normal move-out was very small and prevented any detailed velocity analysis.

Side-scan sonar and Chirp sub-bottom profiler data have been obtained using the DTS-1 system of IfM-Geomar. During the SAGA

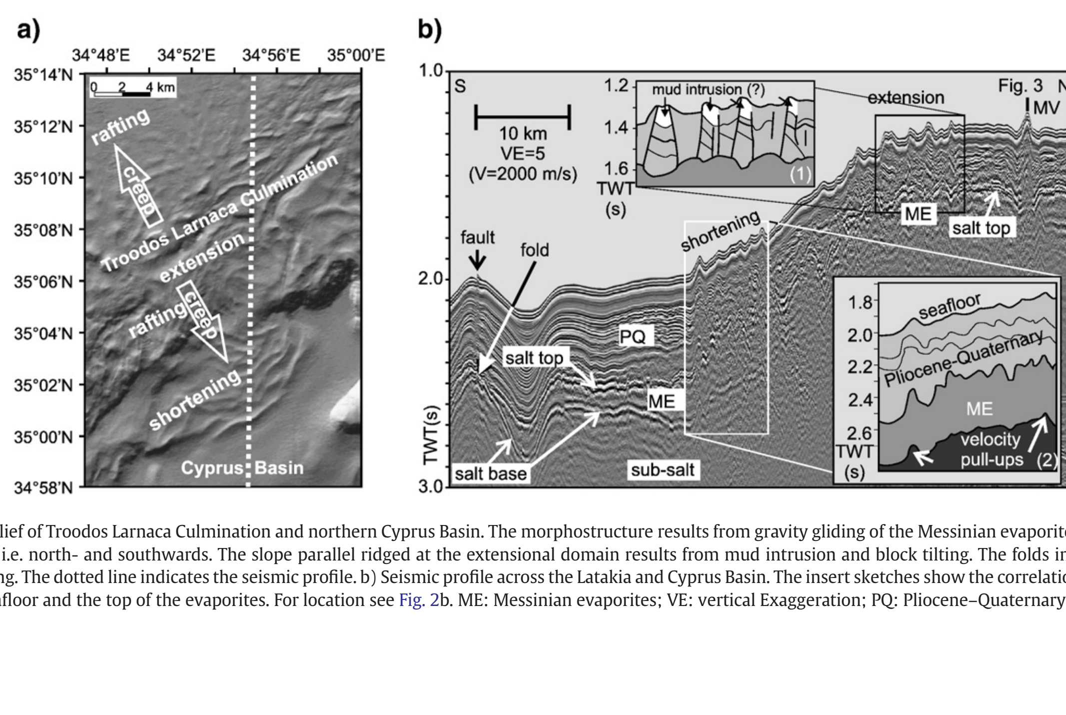

Fig. 4. a) Shaded relief of Troodos Larnaca Culmination and northern Cyprus Basin. The morphostructure results from gravity gliding of the Messinian evaporites. The evaporite layer creeps downslope, i.e. north- and southwards. The slope parallel ridged at the extensional domain results from mud intrusion and block tilting. The folds in the Cyprus Basin are caused by shortening. The dotted line indicates the seismic profile. b) Seismic profile across the Latakia and Cyprus Basin. The insert sketches show the correlation between ridges and trenches on the seafloor and the top of the evaporites. For location see Fig. 2b. ME: Messinian evaporites; VE: vertical Exaggeration; PQ: Pliocene–Quaternary; MV: Mud Volcanoes.

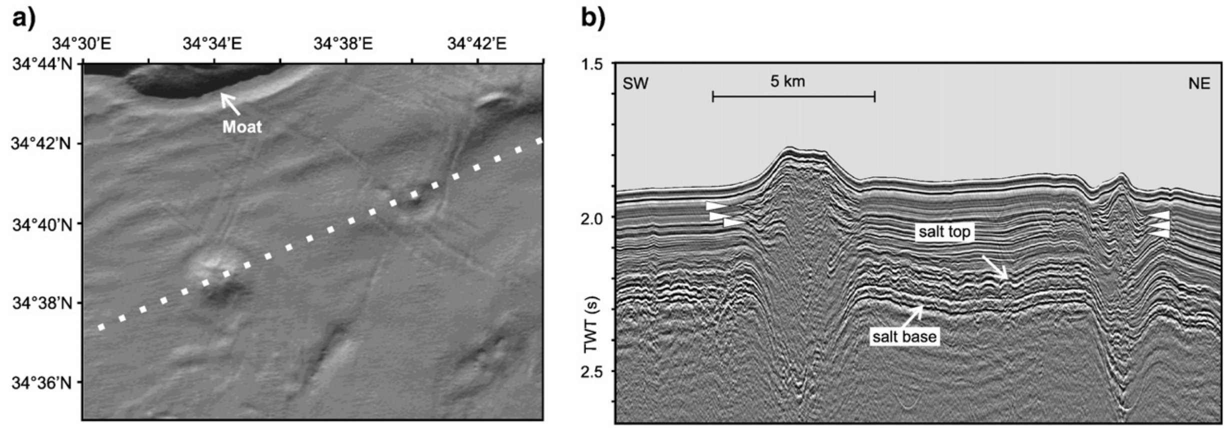

Fig. 5. a) Shaded relief of two mud volcanoes in the Cyprus Basin. The dotted line marks the seismic profile. A current moat channel indicates strong bottom currents b) Seismic profile across the mud volcanoes. Buried mud flows are expressed as X-mas structures. Individual mud flows are marked by white arrows. For location see Fig. 2b.

cruise this system operated with 75 kHz centre frequencies for the side-scan data and a 2–8 kHz Chirp signal for sub-bottom profiling. The side-scan data provide a 1500-m wide swath and the data have been processed to a pixel size of 1 m. The tow-fish was located using an ultra-short baseline system providing an accuracy of 1% of the range (cable length), i.e. about 30-m in the survey area.

Seafloor images were obtained during the SAGA project using a towed camera sled (OFOS) equipped with a black-and-white video camera and a still camera. The sled is towed at about 0.5 kn allowing to continuously observing a 2-m wide stripe of the seafloor along the track. An ultra-short baseline system provided accurate underwater positions.

4. Mud volcanoes at the Troodos Larnaca Culmination

The seismic profile shown in Fig. 3 crosses a circular topographic high of 70-m relief height and 1500-m diameter in the Latakia Basin in a water depth of about 970 m. The post-Messinian succession has a thickness of about 270 m (300 ms TWT). The top of the Messinian evaporites can be easily identified. The phase-reversed and smoothly undulating reflection 300–400 ms beneath the top of salt is interpreted as the base of the Messinian. Therefore the entire salt is up to 900 m thick (400 ms TWT), which is about three times the thickness of the overburden. An about 2500 m wide crater in the subsurface and upper Messinian evaporites, respectively, has a depth of app. 100 ms TWT and 70–100 m, respectively. A second profile perpendicular to the first one proves the circular structure of this subsurface crater (Fig. 2).

Beneath the crater the base of the Messinian evaporites is blurred and can not be identified in the seismic data. In the central part of the profile and above the complete swag of the internal reflection the top of salt is disrupted and down faulted. The faults that disrupt the top of salt dissect the lower part of the overburden. The upper evaporites and the lower overburden have collapsed. The uppermost 100 m of the sediments are less disturbed. A phase-reversed and garland-like reflection within the evaporites terminates against the top of salt and the crater, respectively. Seismic data from the outer Latakia Basin published by Calon et al. (2005; their Figs. 5 and 6) reveal similar garland-like reflections within the Messinian terminating against the top of the Messinian.

The circular structure is interpreted as a mud volcano (see review of Kopf, 2002). However, individual mud flows are not resolved in detail; they may be represented by the diffraction hyperbolae in the Pliocene–Quaternary succession beneath the central cone. The rim synclines indicate that the volume of mud transported from the sub-salt towards the Pliocene–Quaternary succession is relatively small.

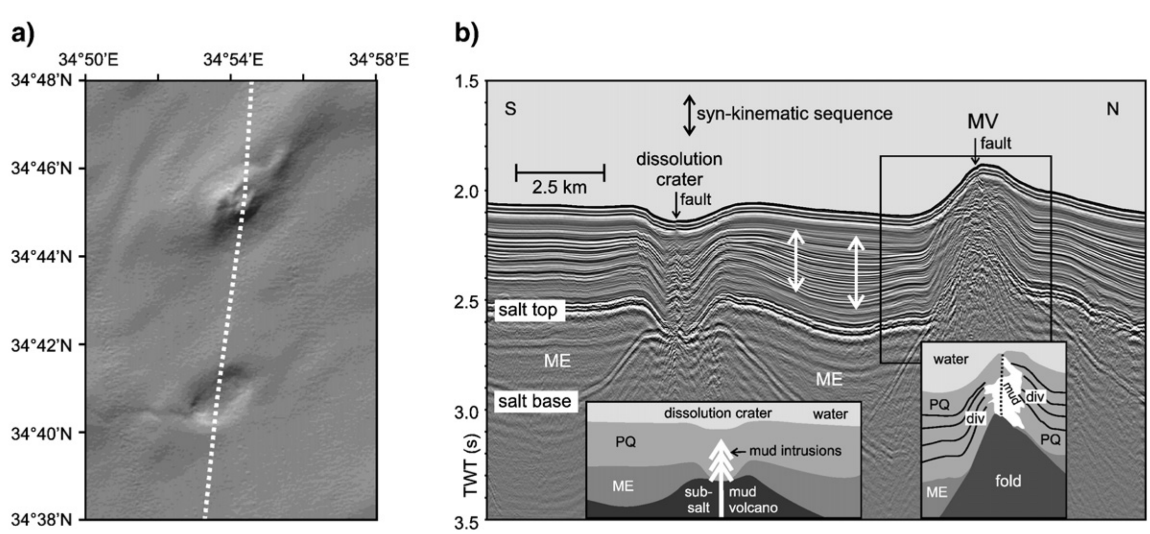

Fig. 6. a) Shaded relief of sub-salt mud volcano and a fold in the Cyprus Basin. The dotted line marks the seismic profile. b) Seismic profile and line drawing. For location see Fig. 2b. Div: divergent reflections; ME: Messinian evaporites; MV: Mud Volcanoes; PQ: Pliocene–Quaternary.

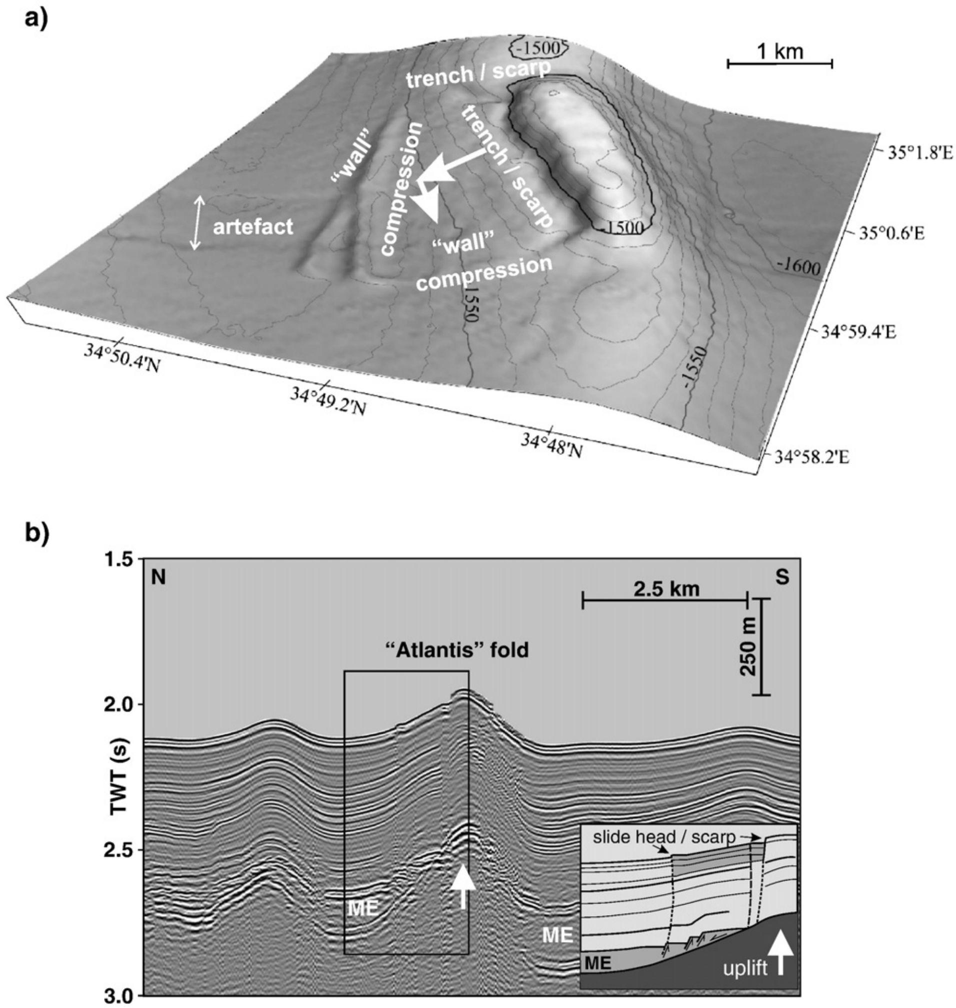

Fig. 7. a) Topography of "Atlantis" fold. b) Seismic profile, for location see Fig. 2b. The depth axis is valid for the water column only. ME: Messinian evaporites.

The net sum of added mud equals approximately the dissolved salt. The crater in the upper evaporites is caused by salt dissolution. Dissolution craters of similar characteristics formed by fluid through flow have been described by means of 3D seismic data off Israel (Bertoni and Cartwright, 2005).

However, salt dissolution caused by vertical fluid through flow from beneath the salt upwards to the seafloor does not explain the collapse of the upper evaporites and the lower Pliocene–Quaternary succession north-west of the mud volcano. The faulted top of the Messinian evaporites and the collapse of the Pliocene–Quaternary overburden above the garland-like intra-salinar reflection are caused by a thickness and volume reduction of the upper evaporites, respectively. Such a volume reduction can be caused by Gypsum–Anhydrite conversion, the released fluids migrated along the intra-salinar and phase-reversed reflection towards the subsurface crater (Fig. 3b). Similar fluid flow out of Messinian evaporites has been described by Gradmann et al. (2005) and Netzeband et al. (2006a).

Both the upper and lower evaporite layers are seismically transparent which is typical of pure Halite (Mitchum et al., 1977). The thickness of the Anhydrite/Gypsum layer is either below seismic resolution, or this explanation does not apply to the situation here. Garfunkel and Almagor (1984) interpreted reflections within the Messinian evaporites off Israel as overpressurized clastics, such a layer represents an alternative fluid reservoir. In both cases the phase-reversed intra-salinar reflection does most likely represent the fluid migration path (Fig. 3b).

The seismic transparency in Fig. 3 is presumably just a local characteristic, since the data presented in Figs. 5 and 6 of Calon et al. (2005) clearly show several internal reflections within the Messinian evaporites. The stratigraphy of the Messinian evaporites in the Latakia Basin is obviously different from that of the deeper Levantine Basin, where 6 sequences of different reflection characteristics have been observed (Hübscher and Netzeband, 2007).

Since the upper third of the Pliocene–Quaternary succession is much less dissected than the rest of the overburden a declining dynamic of any causative process is likely. For example, the transition from subduction to continent–continent collision in the latest Miocene or lower Pliocene (Hall et al., 2005) should result in an overall stress release which should also reduce the fluid pressure and mud volcanism, respectively.

5. Salt tectonics and mud volcanism

The salt and fluid dynamic between the Troodos Larnaca Culmination and the Cyprus Basin is elucidated by Fig. 4. Along the culmination several ridges are disrupted by W–E and NE–SW trending bathymetric lows (Fig. 4a). Further down the slope the ridges bend around the steepest part of the slope.

According to Calon et al. (2005) suggested that the Pliocene–Quaternary sediments at the Troodos Larnaca Culmination are floored not by Messinian evaporites. Instead, they assume Lower to Upper Miocene deposits which are correlated with the reefal carbonate build-ups of the Koronia Member of the Pakhna Formation as exposed

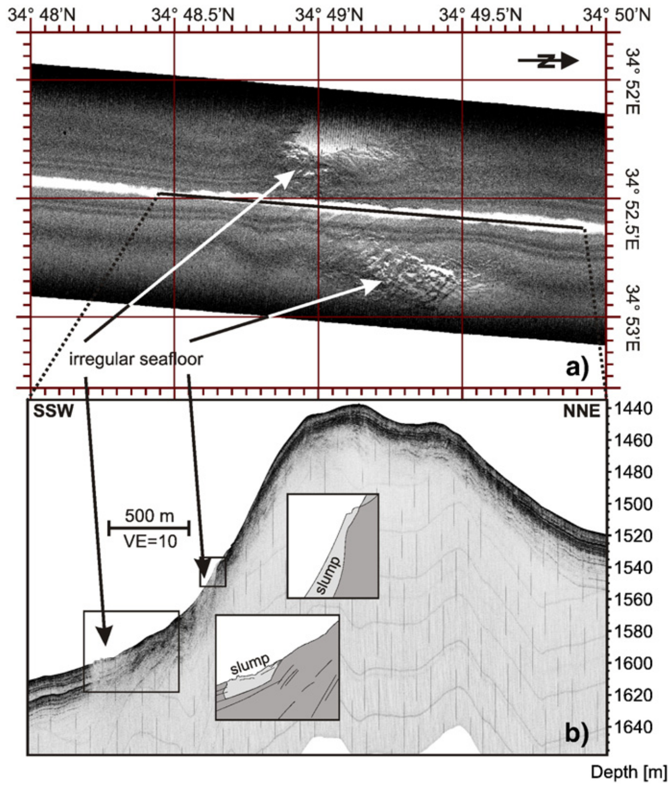

Fig. 8. a) Deep-towed side-scan sonar image of a fold anticline in the Cyprus Basin. Irregular seafloor patches are present on the southern flank of the ridge. b) CHIRP subbottom profiler profile along the center of the side-scan image. Water depth and vertical exaggeration (VE) was calculated with 1.5 km/s. The ocean floor observation system (OFOS) was also operated along this track. For location see Fig. 2b.

in southern Cyprus. According to these authors the ridges and trenches further upslope are associated with a deep-rooted strike-slip fault zone transecting the crest of the culmination (thick-skinned or plate tectonics). The ridges at the lower slope of the culmination are associated with thrust or reverse faults (Fig. 2a).

Here, we suggest an alternative end-member model in which the observed structures and features are explained by thin-skinned salt tectonics and mud volcanism. This model is based on the assumption that the ridges along and downslope the Troodos Larnaca Culmination are created by lateral salt creep (upslope extension and downslope shortening) and that the lessons learned from the mud volcano in Fig. 3 can be applied on the particular area here. Consequently, we suggest that the Troodos Larnaca Culmination is floored by (ductile) Messinian evaporites instead of reefal carbonate build-ups.

According to the seismic data the elongated topographic highs at the Troodos Larnaca Culmination correlate with trenches in the Messinian beneath (Fig. 4b, insert 1). Individual reflections within the Pliocene–Quaternary succession are tilted to the north. At the lower slope and towards the Cyprus Basin bathymetric highs correlate with elevations of the evaporites (Fig. 4b, insert 2). The topography of the evaporite base runs sub-parallel to the top of the evaporites, which is rather a velocity than a depositional or tectonic effect. A velocity pull-up occurs if the Messinian evaporites thicken, because the evaporites have an interval velocity of roughly 4.5 km/s which is more than twice the velocity of the overburden. Further south the evaporites terminate against folded pre-Messinian and Pliocene–Quaternary strata.

North of the Troodos Larnaca Culmination the base of the evaporites dips northward and south of the culmination it dips southward (Calon et al., 2005; Hall et al., 2005). Since the Messinian evaporites consist of ductile salt, the tabular evaporites likely creep under the influence of gravity in the dip direction of the sub-salt strata (Fig. 4b). The folded pre-Messinian strata act as a backstop. Consequently and in terms of thin-skinned salt tectonics the Troodos Larnaca Culmination represents an extensional domain. The southward tilting of the Pliocene–Quaternary sediments above the trenches results from this extension. According to the model of Letouzey et al. (1995) the northern Cyprus Basin, where both evaporites and overburden are folded, represent the shortening domain. Along the southern slope the Pliocene–Quaternary overburden is rafted on top of the salt.

The elongated depressions in the top of the evaporites at the Troodos Larnaca Culmination can be explained by extension, either by ductile stretching or boudinage. However, the seismic cross-sections of these trenches are very similar to those of the dissolution crater beneath the mud volcano in Fig. 3, which suggests a similar causative process like fluid flow related salt dissolution. The thin-skinned extension may open fluid pathways through the evaporites. The Pliocene–Quaternary succession above the depressions is thickened compared to adjacent areas. The thickening of the overburden is caused by mud intrusion, which forms the morphological ridges as observed in the shaded relief (Fig. 2a). Block tilting enhances the hummocky seafloor topography.

6. Mud volcanoes and folding in the Cyprus Basin

Two circular topographic highs from the Cyprus Basin are shown in Fig. 5. The top of the thin evaporite layer lies about 350 m beneath the seafloor. The western topographic high is 4 km wide and more than 100 m high. A crater within the evaporites and sub-salt strata is 250–300 m deep and has the same width than the bathymetric high itself. Several "Christmas tree" like reflections can be identified in the Pliocene–Quaternary succession. The eastern topographic high is smaller and surrounded by rim synclines. "Christmas tree" reflections are also resolved here.

Further to the east, a 60–70 m deep depression lies south of an elevated topographic high (Fig. 6a). The southern circular seafloor depression overlies a mound-like structure beneath the evaporites (Fig. 6b). The circular shape of the sub-salt mound has been confirmed by a second and perpendicular seismic profile (Fig. 2). The evaporites vanished above the mound and beneath the crater, respectively. The rim of the crater within the evaporites is slightly elevated. Short reflection patches are resolved within the lower 2/3 of the Pliocene–Quaternary succession and at both sides of a fault that reaches from the middle of the seafloor expression to the center of the sub-salt mound. The Messinian evaporites terminate against the topographic high in the northern part of the profile (Fig. 6b). Within the Pliocene–Quaternary cover and above the folded pre-Messinian a wider area of strong reflection patches is present. Also here a fault starts at the summit of the pre-Messinian fold and pierces the seafloor.

The bathymetry of an elongated topographic high further NW reveals northwards two 100 m wide and 10 m high walls which strike perpendicular to each other (Fig. 7a). The walls and two trenches form approximately a rectangle with wall and graben on the opposite sides. The seismic data show that the pre-Messinian strata are also folded. The evaporites are uplifted and faulted above the flanks of the pre-Messinian fold. The faults within the evaporites correlate with the walls, the termination point of the evaporites towards the fold correlated vertically with the trench.

The observed topographic highs within the Cyprus Basin can be subdivided into two groups. All those topographic highs which reveal a dissolution crater in the Messinian unconformity beneath are interpreted as mud volcanoes (Figs. 3a, 5b and 6b). Elongated topographic highs which reflect anticlines of the pre-Messinian strata beneath are considered to represent compressional folds (Figs. 4b, 6b and 7b).

The "Christmas tree" reflections or reflection patches beneath the mud volcanoes are typical of mudflows which are intercalated into the Pliocene–Quaternary succession. The craters in the upper evaporites are also interpreted as dissolution craters. The volume of the mud flows of the eastern mud volcano in Fig. 5b is obviously not big enough to compensate the salt dissolution which results in the evolution of rim synclines. The circular sub-salt mound in Fig. 6b is interpreted as a mud volcano that existed before the deposition of Messinian evaporites. Fluids escaped after the Messinian and dissolved the overlying salt. The dissolved volume was not compensated by mud intrusion and the circular depression was formed on the seafloor.

A near vertical fault connecting the seafloor with the edge of the evaporites (Figs. 4b, 6b and 7b) at the compressional folds indicates active "thin-skinned" tectonic. The folds are still rising and/or the evaporites glide downwards with the salt base as the gliding surface. The ridge in Fig. 7, which has been named "Atlantis" by Sarmast (2004), is surrounded by walls and trenches. Fold growth caused disruption of the Messinian evaporites that carried the overburden with them resulting in the formation of a slide scar and surficial compressional folds at the downslope end of the slide.

Mud volcanoes and folds align along arcs parallel to the Cyprus Arc which indicates correlated causative processes. Hall et al. (2005) describe positive flower structures which emerged in the early Pliocene when the plate-kinematic regime changed from collision to strike-slip movements. We suggest correlating the evolution of mud volcanoes and folds in the Cyprus Basin with deep-rooted strike-slip faults that produced the flower structures. The elongated topographic folds in the Cyprus Basin result from transpression and align above the strike-slip faults. The faults themselves act as migration paths for fluids and align also above the deep-rooted faults.

7. Timing of main morpho-structural evolution and active fluid migration

The Messinian evaporites onlap the pre-Messinian strata of the compressional folds (Figs. 4b, 6b and 7b). There is no evidence that the folds broke through a tabular and closed evaporite sheet, but the evaporites were uplifted by the emerging folds after their deposition. Since the folds were already present prior to the evaporite sedimentation, the folding was active at least in the early Pliocene. The Pliocene–Quaternary overburden bends upwards and thins towards each fold axis. The parallel-stratified lower part of the Pliocene–Quaternary was deposited during a tectonically quite phase because this sequence reveals an almost constant thickness. This sequence corresponds to the almost isopachous "Wedges" 6 and 7 from the Cyprus Arc as discussed by Hall et al. (2005). The majority of the Pliocene–Quaternary succession thins towards the folds. Consequently, these strata were deposited syn-kinematically during the phase of main folding. The data of this study reveal an almost isopachous uppermost sequence which drapes the central sequence and is considered as the post-kinematic sequence. Consequently, active folding occurred in the middle Pliocene–Quaternary but ceased later on. These findings further corroborate the stratigraphic interpretation of seismic data from the Cyprus Arc of Hall et al. (2005). The presence of faults piercing the seafloor suggests recently active strike-slip faulting.

A detailed small scale survey with the deep-towed side-scan sonar and the CHIRP subbottom profiler from a fold anticline showed a 5 m thick undisturbed sediment layer atop the ridge (Figs. 2b and 8). However, slumps are present on the flanks of the fold anticline (inserts Fig. 8). It can be assumed that the slumping results from episodic folding or earthquakes.

The sub-salt mud volcano of Fig. 6b proves that at least some local fluid extrusion occurred in pre-Messinian times. The Figs. 5b and 6b show mud flows intercalated into the Pliocene–Quaternary succession but no mud flows on the seafloor. Back-scatter data collected during the BLAC cruise in 2003 include no hints for fluid extrusion on the seafloor at all (unpublished data). The mud volcano at the Troodos Larnaca Culmination is covered by undisturbed sediments and is consequently inactive.

Fluid and associated mud extrusion is related not only to mud volcanoes. Reflection patches within the Pliocene–Quaternary succession above compressional folds in the Cyprus Basin (Fig. 6b) may also be interpreted as mud in- or extrusions. Side-scan and CHIRP data from the slump heads on the fold flanks in Fig. 8 reveal an irregular seafloor and blurred reflections, respectively. These features are typical of gassy sediments or carbonate build-ups (chemoherms) above methane seeps (e.g., Hübscher and Kukowski, 2003). However, video images did not show any evidence for active fluid escape structures or carbonate build-ups. Fluid escape structures are obviously covered by a sediment cover with a thickness beyond the penetration of the CHIRP subbottom profiler.

8. Conclusions

Both thick-skinned plate tectonic and thin-skinned salt tectonic control fluid dynamics and associated mud volcanism in the Latakia and Cyprus Basin as well as at the Troodos Larnaca Culmination, which separates both basins. Beside the plate-tectonic processes as described by Calon et al. (2005) thin-skinned salt tectonics is evident at the Troodos Larnaca Culmination (Fig. 9). The evaporites creep down dip driven by gravity. The thin-skinned extension in the Troodos Larnaca Culmination and salt boudinage facilitate fluid flow through and out of the salt. The fluid or mud flow dissolves the upper salt layer which

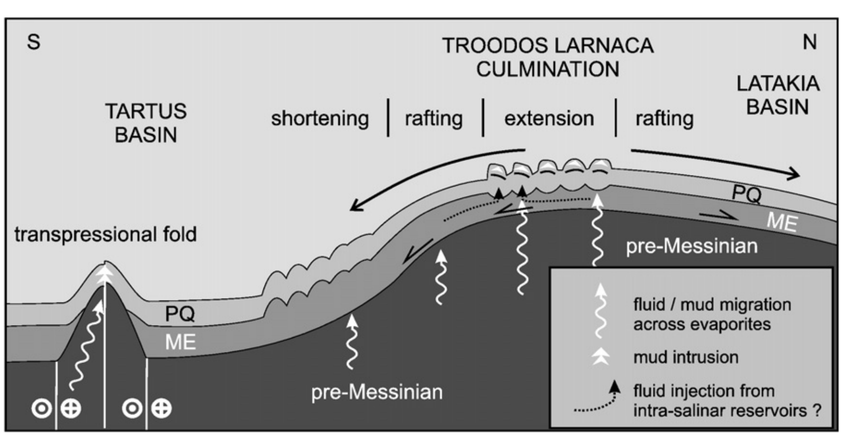

Fig. 9. End-member model explaining the morphostructure along the Troodos Larnaca Culmination by salt tectonics only. The downslope creeping salt leads to extension or salt boudinage at the culmination itself. Here, fluids flow through or out of the salt and dissolute elongated trenches. Mud intrusions thicken the overburden. Downslope creeping results in compressional folds in the salt and overburden. The skin-skinned tectonics as outlined here superimposes active plate tectonics as described by Calon et al. (2005). In the Cyprus Basin fold anticlines emerged above fault traces of deep-rooted strike-slip fault systems. ME: Messinian evaporites. PQ: Pliocene–Quaternary.

creates trenches. Mud intrudes into the upper Pliocene–Quaternary sediments above the trenches. The overburden is thickened and forms morphological ridges above the trenches. Here, the overburden is tilted due to thin-skinned extension. The block tilting enhances the hummocky seafloor topography. South of the culmination the evaporites and overburden are folded due to thin-skinned shortening.

Origin and location of the fluid reservoirs are unknown but assumed to be beneath the evaporites. The overpressure may result from plate tectonics (subduction, continent–continent collision) or from the load of the evaporites. In one instance fluid extrusion out of the evaporites was inferred from seismic data interpretation. The outflow caused a volume reduction and collapse of the evaporites.

Mud volcanoes and fold anticlines of the Cyprus Arc align above and between deep-rooted transpressional fault system traces which are associated with the African–Anatolian collision zone (Hall et al., 2005). Faults above the summit of the mud volcanoes or folds can be explained in the same manner (Fig. 9). The faults may act as conduits for rising fluids. In the western part of the survey area, where the Cyprus Arc strikes almost West–East and the collision occurred more frontal and stress was highest, mud volcanoes emerged. Further to the east, where the Cyprus Arc runs SW–NE and sinistral strike-slip has been proposed, compressional folds evolved. Particular mud volcanoes and folds emerged prior to the deposition of the Messinian evaporites. The undisturbed upper Pleistocene sequences as well as the absence of significant mud outflow on the seafloor strongly suggest that the main fluid dynamic ceased.

Acknowledgement

We sincerely thank Captain John Ellen and his outstanding crew of *RV Pelagia* for the support during the SAGA cruise. We are grateful for the financial support of the University of Hamburg. The paper strongly benefited from reviews and comments by Jeremy Hall, Ali Aksu and Jean Benkhelil.

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