THE STRUCTURAL EVOLUTION OF THE MESSINIAN EVAPORITES IN THE LEVANTINE BASIN

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ABSTRACT

The Levantine Basin in the South-eastern Mediterranean Sea is a world class site for studying the initial stages of salt tectonics, because the Messinian evaporites are comparatively young, occur in a basin with a well-defined geometry, and are not tectonically overprinted. About 2 km of halite, gypsum and anhydrite were deposited in the basin during the Messinian Salinity Crisis, 5.3 - 5.9 Ma. We have mapped the evaporite thickness and the overlying sediment layer based on multi-channel seismic data. The evaporite body is not uniform, but characterized by 5 transparent layers sequenced by four internal reflections. This leads to the conclusion that there have been five cycles of evaporite deposition, each with a succession of upper and lower evaporites. All of these internal reflections are differently folded and distorted, proving that the deformation was syn-depositional. Thrust angles up to 14 degrees are observed. Backstripping of the Plio-Quaternary reveals that the direction of salt movement is SSW-NNE.

INTRODUCTION

The Levantine Basin lies in the south-eastern Mediterranean Sea and is considered to be a relic of the Mesozoic Neo-Tethys Ocean (Robertson and Dixon 1984, Garfunkel 2004)(Fig. 1). It opened during several rifting stages in the Triassic (Garfunkel 1998, Robertson 1998). Whether the crust underneath the basin is of oceanic origin or stretched continental crust has been a matter of debate for many decades (e.g. Woodside 1977, Makris et al. 1983, Dercourt et al. 1986, Hirsch et al. 1995, Ben-Avraham et al. 2002), but recent studies indicate that the crust in the Levantine Basin is of continental origin (Vidal et al. 2000a, Gardosh and Druckman 2006, Netzeband et al. submitted). The sediment fill of the Levantine Basin reaches a thickness of up to 14 km (Ben-Avraham 2002 et al., Netzeband et al. submitted). It is composed of a carbonate layer of possibly Cretaceous to Jurassic age with a thickness of 1 - 3 km, followed by a several km of Paleogene-Neogene pelagic sediments, a layer of Messinian evaporites of up to 2 km thickness, and a Plio-Quaternary cover, which mainly consists of Nile sediments (Druckman 1995, Vidal et al. 2000b, Ben-Avraham et al. 2002, Ben-Gai et al. 2005). The Messinian evaporites were deposited during the Messinian Salinity Crisis, when the evolving Mediterranean Sea lost its connection to the Atlantic, mainly because of the collision of the African and Eurasian plates (Hsü et al, 1973, 1978). The blocked water exchange and the high evaporation rate caused a drop in sea level, an increase in salt concentration and finally precipitation of evaporites. Druckman et al. (1995) estimate the fall of the sea level to approx. 660 - 820 m, Ben-Gai et al. (2005) find evidence for a sea level fall of 800 - 1300 m. As a consequence the Mediterranean Sea was a succession of more or less separate basins with different rates of sedimentation and different depositional environments (Montadert et al. 1978). According to Hsü et al. (1973) the reflooding has been a very rapid event, lasting only 1000 - 2000 years. Rouchy and Saint Martin (1992) estimate that about 25 cycles of refill and subsequent drawdown or a semi-permanent inflow of fresh water or a combination of both are required to deposit the amount of evaporites found in the basins in the Mediterranean Sea. Whereas Hsü et al. (1978) only acknowledge one single transparent evaporite layer, Rouchy and Saint Martin (1992) assess from

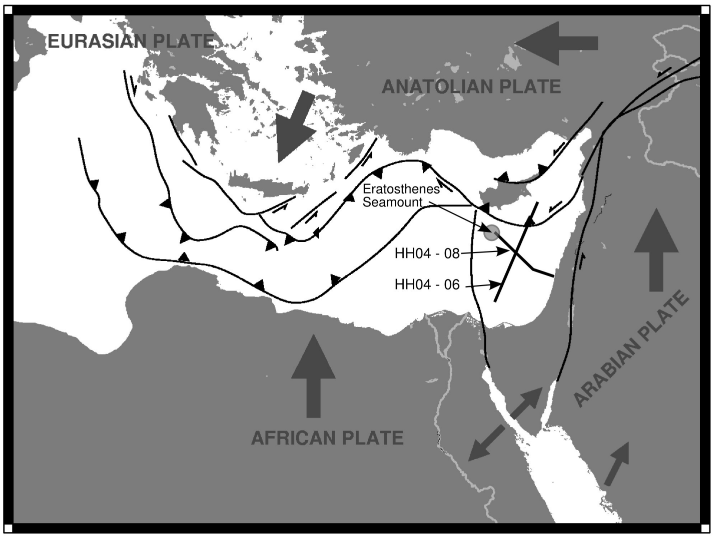

Figure 1: Simplified tectonic map of the Eastern Mediterranean Sea. Arrows indicate the sense of plate motion, half arrows indicate transform/strike-slip faults. Black lines mark profiles HH04-06 and HH04-08, and the Eratosthenes Seamount is indicated by the grey circle.

borehole analysis in the Western Mediterranean Sea that basinal evaporites generally consist of 2 successive units, one consisting of massive chloride salt and the other of calcium sulphate - marlstone interbedded with rare chloride salts. Polonia et al. (2002) observe even 4 subunits of Messinian evaporites in the Herodotus Abyssal Plain southwest of Cyprus. Gradmann et al. (2005) also find prominent internal reflections within the evaporite layer in the Levantine Basin. Garfunkel and Almagor (1984) and Garfunkel (1984) offer an interpretation of such internal reflections as embeddings of overpressurized clastic sediments between evaporites. The deposition of the Plio-Quaternary sediments above the Messinian evaporites is determined by the sediment supply of the Nile River (e.g. Mart and Ben-Gai 1982). The thickness of the sediment cover and sedimentation rate decrease accordingly to the north, a sedimentation rate of 111 m/my in borehole Delta-1 (near HH04-06) in about 120 m water depth) and 162 m/my in Echo-1 (further south $<$ 50 m water depth) are given for the Pleistocene by Tibor et al. (1992). According to Tibor and Ben-Avraham (2005) the Levantine Basin becomes shallower, because sedimentation exceeds subsidence. After anomalously high subsidence rates in the Pliocene (123 m/my in Echo-1) as a flexural response to the rapid deposition of Messinian evaporites the subsidence has significantly reduced (7 m/my in Holocene in Echo-1) (Tibor et al. 1992, Ben-Gai et al. 2005). The entire subsidence of the top of the Messinian amounts to 500 m in the basin (Tibor et al. 1992). During the Messinian Salinity Crisis, 5.9 - 5.3 Ma ago, thick evaporite layers were deposited in the main basins of the entire Mediterranean Sea (Hsü et al. 1973). The Messinian evaporites were the target of two DSDP legs (Hsü et al. 1973, 1978) and a number of other studies (e.g. Cohen 1993, Clauzon et al. 1996, Gradmann et al. 2005). The evaporite facies are differentiated in basinal and marginal evaporites (Garfunkel and Almagor 1984, Cohen 1993, Gradmann et al. 2005). The marginal evaporites mainly consisting of gypsum, anhydrite, carbonates, and intercalated shales are known from offshore and onshore drillings in Messinian and Pre-Messinian drainage channels (Gvirtzman and Buchbinder 1978, Garfunkel et al. 1989, Druckmann et al. 1995). The basinal evaporites presumably consist mainly of halite (e.g. Cohen 1993). Drilling of these basinal facies did not reach the halite layer, but only an upper evaporitic layer with several tens of meters of carbonates and gypsum interspersed with Nile sediments. The reflection marking the bottom of the Messinian evaporites has been termed N-reflection, that marking the bottom of the Plio-Quaternary overburden has been termed M-reflection (Ryan et al. 1970). The M-reflection constitutes an erosional unconformity in the entire Mediterranean Sea (Hsü et al. 1973, Almagor 1984). Salt tectonics as described by e.g. Letouzy et al. (1995) and Waltham (1997) can be studied in the initial stages, because of the comparatively young age of the evaporites and because of little tectonic overprint. Gradmann et al. (2005) have investigated Post-Messinian deformation in the basin in E - W direction, but did not consider deformation in N - S direction. Processes in N-S direction are of special interest, because the sediment transport is controlled by the sediment load of the Nile river and therefore predominantly S - N. Also, the effect of the Eratosthenes Seamount and the Nile Scarp as a potential backstop has not been studied yet.

DATA

The data of this study were collected during the cruise PE228 with the Dutch research vessel RV PELAGIA. 12 reflection lines were recorded. All were recorded with a streamer of 600 m active length, 24 channels with a group distance of 25 m, and a maximum offset of 700 m, respectively. The sampling rate was 1 ms. The source consisted of 2 G-Guns with 6 l each. The shot spacing was 25 m (10 s). The recordings were CMP-sorted with a CMP spacing of 12.5 m, then stacked and bandpass filtered with passing frequencies between 10 and 150 Hz. Further processing consisted of:

- a stacking velocity analysis on every 100th CMP in supergathers of 5 - 9 CMPs. The deeper the analysed horizon, the more CMPs in the supergather.
- smoothing or the resulting velocity field
- time-migration and stacking
- interval velocity analysis
- model based pre-stack depth migration

Interval velocities of Post-Messinian sediments and evaporite layers were 2.0 $\pm$ 0.2 km/s and 4.2 $\pm$ 0.3 km/s. With a maximum offset of 800 m and the base of the evaporites at $\sim$ 4 km, the interval velocity of the evaporite layer was difficult to determine, and it was impossible to find any reliable interval velocity from below. We carried out an Airy-backstripping of the Plio-Quaternary sediments after Allen and Allen (1990). We simply removed the sediment load, not taking into account any effect of compaction of either evaporites or Pre-Messinian sediments.

RESULTS

Top (M) and base (N) of the evaporite layer are clearly visible on all seismic lines (Figs. 2, 3). Line drawings of depth migrated lines HH04-06 and HH04-08 are shown in Figs. 4 and 5. The sediment thickness is noticeably influenced by the sediment contribution of the Nile River. Near the Nile Delta the sediment thickness reaches almost 3 km, while in the center of the basin the thickness of the sedimentary cover is less than 500 m. The sedimentary cover is also reduced around the Eratosthenes Seamount (Fig. 3). The thickness of the Messinian evaporites, in contrast, increases towards the center of the basin to over 2 km (Fig. 2 and 3). The top of the evaporites, M, declines towards the pinchout on HH04-08 (Fig. 5). In E-W direction, on line HH04-08, M is basically horizontal after backstripping of the Plio-Quaternary sediment layer, except for some small-scale undulations (Fig. 6). On line HH04-06, which is N-S-oriented, M is clearly planer after the backstripping, but the depth still varies between 1.8 and 2.4 km (Fig. 8). Near the pinchout of the evaporite layer, the depth of M is about 2.1 km, going north we see forebulging with M rising for approx. 80 km to only 1.8 km depth and then declining again towards the center of the basin to 2.4 km. The removed Plio-Quaternary sediment layer is of more or less constant thickness along the Israeli margin, with about 500 m in the basin and 1.1 km at the shelf (Fig. 6). In the south of line HH04-06, however, nearly 3 km of sediments overlie the evaporites due to the proximity to the Nile Fan. The calculated subsidence in the basin amounts to 200 m, which is in accordance to the results of Tibor and Ben-Avraham (2005). Up to 4 internal reflections (E1 - E4) are observed within the evaporite layer with varying reflection and deformation patterns (Fig. 5). These mostly well pronounced reflections alternate with transparent layers. The depth interval between N, E1 - E4, and M is more or less constant with 0.2 - 0.4 km in the basin, leading to a total evaporite thickness of approx. 1.6 km. The deformations of these internal reflections and M and N do not necessarily correspond to each other. Different kinds of deformation can be observed at the same location in different layers (Fig. 7, cmp 23200, cmp 23600, cmp

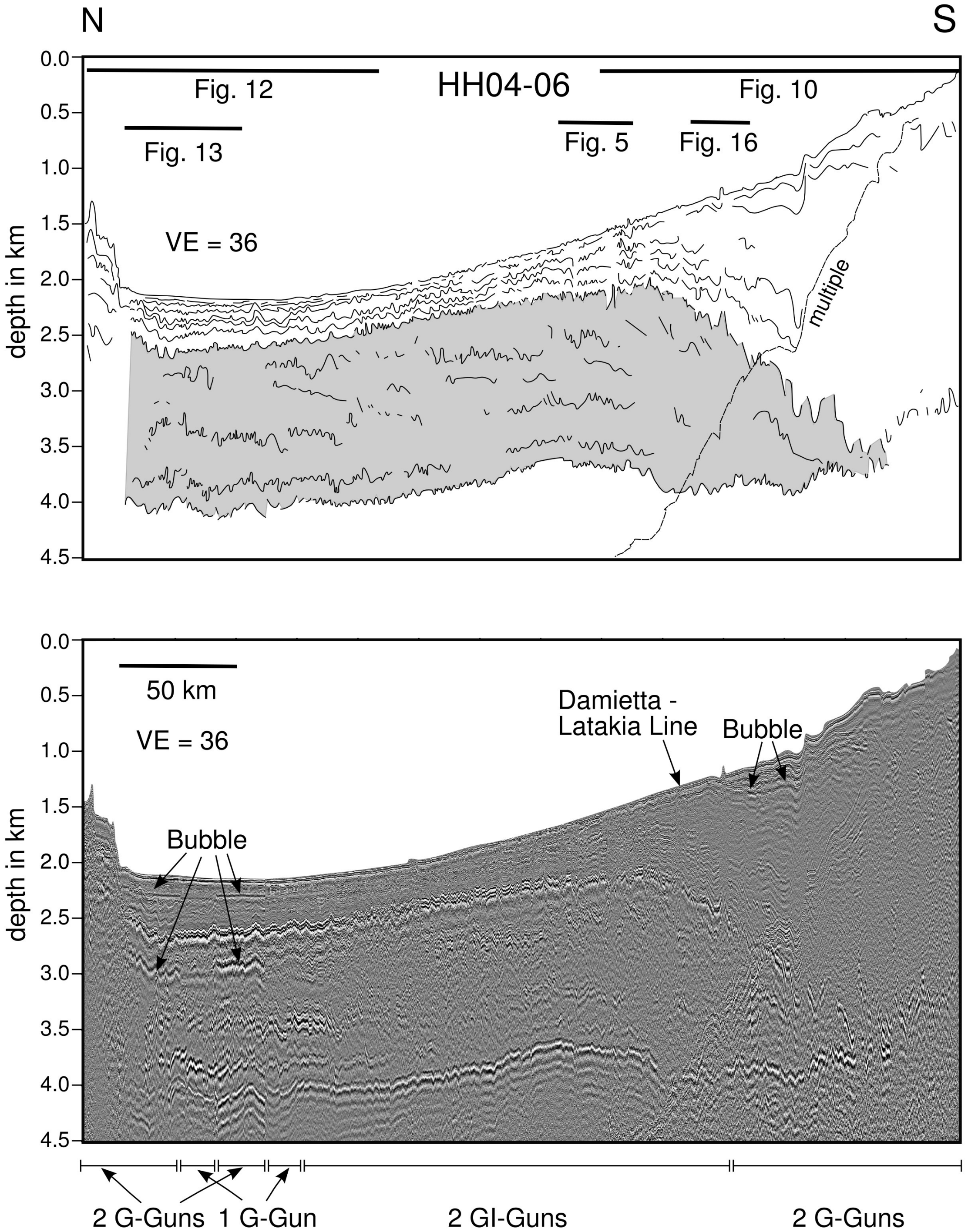

Figure 2: Depth migrated seismic line HH04 -06 (below) and corresponding linedrawing (above). The seafloor multiple is marked by the dashed line, the grey shaded area indicates the evaporite layer. Internal reflections within the evaporite layer are observed. The forebulging of the evaporite body is clearly visible.

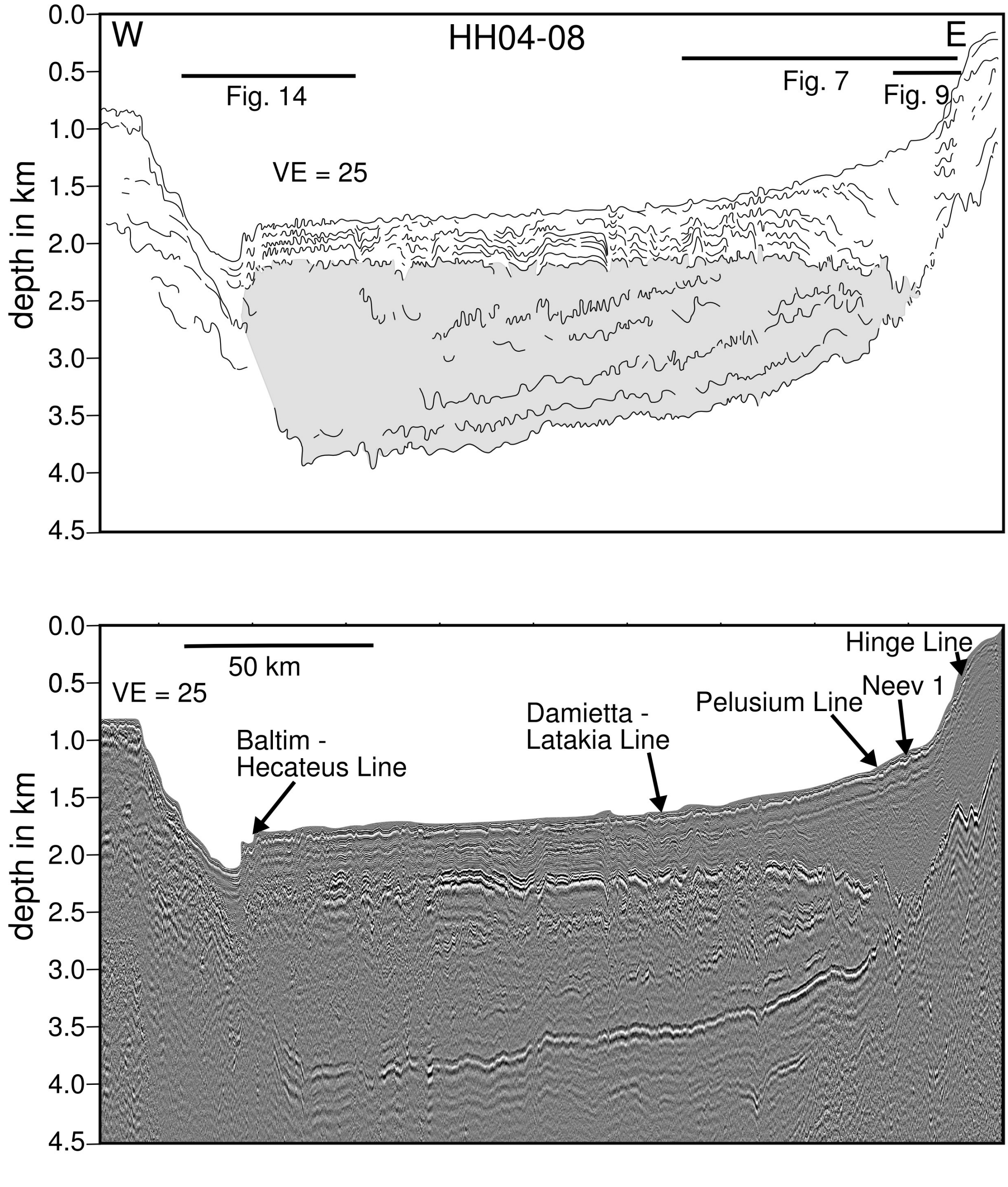

Figure 3: Depth migrated seismic line of HH04-08 (below) and linedrawing (above) of line HH04-08, analogue to Fig. 2.

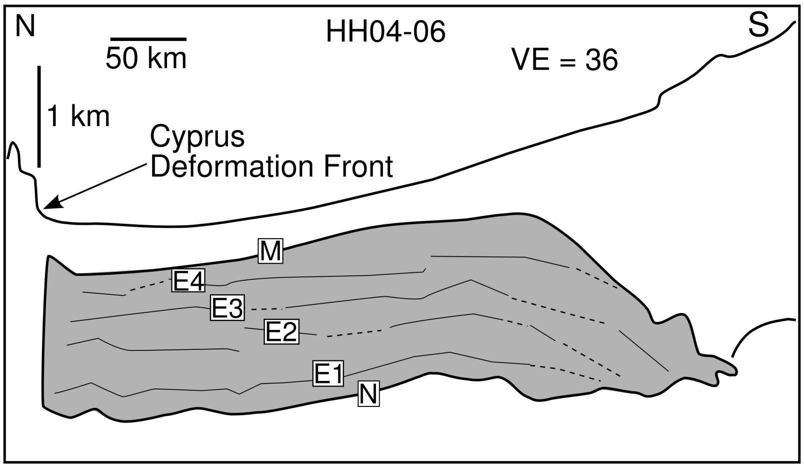

Figure 4: Simplified line drawing of line HH04-06. The grey area marks the evaporite body, M and N correspond to top and bottom of the evaporites, respectively. The solid lines labeled E1 - E4 indicate the observed internal reflections, the dashed lines indicate interpolation, where the internal reflections are not clearly visible.

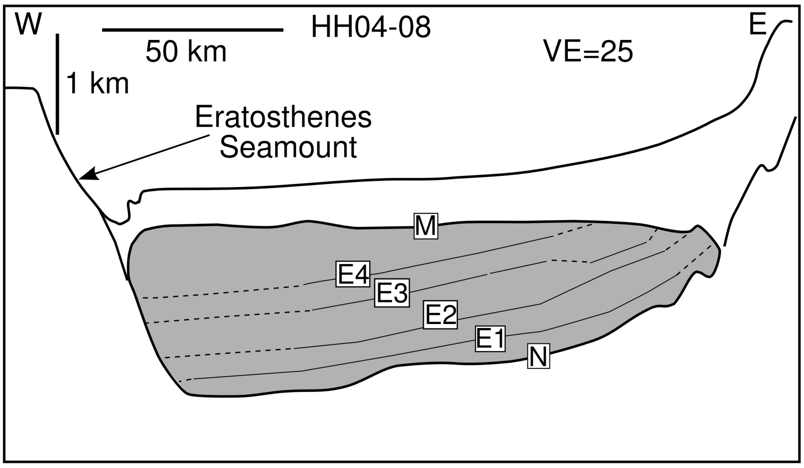

Figure 5: Simplified line drawing of line HH04-08, analogue to Fig. 4

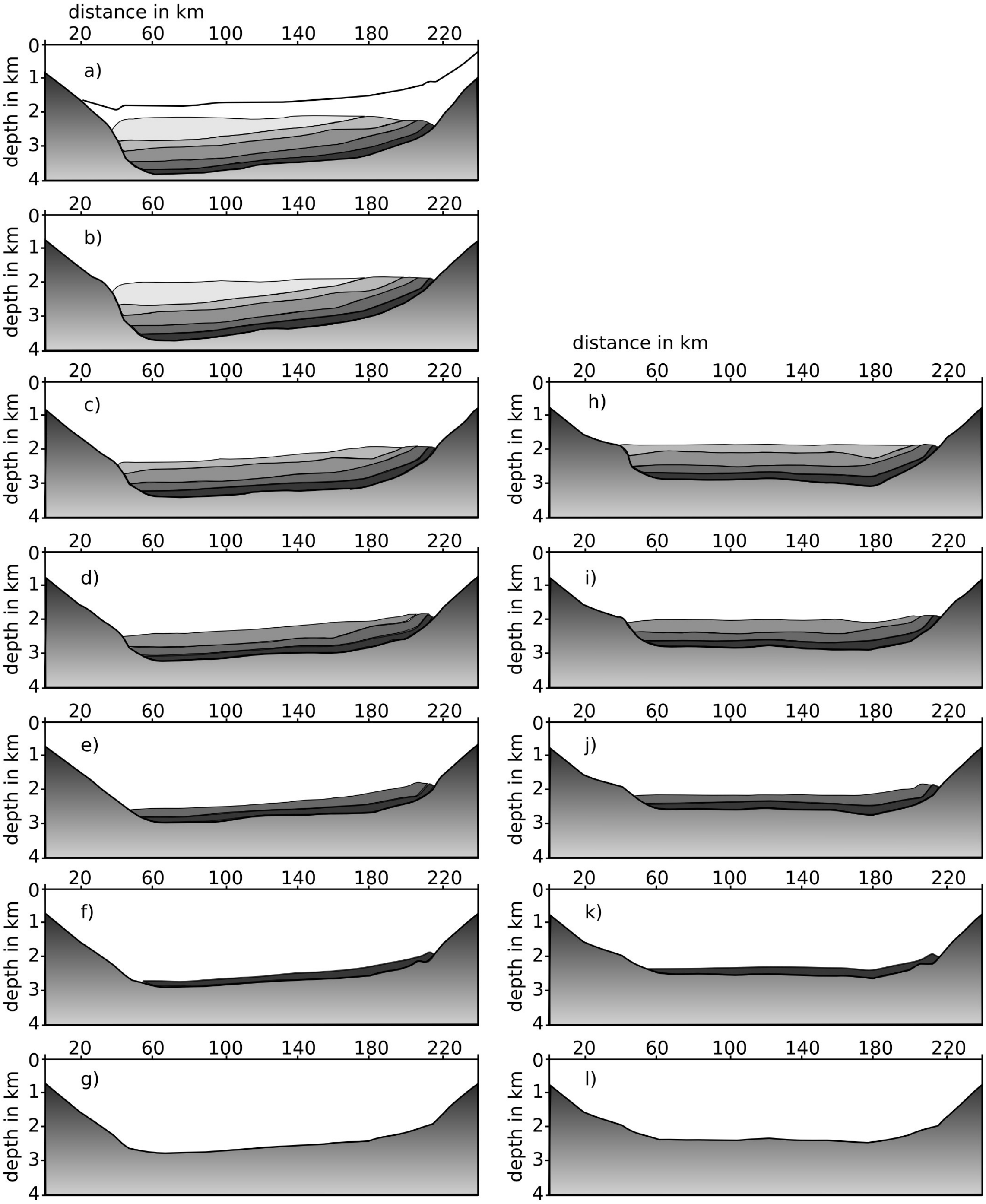

Figure 6: Airy backstripping of line HH04-08, including the internal salt reflections. The left column, a - g represents the backstripping results, as one layer at a time is removed. The right column, h - l, shows a modification of the backstripping: After removal of the Plio-Quaternary and the uppermost salt layer, the basin is partially uplifted, basinwards from km 180, until the top of salt is horizontal. Then backstripping is continued. Note, that the thickness if the internal salt layers is more or less constatnt, aprt from the uppermost layer. Also note, how in Fig. 6 h-l the top of the internal reflections stays almost horizontal.

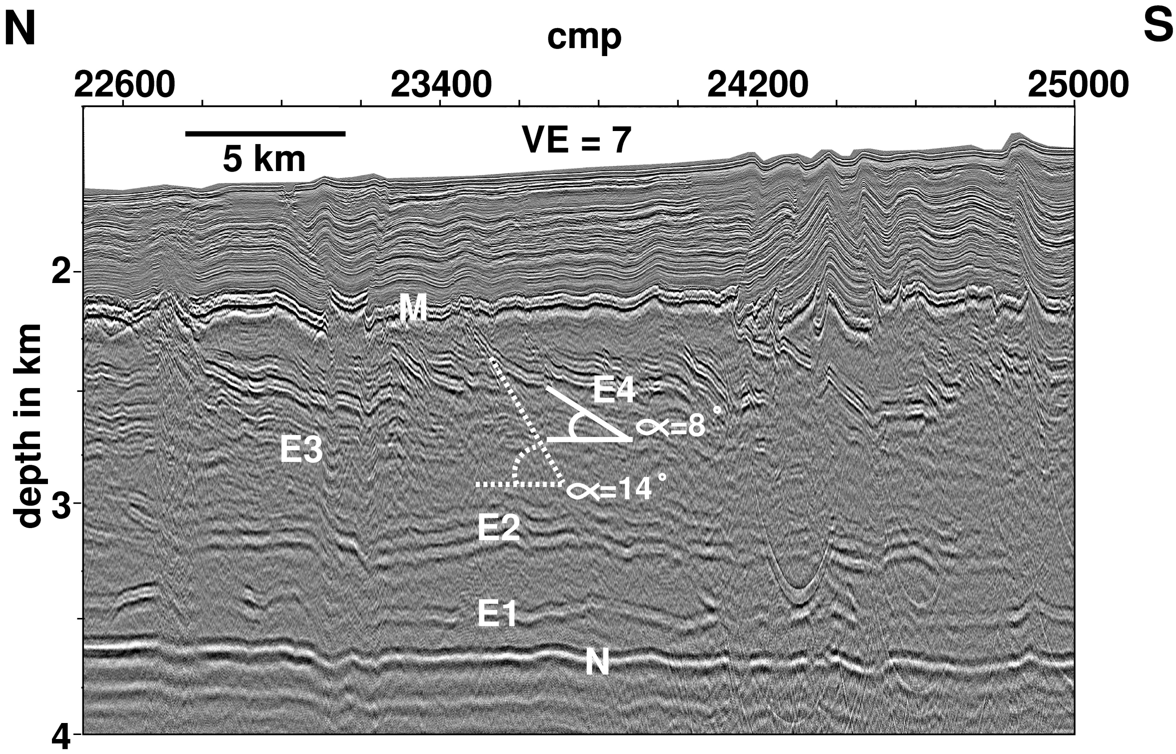

Figure 7: Section of seismic line HH04-06, depth migrated. Top and bottom of evaporite layer are indictaed by M, and N, respectively. E1 - E4 mark the internal evaporite reflections. Note the large angles of thrust within the internal reflections, particularly in E4. Two angles (the solid angles corresponding to 8^o, the dashed one to 14^o) are drawn for reference.

24100). A steep thrust in E4 is visible at cmp 23500 on line HH04-06 (Fig. 7), while M and the seafloor above are not affected and the overburden overlies M concordantly. The maximum thrust angle of the internal reflections is highest in E4 and decreases with depth. In E4 on line HH04-06 thrust angles of $86o$ are observed, up to 14^o are reached at the tip of the thrusts (Fig. 8).

Fig. 6a) - g) shows HH04-08 (Fig. 3, 5) after backstripping the layers between the internal reflections. The top of the evaporite layers is not horizontal after backstripping the overburden, but still dipping westwards. After removal of the lowermost evaporite layer, the basin remains asymmetric. Tilting the basin at 180 km after backstripping the Plio-Quaternary and the uppermost evaporite layer until the top of the evaporites is horizontal shows that the deeper evaporite layers become also almost horizontal (Fig. 9 h) - l). After backstripping all evaporite layers the basin is approx. symmetric.

INTERPRETATION AND DISCUSSION

Up to 4 internal reflections within the evaporites are observed in the Levantine Basin (Figs. 2, 3, 4, 5, 7). Internal reflections and layering of evaporites have been found before in the Mediterranean Sea (e.g. Réhault et al. 1984, Garfunkel, 1984, Rouchy and Saint Martin 1992, Polonia et al. 2002, Gradmann et al. 2005, dos Reis et al. 2005). Three explanations have been given for these reflections: a) interbedded shales, b) layers of different evaporites, and c) several depositional cycles. a) Garfunkel (1984) and Garfunkel and Almagor (1984) postulate overpressured shales interbedded within the impervious evaporites. However, the clear seismic signature and the regular intervals between the internal reflections rather suggest cyclic deposition than constant interbedding. b) Réhault et al. (1984) identify three layers within the evaporite succession in the Western Mediterranean: upper evaporites (composed of halite, gypsum and marls), salt (halite), and lower evaporites (possibly of the same composition as the upper evaporites). Dos Reis et

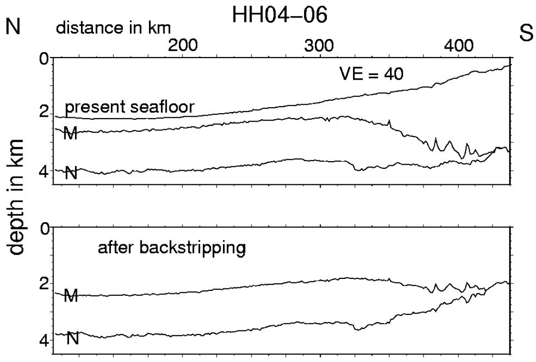

Figure 8: Airy backstripping of HH04-06. Sketches are split in two parts: the present seafloor, top and bottom of the evaporites in the upper part, and top and bottom of the evaporite layer after backstripping of the Plio-Quaternary sediments in the lower part. Note how M, the top of the evaporites, is not flattened after the backstripping.

al. (2005) also find these three layers in the Gulf of Lions. Polonia et al. (2002) detect two units within the Messinian in the Eastern Mediterranean Sea. They interpret the upper unit, which is characterised by folded high-amplitude reflections, as upper evaporites composed of marls and gypsum, and the lower unit, which is almost transparent and reflection-free, as halite. These observations and interpretations delineate a single cycle of evaporite deposition. c) Cohen (1993) describes a typical depositional cycle of Messinian evaporites in the Levantine Basin as marine clay -> gypsum -> halite, although he finds from well measurements that quite often one of the evaporitic members is missing and cycles become a couplet of either clay -> gypsum or clay -> halite. Our observation of 4 reflections, 5 including M, with 5 transparent layers in between leads to the assumption of 5 cycles of evaporite deposition. Cohen (1993) also observes up to 5 cycles of evaporites in boreholes offshore Israel, which confirms our hypothesis. The different distortion patterns of each reflection indicate that each layer was deformed after or during its deposition and before deposition of the next layer, i.e. in the Messinian. The perception of five layers successively deposited and deformed further supports the hypothesis of five depositional cycles of the Messinian evaporites in the Levantine Basin. The orientation of the internal reflections in N - S direction differs significantly from their orientation in E - W direction (Figs. 4 and 5). In N - S direction the internal reflections are mostly horizontal apart from the forebulging and generally parallel to M and N. In E - W direction, however, the internal reflections are parallel to N, and M is onlapping them. The subsidence analysis indicates that in E - W direction, in contrast to the N-S direction, the evaporite body has only undergone subsidence due to sediment load and its shape can be restored by removing this sediment load (Fig. 6). Therefore the E-W line gives the better picture of the status of the evaporites after the Messinian. It seems that the first layers of evaporites were deposited parallel to N, while only the last layer has actually been deposited horizontally. The onlap of M on E1 - E4 (Fig. 5) suggests that these were eroded during the Messinian. Possibly also the uppermost layer was initially deposited parallel to the slope and later eroded. This leads to the question whether the sea level drop could have been greater than 1200 m. The depth of the seafloor after backstripping is 1800 - 1900 m in the basin. The slope-parallel deposition of the evaporites might also be associated with the internal deformation of the evaporite layers. Because of their own weight they might have slightly slid down the slope after their deposition. Another possible explanation is that the basin was tilted during the Messinian, as suggested in Fig. 6 h - l. Under this assumption, the evaporites would have been deposited more or less horizontally, and their westward dip would be a result of increased subsidence, maybe of tectonic origin, in the basin.

CONCLUSIONS

We have investigated the Messinian evaporites in E - W as well as in N - S direction. We have shown that only little lateral evaporite movement has taken place in the Levantine Basin in the past 5 Ma, mainly in the SSW-NNE direction. In this initial stage of salt movement, the direction of this movement is controlled by the sediment load of the Nile River. Five sub-units of evaporite deposition have been found, which have been deformed syn-depositionally.

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