Diapiric features in the southeastern Mediterranean Sea: possible indication of extension in a zone of incipient continental collision

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Diapiric features in the southeastern Mediterranean Sea: possible indication of extension in a zone of incipient continental collision

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Abstract

Several types of diapiric structures were studied in the zone between the Nile deep-sea fan and the Eratosthenes seamount in the SE Mediterranean Sea. The study discovered four stages in the structural evolution of the diapiric features, starting as a domal piercement structure, and developing into initial basin as seawater dissolution starts to effect the diapiric salt. Subsequently V-shaped, and then mature, U-shaped basins formed as products of dissolution, sedimentary collapse and sediment deposition. The structures—both protrusions and depressions, are aligned along discrete lineaments, most of them trending NE–SW and a few NW–SE. The NE–SW lineaments are probably a series of normal faults and the NW–SE ones seem to be strike-slip faults. The development of extensional structures on the underthrust edge of the African Plate, as it approaches the subduction zone, are commonplace in the Mediterranean and elsewhere, and the occurrence of normal faults in this area is compatible with the intensive subsidence of the Eratosthenes Seamount in the Plio-Pleistocene. The lithostatic load of the Nile deep-sea fan could have contributed to the subsidence and thus enhanced the diapirism in the SE Mediterranean.

Key words: salt diapirs; SE Mediterranean; structural extension; tectonic collision

1. Introduction

One of the significant traces of the Messinian desiccation of the Mediterranean Sea is a series of evaporitic diapirs that penetrate the seafloor (Ryan et al., 1970, 1973; Hsü and Montadert, 1978; Ryan, 1978). In the eastern Mediterranean Sea, diapirs are abundant at the Levant basin, located between the Nile deep-sea fan and the Cyprus basin (Ross and Uchupi, 1977). Extensive diapirism along the northern and eastern margins of the Nile deep-sea fan is reflected in seafloor bathymetry by local domes, elongated ridges and, in places, rounded or elongated depressions, which resulted from the diapiric penetration of salt into the seafloor. The diapirs, which are accompanied in some places by salt dissolution and collapse of the seafloor, build series of 1–5 km wide grabens in many places (Woodside, 1977). The diapirs of the Levant basin were surveyed in the past by Ryan et al. (1970), Kenyon et al. (1975), Neev et al. (1976), Ross and Uchupi (1977), and Woodside and Williams (1977) and others.

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The area of the present study, located between the Eratosthenes Seamount and the central section of the Nile deep-sea fan (Fig. 1a), is largely congruent with the extent of the diapirc features at the eastern part of the late Miocene Xenophon Basin (Fig. 1b), where halite is probably the dominant component of the Messinian series (Ryan, 1978). Mapping this area by GLORIA side-scan sonar surveys revealed a fault pattern that is probably related to diapirism (Kenyon et al., 1975). The Xenophon diapirs, mentioned in studies such as Finetti and Morelli (1973), Kenyon et al. (1975), Neev et al. (1976), Ross and Uchupi (1977), Woodside (1977), Woodside and Williams (1977), Ryan (1978) and Garfunkel and Almagor (1987), are large-amplitude diapirc structures. These diapirs are a few hundred meters high, 1–3 km wide, and they extend along lines of preferred orientations for tens of km. Similar structures appear in the southeastern Mediterranean in the Haifa Diapirs group (Garfunkel and Almagor, 1985), and in the elongated diapirs off northern Sinai (Ben-Avraham and Mart, 1981) (Fig. 1b). Along the distal continental slope off central Israel there are several slumps, the decollement of which takes place along the Messinian evaporites (Almagor, 1976; Garfunkel and Almagor, 1987). Elsewhere in this basin, the diapirs are scattered, relatively small-amplitude anticlinal undulations of the top-Messinian M reflector and the overlying sediments (Mart et al., 1978; Garfunkel and Almagor, 1987).

The research in salt tectonics gained momentum with the recognition of the huge dimensions of allochthonous salt sheets in the Gulf of Mexico in the 1980's. New insights into salt tectonics, provided by improved seismic acquisition and processing, lead to geometric and kinematic restorations, reinterpretation of previous data, and enabled physical and numerical modeling that elucidated the importance of faulting and extension in the formation of diapirs (Pautot et al., 1984; Mart and Ross, 1987; Vendeville and Jackson, 1992a, 1992b; Cobbold, 1993; Jackson and Talbot, 1994). The previous approach, which attributed the growth of

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Fig. 1. (a) Location map. Analog seismic reflection profiles obtained in this study are drawn continuously, the locations of specific features described in the text are marked in bold line and the figure number. Profiles from previous studies are drawn in dashed lines, C for RV Chain profiles (Ross and Uchupi, 1977), SH for RSS Shackleton profile (Woodside and Williams, 1977). (b) Late Miocene morphological features in the eastern Mediterranean (after Ryan, 1978).
salt domes to gravitational instability due to density contrasts, has currently changed into a consensus that different factors, including faulting and folding in the overburden, determine the style of salt structures. Jackson and Vendeville (1994) even concluded that extension is the most common initiator of salt upwelling. They show that extending salt basins typically develop diapiric structures.

The R/V Shikmona cruise in August 1994 surveyed an area of some 4000 km² in the area between Eratosthenes Seamount and the Nile deep-sea fan, the eastern part of the Xenophon basin, using 1 kJ EG and G sparker system at 350 Hz mean frequency. Nearly 650 km of analog seismic reflection profiles were obtained, trending east-west, along 6 lines which extend approximately 3–5 km apart (Fig. 1). We distinguish in this new set of data approximately 40 diapiric occurrences of four main types, classified according to their configuration. We discuss here the structural and spatial relationships between the different diapiric features in terms of their evolution and in the context of the local structural and the regional tectonic patterns.

2. Salt structures between Eratosthenes Seamount and the Nile deep-sea fan

Salt structures in the area between the Eratosthenes Seamount and the Nile deep-sea fan comprise four main types, namely, protruding diapirs, incipient basins, V-shaped dissolution basins, and U-shaped dissolution basins.

2.1. Protruding diapirs

Protruding features in the study area appear as prominent domes, tens to hundreds of meters higher than the surrounding seafloor, and, in places, flanked by deep bathymetric depressions (Fig. 2a). In this group we consider only features which do not show correlation with basins of the types described below. These features are commonly asymmetric where compared to the dips and thickness of the adjacent upper sediments, and their seismic signature differs significantly from that of their surroundings (Fig. 2b). The protruding features are seismically transparent and show no internal bedding, their topographic surface is usually irregular, and the seismic signature of their contact with the adjacent sedimentary sequence is, in many places, associated with seismic diffractions. This suggests that protruding features in the study area are emergent salt diapirs.

2.2. Incipient basins

In this category we include small depressions located above diapiric features, usually in asymmetric dips and thicknesses of the upper sediments in the basin (Fig. 3a). In places, the location of the incipient basins are located on the flanks of piercing diapirs, and in other places—on their crests (see, for example, Fig. 3b). We suggest that these depressions represent early stages in the evolution of the larger basins described below. This interpretation is suggested due to the unique spatial relations between piercing diapirs, small depressions and well-developed basins in the study area, as will be discussed later. The structural setup of these structures suggests that they originated mainly due to uplift, and they are not collapse structures.

2.3. V-shaped dissolution basins

Most of the basins deeper than 100 m show a remarkable V shape (Fig. 3c). These basins are usually asymmetric and associated with diapirs on either one or both flanks. The thickness and dip of the young sedimentary strata on one of their flanks are also significantly different from those on the other flank, the differences in thickness reaching 20–30%. Unlike other basins in the study area, the bedding in this particular type of structure can barely be discerned at the base of the basins. On the contrary, much of the seismo-stratigraphic sequence around the lower part of the basins is seismically transparent, a signature typical of the Messinian evaporites in the Mediterranean Sea. The bottom reflection of such basins is unclear, probably as a result of the rough topography there, due to the effect of dissolution, which disperses the seismic wave and eliminates good bottom reflection.
2.4. *U-shaped dissolution basins*

These basins are a few tens of meters deep and a few hundred meters wide at their base. Their walls resemble those of piercing diapirs in their seismic character and morphology. Inner steps are seen adjacent to these walls, and bedding is discernible at the bottom of the basins (Fig. 3d). This association suggests that these are mature dissolution basins, which probably accommodate collapsed blocks and young sediments, subsequent to the dissolution of the salt.
Fig. 3. Stages in the evolution of diapiric basins in the study area; arrows indicate slumps. (a) incipient basin, (b) incipient basin located adjacent to a piercing diapir, (c) V-shaped basin, (d) mature, U-shaped basin. See Fig. 1 for location.

3. Recurrent asymmetry and spatial relationships

The strong asymmetry depicted in the analog seismic reflection profiles concerns the topographic configuration of the basins, their affinity to diapiric structures, and the uneven distribution of the sediments along their flanks (Fig. 3d). The occurrence of piercing diapirs was encountered, in most places, at only one of their flanks, but diapirs occur also on both flanks of several basins.
(Fig. 4a). A drastic change in dip, depth, and in some places, thickness of the upper sediments occurs repeatedly across piercing diapirs and various basins. These features were also discerned in several previously available seismic reflection profiles, such as the RV Chain profiles (Ross and Uchupi, 1977). Chain profile 31 (Fig. 5) emphasizes the asymmetry in both the dip and depth across a V-shape basin, and shows another clear example for the evolution of an incipient basin along the flank of a piercing diapir, rather than on its crest. The prominent change in the dip and the flexure of the strata across the diapiric structures suggests that these features formed along fault planes in the upper sedimentary succession, which can not be determined with certainty from

Fig. 4. (a) Repeated asymmetry across diapirs and depressions is reflected in the dip, depth and thickness of young sediments. (b) A single crestal graben emphasizes the asymmetry of all other diapiric features in the study area. See Fig. 1 for location.
the analog, single-channel seismic profiles. However, much information is gained from the spatial relations between these diverse features.

The most prominent characteristic of the spatial relations between the diapirc features in the study area is their occurrence along lineaments. Most diapirs show a NE–SW orientation, but NW–SE trending diapirs occur as well (Fig. 6). Likely correlations between neighbouring structures along these trends of preferred orientation, based on similarities in shape and dimension, suggest that diapir ridges, and subsequent collapse basins, are linear features not only in the study area, but in the SE Mediterranean region. Our correlations are well supported by comparison with the previous investigations, and seismic reflection profiles from the region published by Neev et al. (1976), Ross and Uchupi (1977), Woodside and Williams (1977) and others. The RRS Shackleton profile D (Woodside and Williams, 1977) extends in E–W direction in the center of the area of the present study, parallel to most of the seismic reflection profiles taken in this study (Fig. 1). When combined with our new data, this profile strongly confirms the trend of the linear structures in the NE–SW direction in the central and eastern part of the study area. In the northwestern part of this area, this RRS Shackleton profile suggests that two linear structures trend NW–SE. This exception is most probably related to a NW–SE trending strike-slip fault. The RV Chain profile 21 (Ross and Uchupi, 1977) crosses many of our present profiles almost at a right angle (Fig. 1), and confirms the correlation between the two basins in the northwestern corner of the study area, as well as the difference between the two sedimentary provinces across the continuation of the line interpreted here as a strike-slip fault.

Diapir ridges are not a rare phenomenon; they were observed in other parts of the eastern Mediterranean as well (e.g., Ryan, 1978; Ben-Avraham and Mart, 1981; Garfunkel and Almagor, 1985). We suggest that faults control the distribution of the diapirs, and that diapir ridges control the occurrence of elongated basins. However, diapirs are not the only structural parameter that determines the mode of basin evolution in the area between the Nile deep-sea fan and the Eratosthenes Seamount. This situation is demonstrated through the spatial relationships and the similarity in the surroundings of diapirs and basins in neighbouring profiles.

4. A suggested model for the evolution of the diapir basins

Based on these observations, we suggest that the diapirs in the study area, ascended and developed along fault-planes, as previously described by Mart...
and Ross (1987). The available data and previous studies suggest that these faults have been active in post-Miocene times, though evidence exists for the offset of beds that underlie the Messinian evaporites by these faults (Mart, 1984; Garfunkel and Almagor, 1987). The normal faults create weakness zones, that served as routes for diapir penetration (Fig. 7a), whereas the vertical displacement along these faults builds a differential load which enhances, if not activates, the ascent of salt at the footwall side of the fault (cf. Parker and McDowell, 1955; Jackson and Vendeville, 1994).

The piercement of diapirs through the seafloor or close to the seafloor is accompanied by dragging the upper sediments, thus increasing their dip at the shallower side of the fault and diapir complex (Fig. 7b). This stage in the evolution of salt structures accounts for the strong asymmetry across piercing diapirs and various subsequent basins. Incipient basins develop at the contact plane between piercing diapirs and the country rock, where the original fault plane serves as a weakness zone on which the penetration occurs (Fig. 7c). Dissolution of the piercing salt diapirs close to this fault plane could be a tentative cause for asymmetric, V-shaped, relatively deep and narrow depressions (Fig. 7d), although the asymmetry can also be attributed to the initial shape of the diapir (Nelson, 1991). Finally, collapsed blocks from the basin’s shoulders fall into the dissolved basin, and young sediments are deposits at the basin bottom (Fig. 7e). Mature, U-shaped basins of this kind are the most advanced stage recognized in the study area.

A single symmetric structure in the study area suggests similarities with other diapir areas. This graben is an approximately 4 km wide, a few tens of meters deep (Fig. 4b), similar in shape and dimensions to structures in the Gulf of Mexico (e.g., Garrison and Martin, 1973). Models proposed by Vendeville and Jackson (1992a) for diapir piercement during thin-skinned extension explain the formation of such grabens in three main stages. First occurs graben formation in response to local thinning of the overburden by normal faulting. When the fluid pressure at the crest of the diapir becomes sufficient for the diapir to lift and shoulder aside its thinned roof, it pierces the overburden actively. Passive diapir growth continues, its rise depends on coeval sedimentation and its widening depends on coeval extension.

Therefore we suggest that diapirs in the eastern Xenophon basin form as ridges along normal faults in the Pliocene–Quaternary sedimentary cover of the Messinian evaporites. Diapir basins develop along these ridges by erosion and dissolution along the fault plane between these diapirs and the surrounding rocks, and evolve through V-shaped basins into mature, U-shaped basins, that accommodate collapsed blocks and young sediments at their floor (Fig. 7).
5. Regional tectonic framework

Wherever the diapiric features are traceable beyond a single occurrence, they follow a linear pattern. Commonly this trend is NE–SW, where diapir ridges, with either local basins or longer canyons along them, occur. This pattern changes significantly only in the NW section of the study area. There, a diapir ridge and sub-parallel canyon or series of local basins, interpreted to extend along a strike-slip fault, extend in the NW–SE direction (Fig. 6). This spatial distribution is in remarkable agreement with that presented by Kenyon et al. (1975), who suggested that the grabens they mapped on the lower Nile cone are crestal grabens, founded above diapirs. The distribution also agrees with the dominant direction of elongated depressions that accommodate evaporitic diapirs, noted by Neev et al. (1976). Kenyon et al. (1975) proposed that the ENE–NE trending grabens developed due to downslope gravity creep, but mentioned that they could be the surface expression of more deeply-seated control as well. The NW trending grabens, which are sub-parallel to the western edge of the Xenophon fault belt or diapir zone and to the Gulf of Suez trend, formed probably in response to regional deep-seated tension (Kenyon et al., 1975). This approach was re-examined by Garfunkel and Almagor (1987), who noticed that the diapir trends in the southeastern Mediterranean are at oblique angles to the gradients of the seafloor.

The similarity between the diapirs array in the eastern Xenophon basin (Fig. 6) and in the southwest Nordkapp basin (Koyi et al., 1993) is remarkable. However, while in the SW Nordkapp basin the relations between regional extension and the diapirs piercement is well established, the SE Mediterranean has been subjected to compression due to incipient continental collision ever since the Late Miocene (Kempler, 1994).

This inconsistency between the spatial relations of the diapirs, which imply extension, and the regional tectonic regime of post-Miocene compression, remains a major enigma in the understanding of the process of incipient continental collision in the eastern Mediterranean region. It is probably worthwhile to note that the diapiric features in the eastern Xenophon basin are sub-parallel to the dominant tectonic trends in the eastern Mediterranean and, in particular, to the boundary faults of the moat which surrounds the Eratosthenes Seamount (Fig. 6). Enhanced subsidence of the Eratosthenes Seamount during the Pliocene (Kempler, 1994) is probably related to local extension, as well as to the thrusting of the Seamount underneath Cyprus (Robertson et al., 1995). Moreover, Garfunkel and Almagor (1987) found that the deformation of the Messinian evaporites began 2–3 Ma ago. Therefore, this deformation is coeval or subsequent to the collision of the Eratosthenes Seamount at the Cypriot Arc, which most probably caused its subsidence since the Pliocene (Robertson, 1990; Kempler, 1994; Robertson et al., 1995). Convergence between the African and the Anatolian plates occurs here in the NE–SW direction (Kempler, 1994), which may allow for extension in a roughly NW–SE direction. The contemporaneous accumulation of the Nile deep-sea fan, which is a Plio-Quaternary feature, could have contributed its lithostatic load to the structural subsidence of the areas off the fan, and comparable phenomena under similar geologic setup were encountered off the deep-sea fan of the Rhône river (Pautot et al., 1984; Bellaiche and Mart, 1995).

6. Conclusions

The data acquired by R/V Shikmona cruise of summer 1994 reveal series of diapirs and basins. These findings corroborate earlier studies (Ross and Uchupi, 1977; Woodside, 1977; Ryan, 1978), suggesting that the grabens mapped by Kenyon et al. (1975) between the Nile deep-sea fan and the Eratosthenes seamount are related to salt diapirs. The detailed investigation carried out during our survey, enables us to distinguish between different types of diapiric occurrences, which probably represent four stages in the structural evolution of the diapir basins. Many diapir basins were found to be asymmetric. The asymmetry of these basins is expressed in their morphology and their near-surface sedimentary stratification, and in the occurrence of the piercing diapir at only one flank.
of several basins. Evidence for the evolution of these basins adjacent to the diapirs suggests that the fault plane between a diapir and the adjacent sedimentary sequence, serves as a weakness zone for the ascent of the diapirs and the subsequent evolution of the basins. It is possible that both the morphological and the chemical conditions at this interface facilitate dissolution. Collapse seems to be of only secondary significance in the evolution of these diapiric basins.

The spatial relations between the diapiric occurrences in the study area imply that most of them form elongated diapiric ridges extending in the NE–SW direction, and that the basins are located along these ridges. The ridges are probably located along a series of similarly oriented, post-Messinian normal faults, and their occurrence is a regional phenomenon. However, the evolution of the diapiric basins adjacent to the diapir ridges is a local process. The proximity of extensional structures to a subduction zone is commonplace in the underthrust tectonic plates, and, in the SE Mediterranean, the correlation between the extension and the diapiric ascent seems reasonable.

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Edited by P.F. Ballance

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