

STRUCTURAL EVOLUTION OF THE NEOGENE SALT BASINS IN THE EASTERN MEDITERRANEAN AND THE RED SEA

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ABSTRACT

This paper attempts to describe the Neogene evaporite basins in the Eastern Mediterranean and the Red Sea Rift in the context of the regional tectonic framework and the regional tectonic phases of the Alpine-Mediterranean region.

It is mainly based on airgun seismic surveys in the Mediterranean and Red Sea carried out in the time span between 1971 and 1973.

The Neogene basins of the *Eastern Mediterranean* as well as the Red Sea began to form after the main Oligocene – Lower Miocene Alpine orogenic phase.

The morphological conditions for evaporite deposition in the Mediterranean basins, during a short period of time were provided by late Miocene – early Pliocene tectonic movements in the basin peripheries, which caused a temporary restricted connection with the open sea. It was followed by open marine conditions during the Pliocene.

Graben subsidence in the *Red Sea Rift* began during Oligocene – early Miocene. Initial terrestrial sedimentation was followed by widespread evaporite deposition, which lasted throughout a considerable part of the Miocene period. The late Miocene – early Pliocene tectonic phase caused a final disruption of the connection with the Mediterranean. Open marine conditions were established in the Pliocene through a connection with the Indian Ocean.

Regional doming of the Arabian-Nubian shield and axial collapse, first of the main graben and later of the axial trough, is thought to represent the dominant mechanism for the origin of the Red Sea Rift.

INTRODUCTION

Thick Neogene evaporites, including rock salt, are known from the Eastern Mediterranean basins and the Red Sea graben.

Regional reconnaissance seismic surveys carried out over the past few years have contributed to a better understanding of the broad tectonic setting of the salt basins of the Eastern Mediterranean and the Red Sea. Magnetometer readings appeared of particular value in the interpretation of the Red Sea seismic lines.

The interpretations of the seismic lines, which represent a large part of the basic data for the present publication, have been carried out by T. Dürst and Ph. Boegner of Shell International Petroleum Company in The Hague.

The paper is divided into two parts, the first part describing the Eastern Mediterranean salt basins and the second the Red Sea.

EASTERN MEDITERRANEAN SALT BASINS

Messinian evaporites in the Eastern Mediterranean form an integral part of the Neogene basin fill. In the deeper portions of the individual basins they were deposited in apparent depositional continuity with the underlying marine Miocene and the overlying Plio-Quaternary beds.

Stratigraphy (fig. 1)

Evaporite deposition began during uppermost Miocene (Messinian) and persisted locally into the lowermost Pliocene.

In the deeper portions of the basin the evaporite layer reaches a thickness of around 1 km or more. Where the overlying Plio-Quaternary sequence is thin the evaporites are generally undisturbed.

Where loaded with thick sediments salt domes and salt ridges were formed.

In the central areas of the basins the evaporites are overlain and underlain by and locally interbedded with pelagic sediments (Sicily) whose paleobathymetry is difficult to establish. Pelagic faunas and the undisturbed nature of the beds, however, indicate a considerable water depth. A basal unconformity or a stratigraphic gap generally separates the Neogene from underlying older Tertiary or Mesozoic sediments and the total thickness of the Neogene often reaches 3-5 km.

In the Eastern Mediterranean the pre-Messinian Miocene is commonly developed in a pelagic facies of marls and marly limestones. Thick flysch deposits were deposited along the Alpine front. Outcropping carbonates in southern Cyprus indicate an upward gradation from open pelagic conditions to shallow shelf and restricted shelf toward the end of the Miocene.

Near the basin margins evaporites are intercalated between shallow marine or locally non-marine beds. These sequences

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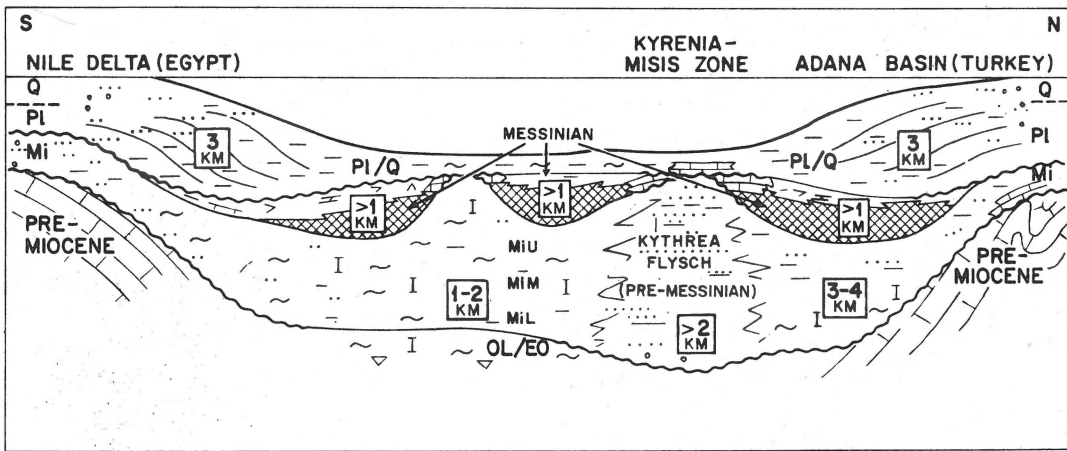


Fig. 1
Generalized stratigraphic scheme of Neogene facies distribution in the Eastern Mediterranean. The pre-Messinian Miocene shows largely an open marine facies development with indications of shallowing upwards and towards the basin margins. Late Miocene and early Pliocene tectonic movements led to evaporite deposition in a number of partially isolated restricted basins and to erosion on the basin margins. Subsequent Plio-Quaternary subsidence was accompanied by local thick deltaic accumulations.

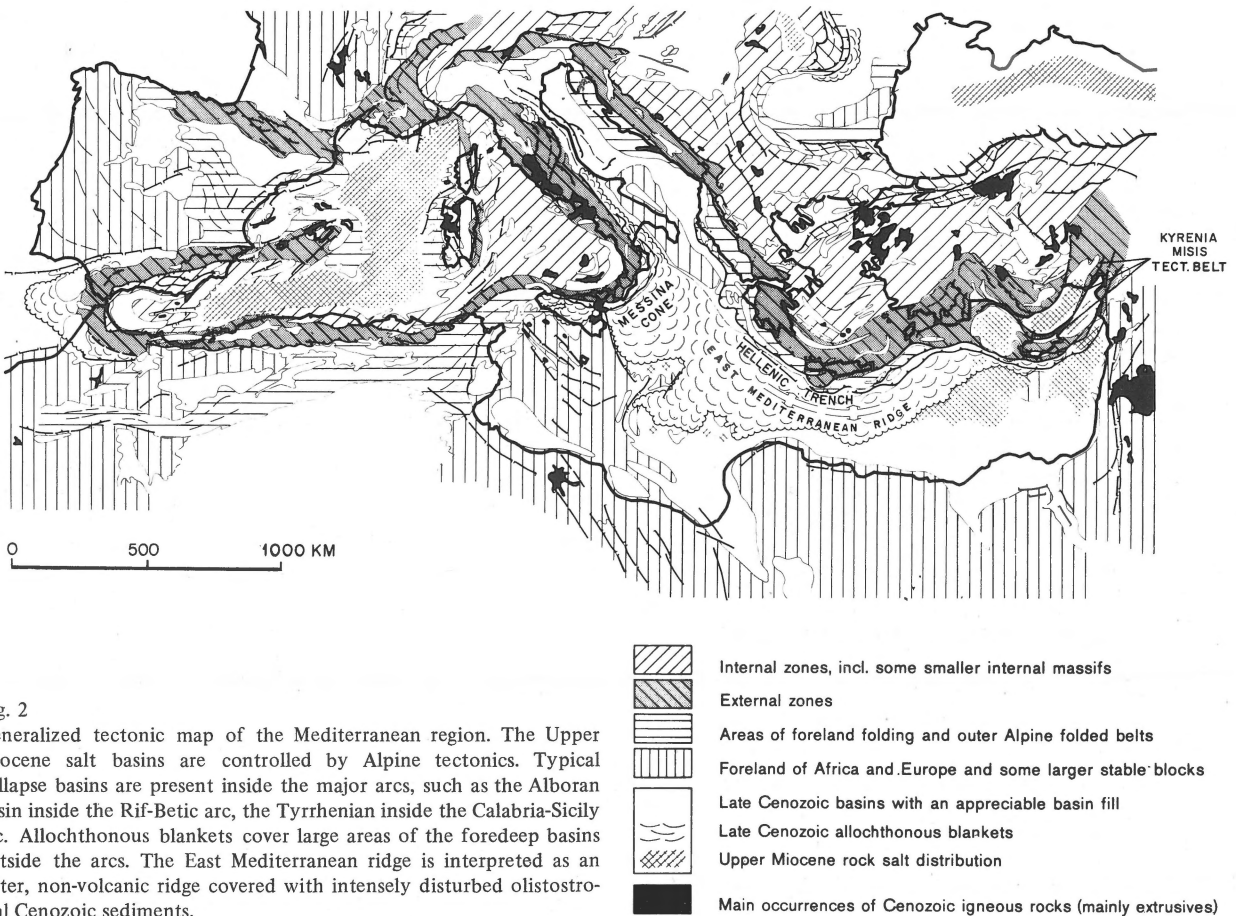


Fig. 2
Generalized tectonic map of the Mediterranean region. The Upper Miocene salt basins are controlled by Alpine tectonics. Typical collapse basins are present inside the major arcs, such as the Alboran basin inside the Rif-Betic arc, the Tyrrhenian inside the Calabria-Sicily arc. Allochthonous blankets cover large areas of the foredeep basins outside the arcs. The East Mediterranean ridge is interpreted as an outer, non-volcanic ridge covered with intensely disturbed olistostromal Cenozoic sediments.

indicate continuous steady subsidence throughout the Neogene. Within the Neogene basins the evaporite level is not marked by any erosional features, channels or cut and fill phenomena. On the basin rim, however, the Pliocene is often transgressive and overlaps the evaporite interval and older beds. Locally, thick deltaic sediments are deposited during the Pliocene-Quaternary (Adana basin, Nile Delta).

Tectonic setting (fig. 1 and 2)

Late Miocene and Pliocene tectonic movements are largely responsible for the present configuration of the Neogene basins in the Mediterranean.

The earlier Miocene basins were much larger and of a different shape than the late Miocene evaporite basins. Portions of the pre-salt basins were folded and inverted during the late- and post-Miocene tectonic movements (Northern Apennines, Kyrenia). As a consequence thick Miocene deeper water sediments are locally incorporated in folded mountain ranges, bordering the late Miocene evaporite basins.

The frontal parts of the Alpine orogenic arcs (fig. 2) were intensely deformed during the early Pliocene. Mesozoic and Tertiary sediments of the Alpine foredeep here became involved in folding, imbrication and overthrusting. Plate tectonic models explain this deformation by a phase of underthrusting of the African craton below the Alpine front in the Hellenic and Calabrian arcs (P a p a z a c h o s and C o m n i n a k i s, 1971; R i t s e m a, 1972).

Uplifting of portions of the Alpine arcs created the slopes for large-scale gravity slides (olistostromes), facilitated by the presence of salt in the olistostrome mass (M u l d e r, 1973). In the central Mediterranean such Cenozoic slump deposits are known from Sicily and the Fossa Bradanica in southern Italy (C a r i s s i m o e t a l., 1963). In the offshore areas, the sub-marine Messina cone (recently referred to as Calabrian ridge, B e l d e r s o n e t a l., 1974) and the East Mediterranean ridge (fig. 2) are covered by thick olistostrome deposits. Seismic profiles across the Messina cone in front of the Calabrian arc indicate that it consists of a pile of sub-marine slumps, and deep reflections can be traced from the abyssal plain area underneath the thrust front of these olistostrome masses for a distance of around 30-50 km (fig. 3 and 4). In a similar way the arcuate East Mediterranean ridge is located in front of the Hellenic arc and is also covered with thick olistostromal masses. The present shape of the ridge, particularly its north flank, is due to faulting and back-tilting during Plio-Quaternary, and to the subsidence of the Hellenic trench system (fig. 5, 6 and 7). The thick cover of intensely deformed Neogene strata across the Mediterranean ridge appears to scatter seismic energy and make the mapping of the underlying strata extremely difficult. From present data it is not possible to say whether the underlying early Tertiary and Mesozoic strata could also be more strongly deformed than suggested on fig. 6 and 7.

In the easternmost Mediterranean the olistostrome masses

of the East Mediterranean ridge diminish in size and pass laterally into little-disturbed salt basins (fig. 2). In this region several elongated salt basins are separated by narrow thrust belts that were folded and uplifted in late Miocene – early Pliocene. The Kyrenia-Misis (N. Cyprus-Turkey) tectonic zone is an example of such a thrust belt (fig. 2 and 8).

In the Adana and Iskenderun basins which are separated by the Kyrenia-Misis tectonic belt, the Upper Cenozoic basin fill reaches a thickness of 5-6 km. In the offshore Adana basin, the pre-salt sequence consists mainly of *Globigerina* marls and has a thickness of several kilometres. The Upper Miocene evaporites, mainly rock salt, are up to 1.5 km thick and develop salt pillows and salt domes. The top of the evaporites is observed at a depth of 2-3 km below sealevel in the basin centre. The evaporites are overlain by deltaic shallow marine to continental Plio-Quaternary sediments which show shelf accretion foreset beds in their lower part. These shallow marine and continental beds prove a subsidence during Pliocene-Quaternary time of at least 3 km.

The distribution of the Messinian evaporites of the Eastern Mediterranean thus can be related to late Miocene – early Pliocene tectonic events that restricted the access of these basins to the open ocean. Similar conditions probably existed in the basins of the Western Mediterranean. This Neogene deformation not only affected the Alpine orogenic belt, but also the foreland and the margin of the African craton. In these latter areas it is reflected by taphrogenic deformation with dominant NW to NNW trends. Some rift systems originated late in the Cenozoic and may still be active, as for instance the central grabens on the Malta-Lampedusa platform, the Hon graben in western Libya and the axial trough of the Red Sea. The origin of others coincides in time with the main Alpine orogenic phases, like the Sirte graben, which developed mainly in Upper Cretaceous – Lower Tertiary time and the Gulf of Suez – Red Sea graben system, which began to form in late Oligocene and Miocene time.

THE RED SEA EVAPORITE BASIN

In a classical paper on the relation between uplift, rifting and volcanism C l o s (1939) explained the Red Sea Rift as resulting from tension on the crest of the updoming Arabian-Nubian shield. However, in modern concepts of continental drift and plate tectonics, the present tectonic setting of the Red Sea has been used as a model for the proto-Atlantic – an early stage of crustal separation. This concept implies horizontal separation and relative rotation of Africa and Arabia. However, the amount of separation, the mechanism of movement and the number of crustal plates involved varies widely in the various models proposed. They fall mainly into two categories:

- those assuming crustal separation of the Red Sea over its entire width, joining the remarkably well fitting shorelines (S w a r t z and A r d e n, 1960; M c K e n z i e, 1970),

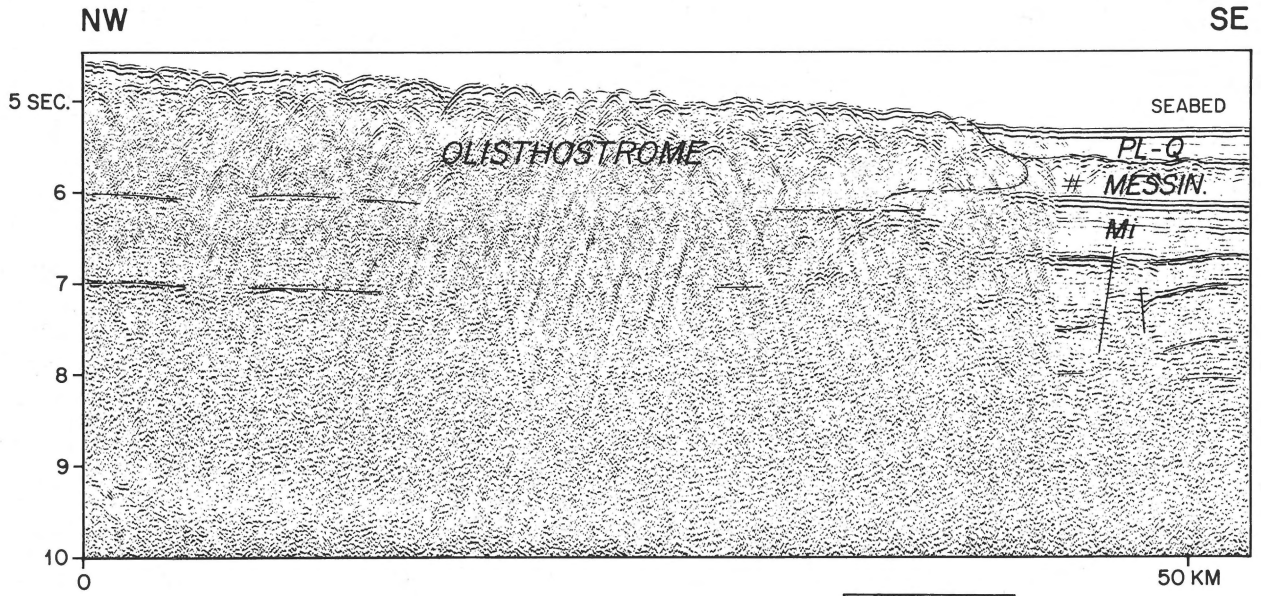
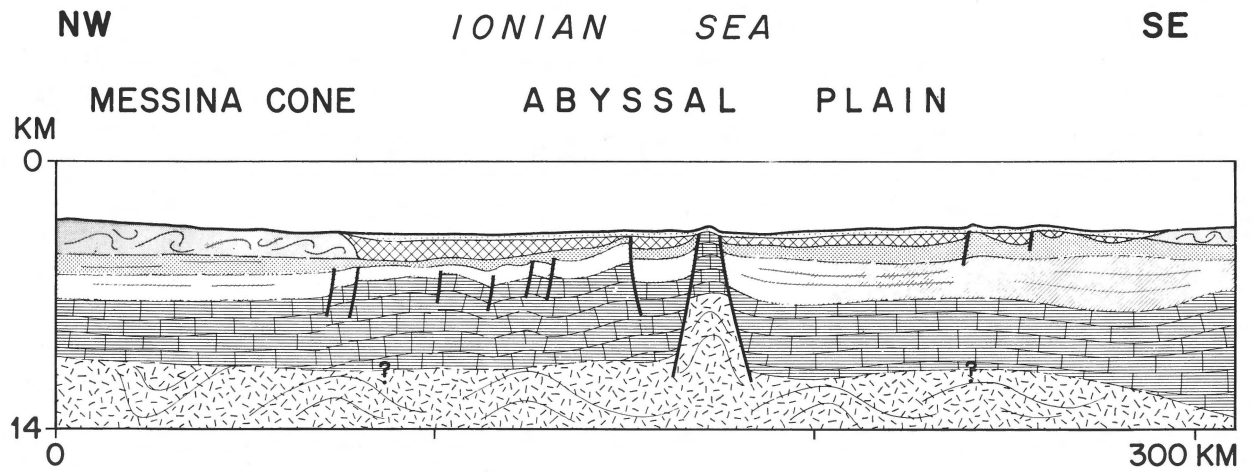









Fig. 3
Seismic reflection profile showing the SE front of the Messina cone in the Ionian Sea. The Messina cone is interpreted to consist of late Tertiary to Recent deformed sediments, passing laterally into undisturbed beds of the abyssal plain. Although the disturbed sediments absorb most seismic energy, deeper reflections can be seen locally below the disturbed sediments.



-  PL-Q
-  ALLOCHTHONOUS
-  Mi U (EVAPORITIC)
-  Mi
-  TL
-  Mz
-  Pz+MET

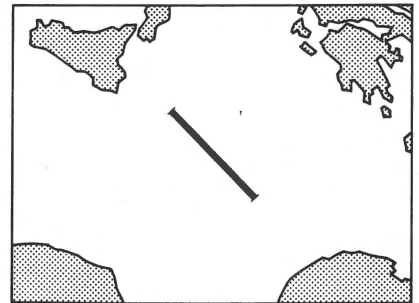


Fig. 4
Tentative geological interpretation of a seismic profile in the Messina cone and abyssal plain in the Ionian Sea. Interpretation in greater depth is highly speculative.

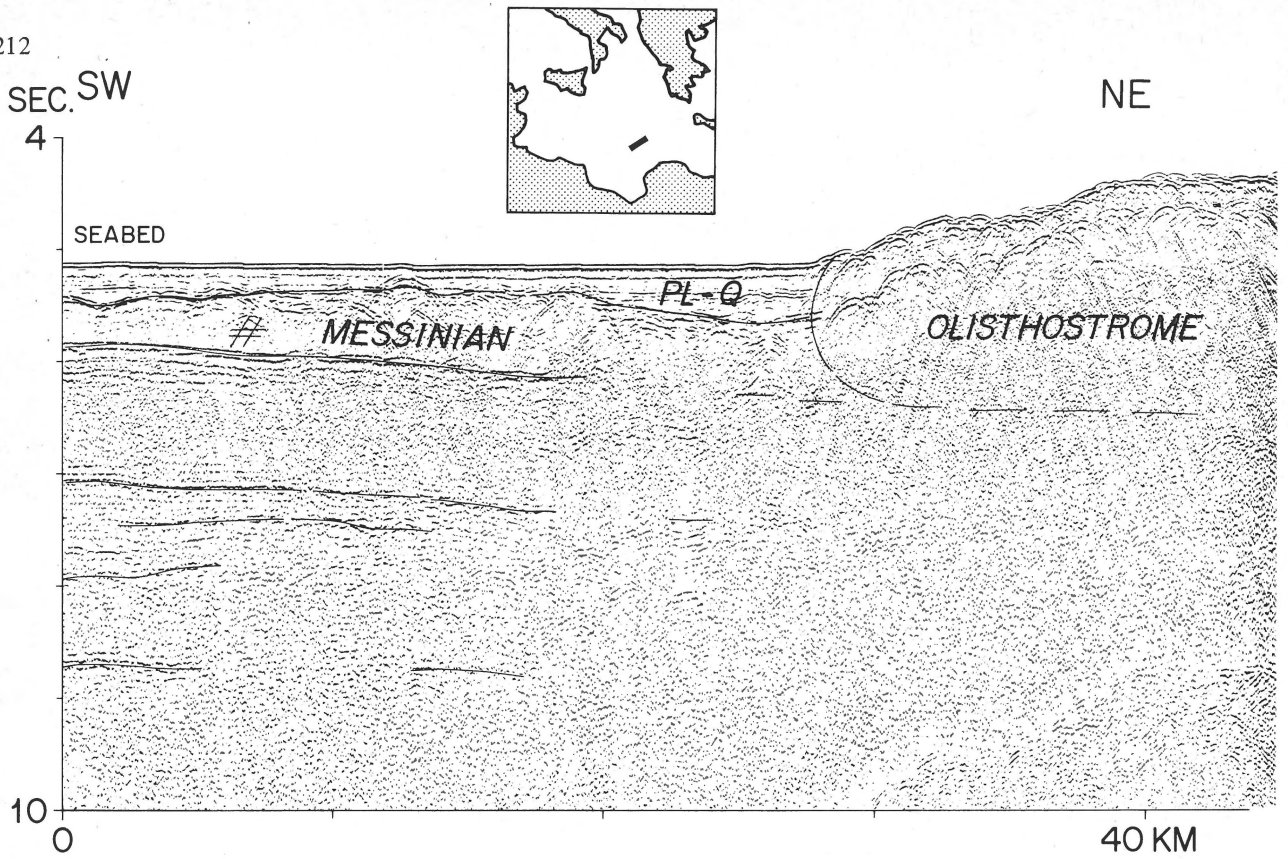


Fig. 5
Seismic reflection profile showing the SW margin of the East Mediterranean ridge in the Ionian Sea. The supposedly olistostromal sediments of the Mediterranean ridge pass laterally into the undisturbed sediments of the abyssal plain.

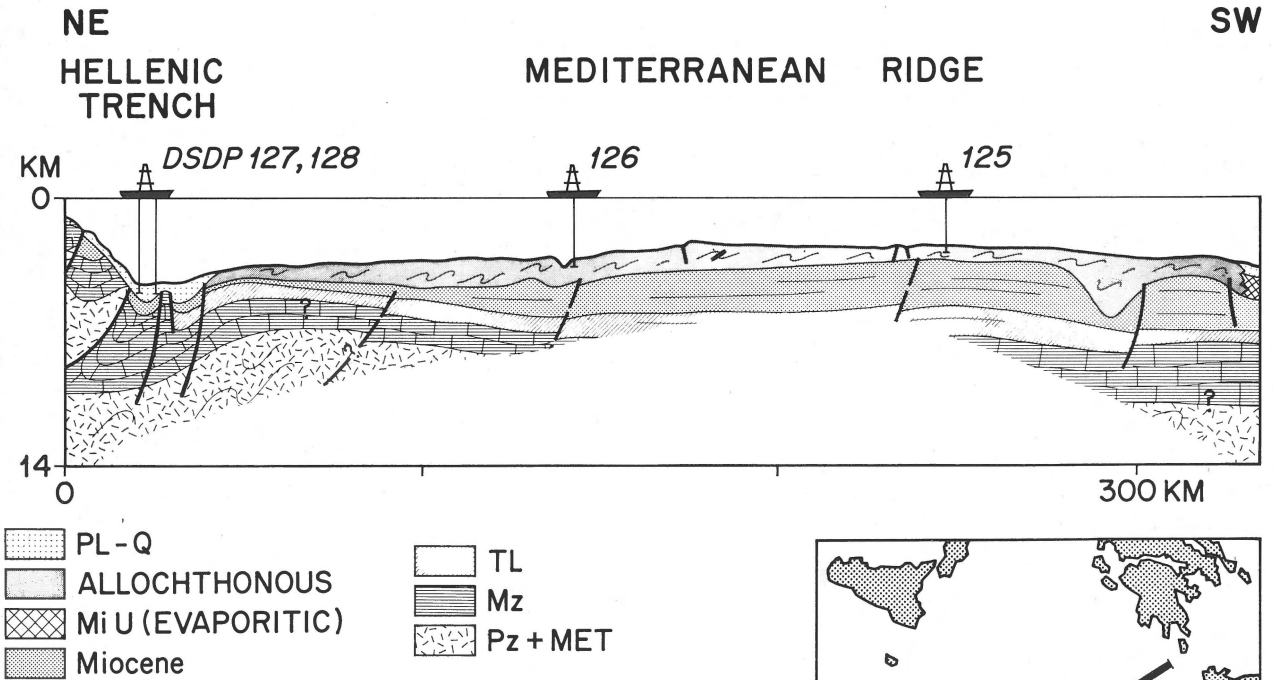


Fig. 6
Tentative geological interpretation in the western part of the East Mediterranean ridge, adjoining Hellenic trench and Ionian abyssal plain. Interpretation in greater depth is highly speculative.

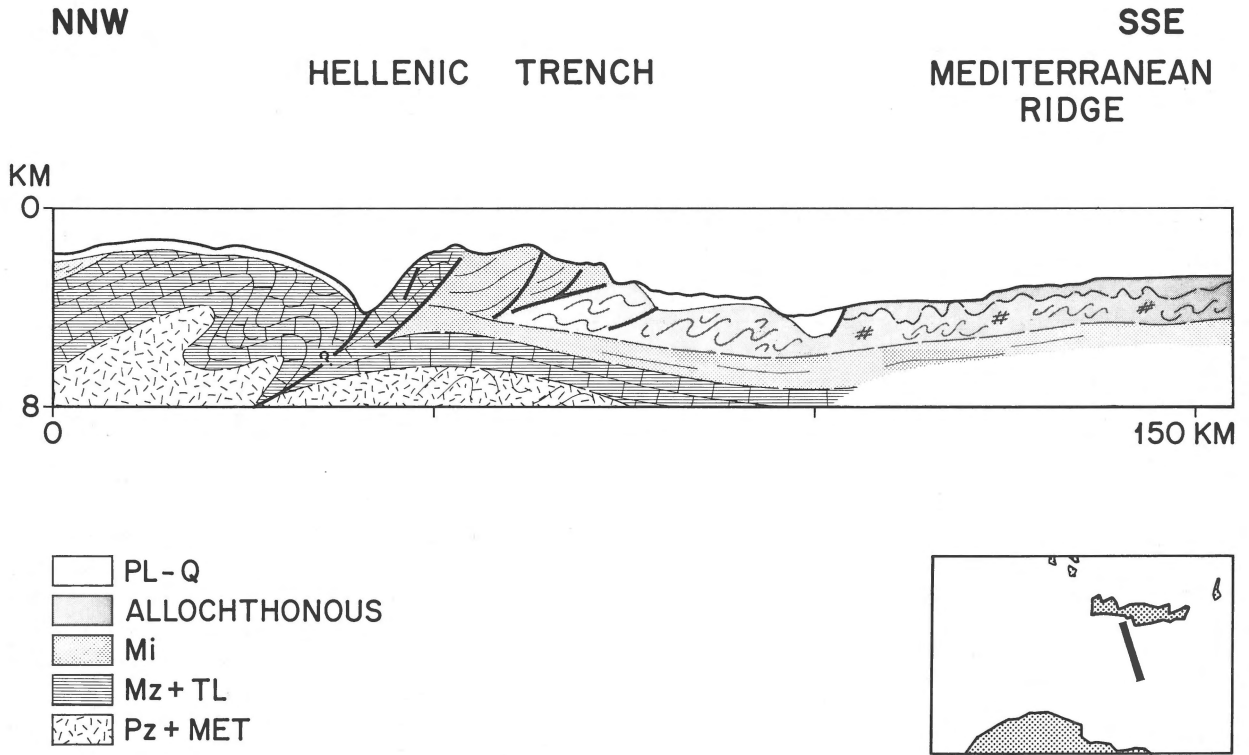


Fig. 7
Tentative geological interpretation of a seismic profile south of Crete. It shows the Alpine front, the Hellenic trench system and the north slope of the supposedly deformed East Mediterranean ridge.

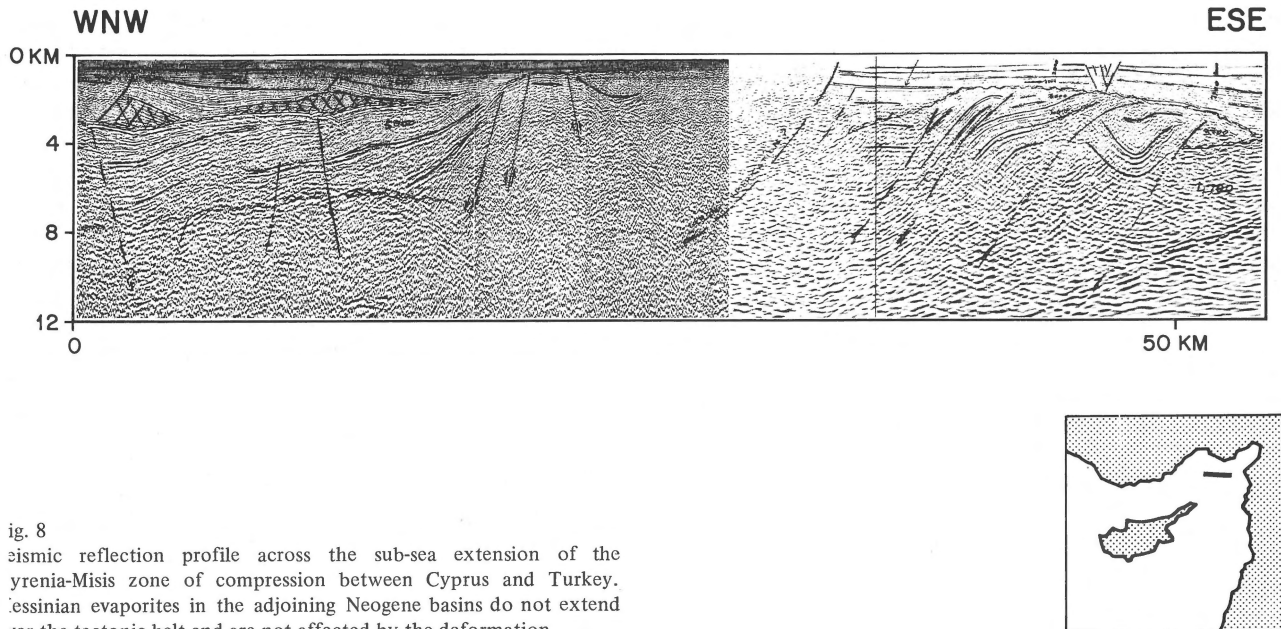


Fig. 8
Seismic reflection profile across the sub-sea extension of the Taurus-Misis zone of compression between Cyprus and Turkey. Neogene Messinian evaporites in the adjoining Neogene basins do not extend over the tectonic belt and are not affected by the deformation.

— those assuming crustal separation over part of the present width of the Red Sea only (Phillips, 1970; Le Pichon, 1974).

Complete pre-drift closure of the Red Sea, using the best shoreline fit, inevitably leads to a large overlap in the south, including the Danakil horst in which a Pre-Cambrian basement is overlain by Jurassic sediments. Hence many authors suggested models, assuming crustal separation over only part of the width of the Red Sea.

Correlation of strong magnetic anomalies which are restricted to the axial trough and believed to be related to periodic reversals of the magnetic pole, is thought by many authors to prove that the central part of this trough represents a spreading axis and that spreading took place over the entire width of this axial trough (Phillips, 1970).

It also led Drake and Girdler (1964) to propose a model that assumes crustal separation in the central graben (axial trough) only. Their refraction seismic indicates that the remaining portion of the Red Sea may be underlain by downdropped outward tilted blocks of the Pre-Cambrian basement. The wide range of velocities in the basement (5.5-7.1 km/sec), however, allows no conclusive statement.

Geological history (fig. 9 and 10)

The main subsidence of the Red Sea Rift began in Oligocene and Lower Miocene time with the formation of local grabens which were filled with continental sediments. This first taphrogenic faulting was accompanied by volcanic activity (dike intrusions, trap basalt), not only in the Red Sea Rift proper, but also in some other parts of the Arabian-Nubian shield (Afar, Yemen).

NW-trending fault-block movements and volcanism in the central and southern parts of the Red Sea continued in Middle and Upper Miocene time, when a connection with the Mediterranean was established and marine clastics and evaporites were deposited (Heybroek, 1965).

It is possible that the axial part of the present Red Sea was still relatively elevated and even partly emerged during earlier Miocene time. Glomar Challenger coreholes 225 and 227 (fig. 10) encountered Upper Miocene in the axial trough (Geotimes, 1972).

In latest Miocene times the connection with the Mediterranean was interrupted and it seems likely that evaporite deposition ceased in the Red Sea Rift before the uppermost Miocene (Messinian) and was followed by open marine conditions in the Pliocene.

Submarine erosion or possibly even local emergence preceded Pliocene deposition. In later Pliocene and Quaternary times renewed subsidence took place. It was most pronounced in the axial trough which reaches its greatest width (> 60 km) in the central and southern parts of the Red Sea, where it is marked by strong tholeiitic volcanism.

Plio-Quaternary volcanic events in the axial trough can be studied on Jebel at Tair and the Zubair Island Group in the south (Gass et al., 1973). Further to the north it is

represented by sub-marine tholeiitic basalt flows as shown by dredge samples and sub-marine photographs of pillow lavas (Schneider and Wachen-dorf, 1973; Young and Ross, 1974) and by Glomar Challenger corehole 226 (Geotimes, July 1972).

Marine Pliocene beds in the northern part of the Gulf of Suez area have a fauna of Indian and Pacific Ocean characteristics. This led to the postulate that the Red Sea was isolated from the Mediterranean during the Pliocene and connected with the Indian Ocean, probably through the Straits Bab el Mandeb (Heybroek, 1965).

The Glomar Challenger coreholes show that in the central parts of the Red Sea the Plio-Quaternary consists of open marine oozes and chalk with some silty clays. At site 229 in the south these beds contain intercalations of volcanic tuff, apparently related to Quaternary sub-aerial volcanism of the southern Red Sea volcanic islands.

Contemporaneous sedimentation in the Danakil Rift, west of the elevated continental block of the Danakil Alps, shows evidence of strong subsidence, also accompanied by strong volcanic activity and by the deposition of thick evaporites.

Cenozoic uplift of the Arabian-Nubian shield was strongest in the south. Here it gave rise to mountains of over 3000 m altitude. This uplift was not a regular doming, but involved separate tilting of blocks determined by the Pre-Cambrian tectonic configuration (Brown, 1970). In Saudi Arabia and Afar fracturing was accompanied by the extrusion of extensive plateau basalts during the Pliocene and Quaternary.

Tectonic setting and sediment fill

The Red Sea appears as a large fault-bounded depression on the crest of the Arabian-Nubian shield that has been a positive tectonic element since early Palaeozoic times. The Red Sea depression itself is usually subdivided into a main trough and an axial trough. The axial trough shows a variable and discontinuous development in the median zone of the Red Sea graben (fig. 10).

The detailed structural interpretation presented in this paper is based on airgun seismic and magnetometer surveys (fig. 11 and 12).

Reflections appear to be from Miocene and younger beds. Relatively deep pre-salt reflections are observed in many localities, but are usually discontinuous and difficult to interpret stratigraphically. This is ascribed to the presence of thick evaporites subjected to salt tectonics, and rapid facies changes in the main part of the section. Few reliable basement reflections have been obtained, but the base of the evaporite sequence is locally represented by a clear reflector, to a depth of around 3 seconds. Pre-evaporite and possibly pre-Miocene reflections are mainly found in the Southern Red Sea.

Our observations can be summarized as follows:

a. *Main trough.* — Tilted fault block and halokinesis are the

NW

SCHEMATIC FACIES DIAGRAM RED SEA

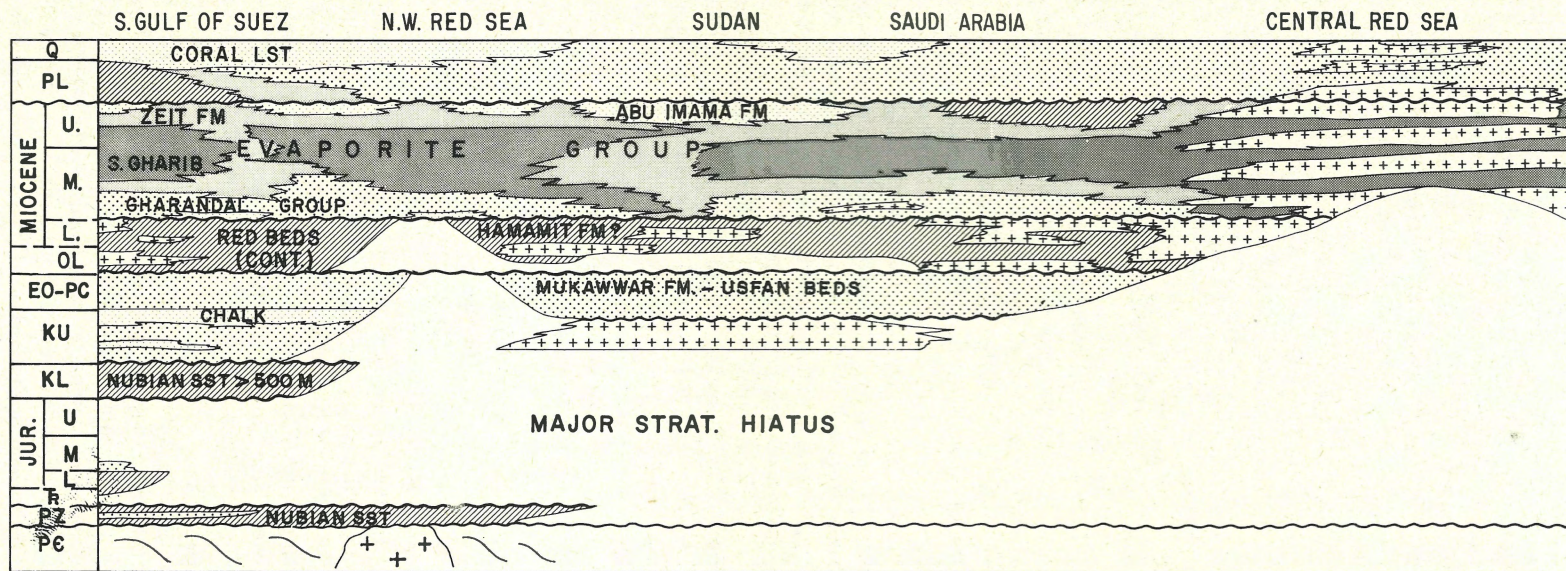
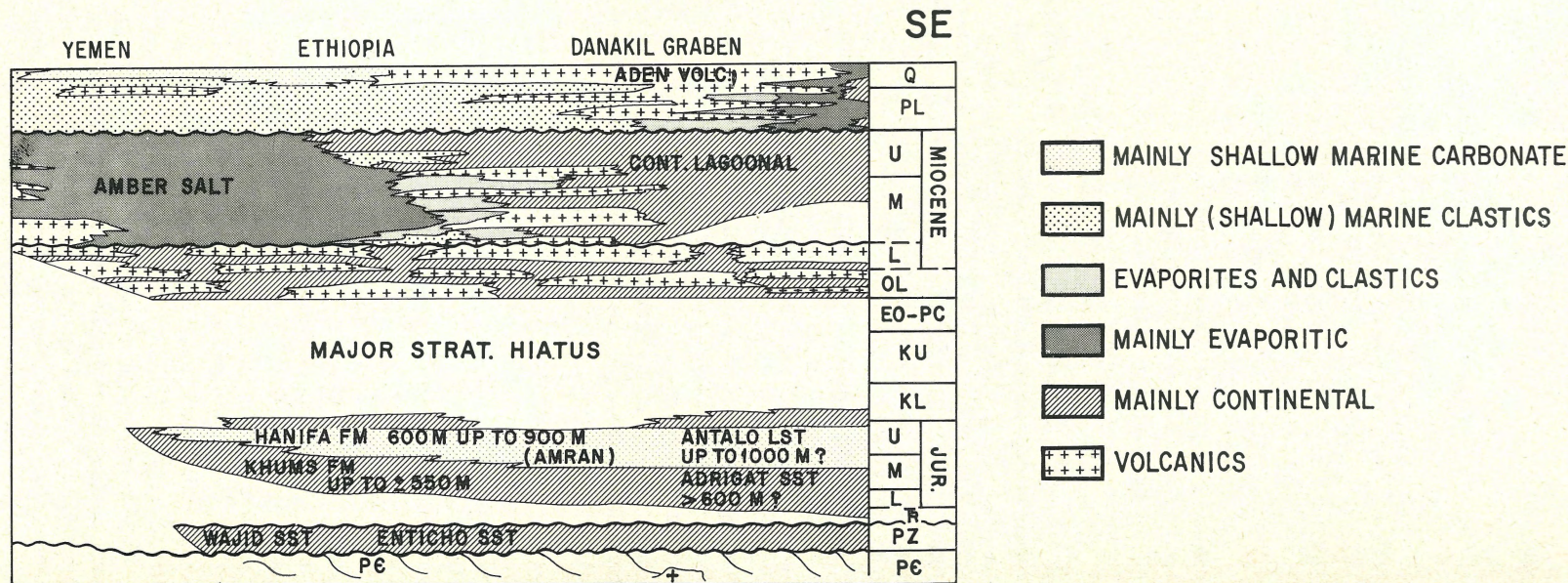


Fig. 9
Schematic facies diagram of the Red Sea area.



main types of structural deformation observed in the Miocene basin fill. The thickest Miocene sections (> 3.4 km) are seen near the outer margins and in the southern parts of the Red Sea. Here salt tectonics are also most pronounced.

Comparison of interval velocities with refraction velocities (Fairhead, 1973; Tramontini and Davies, 1969; Drake and Girdler, 1964) leaves little doubt that refractors with velocities of ± 3.7 - 4.8 km/sec indicate the Miocene. They may be partly modified by the presence of basalt dikes or flows. Interpretation of basement refraction velocities (± 5.5 - 7.1 km/sec) remains ambiguous.

The seismic sections show that the Miocene evaporites and halokinesis extend southward at least towards the area of the Hanish-Zukur volcanic islands (latitude 14° N). Thick Miocene sediments may extend still farther south, but no clear evidence for salt tectonics is seen.

There is evidence for a basal Miocene unconformity and the possible local presence of pre-Miocene sediments, particularly in the Southern Red Sea (fig. 16). Our information is too fragmentary to decipher the nature of the pre-Miocene deformation. Surface mapping in the Danakil Alps shows the Jurassic sediments to be faulted into an intricate pattern of tilted blocks along both NW and SE directed faults (Baner et al., 1971).

The Pliocene-Quaternary is marked in many places by a clear basal unconformity, cutting previous Miocene structures. In other places the Plio-Quaternary seems to be conformable with the Miocene (fig. 13, 15). The Plio-Quaternary sediments are in general but 200-500 m thick. Only locally greater thicknesses of more than 1000 m are found in structural depressions between salt structures. In some places, Plio-Quaternary sediments are also deformed by salt tectonics. Occasionally this may give rise to slight elevation of the sea floor (fig. 14).

b. Axial trough. — On many seismic profiles indications are found that Miocene evaporites and salt tectonics extend into the axial trough of the Red Sea. The occurrence of these sediments in the axial trough has been confirmed by Glomar Challenger coreholes 225 and 227 (Geotimes, 1972).

The Plio-Quaternary sediments in the axial trough are in general thin, but if not interrupted by recent volcanics, they seem to be continuous, even in the strongly subsided parts of the axial trough (fig. 13, 15, 17). Although the Plio-Quaternary is locally affected by small faults within the axial trough, the transition from the main Red Sea graben, towards the axial trough seems to be effected more by flexuring than by faulting.

Strong magnetic anomalies occur in the axial trough. In some cases a major anomaly marks the edge of the trough. In other places, anomalies more or less coincide with marked topographic bottom features (sea mounds), presumably representing sub-marine volcanic manifestations. These volcanic features are not restricted to the central part of the axial trough, but are distributed quite irregularly and also occur along its rim.

The main trough is, as a whole, deeper and more clearly expressed in the central and northern parts of the Red Sea, whilst the axial trough becomes more prominent in the south (fig. 10, 11 and 12). Since no large changes in average thickness of the Plio-Quaternary fill occurs it proves a more regional and evenly distributed subsidence during the Plio-Quaternary in the centre and north, whilst subsidence in the south was largely concentrated in the axial trough. In fact in the northern part of the Red Sea and in the extreme southern part the axial trough loses its identity or practically disappears; the magnetic anomalies are in general weak or absent (fig. 10).

All these observations cast doubt on the validity of magnetic anomaly correlations in the Red Sea which are fundamental for the seafloor spreading model of the axial trough (Drake and Girdler, 1964; Phillips, 1970).

CONCLUDING REMARKS

Evaporites in the Mediterranean and Middle East are not restricted to the Neogene. They occur in a number of stratigraphical levels throughout the Mesozoic and Tertiary. We must assume that climatic conditions for evaporite deposition were in general favourable from early Mesozoic to late Tertiary time. The episodic occurrence of evaporites therefore was related to tectonic events, causing the development of temporary and local barriers which disconnected the basins from the oceans. A rough correlation with regional Alpine tectonic phases can be observed for the Neogene evaporites discussed in this paper.

The Neogene basins of the Mediterranean region began to form after a major Alpine orogenic phase during the Oligocene (Trümpy, 1973). In the Alpine (intra-orogenic) basins a strong unconformity separates the Neogene from folded and truncated older beds. In the external basins or the foredeep area this unconformity is often absent but discontinuities or stratigraphic gaps are observed below the Neogene.

A late Miocene to early Pliocene orogenic phase intermittently disconnected the basins from the ocean and created the conditions for widespread evaporite deposition during a short period of time.

In the deeper portions of the basins evaporites are interbedded with pelagic deposits as for instance encountered in Sicily. Near the basin margins Messinian evaporites mark a temporary restriction of shallow marine shelf conditions. Here it may also be represented by a stratigraphic hiatus. Elsewhere basin subsidence was continuous throughout the Neogene.

Shallow water (deltaic) deposits of Plio-Quaternary age reach a thickness of 2-3 km in many parts of the Mediterranean, indicating subsidence of at least that amount. This strong Plio-Quaternary subsidence of the Mediterranean basins appears to be related to the rise of the Alpine chains.

The origin of the Red Sea Rift can be correlated in time

TECTONIC MAP RED SEA

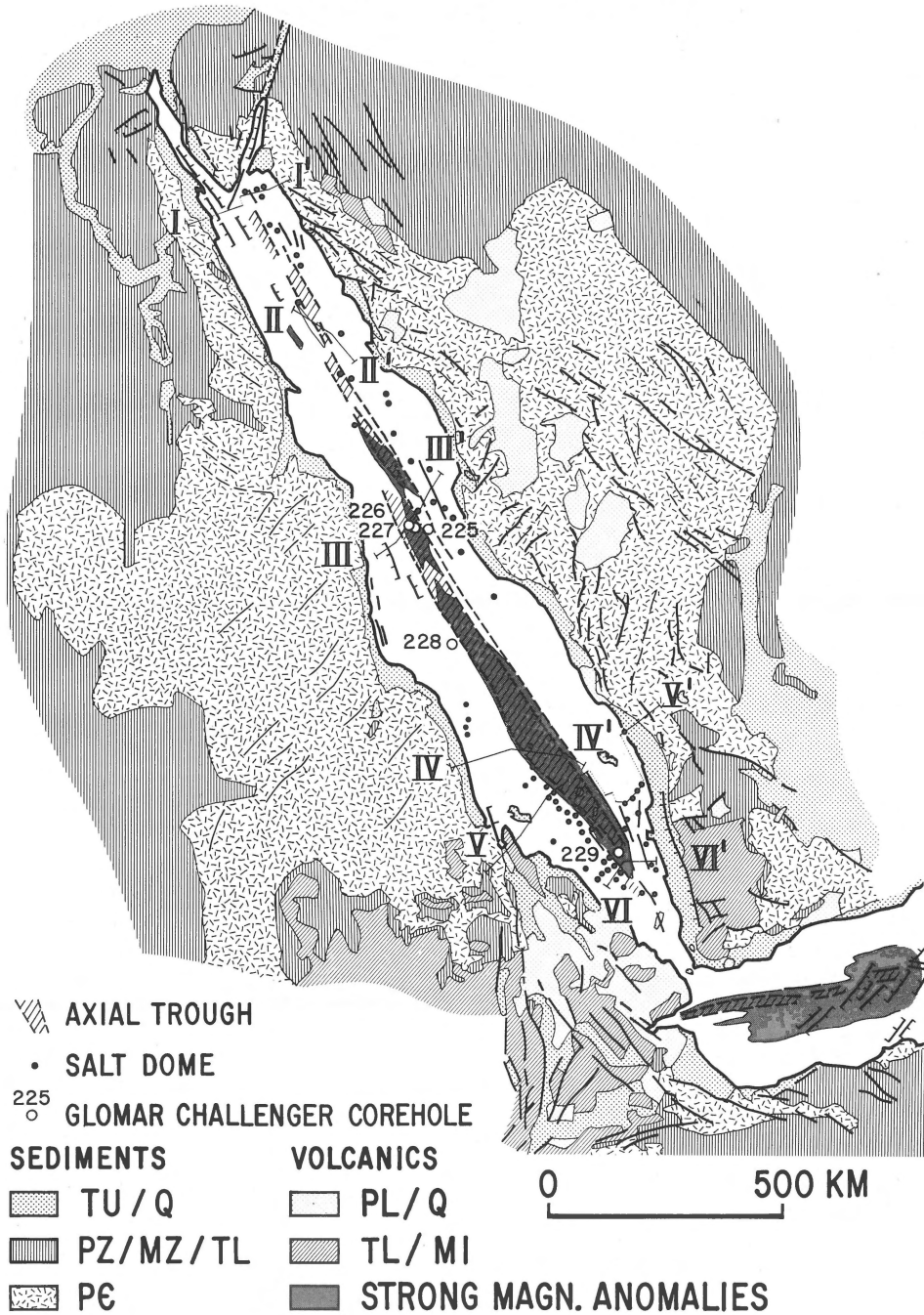


Fig. 10

Tectonic map of the Red Sea area. The Red Sea appears as a large crack on the crest of the doming Arabian Nubian shield. Late Cenozoic to recent tholeiitic volcanism (and earthquakes) are discontinuous along the axial trough. A relationship exists between the abundance of this axial volcanism, the associated magnetic anomalies and the degree of definition of the axial trough. The indicated cross sections are depicted on Fig. 11 and 12.

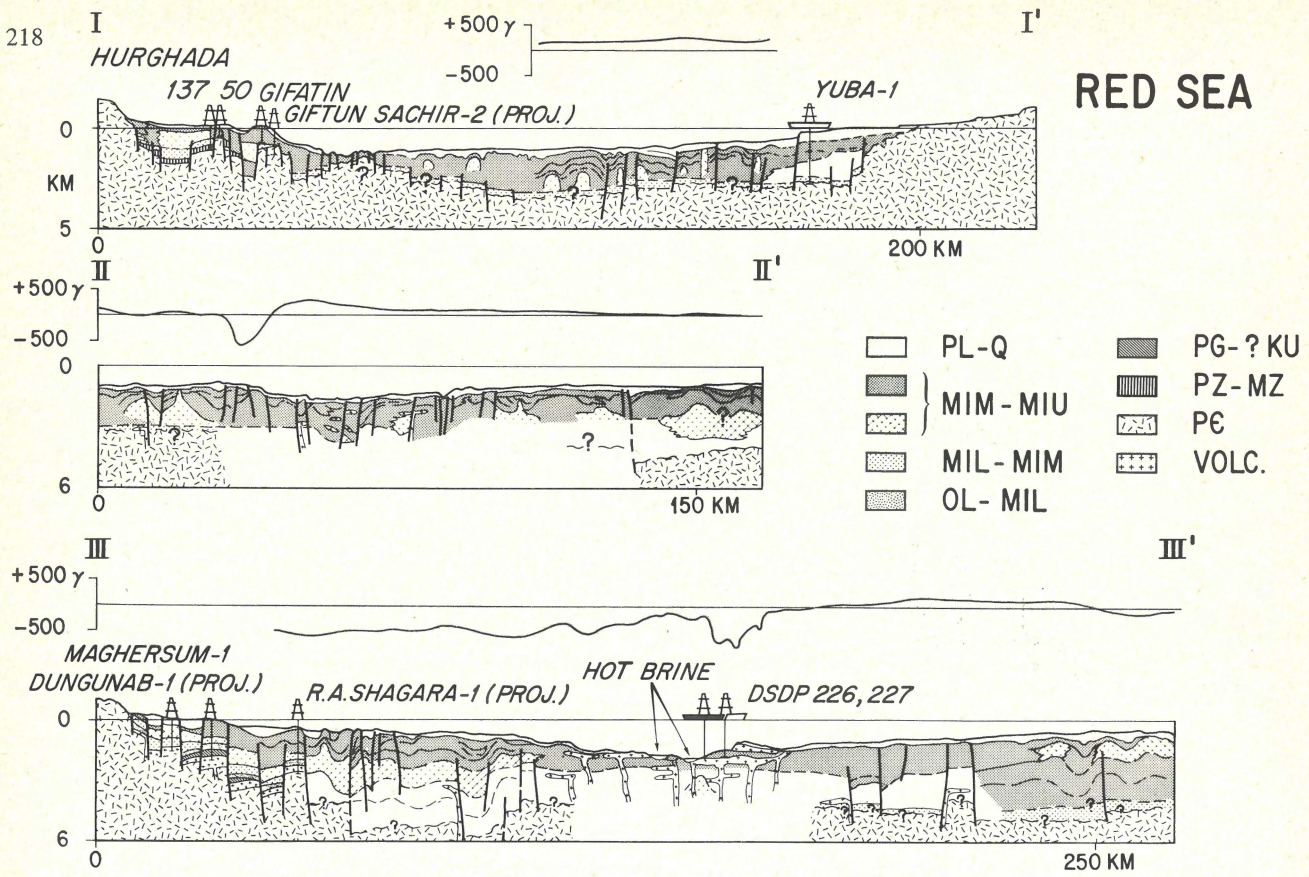


Fig. 11
Geological cross-sections in the northern and central parts of the Red Sea, and magnetic anomaly profiles. Both the Plio-Quaternary and the Miocene seem to have a continuous development throughout the Red Sea, except where interrupted by later volcanics. The locations of the profiles are shown in Fig. 10.

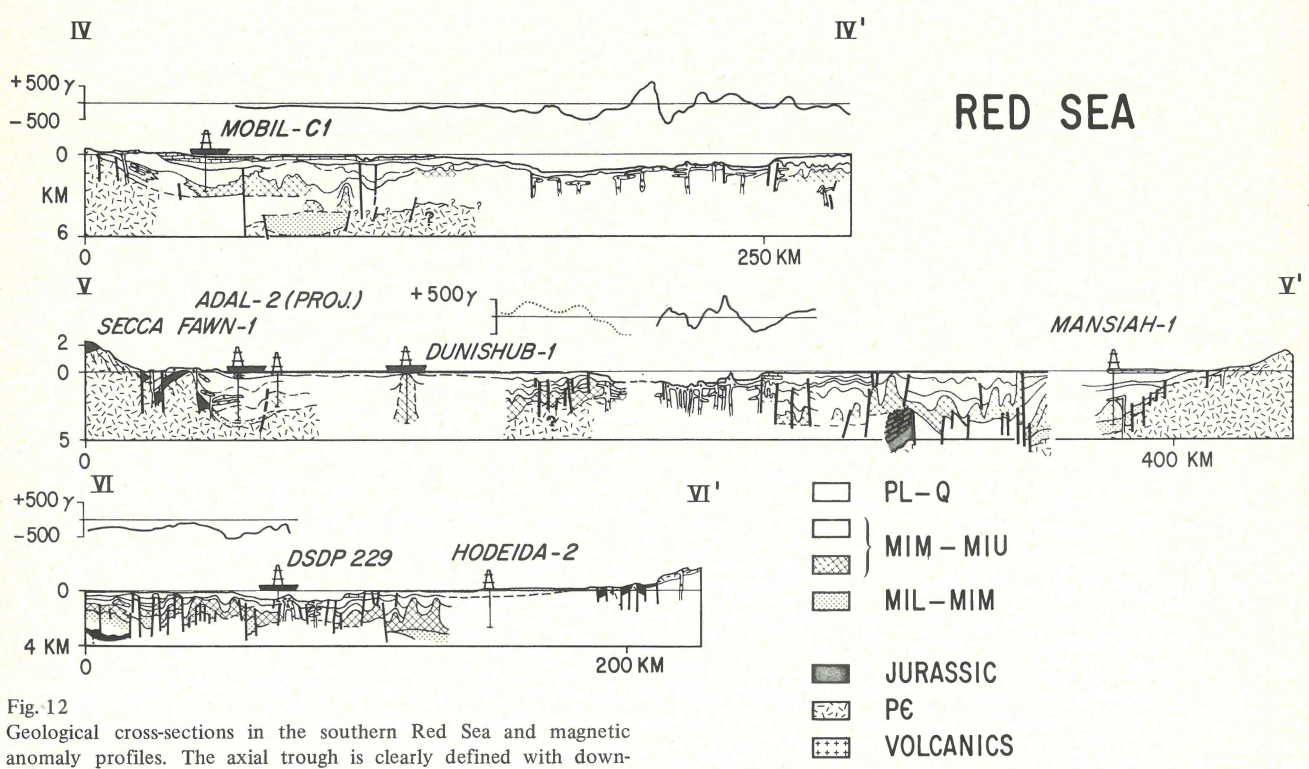


Fig. 12
Geological cross-sections in the southern Red Sea and magnetic anomaly profiles. The axial trough is clearly defined with downflexing of its margins. The locations of the profiles are shown in Fig. 10.

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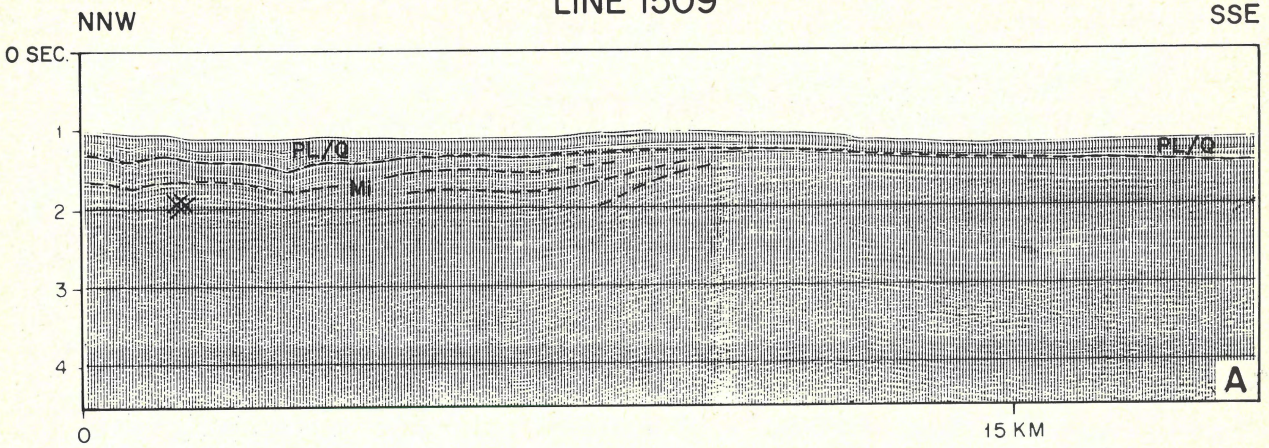


Fig. 13
Seismic reflection profile in the central part of the northern Red Sea, showing continuity and unconformable character of the strong reflector supposed to represent the base of the Pliocene.

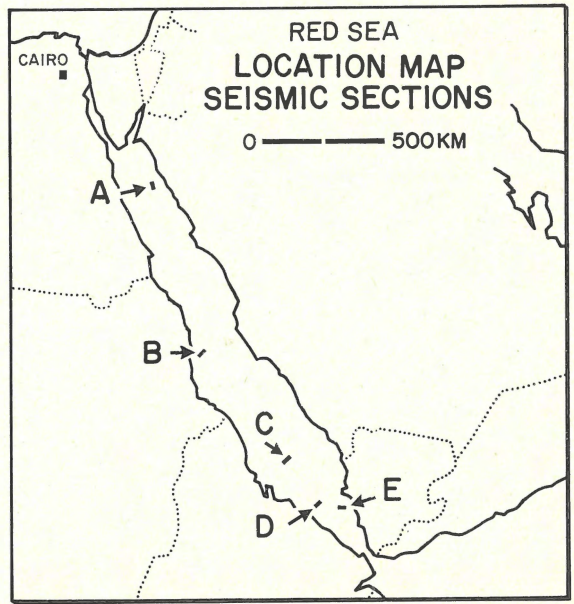
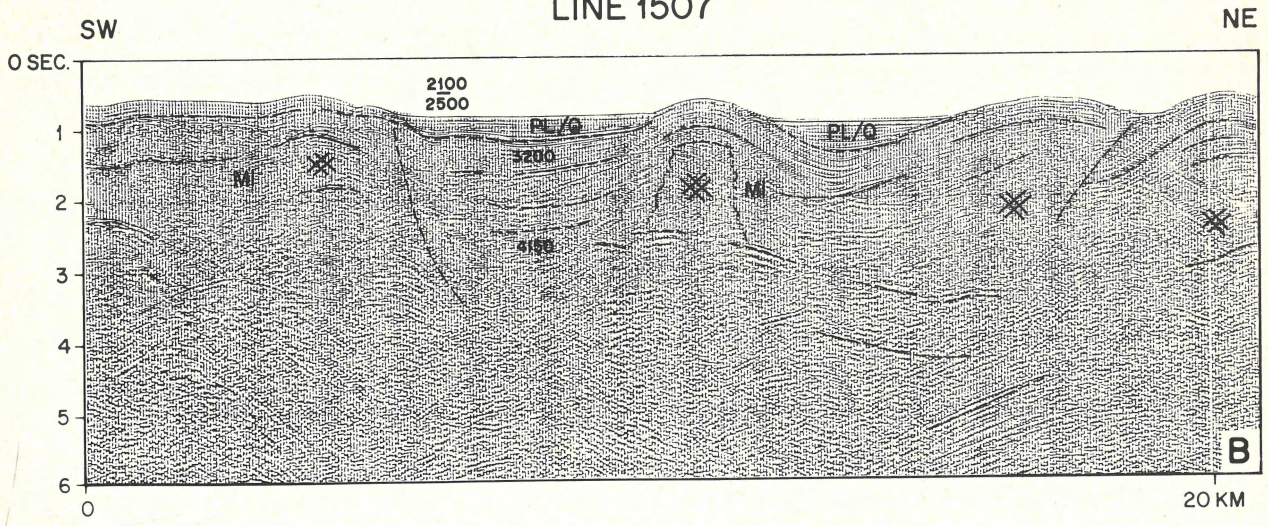


Fig. 14
Seismic reflection profile off the Sudanese coast. Salt tectonics have affected the seafloor topography. Deep reflections represent the base of the Miocene salt as well as older beds (cf. Fig. 11, section III).

LINE 1507



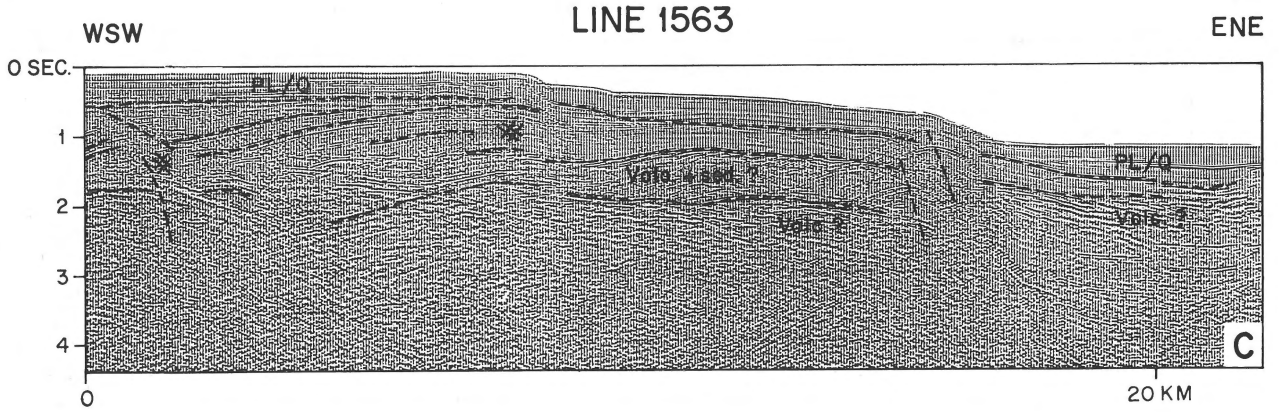


Fig. 15 Seismic reflection profile on the western margin of the axial trough in the southern Red Sea. The unconformable Plio-Quaternary shows down-flexuring into the axial trough. Volcanic intercalations are probably present in the underlying Miocene (evaporite) sequence. (cf. Fig. 12, section V).

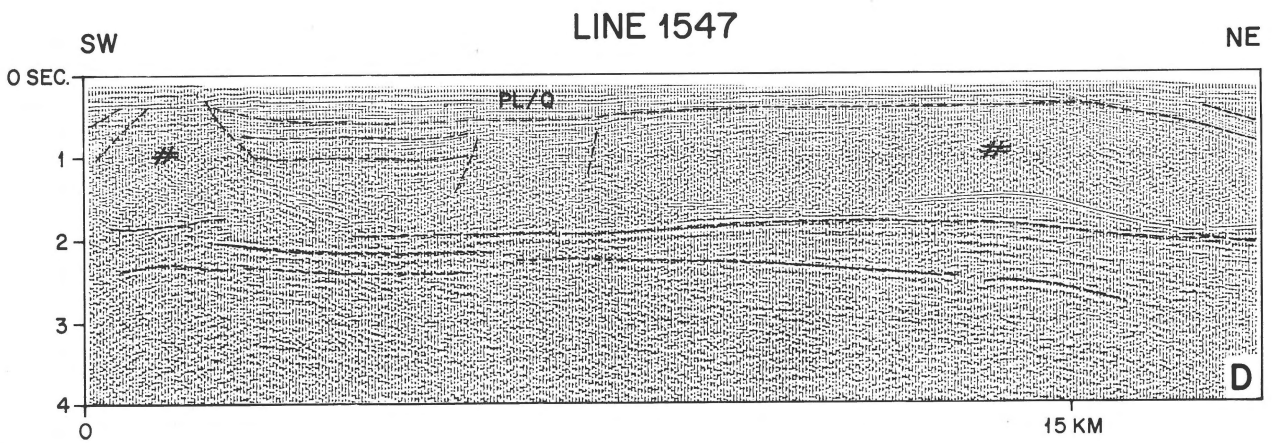


Fig. 16 Seismic reflection profile on the Ethiopian shelf. The Miocene evaporite interval shows evidence of lateral facies changes. A marked pre-evaporite unconformity is also indicated.

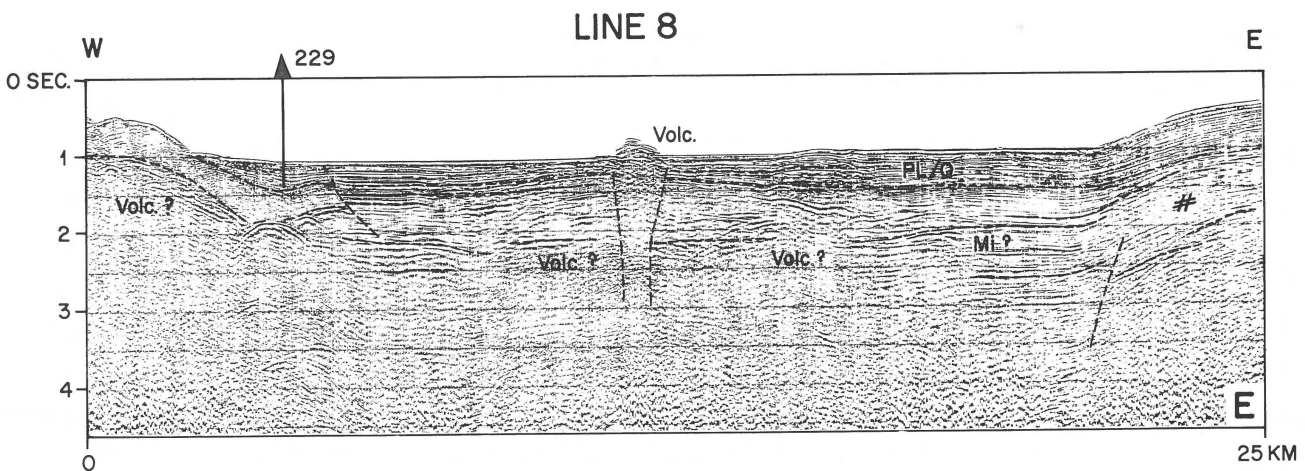


Fig. 17 Seismic reflection profile in the eastern part and margin of the axial trough off North Yemen. A thick down-flexured Plio-Quaternary sequence is inferred and partly confirmed by Glomar Challenger corehole 229. Deeper reflections also occur in the axial trough area, but are partly obscured by volcanic intercalations. A young volcanic plug forms a mound in the centre of the trough depicted above. (cf. Fig. 12, section VI).

with the Oligocene Alpine orogenic phase. Marine beds of Upper Cretaceous and Eocene age encountered within the Rift are interpreted to belong to a pre-Rift stage.

In contrast to the Eastern Mediterranean, evaporite deposition in the Red Sea extended through a large part of the Miocene. During this time the rift probably had limited connection with the Mediterranean. After a break in sedimentation and possible local erosion during latest Miocene, a connection with the Indian Ocean and open marine conditions were established during the Pliocene.

The Miocene and Pliocene-Quaternary sediments are not restricted to the main Red Sea trough, but appear to be continuous across the graben, including the axial trough.

The observed tectonic configuration shows a spatial relationship between the abundance of (tholeiitic) volcanism (largely deduced from the associated magnetic anomalies), the development of the axial trough and the magnitude of uplift of the Arabian-Nubian shield. All three are most pronounced in the central and southern part of the Red Sea.

The origin of the Red Sea Rift is explained as the result of regional doming of the Arabian-Nubian shield and its axial collapse. Intensive magmatic activity, earthquakes and high heat-flow values indicate a deep-seated cause, such as a mantle up-well or spreading axis.

Outcrops on the rim of the Southern Red Sea show that the crust has been intensely dissected and intruded with basaltic dike swarms and igneous masses. Subsequent cooling of the overloaded crust probably led to subsidence and axial collapse.

It is of interest to note that the tectonic development of the Mediterranean basins has been explained in a similar way by van Bemmelen's model of rising mantle diapirs during early Tertiary and its subsequent collapse which led to the formation of the Neogene basins (van Bemmelen, 1972).

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REFERENCES

- Bannert, D. et al. (1971) – Beiträge zur Geologie der Danakil Senke (NE-Äthiopien). Beiheft geol. Jb. 116.
- Belderson, R.H., N.H. Kenyon and A.H. Stride (1971) – Calabrian Ridge, a newly discovered branch of the Mediterranean Ridge. *Nature*, 274 (5441): 452-453.
- Bemmelen, R.W. van (1972) – Geodynamic models, an evaluation and a synthesis. Elsevier, Amsterdam.
- Bemmelen, R.W. van (1972) – Driving forces of Mediterranean orogeny (Tyrrhenian Test Case). *Geol. en Mijnb.* 51: 548-573.
- Brown, G.F. (1970) – Eastern margin of the Red Sea and the coastal structures in Saudi Arabia. *Phil. Trans. Roy. Soc. London*, (A) 267: 75-87.
- Carissimo, L., O. D'Agostino, C. Loddo and M. Pieri (1963) – Petroleum exploration by AGIP Mineraria and new geological information in central and southern Italy from the Abruzzi to the Taranto Gulf. 6th World Petrol. Congr., Frankfurt/Main.
- Cloos, H. (1939) – Hebung – Spaltung – Vulkanismus. *Geol. Rundschau*, 30: 405-527.
- Drake, C.L. and R.W. Girdler (1964) – A geophysical study of the Red Sea. *The Geoph.* 8 (5): 473-495.
- Fairhead, J.D. (1973) – Crustal structure of the Gulf of Aden and the Red Sea. *Tectonophysics* 20: 261-267.
- Gass, I.G. et al. (1973) – Volcanic islands of the Red Sea. *Geol. Soc. London*, 129: 275-310.
- Geotimes (July 1972) – Deep Sea Drilling Project in the Red Sea: 24-26.
- Girdler, R.W. and P. Styles (1974) – Two stage Red Sea floor spreading. *Nature*, 247: 7-11.
- Heybroek, F. (1965) – The Red Sea Miocene Evaporite Basin. *In: Salt Basins around Africa*. The Inst. of Petrol., London: 17-40.
- Hutchinson, R.W. and G.G. Engels (1972) – Tectonic evolution in the southern Red Sea and its possible significance to older rifted continental margins. *Geol. Soc. Am., Bull.* 83: 2989-3002.
- Knott, S.T., E.T. Bunge and R.L. Chase (1965) – Red Sea seismic reflection studies. *In: The World Rift System*. Geol. Survey of Canada: 66-14.
- Le Pichon, X., J. Francheteau and J. Bonnin (1974) – Plate tectonics. *Developments in Geotectonics*, 6, Elsevier, Amsterdam.
- Lowell, J.D. and G.J. Gernik (1972) – Sea-floor spreading and the structural evolution of Southern Red Sea. *A.A.P.G., Bull.* 65 (2): 247-259.
- McKenzie, D.P., D. Davies and P. Molnar (1970) – Plate tectonics of the Red Sea and East Africa. *Nature*, 226: 243-248.
- Mulder, C.J. (1973) – Tectonic framework and distribution of Miocene evaporites in the Mediterranean. *In: Messinian events in the Mediterranean*. Kon. Acad. Wet., Amsterdam.
- Papazachos, B.C. and P.E. Comninakis (1971) – Geophysical and tectonic features of the Aegean arc. *Journ. Geoph. Research*, 76 (35): 8517-8533.
- Phillips, J.D. (1970) – Magnetic anomalies in the Red Sea. *Phil. Trans. Roy. Soc. London*, (A), 267: 205-218.
- Phillips, J.D. and D.A. Ross (1970) – Continuous seismic reflection profiles in the Red Sea. *Phil. Trans. Roy. Soc. London*, (A), 267: 143-152.
- Ritsemá, A.R. (1972) – Deep earthquakes of the Tyrrhenian Sea. *Geol. en Mijnb.* 51 (5): 541-545.
- Ross, D.A. and J. Schlee (1973) – Shallow structure and geological development of the Southern Red Sea. *Geol. Soc. Am., Bull.* 84: 3827-3848.
- Ryan, W.B.F., K.J. Hsü, D. Nesteroff, G. Pautot, F.C. Wezel, J.M. Lort, M. Cita, W. Maync, H. Stradner and P. Dumitricia (1973) – Initial reports of the Deep Sea Drilling Project, Lisbon to Lisbon. 13, U.S. Gvt. Printing Office, Washington D.C.
- Schneider, W. and H. Wachendorf (1973) – Vulkanismus und Graben-Bildung im Roten Meer. *Geol. Rundschau*, 62 (3): 754-773.
- Swartz, D.J. and D.D. Arden (1960) – Geologic history of Red Sea area. *A.A.P.G., Bull.* 44: 1621-1637.
- Tramontini, C. and D. Davies (1969) – A seismic refraction survey in the Red Sea. *Geop. R. astr. Soc.* 17: 225-241.
- Trümpy, R. (1973) – L'évolution de l'orogénèse dans les Alpes Centrales: Interprétation des données stratigraphiques et tectoniques. *Eclog. geol. Helv.*, 66/1: 1-10.
- Young, R.A. and D.A. Ross (1974) – Volcanic and sedimentary processes in the Red Sea axial trough. *Deep Sea Research*, 21: 289-297.