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POST-MIOCENE RIFTING AND DIAPIRISM IN THE NORTHERN RED SEA

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Abstract

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Rifts and diapirs are the dominant structures in the bathyal zone of the northern Red Sea, where commonly the diapirs ascend along normal faults associated with the rifts. In this manner, the diapirs form elongated features sometimes exceeding lengths of 30 km and widths of 4 km. They also penetrate a sedimentary sequence about 1000 m thickness or less, thicknesses generally considered to be barely adequate for the gravity conversion required to initiate diapiric motion. We suggest that development of diapirs under these minimal overburden conditions was made possible by the high thermal gradients in the area, resulting from the underlying attenuated continental crust and ascending mantle, that prevail in the rift system of the northern Red Sea. Diapiric evolution was also dependent on the extensional tectonic regime, with its numerous normal faults forming weaknesses along which the diapirs could move upwards.

Introduction

The northern Red Sea is a unique example of a pre-sea-floor rift system separating the relatively undeformed Arabian and African plates. The region is characterized by the remarkable jigsaw fit of the NW–SE trending opposite coastlines, which led Wegener (1929) to present the Red Sea as an example of the early stages of continental drift. The mountainous terrains that border the Red Sea on both the African and the Arabian coastlines show steep seaward slopes flanked by narrow coastal plains and continental shelves (Fig.1). Whereas the coastal plains are built of Neogene and Quaternary sediments, the adjacent mountains consist of extensive outcrops of Precambrian, igneous, and metamorphic suites (Coleman, 1974). Continental slopes are steep, descending to a main trough at depths of 1200–1500 m. The deep axial trough, which is a dominant morphological feature in the central Red Sea, is conspicuously absent in the north (Mart and Hall, 1984; Uchupi and Ross, 1986). The morphology of the main trough of the northern Red Sea is commonly rugged (Fig.2). Faults, rifts and diapirs are abundant, and the dominant tectonic regime is one of crustal extension (Cochran, 1983; Mart and Hall, 1984). As a rule, the structural association of rifts and diapirs is a common occurrence, but the northern Red Sea association is unique, and differs from most occurrences in several aspects:

(1) The diapirs in the northern Red Sea are covered by a 1 km or less thick overburden, whereas in most regions diapirs result from a

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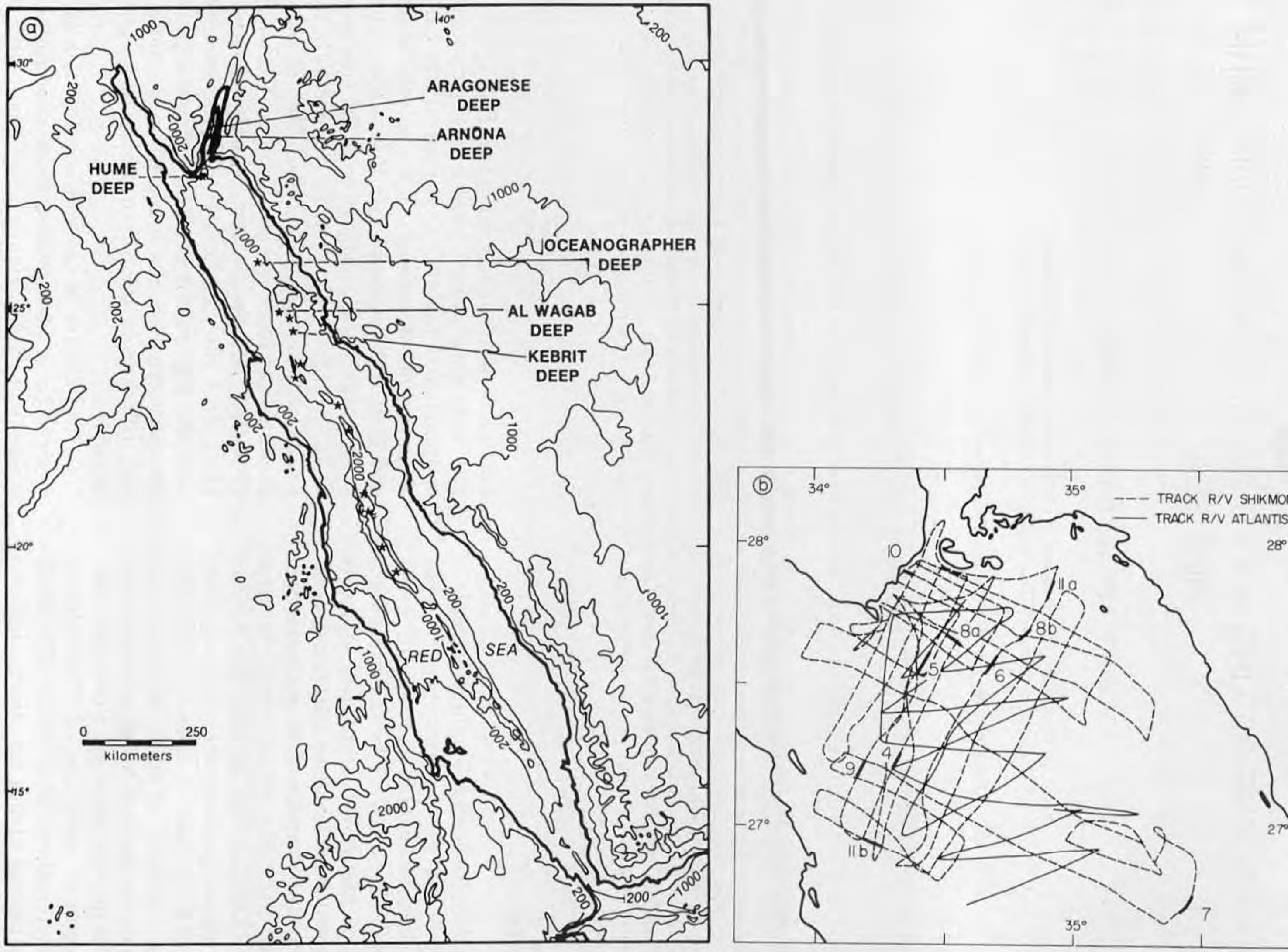


Fig.1. (a) A generalized morphological map of the Red Sea and adjacent terrains. Deeps are marked by asterisks, and contours are in meters. (From Choubert, 1968, and Coleman, 1974). (b) Ship tracks of the R/V "Atlantis II" and the R/V "Shikmona" in the northern Red Sea and locations of profiles shown in subsequent figures.

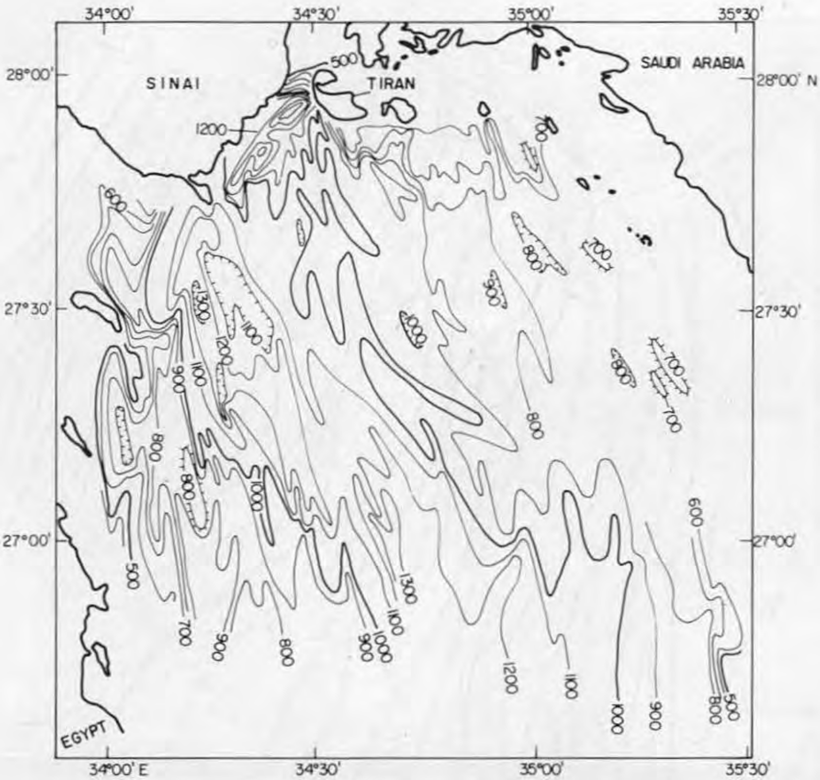


Fig.2. Bathymetric map of the bathyal zone of the northern Red Sea (contours in meters). Note that the deeper parts of the northern Red Sea are located in its western section. The arcuate configuration of the deeper parts of the bathyal zone changes its trend from NNW–SSE to NNE–SSW, so that a gradual orientational shift from the Red Sea trend to the Dead Sea trend can be discerned. See Fig.1b for the ship tracks.

salt layer buried under an overburden sequence attaining thicknesses of 3–6 km (Gussow, 1968; Humphris, 1979).

(2) In the northern Red Sea the diapirs are typically elongated, attaining lengths exceeding 30 km and widths of about 4 km (Fig.3), whereas in many other places diapirs commonly form structural domes that are round or oblate.

(3) In the northern Red Sea the diapirs commonly ascend either along the boundary faults of the rift or into the rift floor.

Geological setting

The evolution of sea-floor spreading axes proceeds from an initial stage of continental uplift and igneous activity, through an intermediate stage of rifting and attenuation of continental crust, to the mature stage of accretion of oceanic crust and sea-floor spreading. These stages are well represented in the Red Sea region. The separation between the African and Arabian plates started during the late Oligocene–early Miocene with a NW–SE trending regional uplift and extensive intrusive and extrusive volcanism (Coleman, 1974). The early Red Sea uplift probably exceeded 3 km, as indicated by the widespread outcropping of the Arabian–Nubian Precambrian massif on both flanks of the Red Sea (Choubert, 1968). The 22–20 Ma old alkali-basalt dikes associated with this tectonic phase in the northern Red Sea show a dominant northwestward trend (Bartov et al., 1980).

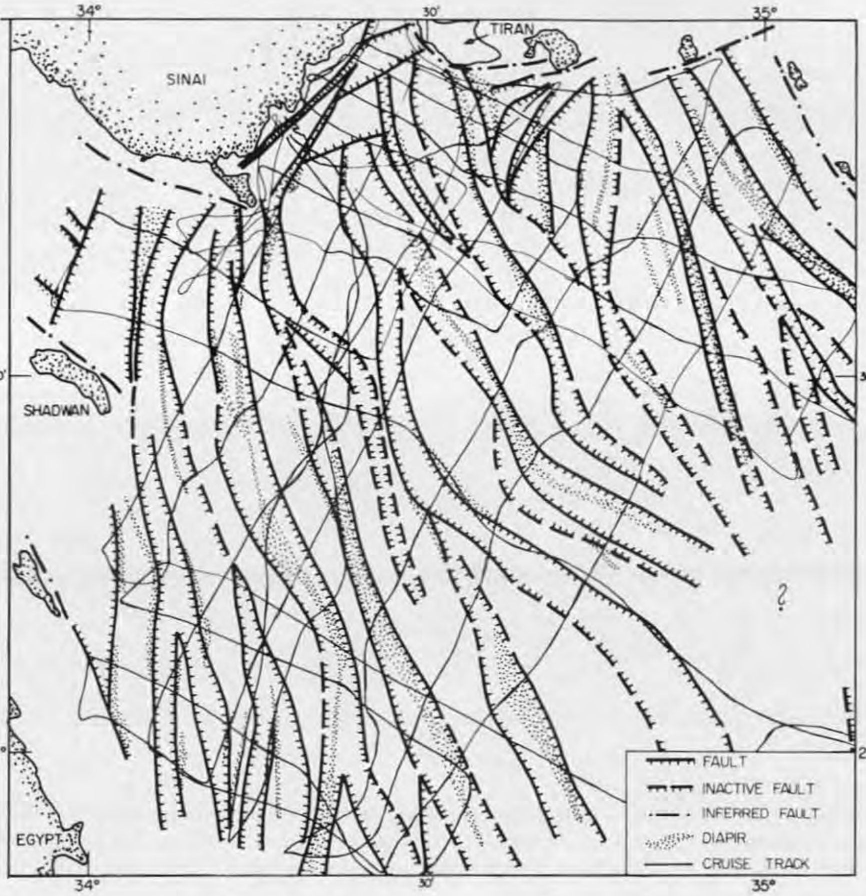


Fig.3. Distribution of rifts and diapirs in the northern Red Sea. The arcuate configuration of the bathymetric features (Fig.2) can be closely correlated to the structural elements, showing the gradual change of tectonic trends. The association between the rifts and the diapirs can be seen in most places.

Following the regional uplift and volcanism, rifting occurred along the axis of the elongated dome and eventually a marine basis developed. Rifting of the Red Sea occurred during the early to middle Miocene along the same northwestern trend. It is of interest to note that whereas the tectonic development of the Red Sea and the Gulf of Aden is similar and almost contemporaneous, and both are extensions from the northern segment of the NW Indian Ocean tectonic spreading system, the Red Sea was connected during this time to the Mediterranean Sea (Stoffers and Ross, 1974; Cochran, 1981, 1983). The Red Sea–Mediterranean connection is significant, because when the Mediterranean was affected by its late Miocene salinity crisis (Ryan et al., 1973), the Red Sea was affected as well, and a sequence of evaporites attaining thicknesses of about 3 km was also deposited there (Ahmed, 1972).

Accretion of oceanic basalts in the Red Sea in the center of the main trough near latitude 18°N started 5 Ma ago (Roeser, 1975; Le Pichon and Francheteau, 1978), and the accretion zone propagated northwestwards and southeastwards at an average rate of 120 mm yr^{-1} (Mart and Hall, 1984). An essentially continuous zone of sea-floor spreading now extends from latitudes 16° to 21°N. From 21° to 24°N is a transitional zone where oceanic basaltic accretion is sporadic and occurs in basins separated by attenuated continental crust (Pautot et al., 1984). Farther north, between 24° and 28°N, is a rifted zone underlain by attenuated continental crust (Cochran, 1983; Uchupi and Ross, 1986).

The basis structural trends in the northern Red Sea region were set during the middle–late Miocene. These include the NW–SE-oriented regional rifts that led to the evolution of the coastal plains and the continental margins on the Arabian and the African flanks. This structural framework extended from the southern Red Sea into the Suez rift, and was associated with the NE–SW extension into the Red Sea.

The late Miocene–early Pliocene was a critical period in the development of the Red Sea. Concurrently with the beginning of seafloor spreading in the central part of the sea, the axis of the continental separation between Arabia and Africa in the northern region changed its trend from NW–SE to N–S. This change caused the termination of large-scale tectonic activity in the Suez rift and initiated the evolution of the Dead Sea rift (Mart and Hall, 1984). As a result of these tectonic changes, the Red Sea–Mediterranean connection was disrupted and the Red Sea–Indian Ocean connection was opened through the Straits of Bab-al-Mandeb at the southern end of the Red Sea. The Indian Ocean connection ended the evaporitic deposition in the Red Sea.

The continuation of the continental divergent motion in the Red Sea region during the Plio-Pleistocene led to the evolution of a double trough system in the central Red Sea. This consists of the main trough, formed in the Miocene and underlain by the late Miocene evaporites resting on attenuated continental crust (Drake and Girdler, 1964), and an axial trough, where accretion of oceanic crust occurred, dissecting the evaporitic sequence. At the same time crustal attenuation and tectonic distension continued in the Red Sea, leading to the formation of a series of rifts within the main trough. Concurrent with this distension, diapirs started to develop.

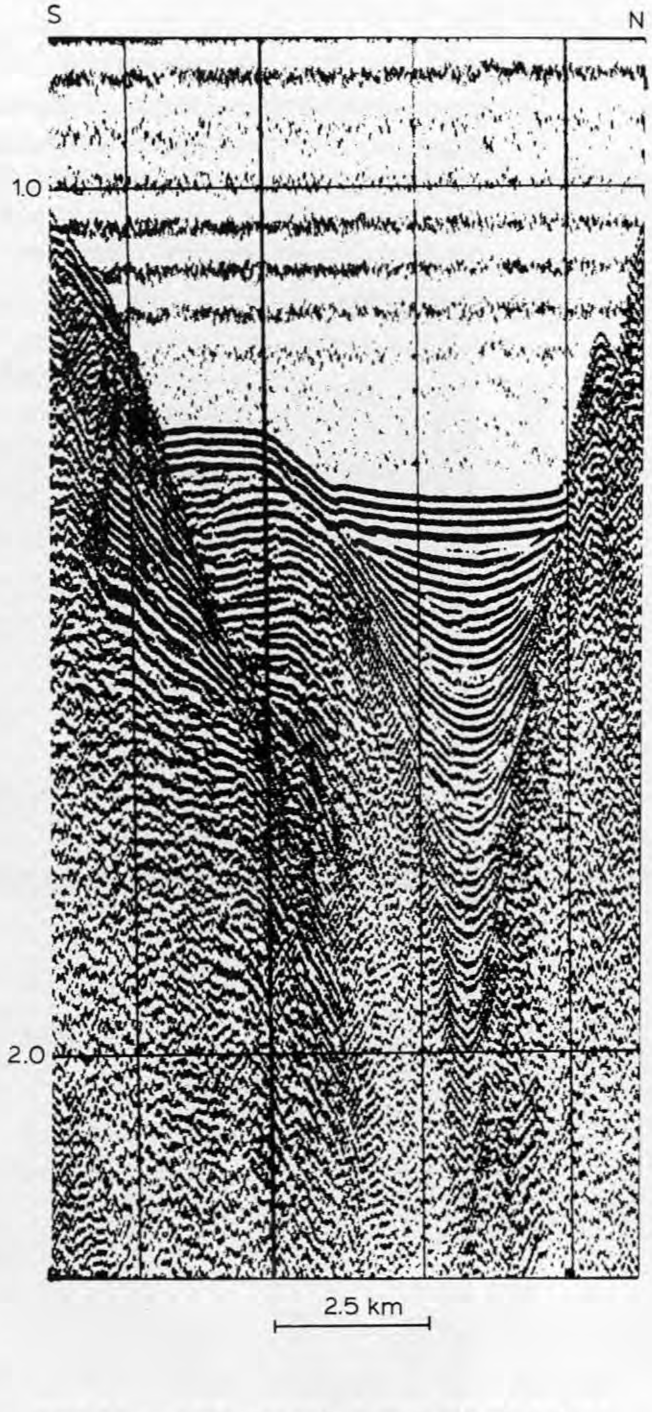


Fig.4. A seismic reflection profile across a rift. The bedding patterns clearly suggest several unconformities in the deposition, probably due to intermittent tectonic activity. See text for further discussion and Fig.1b for location.

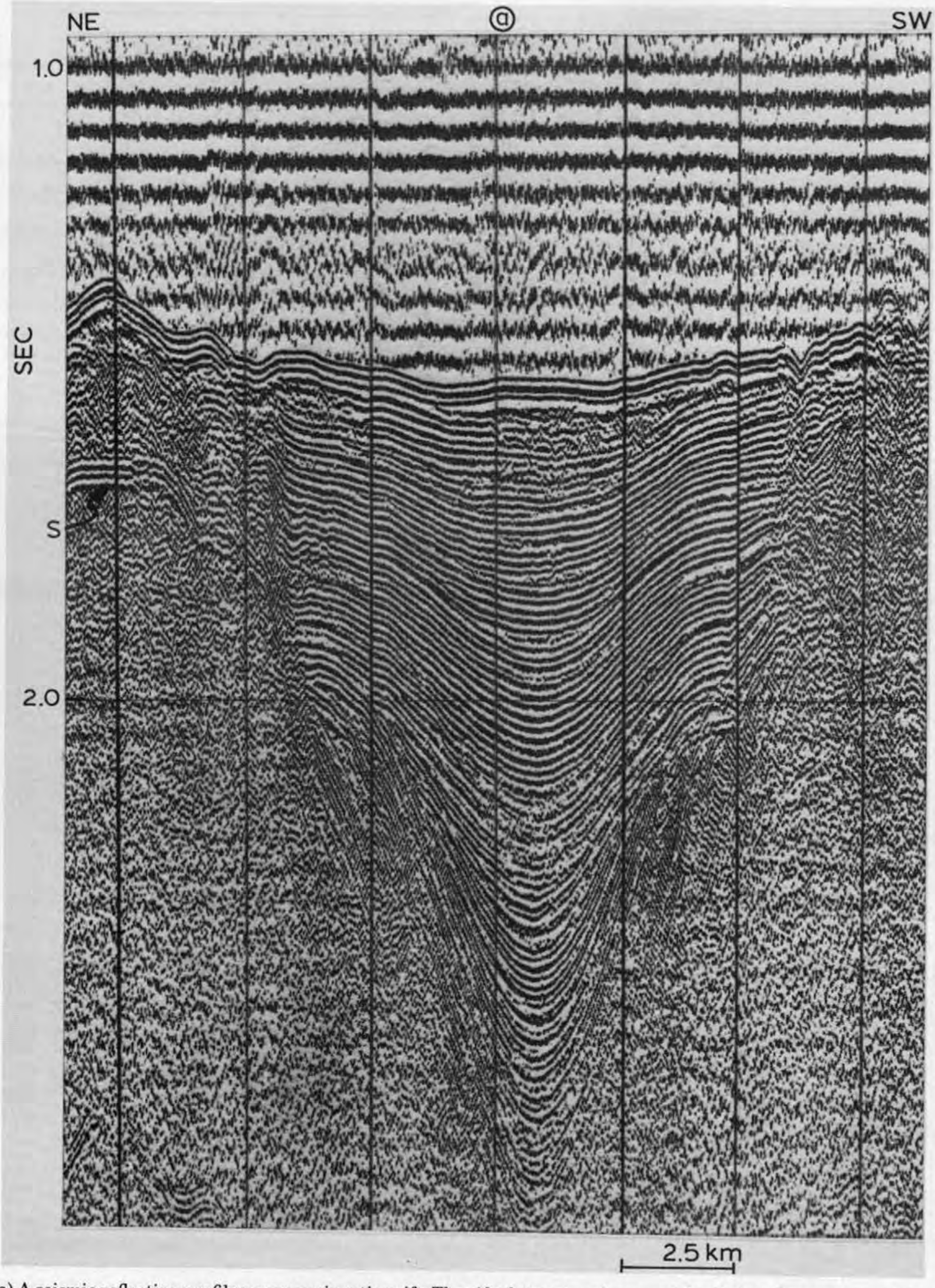


Fig.5. (a) A seismic reflection profile across an inactive rift. The rifted structure is seen at depth, but the uppermost layers are hardly offset.

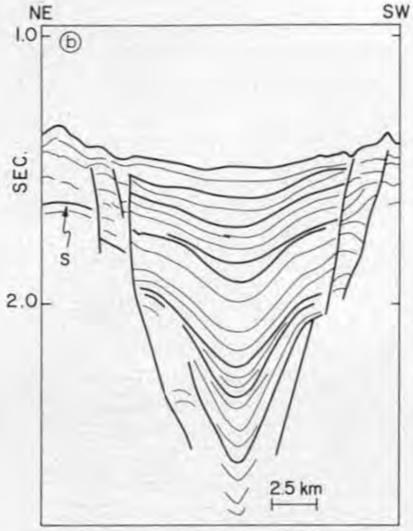


Fig.5 (*continued*). (b) Interpretation of (a). Note the sequence of alternating concordant bedding and unconformities (heavy lines), suggesting a sedimentation regime of intermittent activity. See Fig.1b for location.

Mechanical constraints of shallow diapirs

The diapirs in the northern Red Sea occur in a region where their sediment overburden is relatively thin. In most of the well-known diapiric regions, such as the Gulf of Mexico or northern Germany, diapirs pierce upward through a thick overburden, exceeding 5 km in places (e.g. Kupfer, 1968; Murray, 1968). These thick overburdens and the subsequent burial depths of the rock–salt sequences cause high pressures and high temperatures. The high pressure leads to consolidation of the overburden and to the increase in its density from about 2.0 g cm^{-3} to values of 2.6 g cm^{-3} or more, whereas halite maintains its 2.0–2.2 g cm^{-3} density. The high temperature enhances the ductility of the rock salt (Carter and Hansen, 1983). The density contrast between the evaporites and the overburden results in a metastable gravity configuration that leads to diapirism when enhanced by increased salt ductility and affected by a perturbation (Parker and McDowell, 1955; Gussow, 1968). The perturbation is considered to be associated with faulting, which both triggers a seismic shock and provides a favorable emplacement zone for the ascending diapir along the fault plane.

The thickness of the Plio-Pleistocene sedimentary sequence, atop the late Miocene evaporites in the northern Red Sea, is approximately 500–1000 m. This approximation is based on a 0.5–1.0 s average reflection time from the sea floor to reflector S (Phillips and Ross, 1970), which marks the top of the evaporite sequence, and on interval seismic velocity of about 2.0 km s^{-1} (Drake and Girdler, 1964). Evidence that the northern Red Sea diapirism was indeed triggered under thin overburden is suggested by the density conversion encountered in DSDP borehole 225. At this site in the central Red Sea, the density of the sediments at 5 m was 1.7 g cm^{-3}, at 100 m the same type of detrital sediments had a density of 2.2 g cm^{-3}, and dolomite beds encountered at 150 m depth had a density of 2.8 g cm^{-3}. In comparison, halite found in the same borehole at depths greater than 180 m had a density of 2.2 g cm^{-1}, which is its normal density.

Heat flow measurements in the central Red Sea showed anomalously high values of 153–276 mW m^{-1} (Langseth and Taylor, 1967; Girdler, Ericson et al., 1974). These high values indicate favorable thermal conditions required for initiation of salt flow (Carter and Hansen, 1983). The measured thermal gradient of 117 K km^{-1} in the Red Sea (Whitmarsh et al., 1974) further supports this presumption, because laboratory tests have shown that lithostatic confining pressure is a critical parameter to salt ductility at pressures below 20 MPa. However, under conditions of higher pressures, temperature becomes the determining parameter (Carter and Hansen, 1983).

The analysis of the origin of the northern Red Sea diapirs is based on the rough calculation of possible pressure and temperature at a depth of 1 km, which suggests a confining lithostatic pressure of about 30 MPa and a temperature of approximately 130°C. These temperatures and pressures are barely sufficient to trigger diapirism (Carter and Hansen,

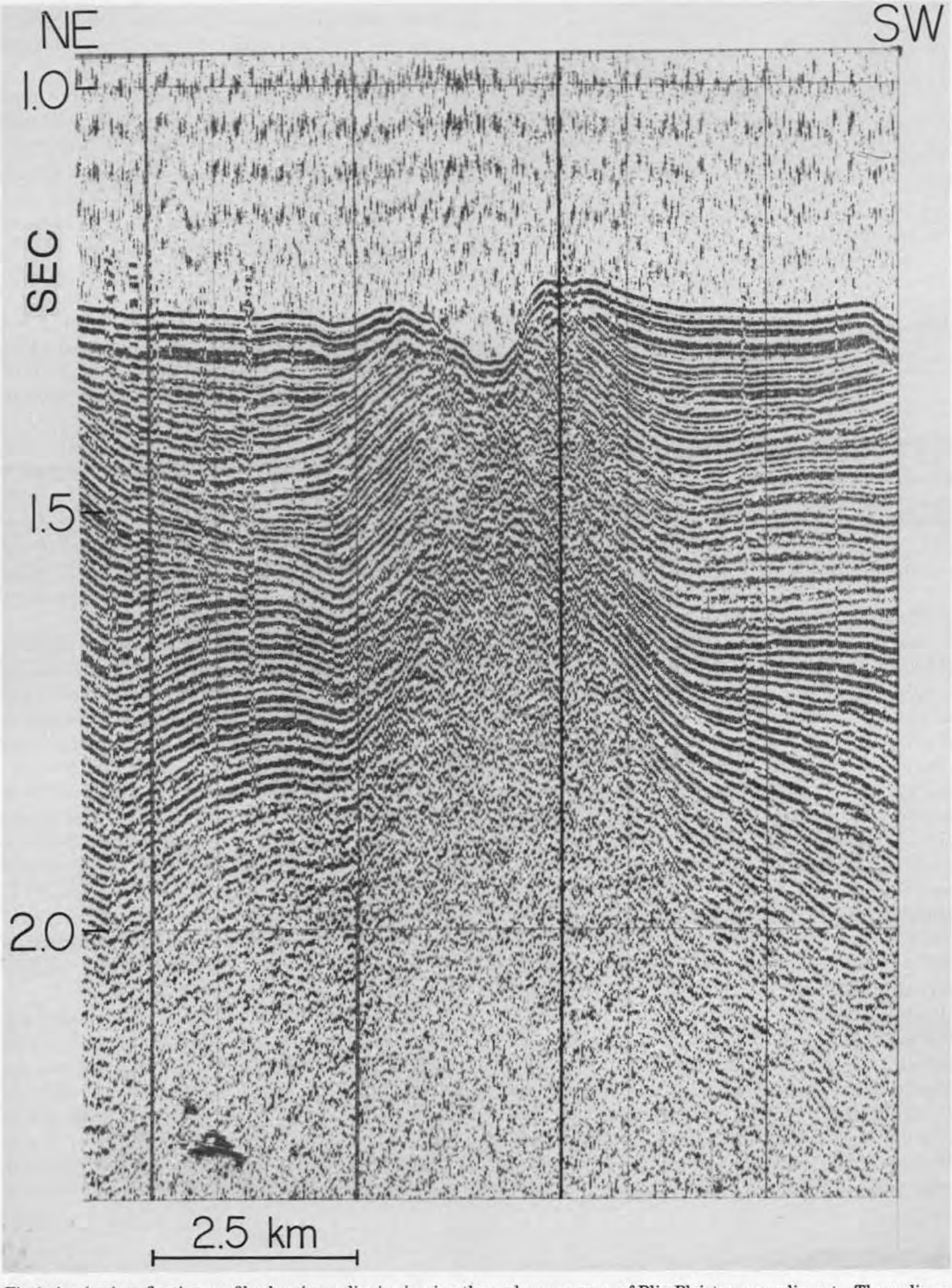


Fig.6. A seismic reflection profile showing a diapir piercing through a sequence of Plio-Pleistocene sediments. The sediment thickness is at least 0.75 s reflection time, which is approximately 750 m. The diapir is topped by a collapse structure due to dissolution of its upper part when it reaches the sea floor. See Fig.1b for location.

1983). However, the tectonic regime of extensional movement and normal faults in the region also can contribute to the development of the diapirs. The fault planes can be preferred zones for salt flow since they represent zones of weakness as a result of lithological discontinuity and structural gaps. Most fault types are favorable zones for diapiric ascent (Bishop, 1978), but normal faults seem to be the most likely to enhance diapirism under otherwise marginal conditions. Thus the burial depth of the Red Sea salt, the subsurface temperature, the overburden density, and the faulting regime all seem to enhance the development of diapiric structures provided that adequate perturbation occurs.

The perturbation that triggers the diapirism is probably associated with the faulting and rifting in the northern Red Sea, but other types of triggering mechanisms should not be ruled out. A structural analysis of the salt domes of east Texas suggests that these diapirs were triggered by differential loading (Jackson and Seni, 1983). Reconstruction of the sequence of events in east Texas indicates that gravity gliding and prograding deltaic deposits initiated a flow of the underlying middle Jurassic Louann Salt. Deposition of the salt was probably associated with rifting, but the latter developments preceded the diapirism. Basin analysis of the east Texas salt domes enabled Jackson and Seni (1983) to suggest that there are critical thicknesses of the salt as well as the overburden below which the diapirs are not likely to develop. They suggested that the critical salt thickness for the initiation of the flow is approximately 600 m, and a similar thickness of the overburden is required as well. Although the triggering mechanism of the east Texas salt domes seems to differ from that of the northern Red Sea, the basic mechanical characteristics are very similar.

Rifts, diapirs and tectonic regime

Rifts are very prominent in the northern Red Sea: a NW–SE trending system occurs at the continental margins, and a NNW–SSE to N–S trending one is present in the bathyal zone. The outer system is associated with at least two levels of seaward reduction of topographic elevation — the first drops from the elevated plateaus of Arabia and Africa to the coastal plains of the Red Sea, and the second drops from the coastal plains, across the continental margins, to the bathyal zone. The combined drop in elevation, including the calculated effect of erosion, is at least 5 km (Choubert, 1968; Coleman, 1974). The inner or bathyal rifting system, on the other hand, is associated with vertical offsets that rarely exceed 500 m, and the combination of grabens and horsts yields only a small change in bathymetry. The difference in the orientation between the two rifting systems is significant. Whereas the outer rifts extend from the northern Red Sea into the Gulf of Suez, the bathyal rifts extend from the Red Sea into the Dead Sea rift (Figs.1 and 3).

The dimension of the rift-lows in the bathyal rift system can reach lengths exceeding 50 km and widths of up to 10 km (Fig.3). Their morphology and internal structure suggest that they are active, as indicated by the concave stratification of the fill and normal boundary faults (Fig.4). The boundary faults are longer than the morphological depressions associated with them. However, structural evidence shows that these faults are not presently active along their entire lengths. In places of regular bathymetry, seismic reflection profiles show that the subsurface layers have the typical concave, inter-rift structure except for their upper sections, where the stratification shows little displacement between the rift and the adjacent terrain. These rifts are buried and do not affect the sea floor (Fig.5), but their correlation with active rifts and half-rifts supports the interpretation of structural continuity (Mart and Hall, 1984).

The spatial association of the rifts of the northern Red Sea and diapiric structures suggests generic correlation between them. Although the diapirs have not been sampled in the northern Red Sea, they probably are built of late Miocene evaporitic rocks comparable to the late Miocene evaporites that crop out nearby and have been sampled in wells near the coast. Drilling results from the marginal and bathyal zones of the Red Sea (Ahmed, 1972; Whitmarsh et al., 1974) suggest that gypsum was deposited on the margins and rock salt in the bathyal zone during the late Miocene. Further evidence of the composition of the evaporites is provided by several diapirs topped by collapse structures, resulting from dissolution of the evaporites by sea water (Fig.6). In some places the diapirs pierce the overlying sediments and affect the sea floor forming elongated hills reaching lengths exceeding 30 km (Fig.3). These diapirs which protrude through the sea floor are commonly covered by an envelope of non-evaporitic sediments so that they are not affected by sea water dissolution (Fig.7). Piercement structures are also evident in the seismic profiles from places where the diapirs do not affect the sea-floor morphology. In these instances it is suggested that the diapirs either ceased to ascend or, alternatively, have not yet reached the sea floor (Fig.8). Where the diapirs barely reach the sea floor, they cause the uppermost sediments to be uplifted, folded and faulted by the ascending diapir (Fig.9).

Diapirs that cause intensive upward folding in the overlying sediments without piercing them are common. This type of diapir is also abundant in other diapiric provinces (Bishop, 1978), but is difficult to identify positively from the seismic profiles due to its similarity to non-diapiric fold structures. The proximity and the structural association between the piercing and the non-piercing diapirs, as well as the abundance of anticlines compared with the extreme rareness of synclines in the northern Red Sea, support the presumption that most of the anticlinal structures in the northern Red Sea are probably fold-forming, non-piercing diapirs.

Most of the diapirs observed in the northern Red Sea are associated with faulting and rifting. Many of the diapirs pierced their way upward along boundary faults of rifts (Figs.7 and 10); others just forced their way into rift floors (Fig.11). The displacements between the diapirs and the most recent sediments suggest that in many places diapirism is active at present (Fig.9). Red Sea diapirs are smaller than the associated rifts, and it seems the rifting was instrumental in initiating the diapiric ascent. Our findings are supported by experimental and theoretical models, which indicate that rifts can be the product of structural extension and collapse that resulted from diapiric piercing and uplift motion (Withjack, 1979; Withjack and Scheiner, 1982). Therefore the evidence indicates that the faults of the northern Red Sea bathyal rift formed planes of weakness in the overburden which facilitated the diapiric activity under marginal constraints.

The origin of the diapirs and the rifts

Data from the northern Red Sea show two systems of rifts: regional and local. The regional rift system is the Dead Sea–Red Sea–East African Rift system which is a product of mantle diapirism that led, in the central Red Sea, to accretion of new oceanic crust (Ross and Schlee, 1973). The local system is that of rifts in the bathyal zone. The regional system was initiated in the late Oligocene–early Miocene, whereas the local system is of Plio-Pleistocene age. However, both systems are presently active. The evolution of the regional system started with uplift and subsequent development of a rift along the apex of the uplifted zone. This type of structural evolution was described by experimental and numeric models (Withjack, 1979; Withjack and Scheiner, 1982).

Analysis of the local diapir system suggests that the evolution of the Red Sea bathyal-zone structures was dependent primarily on the deposition of the thick evaporitic series during the late Miocene. Then in the Plio-Pleistocene continued crustal attenuation contributed to the structural evolution of the northern Red Sea by steepening the thermal gradient and thus increasing ductility of the late Miocene

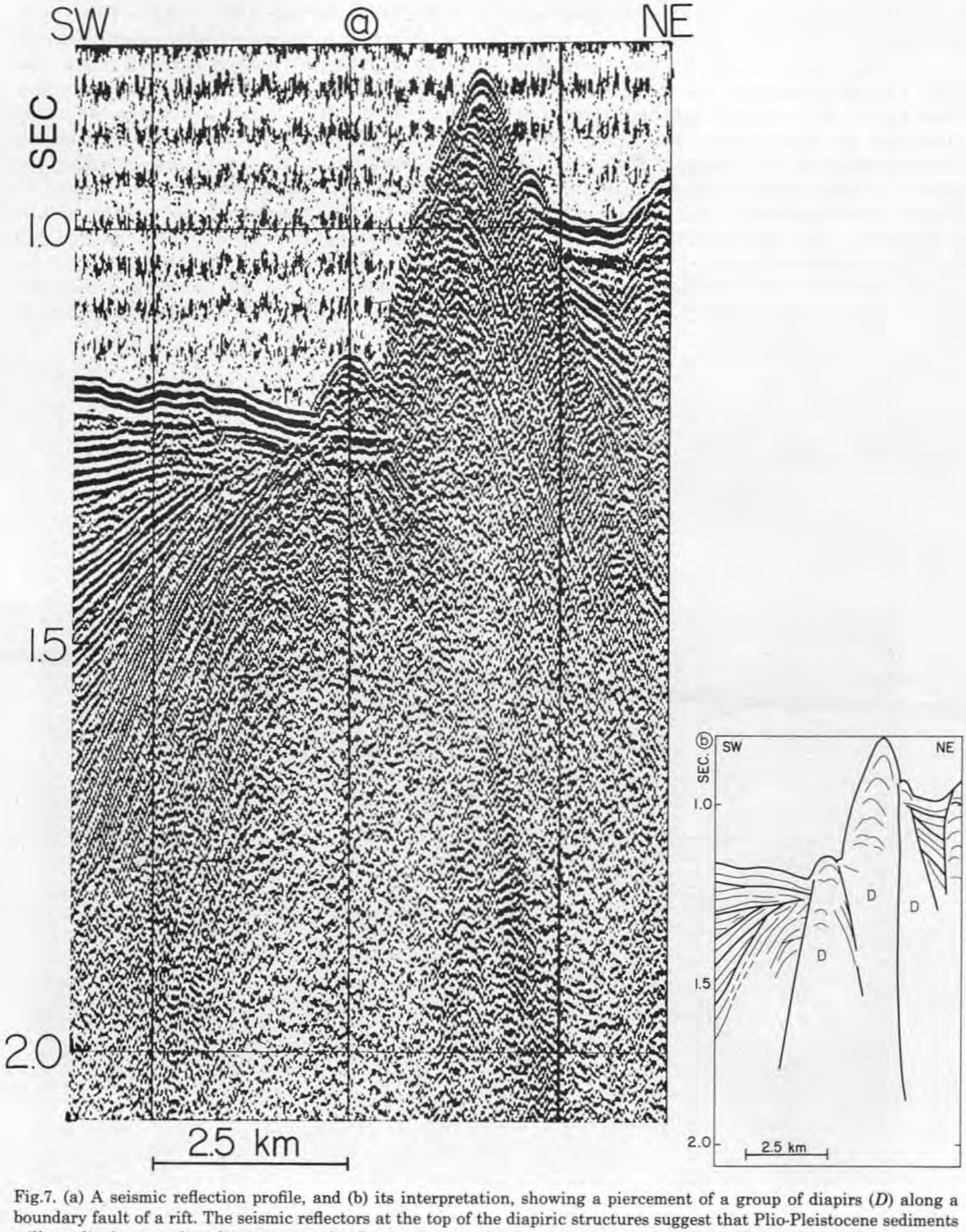
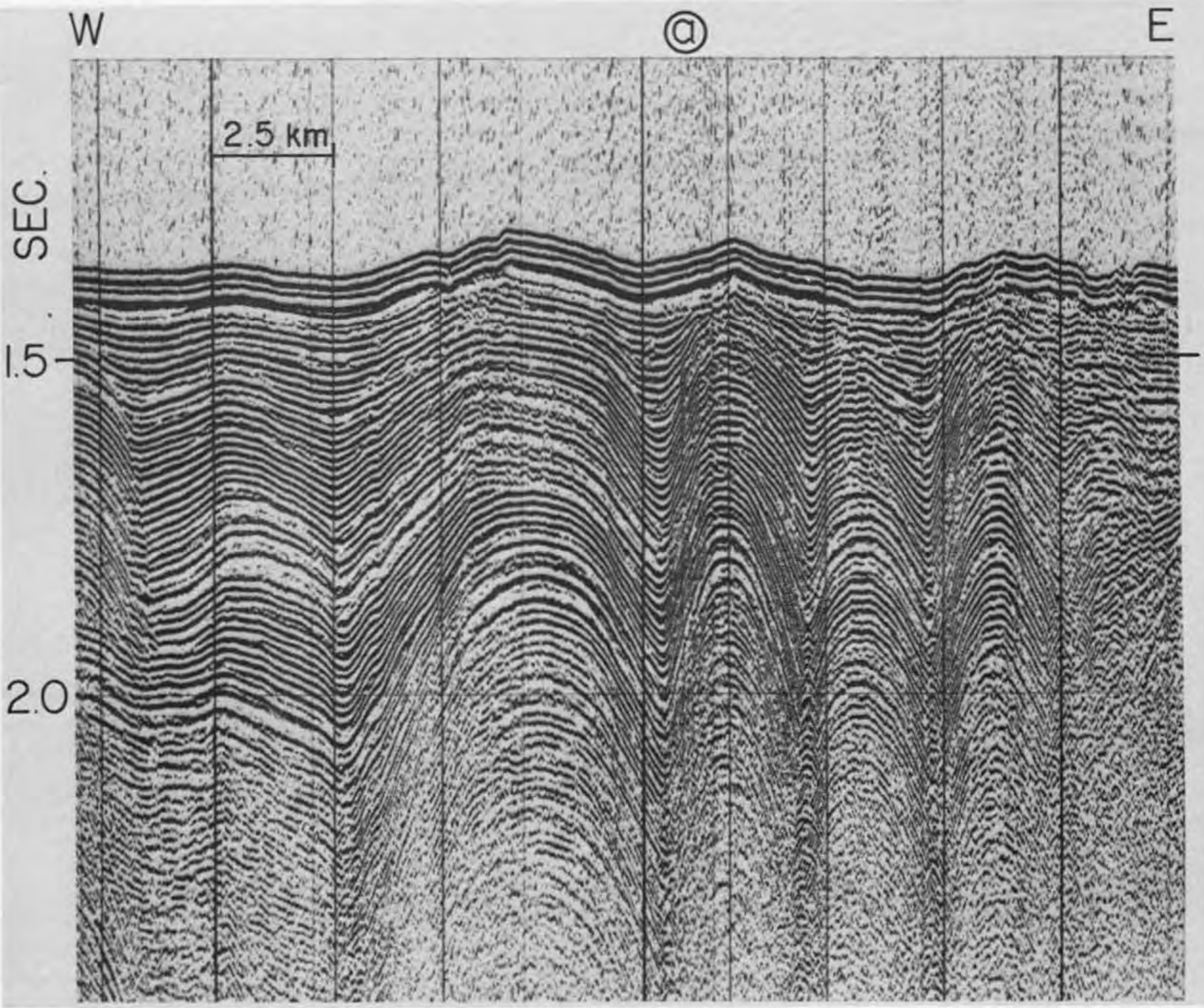


Fig.7. (a) A seismic reflection profile, and (b) its interpretation, showing a piercement of a group of diapirs (D) along a boundary fault of a rift. The seismic reflectors at the top of the diapiric structures suggest that Plio-Pleistocene sediments still overlie the ascending diapir, accounting for the absence of collapse structures. Stratigraphic unconformities, marked by heavy lines in the interpreted profile, suggest changes in the depositional regime, probably due to rifting and diapirism. See Fig.1b for location.

evaporites. Furthermore, the extensional tectonic regime led to the development of a series of rifts in the bathyal zone of the northern Red Sea. The rifts developed in the Plio-Pleistocene, and the late Miocene evaporites were not deposited in them (Mart and Hall, 1984). Sedimentation in the northern Red Sea also played a critical role in the evolution of the diapirs. The thickness of the Plio-Pleistocene sedimentary sequence, which seems to be barely adequate for the densities required for gravity inversion, was an essential step in the process. The average rate of sediment deposition during the last 5 Ma is 0.2 m 1000 yrs^{-1}, which is low compared with the calculated rate of 1.0 m 1000 yrs^{-1} in the Gulf of Elat (Reiss et al., 1980). However, sediment densities higher than 2.8 g cm^{-3} found at depths of 150 m indicate that the lithostatic confining pressure was sufficient to trigger diapirism under the prevailing geothermal and tectonic regimes.

The depicted sequence of events in the structural evolution of the northern Red Sea indicates that the diapiric structures of the region stemmed from late Miocene evaporites. Subsequent to burial under at least 600 m of



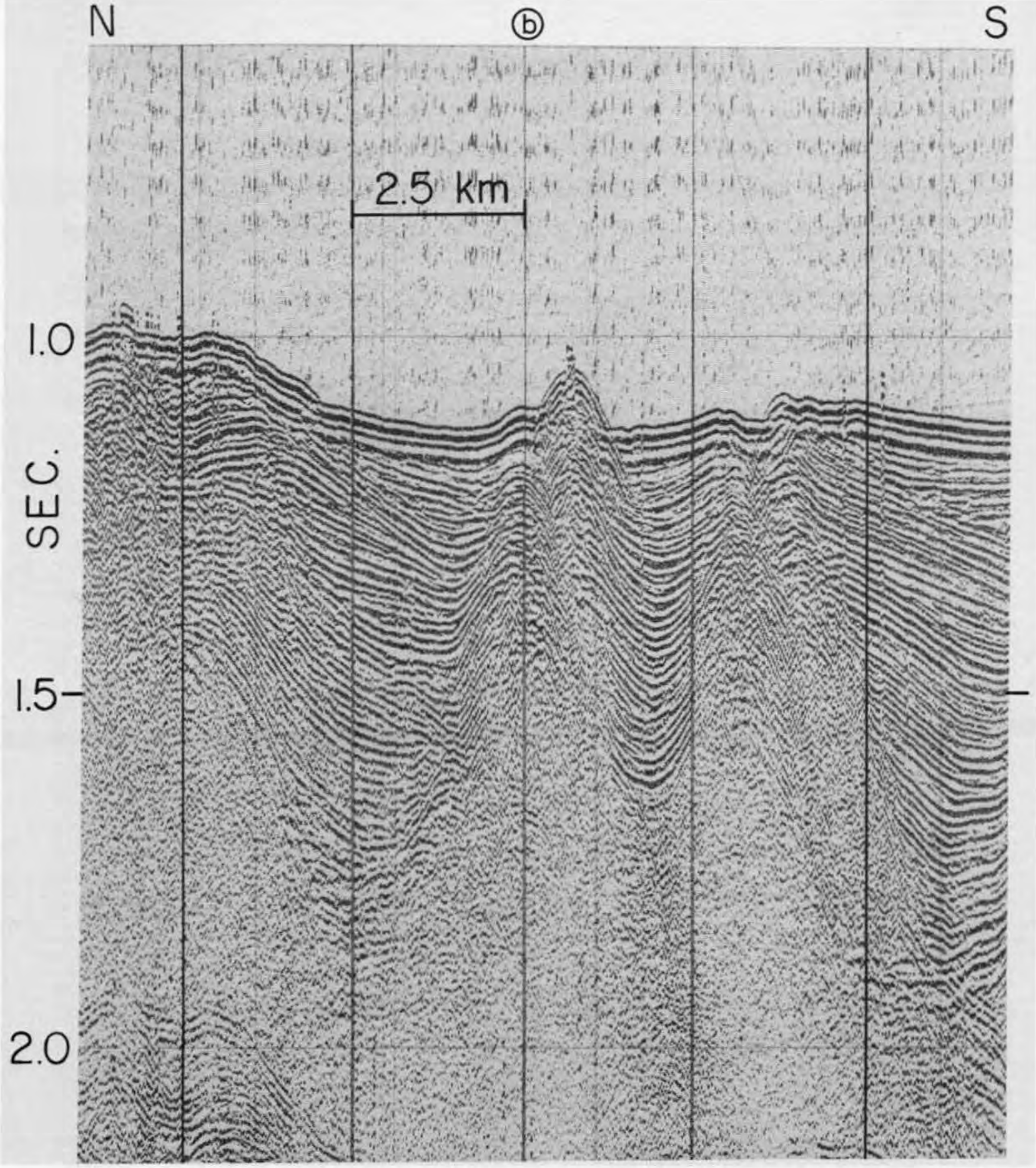


Fig.8. (a) A seismic reflection profile showing a series of anticlines. The flanks of the anticlines dip steeper with the increase in depth, and it is suggested that they represent incipient diapirs. The steeply dipping seismic reflections should not be confused with diffraction effects. (b) A seismic reflection profile showing two adjacent diapirs. The northern one has already pierced its way through the sedimentary cover, but the southern one is still in its incipient stage, upfolding the overlying strata. See Fig.1b for location.

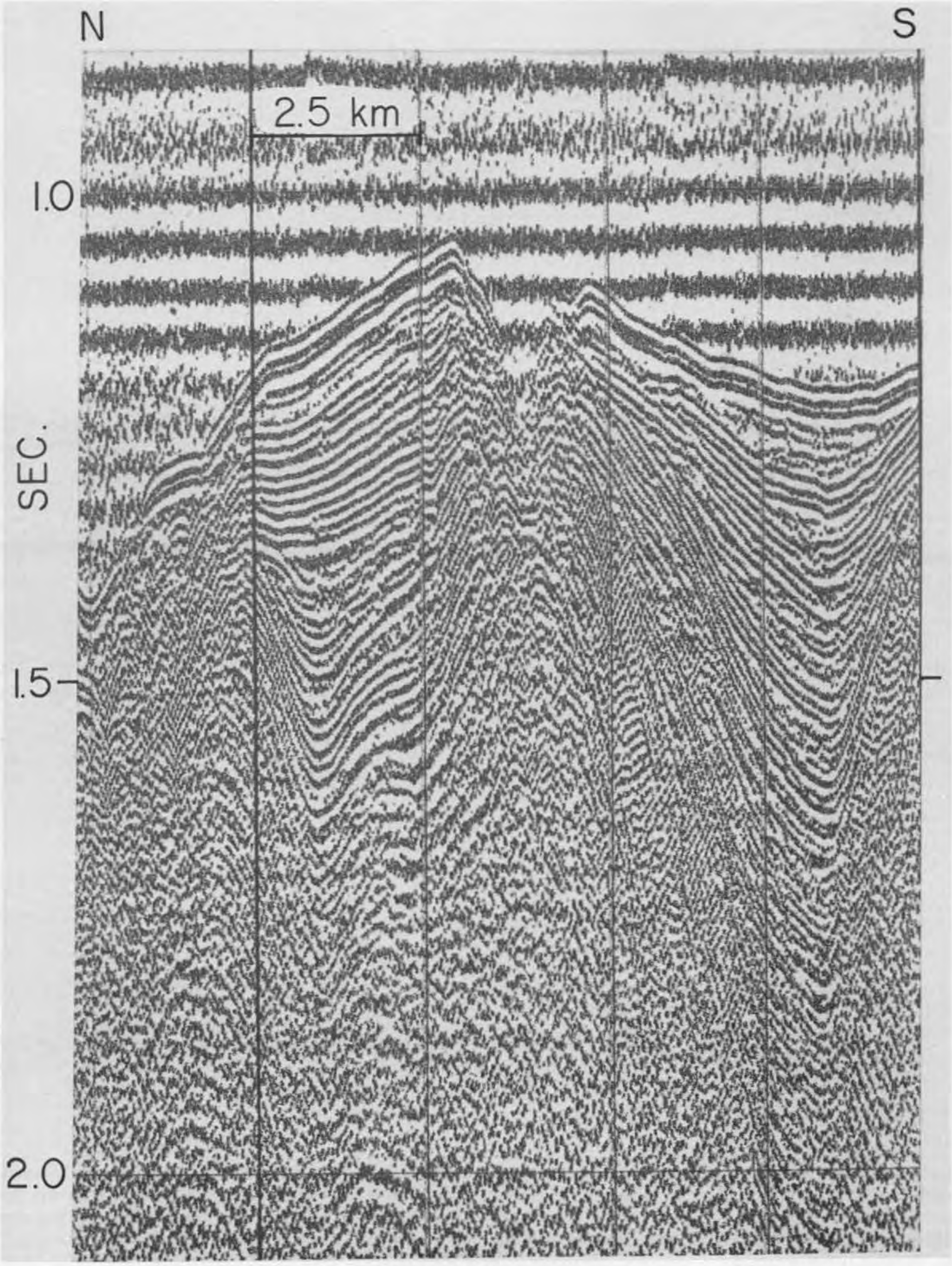


Fig.9. A seismic reflection profile of an ascending diapir that uplifts and breaks the overlying sediments. See Fig.1b for location.

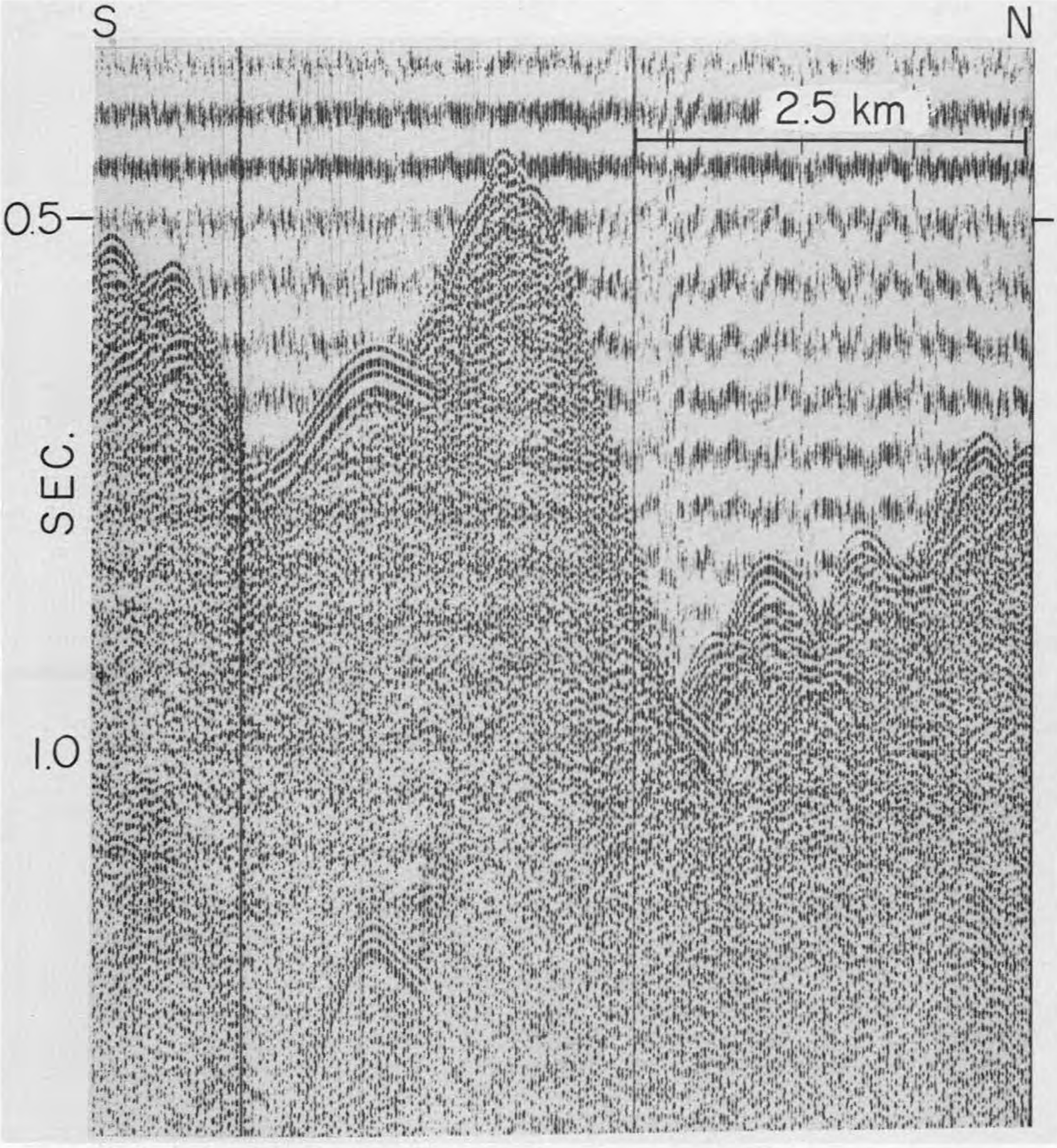
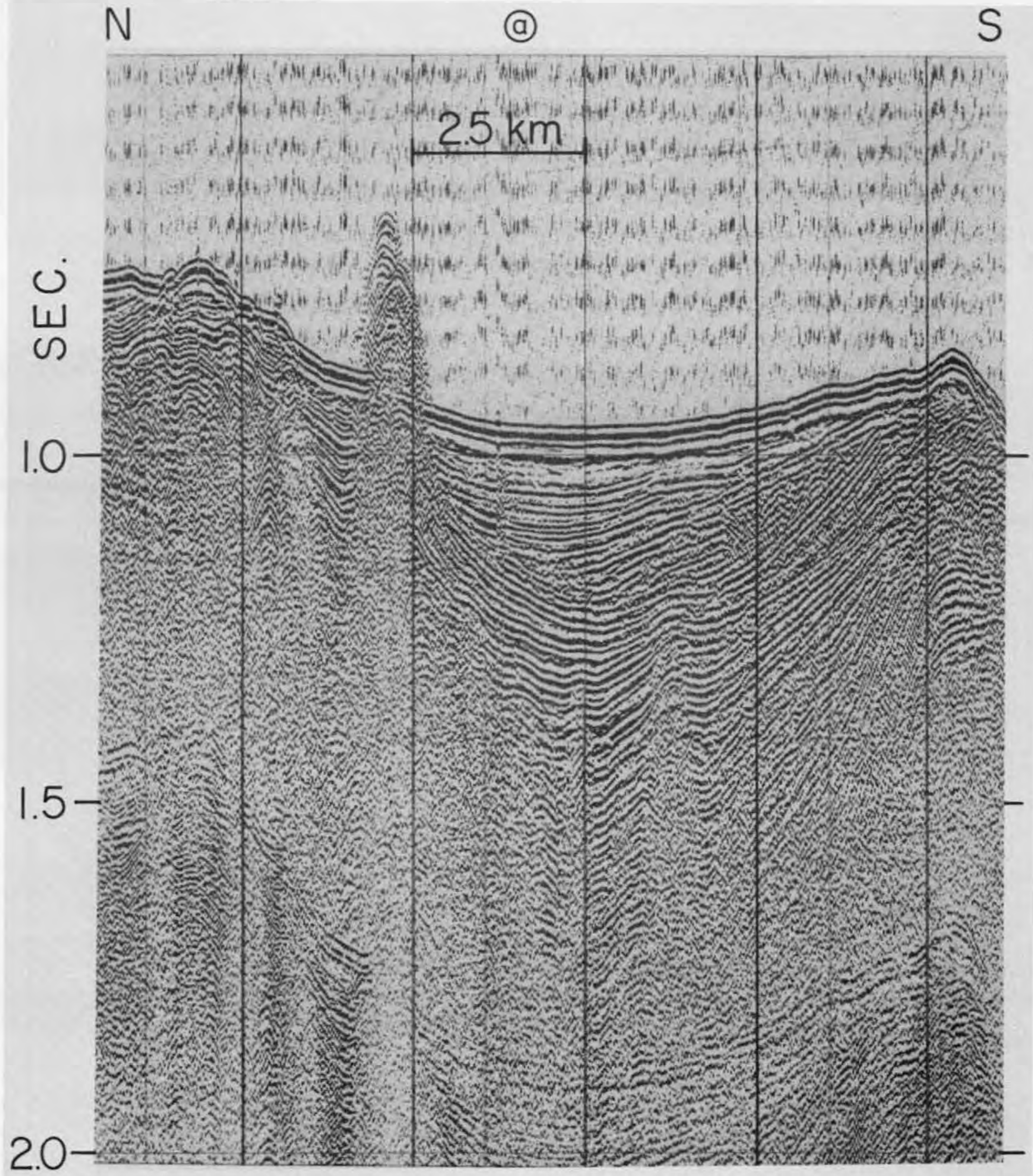


Fig.10. A seismic reflection profile showing multiple diapiric structures in a faulted zone. See Fig.1b for location.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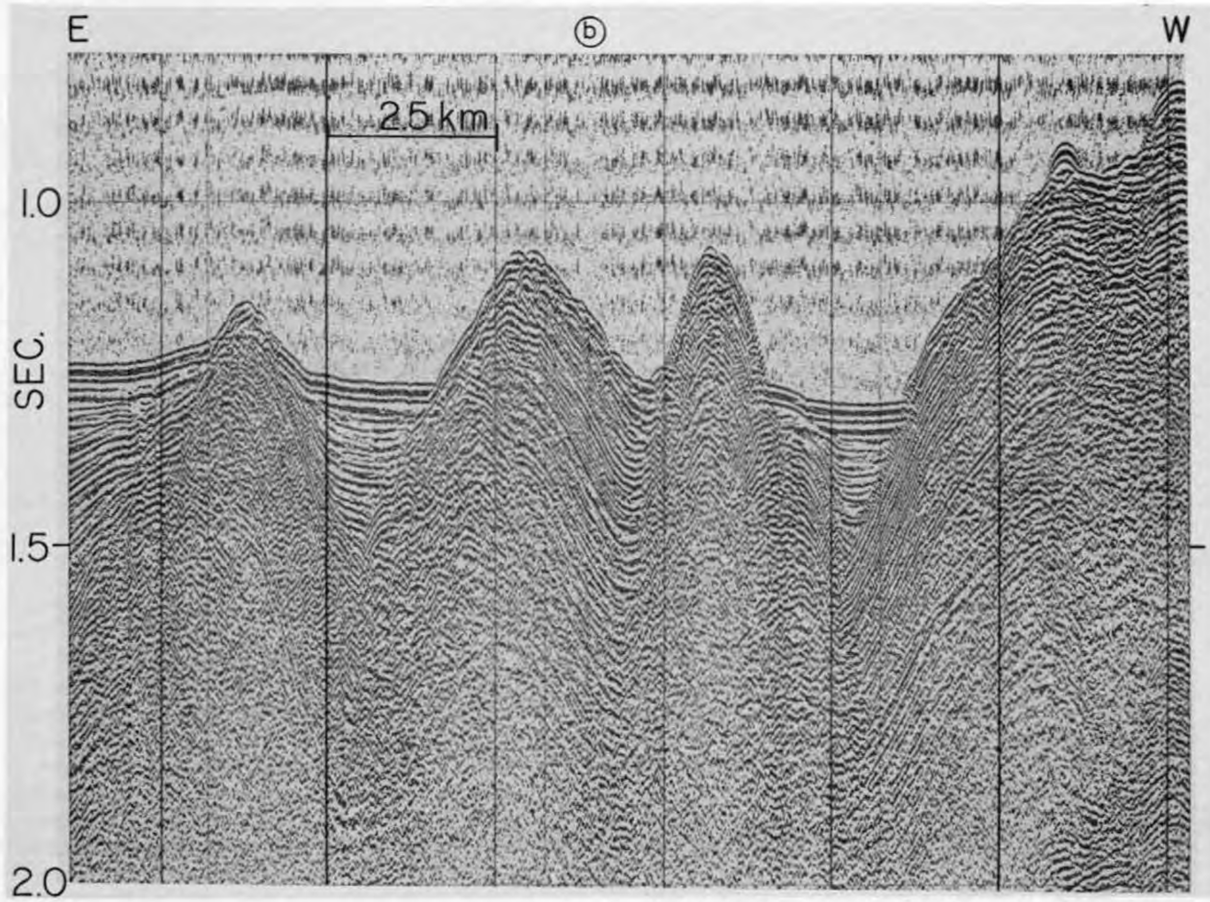

Fig.11. (a) A seismic reflection profile showing a diapiric piercement into a rift floor. (b) A seismic reflection profile showing a series of diapirs that penetrated a rift floor. Note the morphological similarities between these diapirs and the incipient diapirs presented in Fig.8a. See Fig.1b for location.

Plio-Pleistocene sediments, diapiric growth was triggered by high heat-flow and controlled by rifting. There is ground to presume that diapiric terrains along rifted passive continental margins started their evolution under constraints similar to those of the northern Red Sea.

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