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# Transverse faults and segmentation of basins within the Dead Sea Rift

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**Abstract** - The Dead Sea rift is a large transcurrent fault system extending from the Red Sea to Turkey. Several morphotectonic depressions of various sizes exist along its length. Most of them are divided into several sedimentary basins which are in turn divided into smaller units by transverse faults.

Several transerve faults extend beyond the boundaries of the basins into areas which are otherwise unaffected by the rifting activity. In some cases the transverse faults are active at present as strike slip faults. In the Dead Sea area where multichannel seismic profiles are available across several transverse faults, there are indications that some of these faults have changed their mode of activity from normal to strike-slip faults during the evolution of the basins.

The apparent uniform spacing between transverse faults (20-30 km) indicates that their location was, probably, not dictated by the location of oversteps in the en-echelon system of longitudinal faults. Rather, they may have formed to accomodate the internal deformation of the rapidly subsiding basins.

## INTRODUCTION

The Dead Sea rift is a large left-lateral transcurrent fault system extending from the Red Sea to Turkey. Movement along the Dead Sea rift, which is usually considered as a transform fault separating the African (or Sinai) and the Arabian plates, started less than 20 m. y. ago (Steinitz *et al.* 1978, Garfunkel 1981). Since the time of its formation, 105 km of lateral displacement took place along the fault (Freund *et al.* 1970). Similar to other strike-slip fault systems, several sedimentary basins of various sizes exist along its length. These basins, which form morphotectonic depressions are, from north to south, the Hula, Sea of Galilee, Dead Sea, and the Gulf of Elat (Aqaba) (Fig. 1). The basins lie between left-stepping offsets of the left-lateral strike slip system (Dead Sea transform) in the areas of releasing bends.

Various models have been developed to explain the formation of these basins, often referred to as "pull-apart" basins. They include the calculation of the stress field in a homogeneous elastic medium around an overstep in discontinuities (Segall and Pollard 1980), the modeling of the subsidence and thermal history using stretching models (Royden 1985; Pitman and Andrews 1985) and empirical qualitative models based on features observed in several basins (Crowell 1974; Garfunkel 1981; Aydin and Nur 1982; Mann *et al.* 1983).

According to most models, pull-apart basins develop where strike-slip fault segments are arranged in an en-echelon pattern. Either grabens or horsts are formed depending on whether the fault motion has the same or opposite sense as the sense of fault stepping. Thus, right and left strike-slip faults with right and left oversteps, respectively, produce pull apart basins. The basins develop between longitudinal en-echelon strike-slip faults interconnected by transverse diagonal dip slip faults (e.g. Aydin and Nur 1982). In spite of this simple model, numerous difficulties arise in the analysis of full-scale pull-apart basins and especially in the nature of the faulting at their ends.

The larger depressions within the Dead Sea rift are the Gulf of Elat, which is 200 km long, and the Dead Sea, which is over 100 km long. Each of them is divided into several basins which are in turn divided into smaller units. This is also true for the small depressions such as the Sea of Galilee. In this paper we review various geophysical evidence for several of the transverse faults in the Sea of Galilee, Dead Sea and the Gulf of Elat. Our data reveal many details about the mode of deformation and timing of the transverse faulting in the Dead Sea rift. The observed activity of these faults is then compared to existing models for the development of pull-apart basins and its significance to the overall deformation pattern in the Dead Sea rift is discussed.

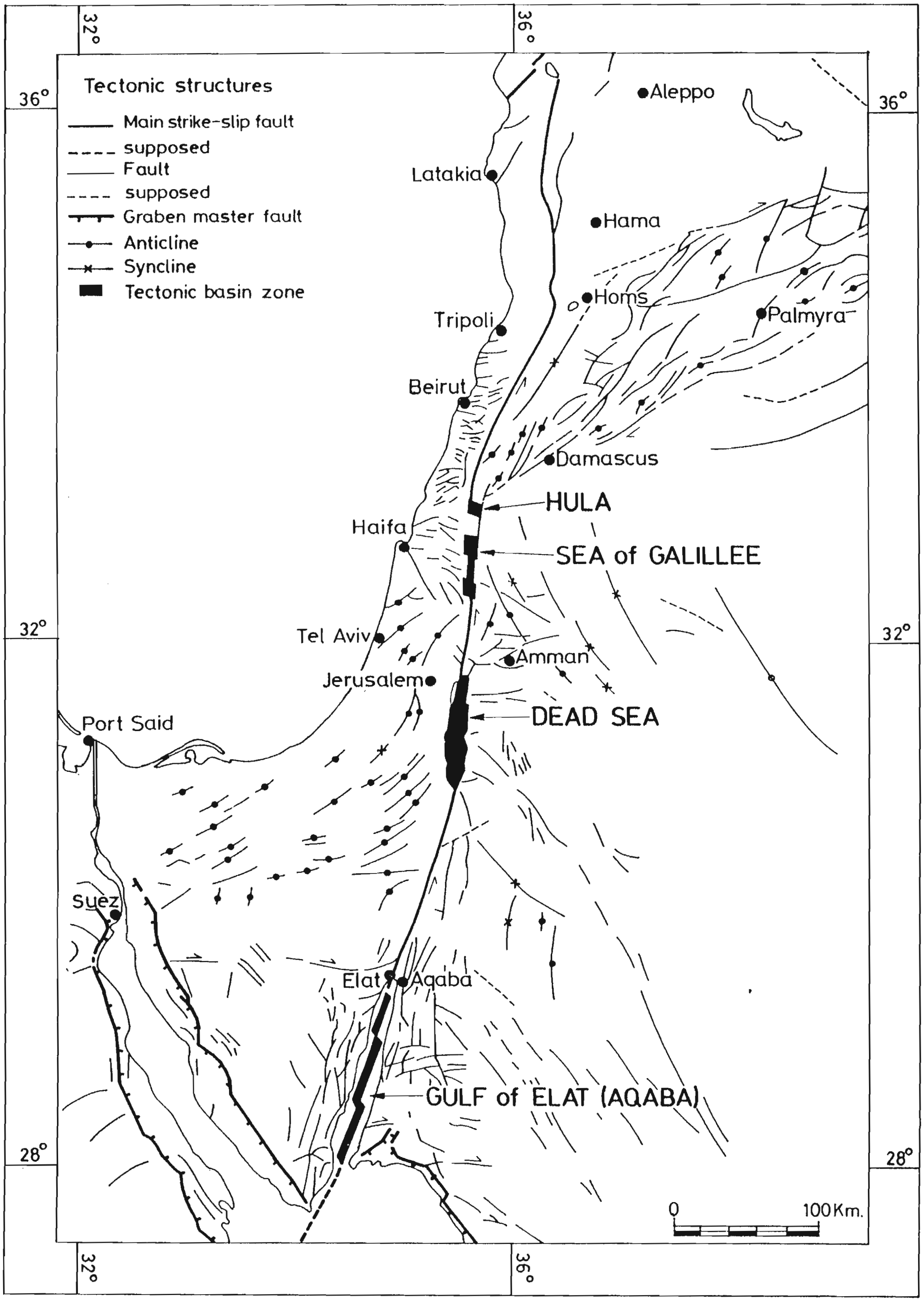



Fig. 1 Location of the pull-apart basins within the Dead Sea transform system (also known as the Dead Sea Rift) (modified from H. - J. Bayer, Applied geology, Karlsruhe University, SFB).

## SEA OF GALILEE

The Sea of Galilee and the plain south of it are located in a depression bounded on the east and west by fault scarps and steep topographic gradients. The geometry of the basins within this depression are the least understood of all of the basins within the Dead Sea rift (Freund 1978). One of the major problems is the location of the transverse boundaries of the Sea of Galilee graben. Freund (1978) assumed that the graben extends to a distance of about 35 km south of the lake itself.

In recent studies two possible transverse fault zones have been mapped. One zone is located within the lake itself. The surface of the lake is about 210 m below MSL; its maximum width about 12 km, and its maximum depth 42 m. Because of the considerable sedimentation rate of 2-7 mm $yr^{-1}$, the floor of the lake is quite smooth. A notable exception is a small WNW - trending bathymetric scarp at depths 13-21 m, in the southern part of the lake (Fig. 2). This scarp could be the surface expression of a fault which extends westwart towards the Galilee.

In a survey of the lake's floor with a shallow penetrating 3.5 kHz seismic system (Ben-Avraham *et al.* 1986) it was found that over most of the lake there is no acoustic penetration in this frequency range because of the high gas content within the top sedimentary layers. However, in several areas excellent acoustic penetration was achieved. The most prominent area is the terrace south of the bathymetric escarpment (Fig. 3). Although the escarpment does not cross the entire width of a lake, the boundary between areas with or without acoustic penetration forms a line which extends across the lake. Clearly, there must be a large difference in the composition of the top sedimentary layers north and south of the escarpment. It had been suggested even prior to the obtaining of the 3.5 kHz profiles that this scarp is the surface expression of a fault (Golani 1962; Ben-Arieh 1965; Neev 1978; Ben-Avraham *et al.* 1981).

Magnetic measurements in the Sea of Galilee and the plain south of it (Ben-Avraham *et al.* 1980; Ginzburg and Ben-Avraham 1986) have indicated the possible existence of another fault (Zemah Fault) about 4 km south of the lake, or 8 km south of the bathymetric escarpment within the lake (Fig. 4). It is associated with a volcanic body. Similar intrusive bodies probably exist in this area along the longitudinal faults.

It is possible that two other sedimentary basins bordered by transverse faults exist south of the Zemah faults. One fault is the northern Beit Shean Fault which is inferred from the gravity map of this area. The existence of these two faults is speculative. Future geophysical studies in these areas should provide information on the possible existence of such transverse faults.

We suggest, then, that the Sea of Galilee depression is divided into several segments which are separated by transverse faults. All four faults described above extend away from the graben westward into the Galilee and the Beit Shean Valley. The northern boundary of the northern basin, which includes the lake itself, is not clearly defined. The geometry of the various basins described in this paper in this area and the nature of the transverse faults need further study.

## DEAD SEA

The Dead Sea basin is located in a deep topographic depression, created by eastern and western longitudinal boundary faults with vertical throws of many hundreds of meters. The basin is 110 km long and is divided into northern and southern sub-basins separated by the Lisan promontory (Fig. 5). This division is reflected by the surficial cover of the sub-basins. The southern basin is subaerial and reaches a maximum depth of about -405 m (the deepest subaerial point on earth), while the northern sub-basin is submerged and the sea floor reaches depths of -730 m. The basin appears to be structurally divided into several segments 20-30 km long each (ten Brink and Ben-Avraham, 1989).

The southern end of the northern basin of the Dead Sea is delimited by a NW-SE striking fault (Neev and Hall 1979), named here the Ein Gedi fault. A 3.5 kHz seismic survey (Ben-Avraham and Beyth 1985) indicates that the recent activity along the fault had a normal sense of motion. This sense of motion is also inferred from the pinching out of some sedimentary layers toward the south (Fig. 6). The Ein Gedi Fault is the most seismically active transverse fault at the present time (Rotstein and Arieh 1986) but no fault plane solutions are available.

An abundance of multichannel seismic (MCS) reflection data in the southern sub-basin helps illuminate the deep structure there (Ginzburg and Kashai 1981; Arbenz 1984; Kashai and Crocker 1987; ten Brink and Ben-Avraham, 1989). The northernmost transverse fault, named here Boqeq fault, shows a combination of «flower» structure and listric faulting which probably soles into Pliocene salt (Fault I, Fig. 7). The Fault's complex nature suggests the possibility of lateral movement (Ben-Avraham *et al.*, in prep.). A system of E-W trending right-lateral strike-slip faults with a maximum offset of 2 km was found on land facing the Boqeq fault (Arkin *et al.* 1981). The Boqeq fault may continue landward into the Massada Graben (Fig. 9).

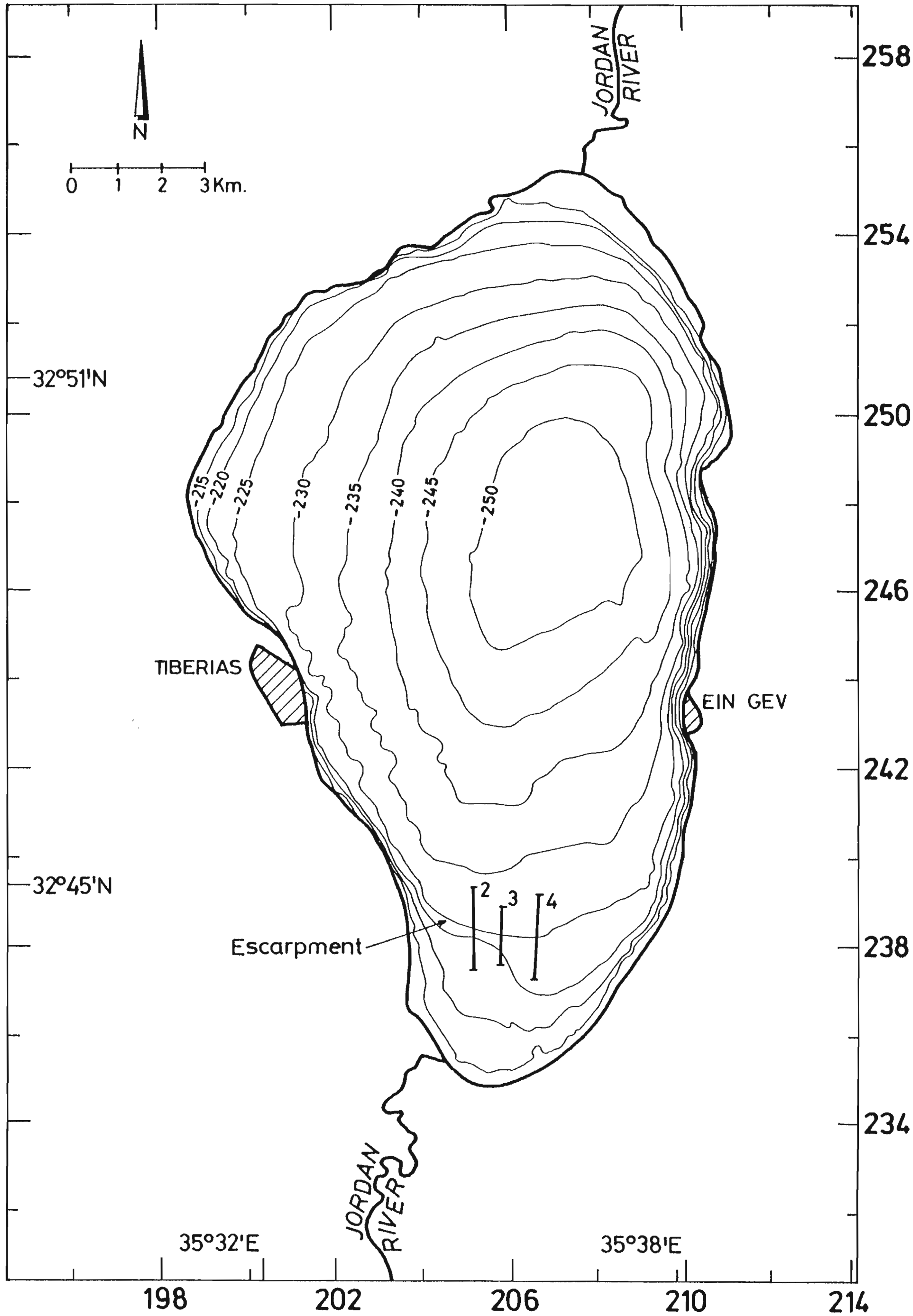



Fig. 2 Bathymetric map of the sea of Galilee (Lake Kinneret) (from Ben-Avraham *et al.* 1986). The positions of seismic profiles 2, 3, 4 in Figure 3 are shown. Israel grid coordinates and geographic coordinates are marked on the margins.

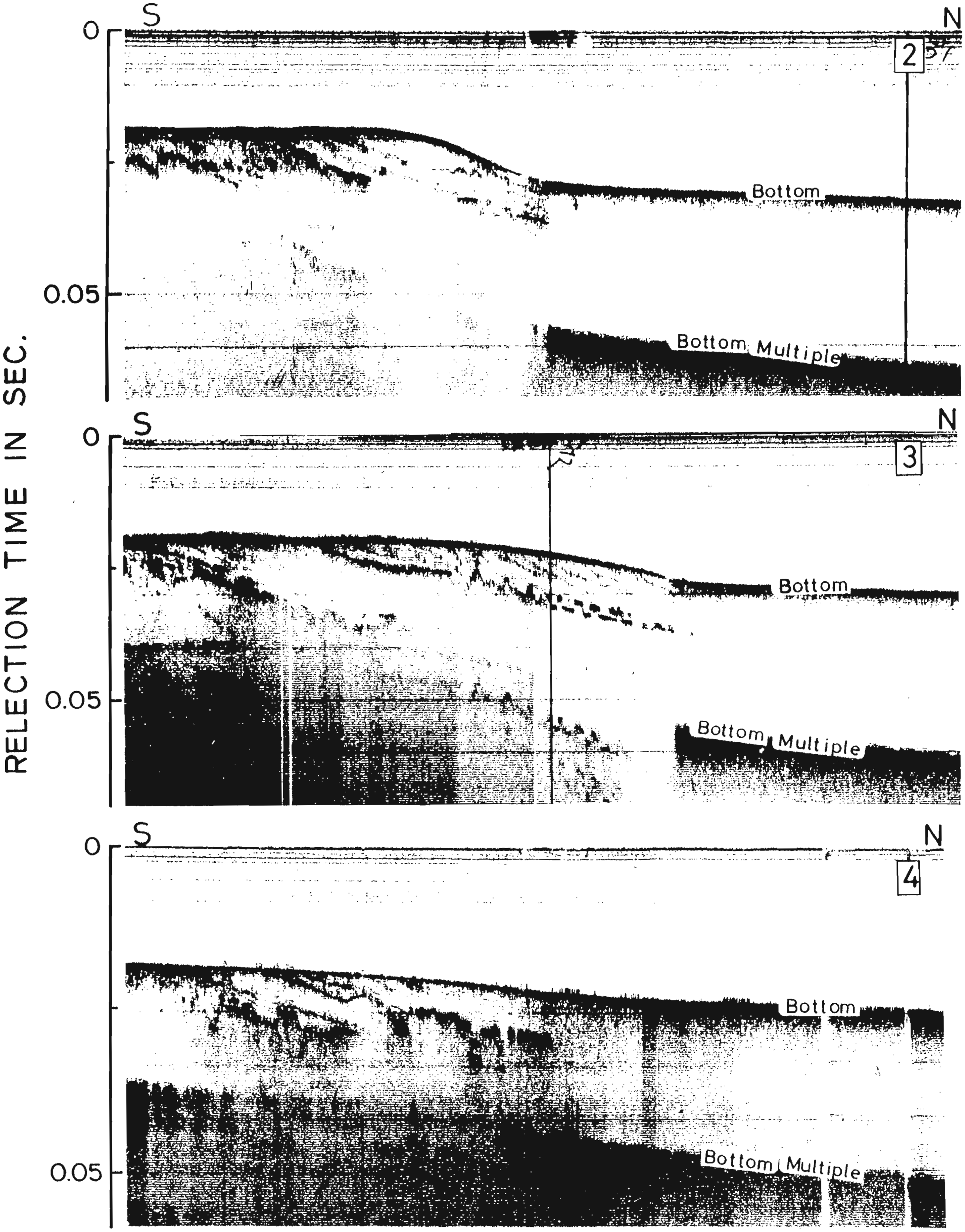
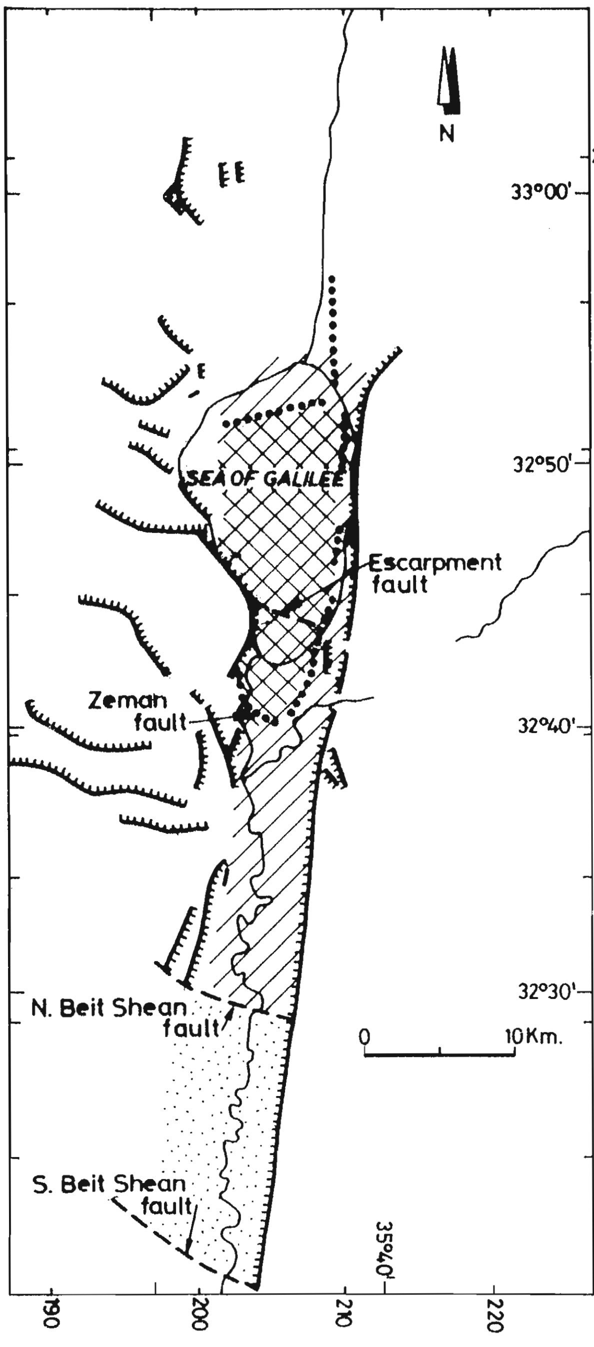



Fig. 3 3.5 kHz seismic profiles in the southern Sea of Galilee (from Ben-Avraham *et al.* 1986). The profiles, oriented N-S, cross a mild bathymetric escarpment which is interpretes as an expression of a transverse fault. Note the change in subsurface reflectivity across the escarpment.



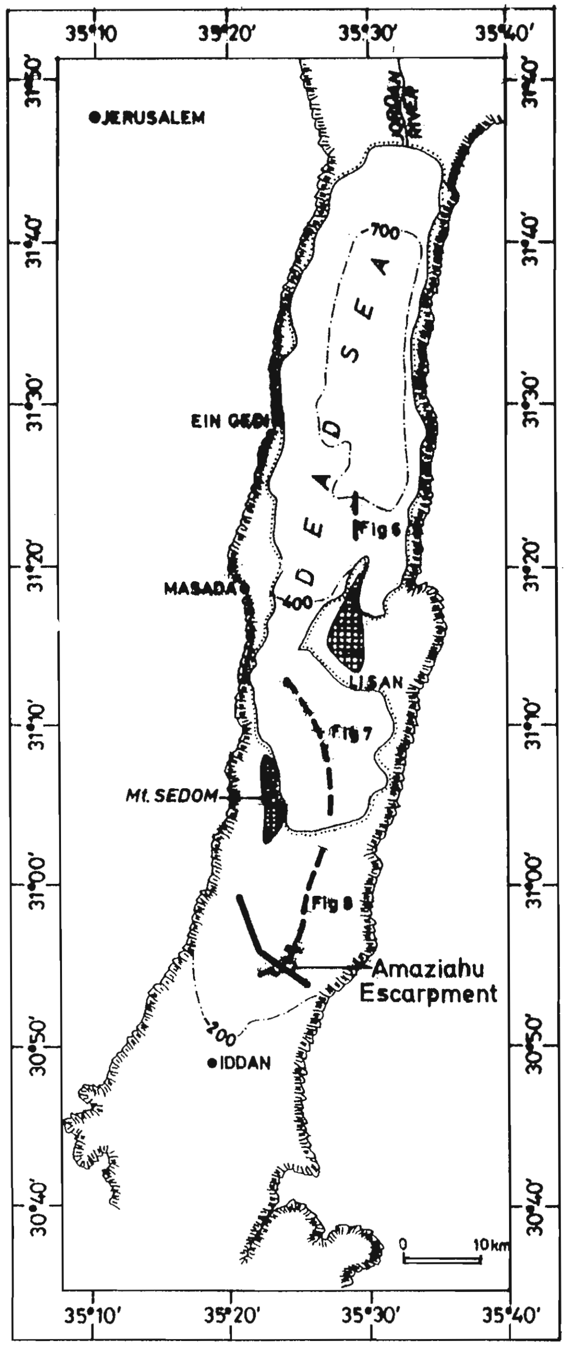
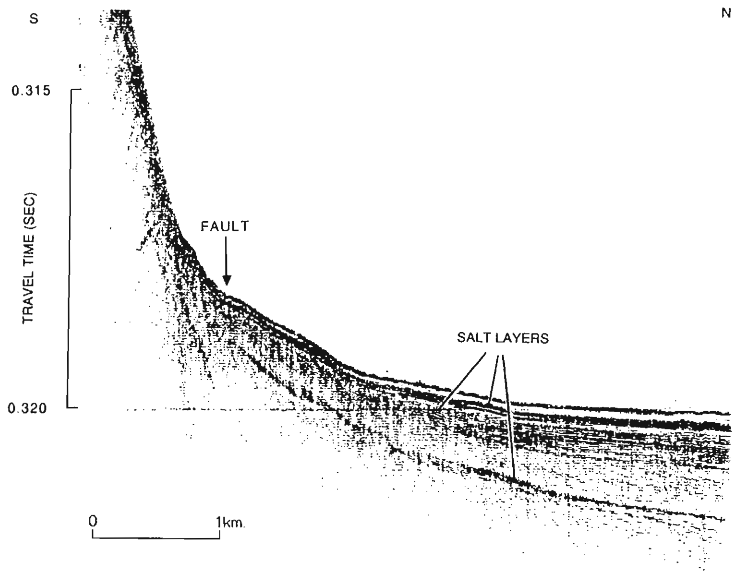




Fig. 4 Map of the Sea of Galilee - Beit Shean basin showing the location of inferred transverse faults. Barbed lines indicate boundary faults and faults outside the basin from Bartov (1973). The cross-hatched area, delimited by dotted lines, mark the extent of the basin according to Freund (1978). We suggest, based on the gravity map, that the basin extends farther south (indicated by the dotted area).

Fig. 5 Location map of the Dead Sea basin. Stippled lines indicate the large (up to several hundred meters) boundary escarpments. Dashed and dotted lines are depth contours below MSL. Thick dashed lines mark (from north to south) the location of seismic lines shown in Figures 6, 7, and 8.



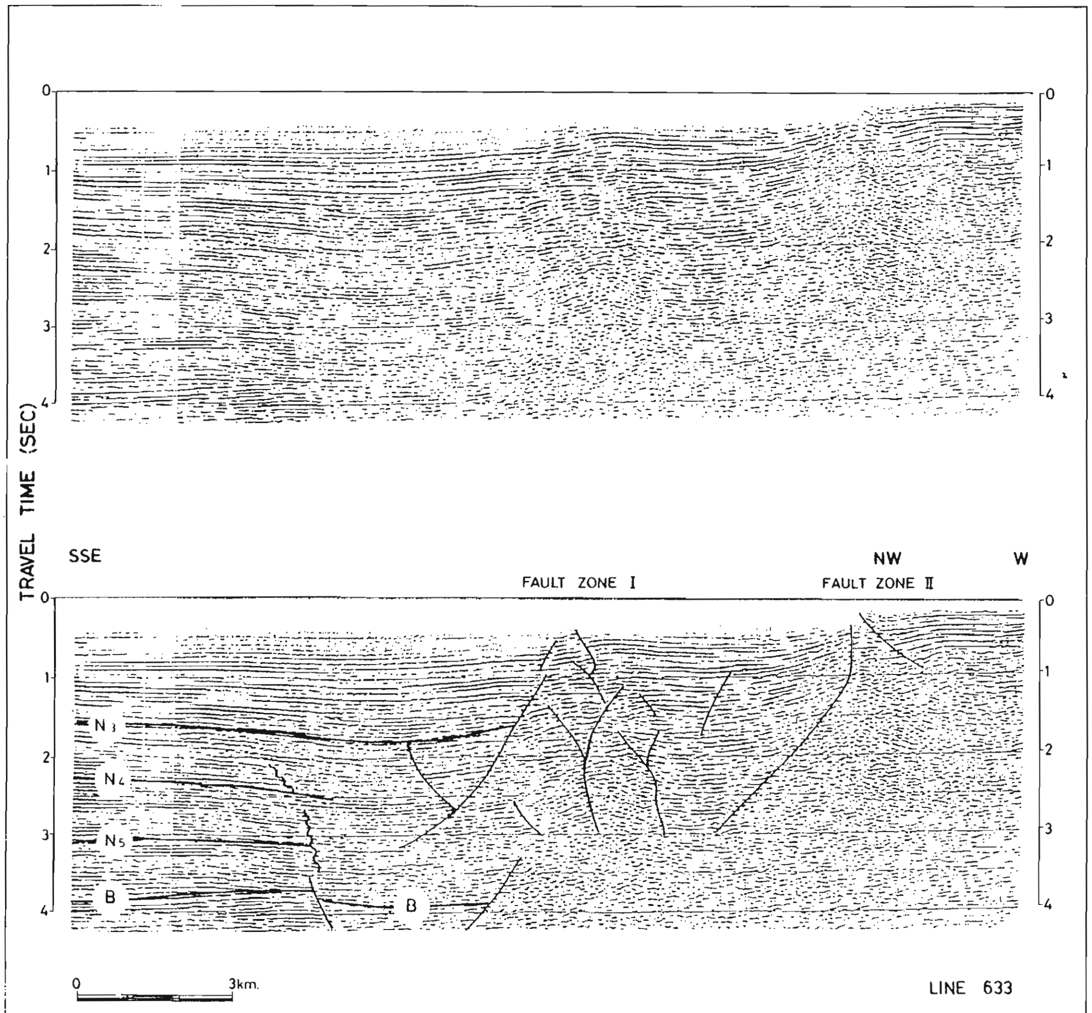




**Fig. 6** A shallow 3.5 kHz seismic profile across Ein Gedi transverse fault north of the Lisan. Note the recent activity with a normal sense of motion on the fault (from Ben-Avraham and Beyth 1985)

**Fig. 7** Multichannel seismic profile across the Boqeq fault zone (Fault zone I). Note the «flower» structure, the slight compressive fold in the upper part of the section, and the lack of simple correlation of reflections across the fault, which indicate a complex (probably lateral shear) movement. Changes in the reflectivity of the lower part of the section and the listric shape of the fault may indicate that normal sense of motion prevailed earlier in the history of the fault (from Ben-Avraham *et al.* in prep.)

The Amaziahu Fault farther south is expressed on the surface as a 50 m high escarpment traversing the Dead Sea Basin. In the subsurface, MCS profiles show a spectacular listric normal fault dipping northward (Fig. 8). This fault zone has probably been active since the early to Middle Pleistocene, and has accomodated an estimated 9 km of north-south extension (ten Brink and Ben-Avraham, 1989).

The southern boundary of the Dead Sea basin is the Iddan transverse fault, which curves and merges at its NW end with the western boundary fault. There may be some evidence for a complex sense of motion on this fault as well, but the predominant motion seem to be normal. Tentative correlation of seismic horizons places the initiation of the fault in the lower Pleistocene (ten Brink and Ben-Avraham, 1989).

The transverse faults described above separate the southern part of the Dead Sea into three roughly equal units, 20-30 km each (Fig. 9). The northern submarine part of the basin is less well mapped, and the location of its northern boundary is unknown. Interpretation of single-channel seismic data (Neev and Hall 1979) may indicate an additional transverse fault breaking the 50-60 km northern long part of the Dead Sea into two units.

## GULF OF ELAT

In the Gulf of Elat (Aqaba), which comprises three large pull-apart basins (Fig. 10) (Ben Avraham *et al.* 1979), the great water depth provides an excellent opportunity to study the internal structure of the basins by marine geophysical techniques. The bathymetry provides much information about the fault pattern in this area and seismic reflection profiles give many details about the nature of faults.

The largest basin in the Gulf is the northern basin (Elat Deep) which is approximately 50 km long and up to 8 km wide. It has a rather flat floor, mostly at water depth of 700 - 900 m. The basin appears to be divided into two separate units at depth (Ben-Avraham *et al.* 1979; Ben-Avraham 1985).

The southern extremity of the Elat Deep was studied in great detail by seismic reflection profiles (Ben - Avraham and Garfunkel 1986). The results of that study show that the southern edge of the Elat Deep consists of a complicated deformed zone which contains several oblique faults (Fig. 11). Most faults in this area are characterized by a dominantly dip-slip offset, although some are strike-slip. Not all faults show evidence of recent activity. Some die out in the shallow sediments, whereas others reach the seafloor and even form bathymetric features where sedimentation is not sufficiently rapid to mask the fault offset. This suggests that the distribution of displacement in the southern boundary of the Elat Deep has changed with time. Another important feature is the widening of the basin at its southern edge.

At the north, the Elat Deep is bordered by a baslatic dyke at the base of the continental slope (Ben-Avraham 1985). This is probably a young dyke since it penetrates the young sediments and protrudes from the seafloor itself. It is probably located along a fault. At this location the Gulf narrows considerably. The fault seems to continue northwestward to the Shlomo Graben on land. North of this transverse fault (Shlomo Fault) another sedimentary basin exists. It includes the northern part of the Gulf of Elat and the southern part of the Arava Valley.

The two other basins which comprise the Gulf of Elat (Aqaba) south of latitude 29°00' , are also divided into distinct units by transverse faults (Fig. 12). Like the northern basin (Elat Deep), the southern basin is also divided into two units (Dakar and Tiran Deeps), each about 20km long. The structure of the central basin (Aragonese and Arnona Deeps) is more complex; it is associated with compressional features and the basin is divided into several units.

## DISCUSSION

Transverse faults are major structural elements in the Dead Sea rift. They define the northern and southern edges of the various basinal areas in the Dead Sea rift and subdivide them into distinct units. The evidence presented above describes several aspects of these faults which were not recognized earlier.

Classical pull-apart models (Freund 1978; Garfunkel 1981) predict that transverse faults develop as a connection between en-echelon faults and that the motion on the transverse faults is normal. Transverse faults within a pull-apart basin were thought to be the relics of the coalescence of several smaller pull-apart basins (Aydin and Nur 1982).

We find that the length of a typical unit within a basin is about 20 km. The two larger basins, the northern basin of the Dead Sea and the Elat Deep in the northern Gulf of Elat are dominated by deep water, 325 m and 900 m respectably, and a flat floor. Each one may, also, be divided into two parts in the subbottom, each about 20 - 30 km long. The uniform length of each unit suggests that transverse faults are related to the deformation process of the crust rather than to the pre-existing configuration of the en-echelon system. They may develop as parts of the basin are rapidly subsiding. If the length to width aspect ratio of this section is too

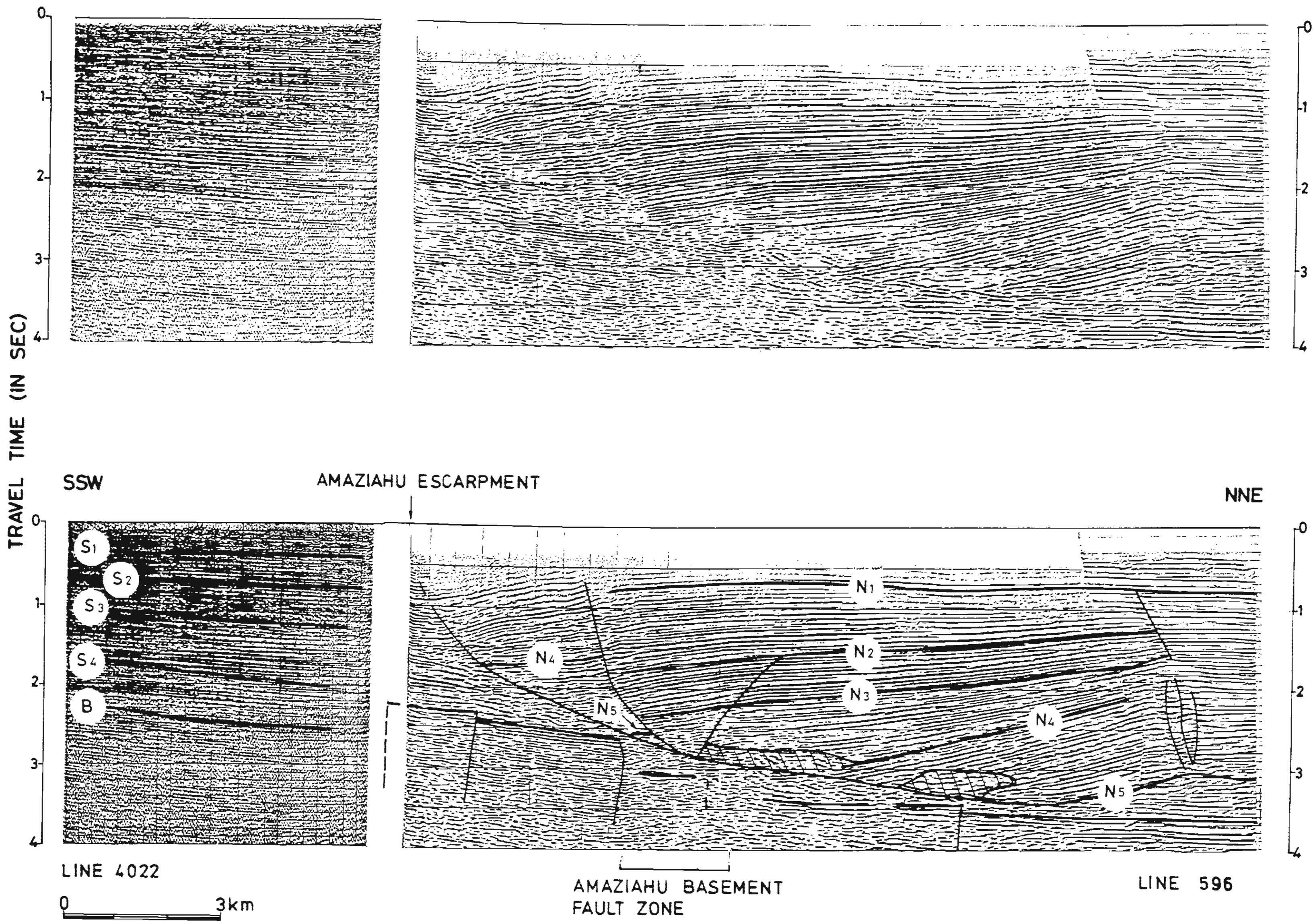



Fig. 8 Amaziahu listric normal fault. The fault soles into a Pliocene salt layer. The amount of extension on the fault is estimated to be about 9 km (from ten Brink and Ben-Avraham, 1989).

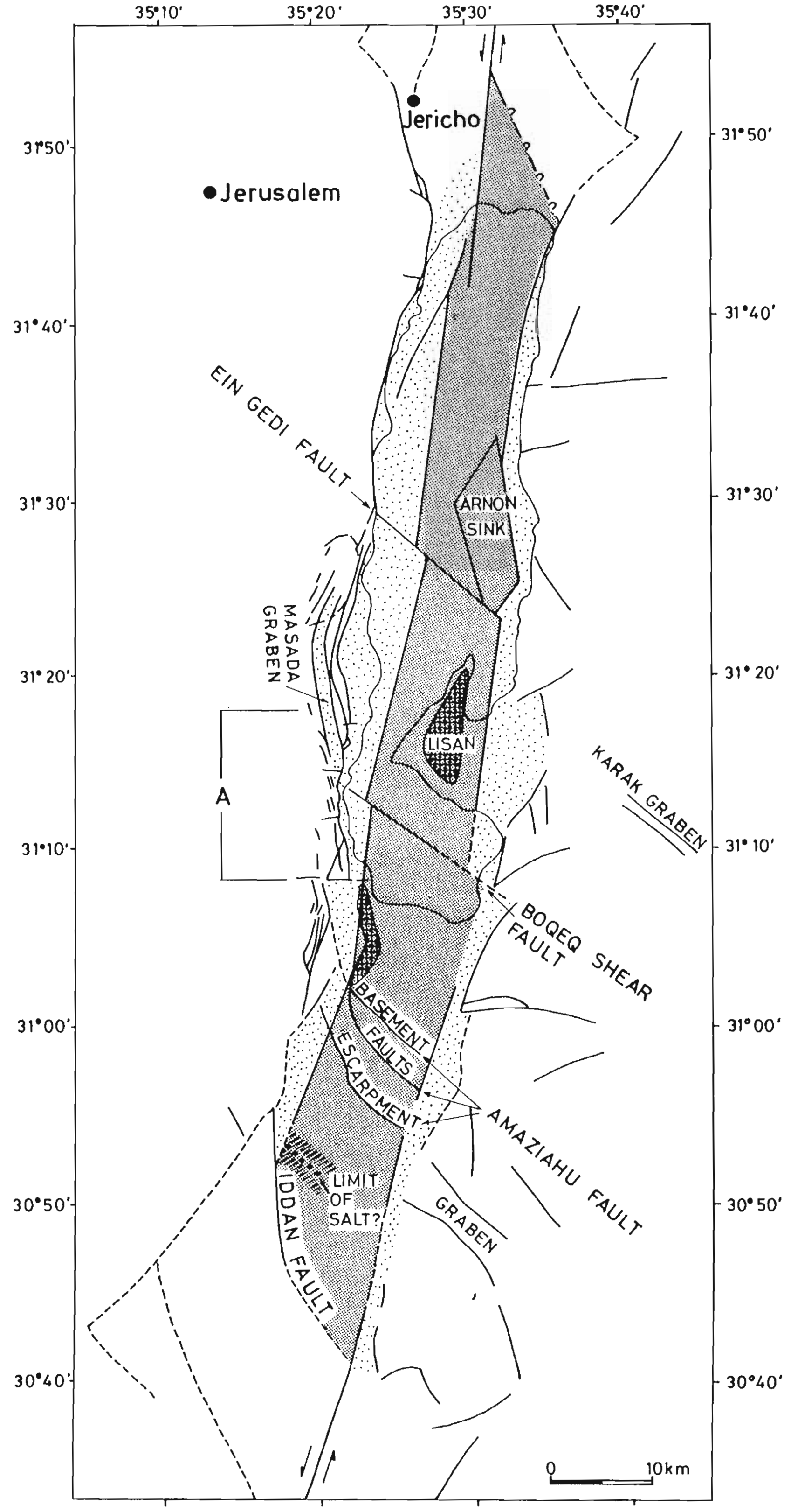



Fig. 9 Map of the proposed internal structure of the Dead Sea basin (from ten Brink and Ben-Avraham, 1989). The basin is divided into 5 units, 20-30 km long, separated by transverse faults. Note the lack of a continious trace of the Dead Sea strike-slip fault system on either side of the basin. It has probably been obliterated by the relative lateral motion of the units. The zone marked by A contains a system of right-lateral strike-slip faults trending E-W (Arkin *et al.* 1981).

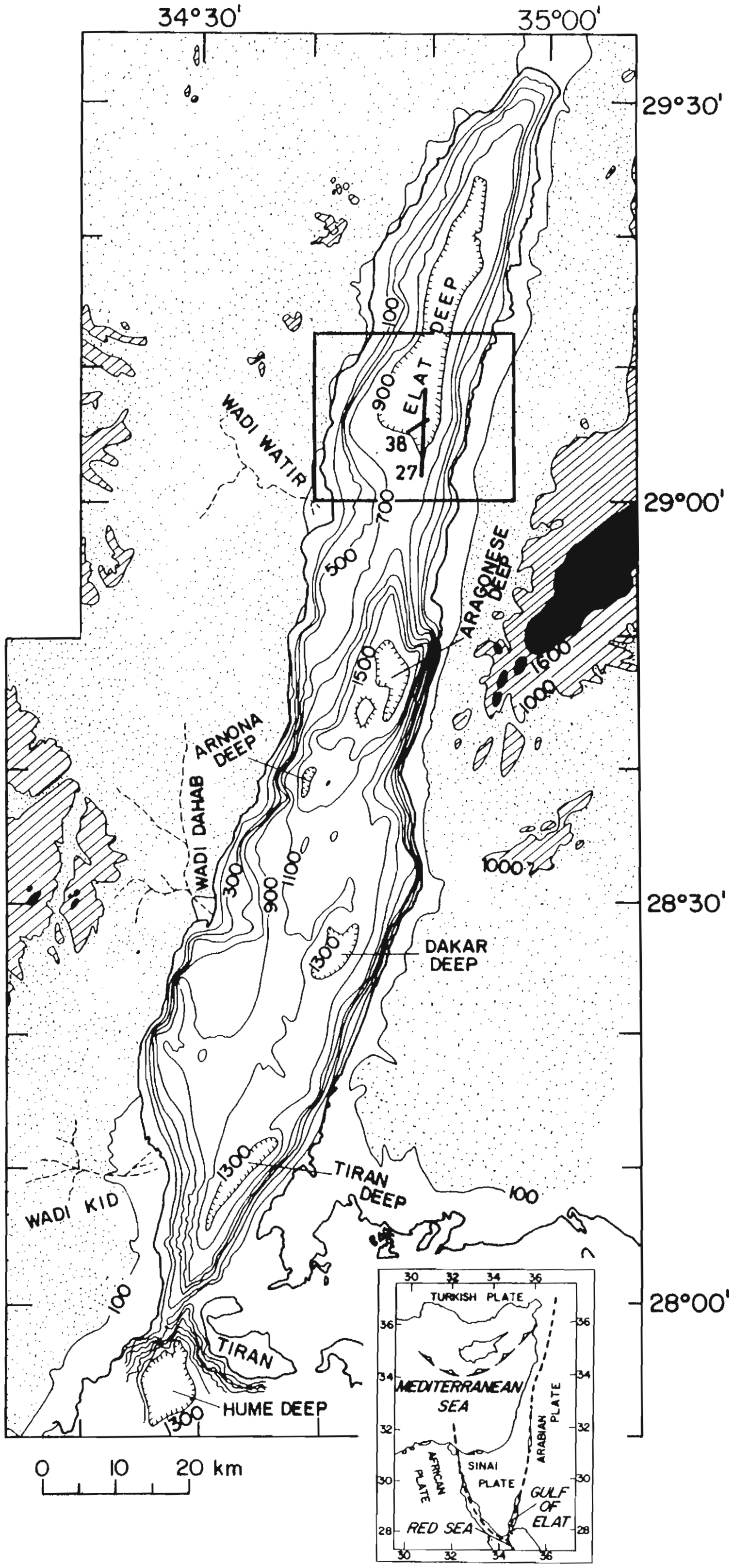



Fig. 10 Bathymetric of the Gulf of Elat (Aqaba) (from Ben-Avraham *et al.* 1979). Contours are in corrected meters with a contour interval of 200 m. The solid lines within the frame mark the location of profiles shown in figure 11.

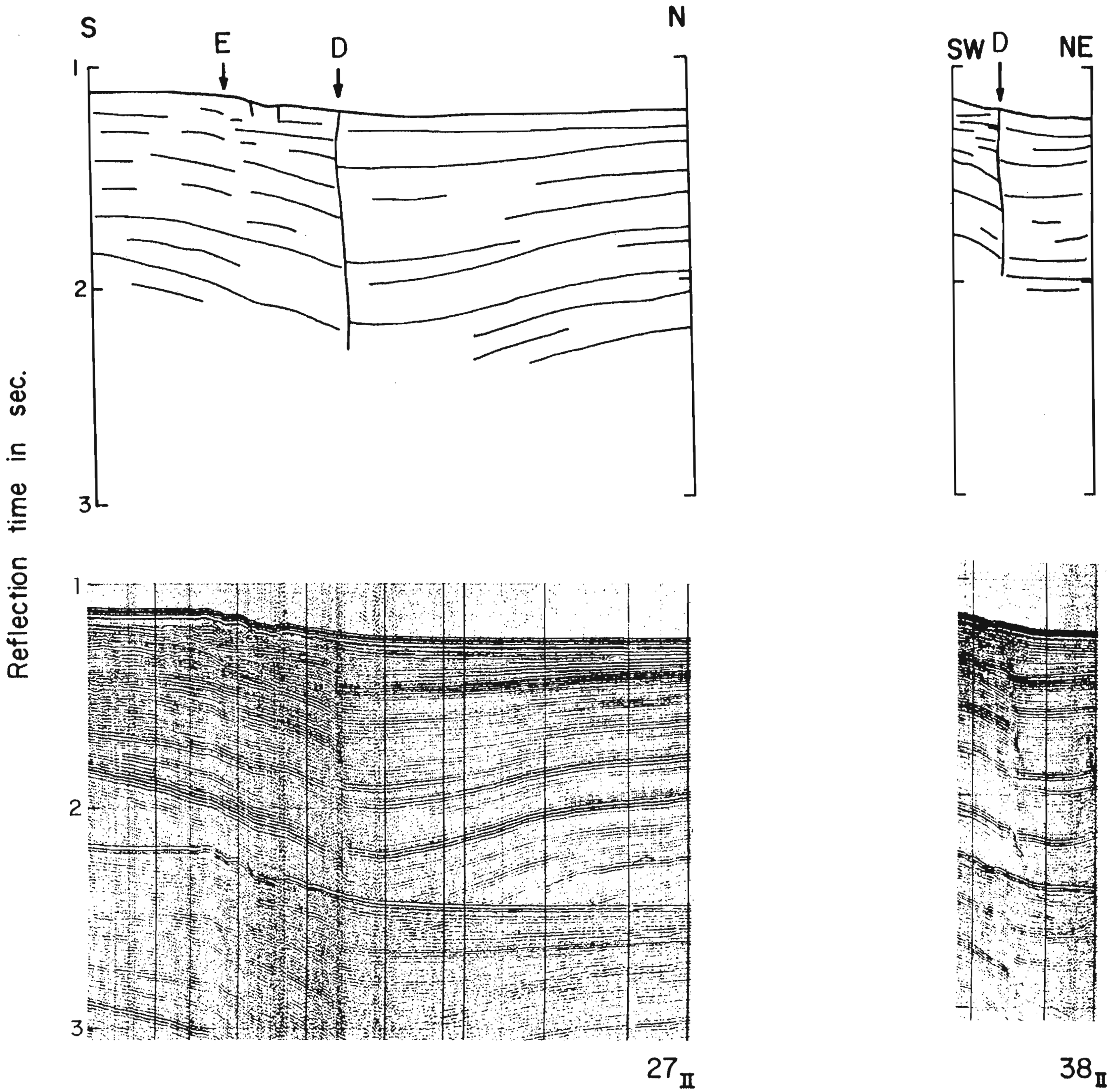



Fig. 11 Continuous single-channel seismic profiles across the southern boundary of the Elat-Deep : bottom-seismic reflection profiles, and top - line drawing interpretation. D marks the location of a transverse border fault showing strike-slip motion. It divides different sequences of subbottom reflectors with no vertical offset of the seafloor (from Ben-Avraham and Garfunkel 1986).

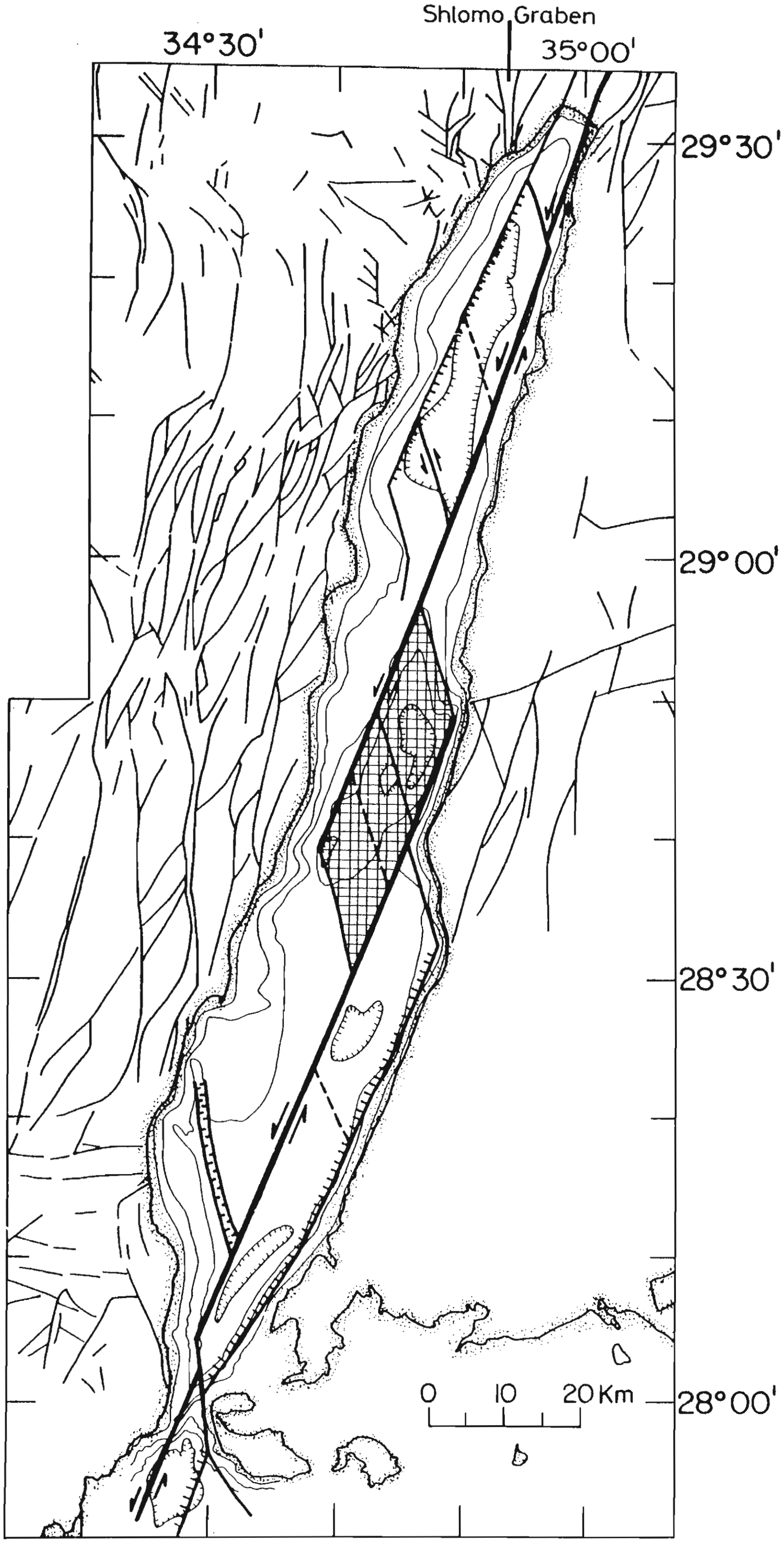



Fig. 12 Generalized model for the structure of the Gulf of Elat (Aqaba). Major inferred strike-slip faults are shown in heavy lines; other faults are shown in medium lines. Normal faults are marked by lines with barbs pointing to the down-thrown side. Also shown is the strike-slip fault at the southern end of Elat Deep (Fig. 11). Faults without barbs or arrows are of unknown nature. Faults on land are shown in fine lines. Note that some faults at sea seem to continue on land (e.g. Shlomo Graben) (from Ben-Avraham 1985).

large, transverse faults will be created. We therefore suggest that transvese faults may be fundamentally related to processes of crustal deformation.

Further support for this suggestion can be seen in other aspects of transverse faults which were presented in this paper. Transverse faults sometimes extend beyond the boundaries of the basins. This is clearly seen in the Sea of Galilee where these faults extend westward into the Galilee. Some of the transverse faults in the Dead Sea area and in the Gulf of Elat also extend westward into the land area.

Several of the transverse faults are active at present as strike-slip faults. In the Dead Sea area some of these faults have changed their mode of activity from normal to strike-slip faults during the evolution of the basins. Similar changes in the nature of the transverse faults may have also occurred elsewhere, but were not documented because of lack of multichannel seismic profiles. This again suggests that transverse faults accomodate the internal deformation of the basin.

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