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Sedimentary and tectonic features in the northwestern Gulf of Elat, Israel

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Abstract

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Sedimentary phenomena and tectonic features in the northern Gulf of Elat were studied at water depths of 50 to 300 m. The study includes bathymetric mapping to a depth of 300 m and diving with a small submersible to 215 m. The bathymetric map displays two sedimentary terraces at depths of 50 to 90 m and 120 to 140 m, a few submarine canyons, a large fault, called here the Elat Fault, and several small faults and slides. The dives with the submersible reveal the nature of the sedimentary cover and the character of the sedimentary terraces. They also permit direct observations of fossil reefs, submarine canyons, the Elat Fault, and other small fractures and faults.

We suggest that the sedimentary terraces represent Late Pleistocene sea level stands. The 50 to 90 m deep terrace probably was formed during stage 3 of the isotopic curve of Shackelton and Opdyke, about 50,000 to 70,000 years B.P., whereas the fossil reef at 120 to 140 m depth is correlated with the climax of the last glacial period, about 18,000 years B.P. The submarine canyons and deltas also developed during the last glacial period. The Elat Fault has been active after the development of the 50 to 90 m depth terrace and probably displaced, in a left-lateral movement, some submarine features by 600 to 800 m.

Introduction

The Gulf of Elat is the southern, active segment of the Dead Sea rift that accommodates about 105 km of left-lateral slip between the Arabian plate and the Sinai-Israel subplate (e.g., Garfunkel et al., 1981). The submarine geology and topography indicate that the deep and narrow shape of the gulf reflects the pattern of long subparallel faults that bound its margins and its internal basins (Ben-Avraham et al., 1979; Ben-Avraham, 1985). The Gulf of Elat is surrounded by arid regions and connected to the Red Sea at its southern end through the narrow Tiran straits. The purpose of this study is to determine whether Pleistocene terraces could be found in the gulf and if they would be faulted as a result of recent tectonics.

A bathymetric map of the northwestern edge of the gulf, southeast of the city of Elat, is presented in Fig. 1. The map covers an area of 2.5 km by 10 km with 150 km of total length of profiles taken for the map. The echosounding was done aboard the R.V. "Arnona", using a Simrad echosounder and a Miniranger navigation system by Motorola. The accuracy of the navigation system was about ± 10 m for most of the area with the exception of some locations for which the accuracy was poorer. The bathymetric map is based on depth profiles with accurate locations.

The submersible "Geo" was designed and built for marine research at shallow depth. It accommodates two crew members, a scientist and a navigator. A small compass mounted outside the pressure cell provides orientations to within ±10°

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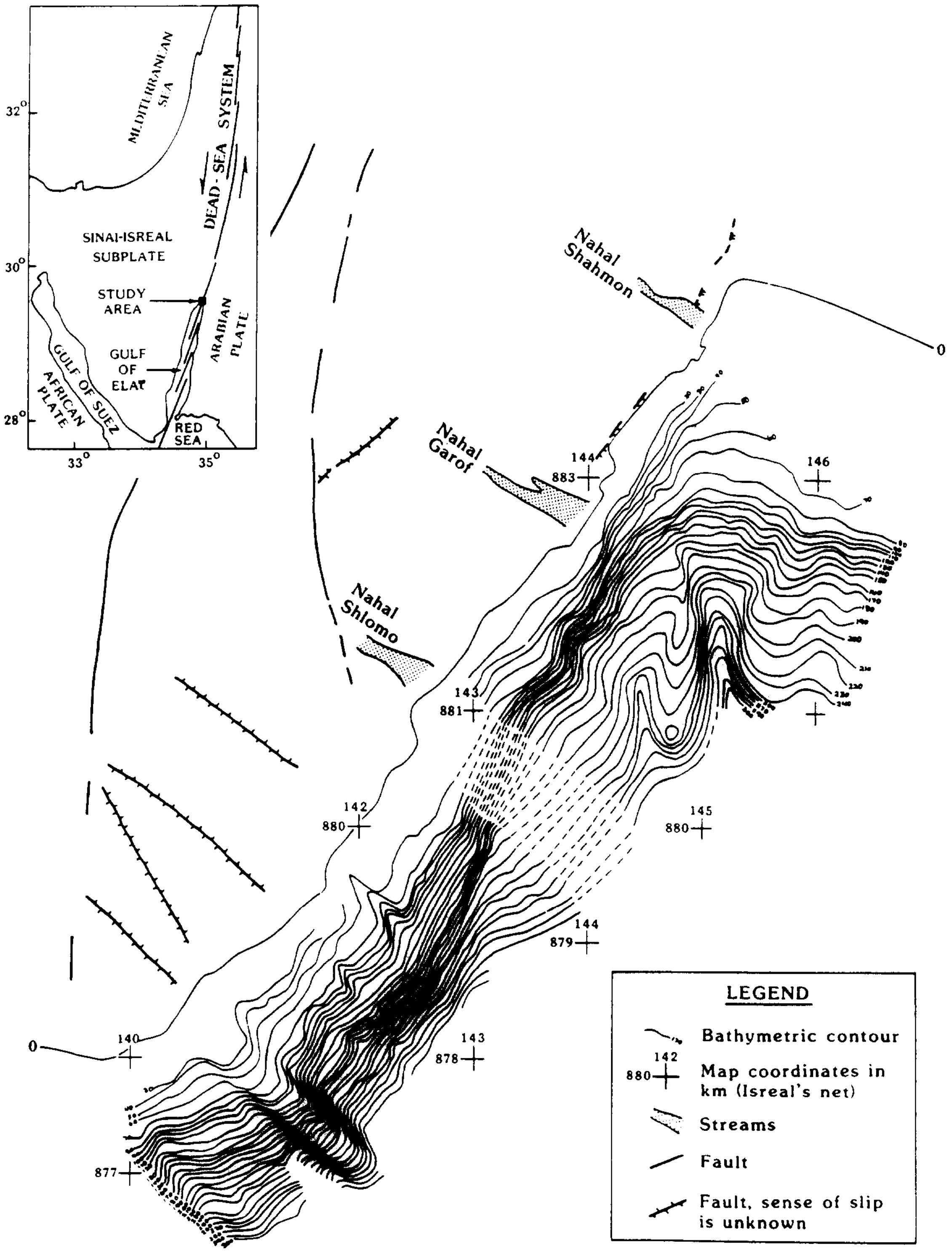

Fig. 1. The bathymetric map of the northern end of the Gulf of Elat. Topographic contours are at 10-m vertical intervals. On land faults and streams are after Garfunkel (1970). Location map after Garfunkel et al. (1981).

accuracy. The maximum diving depth is 215 m, which is slightly below the photic zone in the Gulf of Elat. The "Geo" can stay under water for 3 to 6 hours. Because the electric motors are relatively weak, the "Geo" cannot run against the strong currents in the study area. Photography is possible at all depths, but it is limited to distances of about 2 m in the deeper areas. Due to the lack of a distance measuring device, the dimensions of underwater features can only be estimated. Absolute depths, on the other hand, are measured to within ±1 m accuracy; thus, vertical locations and terrace heights are accurate.

We will first describe the main zones observed on the map, then outline and discuss the sedimentary processes indicated. Finally, we will present the tectonic features and discuss their implications.

The sea-bottom topography

The bathymetric map of the survey area displays the bottom topography from 40 to 300 m in contour intervals of 10 m (Fig. 1). Five zones are distinguished (Fig. 2):

Zone *A* includes the shallow strip to a depth of about 50 m. It is characterized by irregular relief, controlled by recent hermatypic corals forming patch reefs and coral carpets.

Zone *B*, between about 50 m and 100 m in depth, extends south of coordinate 143 (Fig. 2). It is characterized by relatively gentle slopes of about 5° bordered by a small cliff on the eastern side.

Zone *C*, between 100 to 300 m deep in the south and 50 to 150 m deep in the north (again, coordinate 143 separates the two regions). The slopes in this zone are 25° to 30°, perhaps even steeper locally.

Zone *D*, from 150 m deep to the survey depth limit, is characterized by gentle slopes and is crossed by channels and canyons.

Zone *E* includes gentle slopes of a few degrees down to a depth of 120 m similar to zone *B* but without the small cliffs found in *B*.

The bathymetric map allows recognition of sedimentary terraces, canyons, faults and slides (Fig. 3). The fast rate of sedimentation in the Gulf of Elat (e.g., Reiss and Hottinger, 1984), particularly in its shallow portions, causes a rapid obliteration even of prominent topographical features. Therefore, structures that maintain their distinctive appearance are either active or large.

Observations on sedimentary processes

The direct observations of terraces, sediments and biogenic activity made during the dives are essential for the interpretation of the local processes. These observations are summarized below for the vertical zonation and lateral variations. Diving tracks are shown in Fig. 2.

The vertical zonation

Our main observations from the northern end of the Gulf of Elat are presented in the vertical profile shown in Fig. 4A. This profile is based primarily on dives 206 and 207 because these dives provide a general picture for the entire survey area.

The uppermost part of the water column to a depth of about 10 m and to a distance of about 80 m from the coast, is dominated by the live, recent coral reef. This is a typical fringing reef which includes the littoral zone and is characterized by beach rocks, a 30 m wide lagoon, and the main reef (Erez, 1972; Erez and Gill, 1977). The latter is composed of a back reef and a fore reef and forms a seaward facing cliff which is up to 5 m high.

A relatively steep slope (17°), extends below the reef to a depth of 40 to 50 m. Reef knolls are distributed over this slope, stony corals become less abundant, and soft corals, Bryozoa, Hydrozoa and various Algae, become more abundant (Fig. 5A). Locally, however, stony corals may still form a low continuous cover to a maximum depth of 80 m, where they completely disappear.

The zone between 60 to 90 m depth, and 550 to 800 m east of the coast, forms a gentle topographic terrace (Fig. 5B). The upper part of the terrace is covered by brown algae and intensively bioturbated calcareous sand (Fig. 5b). This sand cover may reach a few meters in thickness (Z. Ben-Avraham, pers. commun., 1985). The terrace terminates seaward in a steep cliff-like slope a few meters high, which is locally composed of sub-

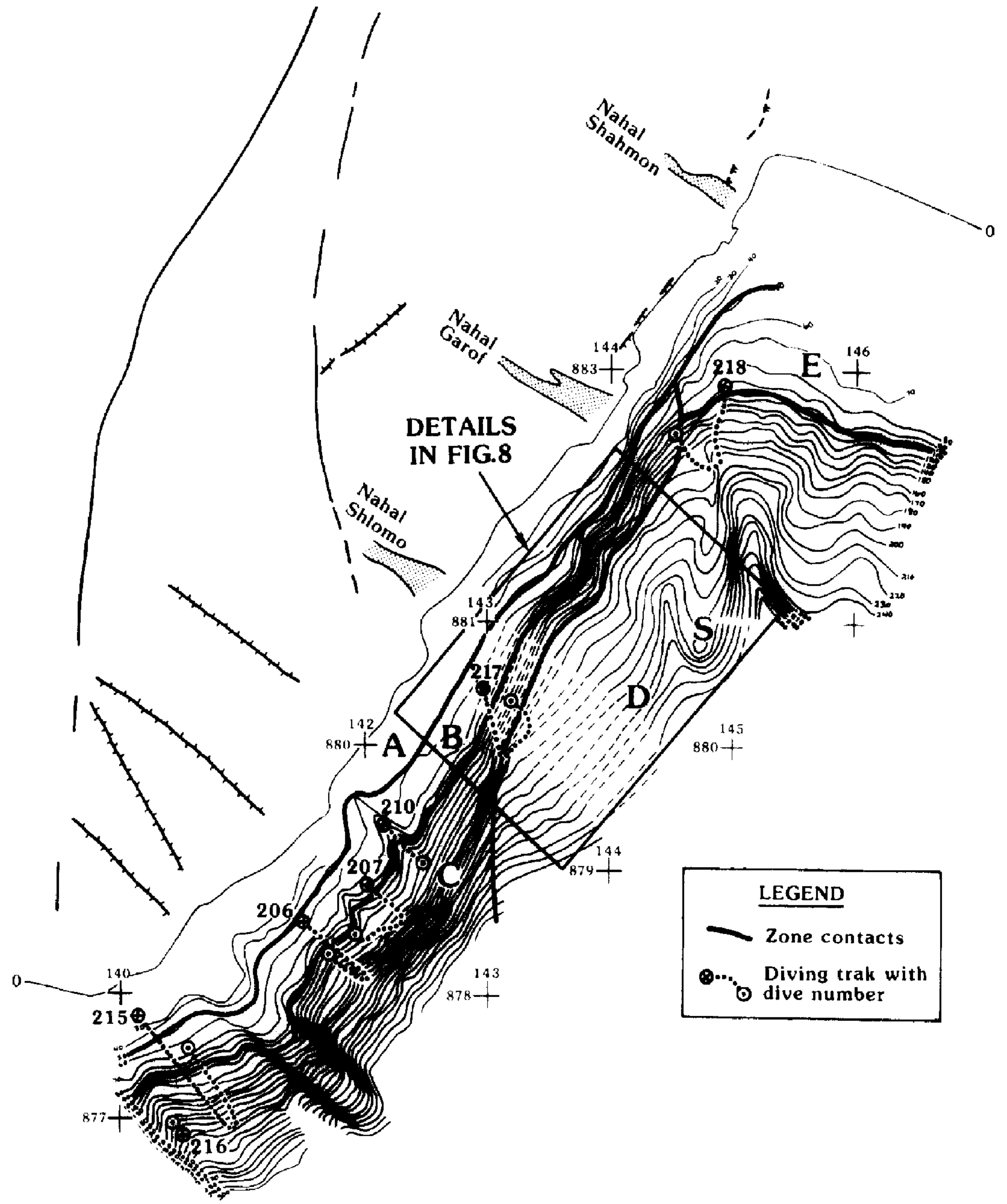

Fig. 2. The division of the study area into five zones according to bathymetric features (see text). The dive tracks are marked in heavy lines.

horizontal rows of biogenic rocks (Figs. 5C, D). The 60 to 90 m deep terrace was found in almost all profiles of the present survey, as well as in the Sharm-e-Sheih area and Ras Burka (Fricke and Schuhmacher, 1983; Reiss and Hottinger, 1984).

A steep slope (14°) with local subhorizontal

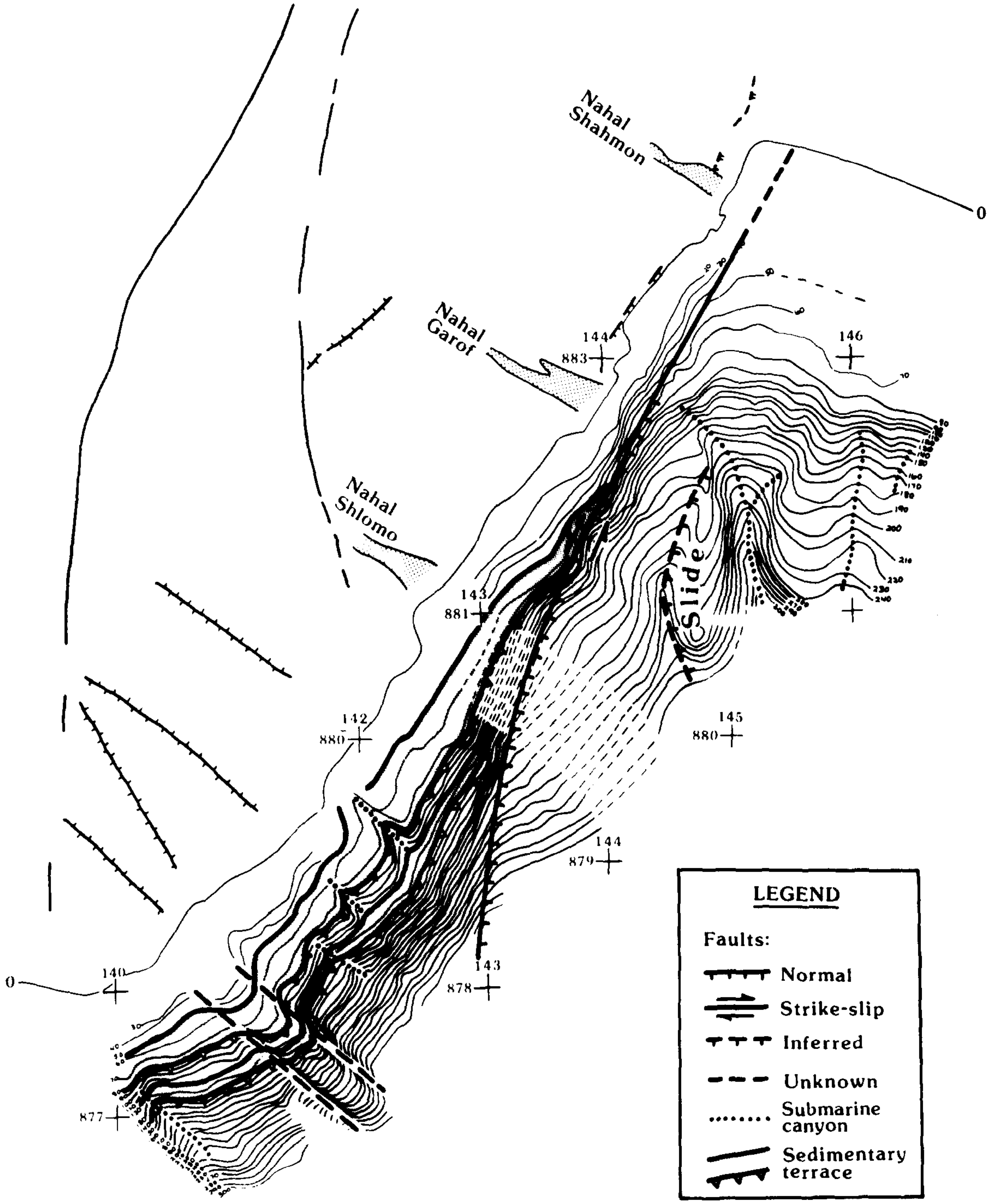

Fig. 3. The main submarine features in the survey area.

rows of biogenic rocks extends from 90 to 125 m depth. A new narrow terrace appears below, between 125 to 135 m depth and at a distance of 1000 m from the coast (Figs. 6A, B, C). This terrace is bounded by a 3 to 8 m high cliff, the most massive cliff found in the survey. It is generally vertical, with local overhangs and karst-like cavities at its base (Fig. 6B). The cliff is com-

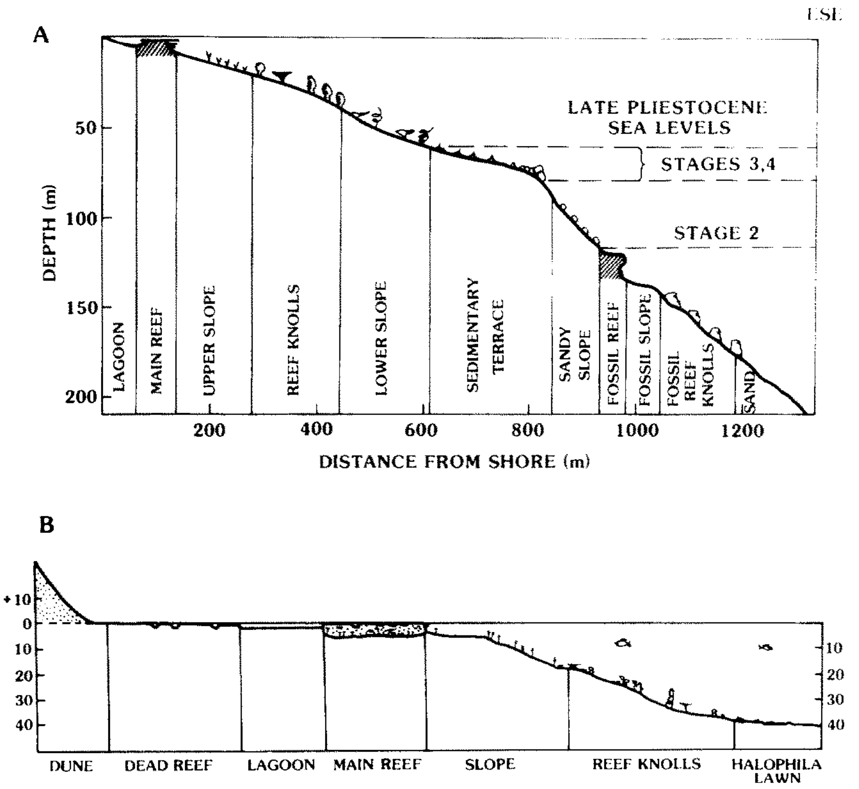

Fig. 4. A. Schematic vertical profile of the western slope in the Gulf of Elat. Based primarily on dives 206–207 with complementary data from the other dives. The zonation and sediment description are all based on direct observations. Vertical exaggeration ×3.5. B. A vertical section through the recent reef complex in Ras Burka (Erez, 1972). No vertical exaggeration. Note the similarity with profile A for depth interval 120 to 170 m.

pletely covered with recent biogenic growth that prevents direct sampling of the inner rocky part of the cliff. This cover is composed primarily of bryozoa, foraminifera and sponges.

A sandy slope with extensive burrowing and small rocky blocks appears below the cliff to about 140 m depth. Below this and extending to 155 m, the size of the blocks increases to 1 m (Fig. 6D). These blocks resemble in their shape the recent reef knolls mentioned above and described in the discussion of the Ras Burka area, about 50 km south of the study area (Erez, 1972; Erez and Gill, 1977). All the blocks are covered by the common biogenic growth. A sandy slope with dispersed rocky blocks appears between 155 to 175 m, and bioturbated sand dominates down to 200 m depth.

The vertical profile between 125 m and 175 m depth is similar to the recent reef of Ras Burka, shown here for comparison (Fig. 4B). Both profiles include a vertical cliff of the main reef, followed by a sandy slope and terminated by a "garden" of reef knolls; both sections even have similar dimensions. This similarity leads us to suggest that the 125 to 175 m section is a fossil reef complex.

Lateral variations

The following lateral changes were observed during the dives: First, the upper part of the fossil reef, from 125 to 175 m deep, is not continuous; its nature changes in dives 215 and 217 and it disappears north of dive 217. In the last two dives the cliff is discontinuous, and locally replaced by rows of patchy reefs. Second, the depth of the lower part of the fossil reef, namely the reef knolls zone, which appears in all the dives south of 217,

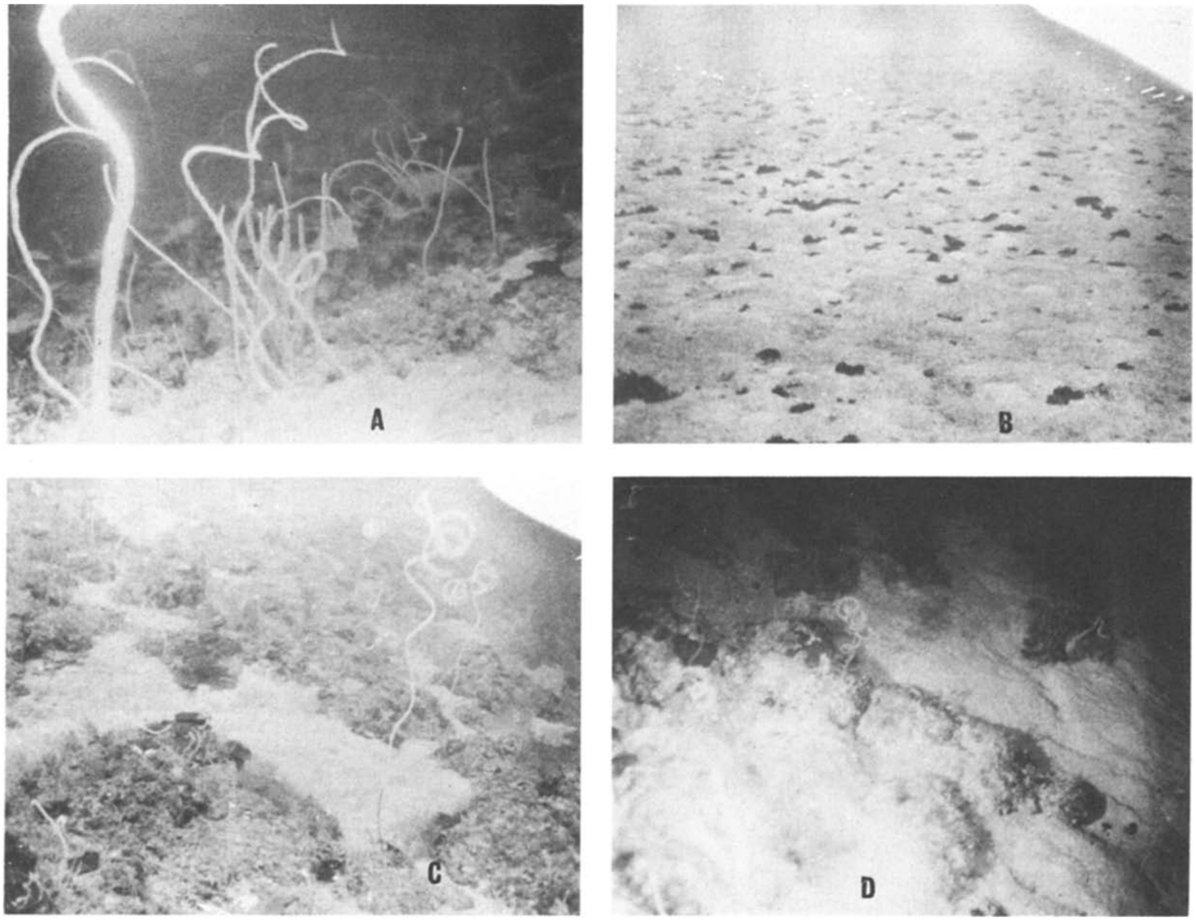

Fig. 5. A. The edge of the recent reef, 60 m depth, dive 206. B. A slope covered with bioturbated carbonaceous sand, and algae, 70 m depth, dive 206. C. The steep, cliff slope in the front of the sedimentary terrace, 90 m depth, dive 207. D. The steep, cliff slope in the front of the sedimentary terrace, 90 m depth, dive 215.

changes between close dives by as much as 30 m. Third, the steepness of the cliff in the lower part of the 50 to 90 m terrace varies between dives from a slope of about 20° to a slope of more than 50°. The bathymetric profiles show that the 50 to 90 m terrace disappears northeast of coordinate 143 (Figs. 1 and 2), where it is replaced by a uniform slope. As discussed below, this disappearance of the terrace is most likely the result of the Elat Fault rather than of sedimentological processes.

Submarine canyons

The largest submarine canyon in the study area is 1.5 km long and extends from 140 to 280 m deep, the limit of the survey (Fig. 3). The upper part of the canyon trends NNW–SSE, whereas the lower part trends N–S. The mean thalweg gradient is about 6° and the side slopes may reach 40°. We think that this canyon formed during the Late Pleistocene, when the sea level was 90 to 130 m below the present sea level (see discussion below).

Dive 218 was directed into this large canyon (Fig. 2). The bottom surface in this area is covered with sediments that appear finer than sand and we found no rock cover at the bottom. A few large displaced reef blocks, up to a few meters in size, have been observed at about 110 m depth. The blocks are surrounded by a muddy surface containing flow structures, mostly ripple marks. At

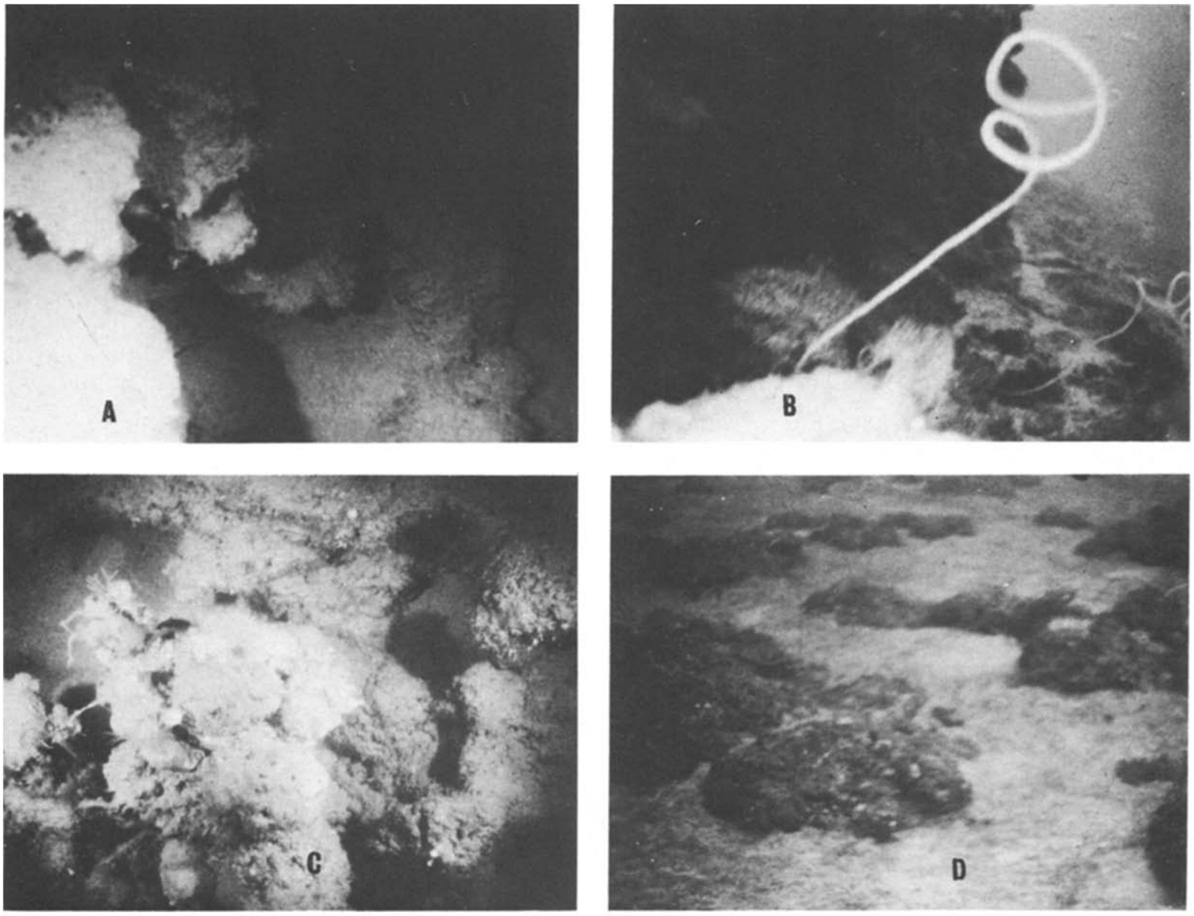

Fig. 6. A. Rocky blocks in the fossil reef, 125 m depth, dive 215. B. A cliff, the front of the fossil reef, 130 m depth, dive 206. C. The front of the fossil reef, 125 m depth, dive 215. D. Fossil reef knolls, 150 m depth, dive 207.

a depth of 150 m we again encountered ripple marks on the bottom. A strong northern current was active during our dive, putting silt and clay grains into suspension and eventually forcing us to stop the dive due to poor visibility. We attribute the sediments here and the lack of reef features to the large amounts of fine-grain sediments supplied by the Nahal Arava, which flows into the gulf about 3 km north of the dive site.

Several additional submarine channels, smaller and shorter than the above mentioned, appear on the map (Fig. 3). In general, these channels occur either above 140 m or below 160 m; the older channels are probably at the lower levels, whereas the younger ones are in the upper levels.

Origin and age of the sedimentary terraces

Figure 4 also illustrates our interpretation of the features described above. We assume that the recent coral reef (e.g., the Ras Burka profile in Fig. 4B) represents the shape of the reef complex for the steep margins of the Gulf of Elat since the Late Pleistocene. This reef complex includes a wide reef flat about 0.5 m below mean sea level, a cliff of the main reef, a sandy slope partly covered with algae, and finally, a slope with reef knolls and hermatypic corals extending to a depth of 50 m.

Shackelton and Opdyke (1973) constructed a curve of the global sea-level changes during the last 125,000 years (Fig. 7). This curve is based on oxygen isotopes and is correlated with reef terraces in Barbados and New Guinea. Figure 7 indicates that the sea level was 120 to 130 m below the present sea level during the last maximum glaciation. Based on the similarity between the 125 to 135 m terrace and the recent reef, we suggest that the terrace indicates the position of the sea level during the maximum glaciation of the Late Pleistocene, about 18,000 years ago. The main reef during this glaciation was much smaller than the recent one, probably a result of more extreme conditions: a minimum temperature of 17° and maximum salinity of 45–47% (Reiss and Hottinger, 1984). Coral reefs can exist under conditions similar to those observed today in the Gulf of Suez. It is possible that during the climax of glaciation the main reef in the Gulf of Elat was partly exposed by a low sea-level; however, the reef knolls at depths of 20 to 50 m grew to appreciable size (Fig. 6D). The occurrence of the fossil reef complex at its original level indicates no significant local uplift or subsidence, at least since the last glaciation.

The sedimentary terrace at 50 to 90 m depth does not have the features of a fossil reef; for example, the terrace lacks the cliff of the main reef and the reef knolls. We think that this terrace was formed by intensive abrasion and degradation of the coastal zone. Considering its height, width and its widespread occurrence in the gulf, this terrace represents a relatively long period of development. Most likely it could have developed between 70,000 and 50,000 years B.P., when the sea level was 100 to 60 m below the present level. This period corresponds to stages 3 and 4 in Fig. 7. The marked variations in sea level during this period could form such a prominent terrace. On the slope at 90 to 120 m deep, we observed subhorizontal rows of rocky blocks (reefs ?). Perhaps these rows are patchy reefs that formed during rising sea conditions, after the last glaciation, or, perhaps, they are preserved reef components of the earlier stages 3 and 4.

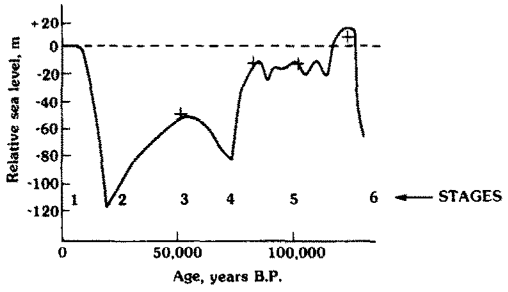

Fig. 7. Eustatic sea-level variations during the last 130,000 years according to stable oxygen isotopes (after Shackelton and Opdyke, 1973).

The dimensions of the recent reef indicate very high rates of growth and abrasion. However, it is difficult to assume that the reef could follow the rapidly rising sea level during the Holocene. Lazar and Sass (1978) calculated the rate of $CaCO_3$ precipitation in the recent reef; they report a value of 5 kg m^{-2} y^{-1}. If we assume minimum porosity of 30% in the reef, the calculated precipitation rate indicates vertical growth rate of about 0.25 cm/y. This is a high estimate as mechanical breakdown and transport of material down slope would strongly reduce this figure (Moore, 1978). On the other hand, the average rate of the sea level rise from the glacial climax to the climatic optimum, 6000 years ago (when the oceans attained their recent level), is about 1 cm/y. Therefore, we do not expect to find a continuous reef that traced the rising sea level. We thus conclude that most of the recent reef growth is younger then 6000 years, in accordance with ^{14}C age determinations of Friedman (1968).

Faulting in the northern end of the Gulf of Elat

A few faults that displace bottom surface features appear on the bathymetric map. The dominant fault is the Elat Fault; it extends for 5 km within the survey area and changes its trend gradually from 10° in the south to 27° in the north (Fig. 3). This fault is traced by the following features (Fig. 8):

(a) At the depth interval of 150 to 280 m the Elat Fault separates between a zone of steep slopes of 20° or more in the south (zone *C*, Fig. 2) from a zone of gentler slopes, 10° or less, in the north (zone *D*, Fig. 2). The sharp transition between zones *C* and *D* is detected in the four left profiles in Fig. 8. The echosounder returns at the fault zone are poor, probably due to very steep slopes.

(b) The upper sedimentary terrace at the depth

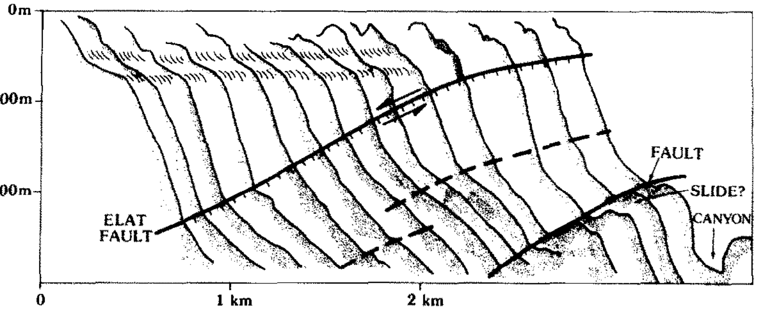

Fig. 8. Bathymetric profiles in the survey area. For location see Fig. 2. Note the sedimentary terrace at 50 to 80 m depth, and the change of bottom slopes across the trace of the Elat Fault.

interval of 50 to 80 m disappears north of coordinate 882: this can be seen by comparing the shape of the four right profiles in Fig. 8, with the other ten profiles. Here the fault divides a southern zone with gentle slopes and a terrace from a northern zone with steep slopes and no terrace. Note that the steeper slope discussed in the previous paragraph is in the south and the gentle one in the north; here it is vice versa.

(c) The two largest streams west of the Elat Fault, Nahal Garoff and Nahal Shlomo, lack corresponding submarine channels (Fig. 2).

(d) During dive 217, roughly 1000 m east of the coast, we made this record: "...At a depth of 206 m large rocky surfaces with some sand; the sand is merely a thin cover. The rocky surface could be a fault plane as no overhang is detected, and it does not resemble a reef". This observation, made before the bathymetric map was compiled, fits exactly, in location and depth, the trace of the Elat Fault, which was determined independently (see Fig. 2.)

A second feature, a 1.5 km long curved line east of the Elat Fault (Figs. 3 and 8), is most likely another fault. Similar in shape and trend to the Elat Fault, it bounds a large slide structure. This slide, marked *S* on Fig. 2, is recognized as a small hill in the four right profiles of Fig. 8, at the depth interval of 220 to 250 m. This hill slopes steeply toward the east (the toe) and gently to the west.

A few smaller faults occur in the study area. A slide-like feature, trending NW–SE, appears between coordinates 141 and 142 (Fig. 3). This feature seems to be a direct continuation of two faults in the basement rocks mapped on land by Garfunkel (1970) (Fig. 1). We think, therefore, that this slide-like structure indicates a young movement along these two old faults.

We initially expected to observe many faults, fractures and cracks in our dives; yet, we found only a few. It is possible that the scarcity of these features reflects the real situation. Alternatively, it is possible that the intense biogenic growth and the high sedimentation rate obliterate even subrecent fracturing. We found a few open fractures in the fossil reef. At one site, we found a narrow fracture which is left-laterally displaced along a small fault, trending 340°. At the site of dive 206 the fossil reef terminates abruptly and seems left laterally displaced by about one meter. In dive 208 we found a wide open fracture, trending 340°, in the 130 m terrace; no lateral slip was detected.

The nature and age of the faulting

The northward continuation of the Elat Fault coalesces in its trend with the Evrona Fault mapped recently by Garfunkel and others (1981) (Fig. 9). The latter fault extends from the Yotvata Sabkha in the north, toward the city of Elat in the south. The Evrona Fault is active: it disturbs recent sabkha sediments in Yotvata and southward, and it shows evidence for young left-lateral slip of 150 m and 600 m in Late Pleistocene alluvial fans (Zak and Freund, 1966).

The extension of the Elat Fault south of the study area coincides with a zone of change of bottom slope in the bathymetric map of the Gulf

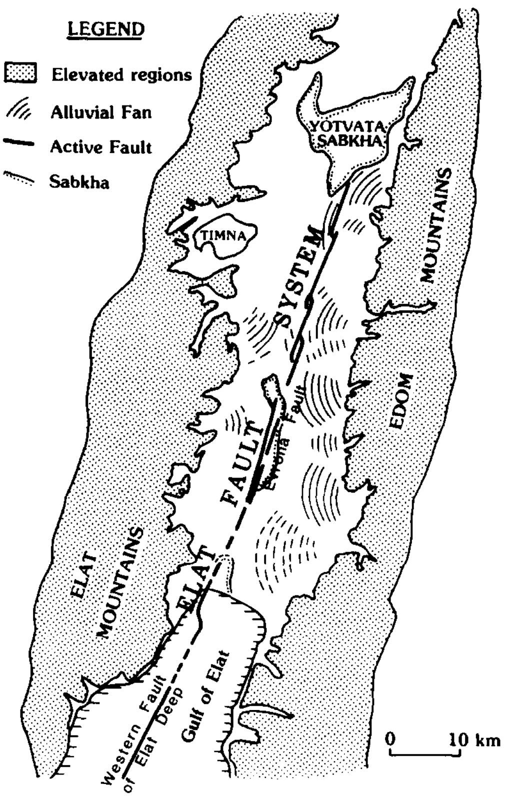

Fig. 9. The Elat Fault System, 90 km long, extends from the Yotvata Sabkha in the north, to about Ras Burka in the south. The present study delineates the link between the northern and southern segments. Base map after Garfunkel et al. (1981).

(Hall and Ben-Avraham, 1978). Its continuation along this zone for a few kilometers enables the Elat Fault to coalesce with the main western fault of the margins of the Elat Deep, mapped by Ben-Avraham et al. (1979). These authors traced the western fault at 600 to 800 m depth, with about 25° trend. The western fault is about 40 km long and its northern end is southeast of the study area. It appears that the Elat Fault mapped here links the western fault of the Elat Deep and the Evrona Fault on land to form a 90 km long fault system (Fig. 9). This system is a segment of the Dead Sea rift (Fig. 1), and we suggest calling it the Elat Fault System (Fig. 9).

The geometry of a left step along the trace of a left-lateral fault, as displayed by the Elat Fault, is common along the Dead Sea rift as well as along other wrench fault systems (e.g., Garfunkel et al, 1981; Reches, 1987). A left step along a left-lateral fault generates a rhomb-graben or a pull-apart basin. We speculate that the survey area is an incipient rhomb-shaped basin between the Evrona Fault and the western fault of Elat Deep and that the region marked *D* in Fig. 2a is the subsiding, new basin. It is possible that this new basin is the continuation of the series of four older basins of the Gulf of Elat (Ben-Avraham et al., 1979).

The Elat Fault shows some evidence of its recent activity. First, the prominent sedimentary terrace of depth 50 to 90 m is discontinuous for a distance of about 1000 m, where it is cut by the fault (Figs. 3 and 8). This discontinuity of the terrace indicates left-lateral displacement, or at least obliteration by the Elat Fault. If this terrace is indeed 70,000 to 50,000 years old, then the fault was active during the last 70,000 years. Second, the 18,000 year old fossil reef is missing in zone *D*, a zone which is strongly disturbed by the Elat Fault. However, as this reef is not continuous in the entire study area (unlike the older terrace), it is possible that the reef is missing in zone D for sedimentological reasons rather than for tectonic ones. Third, three features which were described above, the large submarine canyon, the large slide (*S* in Fig. 2) and zone *E* (Fig. 2), provide indications of the horizontal slip along the fault. We suggest that the submarine canyon is the seaward continuation of Nahal Garof and that the slide occurs in the sediments of the delta of Nahal Shlomo (Figs. 1 and 2). These two streams, Garof and Shlomo, are the largest ones west of the Elat Fault and they have no corresponding continuations east of the fault. We also speculate that zone *E* is a portion of the 50 to 90 m deep terrace (zone *B*, Fig. 2) which has been displaced northward. If these correlations are valid, then the left-lateral slip of 600 to 800 m will match the three features.

According to the above discussion and assumptions we conclude that a horizontal displacement of at least 600 m occurred along the Elat Fault during the last 70,000 years or less. These values indicate an average slip rate of about 0.9 cm/year. Because the estimated long term slip rate along the Dead Sea rift is about 1.0 cm per year, the Elat Fault appears to be the most active fault in the northern Gulf of Elat.

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