Reports

Continental Breakup by a Leaky Transform: The Gulf of Elat (Aqaba)

Abstract. *The floor of the Gulf of Elat consists of five distinct deeps. Its structure is controlled by faulting which has produced rhomb-shaped grabens. The gulf is a newly formed plate boundary between Arabia and Sinai.*

The Gulf of Elat (Aqaba), some 180 km long, is part of the Syrian-African rift system and thus far one of its least known segments. Of the world rift systems, the Gulf of Elat is of particular interest because it is one of the two places in the world (the Gulf of California is the other) where a mid-ocean ridge system changes into a transform system and runs into a continent. The Gulf of Elat occupies the southern part of the Dead Sea rift, which was formed by Cenozoic breakup of the once continuous Arabian-African platform (*1, 2*). This rift is a plate boundary of the transform type: It connects the Red Sea, where sea-floor spreading occurs, with the Zagros-Taurus zone of continental collision. The transform fault has a slight component of opening. As a result, part of its length is marked by prominent morphotectonic depressions, the Gulf of Elat being the most spectacular. The Dead Sea rift developed in two stages. During the younger stage since 4×10^6 to 5×10^6 years before the present, a left lateral slip of some 40 km took place. The remaining 65 km of left lateral slip probably occurred sometime in the Miocene (*2, 3*). This history resembles the two-stage opening of the Red Sea and the Gulf of Aden, as all these features are part of the same tectonic system (*4*). Thus the Gulf of Elat represents an early stage of formation of a plate boundary by a transform fault. In this report we examine the structures that are forming by this process in an effort to gain some knowledge about the mechanism involved.

Earlier studies (*5, 6*) demonstrate that the Gulf of Elat, only 15 to 25 km wide, is remarkably deep (depths reach 1830 m), whereas the neighboring lands rise to more than 2.5 km above sea level. The free-air gravity anomaly falls from approximately zero at the mouth of the gulf to −190 mgal over the deepest part (*5*), and the Bouguer gravity anomaly reaches −100 mgal. This contrasts with a Bouguer anomaly of +150 mgal over the axial trough of the Red Sea. The source of these gulf anomalies could not be explained (*5*).

A geophysical survey was carried out from the R.V. *Ramona* during 16 to 20 May 1976 (Fig. 1a) and included continuous seismic profiles, echo soundings, and magnetic-field measurements (*7*). The new bathymetric map (*8*) (Fig. 1b) reveals many details of the morphology of the gulf. There are practically no continental shelves bordering the Gulf of Elat, and coastal plains are absent or very narrow. On its western side, large alluvial fans were built. These extend as submarine cones into which many canyons have been incised. These cones are built on sloping terraces. The eastern margin of the gulf descends abruptly to the deep basins; thus the gulf is asymmetric in cross section. Eastern boundary slopes reach 25° to 30°, whereas those on the west average 16° but are usually less. Most of the Gulf of Elat is occupied by three elongated en echelon basins, which strike N20°-25°E. Undulations in the floors of the basins produce several distinct deeps (Fig. 1), which we named Elat, Aragonese, Arnona, Dakar, and Tiran. South of the Straits of Tiran is the Hume Deep. The volume enclosed by the gulf is approximately 2550 km^3.

The high-quality continuous seismic profiles reveal many structural details about the Gulf of Elat, which appears to be quite complicated. The main morphological units—basins, marginal slopes, and terraces—are fault-controlled (Fig. 2). The marginal slopes and terraces are underlain by coarsely stratified sediments. The individual reflectors are undulatory, irregular, and rough. As a whole, these series resemble the morphologically defined alluvial fans. The penetration recorded reaches 1 to 1.5 seconds, without reaching basement. The observed dips are in part depositional, but tectonic warping and faulting are also apparent. The fill of the basins is characterized by smooth and continuous reflectors. Thickness variations, and consequently changes of dip, are common; these features indicate continuing differential movements synchronous with sedimentation. The basins' fill appears to consist of ponded turbidites and pelagic sediments. The total thickness penetrated reaches at least 2 to 2.5 seconds. Similar sequences occur in small depressions on the marginal areas. The contacts between the marginal and basinal sediments are generally sharp and often located at the foot of conspicuous fault scarps. Continuing faulting maintained the distinction between basins and marginal areas in spite of sedimentation (profile I). Within the basins, the relative rates of deformation and sedimentation vary, so that they are characterized by different structures.

North of 29°N, in the Elat Deep, the rate of sedimentation is fast enough to maintain a flat bottom. However, the deeper reflectors dip to the east and south, the dips increasing downward as a result of continuing tilting. The transition to the central basin is through a sill in which most of the width of the gulf is occupied by continental slopes.

The central part of the Gulf of Elat, between 28°35′N and 29°N, is the narrowest part but has a more complex structure. Here most of the basinal sediments were warped and now form an elongated anticlinal fold which extends between the Aragonese and Arnona deeps and is expressed in the bottom topography. Sedimentation here occurs at a slower rate than the deformation (profile II), in contrast with the northern basin. The transition between the central and southern basins is not abrupt.

The southern part of the Gulf of Elat, from 28°35′N southward, is the widest and also structurally the most complex. The deep basin occupies the eastern side

Fig. 1 (facing page). (a) Location of all available geophysical tracks for the Gulf of Elat. Heavy lines with roman numerals identify profiles in Fig. 2. (b) Bathymetry of the Gulf of Elat. Contours are in corrected meters with an interval of 100 m. The inset maps show (top) the regional setting of the Gulf of Elat and the approximate plate boundaries and (center) traces of major faults in the Gulf of Elat which define the rhomb-shaped grabens (hachures) separating the Sinai and Arabian plates.

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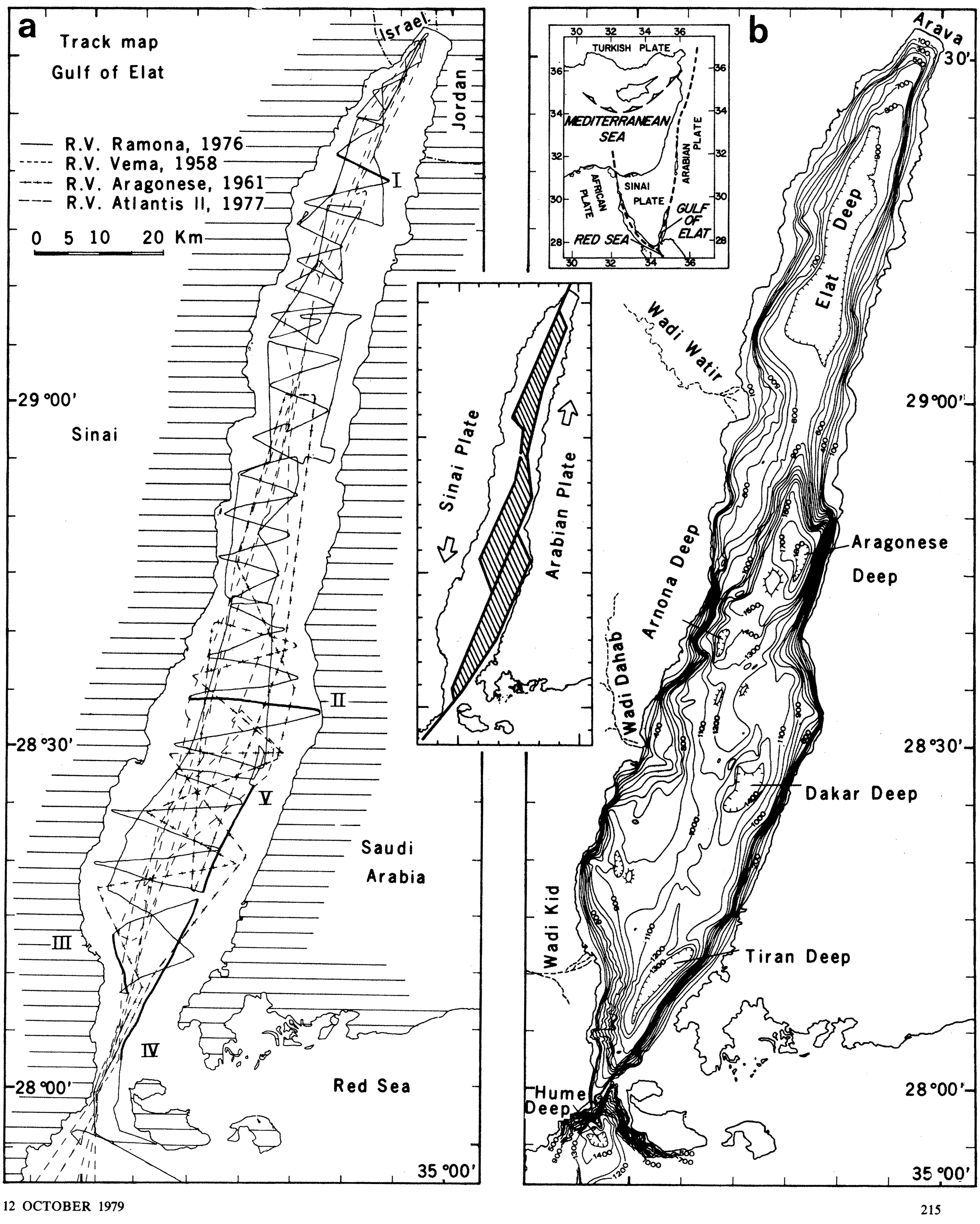
of the gulf. West of it is a wide terrace at water depths of 800 to 1000 m (Fig. 1), on which the large fans of Wadi Dahab and Wadi Kid (profile III) were built. Different parts of the southern basin experienced variable degrees of subsidence (profiles IV and V). The sedimentary sequence filling the flat-bottomed Dakar Deep thins dramatically toward structural highs on the north and south but is not bounded by faults, whereas the Tiran Deep is bounded by faults on all sides. Although Hume Deep is outside the gulf proper, it is a related structure similar to those found in the gulf and it links the gulf with the axial depression of the Red Sea.

Folds of different sizes are best developed in the central and southern basins. They range from quite small structures to arches more than 5 km wide with ampli-



tudes of a few hundred meters. The structural relief and dips appear to increase downward, recording a continuing deformation. In extreme cases, the dips reach 10° to 13° at depths of 2 km or more beneath the sea floor, but generally they are much smaller. Relatively tight symmetric folds 100 to 200 m high and 1 km or less across are developed in the southern half of the gulf. They are not associated with any magnetic anomaly. The protruding shape of these structures makes us suspect that they are diapiric. This may suggest the presence of evaporites at depth similar to those observed in the neighboring Red Sea.

Since the Gulf of Elat is a product of rifting and continental breakup, faults are the dominant structural element. The faults are normal or strike-slip. The data only allow us to identify vertical fault movements, but, since the gulf is a part of the Dead Sea rift in which left lateral slip motion predominates (2), it is reasonable to expect that such movement is an important factor in the gulf as well. The principal faults border the basins and produce very straight and near-vertical scarps, compatible with strike-slip motion. These faults are typically en echelon, producing basins between the faults which are rhomb-shaped grabens (sphenochasms). This type of structure is a characteristic of the Dead Sea rift over its entire length (2), and as a result the new plate boundary is not straight. Active normal faults also run along the western coast of the Gulf of Elat. Faults having other trends are of lesser importance within the gulf. The sediment deformation within the sphenochasms indicates internal strain which is most evident in the central graben. The unusual gravity anomaly observed in the gulf may be due to the thick sedimentary fill, whose complete extent, at least beneath the several kilometers observed here, has yet to be determined. A density contrast of 0.7 g/cm^3 between the sedimentary fill and the basement rocks could explain the observed gravity anomaly if the fill extends 4 km or more below the floor of the gulf. A second explanation for this anomaly could be the absence of a mantle diapir such as that found beneath the axis of the Red Sea, for such a feature probably could not penetrate into this chain of relatively small sphenochasms.

Our study indicates that continuing tectonism, primarily consisting of faulting, controls the structure of the Gulf of Elat. Tectonic activity is most intense in the basins and along the bounding faults and has produced five distinct bathymetric deeps. Diapiric structures were observed in the southern part of the gulf. A thick sedimentary fill has accumulated, consisting mainly of alluvium on the margins and turbidites and pelagic sediments in the basins. The extent of this fill has not been determined, but the present data show that the oldest sediments must lie at least 7 km beneath the present level of the adjacent lands. Thus, the Gulf of Elat is a spectacular cleft in the earth's crust resulting from the still active rifting of Sinai from the Arabian peninsula.

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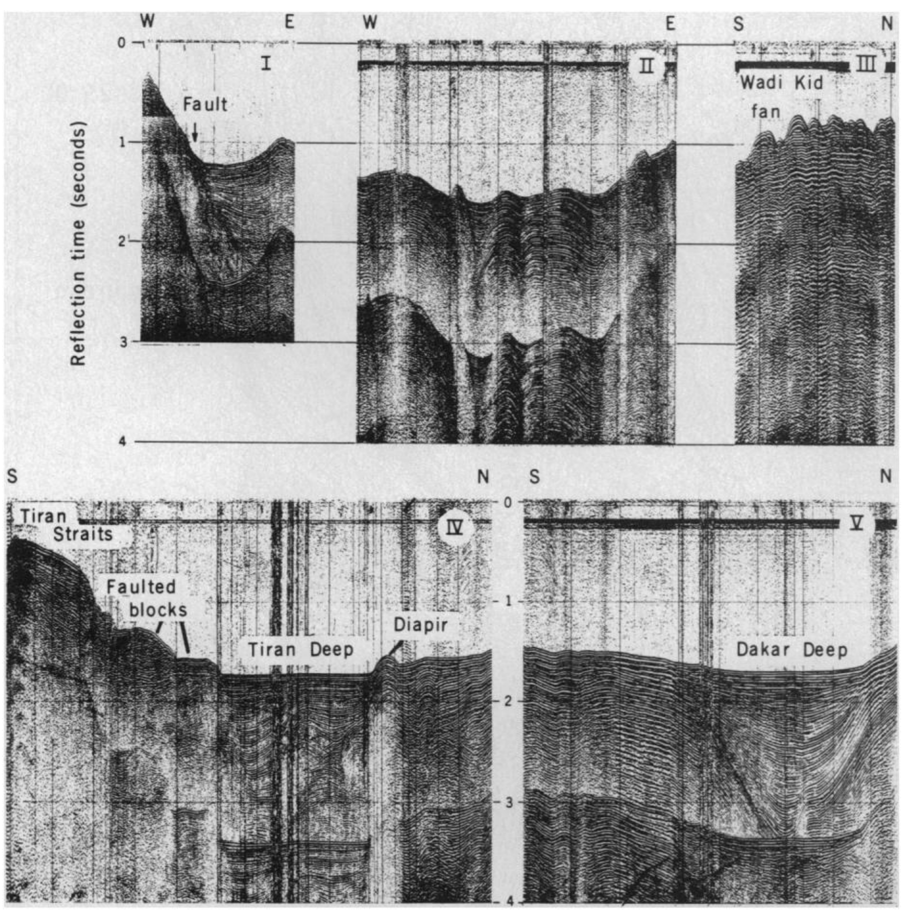

Fig. 2. Five continuous air-gun seismic profiles (4900 cm^3) in the Gulf of Elat. (see Fig. 1 for locations). Profile I traverses the Elat Deep and shows the well-stratified ponded sediments of the deep separated by a fault from the poorly and irregularly stratified sequence on the marginal block. Profile II runs through the sill between the central and southern basins. The basinal sediments are folded; the fold forming the prominent hill may be of diapiric origin. Note the contrast between the basinal and marginal sediments. Profile III is through the fan off Wadi Kid. Note the strong irregular reflectors and the incised submarine canyons. Profiles IV and V cross the southern basin from the Tiran Straits to the Dakar Deep. A diapiric structure is shown north of the Tiran Deep, whereas the deep itself is separated from the straits by several structural steps. There is a gradual transition from undeformed to deformed sediments along the southern margin of the Dakar Deep.

References and Notes

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9. We thank the staff of the Israel Oceanographic and Limnological Research Ltd., for their organizational and technical assistance and the staff of the Marine Geology Division of the Geological Survey of Israel for their participation. A. Nur offered helpful comments and suggestions. Supported by the Israel Ministry of Commerce and Industry.

5 February 1979; revised 16 May 1979