Seismicity and Aeromagnetic Features of the Gulf of Aqaba (Elat) Region

ABDULLAH M. ALAMRI[1] AND FREDERICK R. SCHULT[2]

Department of Geology and Geophysics, University of Minnesota, Minneapolis

CHARLES G. BUFE

U.S. Geological Survey, Denver, Colorado

Recent seismicity in the Gulf of Aqaba region has been examined in relation to pull-apart tectonics and structures indicated by bathymetry, surface geology, and new analyses of aeromagnetic data. Forty earthquakes occurring in the region from 1985 to 1989 were located using data from a network of five telemetered seismographs in the Midyan region of Saudi Arabia east of the Gulf of Aqaba and from a network north of the gulf in Israel. Interpretation of aeromagnetic data from the Gulf of Aqaba and the adjacent Midyan region confirms previous estimates of offsets across the zone of transform faulting in the gulf. Aeromagnetic anomaly patterns, obtained by reduction-to-the-pole techniques, and earthquake locations provide evidence for continuation of the faulting regime from the gulf northeastward into the Midyan region. The vicinity of the Elat Deep (primarily the southwest flank) probably is undergoing active normal faulting. Other seismicity and first-motion polarity data confirm the regional pattern of NNE trending sinistral strike-slip faulting.

INTRODUCTION

The Gulf of Aqaba, about 180 km long and 15-25 km wide, forms the southern part of a major sinistral transform boundary known as the Dead Sea transform. The transform connects the Red Sea, a seafloor-spreading center, with the Zagros-Taurus zone of continental collision (Figure 1). Evidence of seismic activity from 747 A.D. to the present in the Gulf of Aqaba is documented by diverse sources. *Ben-Menahem* [1981] indicated relatively lower seismic activity in the Gulf of Aqaba than in the Red Sea or Dead Sea regions. Focal mechanism studies of the largest instrumentally recorded earthquakes in the region indicate dominant sinistral strike-slip motion [*Ben-Menahem et al.*, 1976].

Models of the Dead Sea transform indicate 105-107 km of sinistral movement, of which either 62 km was Miocene and 45 km was Pleistocene [*Quennell*, 1958] or 40-45 km was Miocene and 60 km was pre-Miocene [*Freund et al.*, 1970]. Miocene dikes intruded into Precambrian crystalline rocks of the eastern Sinai Desert show 24 km of cumulative sinistral offset distributed across a 30-km-wide shear zone neighboring the gulf [*Eyal et al.*, 1981]. Similar displacement is estimated for the eastern coast of the gulf [*Eyal et al.*, 1981]. Thus, some 60 km of the total 110 km offset along the transform system is taken up by faults within the gulf itself. The most recent evidence for *Quennell's* [1958] estimate of sinistral movement is from aeromagnetic data from Jordan that show large east-west magnetic anomalies truncated by the Dead Sea transform [*Hatcher et al.*, 1981]. In the model of *Freund et al.* [1970] the offset was proposed to conform with the timing of the second stage of seafloor spreading of the Red Sea at about 4-5 Ma. The model agrees with details of a complicated second-phase movement of the Tertiary Rashama formation that outcrops adjacent to the Gulf of Aqaba in the Midyan region [*Zakir*, 1982].

Previous research indicates that the Gulf of Aqaba is characterized by the structural development of en echelon rhomb grabens (pull-apart basins). Three such basins are inferred to underlie the Gulf of Aqaba [*Garfunkel*, 1981; *Ben-Avraham*, 1985]. *Garfunkel* [1981] concluded that local extension across the transform zone results in small-magnitude crustal separation and a "leaky" transform boundary. Seismic reflection profiles reveal deformation and faulting in the sediments [*Ben-Avraham*, 1985] that suggest the Elat Deep (Figure 3) is bounded by strike-slip faults along its southeastern and southwestern boundaries, by a normal fault with possible minor strike-slip movements along its northwestern boundary, and by distributed deformation along its northeastern boundary. Some aspects of this model are inconsistent with the *P* wave first motions from our study.

EARTHQUAKE DATA

The earthquake location program HYPOELLIPSE [*Lahr*, 1989] was used to locate earthquakes recorded from 1985 to 1989 by local seismic networks deployed north and east of the Gulf of Aqaba. A gradient-velocity model was assumed, based on the seismic refraction models of *Ginzburg et al.* [1979] and *El-Isa et al.* [1987]. In this model the near-surface *P* wave velocity is 5.9 km s^{-1} with a 0.03 km s^{-1} km^{-1} gradient to the Moho at 30 km depth. The sub-Moho *P* wave velocity is 8.0 km s^{-1}. A Wadati plot of *S* and *P* wave travel times from local events was used to determine an average V_P/V_S of 1.71.

The distribution of the stations and of epicenters of 40 earthquakes ($2.58 < M_L < 3.79$) is shown in Figure 1. Because of the event-station distances and geometries, focal depths cannot be well determined. For 19 of the events, the focal depth had to be fixed at 10 km, which is the average of the free

[1]Now at Department of Geology, King Saud University, Riyadh, Saudi Arabia.

[2]Now at Air Force Technical Applications Center, Patrick Air Force Base, Florida.

Paper number 91JB02104.
0148-0227/91/91JB-02104$05.00

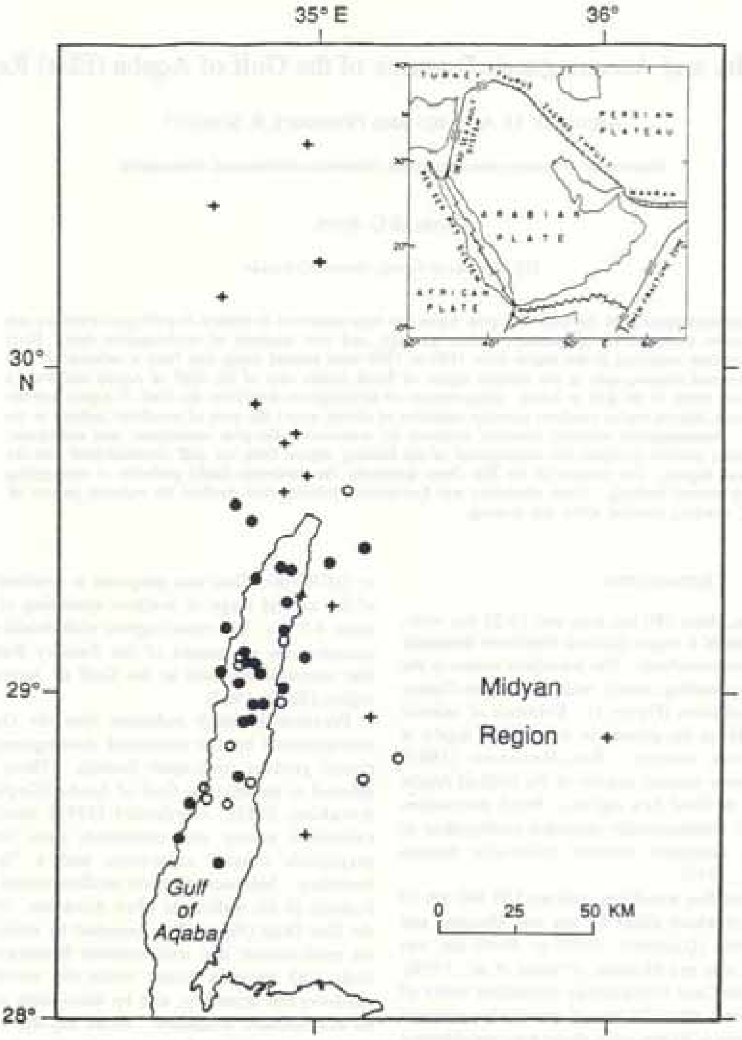

Fig. 1. Location map of the study area showing the Gulf of Aqaba seismographic stations and epicentral distributions. Plus symbols represent stations, and circles represent epicenters reported here for earthquakes from 1985 to 1989. Circles are solid where standard epicentral errors are less than 15 km. Inset map is from *Adams and Barazangi* [1984].

depth solutions for the 21 better determined hypocenters. Although the epicentral uncertainties for these events are commonly large, with 86% confidence ellipses of 2-15 km for most of the earthquakes, the relative locations of neighboring events should be more accurate. Epicenters with uncertainties greater than 15 km are shown by open circles in Figure 1.

Because the number of observed first motions for each event is less than 10, focal mechanism solutions were not attempted for individual events. Twenty-five of the events with reported *P* wave first motions were composited as follows. Eleven of the events south of latitude 29°N (Figure 2*d*) had first motions consistent with strike-slip motion along NNE trending faults (Figure 2*b*), consistent with bathymetric trends (Figure 3). The fourteen events north of latitude 29°N (Figure 2*d*) are consistent with extensional tectonism having a generally NE-SW minimum compressional stress direction (Figure 2*a*). Given the large-scale spatial distributions of events which provide first motions to the mechanisms in Figures 2*a* and 2*b*, the composite focal mechanisms may reflect regional stress orientation more than individual fault plane orientation. The scarcity of polarity data makes it difficult to interpret subsets of these events. First motions for one such cluster of events on the southwest flank of the Elat Deep are shown in Figure 2*c*.

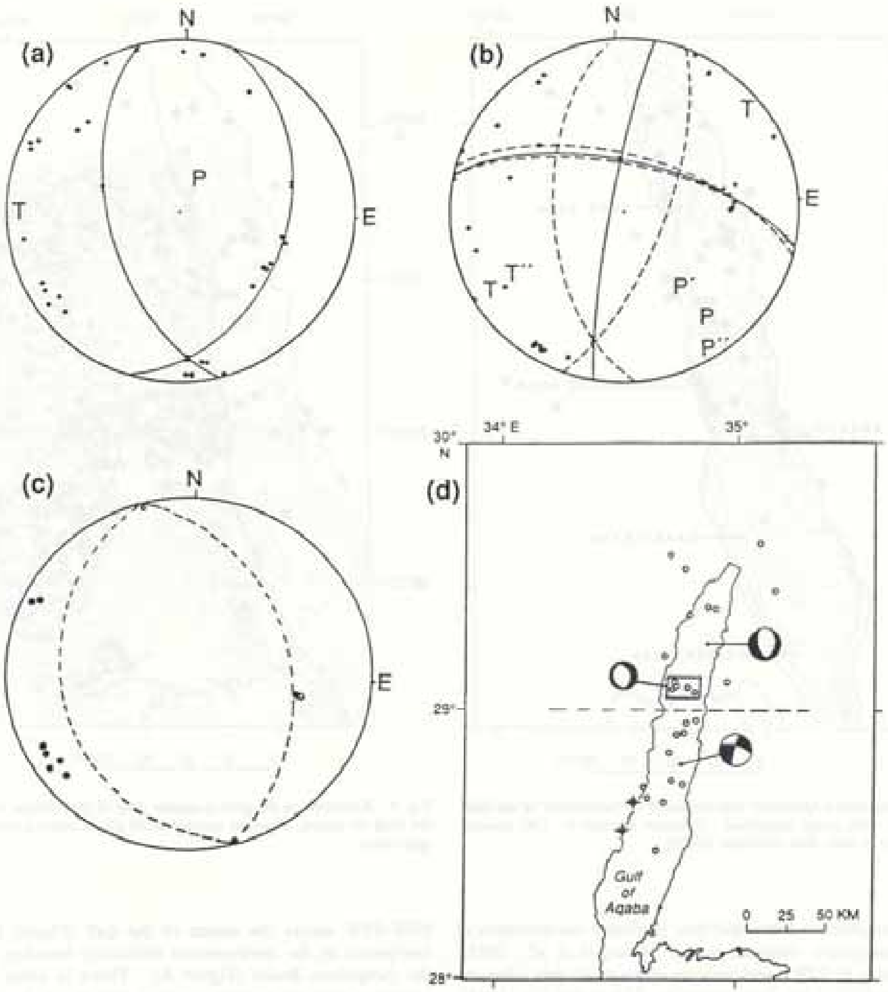

Fig. 2. Composite focal mechanism solutions computed by the FOCMEC algorithm [*Snoke et al.*, 1984] for (*a*) all 14 earthquakes north of latitude 29°N and (*b*) 11 of the earthquakes south of latitude 29°N. (*c*) Polarity data and a possible focal mechanism for the five events on the southwest flank of the Elat Deep are shown. (*d*) Event locations are shown as small circles. The two events that were not used are shown as crosses over small circles.

AEROMAGNETIC DATA

Seven aeromagnetic maps [*Geosurvey International Ltd.*, 1982] were previously compiled between latitude 27°30'-29°30'N and longitude 34°30'-36°30'E. The lines were flown at 800-m line spacing using a proton precession magnetometer. Compilation of these maps included digital removal of the International Geomagnetic Reference Field (IGRF) and the diurnal magnetic field variation recorded at a ground station. Because the original aeromagnetic data are not available, we analyzed the maps themselves using the following procedure.

The aeromagnetic data analysis was organized in four discrete stages: (1) digitization of the original 1:100,000-scale contour maps by hand digitizing the position and magnetic field value at each intersection between flight lines and contour levels; (2) interpolation of a new grid of magnetic total-intensity data at a grid interval of 0.5 km; (3) processing of the magnetic data by reduction to the magnetic pole; and (4) compilation of a new 1:250,000-scale reduction-to-the-pole (RTP) magnetic contour map (data set used in Figure 4) at a contour interval of 50 nT. This procedure was used because magnetic anomalies, especially where the magnetic inclination is low (39° in the study area), are difficult to visually correlate with the geologic features that produce them. Reduction to the pole provides the first step to a direct conversion between the magnetic anomalies and the rock

Fig. 3. Earthquake epicenters superimposed on bathymetry of the Gulf of Aqaba, with deeps identified. Contour interval is 100 meters. Bathymetry is from *Ben-Avraham* [1985].

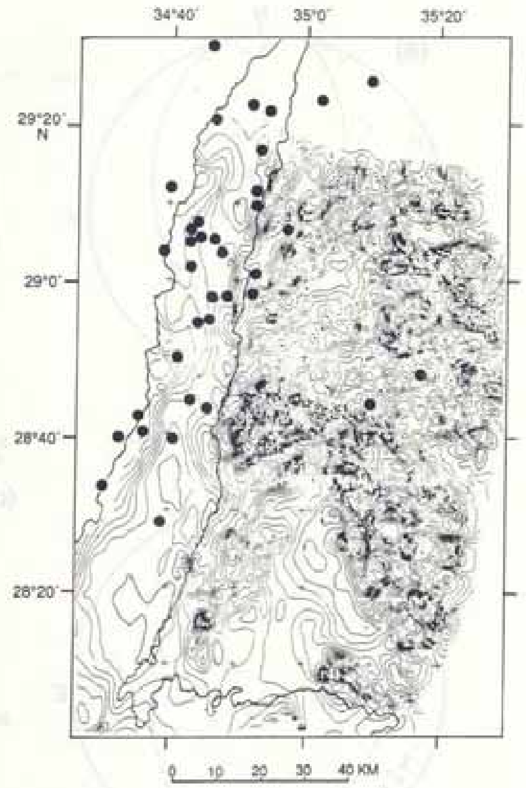

Fig. 4. Reduction-to-the-pole magnetic map of the Midyan region and the Gulf of Aqaba. Contour interval is 50 nT. Circles are earthquake epicenters.

bodies that produce them, and thus facilitates interpretation of the aeromagnetic contour pattern [*Georgel et al.*, 1985]. Computation of RTP transformation of magnetic data using the Fourier transform has been given by *Bhattacharyya* [1967]. The second vertical derivative of the data set was also computed, but it was too noisy to provide new insight into the regional tectonism.

RESULTS AND DISCUSSION

Seismicity

Earthquake epicenters are shown in Figures 1, 2, 3, 4, and 6. In Figure 6, the seismicity is superimposed on a structural model for the Gulf of Aqaba after *Ben-Avraham et al.* [1979]. The distribution of epicenters of earthquakes recorded in the Gulf of Aqaba region between 1985 and 1989 (Figure 1) indicates that tectonic activity inferred by Ben-Avraham et al. for the gulf extends into surrounding regions.

Within the gulf, epicenters cluster along several bathymetric escarpments inferred to be faults (Figures 3 and 6), although magnetic anomalies (Figure 4) show only a weak correlation with these faults. Many of the offshore events south of latitude 29°N fall along a bathymetric feature that cuts NNE-SSW across the center of the gulf (Figure 3) and is interpreted as the northwestern strike-slip boundary fault of the Aragonese Basin (Figure 6). There is some offshore seismicity near the opposite (eastern) side of the basin (Figure 6). The fault on this side of the basin apparently extends northward on land, marked by a magnetic trough (Figure 4) which emerges from the gulf at about 29°N and extends in a NNE direction. Three large historical earthquakes occurred near the northern (land) segment of this fault [*Ambraseys*, 1988], and field geologic measurements indicate past faulting in the region [*Rowaihy*, 1984].

North of latitude 29°N, a cluster of events (Figures 3 and 6) is concentrated on the southwestern flank of the Elat Deep, and other events are scattered near the shores. All of the events in the region indicate a fairly high level of seismic activity (magnitude to 5.1) with the main activity located offshore rather than on land.

Farther south in the Midyan region, two earthquakes occurred east of the gulf along the extension of a possible fault zone, inferred from disruption of magnetic patterns and mapped geology. The trend begins at the east coast of the gulf at about 28.5°N (Figure 4) and extends in a northeasterly direction, on trend with the two epicenters located

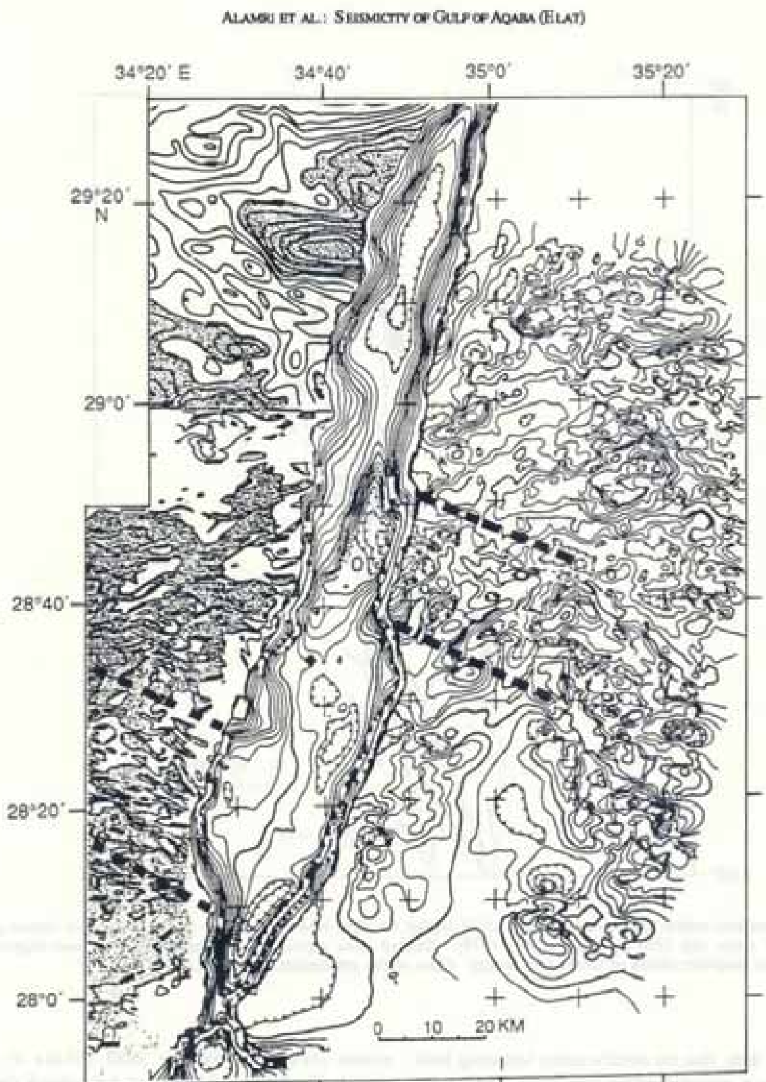

Fig. 5. Bathymetric map of the Gulf of Aqaba, flanked by total-intensity magnetic maps showing the magnetically disturbed areas in Midyan and Sinai (dashed lines) that suggest a 50- to 60-km offset. Magnetic data in the Midyan region are from this study. The Sinai data [*Ben-Avraham*, 1985] are based on the Sinai aeromagnetic map by *Folkman and Assael* [1980] and are a composite of separate analyses north and south of 29°N. Stippled areas represent relative magnetic lows. For a more detailed description of these data, see Figure 12 of *Ben-Avraham* [1985]. Contour intervals are 50 nT for the total field aeromagnetic data in the Midyan region and 100 m for bathymetry in the gulf.

approximately 40 km east of the gulf. These epicenters are among the most poorly determined, and their alignment may be fortuitous. The epicenter of the easternmost event also is within 4 km of the intersection of two short mapped faults [*Clark*, 1985] that cut 550-m.y. and older formations. The proposed NE trending fault, indicated with question marks in Figure 6, has not been field checked. The relationship of the proposed fault to the tectonic framework of the gulf is not clear, although it could help accommodate the decrease in opening of the gulf north of about 28.5°N.

As mentioned earlier, several composite focal mechanisms were constructed (Figure 2). The first (Figure 2*a*), for all events located north of latitude 29°N, indicates normal faulting on a plane striking N15°W and dipping 56° to the west or on a plane striking N15°E and dipping 38° to the east. The mechanism is consistent with rifting and opening of the gulf. Many of the events occurred along the southwestern flank of the Elat Deep. A composite mechanism for just these events (Figure 2*c*) is very poorly constrained but definitely contradicts the interpretation of *Ben-Avraham* [1985], based

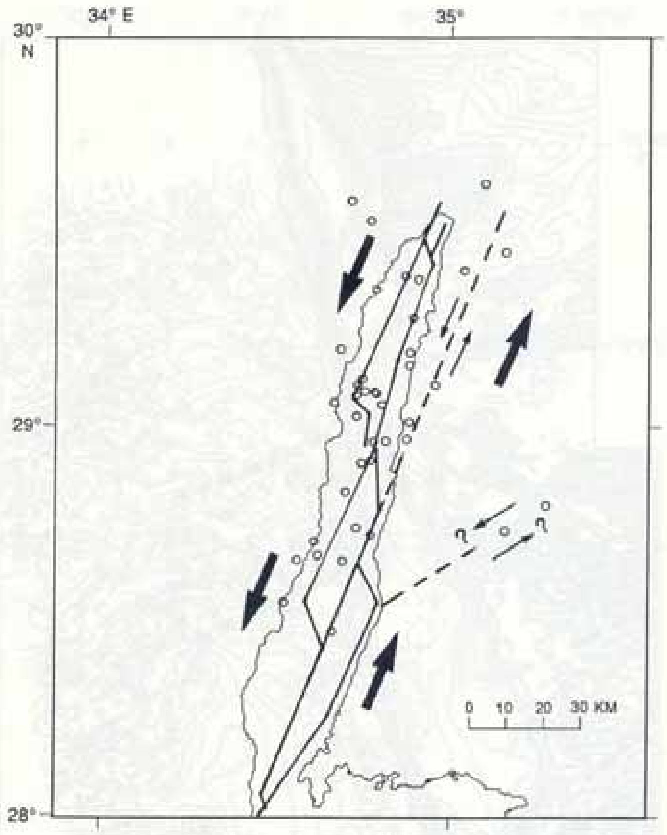

Fig. 6. Generalized model for structure of the Gulf of Aqaba: the three basins result from en echelon rhomb-shaped grabens produced by strike slip [*Ben-Avraham et al.*, 1979]. Dashed lines represent faults extended onto land aligned with epicenters and magnetic offsets or trends (this study). Open circles are epicenter locations.

on marine reflection data, that the southwestern bounding fault of the Elat Deep is a sinistral strike-slip fault. The first-motion data and the NNW trends of the bathymetry and the epicenter locations are consistent with normal faulting along a NNW trending fault, but the first motions are not consistent with the NNW trending left-lateral strike-slip motion proposed by Ben-Avraham.

The second composite mechanism (Figure 2*b*), for a set of events located south of latitude 29°N, indicates a range of acceptable solutions. All of these solutions show strike-slip faulting. The preferred fault plane (fewest polarity errors and close to the trend of the seismicity data and the bathymetric features) strikes N14°E (+/- 14°) with a steep dip. The auxiliary plane is better determined, striking N74°W and dipping 66° to the north. This mechanism is consistent with sinistral slip on NNE trending faults of the Dead Sea transform system. Polarity data from two additional events along the western shore are not consistent with the composite mechanism, so they were not included.

Apart from events in this study, most earthquake data from the area are for aftershock sequences associated with a few events (M=4.85, February 1983 [*El-Isa et al.*, 1984], and M=5.1, December 1985). More main shock data are needed to define the distribution of seismic strain release in the Gulf of Aqaba.

Aeromagnetic Data

Along the northeastern boundary of the magnetically disturbed zone on the RTP map (Figure 4) at about 28.7°N, 35.2°E, are a series of northwesterly trending narrow negative linear anomalies that are associated with Tertiary dikes (approximately 22 m.y.). These negative anomalies are consistent with rocks having intense reversed remanent magnetization. The shape and wavelength of the anomalies partly depend on variations in remanent and induced magnetization vectors depending on geomagnetic latitude. Very strong magnetic anomalies south of the Tertiary dikes and weak magnetic anomalies north of the dikes indicate that the dikes lie along a fault or crustal boundary. The region of low magnetic relief in the southwestern part of the RTP map correlates with very thick surficial sediments of Quaternary age in the Lisan Basin (approximately 28°10'N, 34°50'E).

Offshore magnetic data, digitized after *Ben-Avraham* [1985], show weak anomalies as compared to strong anomalies on land, because the magnetic sources are deeper offshore than on land. Although there is no clear evidence for general counterclockwise rotation of the parts of the magnetic bodies under the gulf relative to those on land, *Ben-Avraham* [1985] showed a clear magnetic signature of a local rotation of this type at latitude 29°15'N on the western side of the gulf.

Magnetic anomalies over the Gulf of Aqaba (Figure 4) trend NNE parallel with the strike of the gulf, parallel with bathymetric features in the gulf (Figure 5), and parallel with contacts identified by field geology [*Rowaihy*, 1984] near the eastern shore to the northeast of the gulf. The boundary of the transform fault zone extends some distance onto the land to the east (Figure 6) and west [*Eyal et al.*, 1981]. The discontinuity of magnetic anomalies from the east to the west of the Gulf of Aqaba is good supporting evidence for regional shear offset (Figure 5). The magnetically disturbed area west of the gulf at about latitude 28°20'N (near the Tertiary dikes in the Sinai) is similar to the disturbed area east of the gulf at about latitude 28°45'N (just south of the dikes in Midyan, opposite the Aragonese Deep). If the western zone was once continuous with the eastern zone, with strikes roughly perpendicular to the gulf, then the present-day 50- to 60-km offset of these zones provides us with an estimate of cumulative sinistral slip on faults within the gulf. This offset is in agreement with the estimate of sinistral displacement along the transform system taken up by faults within the gulf [*Eyal et al.*, 1981].

CONCLUSIONS

Interpretation of aeromagnetic data from the Gulf of Aqaba and the adjacent Midyan region confirms previous estimates of total offset across the zone of transform faulting. Aeromagnetic anomaly patterns and earthquake locations provide evidence for continuation of the faulting regime from the gulf northeastward into the Midyan region. The vicinity of the Elat Deep (primarily the southwestern flank) probably is undergoing active normal faulting consistent with rifting or rhomb graben development. Other earthquake activity confirms the regional pattern of NNE trending sinistral strike-slip faulting associated with the major Dead Sea transform fault system.

Acknowledgements. Dr. Martin F. Kane provided invaluable guidance, assistance, and criticism for the interpretation of the aeromagnetic data. Mark Meremonte's help was essential to processing and displaying the seismic results. Robert Kucks contributed greatly to the display of the aeromagnetic data. Thanks go to John Michael, Bruce Presgrave, Ralph Ricotta, and Stephen Harmsen for their assistance. We also thank William Diment, Robert Hatcher, Al Rogers, Dal Stanley, Paul Thenhaus, and Kaye Shedlock for helpful reviews and comments on the manuscript. We especially thank the Seismological-Geophysical Observatory of King Saud University for providing the seismic data and the Deputy Ministry for Mineral Resources (Jeddah, Saudi Arabia) for providing the magnetic data.

REFERENCES

Adams, R. D., and M. Barazangi, Seismotectonics and seismicity in the Arab region—A brief summary and future plans, *Bull. Seismol. Soc. Am.*, *74*, 1011-1030, 1984.

Ambraseys, N. N., The seismicity of Saudi Arabia and adjacent areas, *ESEE Res. Rep. 88/11*, Imp. Coll. of Sci. and Technol., London, 295 pp., 1988.

Ben-Avraham, Z., Structural framework of the Gulf of Elat (Aqaba), northern Red Sea, *J. Geophys. Res.*, *90*, 703-726, 1985.

Ben-Avraham, Z., G. Almagar, and Z. Garfunkel, Sediments and structure of the Gulf of Elat (Aqaba), northern Red Sea, *Sediment. Geol.*, *23*, 239-267, 1979.

Ben-Menahem, A., Variation of slip and creep along the Levant rift over the past 4500 years, *Tectonophysics*, *80*, 183-196, 1981.

Ben-Menahem, A., A. Nur, and M. Vered, Tectonics, seismicity and structure of the Afro-Eurasian junction—The breaking of an incoherent plate, *Phys. Earth Planet. Inter.*, *12*, 1-50, 1976.

Bhattacharyya, B. K., Some general properties of potential fields in space and frequency domains—A review, *Geoexploration*, *5*, 127-143, 1967.

Clark, M. D., Geology of Al Bad' quadrangle, sheet 28A, Kingdom of Saudi Arabia, *Open File Rep. 03-20*, Deputy Min. for Miner. Resour., Jeddah, Saudi Arabia, 1985.

El-Isa, Z., H. Merghelani, and M. Bazzaris, The Gulf of Aqaba earthquake swarm of 1983, *Geophys. J. R. Astron. Soc.*, *78*, 711-722, 1984.

El-Isa, Z., J. Mechie, C. Prodehl, J. Kakris, and R. Rihm, A crustal structure study of Jordan derived from seismic refraction data, *Tectonophysics*, *138*, 235-253, 1987.

Eyal, M., Y. Eyal, Y. Bartov, and G. Steinitz, The tectonic development of the western margin of the Gulf of Elat (Aqaba) rift, *Tectonophysics*, *80*, 39-66, 1981.

Folkman, Y., and R. Assael, Sinai—Aeromagnetic map, survey of Israel, scale 1:500,000, Surv. of Israel, Tel-Aviv, 1980.

Freund, R., Z. Garfunkel, I. Zak, M. Goldberg, T. Weissbrod, and B. Devin, The shear along the Dead Sea rift, *Philos. Trans. R. Soc. London, Ser. A*, *267*, 107-130, 1970.

Garfunkel, Z., Internal structure of the Dead Sea leaky transform (rift) in relation to plate kinematics, *Tectonophysics*, *80*, 81-108, 1981.

Georgel, J. M., J. Bobillier, J. Delom, and M. Bouvlier, Total intensity aeromagnetic maps of the Arabian Shield, *Tech. Rep. TR-05*, pp. 1-53, Bur. de Rech. Geol. et Minieres, Jeddah, Saudi Arabia, 1985.

Geosurvey International Ltd., Airborne magnetic survey of area O (sheets 27/34B, 28/34D, 28/35C, 28/34B, 28/35A, 28/35B, 29/34D, 29/35C), for the United States Geological Survey Mission, Deputy Min. for Miner. Resour., Jeddah, Saudi Arabia, 1982.

Ginzburg, V., J. Makris, K. Fuchs, B. Perathoner, and C. Prodehl, Detailed structure of the crust and upper mantle along the Jordan-Dead Sea rift, *J. Geophys. Res.*, *84*, 5605-5612, 1979.

Hatcher, R. D., I. Zeitz, R. D. Regan, and I. M. Abu-Ajamiah, Sinistral strike-slip motion on the Dead Sea rift—Confirmation from new magnetic data, *Geology*, *9*, 458-462, 1981.

Lahr, J., Hypoellipse/version 2.00—A computer program for determining local earthquake hypocentral parameters, magnitude, and first motion pattern, *U.S. Geol. Surv. Open File Rep.*, *89-116*, 1989.

Quennell, A. M., The structural and geomorphic evolution of the Dead Sea rift, *Q. J. Geol. Soc. London*, *114*, 1-24, 1958.

Rowaihy, M. N., Geology of the Haql quadrangle, sheet 29A, Kingdom of Saudi Arabia, *Open File Rep. 04-8*, 24 pp., Deputy Min. for Miner. Resour., Jeddah, Saudi Arabia, 1984.

Snoke, J. A., J. W. Munsey, A. G. Teague, and G. A. Bollinger, A program for focal mechanism determination by combined use of polarity and SV-P amplitude ratio data, *Earthquake Notes*, *55*, 15, 1984.

Zakir, F. A., Preliminary study of the geology and tectonics of the Raghama formation, Magna area, Wadi As Sirhan quadrangle, Kingdom of Saudi Arabia, Ph.D. thesis, 239 pp., S. D. Sch. of Mines and Technol., Rapid City, 1982.

A. M. Alamri, Department of Geology, King Saud University, P.O. Box 2455, Riyadh 11451, Saudi Arabia.

C. G. Bufe, U.S. Geological Survey, Box 25046, MS 966, Denver Federal Center, Denver, CO 80225.

F. R. Schult, HQ AFTAC/TTR, Patrick Air Force Base, FL 32925.

(Received October 12, 1990;
revised July 8, 1991;
accepted July 15, 1991.)