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ASYMETRICAL STRUCTURES IN THE GULF OF AQABA

BY

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ABSTRACT

Continental rifting along the Gulf of Aqaba is a complicated tectonic process, which is not completely understood. Interpreting these fracture zones as large-scale, left lateral strike-slip faults, the problem arises that there is no obvious way in which the active faults. This study concerns the asymmetrical structures between the two sides of the Gulf. Also, it is concerned on the location of the depression axis (axis of movement) in between the two borders of the Gulf of Aqaba and the distribution of the seismic activity. By using the simple statistical analysis of the bathymetric digital data and study seismic activity record will carry to study the asymmetrical seafloor structures of the Gulf.

The results demonstrate, according to the distance variation of the borders towards the axial depression and the seismic activity, the Gulf can be divided into three distinct asymmetrical areas, representing different stages in the evolution of the rift. These areas consist of a southern section (from 28.2 ° to about 28.7 ° N) in which slightly seafloor spreading is occurring (the axial depression moved towards the eastern border and has low seismic activity), a central transition zone (from 28.7 ° to about 29.0 ° N) which contains isolated cells of seafloor spreading (the axial depression changes slightly from the eastern towards the western border and has high seismic activity which is concentrated at eastern side), and a northern section (from 29.0 ° to 29.5 ° N) which is currently in the continental rifting (the axial depression lies nearly in the central part between the two borders and it has medium seismic activity which is concentrated at the western side).

INTRODUCTION

The Gulf of Aqaba extends from the Strait of Tiran to port of Aqaba, about 180 km. It is narrow in the north (~5 Km) and widening to the south (reaching a maximum width of 28 Km Opposite Dahab). The Gulf of Aqaba follows a NNE-SSW direction from Aqaba at 29° 33'N 34° 57'E to the Strait of Tiran at 28° N 34° 27'E. The Gulf forms a transition between two tectonic regimes: the extensional Red Sea to the south and the Dead Sea to the north. The Gulf has a maximum depth of about 1850 m (Aragonese deep), the surrounding mountain rising to about 1.5 Km (Fig. 1b). The volume of the Gulf is approximately 2250 km^3 (Bentor et al., 1974, Garfunkel et. al., 1974, Ben-Avraham et.al., 1979a, Ben-Avraham et.al., 1979b, Garfunkel, 1981, Garfunkel et. al., 1981, and Martinez and Cochran , 1988).

The Gulf of Aqaba is characterized by asymmetric basins, Fig.1. There is the suggestion that strike-slip basins with lateral asymmetry are bounded on only one side by transform fault while the other side is a normal fault (Ben Avraham and Garfunkel, 1986, Ben Avraham and Tibor, 1993). The asymmetry in the northern basin (Elat Deep) of the Gulf of Aqaba, is to the east because the fault on the eastern boundary is strike-slip whereas that on the western boundary is predominantly normal. On the other hand, the asymmetry within the southern basin (Dakar Deep) of the Gulf of Aqaba, is to the west, because the fault on the western boundary of the basin is strike-slip. Where as that on the eastern boundary is predominantly normal (Ben Avraham and Zoback, 1992). The asymmetric basins of the Gulf of Aqaba have effect on the asymmetric boundary of the Gulf, Fig. 1(a). So, the study of the asymmetric boundary of the Gulf of Aqaba will be good criteria to understand the effect of the horizontal principal stress along the Gulf.

Geological and geophysical evidence from the Gulf of Aqaba, at the southern part of the Dead Sea rift, and other parts of the rift indicate that two kinds of geodynamical processes occurred in the Gulf of Aqaba simultaneously (Ben Avraham, 1992). The first process is a left lateral transform motion, which has led to a total displacement of 105 km on the faults along the Dead Sea rift since the time of its formation less than 25 Ma (Garfunkel, 1988) and to the formation of a series of pull-apart basins along the entire length of the rift zone. This process occurs in two stages, the first stage, about 65 km, displacement occurred during Miocene and the second stage of rifting, involving displacement of about 40 km took place 4 to 5 million years ago. The second process is a propagation of actual crustal spreading activity from the Red Sea northward into the Gulf of Aqaba (Ben Avraham, 1987, Abdel khalek et al. 1993).

This study concerns the asymmetrical seafloor structures between the two sides of the Gulf. Also, the relation between the borders (two sides) of the Gulf with the main transition strike slip fault. It is interesting focus on the stress effect and the seismic activity along the axial depression of the Gulf of Aqaba.

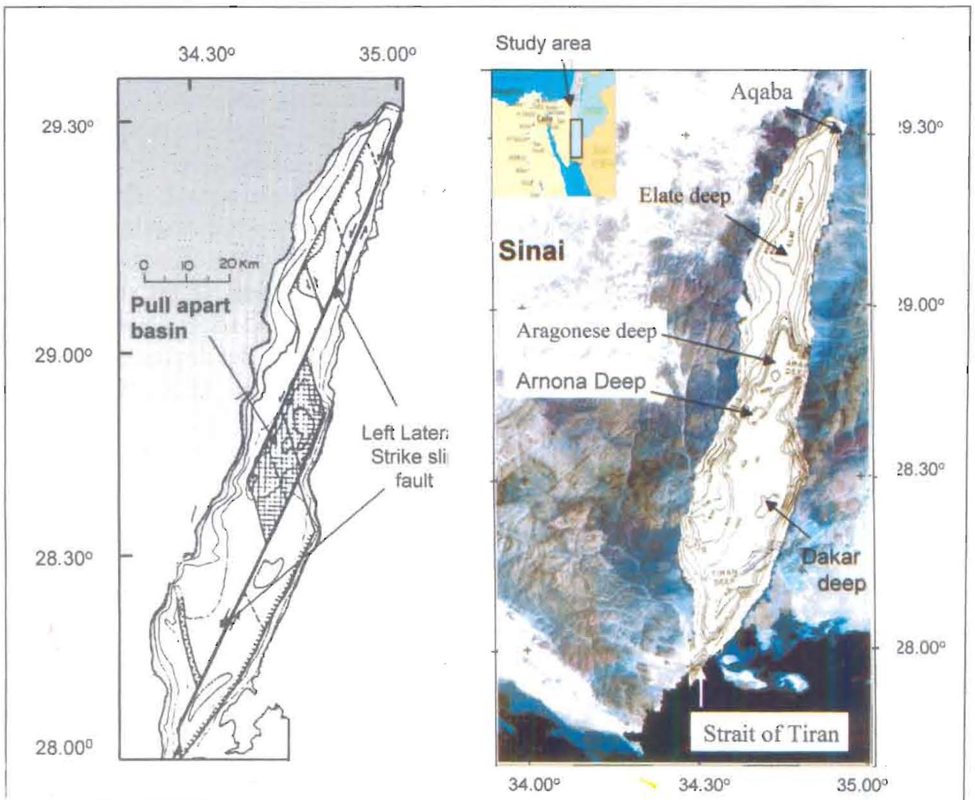

Fig. 1: (a) Structures of the Gulf of Aqaba. (b) The bathymetric map of the Gulf of Aqaba with the Remote sense (M7, 4 & 3) of the study area. Integrated from, Ben Avraham, 1985 and 1987 and bathymetric data of Meteor leg no. 44/3)

BATHYMETRIC STUDY

In 1999, the first authors participated in the cruise "Meteor leg no. 44/3" in the Gulf of Aqaba with a German scientific group. The measurement of the bathymetry was carried out by a swath sounder Hydrosweep while the imaging of the uppermost sediments of the floor is taken by a narrow beam echosounder. Parasound have been also continuously applied during the entire cruise. Also, two other sources of bathymetric data were used: a bathymetric contour map, by Hall and Ben-Avraham, (1978), and digital bathymetric data obtained from the Natural Geophysical data Center (USA).

The result of the digitized bathymetric data of the Gulf of Aqaba is represented in 3 D, Fig. 2(c). It shows that the eastern part is deeper than the western part (about 100 m to 500 m). So, there is asymmetry in a cross section alone the sea floor between the eastern and western borders of the Gulf. The Gulf of Aqaba is occupied by three elongated en echelon basins, which strike N20°-25°E. Undulations in the floors of basins produce several distinct asymmetrical deeps, which are named Elat, Aragonese, Arnona, Dakar, and Tiran. The maximum depth observed on the eastern side is about 1540 m (Arnona deep, B`), and the western side is about 1850 m (Aragonese deep, B). Related to seismic and crustal structure study of Hamouda, 2000, the horizontal separation distance between the two deepest points (B & B`) is related to the movement of each side of the Gulf along the left lateral strike slip fault. The displacement between the two deepest points (B & B`) is nearly equivalent to 0.18° (i.e. about 20.4 km) and is assumed to be achieved in about 4.08 to 3.4 million years ago, according to the estimated rate of the transform motion along the Gulf of Aqaba (Dead Sea transform) which is about o.5 to o.6 cm/y, (Joffe and Garfunkel, 1987).

Faults bounding the deeps (Elat, Aragonese and Dakar) are part of the transform fault system but also have a large component of vertical displacements. They are usually straight and form two main systems with different orientations, i.e., N20°-25° E parallel to the axis of the Gulf, and NNW (i.e. pull apart basin). Both apparently show strike slip as well as dip slip motion. The deeps were produced by these two main fault systems. Active normal faults run along the sinuous western and eastern coasts and have a zigzag shape (Abdel Khalek et.al.1993). the direction of the fault plane dose not exactly corresponds to the direction of spreading on either side so that there is a component of extension across the fault. When extension occurs the fault may adjust its trajectory so as to become approximately parallel to the main spreading direction by devolving into a series of fault segments (Zigzag shap) joined by small length of spreading center.

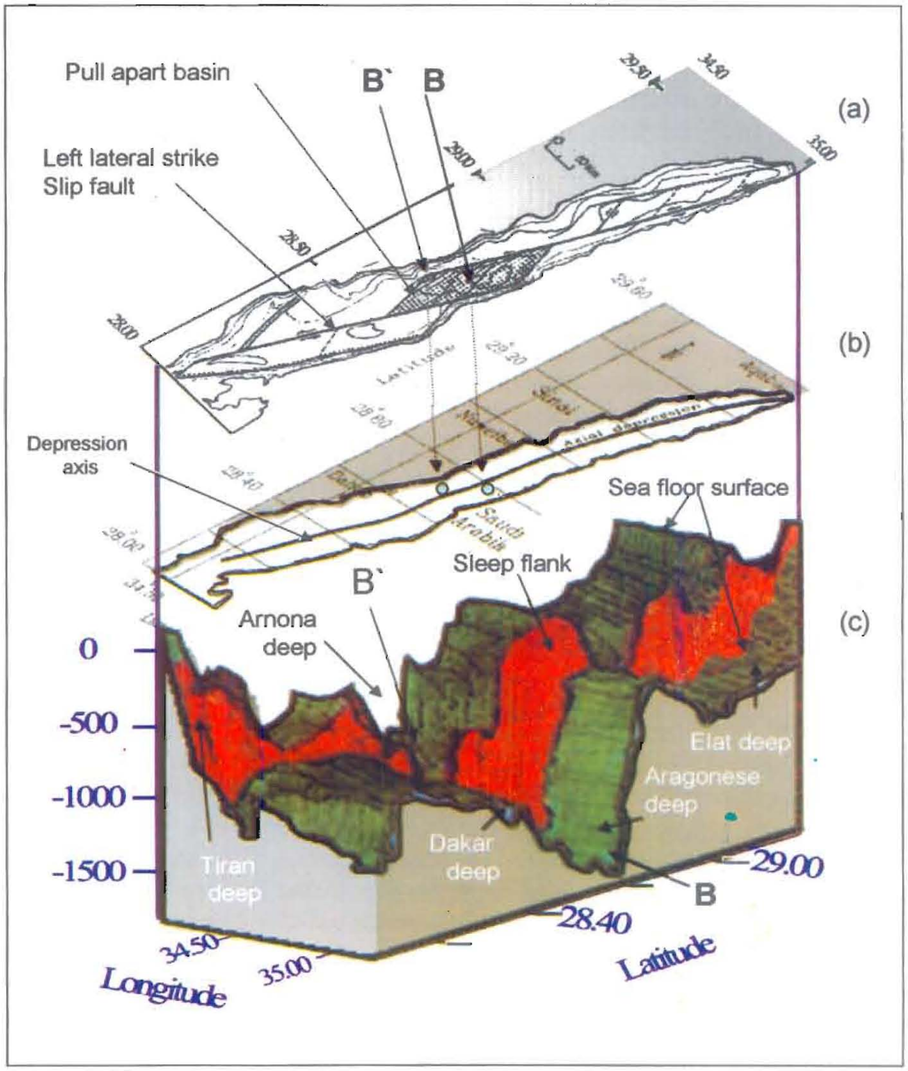

Fig. 2: (a) The asymetrical structure of the Gulf of Aqaba (after Ben Avraham, 1985). (b) the depression axis along the Gulf of Aqaba. (c) the 3 D structure of see floor of the Gulf of Aqaba, (a) and (b) based on the Bathymetric data.

The Gulf of Aqaba has been identified as the marginal areas and the axial depression (reasonable to the main left strike slip fault of the Gulf) where the movement occurs along this axis. The marginal areas form a series of bathymetric terraces that step down from the eastern and western shelves towards the central part. The determination of the axial depression was revealed from the digital bathymetric data, by using the Fortran software. This software detects the points, which have high abrupt variation (from the mean values along each horizontal profile) of the sea floor.

The axial depression is a nearly narrow zone, which is characterized by abruptly descending depth and located near the center of the Gulf of Aqaba, except, in the southern part where it shifts to the east in alignment after the entrance from the Strait of Tiran. So, the area, which we refer to as the axial depression, is a region of abrupt variation in deeper sea floor. The depth along the axial depression ranges from -600 m to -1500 m depth and is generally about 1 km wide, Fig. 2 (b & c). This area may represent the zone of main movement of the Gulf of Aqaba. The axial depression may be reasonable to the main axis of the lateral strike slip fault. So, the continental rifting in the Gulf of Aqaba has progressed nearly to the point of initiation of seafloor spreading and has resulted in the formation of two morphological provinces within the main trough, which are referred to here as the marginal areas and the axial depression.

STATISTICAL STUDY

Bonatti (1978) considers that the most reasonable mechanism for uplift is compressional (and tensional) horizontal stresses across the fracture zone which originate from small changes in the direction of spreading, so that transform movement is no longer exactly orthogonal to ridge. Several small changes in spreading direction can give rise to episodic compression and extension affecting different parts of fracture zone. Fig. (3) shows the strain ellipsoid for strike-slip faults. The strain ellipsoid shows the possibilities for transferred motion to thrust or normal-slip domains. Also, it shows that the fundamental basis of strike-slip faults is horizontal compression. It is the main stress, which controls this movement (rate of movement and direction). So, the position of the axis of movement (axis of extension) depends on the direction of the compression stress (perpendicular to each other), which has an effect on the strain ellipsoid (between the boundaries of the strike slip zone).

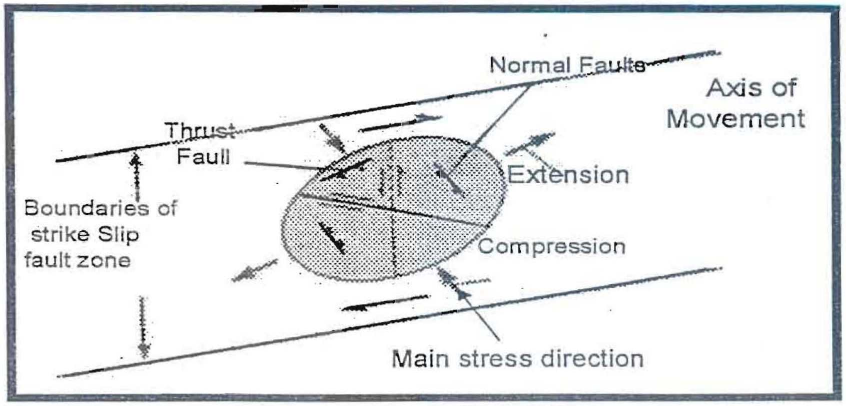

Fig. 3: the strain ellipsoid for the strike- slip faults, after Stylvester (1988).

This study is concerned with the position of the axial depression (axis of extension) in between the two borders of the Gulf of Aqaba. The location of the axial depression towards to the two borders of the Gulf depends possibly on the variation of compressional stresses, which attached the weak points of the axial depression, i.e. the fracture zone. When the continental plates of Saudi Arabian and Sinai are subjected to extension approximately parallel to these lines of contact, an incipient fracture may develop which is largely perpendicular to the direction of tension. The vicinity of the lines of weakness, however these lines or old fractures lines will be reactive. So, the maximum horizontal compressive stress from the two borders will be perpendicular to the axis of extension (main strike slip fault), which is reasonable to the main axial depression, Fig. 4.

The axial depression will be divided into equal distances; each interval is 2 km. The axial depression will has about 68 fixed points. The tangential line will be done at each fixed point after then determine a perpendicular distance on the tangential line at each points to the border of the Gulf at each side. The variations of these perpendicular distances are related to the variation of the asymmetrical location of the axial depression towards the two borders of the Gulf. Z_E and Z_w are the perpendicular distances (may be parallel to the direction of compressional stress which has effect on location and orientation of the main axial depression along the Gulf of Aqaba), Fig.4. So, the Z_{E1} and Z_{w1} are the perpendicular distance from point no. 1 at the depression axis towards the eastern and western borders respectively. Also, the calculation differences between each successive distance (Δ Z_E and Δ Z_W) are to help to make a focus on the points along the depression axis, which has abrupt variations.

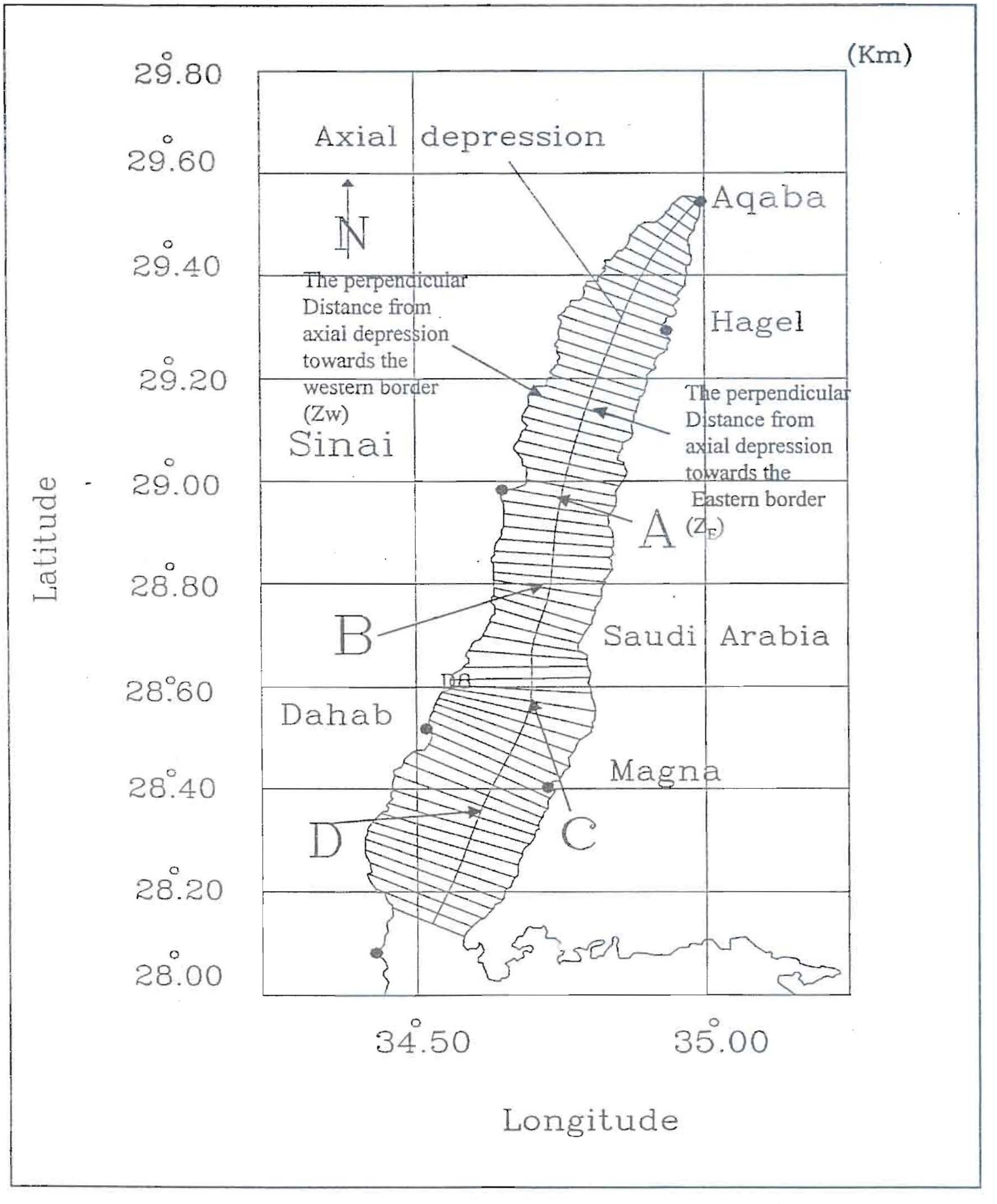

Fig. 4: The estimated axial depression and perpendicular distance (ZE and ZW) along this axis towards the eastern and western borders of the Gulf. The areas (A, B, C and D) are direction changes of the ZE and ZW .

$\Delta Z_{E1} = (Z_{E2}-Z_{E1})$ .... (1)

ΔZ_{E1}: The difference values between the two successive perpendicular distances of the points 1 and 2 towards the eastern border.

$\Delta Z_{W1} = (Z_{w2}-Z_{w1})$ .... (2)

ΔZ_{w1}: The difference values between the two successive perpendicular distances of the points 1 and 2 towards the western border.

Figure (5) represented the values of Z_E, Z_w, ΔZ_E and ΔZ_W. The northern part (Elat deep) until point no. 24 the main axial depression may be located in the mid distance between the two borders, Fig. 5. The northern part until point 24 characterized by the Z_E is nearly equal or slightly less than the values of the Z_w. The similarity of separation distance of each sides (Z_E and Z_w) along the depression axis of movement (axis of extension is slightly between the two borders), may be this part exposed to the similarity of the compression stress towards the axis of movement from the each side. The central part (Aragonese deep) from point 25 to 39 at the depression axis is slightly towards the Eastern border. Where the values of Z_w will slightly increase compare to the values of Z_E. This change will be related to the characteristics of the pull part basin of this area, where the movement along the strike fault will change from the eastern side (extend from south) to the western side (extend to the north), Fig. 1 (a).

Fig. (5) shows the two main inflection points (A) and (B). The first point (A) located between the northern and middle parts, and the second inflection point (B) is between the middle and southern parts. After each inflection point A and B there is an abrupt change of the distance values Z_E and Z_w. This may indicates that the Gulf of Aqaba has two main tectonic movements or tectonic cycle. These tectonic movements characterized by an increasing separation between the two borders and affect the direction of the depression axis.

In the southern part (Dakar and Tiran deeps) from point 42 to 62 the main depression axis will be mainly towards to the Eastern side, and the distances of the Z_w is longer. There is abrupt changes of the values (Z_E and Z_w) in between Dakar and Tiran deeps (c) and also, at the south of Tiran deep (d). These deeps may have effect on the location of the movement main left strike slip fault of the Gulf. Also, the crustal structure of the southern part of the Gulf more closely resembles oceanic structure than that in the north (Ben Avraham, 1985), suggesting that sequential tectonic stages may propagate along the Gulf from south to north, where the heat flow increases from north to the south in the Gulf. This increase may be related to the more advanced rifting stage of the Red Sea immediately to the south, which presently includes the creation of oceanic crust. According to Abdel Khalek et. al., (1993), this separation followed by slight clockwise rotation of the Sinai subplate which clearly appear in the southern part of the Gulf. The deeper structure within the gulf suggests that a transition takes place between crustal spreading in the Red Sea to transform structures along the Dead Sea.

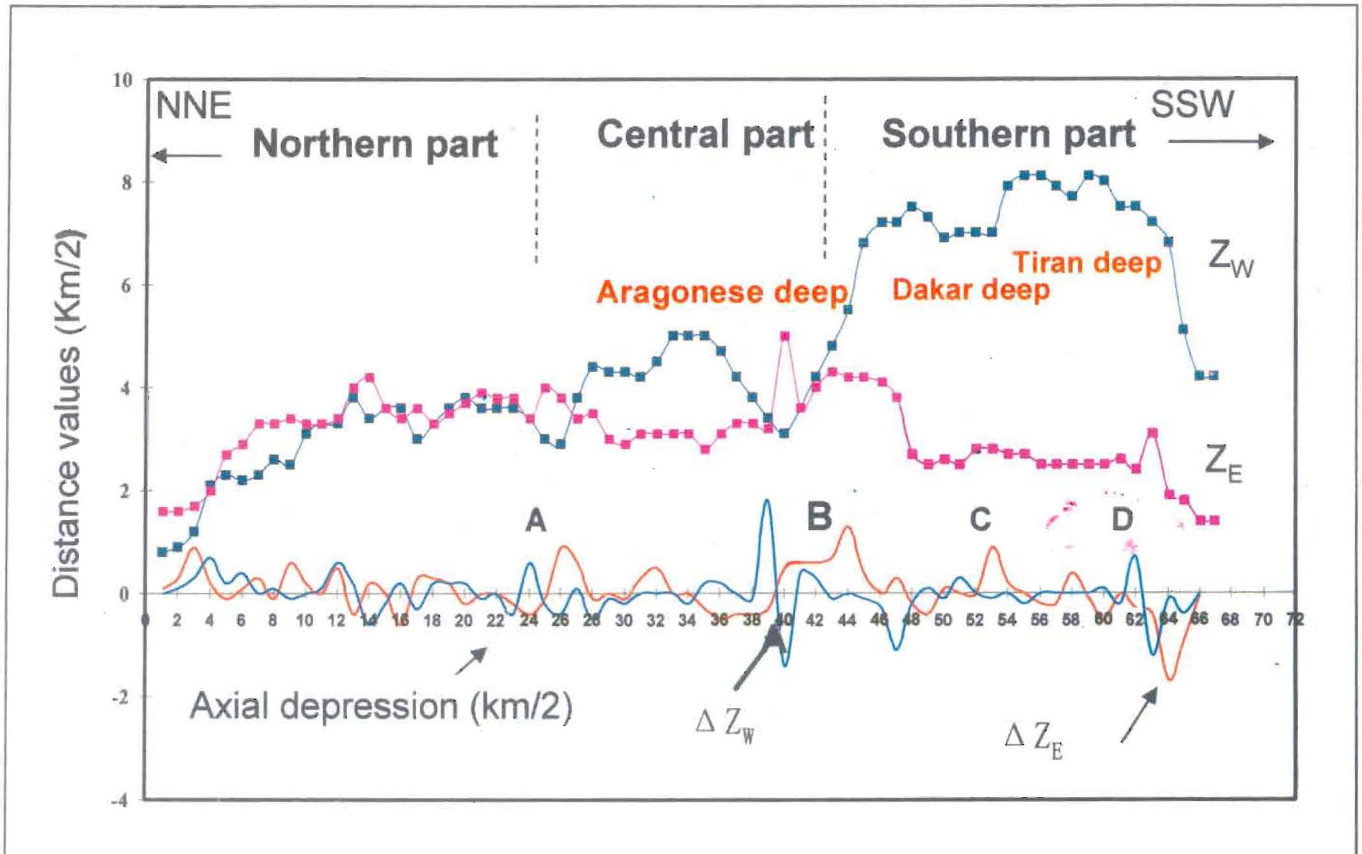

Fig. 5: The distance values of Z_E, Z_W from the depression axis toward the borders (east and west) of the Gulf. The ΔZ_E and ΔZ_W are difference successive distances at each side.

The irregularity of the values of the Z_E and Zw reflects the irregularity of the borders toward the depression axis. The stability of the boundaries between plates is dependent upon their relative velocity vectors. If a boundary is unstable it will exist only instantaneously and will immediately devolve into a stable configuration.

According to the various distance from the borders towards the axial depression, the Gulf may be divided into three distinct asymmetrical areas that have been interpreted as representing different stages in the evolution of the rift. These areas consist of a southern section (from 28.2 ° to about 28.7 ° N) in which active seafloor spreading is occurring (the axial depression towards the eastern border), a central transition zone (from 28.7 ° to about 29.0 ° N) which contains isolated cells of seafloor spreading (the axial depression change slightly from eastern towards the western border), and a northern section (from 29.0 ° to 29.5 ° N) which is currently in the stage of continental rifting (the axial depression is in the central part between the two borders).

SEISMIC STUDIES

Sylvester (1988), has suggested that the small amount of dip-slip motion could give rise to fracture zone seismicity and deformation of rocks within the floor and walls. A rupture typically starts as small crack, which grows rapidly as it propagates (along the fault). As the rupture propagates, elastic energy stored in the rocks on either side of the fault is radiated in form of seismic waves. The size of the accompanying earthquake depends on two factors. The first is the amount of elastic energy per unit area of the fault released at the time of the rupture. The second is the area or length of the rupture. The latter is the most variable of the two factors and largely determines the size of the earthquake. In the largest earthquakes the rupture propagates for several hundred kilometers whereas in the small detectable earthquakes the rupture may propagate for only few kilometers or less.

The authors collected the data of earthquake events (Magnitude $\geq$ 3 Richter) during the period 1900 to 2000, from different sources: the International Seismological Center (ISC), National Earthquake Information Center (NEIS), National Research Institute of Astronomy and Geophysics (NRIAG), The Egyptian Geological Survey & Mining Authority (EGSMA), National Research Institute of and Jordan Seismological Observatory. From the collected data (earthquakes activity from 1900 to 2000) the authors introduce in three dimensions the location of these events by using the Fortran software, Fig. 6.

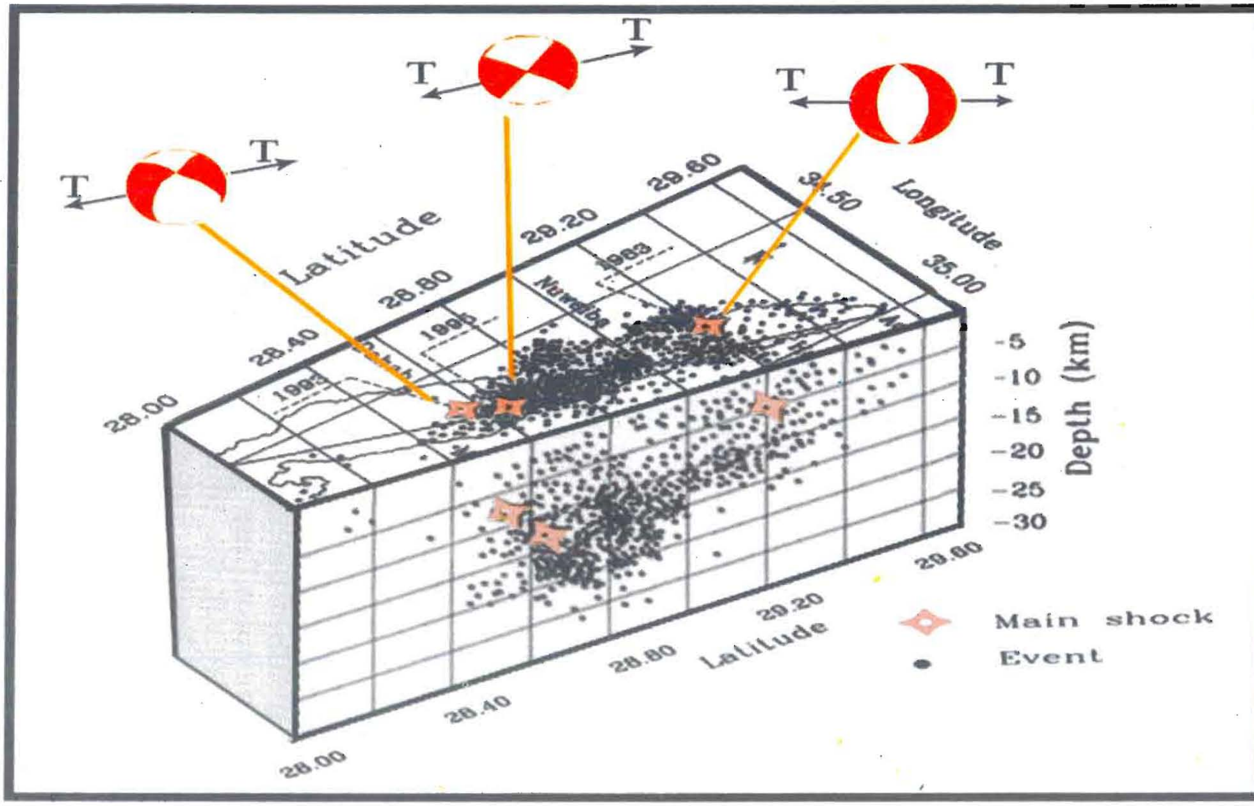

Fig. 6: The earthquakes activity (3 D) along the Gulf of Aqaba from (1900 to 2000), based on the recorded data of NEIS, ISC, NRIAG and EGSMA. The focal mechanism for the mainshock of 1983 is normal faulting, mainshock of 1993 has normal faulting mechanism with minor sinistral strike slip component (Abdel-Fattah et., 1997). The mainshock, 1995, Left lateral strike slip motion with a minor normal component (Hamouda, 2000).

The epicenters of events appear to be concentrated in the middle parts (Aragonese deep) and extend to the northern part. Also, In the central part (Dakar and Aragonese deeps) most epicenters are on the eastern side. In the northern part most epicenters are in the western side of the main strike slip fault of the Gulf (many overlaps of epicenters). There are three large mainshocks observed in the Gulf of Aqaba from 1900 to 2000, two of them observed in the central part (1993 & 1995) and one mainshock located in the northern part (1983). The local magnitude of these mainshock in the northern part is 5.3 (Richter scale) in 1983, and in the central part the local magnetudes are 5.6 and 7.2 in 1993 and 1995 respectively). The northern mainshock is located along a normal fault, where as the southern mainshoks are located along the main strike slip faults of the Gulf. The best fitting focal mechanism for the mainshock of 1983 is normal faulting, mainshock of 1993 has normal faulting mechanism with minor sinistral strike slip component (Abdel-Fattah et al., 1997). The focal mechanism for the mainshock of 1995 has a left lateral strike slip motion with a minor normal component (Hamouda, 2000, Fig. 6).

The concentration of the epicentral events of magnitudes greater than or equal three of Richter scale ($Mg \geq 3$) are located in the eastern side of the central part on the Gulf. This means that this part is the main source of high storage and release of energy in the Gulf of Aqaba. The second activity zone is located at the eastern side of the main strike slip fault (north Nuweiba, latitude 29.2°). The southern part (from Dakar to the Strait of Tiran) has a low seismic activity and magnitude ($Mg < 3$) not located in Fig. 6. According to Hussein et al., (2001) the friction along the axial depression and the separation distance between the two borders of the Gulf in the central part (width about 18 km) may tend to be as separated like the southern part (more separated about width 28 km). This movement is followed by this seismic activity in the central part. Also, according to Hamouda (2000) and El-Gendy et al., (2001), the spatial distribution of events, show an end-to-end migration of sources from the central part of the Gulf to the southern part. This may indicate that the sequential tectonic stages are propagating along the Gulf from south to north.

The hypocenters are also shown in Fig. (6). Most hypocenters are located between latitude 28.4° to 28.8° (in the central part of the Gulf) at depths from 8 km to 20 km. The northern hypocenters are shallower than the central part where generally the maximum depth is about 15 km. This indicates the influence of oceanic lithosphere in the central part where the hypocenters are generally slightly deeper. The hypocenters of the mainshocks in the central part are about 8 km and 12 km (1993 and 1995 respectively). The hypocenter of the northern mainshock is about 5 km. The seismic activity may be transfered from the central part towards the northern part. So, the central part of the Gulf is considered to be the most tectonically active part. It has the deepest seismic activity that is observed on the recorded data from 1900 to 2000. Also, there is an asymmetrical distribution of the seismic activity along the Gulf, which follows the trend (asymmetrical location) of the main strike slip fault of the Gulf. The seismic activity may be related to the tectonic movements along the axial depression of the Gulf. Along other parts of the fault where friction is high, plates tend to get stuck temporarily. Continued plate motion produces distortion in the form of elastic strain at the vicinity of the rough spots. Rocks, since they are elastic, resemble springs in being capable of storing up elastic energy when stretched or compressed. Prior to an earthquake, the rocks along a fault can be regarded as a spring-loaded system waiting to go off. Eventually, one more millimeter of plate motion provides the frictional forces are exceeded, and the rocks on either side of the fault suddenly leap past each other in opposite directions.

CONCLUSIONS AND DISCUSSION

Generally, the eastern side along the main axis of the sinistral strike slip fault boundary is deeper (about 100 m to 500 m). Thus the sea floor of the Gulf is asymmetric in a cross section. This asymmetry could be attributed to simultaneous strike-slip motion. The deepest point (central part of the Gulf) observed on the eastern side is about 1500 m (Arnono deep), and the western side is about 1850 m (Aragonese deep). This indicates that each side of the Gulf (including the deepest point) move in different direction along the main left lateral strike slip fault. of the Gulf. So, the horizontal displacement between the two deepest points is nearly equivalent to 0.18° (i.e. about 20.4 km) and is assumed to be achieved in about 4.08 to 3.4 million years ago, according to the estimated rate of the transform motion along the Gulf of Aqaba (Dead Sea transform) which is about o.5 to o.6 cm/y.

The axial depression of the Gulf is a very narrow zone (about 1 km wide), which is characterized by steep flanks and located near the center of the Gulf of Aqaba, except, in the southern part where it shifts to the east in alignment after the entrance from the Strait of Tiran. The depth along the axial depression ranges from 600 m to 1500 m depth. This area may represent the zone of main tectonic movement of the Gulf of Aqaba. The axial depression coincides with the main tectonic axis of the left lateral strike slip fault.

The concentration of seismicity ($Mg \geq 3$) is located in the eastern side of the central part of the Gulf. This means that this part is the main source of high storge and release of energy in the Gulf of Aqaba. Also, the second activity zone is located in the eastern side of the main strike slip fault (north Nuweiba, latitude 29.2°). The southern part (from Dakar to the strait of Tiran) has only minimum seismic activity ($Mg < 3$).

Most hypocenters are located between latitude 28.4° to 28.8° (in the central part of the Gulf) at depths of 8 km to 20 km. The northern part hypocenters are shallower than the central part. The asymmetrical distribution of the seismic activity along the Gulf may affect by the trend (asymmetrical location) of the main strike slip fault of the Gulf. This seismic activity may be related to the movement along the axial depression in the central part of the Gulf, a process sometimes described as a seismic creep.

The southern part may be an older tectonic movement compared to the northern part, but the central part may represent the transition zone between them. From the seismicity studies, it is clear that the deep seismogenic activity was located in the region of Aragonese basin than the other basins located along the Gulf of Aqaba and the Elate basin where they are mostly characterized by shallower seismic activity. So, the central and deepest part of the Gulf is the most tectonically active and has deeper seismic activity. In this region it can be demonstrated that distributed deformation does not play a significant role; all creep activity are closely associated with faults of basins. So, the active thickness of the seismogenic region is nearly about 22 km. The lateral and vertical variations of the deformed layers are indications of variable earthquake intensities and/or epicentral distances and amounts of possible associates.

The irregularity of the rupture lengths and the complicated different structures of the Gulf of Aqaba are lead to complex seismic activity, which is observed from the locations of epicentral zones and the recurrence of earthquakes. So, the variations in earthquake source parameters can be used to describe the complexity of earthquake rupture and to discriminate between the earthquakes occurring at different sites.

According to the of the variation distance the borders towards the axial depression and the seismic activity, the Gulf can be divided into three distinct asymmetrical areas, representing different stages in the evolution of the rift. These areas consist of a southern section (from 28.2 ° to about 28.7 ° N) in which slight seafloor spreading is occurring (the axial depression towards the eastern border and low seismic activity), a central transition zone (from 28.7 ° to about 29.0 ° N) which contains isolated cells of seafloor spreading (the axial depression change slightly from eastern border towards the western border and has high seismic activity which concentrated at eastern side), and a northern section (from 29.0 ° to 29.5 ° N) which is currently in the continental rifting (the axial depression nearly the central part between the two borders and medium seismic activity which concentrated at the western side).The activity of earthquakes along the Gulf of Aqaba clearly shows the urgent need for an assessment and rehabilitation program to mitigate seismic risk hazard in building structures.

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