PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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J. J. Jarrige, P. Ott d'Estevou, P. F. Burollet, J.-P. Thiriet, J. C. Icart, J. P. Richert, P. Sehans, C. Montenat and P. Prat

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Inherited discontinuities and Neogene structure: the Gulf of Suez and the northwestern edge of the Red Sea†

By J. J. Jarrige,[1] P. Ott d'Estevou,[2] P. F. Burollet,[3] J.-P. Thiriet,[3] J. C. Icart,[1] J. P. Richert,[1] P. Sehans,[1] C. Montenat[2] and P. Prat[2]

[1] *Elf Aquitaine Company, Tour ELF,* 92078 *Paris La Defense, Cedex* 45, *France.*
[2] *I.G.A.L.,* 21 *Rue d'Assas,* 175270 *Paris, Cedex* 06, *France.*
[3] *C.F.P. – Total Company,* 39–43 *Quai André Citroën,* 75739 *Paris, Cedex* 15, *France.*

The Gulf of Suez and the northern Red Sea rifts are the result of intracontinental deformation during Neogene times. The initiation and the development of the rift are controlled by

(i) four main trends of faults: N140°–N150°; NS to N20°; sub E–W; and N40°–60°;
(ii) a zigzag faulting pattern;
(iii) two main tectonic events. The first is characterized by strike-slip displacements inducing the formation of antithetic tilted blocks. The geometry of the blocks changes according to their orientation. Complex structures can result from the combination of several trends. Vertical movements are weak. The second is characterized by synthetic normal movements forming a horst and graben pattern. Vertical displacements are important and induce the generation of the axial trough and uplift of the shoulders of the rift.

The zigzag pattern of the faults that govern the Rift and the initial strike-slip displacements cannot result from a simple extensional model but imply a reactivation of inherited discontinuities in the Miocene stress system induced by the northern convergent boundaries of the African and Arabic plates.

The major trends of faults that control the Neogene structure have been active in this area since Palaeozoic or even Proterozoic times.

1. Introduction

This paper shows the main results of the geological surveys started in 1982 by teams of the Genebas working group. These surveys were done on both shores of the Gulf of Suez and the western side of the Red Sea. The objective of the working group is to study the origin and evolution of sedimentary basins, of which the Gulf of Suez and the Red Sea are good examples.

After an initial survey, various areas were selected (figure 1). A geological map as well as detailed sedimentological and structural studies were made for each of these areas. At the same time, Landsat images of the whole area were analysed (Henry 1985).

2. General setting

The Red Sea rift separates the African and Arabian shields. This 200 km wide NW–SE structure results from continental rifting initiated about 25 Ma ago. The southern part is characterized by sea-floor spreading that occurred 4–5 Ma ago and the northern part corresponds to a less advanced stage of continental rifting (Cochran 1983).

† Contributed by the Genebas Group.

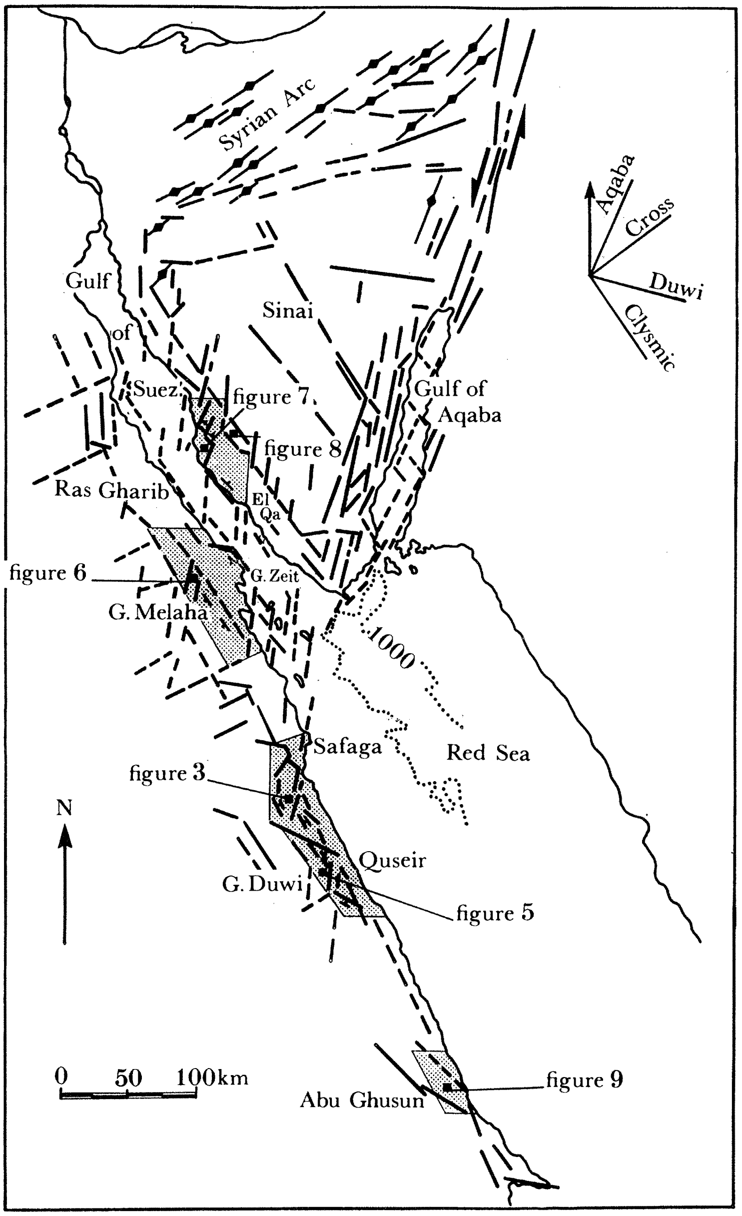

FIGURE 1. General structural framework showing position of the areas studied in detail.

In the area under consideration, the Red Sea rift is divided into two parts. The first part trends NW–SE, and corresponds to the Gulf of Suez rift; the second part trends NNE–SSW, and corresponds to the sinistral shear zone of the Gulf of Aqaba–Dead Sea (Eyal *et al.* 1981, Bahat & Rabinovitch 1983). The NE–SW Syrian arc, folded initially in the Cretaceous and later in the Miocene, occurs to the north (Bartov *et al.* 1977). Three main units outcrop in the studied area.

(i) The Arabian–Nubian shield whose cratonization ended with a strong magmatism contemporaneous with the Panafrican phase (above 500 Ma ago).

(ii) An unconformable platform cover consisting mainly of Cretaceous and Eocene rocks on the western side of the Red Sea. In the Sinai area, units of Palaeozoic to Jurassic age also occur. These series have been thoroughly studied in the Sinai area (Robson 1971; Garfunkel & Bartov 1977).

(iii) The Neogene syn-rift series, made up of four main units:

(*a*) Unit A (Aquitanian – lower Burdigalian): confined or continental series (western side) and marine series (Sinai). This unit is contemporaneous with basaltic volcanism dated at 20–24 Ma (Garfunkel & Bartov 1977);

(*b*) unit B (upper Burdigalian to lower Serravallian): marine series with various facies: reef, globigerine marls and conglomeratic fans;

(*c*) unit C: main evaporatic deposits;

(*d*) unit D: (Pliocene–Pleistocene): carbonate or detrital marine deposits.

Unit A overlies the platform cover either with a weak unconformity or with conformity. In addition, two well defined unconformities appear in the syn-rift series between units A and B and between units B and C. The stratigraphy and sedimentology of these series will be described in another paper, to be published by the Genebas Group (Burollet *et al.* 1985).

3. Main structural trends

Four main fault trends can be determined from observations on various scales.

(i) Clysmic trend, N140°–150°, parallel to the Gulf of Suez and Red Sea axis, frequently observed.

(ii) Aqaba trend, N–S to N20°, occurring as large bundles of which the main one corresponds to the Aqaba alignment.

(iii) Duwi trend, sub E–W, characterized by faults forming narrow bundles, N100°–120° oriented to the South of Safaga and N80°–90° or N100°–120° in the Gulf of Suez.

(iv) Cross trend, N40°–60°, frequent in the vicinity of the Gulf of Suez, corresponding there to the main direction of Precambrian basement dykes. In the north, it corresponds to the general direction of the Syrian Arc folds.

4. Zigzag faulting pattern

The rift structure is mainly characterized by brittle deformation leading to the formation of tilted blocks. This is primarily a result of basement competence and the small thickness of the overlying cover. Some folds can also be observed. They are due either to the draping of the Mesozoic or Miocene layers over buried faults or to the occurrence of structures connected with shear zones (as described below).

The governing fault system rift structure has a zigzag pattern formed by combinations of all the previously described directions, whatever the scale (Garfunkel & Bartov 1977; Richert *et al.* 1984) (figure 2).

Because of this complex pattern and contemporaneous movements on faults of various directions, the structure cannot be the result of a model of simple extension inducing the formation of neoformed faults. Instead, inherited discontinuities are reactivated. The size and complexity of blocks in any one area will depend on the number of trends that occur.

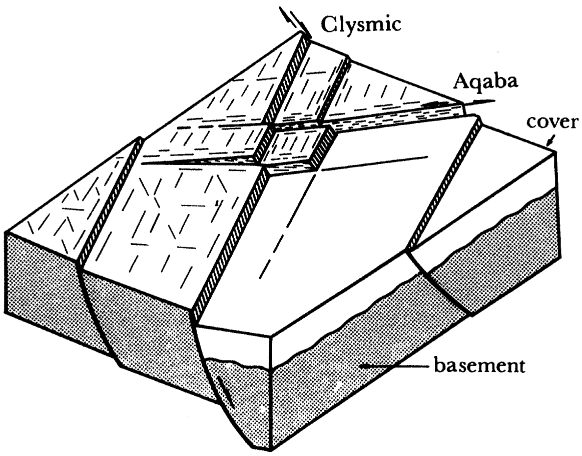

FIGURE 2. Schematic zigzag faulting pattern between Aqaba and Clysmic trends.

5. STRUCTURAL EVOLUTION OF THE RIFT

Superimposed tectonic deformations were observed in some places during field studies with two sets of movements on the fault planes, one set of faults cutting another or a fold cut by a fault. These occurrences are coherent and involve two main phases in the tectonic evolution of the rift (Richert *et al.* 1984). The effect of these two phases can be observed on one cross section in the Safaga area (figure 3).

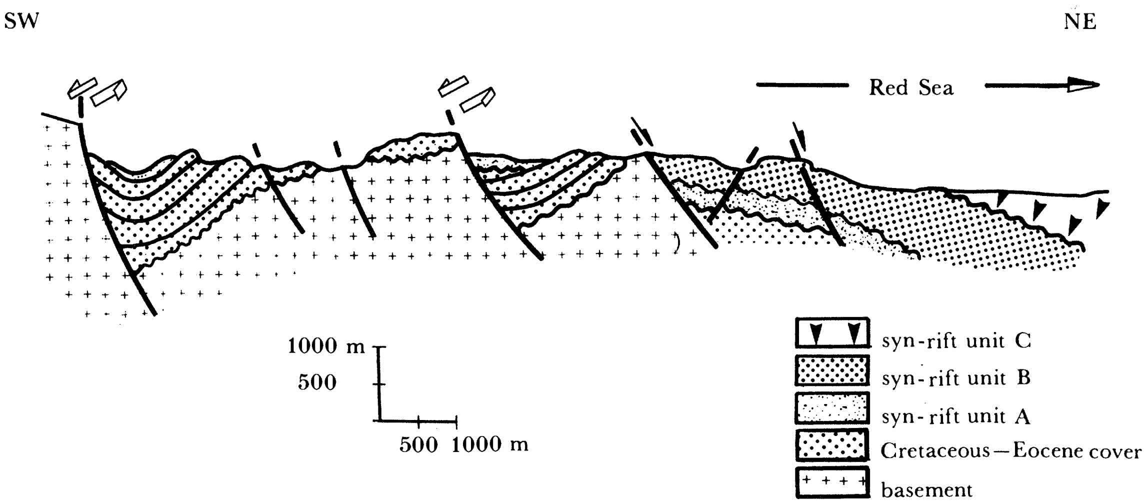

FIGURE 3. Cross section of the Safaga area (located in figure 1) showing the deformations induced by the first, antithetic phase (western part) and by the second, synthetic phase (eastern part).

Phase 1 affects the rift sub-stratum and is contemporaneous with deposition of syn-rift unit A. It is characterized by the following deformations: sinistral movement of the Aqaba faults; dextral movement of the Duwi faults; normal movement of the Clysmic faults (a few dextral and sinistral movements were also observed); and local deformations of little developed Cross faults: reverse faults in connection with folds.

During this phase, the rift is deformed right across. The faults are antithetic, causing a tilting of blocks. Vertical movements are of little importance and basaltic volcanism is present.

Phase 2 starts with deposition of syn-rift unit B and is still developing now. Faults of all four trends are normal.

During this phase, deformation mainly affects the central part of the rift. The faults are synthetic, causing the formation of an horst and graben pattern. Vertical movements are significant, generating the axial trough and uplift of the rift shoulders (Chenet & Letouzey 1983; Selwood & Netherwood 1984).

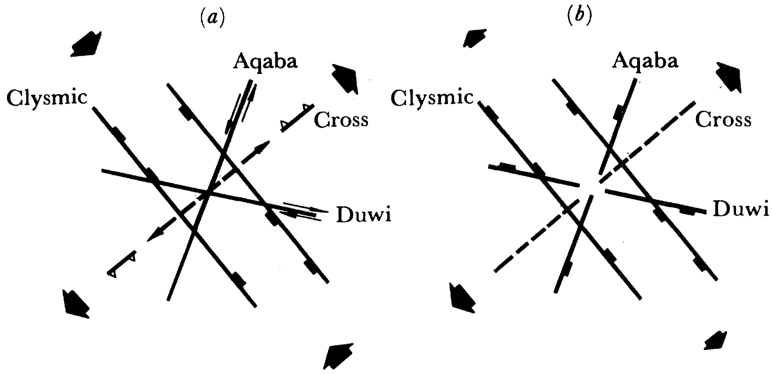

FIGURE 4. Characteristics of the two tectonic phases that control the initiation (*a*) and the development (*b*) of the rift.

The deformations linked to phase 1 are coherent and homogeneous in a stress system characterized by NW–SE compression and NE–SW extension in the horizontal plane (figure 4*a*). This system is coherent with the Syrian Arc folding deformation observed in the north (Garfunkel & Bartov 1977; Richert *et al.* 1984; Jordi 1984).

On the other hand, phase 2 is characterized by a horizontal multi-directional extension (fig. 4*b*).

6. Characteristics of the initial tectonic phase

The initial phase shaped the rift sub-stratum and, therefore, was essential for its future evolution.

(*a*) *Block geometry by one direction*

In the Gebel Duwi area we can determine the differences between the geometry of the different blocks and the relation to fault directions as they are not concealed by syn-rift deposits (figure 5).

A wide antithetic half-graben (about 7 km × 30 km) extends along a Clysmic fault (figure 5*a*). Field observations show that this fault is normal. Large blocks tilted in this direction have been observed in other places, for example, Gebel Melaha, Gebel Zeit, Gebel Abu Durba.

Two small half-graben (about 1.5 km × 5 km) extend along the Aqaba faults (figure 5*b*). Structural observations show that these faults are of the strike-slip type.

Such sub-meridian structures have also been observed in the Safaga area (figure 3) and in the northern end in the Gebel Melaha where they are shaped as small synclines. There, sinistral horizontal slickensides, overturned layers of Eocene or Miocene A age and associated folds with a more or less plunging axis can be observed along the faults (figure 6).

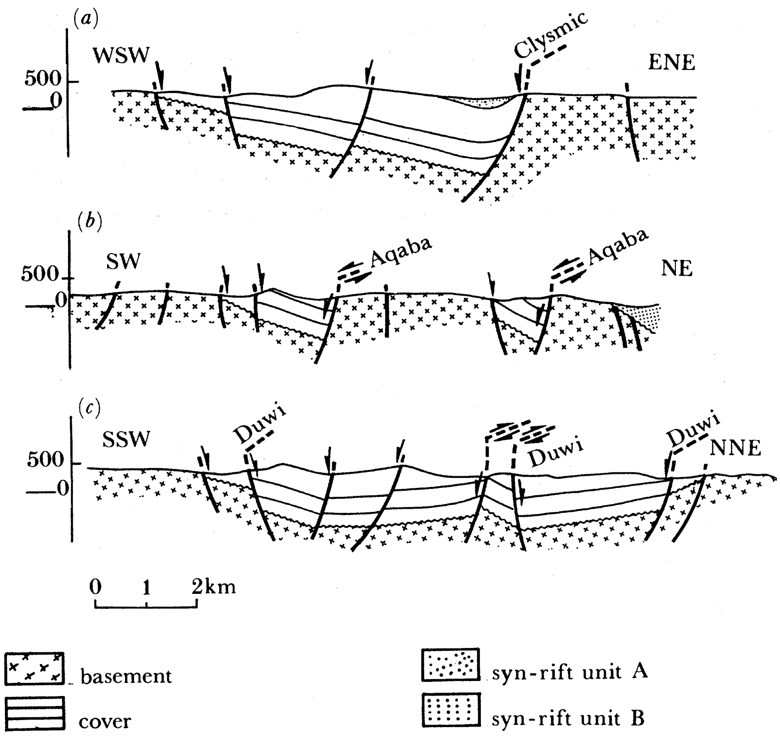

FIGURE 5. Cross sections in the G. Duwi area (located in figure 1). (*a*) Clysmic structure; (*b*) Aqaba structures; (*c*) Duwi structure.

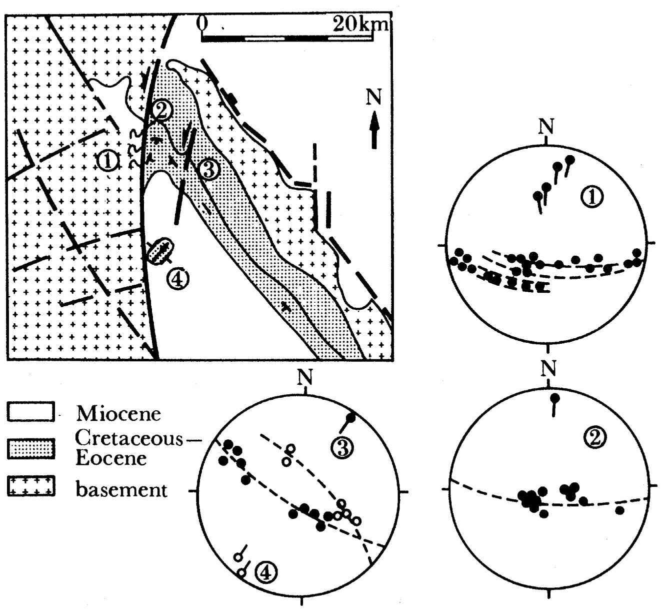

FIGURE 6. First-phase deformations in the Tarbul area (located in figure 1). The stereonets summarize the folded deformations observed along the Aqaba strike-slip faults (Wulf stereonet, upper hemisphere).

An 8 km wide symmetrical graben extends along Duwi faults (figure 5*c*). The vertical movements are weak and the substratum cover is cut by dextral strike-slip faults associated with subvertical folds. As observed on the norther border of the El Qa plain (western coast of Sinai), the N100° flexures of the cover are affected by minor N10°–30° sinistral and N120° dextral displacements, which are also indicative of transpression in the Duwi direction.

(*b*) *Geometry resulting from combined directions*

As the rift structure is controlled by a zigzag fault pattern, the geometry is more complex and the blocks are smaller in those areas where several trends are expressed.

(i) *Combined Clysmic and Aqaba directions*

The resulting geometry is well defined in the Abu Rudeis area (figure 7).

Anticlinal and synclinal folds can be observed in the sub-stratum cover and in syn-rift unit A, mainly at the end of the major Aqaba faults. They are interpreted as accommodation compressional structures. Combined Aqaba and Clysmic trend movements generate pull-apart structures. The distribution of extensional and compressional areas is in conformity with theoretical models (figure 7*b*; Xiahoan 1984). The folds are sealed by deposits of the Miocene unit B.

(ii) *Combined Duwi and Clysmic directions*

The half-graben structure in the Clysmic direction may be complicated locally by Duwi faults. These faults control E–W trending borders where the half-graben structure can be replaced by an en echelon graben geometry (figure 8). This configuration, well expressed in the Wadi Feiran area, features a real or potential dextral displacement. Between the two Duwi faults, the cover directly overlies basement on the border of the rift, showing that vertical movements are weak in areas controlled by Duwi faults as in the Gebel Duwi zone (figure 5*c*).

(iii) *Other combinations*

All other direction combinations are possible. Combined Aqaba and Cross directions are described by Thiriet *et al.* 1985) in the Safaga area as the passage from a sinistral strike-slip fault to a set of reverse faults.

7. Characteristics of second phase structuration

In favourable areas, syn-rift unit B can be seen to seal the initial phase structures. In addition, syn-rift units B, C and D are not horizontally displaced by Aqaba and Duwi trends. All faults, especially the Clysmic faults, are normal.

These normal downthrows are synthetic and, generally tilted towards the rift axis (figure 3). Some faults are reactivated but most are sealed, frequently by the evaporitic unit (Heybroek 1965; Metwalli *et al.* 1978; Brown 1980). These major faults, generally Clysmic, generate the central trough and rift shoulders (Chenet & Letouzey 1983; Selwood & Netherwood 1984). Flexures in the Miocene units mould the underlying fault scarps (Thiebaud & Robson 1979). Also, in the central trough, unit C is affected by halokinetic movements controlled by the initial phase faults (Lowell *et al.* 1975; Tewfik & Ayyad 1982).

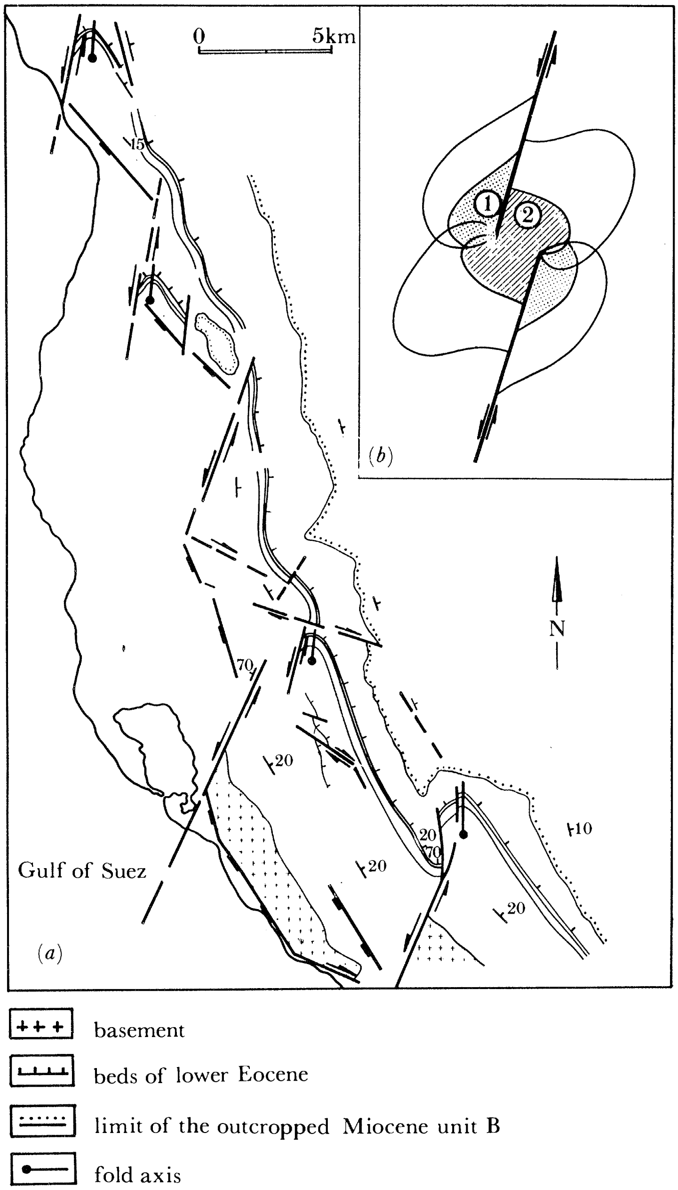

FIGURE 7. Geometry resulting from the combined Aqaba and Clysmic trend movements in the Abu Rudeis area (located in figure 1). (*a*) Simplified tectonic sketch. (*b*) Theoretical model of stike-slip faults showing the distribution of compressional area (1) and extensional area (2).

8. Heritage of the rift tectonic pattern

Two main questions arise. First, are Suez and Red Sea rifts occurring on a major dislocation in the crust? And secondly, are the rift dislocations which control the tectonic pattern inherited or newly formed?

The answer to the first question would require a thorough study of the basement and Palaeozoic and Mesozoic cover. A few authors propose the existence of a protorift in the Gulf of Suez since the Carboniferous (Said 1962). This hypothesis has been contradicted in more recent papers (Garfunkel & Bartov 1977).

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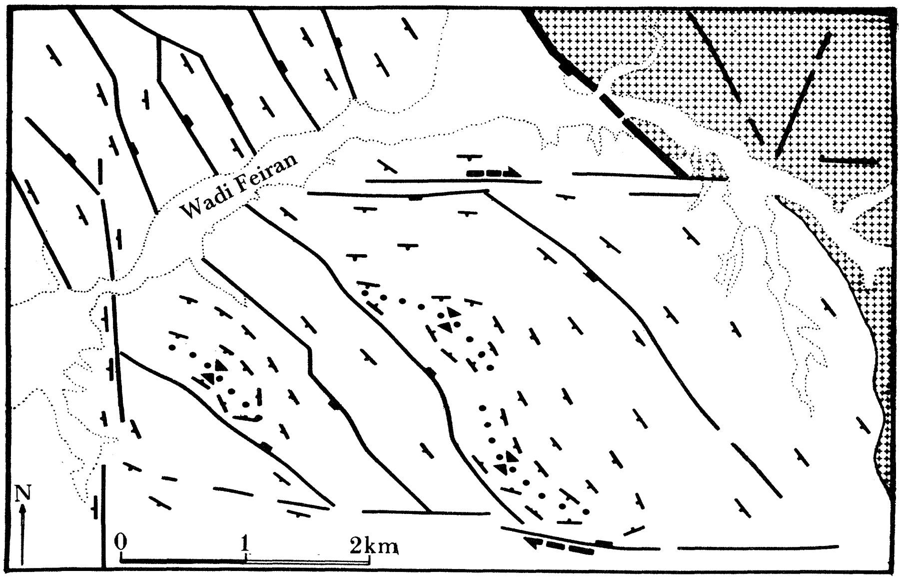

FIGURE 8. Geometry resulting from the combined Clysmic and Duwi trend movements in the Wadi Feiran area (located in figure 1). The crosses represent the outcropped basement and dip symbols indicate the shape of tilted blocks in the cover (Cretaceous to Eocene).

However, the problem concerning the inheritance or neoformation of discontinuities can be solved.

(i) The zigzag faulting pattern cannot result from simple extension but supports the idea of reactivation of pre-existing dislocations.

(ii) The simultaneous occurrence of volcanic rocks, contemporaneous with the start of rifting in the Clysmic, Aqaba and Duwi directions confirms this hypothesis. These dykes are aligned over 200 km along a major Clysmic dislocation that separates basement compartments with different magnetic properties (Folkman & Assael 1980).

(iii) The directions controlling the Neogene structure are inherited from the preceding tectonic pattern: information is scattered in the literature and fits our results. In this connection, the following can be noted:

(*a*) instability along the Aqaba and Clysmic directions in the Eocene in the form of slumps and silicified sedimentary dykes;

(*b*) Duwi movements during the Mesozoic in the Syrian arc (Bartov *et al.* 1980);

(*c*) intrusion of alkaline complexes in the Nubian shield between 400 and 89 Ma aligned in Clysmic and Cross directions (de Gruyter & Vogel 1981; Burollet *et al.* 1982);

(*d*) occurrence in the basement of numerous dykes in Cross and locally Aqaba directions sealed by the Palaeozoic cover;

(*e*) complex tectonic pattern of the Panafrican shield at the end of Proterozoic (Nadj faulting) generating folding and schistosity in Aqaba, Clysmic and Duwi directions (Delfour 1979, Moore 1979).

An example of reactivation of these Pan-African discontinuities is well expressed in the Abu Ghusun area (figure 9). There, the Miocene active faults obviously respond to reactivation of some Pan-African schistosity planes.

These data confirm that the Neogene tectonic pattern is inherited from the trends of earlier dislocations.

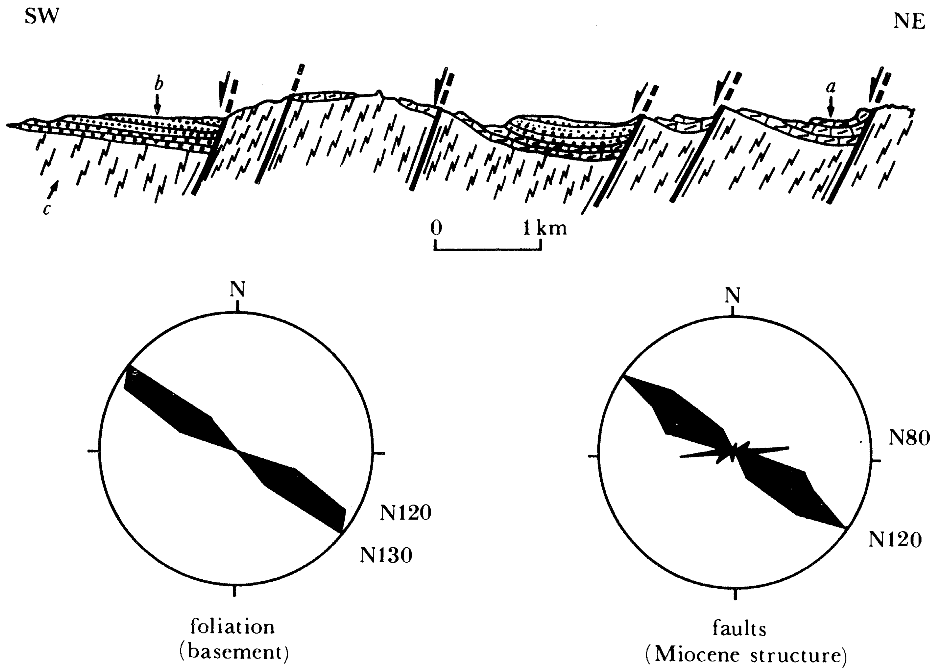

FIGURE 9. Relations between the Neogene faults and Proterozoic dislocation directions in the Abu Ghusun area. The schematic cross section is without vertical scale. (*a*) Syn-rift unit A; (*b*) syn-rift unit B; (*c*) basement.

9. CONCLUSIONS

Rift formation in the Gulf of Suez and northern Red Sea area is the result of intracontinental deformation.

The tectonic pattern is controlled by reactivation of inherited dislocations, leading to a zigzag fault pattern.

Two main phases can be distinguished. An initial phase that is characterized by antithetic movements along the faults with insignificant vertical displacements. These deformations are coherent within a regional stress system of NW–SE compression and NE–SW extension. In addition, there is a synthetic phase that is characterized by normal faults with significant vertical movements in all directions. Only a few major faults are reactivated, generating the central trough and the formation of rift shoulders.

Initiation of the rifting is not the result of thermal doming but is controlled by the regional stress distribution induced by the northern convergent boundaries of the Arabic and African plates. Consequently, the rift initiation hypothesis based only on curved and listric normal faults cannot be retained. Such structures have been locally observed in the field but they are small and superficial.

The results obtained from this area, usually considered to be a conventional rift, may question the validity of crustal thinning and stretching models. These models, which do not fit easily in this well exposed example, should be used with caution in older and less defined cases.

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