Journal of Structural Geology, Vol. 10, No. 1, pp. 9 to 19, 1988
Printed in Great Britain

0191-8141/88 $03.00 + 0.00
Pergamon Press plc

Fault-block tilting: the Gebel Zeit example, Gulf of Suez

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(*Received 5 September* 1986; *accepted in revised form* 4 *September* 1987)

Abstract—The Gebel Zeit consists of the eroded crest of a tilted block in the southern part of the Suez rift. The Zeit block displays a typical asymmetrical geometry: it is bordered to the east by a 35–45° E-dipping normal fault with kilometric throw and has a 30° SW-dipping homoclinal flank. Part of the pre-rift sedimentary sequence has been preserved on this flank and is unconformably covered by Upper Burdigalian (NN4) Globigerina marls. In the southern part of the block crest, the complete pre-rift series has been eroded and evaporites of Langhian age (NN5) rest directly on the Precambrian basement. Field evidence indicates alternations from erosion to sedimentation at the crest of the Zeit block. In an attempt to characterize its tilting, subsidence curves were computed along a cross-section with the backstripping method. Results indicate three stages in the evolution of the block: (1) a rapid subsidence between 22 and 16 My; (2) a pause between 16 and 10 My; and (3) a slow subsidence until present time. During the tectonic quiescence, the sedimentary loading effect alone produced an increase of 8° in the tilt angle. A simple kinematic model of tilting along a circular fault is proposed to quantify the Zeit rotation. Depth of the brittle–ductile transition is estimated at 10 km to explain the tilting. Strong driving of the tilting by the listric fault induces conjugate movements between the crest and trough of the block and explains the discrepancy between the Zeit and regional tectonic subsidence.

INTRODUCTION

THE Gulf of Suez (Fig. 1) is a 300 km long Cenozoic intracontinental rift trending NNW–SSE, which cuts through the Arabo–Nubian shield, where a 200–1500 m thick continental and marine series of Cambrian–Eocene age overlies a Precambrian metamorphic and granitic basement. Extensional movements began in late Oligocene–early Miocene times, as evidenced by K–Ar ages (between 32 and 18 My) of basaltic dykes around the Gulf province (Siedner 1973, Meneisy & Kreuzer 1974, Steen 1982). First marine deposits are Aquitanian to Burdigalian in age (NN3–NN4). The overall structure of the rift is controlled by normal faults and tilted blocks trending N140°–N150°. On the southwestern coast of the Gulf, the Esh el Mellaha Range and the Gebel Zeit consist of the eroded crests of two major tilted blocks dipping, respectively, 6° and 30° to the SW. The present work focuses on the Gebel Zeit block where tilting can be reconstructed using field evidence, subsidence analysis and simple kinematic modeling.

GEOLOGICAL RECORD

The Zeit block crest constitutes a low elongated N145° trending range (30 km long, 5 km wide). It consists of two prominent outcrops of basement rocks: Gebel Zeit itself is 14 km long with a maximum elevation of 465 m and Little Zeit is only 3 km long with a maximum elevation of 250 m. The Little Zeit is separated from the main range by a topographic saddle (maximum elevation 150 m) covered with Miocene evaporites. The stratigraphy of the Gulf of Suez has already been presented in previous works (i.e. Garfunkel & Bartov 1977, Scott & Govean 1984) and details concerning the Gebel Zeit area can be found in Perry (1983) and Colletta *et al.* (1986).

Pre-rift sequence

The basement consists mainly of metamorphic rocks intruded by pink (orthoclase and biotite) and grey (plagioclase) granites. These granites are cut by numerous dolerite dykes with a general N60° transverse trend. Basement rocks are overlain by a thick unit (~400 m) of Nubian sandstones. They are probably of continental origin, and could range from Cambrian to Lower Cretaceous. They are conformably overlain by a much more diversified marine sequence; two main units can be attributed to the Cenomano-Turonian and to the Senonian. Two small isolated outcrops of cherty limestone have been attributed to the Eocene by facies analogy. These marine deposits are typical of a transgressive sequence on a stable continental platform. During Cenomanian, Turonian and Early Senonian times, abundant clastic sediments and gypsiferous marls indicate a nearshore environment. Pelagic conditions occurred during late Senonian (Campanian Maestrichtian) and Eocene times.

Syn-rift marine deposits

A detailed analysis of sedimentary records and the main tectonic features are shown in Table 1.

Miocene. The pre-rift marine units occur in the central and northern part of the West Zeit Range (Fig. 3). To the south, these units are progressively truncated by Miocene deposits and wedge out (Fig. 2). From north to south these Miocene deposits rest successively on Eocene, Upper Cretaceous, Nubian Sandstones and basement rocks (Fig. 2).

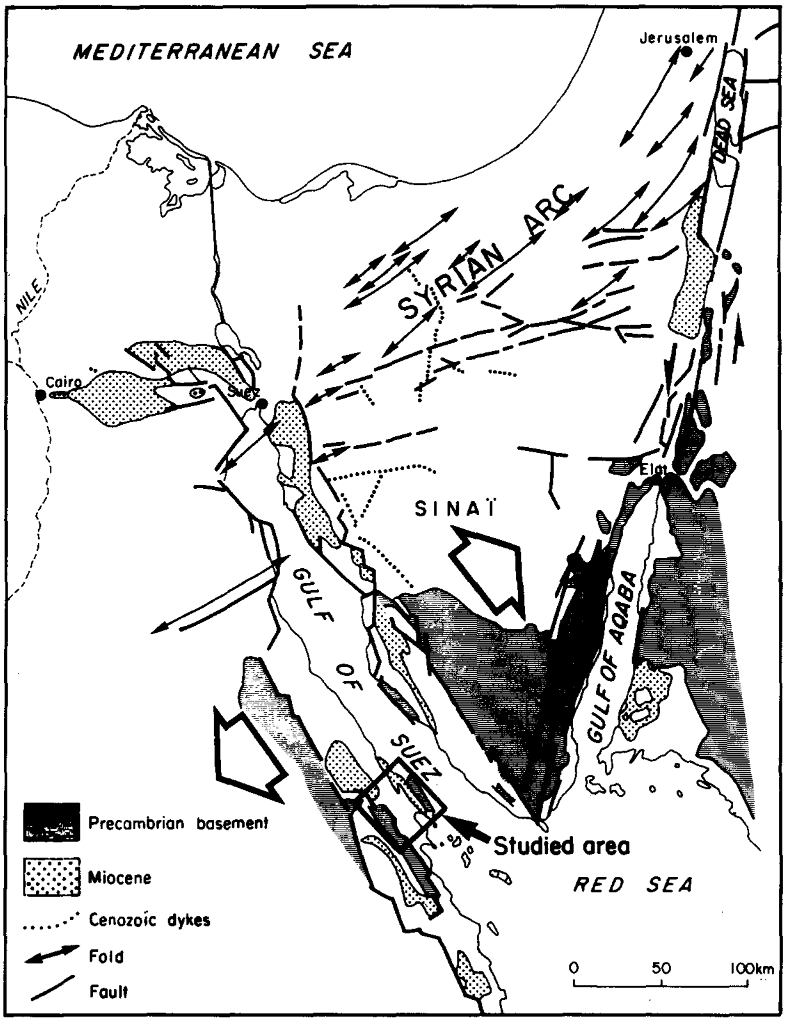


Fig. 1. Simplified tectonic features of the Gulf of Suez–Sinai region and location of the study area. The Syrian Arc fold system was created in a NW–SE compressional regime during late Cretaceous–Eocene times. The Suez rift results of a NE–SW extensional movements (large arrows) during Neogene times. The Gulf of Aqaba and the Dead Sea fault system act as a sinistral transform boundary between the Arabian plate and the Sinai plate during late Neogene times. The two elongated basement outcrops in the southeastern part of the rift are the eroded crests of tilted blocks. The longer one corresponds to the Esh el Mellaha range, the easternmost and smaller one is the Gebel Zeit.

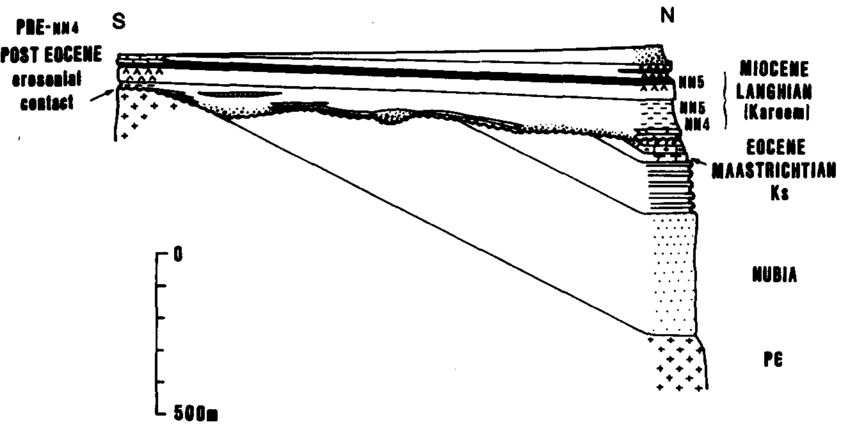


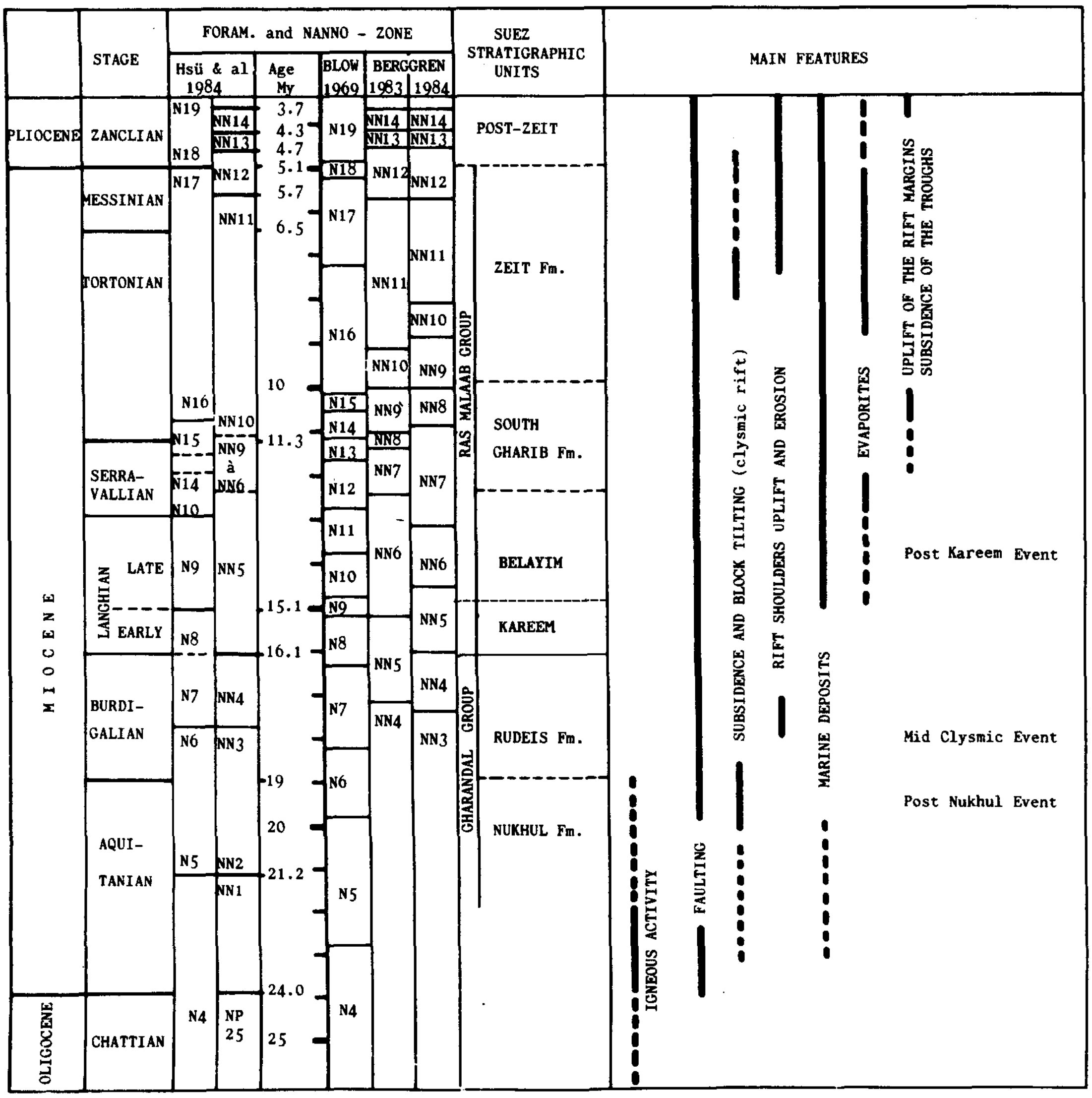
Fig. 2. Schematic longitudinal stratigraphic section at the crest of the Gebel Zeit showing truncation of the pre-rift sequence by the erosional contact at the bottom of the Miocene deposits. Thin marine deposits and shallow water facies close to the crest of the block indicate it remained a relatively high point during Neogene times. Tilt axis was slightly oblique to the border fault as shown by differential erosion from north to south.

Basal deposits display variable lithology and usually contain sandy limestones with a shallow water fauna, as well as conglomerates composed of Eocene chert pebbles. Their thickness varies from 0 to 10 m. Basal conglomerates locally contain up to 1 m boulders of Nubian sandstones (as in the southern Gebel Zeit) and Cenomanian chalk. At the southern end of Wadi Kabrit the basal limestones are cut by two channels infilled with coarse sandstones and debris of Eocene cherts and Nubian sandstones. These 50–250 m wide channels cut through the underlying Nubian sandstones. Measurements of sedimentary dips compiled on the northernmost channel indicate a N100°-trending axis. The same kind of channel cut through Nubian sandstones has been observed in the southern part of the Little Zeit. They indicate a large variation in sea level just after the deposition of basal limestones and are related to tectonic events. However, the exact age of this basal unit cannot be dated precisely and the vertical movements could be post-Nukhul (Beleity 1982) if the basal limestones have an Aquitanian age or mid-Rudeis (Garfunkel & Bartov 1977) if they are older.

Green marls (Globigerina marls) overlie the basal deposits and comprise a shaly–marly sequence of up to 100 m but they decrease to a few meters in the southernmost Gebel Zeit and Little Zeit, where they lie directly on the Precambrian basement. Thickness variations are related to the buried topography. Faunal assemblage of Burdigalian age indicates open marine conditions with water depth over 100 m (Carla Muller personal communication), while a Langhian nannofaunal assemblage indicates a more confined environment, a premise of evaporitic deposits. In the Langhian, we can observe a thin level of coarse ferruginous sandstone with basement pebbles and boulders. Outcropping conditions and downslope creeping prevented us from positively deciding whether these basement boulders were remnants of an old Quaternary fluvial terrace veneering the marls or if they were stratigraphically interbedded. If interbedded, these granite boulders would indicate that the Precambrian basement emerged somewhere in the Zeit region during early Langhian times, showing a constant high position of the block crest.

Green marls are overlain by 50–300 m of gypsum,

Table 1. Summary of stratigraphy and main geological events in the Gebel Zeit block, Gulf of Suez



anhydrite and interbedded diatomaceous shales. The basal contact is very sharp but no clear angular unconformity was observed. Paleontological analysis of interbedded shales indicates a Langhian age (NN5) for at least the lower part of the evaporites. A 15–20 m thick shale band can be followed all along the western side of the Zeit Range and contains diatomite levels with sponge spicules and silicoflagellates, corresponding to a rather confined marine environment. Locally, the evaporitic sequence is reduced or missing as at the top of the West Zeit Range. It is capped, or replaced, by unfossiliferous dark brown recrystallized dolomitic limestones with small vugs and flaggy texture. These limestones are lateral equivalents of the upper evaporitic series and characterize paleo-highs. During this episode most if not all of the crest was submerged, as evidenced by numerous remnants of evaporites resting directly on top of the Precambrian basement.

The Mio-Pliocene. Coarse sandstones and poorly consolidated conglomerates with *Ostrea* debris lie on top of evaporites and are widespread on the eastern flank of the Zeit Range. Near Ras el Ush, conglomerates and diatomites that rest upon the evaporites could be correlative of this unit. Coarse conglomerates as well as the faunal assemblage indicate shallow water conditions and the relative high position of the block crest.

Marine quaternary deposits. At least three marine terraces can be identified along the northeastern faulted flank of the Zeit Range. The highest, at about 70–80 m above sea level, is characterized by well-rounded pebbles but is devoid of fauna. Another terrace, between 50 and 55 m displays a typical beach cobble accumulation with shell debris. The third marine terrace between 20 and 25 m, constitutes a very well preserved reefal buildup with associated fauna. These three terraces are not continuous along the eastern coast but are well exposed in the northernmost Zeit Range and near Ras el Ush. On the western flank of the Zeit Range the highest preserved Quaternary marine deposits are at about 35 m above mean sea level.

At the crest of the Gebel Zeit block, geological maps and cross-sections (Figs. 2 and 3) clearly demonstrate a reduction of the pre-rift units caused by intense erosion prior to the Miocene deposition, and a thinning of the syn-rift units due to non-deposition of the older marine formations and thinning over the constantly high crest of the block.

STRUCTURE

The Zeit Range is the crest of a N150° trending block tilted towards the SW and displaying a typical asymmetric geometry. To the NE, the block is bordered by the Zeit Fault along which the Miocene is directly in contact with Precambrian rocks; normal displacement of several kilometers produced a steep fault scarp. To the SW, the morphology is smoother and consists of a more gently dipping homocline, where part of the pre-rift sequence has been preserved and is covered by Miocene syn-rift deposits. All the observed faults have a normal dip-slip component and most of them strike N120°–N160°. To the north and south, the crest of the block is cut by oblique faults resulting in downdropped wedges. The Little Zeit appears as the southern uplifted edge of such a downfaulted block (Fig. 3). The Ras el Ush Saddle between Little Zeit and the Gebel Zeit is probably fault controlled, but Miocene evaporites conceal most of the structures.

Tilt angle

If we exclude drag zones near faults the average dip of the strata is about 50–70° in Nubian sandstones near the contact with the basement, 40–45° in the Nubian sandstones, 30–35° in the Upper Cretaceous, 20–25° in the Globigerina marls and 10–15° in the evaporite sequence. Thus, the tilt angles of the pre-rift series decrease from bottom to top, although no clear unconformities could be observed. There is an obvious erosional contact between Miocene and pre-rift deposits, but a clear angular unconformity is hardly observed due to differential compaction and draping of the Globigerina marls over the more competent pre-rift rocks.

When basal Miocene sediments were deposited, the tilt angle of the Upper Cretaceous was probably no more than 5–10° and the apparent 3–4° NW component of tilting (section BB′, Figs. 3 and 4) with increasing truncation of pre-rift series to the SE, suggests that the tilt axis was slightly oblique in relation to the present major fault trend. Block tilting increases progressively during Miocene time as evidenced by the thickening of every syn-rift unit toward the western half-graben trough.

High-angle dips and downfaulted wedges

Dips of the basal Nubian sandstones are steeper than dips in the overlying deposits and can reach 70°. It can be seen that high-angle tilting is always associated with closely spaced normal faults. From well data the average dip of the tilted basement block is about 25–30° and the steep dips of the Nubian–basement contact (50–70°) cannot be reasonably extrapolated to depth without structural change. High dips are restricted to the crest itself and may result from rotation along listric normal faults downthrowing the crest of the block. They could also be due to the collapse of the upper part of the footwall block in the void produced by the throw of the Zeit Fault (Fig. 5).

The zig-zag fault scarp that limits the basement outcrops on the eastern flank of the Gebel Zeit is the result of the combined activity of diagonal and longitudinal faults. In our structural interpretation (Fig. 4), we assumed that the Zeit Fault is continuous all along the Zeit Range. If this interpretation is correct, there must be small rhomboidal fault blocks (A, B and C, Fig. 3b) west of the major Zeit fault. Dips measured in the

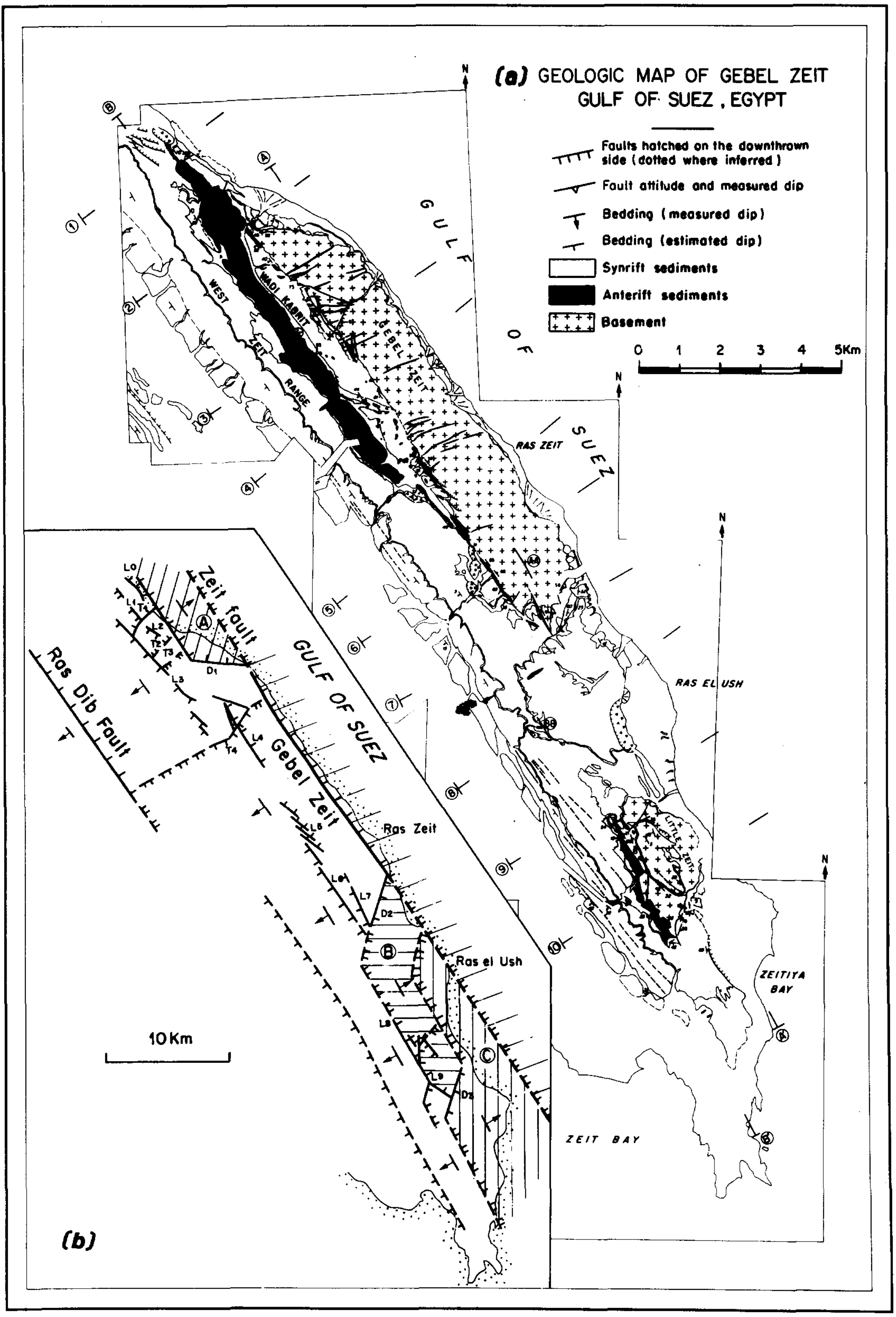


Fig. 3. (a) Geologic map of Zeit elaborated from field observations and supplemented by analysis of aerial photographs. Circled numbers and letters indicate location of cross-sections in Fig. 4. (b) Structural sketch of the crest of the Gebel Zeit. Fault pattern includes three major sets: longitudinal faults (L), diagonal faults (D) and transverse faults (T). Most of the faults are dip-slip and have been active since the beginning of rifting. The Zeit fault which bounds the block to the east has a 3–4 km net slip and a present dip of 35–45°. Hatched zones are downfaulted wedges of the block crest.

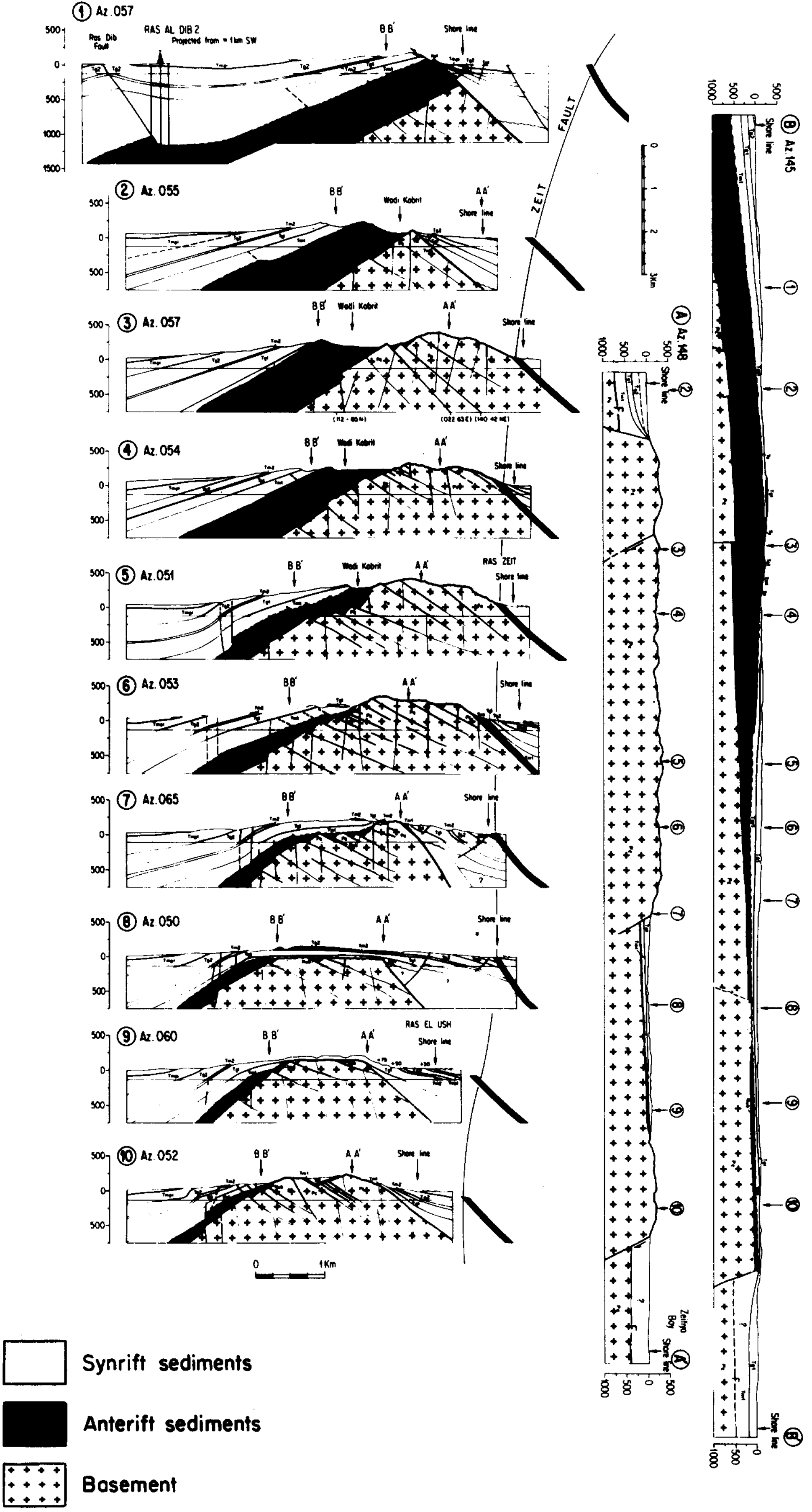
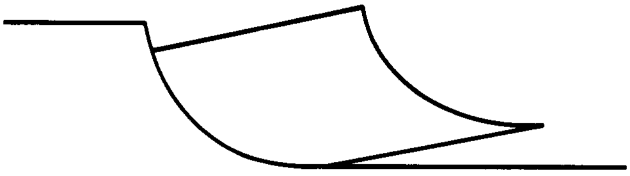
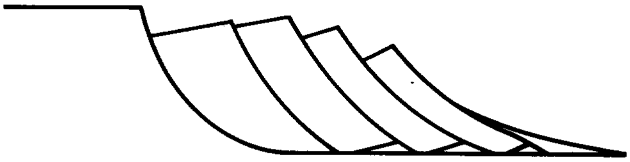


Fig. 4. Serial transverse and longitudinal cross-sections of the Zeit block crest. Note than in the Little Zeit area (sections 8–10) evaporitic sequences rest directly on the Precambrian basement. Normal faults have been tilted with the block and display steeper or lower dip than the original one depending on their dip direction. Steep fault on cross-section 7 corresponds to the diagonal fault D3, see location in Figs. 3(a) & (b).



Theoretical tilting along a listric fault



Adjustement at the crest of the block

Fig. 5. Interpretative sketches showing secondary faulting in tilted blocks induced by rotation. To compensate the void, which would be created at the base of a rigid tilted block, secondary normal faults can appear. The width of the block is then reduced and the uplift of the crest becomes harder.

Miocene cover of these downfaulted blocks are eastward. These gulfward dips are related to drag and rotation of the rock-wedge squeezed between the two merging longitudinal fault planes. Secondary antithetic normal faults developed on the northern block A. Pre-rift deposits are missing on the southern block B, which was probably downfaulted after evaporite deposition. They might be present on block C, which was downfaulted prior to the complete erosion of the pre-rift units, as evidenced by upper Cretaceous outcrops squeezed along the NW bordering fault plane.

TECTONIC EVOLUTION

Subsidence vs time

The tilting of the Gebel Zeit is emphasized by means of the backstripping of a cross-section situated in the computed assuming local isostatic compensation. All required parameters for computation are summarized in Appendix 1 and are similar to those used by Moretti & Colletta (1987) to display subsidence maps in the Gulf of Suez. The cross-section is adjusted by data from three wells on the homoclinal flank and one on the eastern flank.

As a rule, authors distinguish between tectonic subsidence, due to deep processes and subsidence due to the sedimentary loading. To isolate these two components, mechanical hypotheses about crustal behaviour are necessary in order to quantify the lithospherical response under the load. Depending on the area, isostatic compensation is supposed to be local or regional. In extensional areas, the existence of many normal faults, displaying large vertical offset, and of narrow grabens, suggest local compensation, but large upper-crustal blocks like the Zeit indicate some 'regional' rigidity. An alternative model should consider brittle behaviour in the upper crust and regional isostasy in the lower crust and in the upper mantle. It seems to us that part of the vertical movement on a block is also due to 'kinematic' causes: the movement of the block is guided by the fault. To emphasize this phenomenon, we shall study the tilt of the Zeit assuming local equilibrium. Regional subsidence maps made with the same assumptions (Moretti & Colletta 1987) show an abnormal amount of subsidence in the half graben and on the crest of the Zeit block. We shall now try to elucidate these discrepancies.

Figure 6 shows tectonic subsidence vs time, and the resulting tilting of the Zeit block is depicted in Fig. 7. From Kareem to Zeit times, between 16 and 10 My, the increase in tilting (+8°) was due only to sedimentary loading with no tectonic subsidence (Fig. 8). The large discrepancy between the three solid line curves in Fig. 8, corresponding to different points on the same block, shows the danger of using well data only to determine

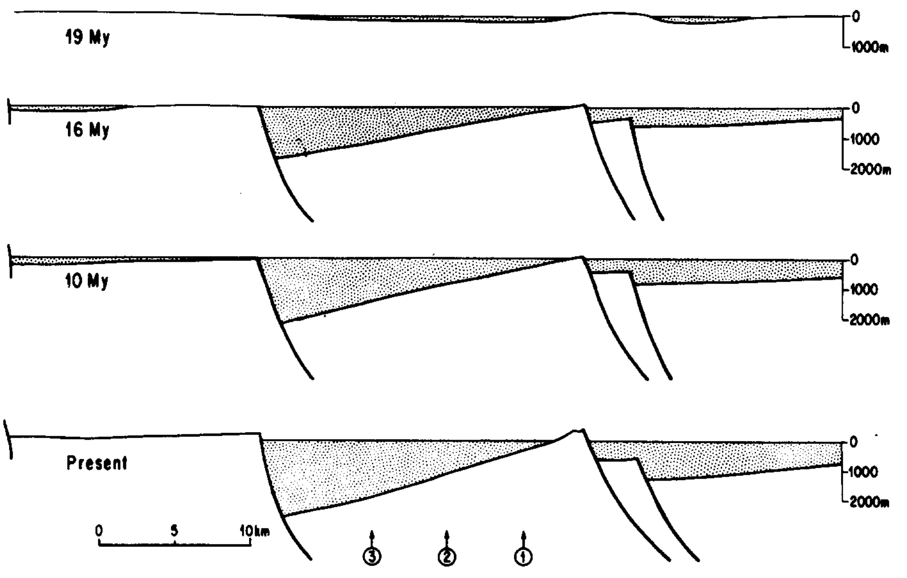


Fig. 6. Calculated tectonic movement along a cross-section in the northern part of the block. The final configuration is determined from subsurface data (wells 1, 2 and 3) and the paleoreconstruction results from the backstripping study. Vertical exaggeration ×2.

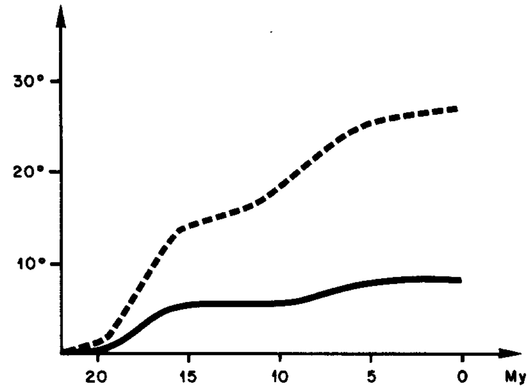


Fig. 7. Tilt angle of the pre-rift layers vs time. Dashed line is the true value. The solid line is determined from the tectonic subsidence shown on Fig. 6 and represents the part of the tilting not due to sedimentary loading effects.

the amount of tectonic subsidence, as already reported by Sawyer (1986). Nevertheless, the pause in tectonic subsidence during the deposition of the Kareem and Belayim formations that affects the entire gulf (Moretti & Colletta 1987) appears in the whole half graben.

Detachment depth

Assuming a circular fault and knowing the dip of this fault at the surface and the depth of detachment, we can compute possible movements of the block. The opposite reasoning is also possible; knowing the movement of the block, we can estimate the detachment depth. A comprehensive discussion of the geometrical analysis can be found in Moretti *et al.* (in press) and is briefly summarized here.

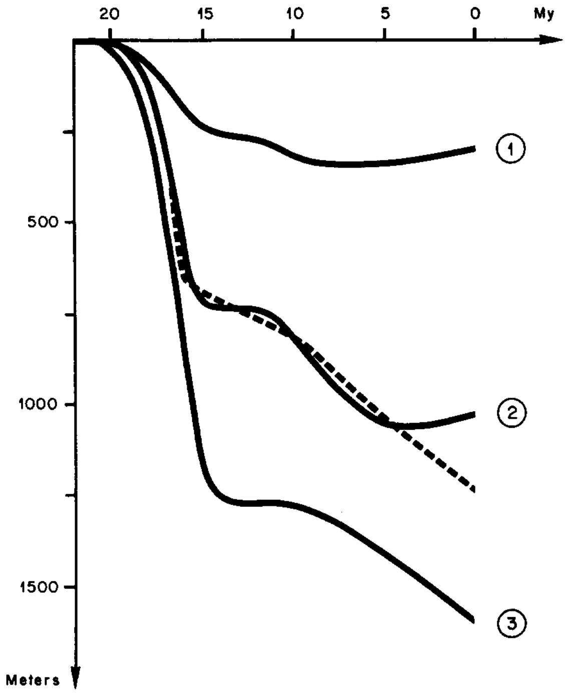


Fig. 8. Tectonic subsidence vs time. The three full curves represent vertical movements of the Zeit block at the top (1), at the middle of the block (2) and in the deeper part (3), respectively, see location on Fig. 7. The dashed line corresponds to a well located offshore east of the Zeit Fault.

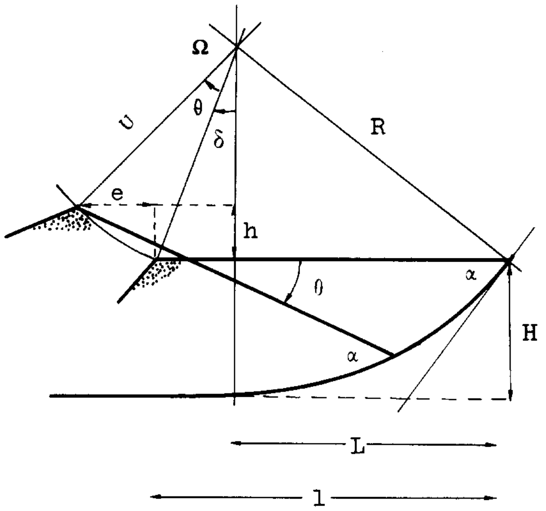


Fig. 9. Driven movement along a circular fault: α, dip of the border fault; H, depth of detachment; l, length of the block; θ, tilt angle; h, vertical displacement of the crest; e, horizontal displacement of the crest; u, distance between the pole of curvature and the crest.

We consider that a fault can be modeled by a portion of a circle. The dip between the tangent and the horizontal direction at the surface is α. The circle is tangent to the horizontal at H km depth (see notation in Fig. 9). On this assumption, the radius of curvature is

$$R = H/(1 - \cos\alpha). \qquad (1)$$

If θ is the dip of tilting and l the length of the block, the vertical displacement of the crest h is

$$h_{\text{crest}} = H(\cos\alpha - \cos(\alpha - \theta))/(1 + \cos\alpha) + l\sin\theta \qquad (2)$$

and at the bottom of the graben

$$h_{\max} = H(\cos\alpha - \cos(\alpha - \theta))/(1 + \cos\alpha). \qquad (3)$$

h is positive for uplift, negative for subsidence.

The crest is uplifted with respect to its initial position if length l is greater than a minimum value L. If M is the projection of the center of curvature along the horizontal plane, L is the distance between M and the origin of the fault.

$$L = R\sin\alpha = H\sin\alpha/(1 - \cos\alpha). \qquad (4)$$

If the horizontal displacement on the crest is e then:

$$e_{\text{crest}} = H(\sin(\theta - \alpha) + \sin\alpha)/(1 - \cos\alpha) + l(\cos\theta - 1). \qquad (5)$$

Along the fault, the horizontal displacement is e_{fault}

$$e_{\text{fault}} = H(\sin(\theta - \alpha) + \sin\alpha)/(1 - \cos\alpha). \qquad (6)$$

The mean angle θ of tilting for the pre-rift layers in the Zeit area is 27° as determined from well data; higher values are restricted to the crest. At the surface the dip of the fault bounding the block to the west is $\alpha = 58°$. The total Miocene subsidence in the deeper part of the half graben $h_{\max}$ is about 7 km. Taking into account Equation (3), we obtain a value for the detachment depth:

$$H = h_{\max}(1 - \cos\alpha)/(\cos\alpha - \cos(\alpha - \theta)) = 9.9 \text{ km}.$$

Uncertainties concerning data ($55° < \alpha < 60°$, $2 5° < \theta < 30°$ and $6.5 < h_{max} < 7.2$ km) induce variations of ±1 km for the depth of detachment. This depth is usually assumed to be the bottom of the brittle upper crust (Le Pichon & Sibuet 1981, Chénet *et al.* 1983). A similar analysis can be made for the Mellaha Range (see location Fig. 1) which is bounded to the west by the border fault of the rift. Its tilt-angle is only 6° and the total amount of subsidence about 1.8 km. With these data, if we assume a fault dip close to 60°, the depth of detachment is 10.2 km.

The results of the Minos seismic survey give a 17 km deep Moho under the Suez rift axis (Gaulier *et al.* in preparation) and Makris *et al.* (1978) estimated a depth of 20 km along the coast in the southwestern part of the Gulf (Safaga area). In the Bay of Biscay seismic data indicate a detachment depth of 9–10 km when the Moho is 15–20 km deep. The two values are very similar and our calculated depth appears to be realistic in spite of the apparent simplicity of the kinematic model.

In the same way, Daggett *et al.* (1986) studying the seismicity of the Egyptian Red Sea margin noted earthquake focus depths ranging from 5 to 16 km with a main mode of 9 km. This value is given for a region 200 km south from the Zeit block. Along the Gulf, data suggest upper crustal active faults but the irregular quality of data preclude precise estimates.

Absolute movement

Using Equations (2) and (4), we can compute the direction of the theoretical movement of the crest. The critical value for the size of an uplifted block is

$$L = H \sin \alpha/(1 - \cos \alpha) = 19 \text{ km}.$$

The initial length of the Zeit block is 20.5 km, hence the crest is uplifted during rotation with respect to the position of the substratum by an amount given by:

$$h_{crest} = h_{max} - l \sin \theta = 2300 \text{ m}.$$

The present top of the Gebel Zeit is 450 m but the pre-rift sequence has been eroded. Taking this erosion into account, an elevation of 1200 m for the pre-rift deposit at the crest can be estimated. Various explanations can be invoked to account for the difference between the two values. Problems of mass conservation are ignored in the kinematic study of the rotation. In fact, an uplift of the crest induces a negative mass balance at the bottom of the block. The void between the block and the detachment fault created by tilting under the uplifted zone has to be compensated (Fig. 5). Destabilization by isostatic phenomena is then expected in the uplifted part of the block and the crest should go down. If we assume complete rigidity of the top of the block and adjustment by ductile deformation at the detachment level, the difference between observed and theoretical elevations of the Zeit results from regional movements in the crust. This means that the crustal substratum has undergone a subsidence of about 1100 m, namely the difference between the 2300 m computed uplift and the present elevation. This amount is consistent with the regional subsidence pattern (Moretti & Colletta 1987).

Extensional ratio

As regards extension at the surface in the Zeit area, the theoretical horizontal displacement of the crest can be calculated using Equation (5).

$$e_{crest} = H(\sin(\theta - \alpha) + \sin \alpha)/(1 - \cos \alpha) + l(\cos \theta - 1) = 4.65 \text{ km}.$$

The length of the block is 20.5 km, hence the extensional ratio at the surface is 1.23.

Other values have already been estimated along the Gulf. In the eastern part, Chénet *et al.* (1983) obtained 1.2–1.3 using faults displacements. Palinspastic sections along the Gulf show values of about 1.25 in the Zeit area (work in preparation). In fact, knowing movement of a block, various extensional ratios can be made (Chénet *et al.* 1983). Using the value of the horizontal displacement along the bounding fault (6.88 km in this case, Equation 6), the extension rate should be 1.34. At each depth, the distance between the western and eastern bounding faults can also be calculated. Discrepancies between the independently computed values are low and the mean extension in the Gebel Zeit area is quite similar to the average amount in this part of the Gulf.

Conjugate movements

The calculated subsidence resulting from sedimentary loading (Fig. 8) increases from −2000 m under the half graben to at least +500 m at the crest of the block. The depth of detachment is 10 km hence we can suppose that the Moho depth is not directly affected by the fault. Thus the lower crustal thinning can be expected to vary gradually from the western to the central part of the rift. The average computed tectonic subsidence in the central part of the Gulf on each side of the Zeit crest is about 1000 m (Moretti & Colletta 1987). Thus we may estimate that the true 'tectonic' vertical movement decreases by more than 500 m from the western bounding fault to the Zeit crest. The discrepancy between this regional pattern and the Zeit curve emphasizes the strong driving of the movement by the fault. The relatively low angle of the Zeit Fault could also be due to this tilting. Indeed if the fault dip is 40° after a 27° tilting, its initial angle was 40° + 27° = 67°, a typical value for normal faults.

DISCUSSION AND CONCLUSIONS

A pure extensional regime, with minimum stress trending N60° (Chénet & Letouzey 1983, Angelier 1985) created the Suez rift and prevailed throughout its tectonic history. Detailed analyses of the sedimentary record (Garfunkel & Bartov 1977, Beleity 1982) and subsidence curve computations indicate three major stages in rift evolution (Steckler 1986, Moretti & Chénet 1987, Moretti & Colletta 1987).

The tilting of the Gebel Zeit block follows a similar tectonic evolution with three phases (Figs. 7 and 8). The block formed during the first opening phase, at the beginning of Rudeis times, and its rotation increased until 15 My. During the Belayim and South Gharib deposition, the tectonic pause, common to the whole Gulf, also affected the Zeit. A second tilting phase began 10 My ago and now seems to have stopped.

Field evidence indicates an early phase of slightly oblique tilting that lead to the erosion of the SE corner of the crest (Little Zeit) which represents an area of Precambrian basement directly overlain by Miocene evaporites. It appears that the crest of the Zeit acted as a ridge or island during most of the Miocene; nevertheless it was completely submerged during evaporite deposition (Langhian time). This alternation is only possible if the length of the Zeit block is slightly greater than the critical value L. The transitions, from erosion to sedimentation at the top of the block, accordingly depend on the balance between two competing effects. Crustal thinning induces regional subsidence, and tilting of large blocks causes uplift of their crests. If the length of the Zeit block is less than L, only subsidence would have occurred along the block, especially during the first stage of rifting, because of the strong tectonic subsidence occurring throughout the Gulf. This phenomenon of alternation in particular rules out the hypothesis of a crustal depth of detachment for the Zeit block. Following the preliminary results of the Minos refraction survey, we shall assume a 17 km deep Moho. In this case, the critical value L for an uplifting block should be 30 km, and a 20 km long block should have undergone subsidence greater than 3000 m during a 27° tilt. Since these values are incompatible with erosion in the Gebel Zeit, the depth of detachment is obviously intracrustal. The lower crust, which is unaffected by this faulting, may be assumed to be more plastic and likely to be thinned by ductile deformation.

The crest of the block displays some complicated features, nevertheless, the tilt history is quite simple. This discrepancy is due to the length of the block being close to the critical length L, allowing alternating erosion and sedimentation when crustal thinning varies, and to gravitational destabilization caused by the uplift of the crest with respect to the detachment depth.

Acknowledgements—Field studies were supported by Total Proche Orient and were carried out between 26 October and 4 December 1984 and in February 1986. We also thank Total C.F.P. for their kind permission to use subsurface data. We are grateful to C. Muller and F. Vieban for paleontological determinations and we acknowledge P. Y. Chénet and P. Gerard for many stimulating discussions.

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APPENDIX

Backstripping

The subsidence of a graben has two main causes: (1) crustal movements and (2) sediment loading. The purpose of the backstripping method introduced by Watts & Ryan (1976) is to isolate these components. It consists in removing the successive sedimentary units step by step, and in decompacting the remaining series. The computer program used in this paper is due to Bessis (1986). Several parameters are required to compute the subsidence from the present pattern (Table A1). For each syn-rift sedimentary unit, it is necessary to know its present depth, its absolute age, the paleobathymetry and the eustatic sea level during its deposition. The results also depend on the compaction laws selected. Discussions concerning the choice of parameters and their influence can be found in Moretti & Colletta (1987) and are treated only briefly here.

Porosity and density

Five distinct lithologies have been considered: sand, marl, carbonate, halite and gypsum. An average porosity/depth relation is chosen

Table A1. Parameters used in backstripping program

Formations	Ages (My)	Paleobathymetry (m)	Sea level (m)
Post Zeit	0	present value	0
Zeit	5.1		0
South Gharib	10		0
Belayim	13.5	0–50	0
Kareem	15		10
Upper Rudeis	16	50–100	20
Lower Rudeis	17	80–100	20
Nukhul	19	80–100	30
	22	0–30	35

Table A2. Porosity variations during compaction assumed in subsidence calculations

Lithology	Density (g/cm^3)	(%) Porosity at 0	200 m	400 m	1000 m	2000 m	4000 m
Sand	2.75	48	44	39	28	18	10
Marl	2.65	70	60	54	37	15	6
Carbonate	2.75	40	38	35	27	16	10
Halite	2.17	0.1	0.1	0.1	0.1	0.1	0.1
Gypsum	2.17	0.1	0.1	0.1	0.1	0.1	0.1

for each one. The composition of each formation is expressed in % of different lithologies. Gypsum and salt are assumed to be incompressible. Their constant porosities are about zero. For the other lithologies, compaction increases with depth as summarized in Table A2. Mantle and water densities are also needed to calculate the tectonic subsidence and are 3.3 and 1.1 g/cm^3, respectively. It is assumed that the sedimentary pre-rift sequence was already compacted when subsidence occurred.

Eustatic sea level changes and paleobathymetry

The paleo-sea levels used for this study are those proposed by Kominz (1984, table 1). During the Cenozoic, variations in sea level remained less than 30 m, and the possible error introduced by this parameter has little influence on the subsidence curves. Paleobathymetry is an important parameter in backstripping reconstruction since a change of 100 m of water causes a similar variation in tectonic subsidence. In the Gulf of Suez, faunal associations indicate rather shallow water (less than 100 m) for most of the formations. Locally, depths of about 300 m could be reached during the deposition of the Rudeis Fm. Because of the relatively slight variations we have considered a homogeneous bathymetry of 80 m for the Nukuhl Fm, 100 m for the Rudeis Fm, and 50 m or less for the post-Rudeis formations (Table A1).

Absolute ages in the Gulf of Suez

An important parameter determining the subsidence history is the dating of the sedimentary layers. The absolute age of each unit has not been definitively ascertained and is inferred from the paleontological record, mainly from nannofauna and microfauna determinations. All the hypotheses and the resulting time scales are given in Table 1.

In the Gulf of Suez, most of the blocks are bounded by faults allowing relatively independent isostatic movements. Hence for subsidence reconstruction we suppose local isostatic compensation. This model appears to be closer to the true behavior of a thinned crust than the flexural model. Nevertheless movements of a block like the Zeit are obviously driven by the geometry of the fault. Assuming a local isostatic compensation, we eliminate the influence of sedimentary loading just perpendicular to the studied area. Therefore, the calculated tectonic subsidence is due to both deep thermal process and force of couple between the outermost parts of the block.