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ASYMMETRY OF THE EARLY RIFT STRUCTURES: A COMPARISON BETWEEN THE GULF OF SUEZ AND THE GULF OF CORINTH

CONTENTS

ABSTRACT

This paper focuses on the structural style of young rifts, with a special emphasis on the Suez and Corinth grabens. The study of the 3D pattern of both gulfs shows that the dip of the major faults on a given cross-sections is fairly constant. In the Gulf of Suez, as in the Gulf of Corinth, the main dip direction of the major faults changes along the rift axis. Major faults dip eastward in the north of the Gulf of Suez, westward in the centre and eastward again in the south. Similarly, major faults dip northward in the eastern part of the Corinth Gulf and southward in the western part. In both cases, it can be demonstrated that this local main direction is inherited from the layout of the pre-rift potential décollement levels and/or from the first fault to appear when rifting begins. The depth of these décollement levels is the key parameter controlling the size of the tilted blocks, their rotation and the relative uplift of the noses and subsidence of the half-grabens. In both the Suez and the Corinth rifts, a narrowing of the subsiding area through time is observed.

KEY WORDS: Rifting, tilted block, Suez, Corinth

1. INTRODUCTION

Extensional processes may start for various reasons: thinning of the lithosphere by mantellic convection, far field stress, back arc phenomena. They may also affect different crusts. The initial crust is sometimes rather homogeneous, as in the case of the Gulf of Suez or, at the opposite highly heterogeneous, as in the Gulf of Corinth, where the extension affects a former mountain belt.

In the Gulf of Corinth, thrusts may be reactivated as décollement levels whereas in the Gulf of Suez, apart from some thin and rather superficial shaly beds, the unique décollement level is the brittle/ductile transition in the crust. These characteristics influence the development of the normal fault pattern and therefore the structural feature of the rift. In this paper, we will document the differences between the two cited examples in terms of fault spacing, block sizes and tilt angles.

The major causes of the extension in both cases are also different: the Gulf of Suez is clearly related to a deep mantellic thermal anomaly, which induces a lithospheric and crustal thinning. Abnormal mantle is not detected below the Gulf of Corinth, but it is located in a back-arc position and is affected by the westward propagation of the north Anatolian fault. These regional features induce very different subsidence and uplift histories of both zones. Subsidence, tilting and uplift, where it occured, have been recorded by the syn-rift sediments.

2. GULF OF SUEZ

2.1. *Geological setting*

Extension started in the Gulf of Suez about 23 Myr ago, at this time the rifting phase affected both the Red Sea and the Gulf. The extensional rate was fast during the initial phase, between 23 and 15 Myr (MORETTI & COLLETTA, 1987). Around 13 Myr ago, extension stopped in the Gulf of Suez and then started on the Aqaba-Levant fault, characterised by a sinistral strike slip component (COCHRAN, 1983). In the Gulf of Suez, a quiescent phase lasted from 15 to 5 Myr ago and led to the deposition of an evaporitic series. From Quaternary times, the rift trough narrowed and the uplift of the shoulders accelerated (MORETTI & COLLETTA, 1987).

As shown by numerous authors (MORETTI & FROIDEVAUX, 1986; BUCK, 1986; STECKLER *et alii*, 1988), the evolution of basin subsidence and rift shoulders uplift is compatible with the secondary convection process (active rifting related to a deep thermal anomaly). The narrowing of the trough and the late uplift of the shoulders are due to the abortion of the Suez branch of the Red sea rift, when the Aqaba branch became active.

The presence of the underlying abnormally hot mantle is confirmed by heat flow, gravity and uplift rate data (COCHRAN *et alii*, 1986, MAKRIS *et alii*, 1991). The crustal thinning is confirmed by refraction data (GAULIER *et alii*, 1988)

2.2. *Structure*

The Gulf of Suez is oriented around N140°, and is rather rectilinear, majority of the normal faults have this azimuth. The original dip of the normal faults is between 60 and 80°. Transverse faults generally have a steeper attitude and accommodate the different vertical displace-

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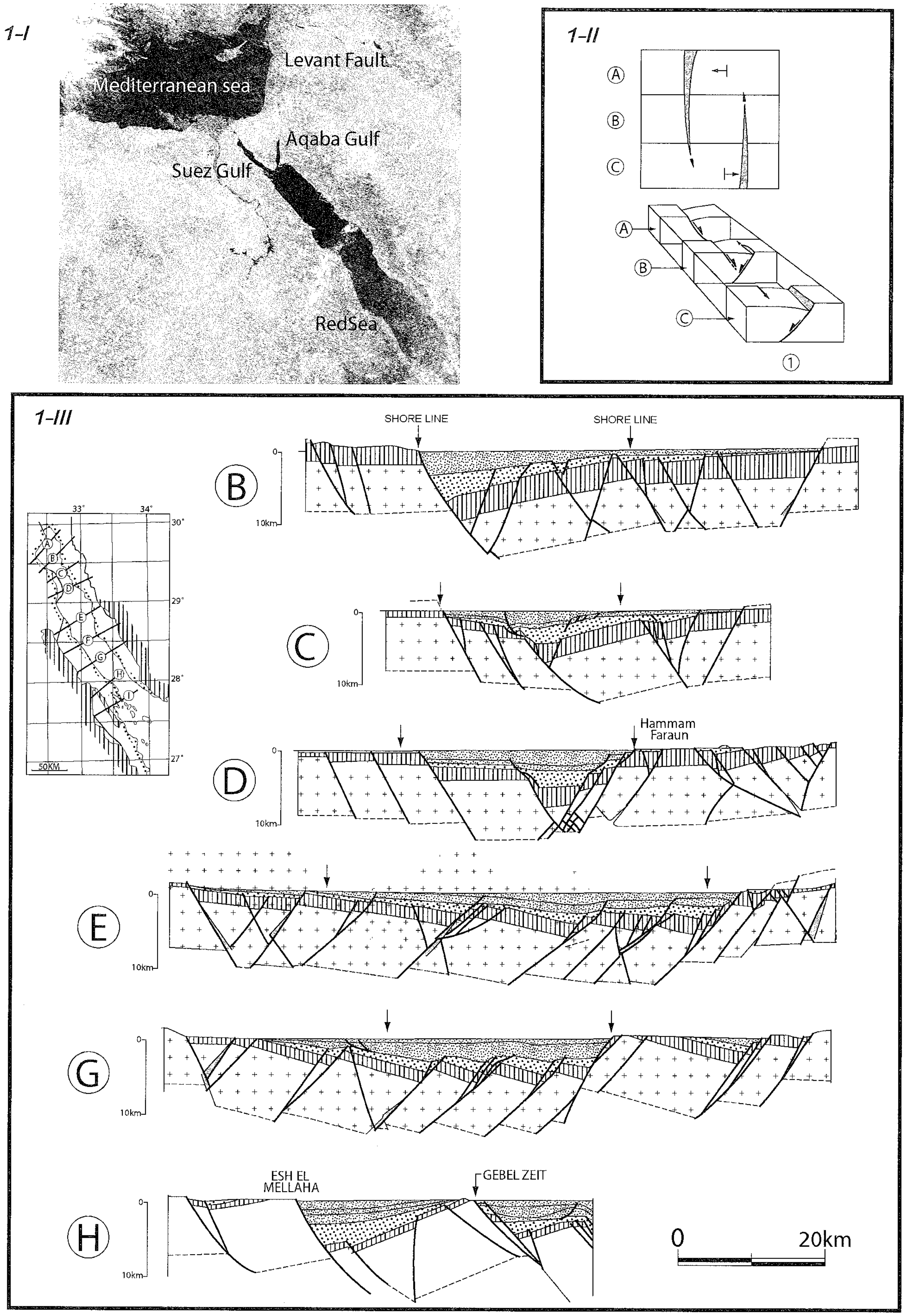

Fig. 1 - I: Regional shema based on a space pictures showing the Gulf of Suez as the northern tip of the Red sea rift system. II – Twist zone: sketch of the change of dip direction along a rift valley (modified from Colletta *et alii*, 1987). III - Cross-sections across the Gulf of Suez showing the North-South structural evolution (modified from Colletta *et alii* 1987).

ments affecting the block that they border. Evidence of horizontal displacement along these transverse faults is very rare. Structural analysis shows that the blocks are tilt to westward in the northern part of the Gulf, eastward in the center and westward again in the south (See figure 1). A subsidence study, based on subsurface data, has proven that the tilted blocks were initially very large. They become divided into smaller ones when the tilt angle increases with increasing extension (Moretti & Colletta, 1987). The new faults that appear at this time are parallel to the previous ones and therefore enhance the apparent asymmetry of the Gulf. The switch from east-dipping to west-dipping parts occurrs without a major transfer fault but rather by a "twist zone", i.e. fault offset decrease (Colletta *et alii*, 1988).

The blocks may be tilted up to 30° (Gebel Zeit) but generally no more than 20°; by comparing the uplift of the crest with the subsidence in the half graben it can be deduced that the rotation is rather rigid (domino style, Angelier & Colletta, 1983), with a decollement level located at about 10 km, i.e. at the upper / lower crust boundary (Moretti & Colletta, 1988).

The first syn-rift sequence, deposited between 23 and 15 Myr ago during the opening phase reflects the tilting of the blocks, with reefal facies developing at the crest whereas conglomerates fill the void in front of the main fault. Numerous sedimentological indicators confirm the emergence and therefore relative uplift of the nose of the tilted blocks (Moretti & Colletta, 1988).

3. GULF OF CORINTH

3.1. *Geological setting*

Extension in the Aegean Sea started in Miocene times (Le Pichon and Angelier, 1979). This extension is thought to be due to both gravitational collapse of the thick crust inherited from earlier mountain building (Jolivet, 2001) and lithospheric thinning in the Aegean back arc region (Doutsos *et alii*, 1988). The extension rate is fast, about 3 cm/yr, with respect to Eurasia (Kahle *et alii*, 2000) and progressively migrates to the south. Within this framework, the Corinth Rift represents one of the most recent extensional features although the relationship between the Aegean Miocene extension and the evolution of the Gulf of Corinth is still unclear. The possible multiple causes for the fast and intense tectonic activity in the Gulf of Corinth itself are still a matter of debate (Armijo *et alii*, 1996). In addition to gravitational instability of the Neogene mountain belt and lithospheric thinning in the back arc region of the subduction zone, the Evia and Corinth grabens may also be considered as accommodation sites at the western-propagating tip of the North Anatolian Fault (NAF) towards the north Aegean Sea during Late Pliocene times (Dinter, 1998).

The crustal thickness changes drasticaly from West (40 km) to East (20 km) whereas the North- South evolution is unclear (Tiberi *et alii*, 2000; Makris *et alii*, 2001). Heat flow data are still scarce and do not show any high heat flow in the Gulf. This could be due either to a normal basal heat flow and/or a blanketing effect due to the high sedimentation rate in the deepest part of the Gulf. Onshore, the high-speed fluid circulation precludes the interpretation of the data in terms of regional heat flow.

3.2. *Structure*

The Corinth Rift, which separates the Peloponnese from continental Greece, is a N100°E oriented elongate graben, 105 km long, which is bounded by systems of very recent roughly E-W normal faults (Fig. 2). These faults are now thought to be younger than 1.2 Myr (Sorel, 2000, Westaway, 2002, Moretti *et alii*, 2003) and are arranged *en echelon*, thus accommodating the gap between their orientation and the graben direction. The Gulf of Corinth is the most seismically active zone in Europe, and the fastest opening area of continental break-up, with up to 1.5 cm/yr of north-south extension, and more than 1 mm/yr of uplift of the southern shore (Tselentis and Makropoulos, 1986; Billiris *et alii*, 1991; Collier *et alii*, 1992).

Subsurface data have been collected offshore by Hellenic Petroleum (Myrianthis, 1984), the National Centre of Marine Research (NCMR) and the Patras University (Stefatos *et alii*, 2002), and more recently onshore by the cluster of European projects called the "CRL" (Corinth Rift Laboratory, Moretti *et alii*, 2002). All these recent studies have shown that the deformation history of the Gulf of Corinth is more complex than that of a simple half graben, bordered southward by an unique active fault, as previously described in the geological literature (Armijo *et alii*, 1996, Sorel, 2000). In particular it has been assessed that:

The Gulf of Corinth is not an asymmetric simple half graben. There are active normal faults on both sides of the Gulf (Fig 2). The more active faults that localize the depotcentre are located near the southern shore and dip northward in the Eastern part of the Gulf, and are located near the northern shore and dip southward in the western part of the Gulf. The maximum water depth is almost always in the central sector of the basin whereas the North-South location of the depotcentre versus the cost line also changes from East to West.

There is no evidence of tilting of the syn-rift sediments in the Aigion area between the three active faults of Pirgaki, Helike and Aigion (see cross section C Fig 2). The Helike fault is about 120 000 myr old and the Aigion fault, which has an offset of 180 m is about 50 000 yr old (see Micarelli and Moretti, 2003 for details on these faults).

The current tectonic activity is mainly characterised by the uplift of the Peloponnese. The differential displacement between the north and the south margin of the Corinth graben is estimated to about 2.0-2.3 m ka^{1}(Lykoussis *et alii*, 2002). This uplift has induced narrowing of the subsiding trough.

Our data suggest that the uplift of the Peloponnese is an "external" phenomenon, which has been superimposed in recent times on the opening of the Gulf. By analogy with similar situations elsewhere, and comparing their evolution through time, we propose that the uplift is related to the subduction, as a gravity anomaly in the subducting plate, rather than being a thermal phenomenon. A similar model has been also proposed by Leeder *et alii*, 2003. The current

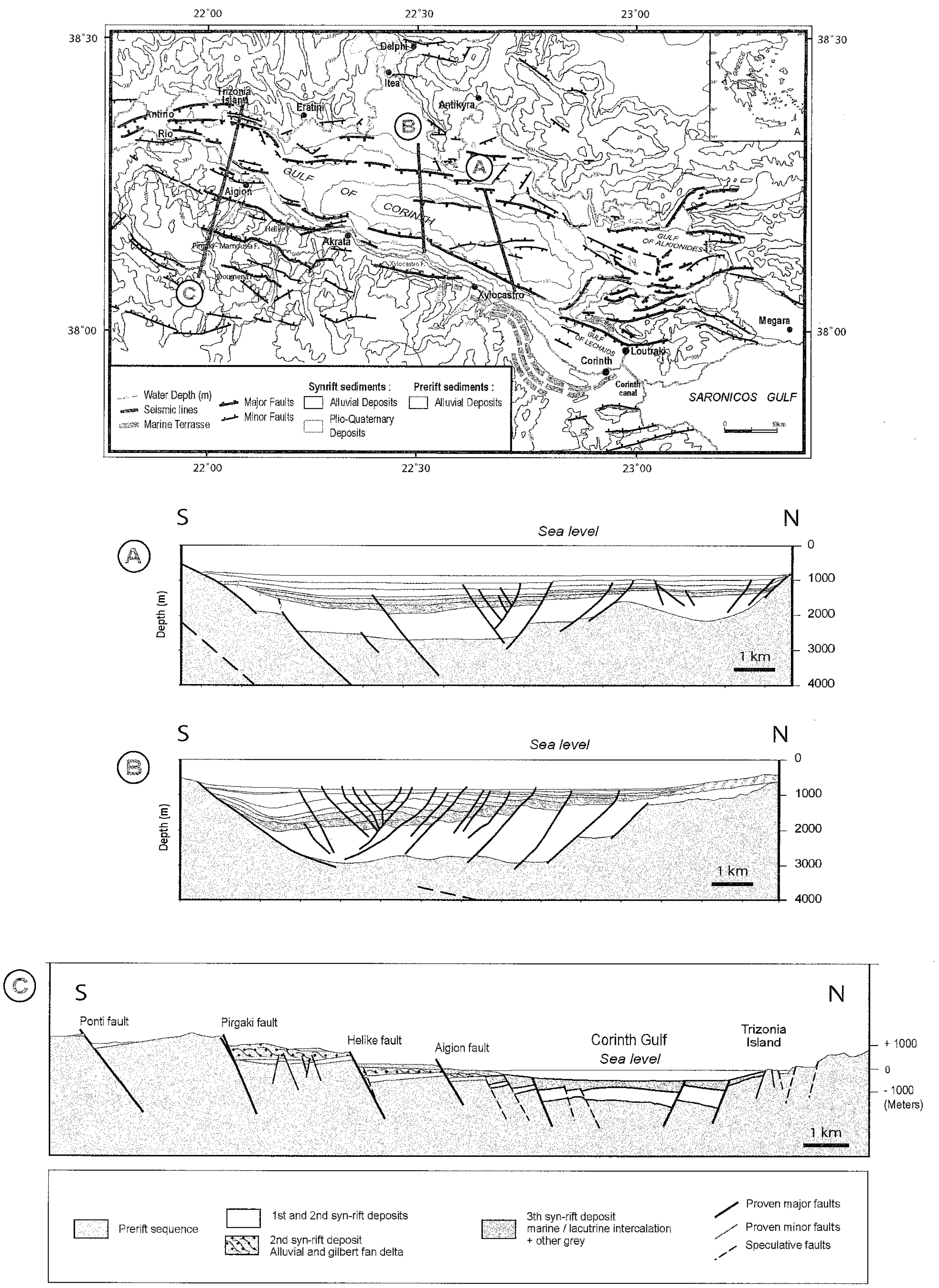

Fig. 2 - Structural map and Cross section in the Gulf of Corinth showing the East – West evolution.
Cross sections A and B are based on the seismic lines recorded by Hellenic Petroleum (Myrianthis, 1984), the time depth conversion was carried out by Clément, the interpretation is modified from Clément's one (2000), cross-section C is modified from Moretti *et alii*, 2003. The position of the numerous markers in the syn-rift series visible on the seismic lines are unknown on the offshore part of the section-C, since the sediments offshore are undated. The correlation between the onshore and offshore synrift phases is therefore speculative. See Moretti *et alii*, (2003) and Lykoussis *et alii,* (2004) for the details concerning our choice of correlation.

subsidence rate and slip rate for offshore active faults, deduced from the piston cores taken in the Gulf of Corinth by the Marion Dufresne Vessel in 2001 are also compatible with a 1 Myr long period of subsidence for the central and eastern part of the Gulf (LYKOUSSIS *et alii*, 2004; MORETTI *et alii*, 2004).

4. COMPARISON AND CONCLUSIONS

Table 1 presents a comparison between the two rifts.

The first obvious similarity is the change of the dip direction of the faults along the rift axis. In both the Gulf of Suez and the Gulf of Corinth, this change is accommodated by a decrease of the offset on one set of faults and increase of the offset of faults with the opposite vergence (Fig 1-II), twist zone as defined by COLLETTA *et alii*, (1988).

This longitudinal evolution has been also described in the Tanganika lake (BOSWORTH, 1985) and may be observed in the Rhine Graben (COLLETTA, pers. comm.). In the Gulf of Suez, subsurface data show that this structure is inherited from the attitude of the first faults to appear in the early stages of the rifting process and that all the following faults are parallel to the first ones (MORETTI ET COLLETTA, 1987).

A second interesting point of comparison between Corinth and Suez is the size and the amount of tilting of the faulted blocks. In the Gulf of Suez, tilted blocks exist, the tilit angle is around 20°, the crest of some of these blocks emerges during the rifting, and when the tilt increases the large blocks are sub-divided. In the Gulf of Corinth, there is almost no tilt, at least for the pre-rift sequence in the southern shore. The sediments do not show any evidence of crest emergence, and the blocks are rather small in size. These differences seem directly related to the characteristics of the décollement levels. In the Gulf of Suez, the prerift sequence (Nubian sandstone & Precambrian) acts as a brittle mono-block and the rotation of the block happens on the lower crust, whereas in the western Gulf of Corinth, the inherited napes act as decollement level below the north Peloponnese. For instance, in the Aigion area (see Fig. 2), the potential décollement level is the Philliades thrust sheet which is located at about 4 km below sea level. The thrust dips to the north and gets deeper below the northern shore of the Gulf. As modelled by LEPOURHIET *et alii*, (2004), we consider that

Characteristics	**Corinth (Western part)**	**Suez**
Age	1 to 0 Myr	From 23 Myr Main active phase between 23 and 19 Myr
Geometry:		
Length	150 km	300 km
Direction	N 100°	N 140°
Synrift max thickness	2.4 km	5 km
Water max thickness	800 m	60 m (more than 400 m during the first phase)
Width (dist. borders faults)	70 km	90 km
Current width of the Gulf	10 km (northward migration of the south shore)	40 km (narrowing due to the uplift of the shoulders)
Tectonic setting	Back arc & Western tip of the North Anatolian fault & gravitational collapse of the Hellenides	aborted rift: crustal and lithospheric thinning during the Miocene. Northward tip of the Red Sea active rift
Crustal thinning	None in North – South 40 km Westward, 20 km Eastward	$\beta = 1.7$ (Moho depth 32 => 17 km)
Upper crustal extension	Now 1.5 cm / yr	$\beta = 1.3$
Vertical movements	Uplift of the Southern shore Subsidence, deepening, of the offshore part	Uplift of both shoulders, mainly from 10 Myr to now No more tectonic subsidence of the central and northern parts, even offshore.
Main normal faults:		
Angle fault / bending	60°	60°
Typical length	Segments from 10 km up to 40 km	20 – 60 km
Typical width	3 km	around 10 km, larger initially
Average offset	Less than 1 km	1 to 4 km
Décollement level	From 5 to 10 km deep (inherited thrusts)	around 10 km (Upper/lower crust boundary)
Bloc tilt	From 0 to 15°	15 to 25°
Syn rift facies	Fluvio-lacustrine sediments during rifting initiation Alluvial fans, fluvial systems and giant conglomeratic gilbert deltas during the main rifting phase	Coarse-grained fan-deltas passing distally to shallow marine mixed platform. Reefal bioherms developed on the block crests. Sands mostly accumulated in transfer corridors associated to the main transverse faults.
Main potential reservoirs	Fluvial channels and lacustrine shorefaces are the best potential reservoir. The seal is problematic	Reefs, shorefaces and mixed platform facies. Seal made of shales and evaporites.

Tab. 1 - Suez / Corinth: A comparison

this inherited thrust sheet corresponds to the seismogenic zone defined by the earthquakes in the area (Rigo *et alii*, 1996). Eastward, this nappe does not exist and the structural pattern of the Gulf of Corinth, and the geometry of the seismogenic zone are different. The earthquakes originate at a deeper level, which is flat (Rigo, 1994; Rigo *et alii*, 1996) and may also correspond to the brittle/ductile boundary in an average continental crust, as in the Gulf of Suez.

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(*) Additional information may be found on http://www.corinth-rift-lab.org

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