Rift Sequences of the Southern Margin of the Gulf of Corinth (Greece) as Exploration / Production Analogues*

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General Statement

The initiation and development of continental rifts is the focus of much debate, nowhere more so than in the Pliocene-Recent Gulf of Corinth Rift, Greece, where active rifting has been widely studied and reported (Jackson et al., 1982; Armijo et al., 1996). Along the southern margin of the Corinth Rift, the deeply dissected mountains of northern Peloponnesos (Figure 1) spectacularly expose extensional half-grabens bounded by approximately WNW/ESE-trending normal fault systems (Doutsos and Poulimenos, 1992). The onshore area of the rift is up to approximately 40 km in width and 120 km long and includes both seismically inactive and active fault systems, and associated syn-rift sediment fill. As such, it provides a rare opportunity to assess the structural and stratigraphic evolution of a rift and, consequently, to gain an insight into basin-forming processes.

Doutsos and Poulimenos (1992) described the structure of the rift in this area and proposed that the surface normal faults were linked to a low-angle fault at deeper crustal levels (>7 km depth). More recently, Sorel (2000) and Chery (2001) have again suggested that the Corinth Rift is underlain by a major north-dipping crustal detachment fault, the "Khelmos detachment" (>100 km long). Based on field studies, Sorel (2000) concludes that this detachment fault is exposed at the southern edge of the rift system, within the valley of the Krathis River (Figure 1). Sorel (2000) also proposed that activity on both the extensional faults and the underlying detachment has progressively migrated northwards through time. Chery (2001), using a mechanical model, has further suggested that the Corinth Rift may eventually evolve to become a metamorphic core complex under continued extension, comparable to the Snake Range Fault System in Nevada, USA. The interpretation of earthquake focal mechanisms (Rietbrock et al., 1996) and inversion of GPS and SAR interferometry data following the 1995 Aigion earthquake (Bernard et al., 1997) have also been used to support a model invoking low-angle north-dipping faulting.

The objective of the current study was twofold. Firstly, we set out to test the presence of a regionally mappable detachment fault. Secondly, we aimed to test the northward basin migration hypothesis of previous authors, based upon new field mapping and observations of stratigraphic relationships in successive half-grabens.

Results of Geological Mapping

The study area includes the deeply incised north-south river valleys that transect the southern margin of the rift around the town of Kalavrita (Figure 1). Exposures of the rift sequences have been mapped over some 500 km^2 at 1:50,000 scale in an area of significant topographic relief. Exposure in this area is variable but numerous road cuts, deeply incised river valleys, and cliffs allow the characterisation of the main outcrop pattern. The geological map has been used to construct cross-sections to show the relationships identified (e.g., Figure 2).

Pre-Rift Sequences

In this area, complexly deformed Mesozoic carbonate-dominated units form the primary basement to the syn-rift fill sequences. These units were emplaced generally from east to west across Peloponnesos during mid-Tertiary continental collision and overthrusting (so the thrust sheets strike perpendicular to the younger rift faults). The internal structure of the Mesozoic units has not been mapped in this study, but it is recognised that pre-existing structure may have played a role in controlling, for example, the segmentation of the rift.

Syn-Rift Sequences

The overlying ?Pliocene to Recent syn-rift fill sequences are dominantly nonmarine, but they include the well known Gilbert-type fan delta deposits in the northern part of the onshore rift (Ori, 1989; Dart et al., 1994) and marine deposits of the present-day Gulf (Brooks and Ferentinos, 1984; Stefatos et al., 2002). Many of the nonmarine sequences are poorly dated; this means that only lithostratigraphic correlation of units between adjacent fault blocks is currently possible. Two major syn-rift, nonmarine, sedimentary formations above Mesozoic basement were distinguished during the current mapping exercise. These are critical to understanding the early evolution of the rift. The majority of the rift deposits are south-dipping, into the major faults.

(1) Basal clastic fluvial/alluvial to lacustrine formation. This unit includes basal conglomerates with massive and trough cross-stratified pebble and cobble conglomerates which overlie the basement units. The formation is up to ca. 800 m thick (north of the Kerpini and Dhoumena faults). Numerous outcrops across the study area show that these sediments are both thickened and back-rotated into the main north-dipping faults. In addition, they strongly onlap the adjacent hangingwall slopes (Figure 2); all of these characteristics indicate their syn-tectonic nature. Clast compositions suggest that these early syn-rift sediments include materials derived from the adjacent footwall blocks, presumably during active footwall uplift and erosion.

The southernmost depocentre, controlled by the Kalavrita Fault (Figure 2), is dominated by coarse-grained clastics supplied by the palaeo-Vouraikos River. The lowermost conglomerates in this half-graben are likely to be equivalent in age to the basal clastic formation, but are lithologically indistinguishable from the subsequent progradational formation, outlined next.

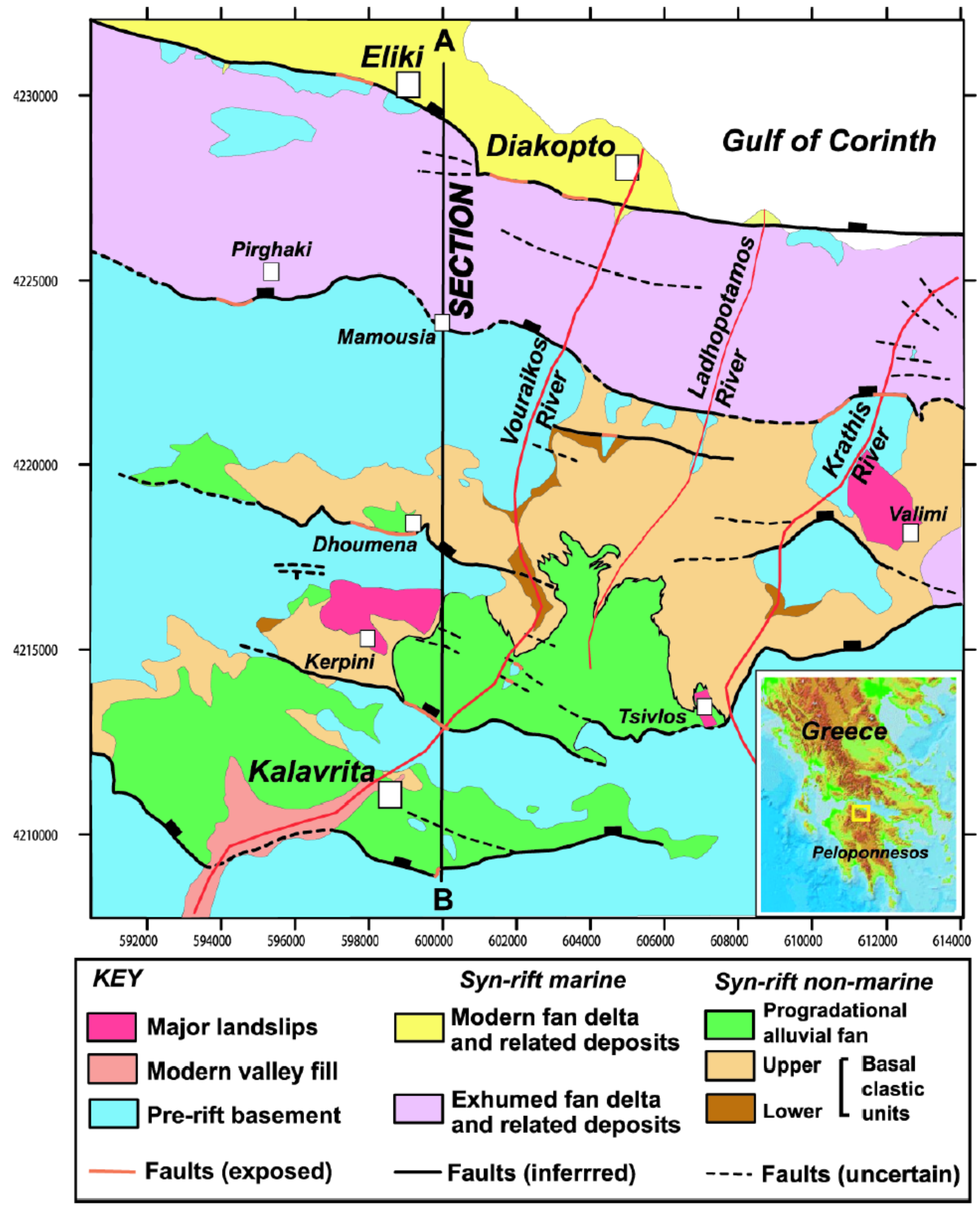

Figure 1. Location of the Gulf of Corinth (inset) and a geological map of the study area.

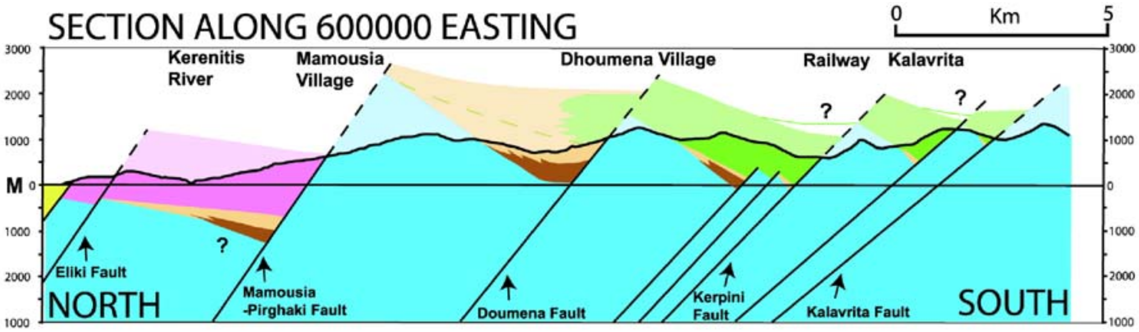

Figure 2 North-South cross-section across the study area. See Figure 1 for location.

(2) Progradational alluvial fan formation. A phase of significant alluvial progradation subsequently transported large volumes of coarse clastic sediment across the rift, from the south. A marked coarsening-up facies boundary defines the base of this formation (north of the Kerpini Fault), the deposits of which were described as braided-river and alluvial-fan units by Doutsos and Poulimenos (1992). The main sediment influx at this time mimics the pathway of the present day Vouraikos River, where ca. 1.5 km of stacked, fluvial conglomerates are laterally transitional into sands and then alluvial to lacustrine fines from south to north. This is best observed in the Ladhopotamos River valley, which provides an 8-km long transect through this facies change. A radial facies-transition pattern seen to the north of the Kerpini Fault describes a major alluvial fan. The formation can be mapped continuously from the Kalavrita half-graben in the south, with its uninterrupted conglomerate infill, to beyond the Mamousia-Pirghaki Fault in the north. Thus the rift consists of one broad alluvial half-graben at this time, >16km wide, bounded by the Kalavrita Fault in the south and with a hangingwall extending to the north of the Mamousia-Pirghaki Fault (Figures 2 and 3).

Large-Scale Faulting

Five main north-dipping fault systems are present in the mapped area (throws of ~2 km, average spacing of ~4 km), including the seismically active coastal fault system, as briefly described below. A number of subsidiary faults and splays (Figure 1) have also been identified. Where typically exposed (bounding the footwall carbonate basement units), the fault zones dip at 40-50^{o} at surface, although in detail they are complex features with multiple slip planes and variable surface dips. Most kinematic indicators suggest dip-slip movement (Roberts, 1996), but regionally where well exposed, more complex kinematics are seen (e.g., parts of the coastal fault system at Alepochori in the eastern Gulf of Corinth; RDR unpublished data, 2001).

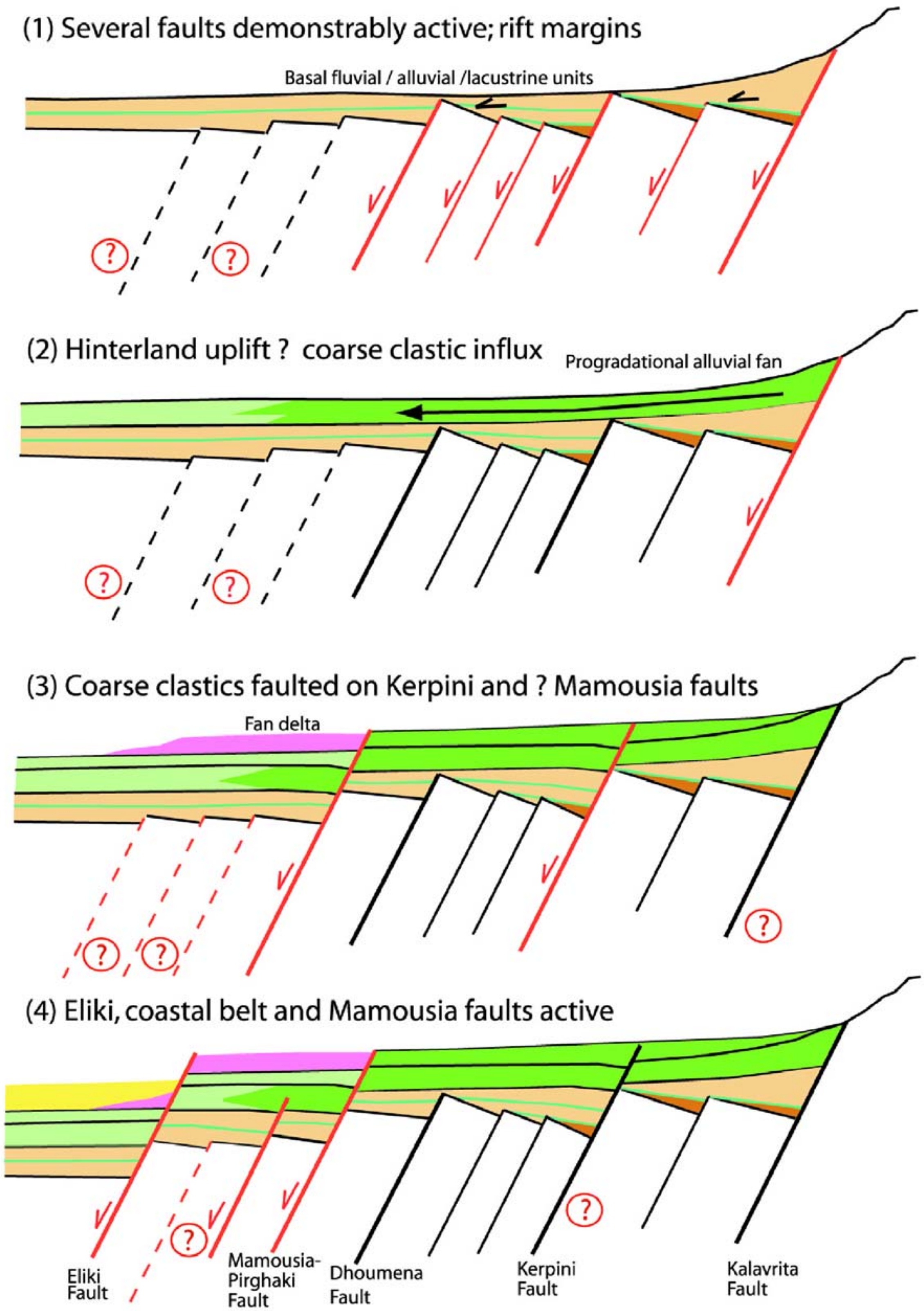

Figure 3 Proposed schematic evolution of the southern margin of the rift from North (left) to South (right).

South and east of Kalavrita, exposures are often limited by surficial deposits but topographic relief suggests a major W/E fault is present, defining the southern margin of the rift. This contact corresponds to the "Khelmos detachment fault" of Sorel (2000). The majority of the exposed rift sediments in the Kalavrita half-graben are interpreted as part of the progradational syn-rift package, with older syn-rift sediments exposed along the footwall onlap surfaces, west of Kalavrita. East of the town, exposures of carbonate suggest a further splay fault is present (Figure 1).

The next significant fault to the north is the Kerpini Fault, which is clearly delineated adjacent to a limestone quarry in the Vouraikos valley, 3.5 km north of Kalavrita; it can be traced several kilometres eastwards (Figures 1, 2). A key observation is that, in the vicinity of the quarry, the extensive alluvial conglomerate packages of the progradational formation are demonstrably offset by this fault (Figure 2). Estimated maximum throw on this fault is 2.5 km. Other smaller-offset extensional faults exposing carbonate footwall crests are seen in the Vouraikos River valley. These faults appear to be mostly buried beneath the progradational syn-rift package, but locally they extend vertically to offset the lower parts of this formation. These faults may also extend westwards and, to the east, could link to the extension of the Kerpini Fault that occurs near Tsivlos, where the basement outcrop makes a distinctive bend.

The Dhoumena Fault is well-exposed (Figures 1 and 2) and has a throw in the order of 2 km. This fault forms a distinctive topographic ridge to the west. To the east (on the east side of the Vouraikos valley) it is interpreted to tip-out as a monoclinal feature, where locally anomalous north-dipping sediment panels are exposed. The basal syn-rift packages associated with the Dhoumena Fault are well exposed in the Vouraikos River valley and to the west. There is also excellent exposure of the onlap of the hangingwall slope / footwall crest to the north within this half-graben (Figures 1 and 2) on the east side of the Vouraikos valley. At Dhoumena, the younger syn-rift, progradational alluvial conglomerate formation is preserved as an outlier, forming a distinctive local topographic feature adjacent to the exposed fault plane.

To the north, the Mamousia-Pirghaki Fault (Figures 1 and 2) is a major topographic feature, marking the boundary between exposed nonmarine and marine/lacustrine syn-rift deposits. The fault plane is locally exposed in the west of the study area and in the Krathis valley in the east. The hangingwall of the fault exposes major Gilbert-type fan deltas now, as a result of footwall uplift related to the presently active faults (Dart et al., 1994).

The active coastal fault system, the Eliki Fault, follows a similar trend to the older faults. Carbonate basement is locally exposed in the footwall crest along the coast. Modern fan delta deposits are accumulating to the north of the Eliki fault, on the subsiding hangingwall of the present day Gulf. The Eastern Eliki Fault trace was last ruptured by a surface-breaking earthquake in 1861 (Schmidt, 1879). Well-defined marine terraces exist to the south of the Eastern Eliki Fault, attesting to uplift through the Late Pleistocene (Armijo et al., 1996; McNeill et al., in press).

Meso-Scale Faulting

Dominantly north-dipping planar and listric meso-scale faults are also seen in the Vouraikos valley (throws of centimeters to ~100 m). A number of these fault systems occur in immediate footwall (e.g., of the Mamousia-Pirghaki Fault) or hangingwall areas (e.g., close to the eastern tip of the Dhoumena Fault) of the larger mapped faults and are believed to relate largely to rift-related deformation on the major fault systems (McGurk, 1999). Where such relationships are harder to prove, the meso-scale structures could also be related to other mechanisms; e.g., more recent landslip events on the valley sides.

Tectono-Sedimentary Evolution

Two issues arise: (1) the presence or absence of a regional basal detachment fault with a fault trace >100 km long, and (2) the spatial and temporal evolution of the rift and fault activity.

Firstly, the Khelmos detachment is not mapped as a 100-km long, continuous detachment feature. For example, the Kerpini fault is not linked southwards to the Kalavrita fault south of Tsivlos, as was suggested by Sorel (2000). Furthermore, the field relations described above are not diagnostic of an underlying detachment fault. The entire system could be described by a set of comparatively high-angled normal faults bounding narrow half-grabens, which were back-tilted by progressive footwall uplift. This process is clearly evident along the present-day rift margin by the exposure, uplift, and backtilting of originally horizontal Gilbert fan delta top-sets in the hangingwall of the Mamousia-Pirghaki Fault. Fault planes across the region dip at ca. 40-60^{o} at outcrop, consistent with backtilting of successive footwall fault blocks.

Secondly, the timing of faulting is more complex than previously recognised (Figure 3). A relative chronology of fault activity that has been established differs significantly in detail from that proposed by Sorel (2000):

1) Activity was initially distributed over a relatively wide area with three major faults (Kalavrita, Kerpini and Dhoumena Faults) and several subsidiary or splay faults active. It is not known if the Mamousia-Pirghaki fault was also active at this time. Neither is it known whether antithetic faults lay farther to the north, forming a northern margin to the rift.
2) Subsidence on the Kalavrita Fault continued, generating accommodation space for a significant thickness of fluvial conglomerates. Progradation of this conglomeratic wedge then resulted in a major fluvial influx northwards across the rift, with a significant alluvial fan developed to the north of the Kerpini Fault. Some combination of regional hinterland uplift, major reactivation of the Kalavrita Fault (footwall uplift), or conversely a reduction of accommodation space in the Kalavrita depocentre, or even climatic change

may have triggered this major progradational pulse across the rift. Some faults remained active during the deposition of the lower parts of this progradational formation.
3) Kilometre-scale faulting on the Kerpini Fault has post-dated accumulation of the progradational alluvial fan formation. Some reactivation and eastward propagation of the Dhoumena Fault also post-dated the progradational episode.
4) Subsequently the Mamousia-Pirghaki Fault system delimited the area of rift subsidence, with ca. 1.5 km of deltaic sediments accommodated to the north. Erosion of early syn-rift sediments would have occurred north of the Mamousia-Pirghaki Fault system, in its uplifting footwall.
5) The final stage of activity has seen the Mamoussia-Pirghaki Fault become (relatively) inactive, with basin-margin stepping-north once again, onto the Eliki Fault system.

This evolution indicates that the rift did not evolve through a simple south to north progression of fault-bounded basins, as previously suggested. Rather, earliest rift activity was broadly distributed across a number of faults (Step 1; Figure 3). At this time, when the basal clastic fluvial/alluvial to lacustrine formation was being deposited, the northern basin margin already lay to the north of the Mamousia-Pirghaki Fault. Fault activity has subsequently focused through time on the larger faults observed at the present. There is irrefutable evidence that the southern margin of the Gulf of Corinth rift has shifted northward (in relative terms) through time. Fault activity has migrated in general terms from the Kalavrita to the Kerpini to the Mamousia-Pirghaki into the Eliki Fault system. However, it is unclear whether the width or the location of the actively subsiding rift has changed significantly throughout its history. Models invoking northward migration of successive, narrow depocentres (Sorel, 2000) can therefore be discounted.

Conclusion

In conclusion, the near continuous exposure of the early rift in numerous river valleys offers a unique opportunity for evaluating the spatial and temporal evolution of a rift and its associated sedimentary fill and for use as extensional basin analogues for the hydrocarbon industry.

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