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# Building up or out? Disparate sequence architectures along an active rift margin—Corinth rift, Greece

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## ABSTRACT

**Early Pleistocene synrift deltas developed along the southern Corinth rift margin were deposited in a single, dominantly lacustrine depocenter and were subject to the same climate-related base-level and sediment supply cyclicity. Two synrift deltas, just 50 km apart, show markedly different sequence geometry and evolution related to their location along the evolving border fault. In the west, strongly aggradational fan deltas (>600 m thick; 2–4 km radius) deposited in the immediate hanging wall of the active border fault comprise stacked 30–100 m thick stratal units bounded by flooding surfaces. Each unit evolves from aggradational to progradational with no evidence for abrupt subaerial exposure or fluvial incision. In contrast, in the central rift, the border fault propagated upward into an already deep lacustrine environment, locating rift-margin deltas 15 km into the footwall. The deltas here have a radius of >9 km and comprise northward downstepping and offlapping units, 50–200 m thick, that unconformably overlie older synrift sediments and are themselves incised. The key factors driving the marked variation in sequence stratigraphic architecture are: (1) differential uplift and subsidence related to position with respect to the border fault system, and (2) inherited topography that influenced shoreline position and offshore bathymetry. Our work illustrates that stratal units and their bounding surfaces may have only local (<10 km) extent, highlighting the uncertainty involved in assigning chronostratigraphic significance to systems tracts and in calculating base-level changes from stratigraphy where marked spatial variations in uplift and subsidence occur.**

## INTRODUCTION

Pioneering work established seismic and sequence stratigraphy as a methodology for subdividing sedimentary basin deposits into genetically related packages bounded by time-significant surfaces, and highlighted eustatic sea-level fluctuations as a fundamental control on depositional sequences (e.g., Vail et al., 1977; Posamentier and Vail, 1988; Van Wagoner et al., 1990). Theoretical arguments further proposed that variation in sediment supply (Vail et al., 1977) and tectonic subsidence (Jervey, 1988) also influenced sequence development. The effects of sediment supply on sequence evolution have since been demonstrated in a range of depositional settings (e.g., Martinsen and Helland-Hansen, 1995), as have regional tectonics related, for example, to dynamic topography (e.g., Jones et al., 2012). There are, however, few detailed studies of the sequence stratigraphic evolution of syntectonic strata developed around normal faults along rifted margins. Case studies to date are largely two-dimensional dip-oriented sections (Prosser, 1993; Dorsey et al., 1997), and those that address strike variability are largely theoretical (Gawthorpe et al., 1994) or lack a well-constrained structural framework (Ghinassi, 2007).

In this paper we bridge the gap between theory and field evidence with an integrated structural and sequence stratigraphic analysis of two contemporaneous early Pleistocene synrift deltas that developed along the southern margin of the Gulf of Corinth (Greece) during growth of an active border fault (Fig. 1). The deltas are located 50 km along strike from one another in a single, dominantly lacustrine depocenter with episodic marine incursions (Rohais et al., 2007; Backert et al., 2010). However, the deltas have markedly different sequence stratigraphic architectures, which we suggest are a response to variations in uplift, subsidence, and inherited topography around the evolving border fault. Many sedimentary basins, not only rifts, have an active phase of evolution controlled by growing faults and folds, and thus our results have wider implications for sequence stratigraphic methodology, reconstruction of fault growth history, and interpretation of the controls on basin stratigraphy.

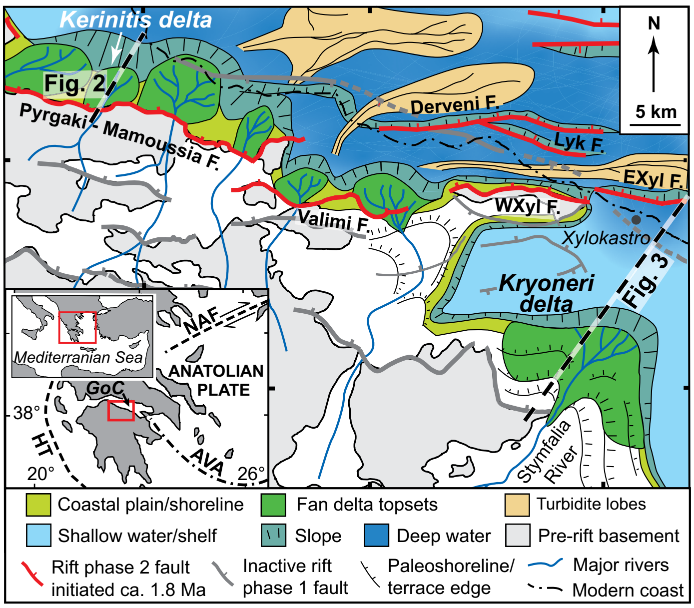


**Figure 1. Early Pleistocene paleogeographic map of the western-central Corinth rift (Greece) during early rift phase 2 with the two studied deltas named. Rift 2 border fault segments are named (Lyk F.—Lykoporia fault; EXyl F.—East Xylokastro fault; WXyl F.—West Xylokastro fault). Inset shows regional setting (AVA—Aegean Volcanic Arc; GoC—Gulf of Corinth; NAF—North Anatolian fault, HT—Hellenic Trench).**


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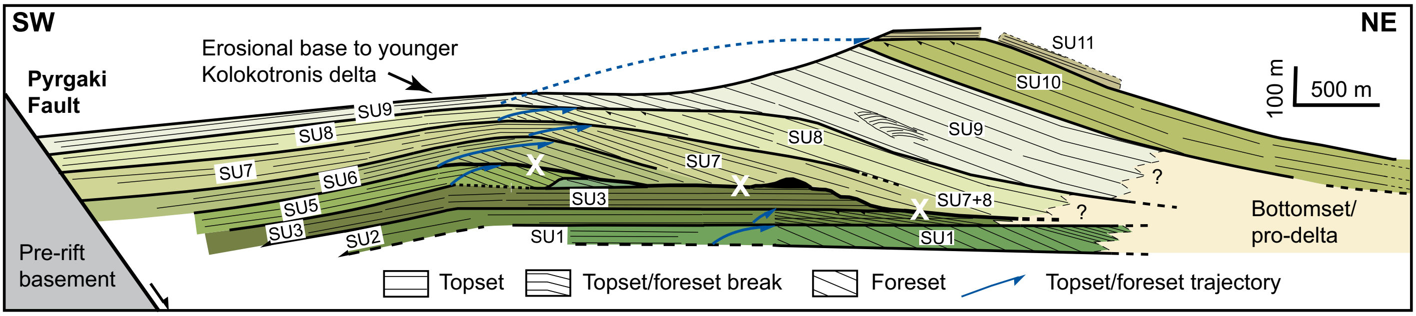


**Figure 2. Cross section of the Kerinitis delta (location in Fig. 1). Note overall aggradation and aggradational to progradational stacking pattern of the individual stratal units (SU) bounded by flooding surfaces. X indicates major erosion surface. Modified from Backert et al. (2010).**

## SYNRIFT SEQUENCES AROUND NORMAL FAULTS

The Corinth rift (Greece) is one of Earth's most rapidly extending continental rifts: geodetic extension rates reach 15 mm/yr, with maximum Holocene rift flank uplift approaching 3 mm/yr (Clarke et al., 1998; Pirazzoli et al., 2004). Northward migration of fault activity occurred along the southern margin of the rift (Ori, 1989; Gawthorpe et al., 1994; Ford et al., 2013), with an early phase of rifting (rift phase 1: starting 5.0–3.6; ending 2.2–1.8 Ma) that produced a 30-km-wide zone of now-abandoned normal faulting. Rift phase 1 deposition is characterized by major fluvial systems in the west, and fan deltas and deep-lacustrine turbidite channel and lobe complexes further east. Rift phase 2 (starting 2.2–1.8 Ma; to present) is focused on the modern Gulf of Corinth. In the west it is characterized by fan deltas that built into a deepening lake, with a shoreline in the immediate hanging wall of the new rift phase 2 border fault (Fig. 1). In the central rift the border fault propagated into the lake inherited from rift phase 1, and the early rift phase 2 deltaic shoreline was located more than 15 km south, in its footwall (Fig. 1).

We focus on two rift phase 2 fan deltas located 50 km apart along the southern coastline of the rift. The Kerinitis delta developed in the hanging wall of the border fault in the western rift, while the Kryoneri delta developed in the footwall of the border fault in the central rift (Fig. 1). Palynological data suggest that the Kerinitis delta developed between 1.8 and 0.7 ± 0.2 Ma (Malartre et al., 2004; Ford et al., 2013). The Kryoneri delta unconformably overlies deep lacustrine rift phase 1 deposits containing ash dated as 2.55 Ma (Leeder et al., 2012) and is older than the highest marine Corinth terrace mapped by Armijo et al. (1996) and interpreted as Marine Isotope Stage 15, ca. 0.6 Ma. The two deltas are therefore contemporaneous. To the east, along strike from the Kryoneri delta, similar coarse conglomeratic deposits also unconformably overlie lacustrine marls, and are capped by paludal and cascade tufa dated as ca. 1 Ma based on preliminary U-Pb isotopic analyses (Brasier et al., 2011).

### Kerinitis Delta

The Kerinitis delta, one of several fan deltas that developed in the immediate hanging wall of the rift phase 2 border fault, has a radius of 4 km, a minimum thickness of 600–800 m, and contains 15–20 km$^3$ of coarse-grained sediment. The delta developed along the steep footwall scarp of the Pyrgaki-Mamoussia fault, the active southern border fault segment in the western rift in the early Pleistocene (Figs. 1 and 2). Northward migration of faulting from the Pyrgaki-Mamoussia fault to the Helike fault occurred ca. 0.7 Ma, leading to uplift, abandonment, and incision of the delta (e.g., Backert et al., 2010).

The proximal delta, extending a distance of ~900 m from the Pyrgaki-Mamoussia fault, comprises pebble-cobble conglomerate fluvial topsets that thicken and are backtilted into the fault (Fig. 2). The next 750 m contain both topsets and foresets, and yet further from the fault the delta is composed almost entirely of spectacular conglomeratic foresets as high as 600 m (e.g., stratal unit, SU10, Fig. 2). The foresets display radial dips away from the Pyrgaki-Mamoussia fault and rapidly decrease in dip from a mean of 25° into bottomsets dipping <10°, with prodelta facies composed of interbedded conglomerates, sandstones, and siltstones. The overall shoreline trajectory in the narrow zone of topsets and foresets is subvertical, highlighting the aggradational stacking pattern of the delta.

Internally the proximal Kerinitis delta is composed of 30–100 m thick stratal units, each characterized by a shoreline trajectory that evolves from aggradation-progradation to predominantly progradation (e.g., SU6 and SU7, Fig. 2). Surfaces bounding these stratal units are major flooding surfaces, marked by a landward shift in the shoreline of several hundred meters and by downlap of overlying foresets (Fig. 2). Rare carbonate buildups as well as prodelta and bottomset facies are locally preserved between topsets and overlying foresets (e.g., Backert et al., 2010; Dart et al., 1994), indicating deepening and reduced clastic sediment supply.

Erosion surfaces are present within the delta, but these are mainly at the base of foresets and are interpreted to reflect erosion by gravity flows. Only one major erosion surface exists in the entire delta succession. This surface has more than 100 m of relief, yet lacks any evidence of updip subaerial exposure and is overlain by foresets (X, Fig. 2). Backert et al. (2010) interpreted this erosion surface as subaqueous in origin, due to either gravitational collapse of the delta front or incision by major gravity flows. Similar structures occur in submarine canyons on the active fan deltas from the modern western Gulf of Corinth (McNeill et al., 2005).

### Kryoneri Delta

The Kryoneri delta is located 7–15 km south of, and thus in the footwall to, the east Xylokastro fault, a north-dipping fault segment that defines the border fault to rift phase 2 in the central rift (Fig. 1). The delta has a radius of 9 km, a maximum thickness of 200 m, and contains 25 km$^3$ of coarse-grained sediment; it lies to the north (basinward) of an older rift phase 1 delta (Kefalari delta) that is tilted into the former border fault (Figs. 1 and 3).

Elevation of topsets of the Kryoneri delta decreases from ~1000 m in the south to 700 m in the north over a distance of 8 km (Fig. 3). The decrease in elevation occurs as discrete steps, expressed in the topography as steep, narrow north-facing slopes, 20–80 m high, that separate terrace flats as much as 2.5 km wide (Fig. 3). The delta top is incised as much as 200 m by dry hanging valleys, the most prominent being the Stymfalia valley, which was the main north-flowing trunk river feeding the Kryoneri delta. These drainages are now reversed and flow to the south.

The basal angular unconformity shows a similar step-wise decrease in elevation from south to north: areas where the top of the delta is a terrace flat are underlain by the subhorizontal basal unconformity (<5° dip) lined by intraclast-rich conglomerate lags. Locally, however, channel-like erosion features, tens of meters deep, are noted paralleling modern river valleys. Internally, the delta units are dominated by pebble conglomerate foresets that dip as much as 25° to the northeast and pass downdip into bottomsets. Topsets are thin to absent over most of the delta, giving each delta terrace a subhorizontal, progradational, shoreline trajectory.

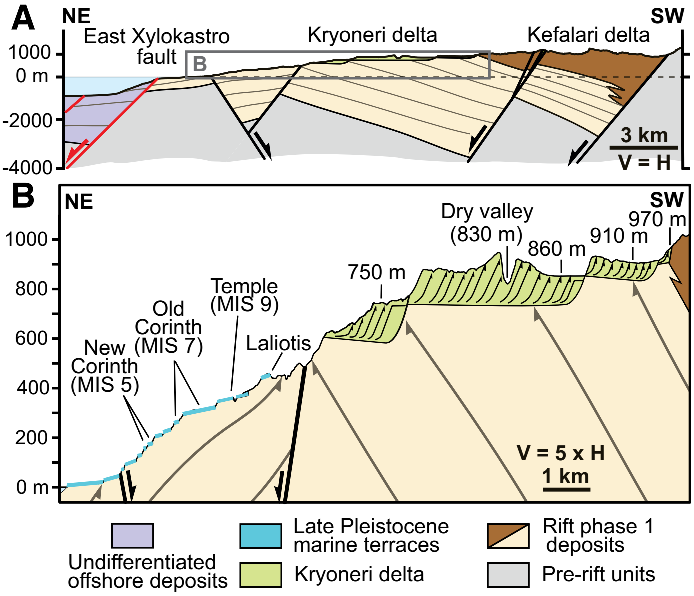


**Figure 3. Cross section of the Kryoneri delta (location in Fig. 1). A: Regional cross section showing delta and rift 2 faults with unconformable relationship to older rift 1 stratigraphy. B: Close-up of Kryoneri delta and younger marine terraces in A, showing overall downstepping geometry and the strongly progradational character. Marine terraces are after Armijo et al. (1996). MIS—marine isotope stage.**

## SEQUENCE VARIABILITY: RESPONSE TO NORMAL FAULT DISPLACEMENT

Both the Kerinitis and Kryoneri deltas were sourced from large catchments that drained the southern rift shoulder and built into a single lake (Fig. 1). Thus the deltas underwent the same early Pleistocene climate cyclicity, which influenced both base level and sediment supply, yet they have markedly different sequence stratigraphic characteristics (Fig. 4).

The Kerinitis delta is in the immediate hanging wall of the southern border fault, and the thick, overall aggradational geometry of the delta deposits and the southward-thickening and southward-tilted fluvial topsets point to a long-term relative rise in base level driven by hanging-wall subsidence. The aggradational to progradational stacking pattern within each stratal unit reflects a decrease in the rate of relative base-level rise and a decrease in the accommodation/sediment supply ratio. In contrast, the bounding surfaces, marked by landward shifts in facies and downlap of overlying foreset toes, represent major flooding surfaces, suggesting a marked increase in relative base level and a significant increase in the accommodation/sediment supply ratio.

Average Late Quaternary slip rates on the active southern border fault are in the range 2.5–5.5 mm/yr (Gawthorpe et al., 1994; Bell et al., 2009). This indicates hanging-wall subsidence rates sufficient to suppress all but the fastest lake or eustatic sea-level falls, while markedly enhancing lake or eustatic sea-level rise. It therefore explains why there are neither sequence boundaries nor features related to relative base-level fall within the Kerinitis delta. Furthermore, as suggested in Gawthorpe et al. (1994) and Backert et al. (2010), progradation within the stratal units occurred during intervals of low rates of relative base-level rise that most likely correspond to phases of regional base-level fall (Fig. 4). In contrast, the major flooding surfaces subdividing the Kerinitis delta are consistent with tectonically enhanced relative base-level rise that significantly outpaced sediment supply and led to the absence of retrogradational deposits (Fig. 4).

The Kryoneri delta is underlain by an angular unconformity that is a composite surface formed partly as a result of subaerial exposure during relative base-level fall. However, its largely planar geometry and associated intraclast-rich lag are indicative of wave erosion during subsequent relative base-level rise and transgression (Fig. 4). These observations suggest that the overlying delta deposits formed during highstands of base level. This is similar to the younger Corinth marine terraces (Fig. 3), which have been tied to glacioeustatic sea-level highstands by U-Th dating of corals (Armijo et al., 1996; Collier, 1990; Keraudren and Sorel, 1987).

Average Late Quaternary uplift rates for the coastal area north of the Kryoneri delta are 1–1.3 mm/yr (Keraudren and Sorel, 1987; Armijo et al., 1996; Bell et al., 2009), so that relative base level largely mimics regional base-level cyclicity, but is superimposed on a long-term relative fall driven by tectonic uplift (Fig. 4). This long-term uplift drove destruction of the lake inherited from rift phase 1 times and the overall forced regression and downstepping trajectory of the Kryoneri delta. It also caused progressive subaerial exposure and incision of the older parts of the delta. Lowstand delta shorelines were located basinward (north) of the highstand deposits, on the shelf south of the active border fault (Fig. 4). However, these deposits have limited preservation potential as they are progressively uplifted and subjected to cyclic post-depositional erosion.

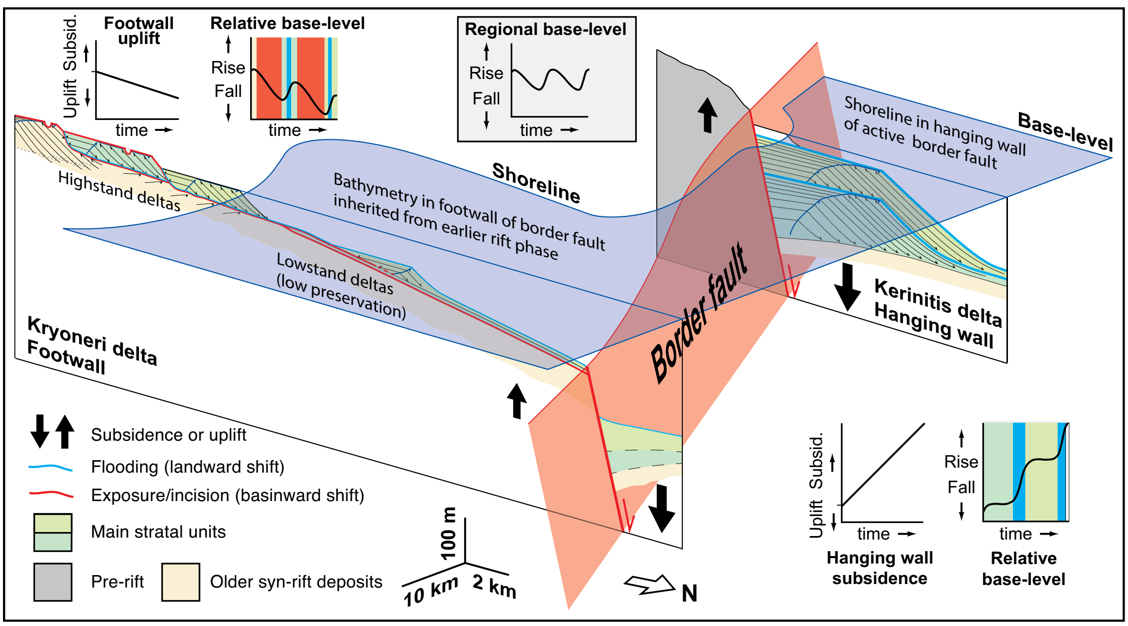


**Figure 4. Sequence interpretation of the Kerinitis and Kryoneri deltas (Greece) and their structural location with respect to the rift phase 2 border fault. Colored stratal units and surfaces on cross sections correspond to colors on relative base-level curves. Inset is background base-level curve. See text for discussion.**

Development of the Kryoneri delta ended when sediment supply to the delta was cut off due to backtilting and reversal of the main (Stymfalia) drainage feeding it.

## SUMMARY AND IMPLICATIONS

Early Pleistocene rift margin deltas along the southern coast of the Corinth rift display major differences in sequence stratigraphy over length scales of several tens of kilometers. We suggest that these differences developed because the deltas had different topographic gradients and relative base-level changes, reflecting: (1) differences in subsidence and uplift due to their location with respect to the active rift border fault, and (2) inherited bathymetry. Our results question the chronostratigraphic significance of systems tracts and highlight the fact that key stratal surfaces may only be of local (kilometer to tens of kilometer) extent where marked spatial variations in uplift and subsidence occur. Such variation is characteristic of many sedimentary basins, particularly those formed by the growth of faults and folds. Furthermore, our results highlight the uncertainty in establishing lake- or sea-level cycles from the stratigraphic record if the structural framework and history of the sedimentary basin are not well constrained.


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