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Corinth rift margin uplift: New evidence from Late Quaternary marine shorelines

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[1] New evidence for uplift of the southern margin to the Corinth rift, one of the world's most rapidly extending continental regions, defines an area of uniform uplift separating a more rapidly uplifting western rift flank from a slowly backtilting eastern flank. This major tectonic boundary coincides with geophysical evidence for a junction between flat underlying subducted oceanic plate and steep subduction. We propose that trench rollback by the Anatolian plate over the subducting African plate has led to differential uplift and possible migration of active faulting at the southern rift margin in the last few million years. *INDEX TERMS:* 5475 Planetology: Solid Surface Planets: Tectonics (8149); 8010 Structural Geology: Fractures and faults; 8107 Tectonophysics: Continental neotectonics; 8109 Tectonophysics: Continental tectonics—extensional (0905). **Citation:** Leeder, M. R., L. C. McNeil, R. E. Ll Collier, C. Portman, P. J. Rowe, J. E. Andrews, and R. L. Gawthorpe, Corinth rift margin uplift: New evidence from Late Quaternary marine shorelines, *Geophys. Res. Lett.*, *30*(12), 1611, doi:10.1029/2003GL017382, 2003.

1. Introduction

[2] Active continental rifting is accompanied by rift margin uplift, hypotheses for which depend upon determination of magnitude and spatial gradient of uplift rates. This requires accurate dating of uplift over intervals of multiple earthquake cycles. We present new field and radiometric age data for the origin of the uplifting southern margin to the active Corinth Rift, Central Greece (Figure 1), one of the world's most rapidly extending continental regions. Geodetic studies show that the rift, a half-graben separated by active faults from the Peloponnisos block to the south, is extending up to 10–15 mm yr^{-1} [*Clarke et al.*, 1997; *Briole et al.*, 2000]. The uplifting Peloponnisos features inactive faults [*Goldsworthy and Jackson*, 2000] and Quaternary marine terraces >600 m above sea level [*Keraudren and Sorel*, 1987]. Terrace levels with corals dated by U-series to OIS highstands 5 and 7 [*Collier et al.*, 1992; *Keraudren et al.*, 1995] may be correlated by regional mapping. Older terraces are dated by correlation with Late Quaternary sea level curves [*Keraudren and Sorel*, 1987; *Armijo et al.*, 1996; McNeill *et al.*, *Observations on the recent history of the Eastern Eliki Fault*, submitted]. In addition, Holocene littoral features are recorded and ^{14}C dated [*Pirazzoli et al.*, 1994; *Stewart and Vita-Finzi*, 1996].

2. Previous Hypotheses for Rift Flank Uplift

[3] Two components to rift flank uplift have previously been invoked (1) footwall uplift [*Collier et al.*, 1992; *Armijo et al.*, 1996] and (2) uniform regional uplift [*Collier et al.*, 1992]. Footwall uplift along the south Alkyonides faults in the eastern rift (Figure 1) has caused backtilting of the Pleistocene Megara basin floor [*Collier et al.*, 1992]. West of the Isthmus, northwesterly increasing elevation of individual marine terraces has been ascribed to footwall uplift on an east-west trending offshore fault continuous from Xylokastron to the Perachora peninsula [*Armijo et al.*, 1996; our Figures 1 and 2a]. *Armijo et al.* [1996] modelled the upper crust as a thick elastic plate overlying a fluid half-space to compute maximum rates of south-decaying footwall uplift of ~1.5 mm/yr, due to fault slip rates of 11 ± 3 mm/yr, over the past 350 ky. *Collier et al.* [1992] suggested that over the wider Corinth Isthmus, uniform Late Quaternary uplift rates (~0.3mm/yr) were due to regional isostatic uplift above the low-angle subduction under Peloponissos discovered by *Spakman et al.* [1988] and *Hatzfeld et al.* [1989].

3. Raised Marine Shorelines of the Perachora Peninsula

[4] The Perachora peninsula (Figures 1 and 3) is a key area to test rival models for rift flank uplift. *Pirazzoli et al.* [1994] ^{14}C-dated raised littoral notches uplifted by Holocene deformation. *Dia et al.* [1997] dated corals (*Cladocora caespitosa*) by TIMS determination of U-series decay, giving mean minimum uplift rates (allowing for coral living depths 1–20 m) in the range 0.2–0.3 mm/yr. Subsequent mapping [*Morewood and Roberts*, 1999] identified three marine terraces, inferred to represent the last three 100 ky highstands, disrupted by faulting. Terrace ages were calibrated from two OIS 5e U-series dates from corals taken from prominent terrace platforms at 22 and 26 m elevation respectively [*Vita-Finzi*, 1993; our Figure 3a]. Proposed faulting was by propagation of a western tip to the South Alkyonides fault system.

[5] In our study (Figure 3) we have mapped diagnostic shoreline features (beachface deposits, terrace platform inner edges, notched and *Lithophaga*-bored paleocliffs and sea stacks) at 1:5000 scale, aided by local levelling and altimetric determinations to give paleo-sea levels to an accuracy of a few metres or less. We have found paleoshoreline deposits up to maximum altitudes of 190 m. We have also searched

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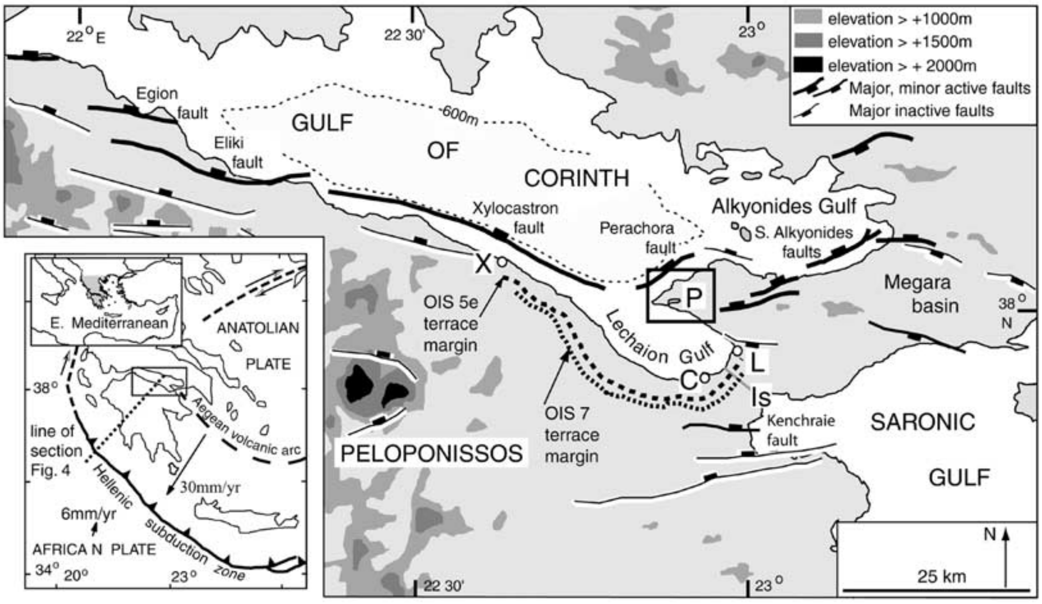

Figure 1. Gulf of Corinth within the wider Aegean context (plate velocities from *Briole et al.*, 2000). Fault distribution mostly after *Goldsworthy and Jackson* [2000] and *Stefatos et al.* [2002]. Co-Corinth city; Is-Isthmus; L-Loutraki; P-Perachora peninsula; X-Xylocastron.

for active fault traces which may have locally altered terrace elevations. Paleo-sea level elevations are correlated with eustatic sea level curves (Figure 3d), underpinned by three published [*Vita-Finzi*, 1993; *Dia et al.*, 1997] and four new Pleistocene U-series dates (Table 1) on coral samples accurately located with respect to local paleoshoreline elevation. Ages and elevations of mapped shoreline features correlate well with global sea level highstands (Figure 3d). In contrast to previous workers [*Morewood and Roberts*, 1999] we find little evidence for regionally-significant late Quaternary faulting, the elevation of both Holocene (Figure 3b; see also *Kershaw and Guo*, 2001) and Late Quaternary shoreline features (Figure 3c) showing no systematic changes. Rare local exceptions occur due to faults with displacements up to 22m around Cape Heraion (Figure 3a).

4. Discussion: Regional Uplift Again

[6] The uniform uplift of the Perachora peninsula extends southwards over the entire Corinth Isthmus. Thus well-dated and correlated OIS 5e shorelines at 25–30 m (Figure 2b) occur over an area of >200 km^2. The uplift occurs despite displacements on Quaternary to Holocene intrabasinal faults, such as those in the classic sections of the Corinth Canal [*Collier et al.*, 1992]. Neither is the uplift significantly countered by subsidence in the hangingwall of the Kenchraie fault (Figure 1; see *Goldsworthy and Jackson*, 2000). We suggest that the uniform uplift across the Perachora-Lechaion-Isthmus region is inconsistent with south-decaying footwall uplift orthogonal to active east-west offshore faulting as proposed by *Armijo et al.* [1996]. These authors processed terrace elevations by extrapolation in a way that gives a non-unique test for a proposed southward gradient, ∇, in scalar elevation field, $\nabla\phi$ (Figure 2a). Our new elevation data allows the 3D morphology of the 5e terrace to be constrained and suggests a gradient broadly to the east (Figure 2b). In support of this we emphasise that a significant reduction in overall Late Quaternary uplift rate occurs between Xylokastron-Kiaton and the Perachora peninsula (Figure 2). Uplift in the west

Table 1. New U-Series Analytical Data For Corals (*Cladacora caespitosa*) From Raised Shorelines (Figures 2 and 3)

Sample[a]	Elevation (m)[b]	^{238}U (ppm)	^{232}Th (ppm)	^{234}U/^{238}U	(^{234}U/^{238}U)i[c]	^{230}Th/^{234}U	^{230}Th/^{232}Th	Age (ky)
V-35-1a	25	3.69	15.45	1.140 ± 3	1.203 ± 3	0.699 ± 2	582 ± 1	125.9 ± 0.7
V-35-1b		3.67	14.79	1.160 ± 4	1.228 ± 4	0.698 ± 3	614 ± 1	124.7 ± 1.0
V-35-2a	20	3.52	22.34	1.176 ± 2	1.257 ± 2	0.725 ± 2	411 ± 2	133.4 ± 0.9
V-35-2b		3.58	28.05	1.175 ± 3	1.252 ± 3	0.711 ± 2	326 ± 1	128.7 ± 0.7
V-35-4a	22	3.12	14.82	1.139 ± 3	1.195 ± 3	0.676 ± 2	496 ± 2	118.4 ± 0.8
V-35-4b		3.12	13.78	1.153 ± 2	1.208 ± 2	0.643 ± 2	516 ± 2	108.5 ± 0.7
290601	20	2.62	N/m	1.140 ± 19	1.203 ± 32	0.718 ± 21	41 ± 4	132.1 ± 8.2

V-35 samples dated by TIMS using a Finnegan MAT262 mass spectrometer, equipped with a retarding potential quadropole and secondary electron multiplier, in dynamic peak jumping mode. Two of the three pairs of duplicate analyses agree within 3 s.d.; a third pair diverge by $\sim 10^4$ years. Sample 290601 (Figure 4) was dated by alpha spectrometry. Slight thorium contamination occurs in all samples, although corrected ages are indistinguishable from the quoted uncorrected ages at 1 s.d. Calculated initial ^{234}U/^{238}U ratios in all cases lie significantly above the accepted modern seawater value of 1.149, probably indicating some degree of diagenetic alteration or open system behaviour. It is considered highly unlikely, however, that any of the corals derive from an interglacial other than OIS 5e.

[a] a and b indicate duplicate analyses on the same sample.

[b] sample elevation in metres above present day mean sea level. All samples relate to deposits below a 30m inner edge.

[c] initial ^{234}U/^{238}U activity ratio. Uncertainties are 1 s.d. and refer to the last figure(s) of the calculated values.

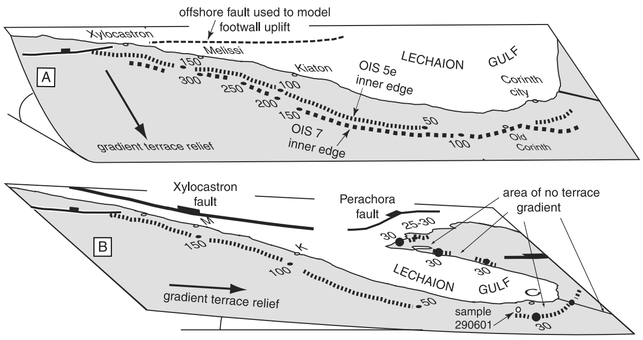

Figure 2. 3D schematic views to show alternative interpretations of Corinthian terrace gradients. Terraces correlated to OIS 5e and 7 by U-series dating (*Collier et al.*, 1992; Vita Finzi, 1993; *Keraudren et al.*, 1995; this paper, Table 1, with sample 290601 from 2 km west of Corinth city). Numbers at spots refer to terrace inner edge elevations (after *Armijo et al.*, 1996 and this study). (a) Hypothesis for southward tilting due to footwall uplift of an offshore fault [*Armijo et al.*, 1996]. (b) New hypothesis for eastward terrace gradient with a wide zone of no spatial gradient around the Lechaion Gulf, illustrated here by elevation of OIS 5e terrace, with dated sites shown by large spots, including new determination for sample site 290601.

(from Eliki to Xylokastron) of c. 1–1. 5mm/yr [*Armijo et al.*, 1996; *McNeill et al.*, submitted] contrasts with c. 0.3 mm/yr in the east. We propose that a significant tectonic boundary around the Gulf of Lechaion (Figure 2b) causes the steep eastward decline in uplift rate towards a zone of no gradient. This is in contrast to earlier discussions of contrasting deformation in the Gulf [*Rigo et al.*, 1996; *Briole et al.*, 2000; *Hatzfeld et al.*, 2000] which have differentiated between low angle normal faulting in the west (e.g., Eliki and Egion faults) and high angle faulting in the east (Xylokastron, South Alkyonides faults), placing a tectonic boundary near Xylokastron.

[7] We further suggest that the uplift of the Perachora-Isthmus area is part of a phenomenon that affects the whole Peloponnisos, as evidenced from widespread uplifted marine Neogene deposits [*Kelletat et al.*, 1976]. Recent tomographic studies of the NE-subducting African plate beneath Peloponnisos and the Gulf of Corinth using teleseismic and gravity data [*Hatzfeld*, 1994; *Papazachos et al.*, 2000; *Tiberi et al.*, 2000] indicate a relatively flat-lying lower plate which steepens rapidly at the position of the proposed tectonic boundary around the Gulf of Lechaion (Figure 4). This spatial coincidence suggests a causal link. We envisage production of flat slab and trench migration forced by southwestwards Anatolian plate motion in the last 5 my at

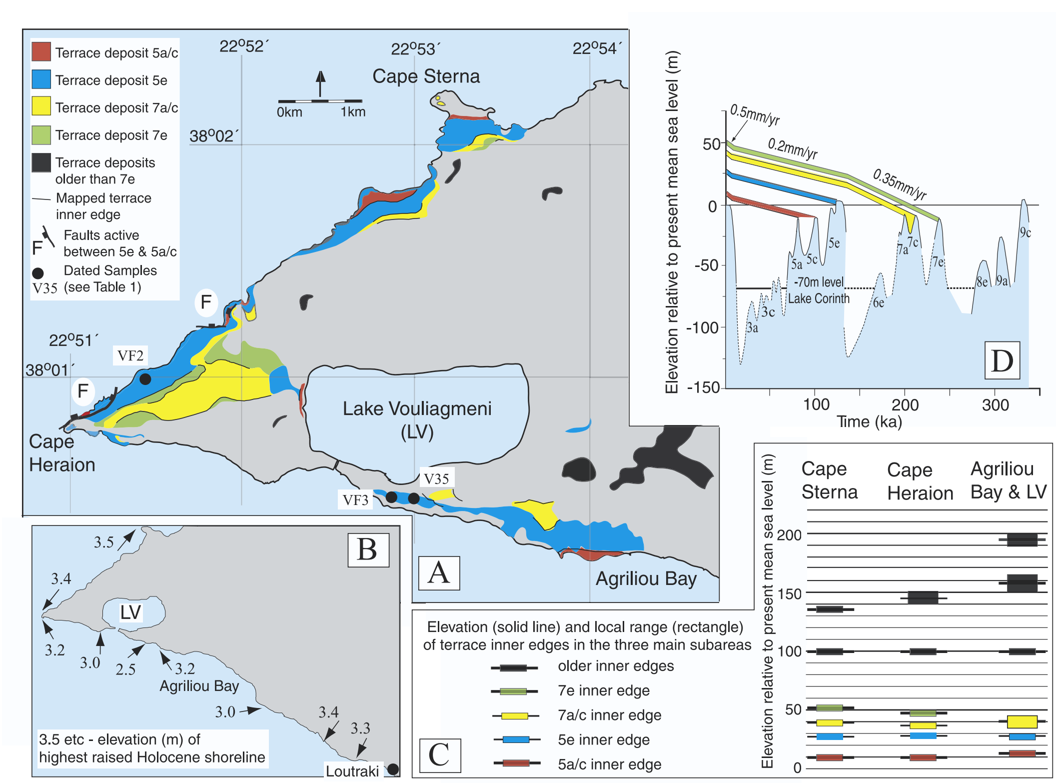

Figure 3. (a) Perachora peninsula to show mapped marine terraces. For dated sample V35 see Table 1; Dated samples VF2(128 ± 3ky) and VF3(134 ± 3ky) from Vita Finzi (1993). (b) New data for elevation of highest Holocene marine shorelines at points around the Perachora peninsula. Shoreline 3.2 m at Cape Heraion dated from 6.6ky BP using radiocarbon dating of in situ mollusc shells by *Pirazzoli et al.* [1994]. (c) Elevation (solid lines) and local range (rectangles) of terrace inner edges at the three main sites on the Perachora peninsula. (d) Eustatic sea level curve (with minor adjustments from Chappell, 1996; Chappell and Shackleton, 1986; *Imbrie et al.*, 1984) and correlations with uplifted Perachora terrace inner edges indicating probable uplift rates from 0.5 mm/yr in the Holocene to 0.2–0.35 mm/yr in the late Quaternary.

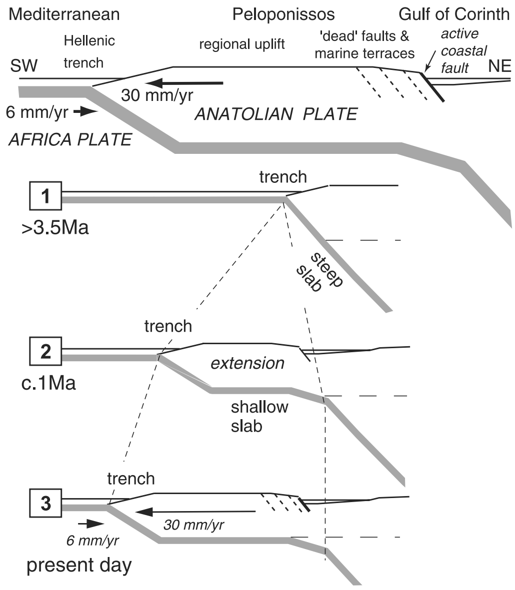

Figure 4. (a) Sketch lithospheric section (location in Figure 1) to illustrate regional isostatic uplift of Peloponnisos and flat slab subduction. (b) Development of flat-slab subduction and trench rollback over time.

a mean velocity of ~30 mm/yr to give ~150 km of flat slab, of the right order for the tomographic observations. Overthrusting by the Anatolian plate has been accompanied by uplift. The observed west to east reduction in uplift rate may mark decreasing influence of the underlying slab, though we stress that 3D slab geometry is currently poorly constrained. The active tilt blocks of Alkyonides and Megara in the extreme east (Figure 1) overlie the steeply-dipping slab. Through the Late Quaternary we envisage a pinned locus of steep subduction with normal fault abandonment and fault propagation northwards across the overthrusting Peloponnisos (Figure 4b). In this way the fundamental nature of the Corinth rift margin as a major upper crustal strain discontinuity has been preserved.

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