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New ^{234}U-^{230}Th coral dates from the western Gulf of Corinth: Implications for extensional tectonics

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[1] We derive rates of uplift of ~0.7–0.8 mm/yr for the western end of the Gulf of Corinth, Greece, using geomorphic paleaoshoreline modeling. We calibrate the modeling with new ^{234}U-^{230}Th dates on the coral *Cladocora caespitosa* collected from raised marine terraces uplifted in the footwall of the active Psathopyrgos fault, the only major active normal fault, reported on published maps controlling the downthrown Rio Straits at the western end of the Gulf of Corinth. In this area of high (15–22 mm/yr) extension rates measured with GPS, the ratio of uplift-rate to extensional velocity is 0.025–0.035, much lower than values of 0.15–0.25 found further east in the gulf. These low values imply that if GPS extension rates are correct then mechanical/kinematic models developed for the eastern and central gulf may not be applicable to the western gulf. *INDEX TERMS:* 1035 Geochemistry: Geochronology; 8109 Tectonophysics: Continental tectonics—extensional (0905); 8107 Tectonophysics: Continental neotectonics. **Citation:** Houghton, S. L., G. P. Roberts, I. D. Papanikolaou, J. M. McArthur, and M. A. Gilmour, New ^{234}U-^{230}Th coral dates from the western Gulf of Corinth: Implications for extensional tectonics, *Geophys. Res. Lett.*, *30*(19), 2013, doi:10.1029/2003GL018112, 2003.

1. Introduction

[2] The Gulf of Corinth in central Greece is a major N-S extensional rift basin in the Hellenic region characterized by intense seismic activity. Continental extension rates of up to 15–22 mm/yr have been measured using global positioning systems in the western Gulf of Corinth, Greece [GPS; *Clarke et al.*, 1997; *Briole et al.*, 2000] with progressively lower rates reported for successively more eastern positions in the central and eastern gulf (Figure 1). Rates of extension measured by GPS in the central and eastern gulf are comparable with rates estimated from offset geology, both over the Quaternary [*Armijo et al.*, 1996], and/or fractions of the Holocene [*Collier et al.*, 1998].

[3] Comparison of uplift rates gained from ^{234}U-^{230}Th dates on *C. caespitosa* corals from elevated marine terraces with 'horizontal' GPS extension rates in the central and eastern gulf (extension/uplift ratios of 0.15–0.25) supports the development of mechanical/kinematic models that are consistent with observed deformation [*Armijo et al.*, 1996]. However, to date, without uplift rates for the Psathopyrgos fault, the only major active normal fault (within its neighbouring longitude), reported on published maps controlling the downthrown Rio Straits at the western end of the Gulf of Corinth, it has not been possible to see whether tectonic models developed for the central and eastern gulf are also applicable at its western end.

[4] This paper reports the results of geomorphic paleoshoreline modelling of a flight of uplifted marine terraces in the immediate footwall of the Psathopyrgos fault at the western end of the Gulf of Corinth. We have mapped the terraces at 1:5000 scale and modeled their uplift, calibrating our results with new ^{234}U-^{230}Th dates corals on *C. caespitosa* corals associated with these terraces. This allows us to identify the ages and elevations of the terraces in order to constrain the uplift rate and compare with the extension rate from GPS data at this site.

2. Existing Data on Deformation Rates in the Gulf of Corinth

[5] Rates of extension across the Gulf, measured with GPS show that relative site velocities between the north and south sides increase smoothly from 2.5 to 10 ± 4 mm/yr across the eastern gulf to 12.7 ± 1 to 22 mm/yr in the west; these are termed GPS extension rates [Figure 1; *Briole et al.*, 2000; *Clarke et al.*, 1997, 1998].

[6] Uplift rates for the footwalls of the faults accommodating the extension on the northern coast of the Peloponnese have been constrained using uplifted and dated *C. caespitosa* corals for a number of sites along the gulf, with the exception of the western gulf [Figure 1; *Collier*, 1990; *Collier et al.*, 1992; *Vita-Finzi*, 1993; *Dia et al.*, 1997; *Leeder et al.*, 2003]. *Armijo et al.* [1996] and *Morewood and Roberts* [1999] have mapped the marine terraces associated with these dated corals, using the results to constrain the development of normal faulting for the gulf. In particular, *Armijo et al.* [1996] use a thick elastic plate model, plus a map of the uplifted marine terraces, to calculate extension rates across the gulf. They show that implied extension rates for portions of the Quaternary are similar to those measured over much shorter time periods using GPS. Extension rates from a palaeoseismic trenching study of Holocene sediments by *Collier et al.* [1998] also agree with those from GPS.

3. Uplifted Marine Terraces and Corals in the Western Gulf

[7] Marine terraces result from the interplay between the rate of global sea-level change and the rate of local tectonic

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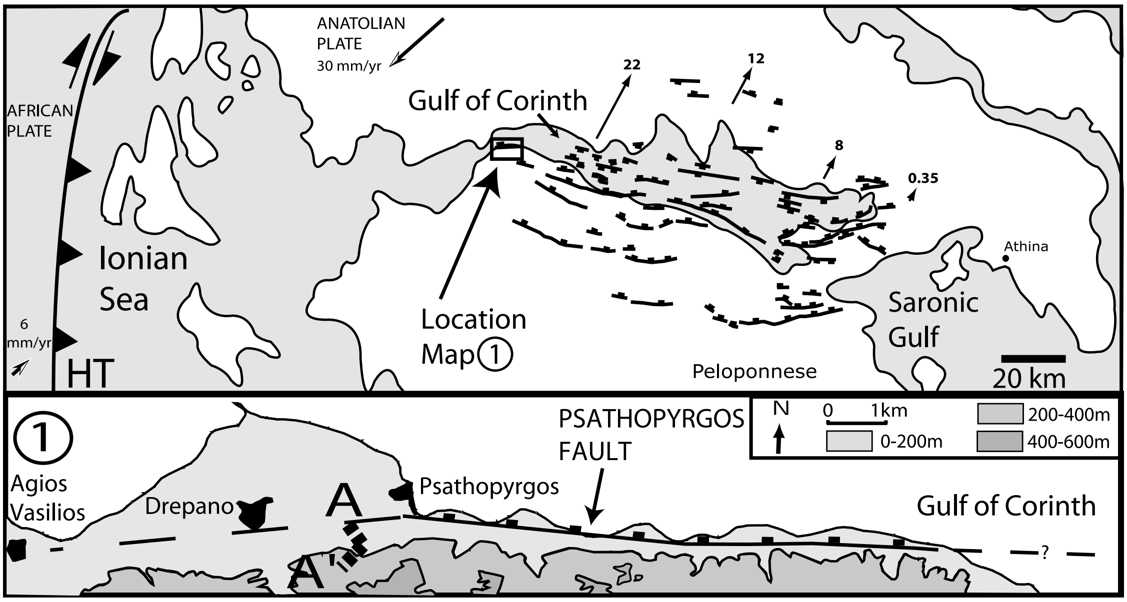

Figure 1. Map of central Greece showing major on-shore and off-shore faults [*Roberts*, 1996; *Stefatos et al.*, 2003], plate velocities [*Briole et al.*, 2000] and 'horizontal' GPS velocities with Location map 1 at the western end of the Gulf of Corinth which is enlarged below. Location map 1 shows the Psathopyrgos fault and geomorphic 2D cross section A–A′. HT- Hellenic Trench. See color version of this figure in the HTML.

uplift [e.g. *Chappell*, 1974; *Lajoie*, 1986; *Valensise and Ward*, 1991]. The position of sea-level at the time of terrace formation is defined by the base of palaeo-sea-cliffs; their elevations are precise markers of the amount of uplift from the sea-level at which they formed; we term such a marker an inner edge.

[8] We have constructed topographic profiles across the marine terraces mapped at a 1:5000 scale with contours at 4 metre intervals in order to identify inner edges in the immediate footwall of the Psathopyrgos fault (Figure 1; cross-section A–A′). Inflections in the profiles are interpreted as palaeosea cliffs (palaeoshoreline inner edges), verified by field observations. The elevations of inner edges allow precise estimates to be made of the amount of uplift from knowledge of the elevation of sea level at the time of their formation. The elevation of sea level at such times is determined from a paleosea-level reconstruction based on the δ^{18}O record of sediment cores from the Red Sea [*Siddall et al.*, 2003].

[9] In order to assess the ages of these paleaeoshorelines, we have modeled elevations of inner edges, with uplift rate as a variable (Figure 2). We use uplift rates that are constant through time, an approach that is consistent with the results of other workers [*Armijo et al.*, 1996, *Morewood and Roberts*, 1999]. Present-day elevations are modeled iteratively by assuming a constant uplift rate of given value and attempting to match the modeled terraces elevations with elevations of topographic inner edges. Highstands are not equally-spaced in time and have different initial elevations, so a fit to topographic inflections that are not equally-spaced in elevation can be considered to be robust. Using the sea-level curve [Figure 2b; *Siddall et al.*, 2003], the best fit to heights of terrace inner edges indicates an uplift rate of 0.8 mm/yr. A better fit is achieved if the original elevations

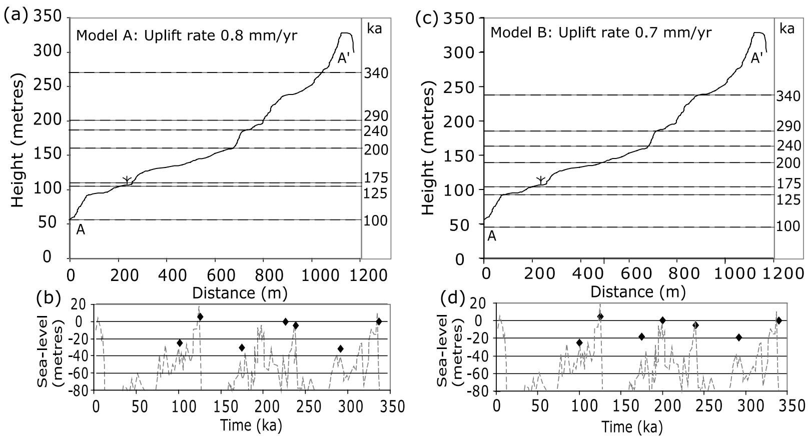

Figure 2. Graphs showing affect of 0.8 mm/yr (a) and 0.7 mm/yr (c) uplift on flight of terraces near the Holy Metamorphoses Church, near Agios Ioannis, given the sea-level curves [*Siddall et al.*, 2003] in (b) and (d). See color version of this figure in the HTML.

Table 1. U/Th Chemical and Isotopic Data for *C. caespitosa* Coral

Sample	^{238}U [ppm]	^{230}Th [ppb]	(^{230}Th/^{234}U)	(^{230}Th/^{232}Th)	^{230}Th AGE [kyr]	δ^{234}U(0)	δ^{234}U(T)
AIC wall	2.074 ± 4	0.0299 ± 3	0.813 ± 9	1500 ± 30	$175.6^{+5.4}_{-5.3}$	82.4	135.4
AIC wall	2.065 ± 4	0.0294 ± 3	0.811 ± 9	1460 ± 28	$175.2^{+5.2}_{-5.1}$	74.0	121.4
AIC septa	2.466 ± 12	0.0369 ± 4	0.816 ± 9	524 ± 10	$174.7^{+6.2}_{-5.9}$	120	196.7
MCC1 wall	2.214 ± 5	0.0323 ± 4	0.838 ± 9	1600 ± 30	$191.3^{+6.5}_{-6.5}$	63.1	108.3
MCC2 wall	2.211 ± 5	0.0288 ± 3	0.748 ± 8	1190 ± 22	$147.4^{+2.9}_{-4.3}$	63.8	96.6

Round brackets denotes activity ratio. Contributions from detrital ^{232}Th were too small to require correction.

of highstands at 175 ka and 290 ka are increased by 12 metres (Figure 2d), which is not unreasonable given the uncertainty on the precise elevations of these highstands. This adjustment results in an uplift rate of 0.7 mm/yr. With this estimate of terrace ages, we carried out dating of corals to validate the ages and thus the uplift rates.

4. Samples and Analysis

[10] *C. caespitosa* coral co-occurred with oysters and gastropods within poorly exposed green-yellow marls at a height of ~100–110 m above mean sea level. Coral samples were mechanically and chemically cleaned prior to analysis by TIMS to determine ^{234}U-^{230}Th ages. Sample preparation and analysis followed standard methods [*Edwards et al.*, 1987; *van Calsteren and Schwieter*, 1995]. Prepared samples were assessed for alteration using XRD and elemental analysis. The results of the chemical and isotopic analysis are given next and in Table 1.

5. Chemical and Isotopic Data

[11] The elemental composition of the samples is typical of modern corals (Table 1): concentrations of U (2–3 ppm) and Ca (38.5–41.8%) are typical of those reported for recent corals [*Stirling et al.*, 1995]. Concentrations of Sr (5600–7770 ppm) are similar to those given for corals by *Stein et al.* [1993], and concentrations of Mg (830–1180 ppm) and Na (3520–3820 ppm) are within the range given for coral by *Bar-Matthews et al.* [1993].

[12] The ^{234}U/^{238}U activity ratio of the modern ocean is 1.145 (δ^{234}U(T) = 145), and samples with an initial ^{234}U/^{238}U activity ratio close to 1.149 (i.e., δ^{234}U(T) 149 ± 4; a limit introduced by *Stirling et al.* [1995] to constrain the 125ka highstand) are considered to give the most reliable ages (*ibid*). Nevertheless, these authors acknowledge that many samples with δ^{234}U(T) very different from 149 give reliable numerical ages. For sample AIC, two subsamples of coral wall yield similar ages which, in turn, are similar to the age derived from coral septa of the same sample, despite the latter containing trace calcite identifiable by XRD. We consider these ages as valid because of the concordance in ages, despite the range of δ^{234}U(T): 121–197.

[13] Analysis of two other samples (MCC1 & 2) give irreproducible ages and more extreme δ^{234}U(T) values, although we note that the mean age for MCC is 169 ± 22 ka, a value within analytical uncertainty of the age of 175 ka we obtain for sample AIC.

[14] We suggest that an age of 175 ka for our terrace is sufficiently robust to link the terrace to the highstand of sealevel at 175 ka noted by *Siddall et al.* [2003], although it might be insufficiently robust to calibrate the time of sea-level highstands. Hence, an age of 175 ka is established for the raised marine terrace at 100–110m elevation, which is consistent with geomorphic modeling of paleoshorelines for this suite of terraces.

6. Implications for Tectonic Models

[15] Using a constant uplift rate of 0.7 mm/year (Figure 2c), the steps in our topographic profile, confirmed as terraces and paleosea cliffs by field observation, co-incide almost exactly with the expected elevations of terraces formed during sealevel highstands. In particular, the elevation of the terrace we date to 175 ka corresponds closely to the height expected for a terrace of this age formed during the 175 ka sealevel highstand [*Siddall et al.*, 2003].

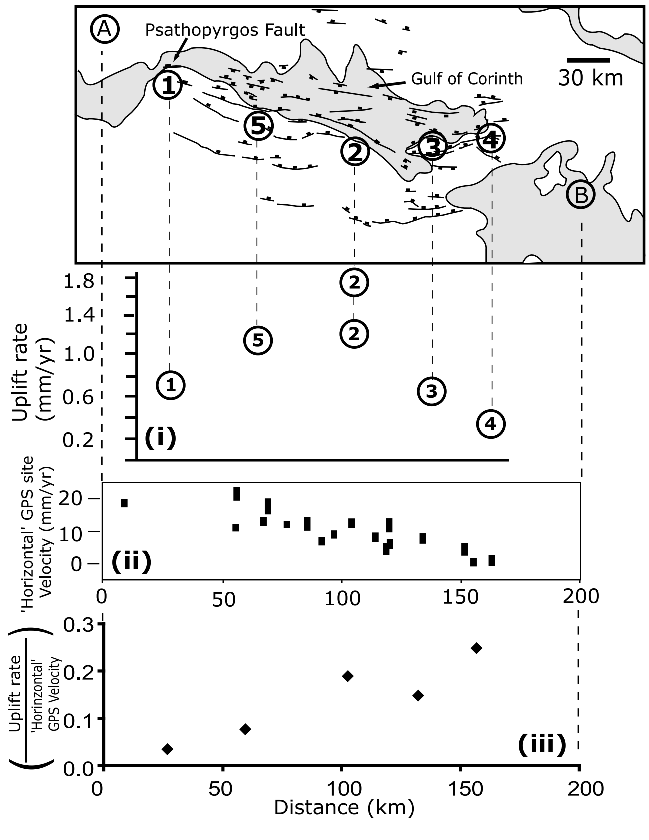

Figure 3. Graphs and map showing (i) uplift rates determined from ^{234}U-^{230}Th dating of corals and (ii) 'Horizontal' GPS site velocities for the Gulf of Corinth and (iii) (Uplift rate/'Horizontal' GPS site velocity). Data points on graph (i) relate to uplift rates gained from the following sources: 1. New uplift rate from this paper; 2. *Armijo et al.* [1996] with position 2 extrapolated 5km further north corresponding to the fault trace; 3. *Morewood and Roberts* [1999]; 4. *Collier et al.* [1992]; 5. *Rigo* [1994]. See color version of this figure in the HTML.

[16] The extension rate measured with GPS across the Rio Strait, in the western gulf, is about 20 mm/yr (Figure 3). GPS–derived extension rates for the longitudes of Xylokastron and Alepochori [c. 7–14 mm/yr; 1–3 mm/yr; *Clarke et al.*, 1997] are consistent with slip rates derived from rigorous modeling of uplifted and deformed Quaternary marine terraces [9.2–15.6 mm/yr; 1.8 mm/yr; *Armijo et al.*, 1996]. This implies that mechanical models can be developed which link rates of uplift and horizontal extension which may help understanding of extension elsewhere.

[17] The uplift rates south of Xylokastron, Heraion and Alepochori are 1.28 mm/yr, 0.5–0.74 mm/yr and 0.31 mm/yr respectively. Thus, the ratio of uplift (from raised marine terraces) to extension (from GPS) is 0.26–0.11 for Xylokastron, 0.071–0.11 for Heraion, and 0.31–0.10 for Alepochori. The value for this ratio is much less (0.025–0.035) where we have studied the deformation. If both the GPS extension rates and uplift rates from marine shorelines reported herein are correct then this ratio specifically modeled by *Armijo et al.* [1996] in their attempt to constrain the mechanics and kinematics of the extension for the central and eastern gulf implies that different mechanical/kinematic models for the deformation may apply to the western gulf.

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