$^{234}U/^{230}Th$ coral growth dating yields reliable ages in restricted basins despite anomalous $\delta^{234}U_i$ values

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Late Quaternary coral growth ages from uplifted coastal regions, such as marine terraces and associated palaeoshorelines, are an essential tool used to derive tectonic and fault controlled uplift and deformation rates, and thus contribute to seismic hazard analysis and constrain past global sea levels. Fossil coral growth ages are assessed for reliability based upon whether the $\delta^{234}U_i$ (or initial activity ratio $^{234}U/^{238}U$) matches the present-day oceanic value of ~145 ±1.5‰. However, $\delta^{234}U_i$ values outside of this range have been measured from corals at palaeoshoreline locations throughout the world (e.g. Greece, Italy, western USA; Iran) where the coral ages obtained are typically consistent with glacio-eustatic sea-level highstand timing, their stratigraphic/tectonic settings and other age constraints. We explore this controversy with a detailed analysis of coral growth ages from within the semi-restricted Gulf of Corinth, where only 4% of 154 dated corals display $\delta^{234}U_i$ within ±10‰ of the open ocean value but appear to have growth ages that agree with highstand timing, stratigraphy and ages from ^{36}Cl exposure dating of wave-cut platforms. We undertook multiple $^{234}U/^{230}Th$ analyses on individual corallites which are used in combination with analysis of existing coral growth age data and $^{87}Sr/^{86}Sr$ values to suggest that $\delta^{234}U_i$ within the Gulf of Corinth was elevated throughout Marine Isotope Stages 5e-7a (125-200 ka highstands), as a consequence of growth within a basin subject to limited seawater entry during marine highstands and freshwater input from rivers and groundwater combined with episodic fault uplift. Within the Gulf of Corinth, our findings are used to explore the late Quaternary pattern of gulf-wide fault-related uplift, and suggest that where corals from marginal coastal/restricted basins are dated, deviations in $\delta^{234}U_i$ from the open ocean value should be carefully considered.

Keywords: Quaternary, Europe, U-Th series, corals, palaeoshorelines, tectonic uplift, $\delta^{234}U_i$

1. Introduction

U-series coral growth ages provide the foundation for the study of global sea level (e.g. Muhs et al., 1994; Gallup et al., 1994) and derivation of uplift rates along tectonically-active coastal margins because they provide numerical ages for palaeoshorelines (e.g. Muhs et al., 1994; Bard et al., 1996; Grant et al., 1999; Houghton et al., 2003; Sieh et al., 2008; Roberts et al., 2009). This latter body of work explores sequences of palaeoshorelines and shallow water coral reefs that have been uplifted as a result of large and moderate earthquakes and thus contributes to seismic hazard analysis (e.g. Grant et al., 1999; McNeill and Collier, 2004; Sieh et al., 2008; Roberts et al., 2009). The reliability of fossil coral growth ages is predominantly evaluated based upon whether $\delta^{234}U_i$ is reflective of present-day homogenous open ocean values (~145 ± 10‰) (e.g. Medina-Elizalde et al., 2013; Chutcharavan et al., 2018); values that have previously been suggested to have not significantly deviated throughout the late Quaternary (e.g. Hamelin et al., 1991). Late Quaternary $\delta^{234}U_i$ variation is usually attributed to post-depositional diagenetic alteration reflective of open system behaviour since the coral formed (Bard et al., 1991; Dutton, 2015).

The problem is that samples of shallow fossil corals used to infer uplift rates are typically obtained from coastal margins and restricted basins, and have been shown to display $\delta^{234}U_i$ outside of the ~145 ± 10‰ range (Chutcharavan et al., 2018), which some authors suggest limits their utility to provide numerical age constraints (e.g. Bard et al., 1991; Hamelin et al., 1991; see Chutcharavan et al., 2018 for a discussion). Whilst corals from these settings display anomalous $\delta^{234}U_i$, in many cases their growth ages are in agreement with other coral ages and age constraints, eustatic sea-level highstands and expected stratigraphical settings consistent with the local tectonics (e.g. Muhs et al., 1994; Bard et al., 1996; Grant et al., 1999; Roberts et al., 2009). It is suggested that corals from coastal margins and restricted basins with anomalous $\delta^{234}U_i$ may represent systematic variation of $\delta^{234}U_i$ as a result of spatial and temporal differences in water chemistry (Andersen et al., 2007; Esat and Yokoyama, 2010), but actual examples and detailed investigations are few.

This study investigates new and existing $^{234}U/^{230}Th$ coral growth ages from within the Gulf of Corinth, Greece, (Fig. 1) a semi-restricted marine basin (Perissoratis et al., 2000) affected by tectonics, glacio-eustatic sea-level changes and influxes of freshwater from rivers and springs (Perissoratis et al., 2000; Roberts et al., 2009; Houghton, 2010; Nixon et al., 2016). Coral growth ages from within the gulf have elevated $\delta^{234}U_i$, but cluster on known glacio-eustatic highstands, agree with other absolute age constraints and can be explained relative to their stratigraphic position. The findings of this study will show that multiple $^{234}U/^{230}Th$ analyses on a number of corallites from the same sedimentary layers reveals age and $\delta^{234}U_i$ clustering, suggestive of unaltered corals. Our results indicate that: (i) $^{234}U/^{230}Th$ analyses on corals from palaeoshorelines with $\delta^{234}U_i$ values that differ from present day open ocean $\delta^{234}U_i$ warrants further investigation and, (ii) that the Late-Quaternary $\delta^{234}U_i$ of the Gulf of Corinth may have been elevated with respect to open ocean $\delta^{234}U_i$ due to a combination of the tectonics of the gulf, freshwater influx and eustatic variations of sea level. This outcome is used to explore patterns of gulf-wide fault-displacement throughout the late Quaternary and to infer that the impact of restricted basins and coastal margins on water uranium isotope composition, and therefore coral $\delta^{234}U_i$, should be carefully assessed when considering the reliability of coral growth ages.

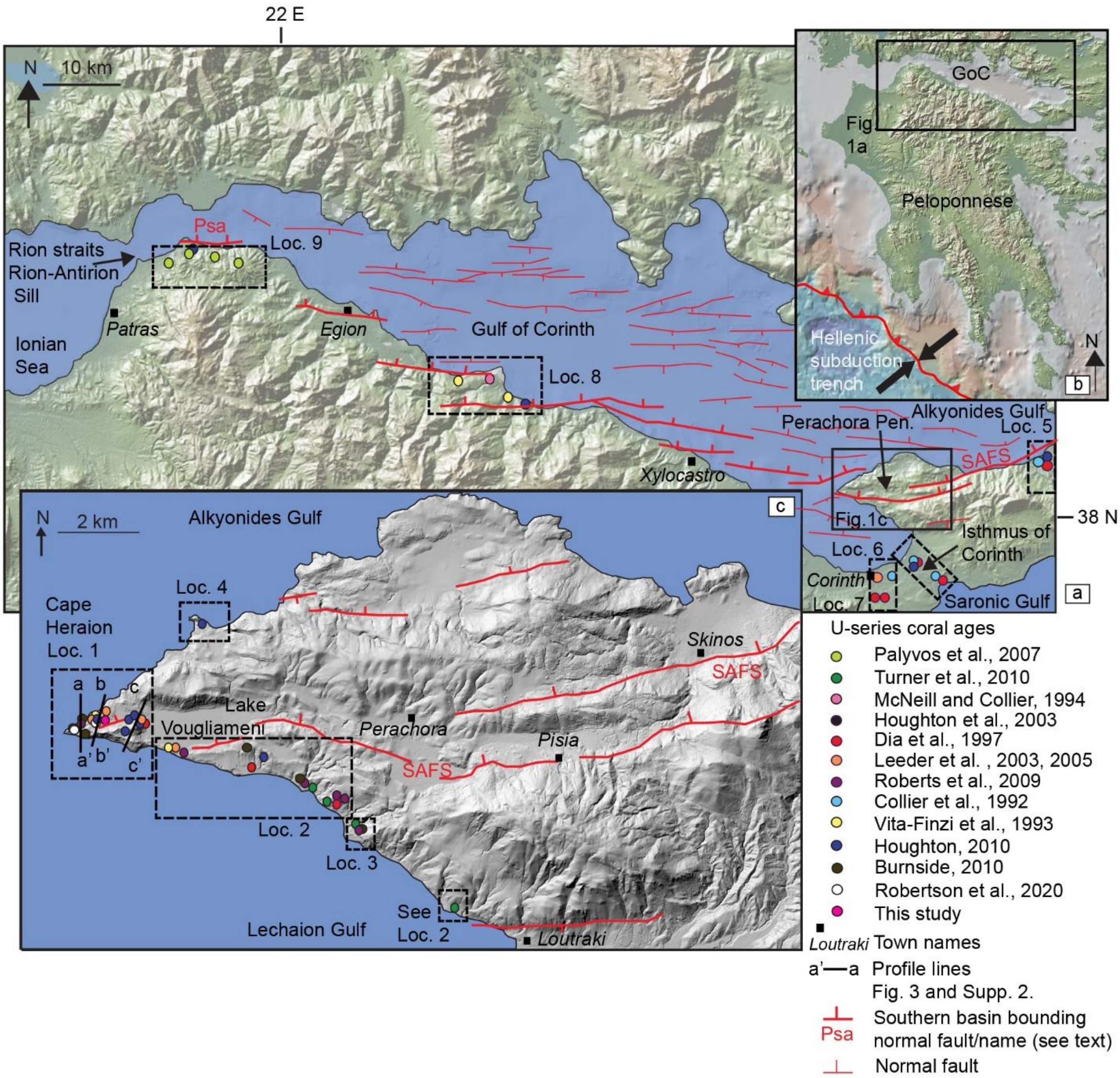

Figure 1: (a) Map of the Gulf of Corinth showing normal faults as per Nixon et al. (2016) and the locations of coral growth ages colour coded by study. (b) Location of the Gulf of Corinth within Greece. (c) Detailed map and coral growth locations on the Perachora Peninsula at the eastern end of the Gulf of Corinth (see Supplementary Fig. 1 for sampling locations for this study). Profile lines relate to cross sections in Fig. 3 and Supplementary Fig. 2. Locality references in (a) and (c) relate to Fig. 3, Supplementary Fig 2 and discussions in the text.

2. Background

2.1 The Gulf of Corinth

The Gulf of Corinth formed as a result of normal faulting in response to high extensional north-south strain rates across central Greece; which continues to be active to the present day. Geodetic extension rates of ~5-15 mm/yr (Clarke et al., 1998; Briole et al., 2000) are accommodated predominantly along north-dipping faults that bound the southern margin of the gulf (Roberts et al., 2009; Nixon et al., 2016) (Fig. 1a). The gulf is a bathymetrically-restricted marine embayment currently linked to the Ionian Sea at its western end via the Rion Straits and at its eastern point via the human-made Corinth Canal, which cuts through the Isthmus of Corinth (Fig. 1a). The hydrochemistry of the gulf is marine and influenced by a combination of freshwater run-off from the surrounding mountains, local climate, and the exchange of waters with the Ionian Sea above the Rion-Anterion sill along the Rion Strait, which is 2 km wide and ~60 m deep (Perissoratis et al., 2000; McNeill et al., 2019).

Multiple seismic reflection studies, boreholes and recent cores from within the Gulf of Corinth provide evidence of alternating lowstand (lake) and highstand (marine) deposits throughout the late Quaternary (e.g. Perissoratis et al., 2000; Papanikolaou et al., 2015; McNeill et al., 2019). Recent results from IODP mission 381 (site M0079) in the centre of the Gulf of Corinth shows that over the past ~750 ka the gulf has experienced changing environmental conditions driven by climatic and eustatic changes whereby a range of basin environments between the simple marine and freshwater end-members occurred (McNeill et al., 2019). During sea level lowstands the gulf is dominated by freshwater influx due to precipitation and run off (Perissoratis et al., 2000; Watkins et al., 2020). The history of seawater ingress into the gulf during highstands is more complex, however, and has changed throughout the late Quaternary as result of the relative motion of uplift and subsidence on normal faults at the eastern and western ends of the gulf (Roberts et al., 2009; McNeill et al., 2019).

In particular, knowledge of highstand ages from sea-level curves combined with observations from uplifted preserved marine terraces and palaeoshorelines throughout the gulf have been used to explore the pattern of water ingress throughout the late Quaternary (Roberts et al., 2009). Roberts et al. (2009) suggest that between 340 ka and ~150 ka the Rion-Anterion sill (western gulf, Fig. 1a) was above relative sea level and that the Rion Strait became an inlet for seawater during Marine Isotope Stage (MIS) 5e (125 ka highstand) due to hangingwall subsidence along the Psathopyrgos fault (Psa, Fig. 1a) (Houghton et al., 2003; Roberts et al., 2009), resulting in a narrow and shallow channel (Perissoratis et al., 2000). During this time seawater from the Saronic Gulf entered the Gulf of Corinth via the narrow Isthmus of Corinth (Roberts et al., 2009) (Fig. 1a), evidenced by subaqueous dunes of oolitic limestones (Collier and Thompson, 1991), late Quaternary corals (Collier et al., 1992; Dia et al., 1997) and microfossil analysis from boreholes (Papanikolaou et al., 2015). The evolution of the Isthmus of Corinth from a marine inlet to sub-aerial setting occurred sometime after MIS 5e (125 ka) as a result of sustained footwall uplift of ~0.3-0.6 mm/yr due faulting along the South Alkyonides Fault System (SAFS) (Roberts et al., 2009; Papanikolaou et al., 2015) (Fig. 1a).

2.2 Gulf of Corinth corals

Coral growth ages sampled from the uplifted footwalls along the southern margin of the gulf (Fig. 1a, c) typically have elevated $\delta^{234}U_i$ (Fig. 2a, b) (Collier et al., 1992; Vita-Finzi et al., 1993; Dia et al., 1997; Houghton et al., 2003: Leeder et al., 2003; McNeill and Collier, 2004; Leeder et al., 2005; Palyvos et al., 2010; Roberts et al., 2009; Burnside, 2010; Houghton, 2010; Turner et al., 2010; Robertson et al., 2020). Previous studies have calculated fault-related uplift rates using coral ages to inform studies on gulf-wide horizontal deformation over long term (10^{4-5} years) timescales and to analyse the behaviour of normal faulting within an active rift system (e.g. Houghton et al., 2003; McNeill and Collier, 2004; Roberts et al., 2009; Bell et al., 2011). Within these studies, coral growth age reliability has been based upon growth ages that fit known eustatic sea-level highstands (e.g. Houghton et al., 2003; Leeder et al., 2005; Roberts et al., 2009; Robertson et al., 2020) (Fig. 2a, c), are stratigraphically consistent with observed and modelled palaeoshorelines along sequences of terraces (Fig. 3a) and palaeoshoreface sections (Fig. 3b) (Roberts et al., 2009), and have additional age controls that support coral growth ages, for example ^{36}Cl cosmogenic exposure dating of wave-cut platforms associated with coral growth (Robertson et al., 2020) (Fig. 3c).

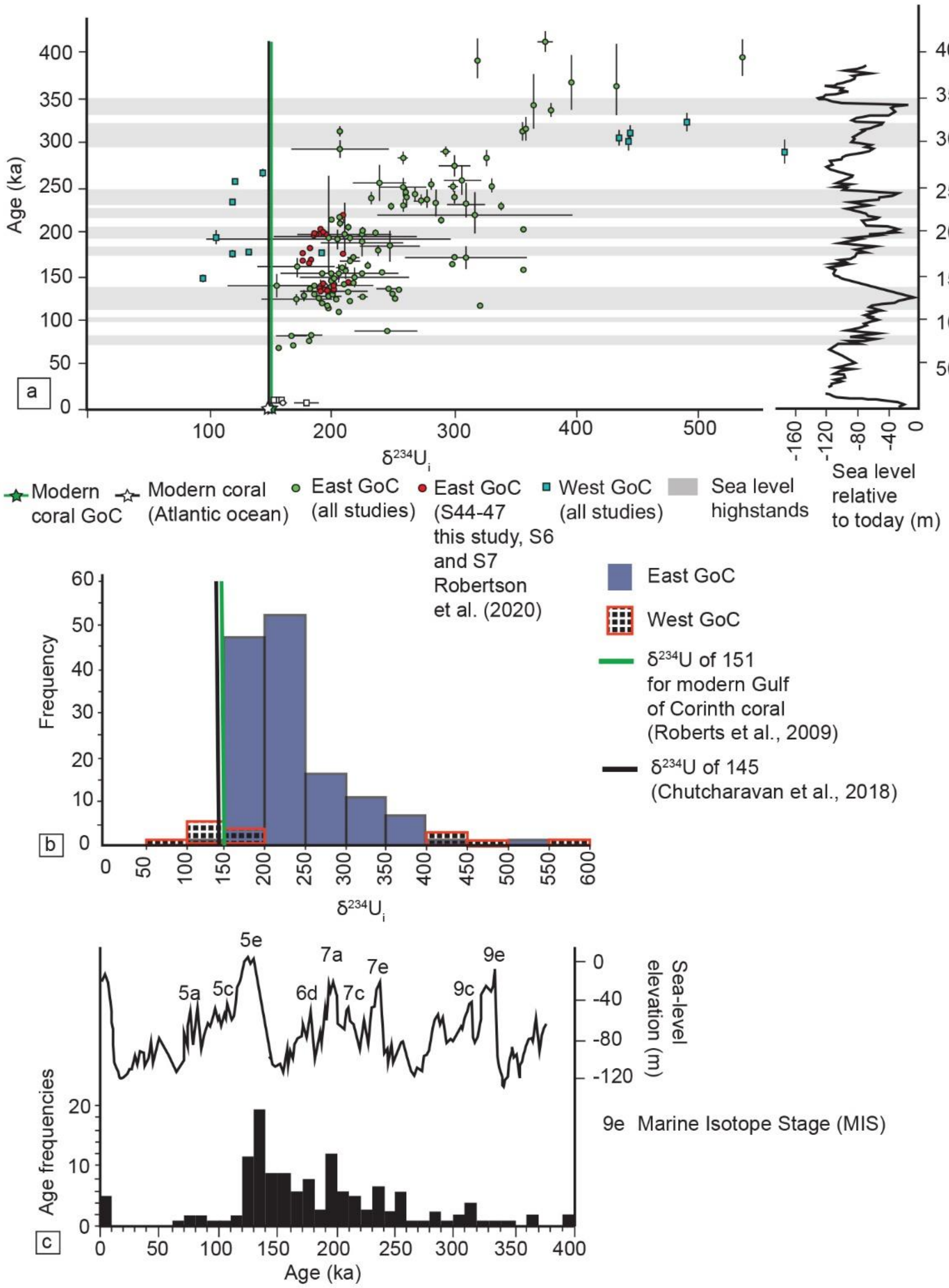

Figure 2: (a) Coral growth ages and $\delta^{234}U_i$ values for the Gulf of Corinth (Collier et al., 1992; McNeill and Collier, 2004; Dia et al 1997; Leeder et al., 2005; Roberts et al., 2009; Burnside, 2010; Houghton, 2010; Turner et al., 2010; Robertson et al., 2020) including this study. All ages and $\delta^{234}U_i$ values have been recalculated according to the decay constants of Cheng et al., 2013. Sea level curve in (c) adapted from Siddall et al. (2003). See Table 1 for MIS and sea-level highstand timing sources. Where uncertainties are not shown, values are within symbol size or not provided from older studies. (b) Histogram of the $\delta^{234}U_i$ values for coral ages from the east and west Gulf of Corinth. (c) Histogram of frequencies of Gulf of Corinth coral growth ages compared to the sea-level curve of Siddall et al. (2003).

Corals from within the Gulf of Corinth are located in three tectonic/stratigraphic settings where different age relationships between growth ages and elevation are observed: (i) sequences of uplifted marine terraces and palaeoshorelines that form during glacio-eustatic highstands and are preserved as a result of the interplay between sea-level change and fault-related uplift; here corals located on sequences of terraces have growth ages that increase with elevation (Fig. 3a), (ii) stratigraphical shoreface sections from shallow marine environments where vertically stacked coral colonies are separated by lowstand exposure surfaces; these sections record the transition through late Quaternary highstands and have coral ages that decrease upward through the stratigraphy (Fig. 3b), and (iii) marine terraces that have experienced faulting since they were formed; here corals from the same highstand are now located at different elevations having experienced relative subsidence or uplift as a result of normal faulting (Fig. 3c). Taken together, these examples highlight the problem explored in this study. Why is that coral growth ages that make sense with their stratigraphic setting and coincide with known glacio-eustatic sea-level highstands, are associated with elevated $\delta^{234}U_i$ values?

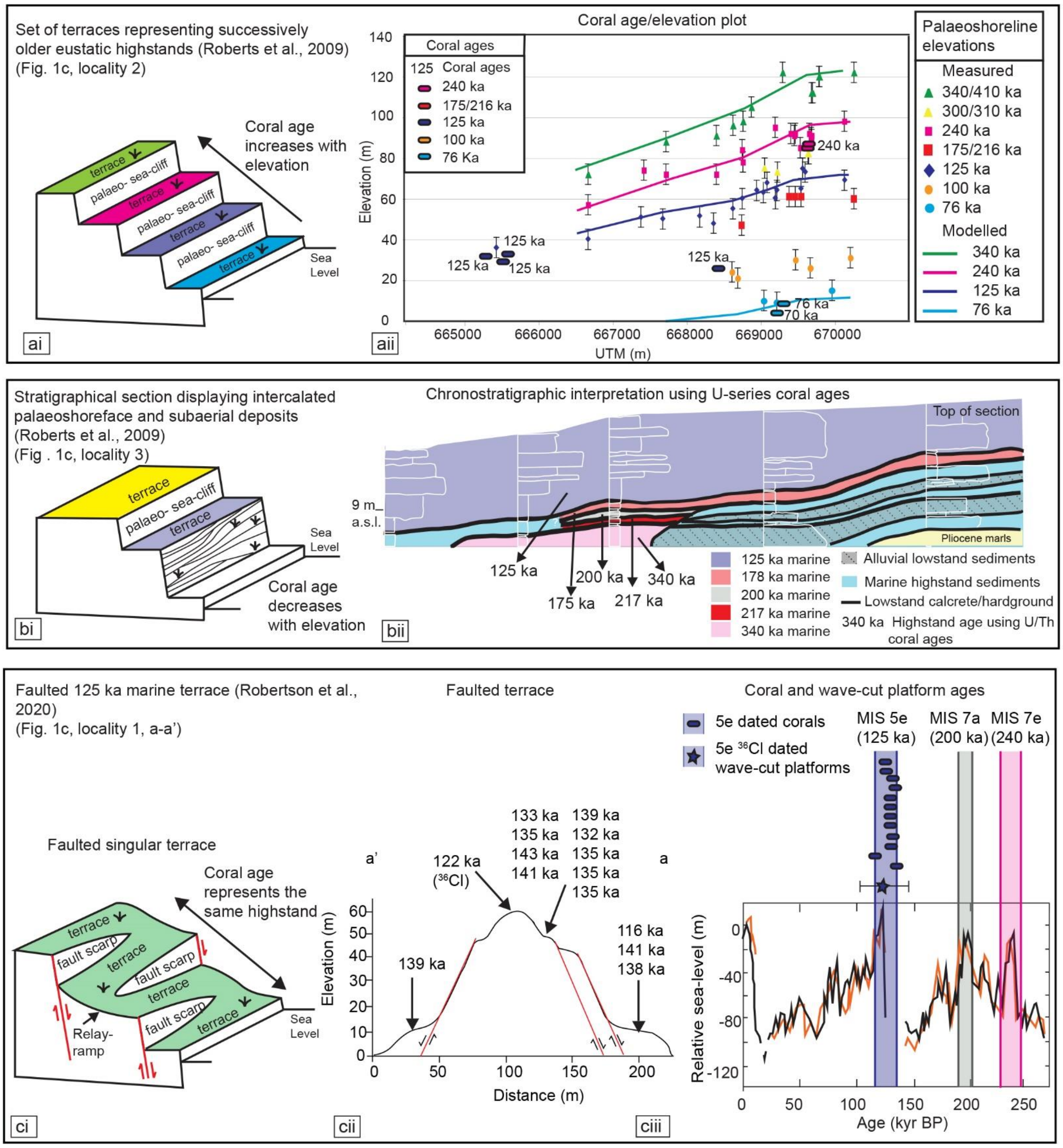

Figure 3: Examples of coral growth ages from within the Gulf of Corinth that have multiple ages in agreement with highstand timescales (Table 1) and are in the correct stratigraphic order given their setting (see Fig. 1a for localities): (a) Locality 2 (i) Cartoon of the geomorphological setting of a sequence of marine terraces. (ii) Coral ages that increase with age representing successively older terraces as elevation increases. The coral ages agree with observed and modelled palaeoshoreline elevations, modified from Roberts et al. (2009). (b) Locality 3 (i) Cartoon of the geomorphological setting of stratigraphical section. (ii) Coral ages in a stratigraphic section recording the transitions between highstand and lowstands, coral growth ages become younger as elevation increases, modified from Roberts et al. (2009). (c) Locality 1, profile a'-a. (i) Cartoon of a faulted marine terrace with multiple corals at different elevations on Cape Heraion. (ii) Coral and 36Cl wave cut platform ages that represent MIS 5e (125 ka highstand) and have been faulted from their original position, modified from Robertson et al. (2020). (iii) Coral and 36Cl wave-cut platform ages plotted on the sea-level curve of Siddall et al., 2003 (note that orange and black lines represent curves obtained using different core data).

Previous work to explore the anomalously high $\delta^{234}U^{i}$ observed in Gulf of Corinth corals used analysis of $^{87}Sr/^{86}Sr$ measured from the dated corals to explore whether the water chemistry of the gulf may have differed during highstands (Dia et al., 1997; Houghton, 2010). Consistently low measurements of $^{87}Sr/^{86}Sr$, relative to the present day in the Gulf of Corinth, were observed. Possible explanations for low $^{87}Sr/^{86}Sr$ were cited as diagenetic processes (Dia et al., 1997) or freshwater influx from a carbonate catchment area with low $^{87}Sr/^{86}Sr$ that altered the chemistry of the gulf (Burnside, 2010; Houghton, 2010).

With the exception of corals studied by Collier et al. (1992) that used *Acropora sp*, all of the coral growth ages from within the Gulf of Corinth are obtained from *Cladocora caespitosa*. *C. caespitosa* in the Gulf of Corinth grew as isolated colonies rather than extensive reefs (Dia et al., 1997) and differ from many other corals in that they thrive in coastal and brackish/fresh water environments because they are able to tolerate alluvial inputs and higher turbidity (Peirano et al., 2004). Modern day *C. caespitosa* occur in shallow water between 4-10 m in depth, but have been known to live down to depths of 40 m (Peirano et al., 2004). Studies on *C. caespitosa* show they are a long-lived species with slow growth rates of up to 3.08 mm/yr (Zunino et al., 2018).

3. Approach and methods

The accuracy of coral ages is dependent on: (i) knowledge of the decay constants of U-series nuclides, (ii) the assumption that ^{230}Th was negligible at the time of coral growth and, (iii) the assumption that closed system conditions prevailed whereby no further isotopic exchange occurred between the coral and its surrounding environment (Dutton, 2015). This latter point is tested by comparing the $\delta^{234}U_i$ of the sample to the $\delta^{234}U$ of the open ocean. While the first two points can be satisfied (see below), we question whether the corals within this study formed in seawater with a $\delta^{234}U_i$ comparable to the present day. To explore this, $^{234}U/^{230}Th$ analyses on corals from the same sedimentary layer on Cape Heraion were undertaken, with multiple $^{234}U/^{230}Th$ analyses on each corallite. These new $^{234}U/^{230}Th$ coral ages were used in addition to data from multiple analyses on two corallites from a recent study (Robertson et al., 2020) also from Cape Heraion (Fig. 1). The approach adopted herein assumes that growth age robustness can be established if clustering of ages and $\delta^{234}U_i$ are observed from different corallites and multiple analyses on the same corallite (Esat and Yokoyama, 2010), especially if the coral age is consistent with independent geological constraints. Such clustering may be indicative of corals displaying closed system behaviour, where $\delta^{234}U_i$ values are representative of the water chemistry at the time of growth. The $\delta^{234}U_i$ of the samples dated herein and in Robertson et al. (2020) are then used as the basis to investigate $\delta^{234}U_i$ on all late Quaternary corals dated within the Gulf of Corinth.

3.1 Recalculation of all coral ages and $\delta^{234}U$ values to the same decay constants

U-series ages of corals from all known studies from within the Gulf of Corinth were compiled (Collier et al., 1992; Vita-Finzi et al., 1993; Dia et al., 1997; Houghton et al., 2003: Leeder et al., 2003; McNeill and Collier, 2004; Leeder et al., 2005; Palyvos et al., 2010; Roberts et al., 2009; Burnside, 2010; Houghton, 2010; Turner et al., 2010; Robertson et al., 2020) (n=154) (Fig. 2a; Supplementary Table 1). As these studies have occurred over three decades, different decay constants of ^{230}Th and ^{234}U have been used to calculate the activity ratios, and thus age and $\delta^{234}U_i$ of the coral samples. To compare the coral ages and $\delta^{234}U_i$ values from different studies, we recalculated coral ages and $\delta^{234}U_i$ (as per Dutton, 2015), using the decay constants of Cheng et al. (2013). Recalculation required the original decay constants, activity ratios and/or isotope data, and resulted in changes of ~<1% to most coral growth ages (Supplementary Table 1). The original decay constants were not published in McNeill and Collier (2004), the ages and $\delta^{234}U_i$ values have been recalculated assuming that the decay constants of Edwards et al. (1987) were originally employed. However, a lack of reported measurement data for Palyvos et al., 2010 and samples 89/1 and 89/4 from Vita-Finzi et al., 1993 mean that these coral age data (n=10) cannot be recalculated and are therefore excluded from this study.

3.2 ^{234}U/^{230}Th dating

The results of new (samples 44-47) ^{234}U/^{230}Th and recent (Samples S6 and S7, Robertson et al., 2020) analyses on *C. caespitosa* coral samples from Cape Heraion are used herein. Samples S6 and S7 (Figs. 1c Profile line a-a’, 3c, Supplementary Fig. 1a, c, d, Supplementary Table 1) were removed from the sandy layer on a MIS 5e (125 ka) wave-cut platform (44 m) constrained using ^{36}Cl exposure dating (Robertson et al., 2020). Samples 44-47 were removed from a layer in a sedimentary succession (41 m) accessed via an ancient cistern (Fig. 1c Profile line b-b’, Supplementary Fig. 1b, c, e). The sandy layer of samples 44-47 occurs beneath a reported 125 ka wave-cut surface (Robertson et al., 2020) and is comprised of whole and disarticulated fossils and coarse sand to pebble grain sizes, suggestive of a high-energy environment.

Coral preparation and cleaning was carried out as per the method outlined in Roberts et al. (2009). This involved fragmenting the coral, mechanical cleaning of the wall of the coral with a scalpel under a microscope (discarding the septa) to remove areas of alteration and sediment, submerging the coral in 10% hydrochloric acid for 2-3 seconds and rinsing in ultra-pure water. This process was repeated until the coral was free from visible signs of alteration. Individual corallites were analysed and, for selected corallites, multiple ^{234}U/^{230}Th analyses were carried out in order to assess for $\delta^{234}U_i$ clustering and age reliability. ^{234}U/^{230}Th analysis was carried out according to the process outlined in Crémière et al. (2016).

Standard methods for screening for anomalous ^{238}U and ^{230}Th were applied as per Dutton (2015). Specifically, modern corals typically have uranium values ~2–3.5 ppm (Shen and Dunbar, 1995); samples with significantly different values may be indicative of diagenetic processes and were rejected. The $^{230}Th/^{232}Th$ ratio was checked to ensure that ^{230}Th was negligible during initial coral growth, rejecting the sample if the value was too low (<100) (van Calsteren and Thomas, 2006) or the concentration of ^{232}Th was too high (as identified by Dia et al. (1997) for their samples). These methods of screening were applied to corals dated in this study and all existing coral data assessed (Supplementary Table 1).

3.3 MIS and sea-level highstands

Coral ages are discussed in reference to MIS and respective glacio-eustatic highstands. Herein, we use the highstand ages from Siddall et al. (2003) and the lengths of MIS obtained from a number of studies (Table 1). The focus was on analysing coral growth ages associated with MIS 5e (125 ka), MIS 6d (175 ka) and MIS 7a (200 ka) (Table 1). MIS 5e is well studied and there is relative certainty that between 129-116 ka the sea-level was above the present day value (Dutton et al., 2015). However, it is expected that coral growth in the gulf would have occurred when lake Corinth experienced sea-water ingress following the penultimate glacial maximum (~150 ka), but the timing of this ingress is poorly constrained. It is suggested that sea-level rise at the beginning of interglacial periods occurs quickly, reaching maximum sea-level rise rates within ~2 kyrs of the onset of deglaciation (Grant et al., 2014). For MIS 5e, Gallup et al. (2002) suggest that 80% of sea-level rise following the glacial period of MIS 6a (~150 ka) occurred before 135 ka. Analysis of the rates of sea-level rise from Grant et al. (2014) suggests that from ~150 ka to ~138 ka sea level rise was 5-8 m/ky. An average rate of 6.5 m/ky is used alongside the relative sea-level at 150 ka of -90 m, to suggest that by 138 ka sea-level within the gulf may have been ~-12 m (±10 m) relative to the present day. We suggest that it is plausible that coral growth at this time could have occurred so 138 ka is used as an approximate age to indicate the beginning of MIS 5e in relation to the gulf.

MIS (highstand)	MIS time period (ka)	References
5a (76 ka)	70-82	N/A (used highstand age from Siddall et al., 2003, ±6 ka error)
5c (100 ka)	94-106	N/A (used highstand age from Siddall et al., 2003, ± 6ka error)
5e (125 ka)	116-138	Grant et al., 2014
6d (175 ka)	169-181	N/A (used highstand age from Siddall et al., 2003, ±6 ka error)
7a (200 ka)	188-202	Dutton et al., 2009
7c (217 ka)	206-217	Dutton et al., 2009
7e (240 ka)	231-249	Dutton et al., 2009
9c (310 ka)	282-312	Rohling et al., 1998
9e (340 ka)	322-340	Rohling et al., 1998
11c (410 ka)	384-412	Rohling et al., 1998

Table 1: References used to inform the highstand time period within this study, where such data was not available, the highstand age ±6 ka uncertainty from Siddall et al. (2003) was applied. See text for discussion on MIS 5e (125 ka) timing.

4. Results and discussion

Coral growth ages and $\delta^{234}U_i$ from 22 coral samples (this study: 12, Robertson et al., 2020: 10) are discussed and used to suggest tentative $\delta^{234}U_i$ values for the Gulf of Corinth from MIS 5e to MIS 7a. Existing Gulf of Corinth coral ages are then investigated using: (i) the tentative $\delta^{234}U_i$ values, (ii) the tectonic/stratigraphic settings from which the corals were sampled and, (iii) their spatial relationship relative to other coral ages or age constraints. The outcome of this analysis suggests that the growth ages of corals are consistent with ages expected given their stratigraphic position and, therefore, elevated $\delta^{234}U_i$ is representative of late Quaternary hydrochemistry of the gulf. These findings are discussed in the context of the gulf-wide uplift rates and use of coral growth ages to derive uplift rates in coastal margins and restricted basins.

4.1 $\delta^{234}U_i$ during MIS 6d (175 ka) and 7a (200 ka)

The results of coral age dating on samples 44-47 (Fig. 1c: Locality 1, Profile line b-b'), removed from the same sedimentary layer (Supplementary Fig. 1b, c, e), reveal ages and $\delta^{234}U_i$ values of multiple analyses on 4 corallites (Fig. 4a, Table 2). Ages from corallites S44 (198 ±1.7 ka, 195 ±3.0 ka, 196 ±2.8 ka, 197 ±2.9 ka) and S46 (200 ±1.6 ka, 179 ±3.6 ka, 196 ± 4.9 ka) suggest formation during the 200 ka highstand (Table 1), the 179 ka sample has a low uranium value of 1.56 ppm and is disregarded (Table 2). Ages from corallite S45 (175 ±1.3 ka, 165 ±1.9 ka, 168 ±1.5 ka, 203 ±2.8 ka) and S47 (181 ±1.6 ka) suggest formation during the 175 ka highstand (Table 1) where the 203 ka age is likely to be an outlier and the 165- ka dated sample may be questionable owing to a low uranium value of 1.82 ppm (Table 2). As described above, corals 44-47 were located below the 125-ka wave-cut platform, so coral ages older than this are not unexpected.

In other words, the ages of samples 44-47 are expected when their geological setting is considered; sampled from the same bioclastic-rich layer, the corals occur stratigraphically below a 125 ka (MIS 5e) ^{36}Cl exposure dated wave-cut surface (Supplementary Fig. 1b, c, e) (Robertson et al., 2020). The presence of 175 ka and 200 ka corals in this location can be explained by the following sequence of events, invoking erosion and isolation of whole corallites followed by re-sedimentation, using the sea level curve of Siddall et al. (2003) (elevations are relative to sea level today): (i) coral samples 44 and 46 grew during MIS 7a (200 ka highstand) below the -5 m (± 12 m) maximum sea level at this time, (ii) sea-level fell during lowstand MIS 6e to beyond ~-60 m; (iii) sea-level rose to a maximum of ~-30 m (± 12 m) within MIS 6d (175 ka highstand), during which the growth of samples 45 and 47 occurred, and was followed by a fall in sea level to between -60 m to -80 m during MIS 6c-6a; (iv) the subsequent 125 ka highstand (MIS 5e) resulted in sea level rise to ~5 m (± 12 m) and a wave-cut platform was formed. This substantial sea-level rise could have eroded the coral colonies of 200 ka and 175 ka from their growth positions and deposited the corallites in their present day location within possible MIS 5e-aged sediments, following which the wave-cut platform formed. Preservation of the wave-cut platform and associated coral samples are as a consequence of sustained fault-controlled uplift since ~125 ka (Robertson et al., 2020). The above scenario suggests an uplift rate of 0.41 mm/yr, a value that is similar to those proposed for this location (Robertson et al. 2020), and is hence not unreasonable.

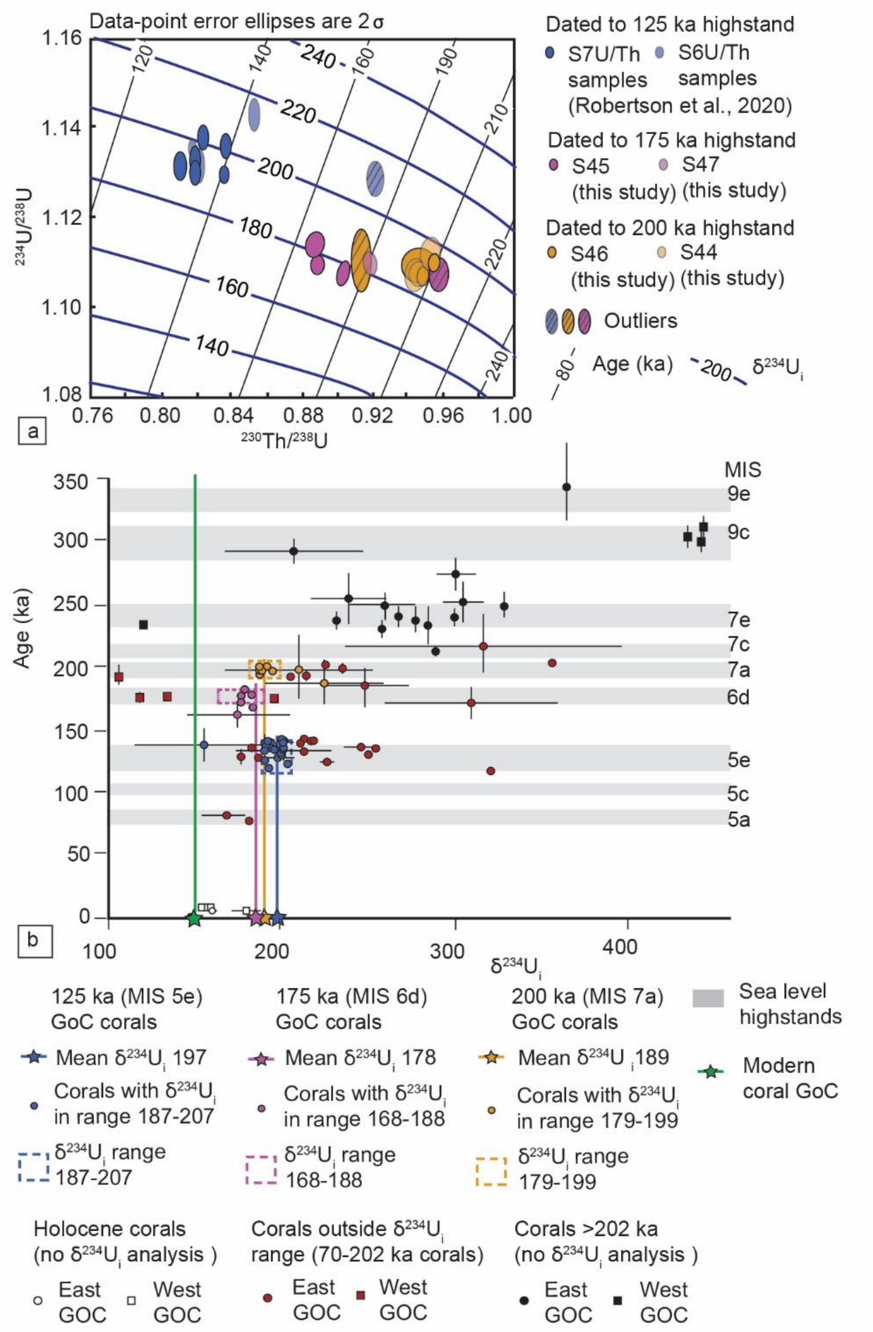

Figure 4: (a) U-Th evolution diagram with the results of dating on samples 44-47 (this study) and S6 and S7 (Robertson et al., 2020). (b) Plot of all acceptable (see text for detail) highstand coral growth ages from within the Gulf of Corinth. For samples 70-202 ka, colour coding is according to whether the sample has δ234Ui within the range identified in this study. Holocene corals and corals ≥203 ka are not evaluated on the basis of their δ234Ui. See Table 1 for detail of the sea-level highstand periods and Supplementary Fig. 2 for analysis for each locality.

Sample ref.	Age (ka)	±2s (abs) (ka)	U (ppm)	$(^{230}Th/^{232}Th)$	$(^{232}Th/^{238}U)$	±2s (%)	$(^{230}Th/^{238}U)$	±2s (%)	$(^{234}U/^{238}U)_m$	±2s (%)	$\delta^{234}U_i$
S44(1)	197.8	1.7	1.91	488.1	0.0019	0.06	0.948	0.25	1.107	0.16	187
S44(2)	195.3	3.0	2.05	379.7	0.0025	0.35	0.943	0.49	1.107	0.27	186
S44(3)	196.1	2.8	2.02	354.2	0.0027	0.36	0.945	0.48	1.108	0.21	187
S44(4)	196.9	2.9	1.91	274.4	0.0035	0.35	0.951	0.47	1.112	0.25	196
S45(1)	174.7	1.3	2.08	159.3	0.0057	0.05	0.903	0.31	1.108	0.20	176
S45(2)	165.0	1.9	1.82	281.8	0.0031	0.34	0.887	0.47	1.114	0.21	182
S45(3)	167.6	1.5	2.06	549.9	0.0016	0.45	0.889	0.35	1.110	0.16	176
S45(4)	203.1	2.8	2.64	213.4	0.0045	0.29	0.957	0.41	1.107	0.27	191
S46(1)	199.5	1.6	1.93	288.9	0.0033	0.05	0.954	0.26	1.110	0.15	193
S46(2)	178.5	3.6	1.56	385.9	0.0024	0.68	0.914	0.58	1.110	0.50	183
S46(3)	195.7	4.9	1.98	235.4	0.0040	0.82	0.946	0.87	1.110	0.30	190
S47(1)	181.2	1.6	1.92	526.4	0.0017	0.06	0.918	0.29	1.110	0.18	183

Table 2: $^{234}U/^{230}Th$ coral age dating analytical results for all samples 44-47 (this study) - activity ratios calculated using the ^{234}U and ^{230}Th decay constants of Cheng et al. (2013). Activity ratios corrected for ^{230}Th, ^{234}U and ^{238}U contribution from the synthetic ^{236}U-^{229}Th tracer, instrument baselines, mass bias, hydride formation and tailing. ^{230}Th blanks amounting to 0.15 ± 0.03 fg were subtracted from each sample. ^{238}U blanks were on the order of 10 pg, and were negligible relative to sample size. Age and $\delta^{234}U$ data were corrected for the presence of initial ^{230}Th assuming an initial isotope composition of $(^{232}Th/^{238}U)$ = 1.2 ± 0.6, $(^{230}Th/^{238}U)$ = 1 ± 0.5 and $(^{234}U/^{238}U)$ = 1 ± 0.5 (all uncertainties quoted at the 2σ level).

Given the above scenario for the deposition of the corals and the fact that coral ages fall into sea-level highstand periods, we suggest that these ages appear to be reliable. The $\delta^{234}U_i$ values of samples S44-47 suggest that for the 200 ka highstand (MIS 7a) (S44, S46), $\delta^{234}U_i$ values range between 186-196. For the 175 ka highstand (MIS 6d) (S45, S47), $\delta^{234}U_i$ values appear to have been between 176-183. All of these values are higher than that of the present day oceans (~145‰), but similar to the values reported in other Gulf of Corinth corals (Fig. 3a; Supplementary Table 1). Differing $\delta^{234}U_i$ values for each highstand within the Gulf of Corinth can be tentatively suggested using the mean of values from the new coral ages herein. These values and their ±10‰ range (Fig. 4b) are 189‰ (179-199) for the 200 ka highstand (MIS 7a) and 178‰ (168-188) for the 175 ka highstand (MIS 6d).

4.2 $\delta^{234}U_i$ during MIS 5e (125 ka)

The coral ages of samples S6 and S7 sampled from 44 m on Cape Heraion (published in Robertson et al., 2020) (Fig. 1c Profile a-a'; Fig. 4a; Supplementary Table 1; Supplementary Fig. 1a, c, d) suggest growth during MIS 5e (125 ka highstand). These results are in agreement with coral growth ages from other studies sampled from Cape Heraion (Fig. 1c) (Vita Finzi et al., 1993; Leeder et al., 2003; Leeder et al., 2005; Roberts et al., 2009; Burnside, 2010; Houghton, 2010), all of which can be mapped into wave-cut platforms dated to the 125 ka highstand (MIS 5e) using *in-situ* ^{36}Cl exposure dating (Robertson et al., 2020) (Figs. 1c, 3c, Supplementary Fig. 1a, c, d). Examination of the multiple analyses of samples S6 and S7 reveal seven growth ages reflective of MIS 5e (125 ka highstand) (Fig. 4a, Supplementary Table 1) within the range 132-138 ka, two growth ages just outside the MIS 5e range of 141 ±0.8 ka and 143 ±1.3 ka that we include in our analysis and an age of 174 ±2 ka (S6) that appears to be an outlier from analysis of corallite S6 and is herein excluded. The nine ages within the range of 132-143 ka all have acceptable uranium concentration levels and ($^{230}Th/^{232}Th$) values. $\delta^{234}U_i$ values of samples S6 and S7 cluster between 191-214 (Fig. 4a) (mean of 197‰, and a ±10‰ range of 187-207). If the growth ages of 141 ka and 143 ka are excluded, then corals with growth ages between 132-138 ka have similar $\delta^{234}U_i$ values that cluster between 191-202 with a mean of 196‰.

In summary, comparing the $\delta^{234}U_i$ values of multiple analyses on individual corallites reveals elevated values for MIS 5e (125 ka), MIS 6d (175 ka) and MIS 7a (200 ka) of 197‰, 178‰ and 189‰, respectively, but growth ages that make sense with their stratigraphic and structural positions (Supplementary Fig. 2). The ages within each highstand appear to broadly cluster together (Fig. 4a, Supplementary Fig. 3). This observed clustering of samples within and between corallites is taken as evidence that the $\delta^{234}U_i$ values may be representative of corals that formed during MIS 5e, 6d and 7a. Alternatively, if the elevated $\delta^{234}U_i$ were caused by diagenesis then it may be expected that sub-samples of the same corallite might have significantly different isotopic compositions, hence clustered values would be unlikely. The similarity of both age and $\delta^{234}U_i$ values allows for a tentative suggestion that the $\delta^{234}U_i$ of the Gulf of Corinth during late Quaternary highstands was higher than that of present values and within the broad range of 160-217.

4.3 Coral ages and $\delta^{234}U_i$ values within their tectonic setting

Assuming that our late Quaternary $\delta^{234}U_i$ values highlighted above are correct, they are applied to the recalculated coral age dataset (n=154) from within the Gulf of Corinth (Fig. 4b; Supplementary Table 1). However, prior to further analysis we exclude a number of samples (n=66), detailed in Supplementary Table 1 and its caption. Plotting the age versus $\delta^{234}U_i$ of the remaining acceptable samples (n=88) shows growth ages that cluster within glacio-eustatic highstand periods; however, we note that samples have $\delta^{234}U_i$ values that fall within and outside of the $\delta^{234}U_i$ range identified herein (for ages 69-202 ka) (Fig. 4b). Detailed analysis on the 88 acceptable samples reveals 5 samples that have Holocene ages, 64 samples that have highstand ages between 69-202 ka (76-200 ka highstands, Fig. 4b, Supplementary Table 1) with the remaining 19 samples ≥203 ka (Fig. 4b). Exploring the 64 samples with highstand growth ages between 69-202 ka, we examine whether the $\delta^{234}U_i$ values are consistent with the ranges identified in Section 4.2. This shows that for the corals with 200 ka highstand (MIS 7a) ages (n=16), 50% have $\delta^{234}U_i$ within the range of 179-189. For the corals with 175 ka highstand (MIS 6d) ages (n=11), 45% have $\delta^{234}U_i$ within the range of 168-188. For the corals with 125 ka highstand (MIS 5e) ages (n=35), 63% have $\delta^{234}U_i$ within the range of 187-207. However, note that the remaining corals with $\delta^{234}U_i$ outside of these ranges have growth ages and sample locations that fit with the stratigraphical and tectonic relationships in addition to agreeing with other coral ages sampled from the same location (Supplementary Fig. 2), suggesting that acceptable $\delta^{234}U_i$ values may have an even wider range that we specify in Section 4.2, perhaps due to relatively variable water chemistry in some locations. Coral growth ages ≥203 ka (n=19) predominantly exhibit higher $\delta^{234}U_i$ that could be due to diagenetic processes or again may be an indication of different hydrochemistry within the gulf at the time of growth. A lack of further analyses on these corals precludes further explanation for ≥203 ka corals. Overall, these results suggest that $\delta^{234}U_i$ may have been elevated during coral growth between 76-202 ka, but they also indicate that within the Gulf of Corinth there appears to have been some spatial and temporal variability of $\delta^{234}U_i$.

We observe that 83% coral growth ages come from the eastern Gulf of Corinth (Figs. 1a, c, Supplementary Table 1), and that all of the MIS 5e (125 ka highstand) dated corals are located in the eastern Gulf of Corinth. One possible explanation for this is that coral growth is reflective of the dominant seawater entry point during the highstands, but we do not discount that this could simply be related to sampling and/or preservation bias. If the interpretation of seawater entry via the Rion Straits and Isthmus of Corinth during MIS 5e proposed by Roberts et al. (2009) is accepted, restricted seawater entry via the Rion Straits did not occur until sea level was near its maximum elevation (stillstand) around 125 ka (MIS 5e). Prior to the MIS 5e stillstand, seawater entry would be predominantly via the shallow Isthmus of Corinth into the eastern part of the gulf ~110 km to the east, and coincidental to the location of all of the MIS 5e corals within this study. Further analysis shows that 75% of MIS 5e corals (with $\delta^{234}U_i$ within the acceptable range determined herein) were dated to the earlier part of the highstand from 138 ka to 125 ka (Supplementary Table 1) which could be used to suggest that marginal water conditions during the early highstand favoured growth of *C.caespitosa*. The coral growth ages herein can be inferred to suggest that sea-level rise during ~143-138 ka was high enough to enter through the Isthmus of Corinth and begin the transition from lake to marine conditions.

4.4 Variable chemistry of the Gulf of Corinth throughout the Late Quaternary

Our interpretation that the Late Quaternary Gulf of Corinth $\delta^{234}U_i$ value was elevated with respect to that of the open ocean is consistent with descriptions of the geological setting of other authors (Collier et al., 1992; Roberts et al., 2009; Burnside, 2010; Houghton, 2010). The hypotheses of elevated $\delta^{234}U_i$ centres around transitions between a lake and semi-restricted marine basin throughout the Late Quaternary as a result of the interplay between eustatic sea-level variation, freshwater influx and fault-related subsidence/uplift along the Rion-Anterion sill and Isthmus of Corinth, respectively (Fig. 1a) (e.g. Roberts et al., 2009). Restricted/silled basins have been shown to have distinctive hydrochemistry compared to that of the open ocean (Middelburg et al., 1991; Andersson et al., 1995; Esat and Yokoyama, 2010). However, temporal and spatial variations of the hydrochemistry within the faulted Gulf of Corinth basin are poorly understood. We know that marine conditions prevail at highstands (Roberts et al., 2009; McNeill et al., 2019) and that during the transition from lowstand to highstand the gulf is likely to become marine with a significant freshwater content (Perissoratis et al., 2000), evidenced by highly variable microfossil assemblages that reveal complex basin environmental variation between highstand and lowstand intervals (Roberts et al.,2009; McNeill et al. 2019). Little else is known about the water chemistry, which is expected to be spatially and temporally variable considering that: (i) the seawater inlets were narrow, shallow and changing over time (Collier and Thompson, 1991; Perissoratis et al., 2000), (ii) sea level rises are spatially complex and may be non-linear through time (e.g. Dutton et al., 2015), (iii) late Quaternary cyanobacterial mounds that dominate Cape Heraion at Locality 1 (Fig 1. c) may provide evidence of rising groundwater altering the water chemistry (Portman et al., 2005), and (iv) coral growth occurs in the footwalls along coastal margins (localities 2-9, Fig. 1a) that are subject to episodic fault-related uplift and freshwater influx from rivers and groundwater (Luijendijk et al., 2020). A study of the Holocene coastal marginal marine environment along the southern western Gulf of Corinth (Soter et al., 2001) provides an analogue to conditions during previous highstands. Spatial and temporal variations in hydrogeochemistry were evidenced by complex sedimentology and stratigraphy suggestive of repeated transitions between freshwater and brackish to marine conditions over periods of 1-3 ka due to a combination of tectonic uplift, river drainage and the variation between rapid and decelerated sea-level rise (Soter et al., 2001).

In summary, we propose that along the fault-controlled coastal margins of the Gulf of Corinth, the dominant factor controlling the $\delta^{234}U_i$ of corals during previous highstands may be restricted seawater entry into the gulf combined with freshwater influx from groundwater (Locality 1) and rivers (localities 2-9) (Fig. 1). The $\delta^{234}U_i$ of both groundwater and riverine input is dependent on the lithology of the host rocks in the catchment or circulation area (Palmer and Edmond, 1993), which are predominantly comprised of Mesozoic limestone and carbonate lithologies in the Gulf of Corinth (IGME, 1993). In the eastern Gulf of Corinth, at Cape Heraion (Fig. 1c, Locality 1) the presence of high Mg/Sr cyanobacterial mounds is interpreted as evidence that groundwater from submarine springs percolating along normal faults was partially equilibrated with Mesozoic limestones, which have relatively high $\delta^{234}U_i$ (Houghton, 2010). This is relevant given that 18 of the coral samples from within Locality 1 are located on or directly adjacent to these cyanobacterial mounds. In terms of the riverine input (localities 2-9, Fig. 1) there are presently ~47 major rivers that drain into the southern gulf (Watkins et al., 2020), one would expect that many of these also drained into the Gulf of Corinth throughout the late Quaternary. Lithological, climatic and seasonal differences mean that riverine $\delta^{234}U_i$ may be highly variable in comparison to seawater, where studies into individual rivers worldwide report significantly higher values beyond 400-500 (e.g. Andersson et al., 1995; Andersen et al., 2007; Grzymko et al., 2007, and *references therein*). While no such data exists for the Gulf of Corinth rivers, spatial and seasonal temporal variation of $\delta^{234}U_i$ due to riverine input and restricted circulation has been observed in other restricted basins such as the Baltic Sea (Andersson et al., 1995). Furthermore, a recent study by Luijendijk et al. (2020) suggested that coastal groundwater discharge (a combination of submarine and nearshore terrestrial groundwater discharge) takes place in a zone that extends 400 m from the shore, and that due to spatial variability, this groundwater discharge can significantly impact coastal hydrology.

4.4.1 Analysis of $^{87}Sr/^{86}Sr$ ratios throughout the Late Quaternary

A test of the hypothesis of elevated $\delta^{234}U_i$ of Gulf of Corinth corals as a direct consequence of freshwater input can be carried out by investigating $^{87}Sr/^{86}Sr$ ratios. Corals and other marine carbonate organisms record the $^{87}Sr/^{86}Sr$ ratios of the water in which they formed. Marine $^{87}Sr/^{86}Sr$ ratios have been shown to be increasing quasi-linearly over the past 2.5 Ma, but exhibit less variation on timescales over hundreds of thousands of years (Hodell et al., 1990). Present day homogenous oceanic $^{87}Sr/^{86}Sr$ values (Hodell et al., 1990) and Gulf of Corinth values (Houghton, 2010) display values of ~0.70917. If freshwater influx dominated conditions along coastal margins, the $^{87}Sr/^{86}Sr$ chemistry of the corals should reflect these conditions. However, this assumption is initially flawed because the significant difference between Strontium (Sr) concentrations of riverine and oceanic waters, 1.0-4.0 µM and 90 µM respectively, means that riverine input into marginal seas may be unlikely to alter the Sr concentrations (Krabbenhoft et al., 2010). The exception is in carbonate organisms grown in brackish/low salinity environments, where the $^{87}Sr/^{86}Sr$ chemistry of the water may be significantly affected by the freshwater $^{87}Sr/^{86}Sr$ (Bryant et al., 1995). Brackish/oligohaline conditions throughout the Holocene and late Quaternary are evident from detailed observations on microfossils (Soter et al., 2001; Roberts et al., 2009; Papanikolaou et al., 2015; McNeill et al., 2019). Consequently, we suggest that the $^{87}Sr/^{86}Sr$ of corals from the Gulf of Corinth corals may be a reliable proxy to investigate the observed elevated $\delta^{234}U_i$.

The $^{87}Sr/^{86}Sr$ ratio of freshwater is directly influenced by the dominant lithology of their circulation/catchment areas (e.g. Palmer and Edmond, 1993; Hodell et al., 1990). Limestones and other carbonate lithologies, which dominate the gulf, have low $^{87}Sr/^{86}Sr$ ratios, with worldwide values of 0.707-0.709 (Burke et al., 1982) and Triassic limestones of the Perachora Peninsula (Fig. 1a) measured as 0.70771 (Houghton, 2010). Comparison of the $^{87}Sr/^{86}Sr$ ratios for corals from the Gulf of Corinth to those from the Pacific and Atlantic throughout the late Quaternary reveals that the Gulf of Corinth corals exhibit a range of $^{87}Sr/^{86}Sr$ ratios, that are moderately to significantly lower than Atlantic and Pacific levels from ~75 ka to ~350 ka (Fig. 5). Low $^{87}Sr/^{86}Sr$ on Gulf of Corinth corals was also observed by Dia et al. (1997) who considered that sample impurities and/or diagenetic processes may be the cause, however, Houghton, (2010) carried out detailed chemical analysis on meticulously cleaned corals and dismissed this explanation. We tentatively suggest that the observed elevated $\delta^{234}U_i$ in corals may be related to the same processes that produced the low $^{87}Sr/^{86}Sr$ ratios, but this needs further work.

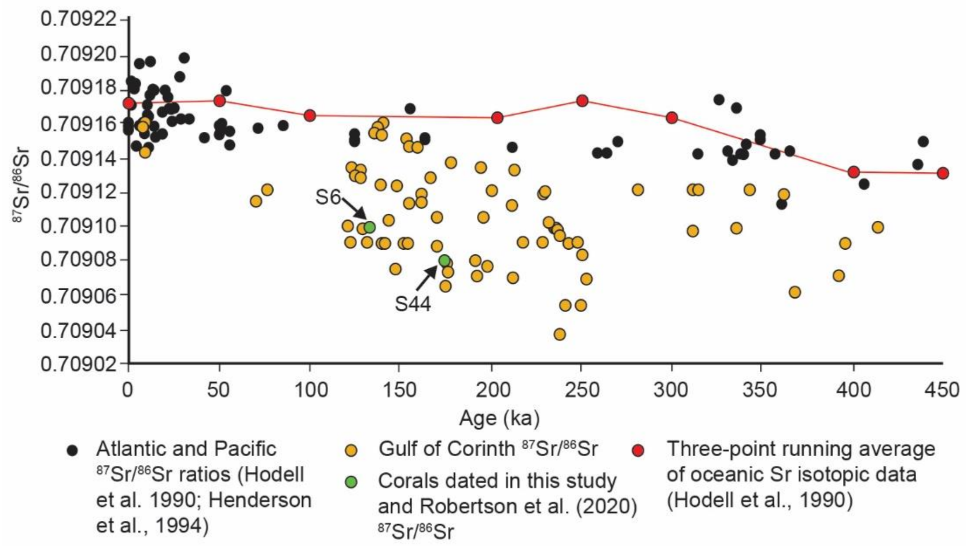

Figure 5: 87Sr/86Sr and age plot for the Gulf of Corinth from corals assessed within this study against those from Hodell et al. (1990) from the Atlantic and Pacific, in addition to a worldwide Sr curve obtained from a three-point running average (Hodell et al., 1990).

4.5 Summary of coral ages and $\delta^{234}U_i$ findings

In summary, our findings suggest that corals from within the Gulf of Corinth with MIS highstand ages (5e, 6d and 7a) have elevated $\delta^{234}U_i$ reflective of their growth environment, where the hydrochemistry of the gulf deviated from that of the present day. A combination of restricted marine input into the gulf during the highstands and coral growth along fault-controlled margins, where water chemistry was influenced by freshwater, is inferred as the likely cause of elevated $\delta^{234}U_i$. Whilst tentative values of $\delta^{234}U_i$ for three Late-Quaternary highstands are suggested, there is likely to be spatial and temporal variation of this value as a result of seasonal and catchment area differences from riverine input. For this reason, coral growth ages are not excluded from this study solely on the basis of the $\delta^{234}U_i$. Our results are strengthened by the observed stratigraphical and tectonic relationships of Gulf of Corinth corals and other age controls (Supplementary Fig. 2). These findings suggest that where late Quaternary coral ages are obtained from coastal margins or restricted/silled marine basins, age reliability determinations based solely upon $\delta^{234}U_i$ should be avoided. Coral age reliability should be assessed based upon clustered ages and $\delta^{234}U_i$ from multiple analyses on the same corallites, in combination with the location of other coral growth ages/age controls relative to the localised tectonic/stratigraphic setting.

4.6 Late Quaternary uplift patterns using coral ages

Uplift rates on the footwalls of active normal faults that bound the south of the Gulf of Corinth (Fig. 1a), calculated using the coral ages discussed herein, can be used to explore Late Quaternary gulf-wide fault-related deformation. East to west along the Gulf of Corinth (Fig. 6), these data show that uplift maxima occur within the central section of the gulf clearly decreasing to the east and appearing to decrease toward the west, though a lack of data prohibits certainty with latter observation (Fig. 6b). These results are consistent with summed late Quaternary fault displacement profiles from Bell et al. (2011) (Fig. 6c) who identified a: "…bell-shaped displacement profile with greatest levels of extension in the central part of the rift". Long-term uplift and fault displacement data (Fig. 6b and c) are not in agreement with short-term geodetic rates of extension (Clarke et al., 1998; Briole et al., 2000; Bell et al., 2011) (Fig. 6d), which suggest increasing extension from east to west. Detailed investigations by Bell et al. (2011) led them to hypothesise that this discrepancy may be as a consequence of variation in the location of maximum extension due to fault growth and linkage. While the discrepancy between short-term geodetic and long-term fault uplift/displacement rates is unresolved, it is clear that the age constraints obtained from uplifted corals make a significant contribution to establishing long-term rates of deformation throughout the Gulf of Corinth.

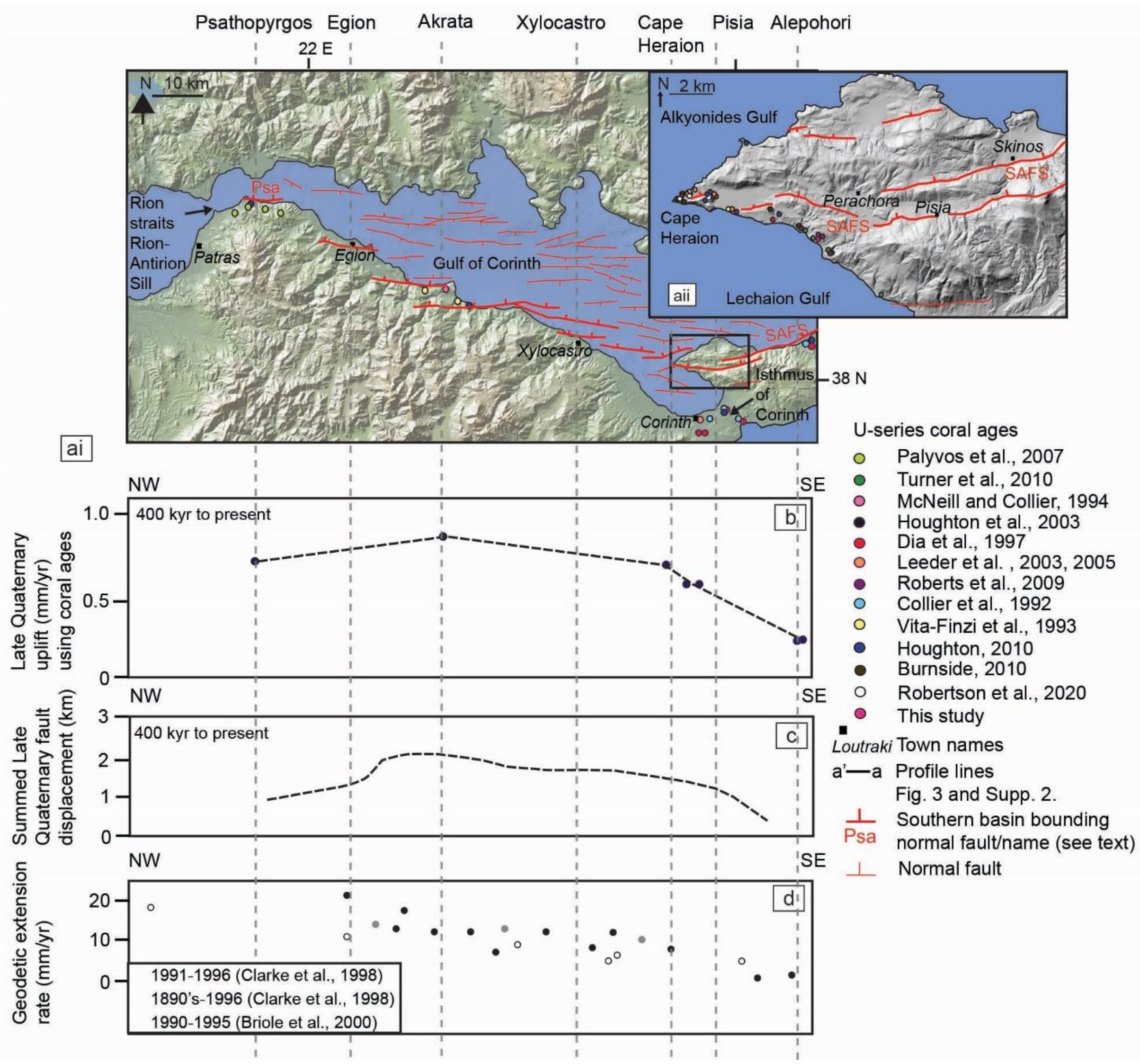

Figure 6: (a) Map of Gulf of Corinth and major faults based upon those used in Nixon et al. (2016). (aii) Perachora peninsula major faults from Roberts et al. (2009). (b) Late Quaternary uplift in the footwall of major north dipping faults that bound the south of the Gulf of Corinth derived from ages of corals from the following studies (west to east): McNeill and Collier, (2004); Houghton et al. (2003); Robertson et al. (2020); Roberts et al. (2009); Houghton (2010); Collier et al. (1992). Uplift values from corals located on the Isthmus of Corinth and eastern Corinth terraces are not plotted as they occur in the back tilted section of the footwall of the South Alkyonides Fault (SAF) and eastern tip of the Xylocastro faults respectively and therefore record minimum uplift values. (c) Summed late Quaternary fault displacement for the Gulf of Corinth, adapted from Bell et al. (2011). (d) Geodetic extension of Clarke et al. (1998) and Briole et al. (2000), adapted from Bell et al. (2011).

5. Conclusions

1. Analysis of new and existing coral growth ages suggest that the $\delta^{234}U_i$ of the Gulf of Corinth during the late Quaternary may been elevated and subject to spatial and temporal variation as a result of the interplay between eustatic sea-level changes, fault controlled uplift/subsidence that limited the marine water ingress into the gulf and freshwater influx from rivers and groundwater.
2. The age reliability of corals that have grown along coastal margins and in restricted/semi-restricted marine environments should not be solely evaluated on the basis of the $\delta^{234}U_i$ relative to open ocean values. Rather, we suggest that corallites from the same layer are analysed and that multiple analyses on the same corallites may be useful to determine age and $\delta^{234}U_i$ reliability, in combination with consideration of the stratigraphic and tectonic setting of the corals and their relative position to other age constraints.
3. Coral ages along the southern margin of the Gulf of Corinth provide a reliable means to explore long-term uplift patterns and are in agreement with other geological measurements such as late Quaternary fault displacement profiles.

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Data availability

All data for this paper are appropriately cited and referred to in the reference list and available from Tables 2 and Supplementary Table 1. These data can be used to reproduce the results.

Andersen, M.B., Stirling, C.H., Porcelli, D., Halliday, A.N., Andersson, P.S. and Baskaran, M., 2007. The tracing of riverine U in Arctic seawater with very precise 234U/238U measurements. *Earth and Planetary Science Letters*, *259*(1-2), pp.171-185.

Andersson, P.S., Wasserburg, G.J., Chen, J.H., Papanastassiou, D.A. and Ingri, J., 1995. 238U234U and232Th230Th in the Baltic Sea and in river water. *Earth and Planetary Science Letters*, *130*(1-4), pp.217-234.

Bard, E., Fairbanks, R.G., Hamelin, B., Zindler, A. and Hoang, C.T., 1991. Uranium-234 anomalies in corals older than 150,000 years. *Geochimica et Cosmochimica Acta*, *55*(8), pp.2385-2390.

Bard, E., Jouannic, C., Hamelin, B., Pirazzoli, P., Arnold, M., Faure, G. and Sumosusastro, P., 1996. Pleistocene sea levels and tectonic uplift based on dating of corals from Sumba Island, Indonesia. *Geophysical Research Letters*, *23*(12), pp.1473-1476.

Bell, R.E., McNeill, L.C., Henstock, T.J. and Bull, J.M., 2011. Comparing extension on multiple time and depth scales in the Corinth Rift, Central Greece. *Geophysical Journal International*, *186*(2), pp.463-470.

Briole, P., Rigo, A., Lyon‐Caen, H., Ruegg, J.C., Papazissi, K., Mitsakaki, C., Balodimou, A., Veis, G., Hatzfeld, D. and Deschamps, A., 2000. Active deformation of the Corinth rift, Greece: results from repeated Global Positioning System surveys between 1990 and 1995. *Journal of Geophysical Research: Solid Earth*, *105*(B11), pp.25605-25625.

Bryant, J.D., Jones, D.S. and Mueller, P.A., 1995. Influence of freshwater flux on 87 Sr/86 Sr chronostratigraphy in marginal marine environments and dating of vertebrate and invertebrate faunas. *Journal of Paleontology*, pp.1-6.

Burke, W.H., Denison, R.E., Hetherington, E.A., Koepnick, R.B., Nelson, H.F. and Otto, J.B., 1982. Variation of seawater 87Sr/86Sr throughout Phanerozoic time. *Geology*, *10*(10), pp.516-519.

Burnside, 2010. Unpublished Thesis. University of Glasgow.

Cheng, H., Edwards, R.L., Shen, C.C., Polyak, V.J., Asmerom, Y., Woodhead, J., Hellstrom, J., Wang, Y., Kong, X., Spötl, C. and Wang, X., 2013. Improvements in 230Th dating, 230Th and 234U half-life values, and U–Th isotopic measurements by multi-collector inductively coupled plasma mass spectrometry. *Earth and Planetary Science Letters*, *371*, pp.82-91.

Chutcharavan, P.M., Dutton, A. and Ellwood, M.J., 2018. Seawater 234U/238U recorded by modern and fossil corals. *Geochimica et Cosmochimica Acta*, *224*, pp.1-17.

Clarke, P.J., Davies, R.R., England, P.C., Parsons, B., Billiris, H., Paradissis, D., Veis, G., Cross, P.A., Denys, P.H., Ashkenazi, V. and Bingley, R., 1998. Crustal strain in central Greece from repeated GPS measurements in the interval 1989–1997. *Geophysical Journal International*, *135*(1), pp.195-214.

Collier, R.L., Leeder, M.R., Rowe, P.J. and Atkinson, T.C., 1992. Rates of tectonic uplift in the Corinth and Megara basins, central Greece. *Tectonics*, *11*(6), pp.1159-1167.

Collier, R.E.L. and Thompson, J., 1991. Transverse and linear dunes in an Upper Pleistocene marine sequence, Corinth Basin, Greece. *Sedimentology*, *38*(6), pp.1021-1040.

Crémière, A., Lepland, A., Chand, S., Sahy, D., Condon, D.J., Noble, S.R., Martma, T., Thorsnes, T., Sauer, S. and Brunstad, H., 2016. Timescales of methane seepage on the Norwegian margin following collapse of the Scandinavian Ice Sheet. *Nature communications*, *7*(1), pp.1-10.

Dia, A.N., Cohen, A.S., O'nions, R.K. and Jackson, J.A., 1997. Rates of uplift investigated through 230Th dating in the Gulf of Corinth (Greece). *Chemical Geology*, *138*(3-4), pp.171-184.

Dutton, A., 2015. Uranium-thorium dating. *Handbook of sea-level research. Chichester: John Wiley & Sons, Ltd*, pp.386-403.

Dutton, A., Bard, E., Antonioli, F., Esat, T.M., Lambeck, K. and McCulloch, M.T., 2009. Phasing and amplitude of sea-level and climate change during the penultimate interglacial. *Nature Geoscience*, *2*(5), pp.355-359.

Dutton, A., Webster, J.M., Zwartz, D., Lambeck, K. and Wohlfarth, B., 2015. Tropical tales of polar ice: evidence of Last Interglacial polar ice sheet retreat recorded by fossil reefs of the granitic Seychelles islands. *Quaternary Science Reviews*, *107*, pp.182-196.

Edwards, R.L., Chen, J.H. and Wasserburg, G.J., 1987. 238U234U230Th232Th systematics and the precise measurement of time over the past 500,000 years. *Earth and Planetary Science Letters*, *81*(2-3), pp.175-192.

Esat, T.M. and Yokoyama, Y., 2010. Coupled uranium isotope and sea-level variations in the oceans. *Geochimica et Cosmochimica Acta*, *74*(24), pp.7008-7020.

Gallup, C.D., Cheng, H., Taylor, F.W. and Edwards, R.L., 2002. Direct determination of the timing of sea level change during Termination II. *Science*, *295*(5553), pp.310-313.

Grant, K.M., Rohling, E.J., Ramsey, C.B., Cheng, H., Edwards, R.L., Florindo, F., Heslop, D., Marra, F., Roberts, A.P., Tamisiea, M.E. and Williams, F., 2014. Sea-level variability over five glacial cycles. *Nature communications*, *5*(1), pp.1-9.

Grant, L.B., Mueller, K.J., Gath, E.M., Cheng, H., Lawrence Edwards, R., Munro, R. and Kennedy, G.L., 1999. Late Quaternary uplift and earthquake potential of the San Joaquin Hills, southern Los Angeles basin, California. *Geology*, *27*(11), pp.1031-1034.

Grzymko, T.J., Marcantonio, F., McKee, B.A. and Stewart, C.M., 2007. Temporal variability of uranium concentrations and 234U/238U activity ratios in the Mississippi river and its tributaries. *Chemical Geology*, *243*(3-4), pp.344-356.

Hamelin, B., Bard, E., Zindler, A. and Fairbanks, R.G., 1991. 234U/238U mass spectrometry of corals: How accurate is the UTh age of the last interglacial period?. *Earth and Planetary Science Letters*, *106*(1-4), pp.169-180.

Henderson, G.M., Martel, D.J., O'Nions, R.K. and Shackleton, N.J., 1994. Evolution of seawater 87Sr86Sr over the last 400 ka: the absence of glacial/interglacial cycles. *Earth and Planetary Science Letters*, *128*(3-4), pp.643-651.

Hodell, D.A., Mead, G.A. and Mueller, P.A., 1990. Variation in the strontium isotopic composition of seawater (8 Ma to present): Implications for chemical weathering rates and dissolved fluxes to the oceans. *Chemical Geology: Isotope Geoscience section*, *80*(4), pp.291-307.

Houghton, S.L., Roberts, G.P., Papanikolaou, I.D., McArthur, J.M. and Gilmour, M.A., 2003. New 234U-230Th coral dates from the western Gulf of Corinth: Implications for extensional tectonics. *Geophysical Research Letters*, *30*(19).

Houghton, 2010. Unpublished Thesis. Birkbeck College, University of London.

Krabbenhöft, A., Eisenhauer, A., Böhm, F., Vollstaedt, H., Fietzke, J., Liebetrau, V., Augustin, N., Peucker-Ehrenbrink, B., Müller, M.N., Horn, C. and Hansen, B.T., 2010. Constraining the marine strontium budget with natural strontium isotope fractionations (87Sr/86Sr∗, δ88/86Sr) of carbonates, hydrothermal solutions and river waters. *Geochimica et Cosmochimica Acta*, *74*(14), pp.4097-4109.

Leeder, M.R., McNeill, L.C., Ll Collier, R.E., Portman, C., Rowe, P.J., Andrews, J.E. and Gawthorpe, R.L., 2003. Corinth rift margin uplift: New evidence from Late Quaternary marine shorelines. *Geophysical Research Letters*, *30*(12).

Leeder, M.R., Portman, C., Andrews, J.E., Collier, R.L., Finch, E., Gawthorpe, R.L., McNeill, L.C., Perez-Arlucea, M. and Rowe, P., 2005. Normal faulting and crustal deformation, Alkyonides Gulf and Perachora peninsula, eastern Gulf of Corinth rift, Greece. *Journal of the Geological Society*, *162*(3), pp.549-561

Luijendijk, E., Gleeson, T. and Moosdorf, N., 2020. Fresh groundwater discharge insignificant for the world's oceans but important for coastal ecosystems. *Nature communications*, *11*(1), pp.1-12.

McNeill, L.C. and Collier, R.L., 2004. Uplift and slip rates of the eastern Eliki fault segment, Gulf of Corinth, Greece, inferred from Holocene and Pleistocene terraces. *Journal of the Geological Society*, *161*(1), pp.81-92.

McNeill, L.C., Shillington, D.J., Carter, G.D., Everest, J.D., Gawthorpe, R.L., Miller, C., Phillips, M.P., Collier, R.E.L., Cvetkoska, A., De Gelder, G. and Diz, P., 2019. High-resolution record reveals climate-driven environmental and sedimentary changes in an active rift. *Scientific reports*, *9*(1), pp.1-11.

Medina-Elizalde, M., 2013. A global compilation of coral sea-level benchmarks: implications and new challenges. *Earth and Planetary Science Letters*, *362*, pp.310-318.

Muhs, D.R., Kennedy, G.L. and Rockwell, T.K., 1994. Uranium-series ages of marine terrace corals from the Pacific coast of North America and implications for last-interglacial sea level history. *Quaternary Research*, *42*(1), pp.72-87.

Nixon, C.W., McNeill, L.C., Bull, J.M., Bell, R.E., Gawthorpe, R.L., Henstock, T.J., Christodoulou, D., Ford, M., Taylor, B., Sakellariou, D. and Ferentinos, G., 2016. Rapid spatiotemporal variations in rift structure during development of the Corinth Rift, central Greece. *Tectonics*, *35*(5), pp.1225-1248.

Palmer, M.R. and Edmond, J.M., 1993. Uranium in river water. *Geochimica et Cosmochimica Acta*, *57*(20), pp.4947-4955.

Palyvos, N., Mancini, M., Sorel, D., Lemeille, F., Pantosti, D., Julia, R., Triantaphyllou, M. and De Martini, P.M., 2010. Geomorphological, stratigraphic and geochronological evidence of fast Pleistocene coastal uplift in the westernmost part of the Corinth Gulf Rift (Greece). *Geological Journal*, *45*(1), pp.78-104.

Papanikolaou, I.D., Triantaphyllou, M., Pallikarakis, A. and Migiros, G., 2015. Active faulting at the Corinth Canal based on surface observations, borehole data and paleoenvironmental interpretations. Passive rupture during the 1981 earthquake sequence?. *Geomorphology*, *237*, pp.65-78.

Peirano, A., Morri, C., Bianchi, C.N., Aguirre, J., Antonioli, F., Calzetta, G., Carobene, L., Mastronuzzi, G. and Orrù, P., 2004. The Mediterranean coral Cladocora caespitosa: a proxy for past climate fluctuations?. *Global and planetary Change*, *40*(1-2), pp.195-200.

Perissoratis, C., Piper, D.J.W. and Lykousis, V., 2000. Alternating marine and lacustrine sedimentation during late Quaternary in the Gulf of Corinth rift basin, central Greece. *Marine Geology*, *167*(3-4), pp.391-411.

Roberts, G.P., Houghton, S.L., Underwood, C., Papanikolaou, I., Cowie, P.A., van Calsteren, P., Wigley, T., Cooper, F.J. and McArthur, J.M., 2009. Localization of Quaternary slip rates in an active rift in 105 years: An example from central Greece constrained by 234U-230Th coral dates from uplifted paleoshorelines. *Journal of Geophysical Research: Solid Earth*, *114*(B10).

Robertson, J., Roberts, G.P., Iezzi, F., Meschis, M., Gheorghiu, D.M., Sahy, D., Bristow, C. and Sgambato, C., 2020. Distributed normal faulting in the tip zone of the South Alkyonides Fault System, Gulf of Corinth, constrained using 36Cl exposure dating of Late-Quaternary wave-cut platforms. *Journal of Structural Geology*, p.104063.

Rohling, E.J., Fenton, M.J.J.F., Jorissen, F.J., Bertrand, P., Ganssen, G. and Caulet, J.P., 1998. Magnitudes of sea-level lowstands of the past 500,000 years. *Nature*, *394*(6689), pp.162-165.

Siddall, M., Rohling, E.J., Almogi-Labin, A., Hemleben, C., Meischner, D., Schmelzer, I. and Smeed, D.A., 2003. Sea-level fluctuations during the last glacial cycle. *Nature*, *423*(6942), pp.853-858.

Sieh, K., Natawidjaja, D.H., Meltzner, A.J., Shen, C.C., Cheng, H., Li, K.S., Suwargadi, B.W., Galetzka, J., Philibosian, B. and Edwards, R.L., 2008. Earthquake supercycles inferred from sea-level changes recorded in the corals of west Sumatra. *Science*, *322*(5908), pp.1674-1678.

Shen, G.T. and Dunbar, R.B., 1995. Environmental controls on uranium in reef corals. *Geochimica et Cosmochimica Acta*, *59*(10), pp.2009-2024.

Soter, S., Blackwelder, P., Tziavos, C., Katsonopoulou, D., Hood, T. and Alvarez-Zarikian, C., 2001. Environmental analysis of cores from the Helike Delta, Gulf of Corinth, Greece. *Journal of Coastal Research*, pp.95-106. .

Turner, J.A., Leeder, M.R., Andrews, J.E., Rowe, P.J., Van Calsteren, P. and Thomas, L., 2010. Testing rival tectonic uplift models for the Lechaion Gulf in the Gulf of Corinth rift. *Journal of the Geological Society*, *167*(6), pp.1237-1250.

van Calsteren, P. and Thomas, L., 2006. Uranium-series dating applications in Natural Environmental Science. *Earth-Science Reviews*, *75*(1-4), pp.155-175.

Vita-Finzi, C., 1993. Evaluating late Quaternary uplift in Greece and Cyprus. *Geological Society, London, Special Publications*, *76*(1), pp.417-424.

Watkins, S.E., Whittaker, A.C., Bell, R.E., Brooke, S.A., Ganti, V., Gawthorpe, R.L., McNeill, L.C. and Nixon, C.W., 2020. Straight from the source's mouth: Controls on field-constrained sediment export across the entire active Corinth Rift, central Greece. *Basin Research*, *32*(6), pp.1600-1625.

Zunino, S., Pitacco, V., Mavrič, B., Orlando-Bonaca, M., Kružić, P. and Lipej, L., 2018. The ecology of the Mediterranean stony coral Cladocora caespitosa (Linnaeus, 1767) in the Gulf of Trieste (northern Adriatic Sea): a 30-year long story. *Marine Biology Research*, *14*(3), pp.307-320.