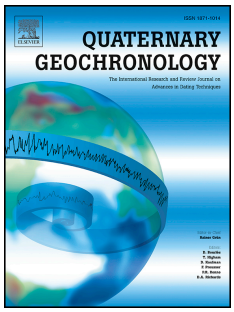
Accepted Manuscript



Uranium-thorium dating potential of the marine bivalve *Lithophaga lithophaga*

P.J. Rowe, J.A. Turner, J.E. Andrews, M.R. Leeder, P. van Calsteren, L. Thomas

PII: S1871-1014(15)30054-6

DOI: 10.1016/j.quageo.2015.08.003

Reference: QUAGEO 721

To appear in: *Quaternary Geochronology*

Received Date: 31 October 2014

Revised Date: 7 August 2015

Accepted Date: 23 August 2015

Please cite this article as: Rowe, P.J., Turner, J.A., Andrews, J.E., Leeder, M.R, van Calsteren, P., Thomas, L., Uranium-thorium dating potential of the marine bivalve *Lithophaga lithophaga*, *Quaternary Geochronology* (2015), doi: 10.1016/j.quageo.2015.08.003.

Uranium-thorium dating potential of the marine bivalve *Lithophaga lithophaga*

Rowe, P. J.[a]*, Turner, J. A.[a], Andrews, J. E.[a], Leeder, M. R[a], van Calsteren, P.[b], Thomas, L.[b]

[a] School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, UK.

***** corresponding author. E-mail address: p.rowe@uea.ac.uk Tel. +44 (0)1603592529

[b] OU-NERC U-Series Facility, Department of Earth Sciences, Faculty of Science, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK

Key words: Uranium-thorium dating; Lithophaga lithophaga; mollusc shells; Mediterranean; raised shorelines; uplift rates; isotope migration.

Abstract: Poor chronological control hampers efforts to constrain uplift event frequency in the Eastern Mediterranean Basin and develop regional tectonic models. Borings of the colonial marine mollusc *Lithophaga lithophaga* are commonly associated with uplifted Mediterranean shorelines and the suitability of its fossil shell for uranium-series dating is investigated to assess its potential for refining uplift chronologies. Living specimens contain very little uranium but Holocene fossils suggest rapid *post-mortem* uptake from a marine source. However, in common with many other mollusc species, Pleistocene samples show clear evidence of subsequent exchange with uranium from groundwater and although two out of eight samples returned ages compatible with their stratigraphic locations, these may be chance results given the compelling evidence for general open system behaviour. Detrital contamination appears not to be a significant problem in pre-Holocene samples. Open system modelling, using techniques developed to correct for alpha recoil effects in reef corals, shows that the recoil mechanism is inadequate to explain the magnitude of the isotopic alterations observed. Our results show that whilst uranium-series dating of Holocene *L. lithophaga* shells may be possible, Pleistocene specimens suffer from significant geochemical alteration and cannot be used to refine crustal uplift chronologies over longer timescales.

1. Introduction

The rate of Pleistocene crustal displacement in the Eastern Mediterranean–Aegean region remains poorly resolved because the timing of uplift events is uncertain due to a paucity of suitable dating material. This

lack of reliable chronologies has hindered construction of robust models that capture the tectonic complexities of the region and which might furnish insights into future seismic events. Uplifted palaeo-shorelines are excellent recorders of relative crustal displacement and here we investigate the uranium-thorium (U/Th) dating potential of *Lithophaga lithophaga*, a rock-boring marine bivalve that chemically excavates sub-horizontal boreholes in lithified carbonate substrates into which the shell is recessed (Morton and Scott, 1980). This species is indigenous to Mediterranean, Red Sea and Atlantic coasts (El-Menif et al., 2007), and its preferred habitat lies in a zone up to ~6 metres below contemporary sea level (Galinou-Mitsoudi and Sinis, 1997). Along uplifted coastlines the linear upper limit of a colony often coincides with marine notches (Fig 1a), defining palaeo-sea level to within about 0.5 m, the approximate tidal range in the Mediterranean. Bored holes sometimes contain preserved shells where degradation by encrusters and bioeroders in the littoral zone has been minimised by abrupt or rapid relative sea-level fall associated with co-seismic uplift. *L. lithophaga* shells have been radiocarbon dated (Evelpidou et al., 2012; Morhange et al., 2006; Pirazzoli et al., 1994; Stewart and VitaFinzi, 1996), but incorporation of old, radioactively dead, carbon into the shells from the limestone substrate significantly increases apparent ages (Shaw et al., 2010), and the ~40 ka upper limit of the method effectively restricts its use to the Holocene highstand. Dating these shells by U-series methods would significantly increase this time horizon and allow chronostratigraphic separation of many mid-late Pleistocene interglacial palaeoshorelines. This in turn would help resolve many tectonic, stratigraphic and palaeoclimatic ambiguities, allow uplift rates to be more accurately calculated and constrain tectonic models in those regions where datable material is available.

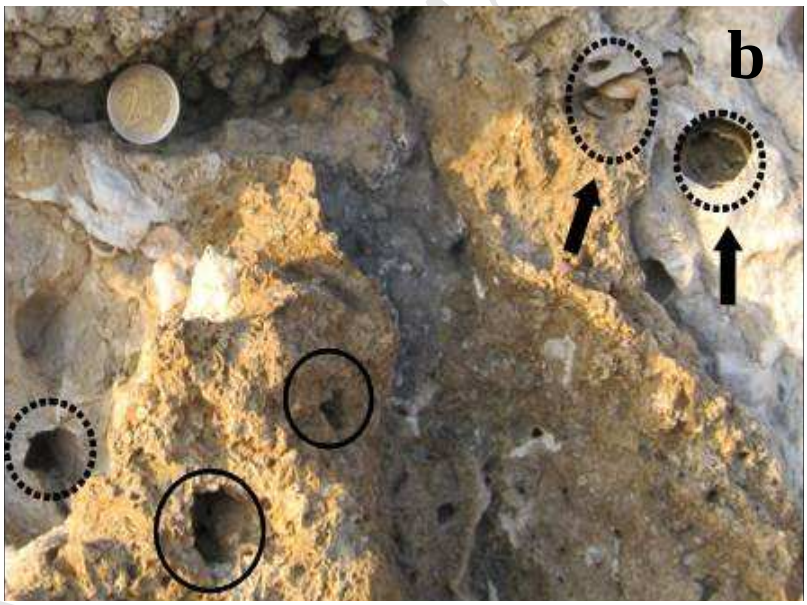


Fig 1(a). *L. Lithophaga* boreholes in limestone bedrock at the base of raised wave-cut notch 1.5 m above modern sea level, Agriliou Bay (Fig. 2) from which samples L5 and L 6 (Table 1) were collected. Notch is about 0.5 m in height (b) *L. lithophaga* borehole entrances in Holocene fossilferous calcarenitic sands which drape limestone bedrock (solid circles), and in the limestone bedrock (dashed circles). Preserved shells L4 and L7 (Table 1) in boreholes at Cape Heraion (Fig. 2) are arrowed. Coin for scale.

However, U-series dates from mollusc shells are widely regarded as unreliable since there is abundant evidence that they behave as geochemically open systems (Kaufman et al., 1971; Kaufman et al., 1996; McLaren and Rowe, 1996). *Post-mortem* burial in unconsolidated sediments, followed by sub-aerial exposure, encourages groundwater infiltration and consequent diffusion of uranium and its daughter radionuclides through the shells, possibly via organic pathways within the shell structure. Where shells are preserved under anhydrous conditions, (in arid climates, or within impermeable substrates), uranium mobility may be minimal and it might be possible to recover reliable ages (Causse et al., 1989; Causse et al., 2003; HillaireMarcel et al., 1996; Ivanovich et al., 1983). The highly unusual habitat occupied by *L. lithophaga* (i.e. recessed tightly in a confined space within a practically impermeable limestone substrate) might isolate fossil shells from later groundwater infiltration sufficiently to reduce isotopic mobilisation within the shells to negligible levels. Here we report and appraise U-series isotopic data from three modern (live-collected) and eleven fossil *L. lithophaga* shells that have been recovered from the rapidly uplifting shorelines of the Perachora Peninsular at the eastern end of the Gulf of Corinth, Greece (Fig. 2), the geology and stratigraphy of which have been previously described and discussed in detail (Andrews et al., 2007; Dia et al., 1997; Leeder et al., 2003; Leeder et al., 2005; Pirazzoli et al., 1994; Roberts et al., 2009; Turner et al., 2010). Uplift of ~0.2-0.3 mm a^{-1} since at least 240 ka has preserved evidence of Holocene and Pleistocene high sea level stands in the form of fossiliferous marine sediments forming constructional terraces, and of wave-cut notches which, when cut in limestone, are frequently bored by *L. lithophaga*. Four of the fossil *L. Lithophaga* samples are of Holocene age based on stratigraphy and radiocarbon dating of similar shells from the same localities (see below). The remaining seven are Pleistocene, with four inferred to be of MIS 5a or 5c age, two MIS 5e and one MIS 7 based on detailed stratigraphic mapping and U/Th dating of associated *Cladocora* coral stems. The locations from which the shells were recovered are detailed in Table 1 and shown on Figure 2. (Andrews et al., 2007; Dia et al., 1997; Leeder et al., 2003; Leeder et al., 2005; Pirazzoli et al., 1994; Roberts et al., 2009; Turner et al., 2010).

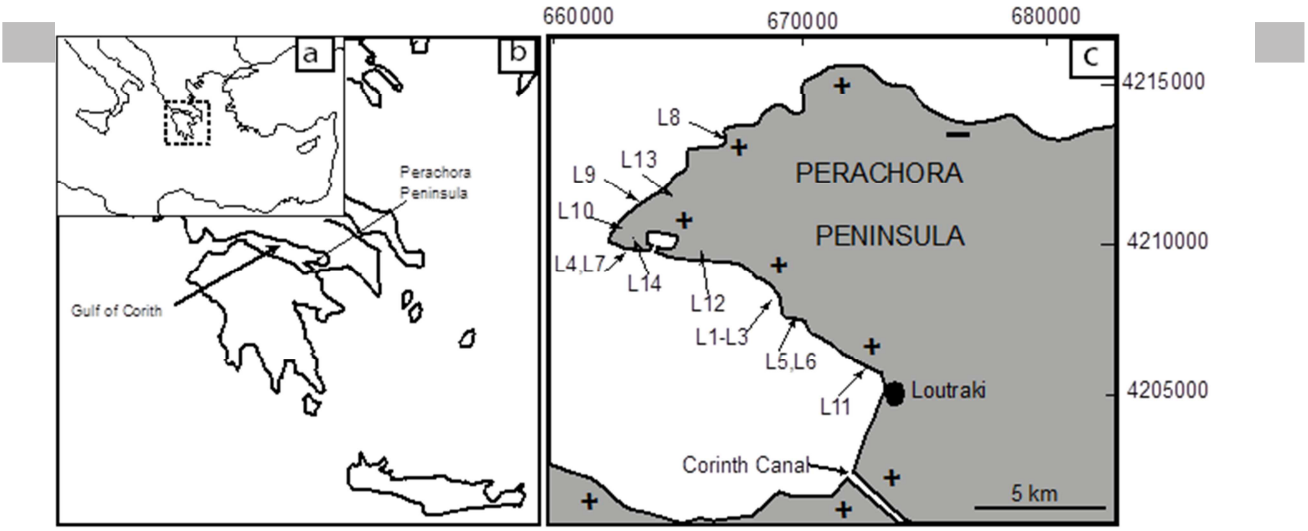


Fig 2. Location maps of (a) central Greece, (b) Gulf of Corinth and Perachora Peninsula, (c) *L. lithophaga* shell samples from raised marine shorelines (+) around the coast of the Perachora Peninsula. Grid reference is UTM zone 34S. See Table 1 for precise sample locations.

2. Materials and methods

Shells were removed from their boreholes using tweezers, penknives or chisels and were usually recovered as fragments. Each was cleaned by gentle scraping followed by etching through brief immersion in dilute hydrochloric acid then in a sonic bath of distilled water. *L. lithophaga* shells are typically 300-800 µm thick and in modern specimens the periostracum is underlain by a distinct layer of calcite ~100 µm thick, beneath which the inner part of the shell is composed of aragonite with nacreous texture (Fig. 3a), a bimineralic microstructure typical of Mytilids. In Holocene and older specimens the periostracum is not preserved due to oxidation. X-ray diffraction (XRD) and scanning electron microscopy (SEM) were carried out on representative shell fractions from the entire chronostratigraphic range of our samples, although not every dated shell could be analysed. These showed that the mineralogy of all our *L. lithophaga* shells, both modern and fossil, is ~85-90% aragonite and ~15-10% calcite, arranged in distinctive microstructural layers (Figs. 3a-d). These microstructural units, and the crystal ultrastructure within them, are well preserved in Holocene, MIS 5 and MIS 7 samples (Figs. 3a-d) demonstrating preservation of primary shell carbonate. SEM analysis showed no ultrastructural evidence for alteration and although the fossil skeletal aragonite has lost its nacreous lustre, it still comprises around 85-90% of the shell mineralogy. Alteration from lustrous nacre to a progressively flaky or chalky

texture is a well-known phenomenon that does not necessarily alter mineralogy (Hallam and O'Hara, 1962; Hudson, 1968).

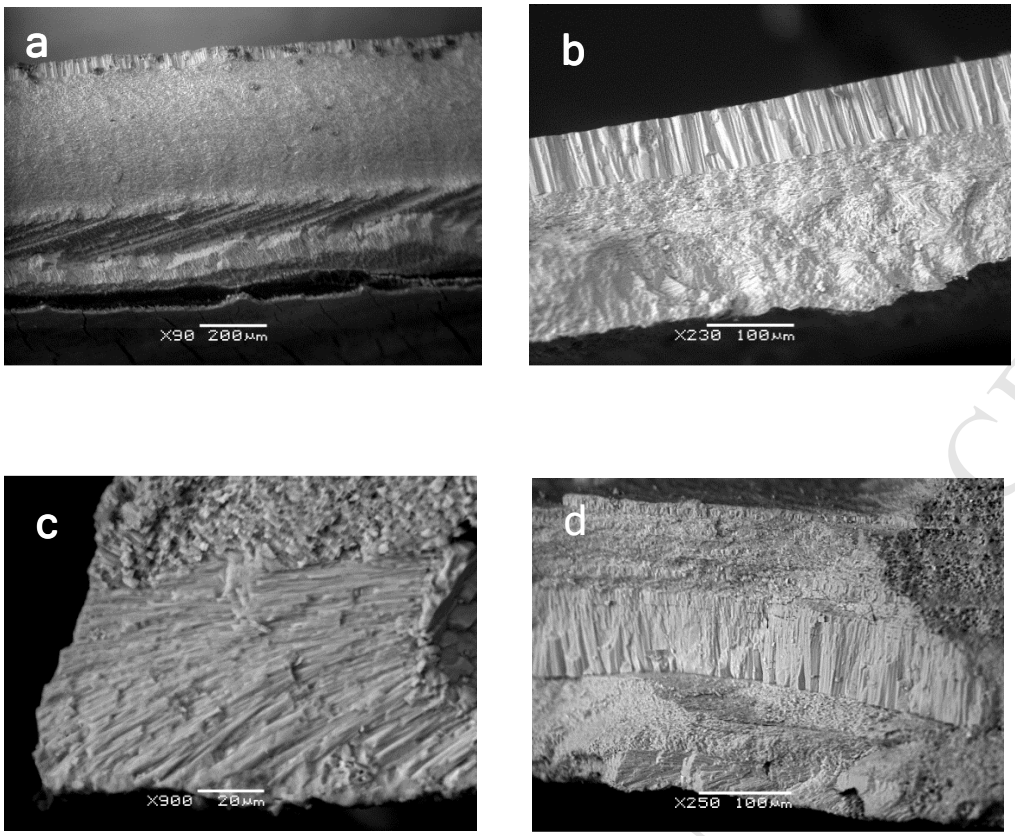


Fig. 3. SEM images of *L. lithophaga* shells taken on uncoated fracture surfaces under low vacuum on a JEOL JSM-5900. (a) modern shell (sample JT 051108-11a). The outer part of the shell is at the bottom of the image where the dark layers are part of the periostracum. A calcite layer with foliate structure, about 100 µm thick, overlies the periostracum, followed by aragonite nacre forming the bulk of the shell and finally a distinctive 50 µm wide prismatic aragonite layer on the inner margin; (b) fossil shell from MIS 5a/c sediments (JEA 11907-2). The outer part of the shell is at the bottom of the image. This image illustrates preservation of the distinctive 50 µm wide prismatic aragonite layer on the inner margin, identical to that in the modern sample. (c) fossil shell from MIS 5a/c sediments (JEA 11907-2). The outer part of the shell is at the bottom of the image. This image illustrates preservation of the foliate structured calcite layer, overlain by aragonite nacre. (d) fossil shell from MIS 7 sediments (JS 091106-2, not dated); despite its antiquity this shell contains well-preserved ultrastructure, including the foliate structured calcite layer (bottom centre of image) and a prominent prismatic aragonite layer (centre of image), itself overlain by more nacreous aragonite layers in this specimen.

U/Th dating followed standard methods which are described in detail elsewhere (Van Calsteren and Thomas, 2012). 300-500 mg samples were totally dissolved following spiking with a mixed $^{229}Th/^{236}U$ spike which was calibrated against gravimetric standards prepared from CRM112a for U and CRM3159 for Th. U and Th fractions were separated on 2 ml 1-X8 Biorad© anion exchange columns. U was loaded onto graphite coated Re filaments and analysed using a Finnigan MAT262 mass spectrometer with a retarding potential quadrupole and secondary electron multiplier. A dynamic peak switching routine was employed measuring $^{234}U/^{236}U$ and $^{235}U/^{236}U$. Th was measured using a standard bracketing approach on a Nu Plasma Multi-Collector ICPMS. Instrumental drift and mass-dependent fractionation were corrected for using TIMS calibrated laboratory standards which are close to the analytical characteristics of the samples. A well-characterised internal calcite powder standard, prepared from pure Iceland spar with an age of >1 Ma and in secular radioactive equilibrium, was analysed with the *L. lithophaga* samples to monitor the accuracy of the results. Since the shells are <1 mm thick, analysing different parts to assess isotopic variability was not generally possible, although replicate measurements were made on one shell.

3. Sample Stratigraphy and Age Control

Three modern (live) *L. lithophaga* were removed for analysis from a single large limestone block in Agriliou Bay on the southern Perachora peninsula from 0.5 m below mean sea level (samples L1-L3, Fig. 2, Table 1). Four Holocene shells were collected from limestone substrate at +1.5-3.0 m, two from Agriliou Bay and two from Cape Heraion, at the south-west tip of the peninsular (samples L4-L7, Figs. 1 and 2, Table 1). Radiocarbon dated *L. lithophaga* shells from the Holocene colonies at these localities gave calibrated ages of 6300 – 6415 yrs BP at +1.9 m in Agriliou Bay (Leeder, 2007), and 6320-6440 and 4440-4260 yrs BP at +3.1 m and +2.2 m respectively at Heraion (Pirazzoli et al., 1994). Age ranges incorporate 2 sigma errors and are corrected for global marine reservoir age (400 yrs) but not local reservoir age (53±85 yrs (Reimer and McCormac, 2002)). These ages are likely to be maxima since there is evidence that *L. lithophaga* shells contain a significant, but variable, amount of dead carbon derived from the substrate. Radiocarbon dates on museum specimens of *L. lithophaga* of known age are 900-

1400 years too old, and measured ages on Holocene uplifted fossil shells from western Crete exceed estimated age by 350-2800 years (Shaw et al., 2010). The precise contribution of dead carbon in the Cretan samples could not be determined accurately as some of the lithophagids may have expired long before uplift occurred.

The Pleistocene samples collected from uplifted shorelines are assigned to MIS 5a/5c, MIS 5e and MIS 7 highstands on the basis of U-series dating of corals and/or stratigraphic associations (Dia et al., 1997; Leeder et al., 2003; Leeder et al., 2005; Turner et al., 2010). One of the two MIS 5e shells (L12) is from a 23 m palaeoshoreline on Makrugoaz Ridge, comprising coraliferous sands and serpulid reefs. The MIS 5e age attribution is based on U-Th dates from associated coral stems (Leeder et al., 2005). The second MIS 5e sample (L13) is from +19 m within a shallow limestone cave on the north of the peninsular and it is correlated with shorelines dated to MIS 5e (elsewhere) and mapped along the north coast of the peninsular to the sample location (Leeder et al., 2003; Leeder et al., 2005). The single MIS 7 shell (L14) is from limestone bedrock on Cape Heraion at an elevation of 43 m which correlates with a MIS 7a terrace ~0.25km to the east, where corals have been U-Th dated to ~190 ka (Dia et al., 1997).

Whilst MIS 5e and 7 palaeoshorelines are well documented at altitudes of ~25 m and ~40 m respectively, the age of a well-defined shoreline at 8-12 m is more ambiguous. Since it is on an uplifting coastline and at a lower altitude than the MIS 5e palaeoshoreline it must be younger than that feature and the only pre-Holocene relative high sea-level stands during the intervening period occurred during MIS 5a and 5c. Direct dating evidence is lacking and the uncertainty on calculated uplift rates is too large to discriminate between the two possibilities and consequently it cannot be confidently attributed to either. The four lithophagid samples (L8-L11) associated with this shoreline are therefore assigned a generic age of MIS 5a/c.

.Sample code	UEA reference	Sample location (see Fig 2c), and elevation	Sample substrate	Control Age Reference	Confidence in Age
Shells live when collected					
L1	JT 03/05/08-2	Agriliou Bay -0.5 m asl 34S 669089 m E 4208440 m	Basement limestone boulder	N/A	Strong
L2	JT 05/11/08-11a	Agriliou Bay -0.5 m asl 34S 669089 m E 4208440 m	Basement limestone boulder	N/A	Strong
L3	JT 05/11/08-12a	Agriliou Bay -0.5 m 34S 669089 m E 4208440 m	Basement limestone boulder	N/A	Strong
Holocene shells					
L4	JS 21/4/07-3	Heraion 3.0 m asl 34S 662464 m E 4210550 m	Basement limestone	Adjacent to shells ^{14}C dated to 6.3 ka (Pirazzoli *et al* 1994)	Strong
L5	JS 12/11/05-5	Agriliou Bay 1.5 m asl 34S 669220 m E 4207994 m	Basement limestone	Adjacent to shells ^{14}C dated to 6.4 ka (Leeder *et al* 2007)	Strong
L6	JT 03/05/08-4	Agriliou Bay 1.5 m asl 34S 669220 m E 4207994 m	Basement limestone	Adjacent to shells ^{14}C dated to 6.4 ka(Leeder *et al* 2007)	Strong
L7	JS 21 /04/07-4	Heraion 3.0 m asl 34S 662464 E 4210550 m	Basement limestone	Adjacent to shells ^{14}C dated to 6.3 ka (Pirazzoli *et al* 1994)	Strong
MIS 5a/c shells					
L8	JEA 11907-2	Laka-Zeza Bay 15 m asl 34S 668032 m E 4214389 m	Lithified calcarentic, fossiliferous sands	Association with raised shoreline dated by extrapolation of average local uplift rates in (Leeder *et al* 2003, 2005)	Weak
L9	JS 05/11/06-2	Gorge Point 4 m asl 34S 663711 m E 4211564 m	Lithified red algae marine drape	Stratigraphic association with raised shoreline dated by U/Th on corals to MIS 5e (Leeder *et al* 2003)	Moderate-strong
L10	JS 08/11/06-12	N side Cape Heraion 5 m asl 34S 662578 m E 4210708 m	Lithified calcarentic, fossiliferous sands	Stratigraphic association with raised shoreline dated by U/Th on corals to MIS 5e (Leeder *et al* 2003)	Strong
L11	JS 10/11/06-2	West Loutraki bay 3.0 m asl 34S 672035 m E 4206040 m	Lithified calcarentic, fossiliferous sands	Extrapolation of average local uplift rates in (Leeder *et al* 2003, 2005)	weak
MIS 5e shells					
L12 L12a	JEA 11907-3 JEA 11907-3b	Makrugoaz Ridge 23 m asl 34S 665141 m E 4209990 m	Lithified coraliferous sands	Adjacent to corals U/Th dated to MIS 5e (Leeder *et al* 2003)	Strong
L13	JS 08/11/06-9	Funnel Cave 19 m asl 34S 665411 m E 4212684 m	Cave in limestone	Stratigraphic association with raised shoreline dated by U/Th on corals to MIS 5e (Leeder *et al 2003,* 2005)	Strong
MIS 7 shells					
L14	JS 09/11/06-3	Cape Heraion 43 m asl 34S 662581 m E 4210611 m	Limestone	Stratigraphic association with raised shoreline dated by U/Th on corals to MIS 7 (Leeder *et al* 2005)	Strong

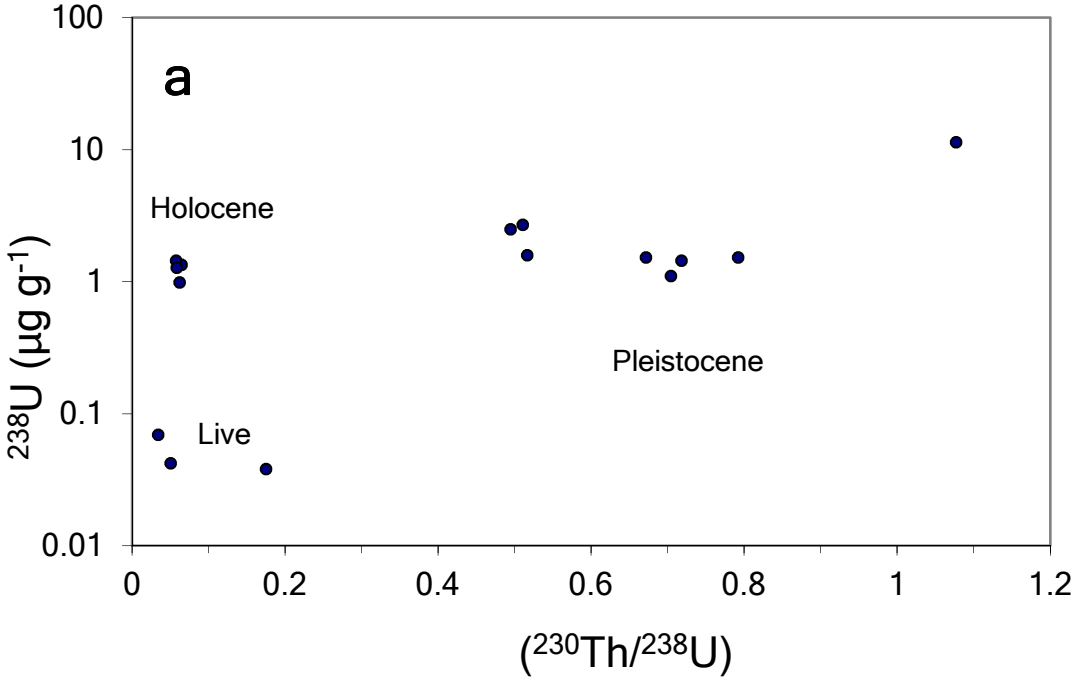
Table 1. *L. lithophaga* shell sample collection data: sample codes and location grid reference (UTM and local site name), elevation above mean sea level (asl), substrate type, and reference for the geological age allocations with degree of confidence in each.

4. Results:

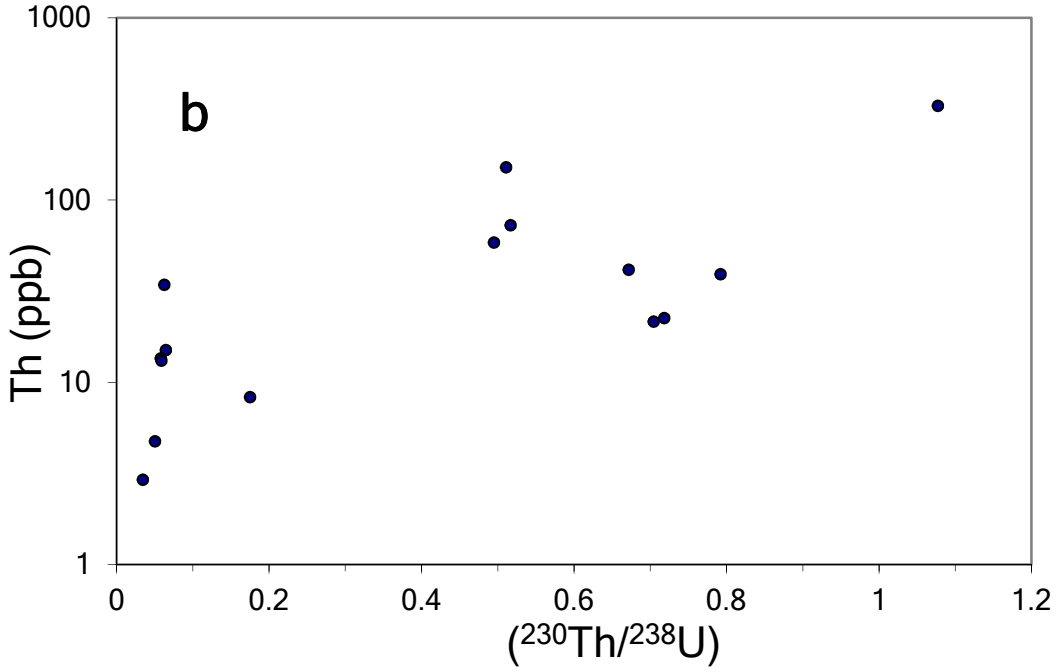
The U-series data for the *L. lithophaga* shells are shown in Table 2. Modern shells all have very low U and Th contents (0.04-0.07 ppm and 2.5-8.5 ppb respectively). In contrast, the Holocene and Pleistocene shells contain significantly higher U and Th concentrations, generally in the range 1-2 $\mu g\ g^{-1}$ and 10-80 ppb respectively, although one sample, L8 (5a/c), records 11.3 $\mu g\ g^{-1}$ and 328 ppb. The U and Th concentrations are both much higher than usually found in fossil molluscs, U levels being more typical of corals and Th an order of magnitude higher than most of the values reported in the literature. It is therefore clear that virtually all the uranium and thorium uptake has occurred *post mortem*. A plot of U concentration vs ($^{230}Th/^{238}U$) (Fig. 4a) shows that five of the seven Pleistocene shells have U concentrations similar to Holocene specimens, (averages 1.76 and 1.26 ppm respectively). This suggests that U uptake may occur relatively early rather than as a late event or continuous process, as has been previously suggested (Ivanovich et al., 1983; Kaufman et al., 1996), although the possibility that these five shells once possessed higher levels of U, some of which has subsequently been lost, cannot be excluded. The difference between Pleistocene and Holocene Th concentrations is more marked (Fig. 4b) with averages of 58 (±45) ppb (excluding L8) and 19 ppb respectively. However, there is almost a factor of three difference between Th concentrations in the two sub-samples of L12 so distribution of Th within the samples is probably very heterogeneous. A plot of U vs Th concentrations in the fossil samples (Fig. 4c) show a strong correlation ($R^2 = 0.91$, $p<0.05$), but this is strongly influenced by two samples with particularly high Th content (L8 and L12a). If L8 is omitted $R^2 = 0.64$ ($p<0.01$) and if both L8 and L12a are omitted $R^2 = 0.32$ ($p<0.01$). The lower correlations may suggest differing uptake patterns for U and Th in most of the samples, or later differential geochemical modification, or both.

Shell No.	Sample i.d.	^{238}U ($\mu g\ g^{-1}$)	^{232}Th (ppb)	($^{230}Th/^{232}Th$)	($^{230}Th/^{238}U$)	($^{234}U/^{238}U$)	Calculated Age (ka)	Model Age (ka)	Allocated Age
	Live Shells								
L1	JT 03/05/08 -2	0.042	4.7±0.9	1.50±0.08	0.0508(9)	1.1428(53)	4.96 ± 0.22	6.08	Modern
L2	JT 05/11/08 -11a	0.038	8.3±1.5	2.59±0.12	0.1754(23)	1.1482(50)	18.04 ± 0.60	15.36	Modern
L3	JT 05/11/08-12a	0.069	2.9±0.5	2.91±0.19	0.0348(10)	1.1395(57)	3.38 ± 0.22	8.33	Modern
	Holocene Shells								
L4	JS 21/4/07-3	1.338(04)	15.0±2.7	19.02±0.81	0.0651(6)	1.1481(57)	6.36 ± 0.13	5.45	Holocene
L5	JS12/11/05 -5	0.983(02)	34.3±6.2	5.73±0.24	0.0628(5)	1.1363(46)	6.21 ± 0.11	9.50	Holocene
L6	JS 21 /4/07-4	1.436(05)	13.5±2.4	19.94±0.83	0.0582(5)	1.1481(49)	5.67 ± 0.11	4.85	Holocene
L7	JT03/05/08-4	1.266(05)	13.1±2.4	17.48±0.73	0.0589(5)	1.1428(55)	5.77 ± 0.10	6.77	Holocene
	Pleistocene Shells								**MIS**
L8	JEA 11907 -2	11.306(46)	328.7±59.4	113.44±4.75	1.0775(85)	1.1684(62)	238.73 ± 12.50	158.97	5a/c
L9	JS 05/11/06-2	1.518(06)	39.1±7.1	94.24±3.94	0.7925(65)	1.1148(66)	131.05 ± 4.03	123.54	5a/c
L10	JS 08/11/06-12	1.520(06)	41.4±7.5	75.42±3.13	0.6719(53)	1.1181(59)	98.12 ± 2.56	95.07	5a/c
L11	JS10/11/06-2	1.101(04)	21.5±3.9	110.49±4.66	0.7046(59)	1.1307(66)	103.80 ± 2.96	93.28	5a/c
L12	JEA 11907-3	2.487(12)	58.3±10.5	64.69±2.71	0.4951(41)	1.1072(80)	64.00 ± 1.49	71.74	5e
L12a	JEA 11907-3b	2.678(13)	150.7±27.2	27.80±1.14	0.5111(39)	1.1021(75)	67.26 ± 1.44	77.08	5e
L13	JS 08/11/06-9	1.436(06)	22.5±4.1	140.62±5.85	0.7187(57)	1.1332(72)	106.83 ± 2.87	94.39	5e
L14	JS 09/11/06-3	1.580(07)	72.6±13.1	34.49±1.46	0.5170(45)	1.1128(64)	67.36 ± 1.68	71.95	7

Table 2. U-series data for *L. lithophaga* shells. Figures in parenthesis are uncertainties in the last digit(s) of the relevant parameters. All errors are 2σ. U concentration errors for modern shells are <0.001. Model ages are calculated using the algorithms of (Thompson et al., 2003). See text for discussion of allocated ages. Isotope ratios are activity ratios.


a
Holocene
Pleistocene
Live
^{238}U (µg g^{-1})
(^{230}Th/^{238}U)
100
10
1
0.1
0.01
0
0.2
0.4
0.6
0.8
1
1.2

211


b
Th (ppb)
(^{230}Th/^{238}U)
1000
100
10
1
0
0.2
0.4
0.6
0.8
1
1.2

212

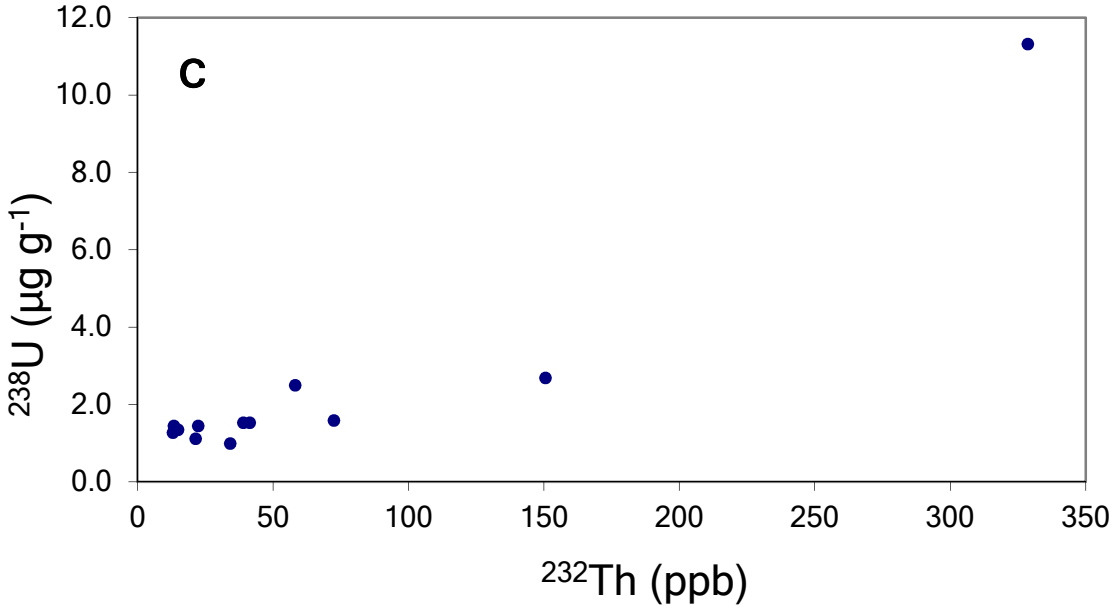


Fig. 4. (a) U concentration and (b) Th concentration plotted vs. (^{230}Th/^{238}U). Note log scales on vertical axes. (c) U vs. Th concentrations for fossil samples. Excluding the two outliers R^2 = 0.32 (see text).

Six of the of seven (^{234}U/^{238}U) ratios in modern and Holocene shells lie between 1.136 and 1.149, close to the modern seawater value of ~1.147 (Stirling and Andersen, 2009), and on or near the seawater evolution curve when plotted vs. (^{230}Th/^{238}U) (Fig. 5). Pleistocene fossils by contrast show considerable scatter and do not follow the seawater (^{234}U/^{238}U) trajectory.

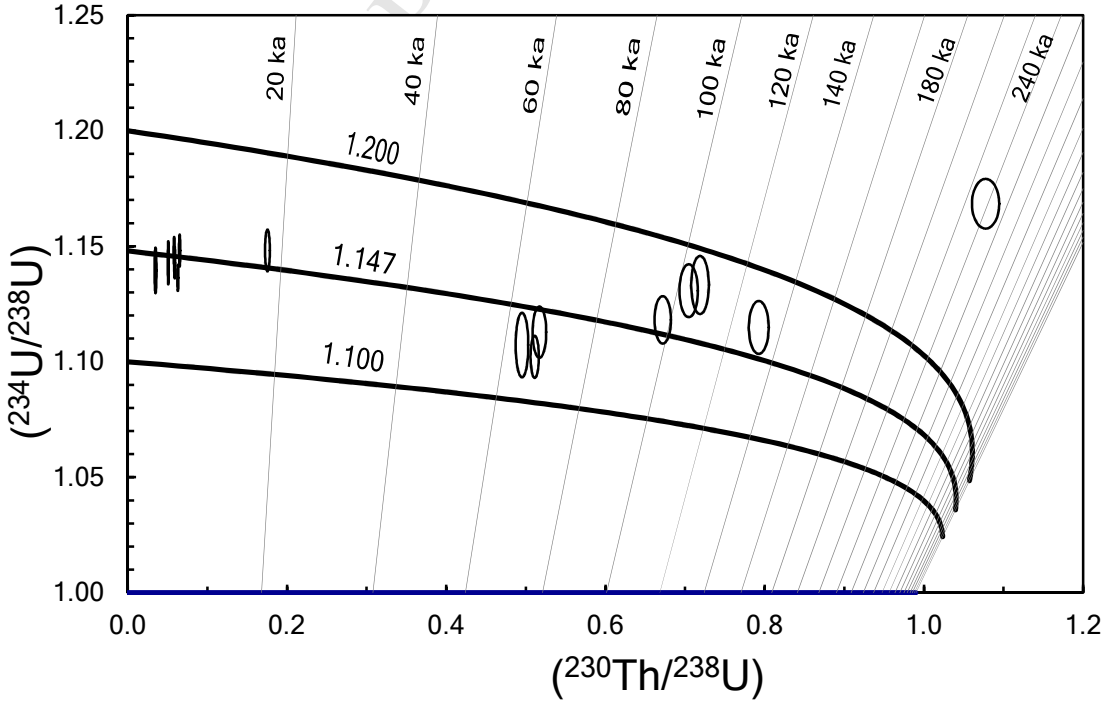


Fig. 5. Plot of all *L. lithophaga* data in ($^{234}U/^{238}U$) vs.($^{230}Th/^{238}U$) space. Pleistocene samples do not lie along the marine ($^{234}U/^{238}U$) evolution line (1.147).

Figure 6 shows measured ($^{230}Th/^{238}U$) ratios plotted against expected values derived from estimated shell ages determined from radiocarbon analyses (Holocene shells) or stratigraphic mapping (Pleistocene shells). The modern lithophagid shells yield Holocene or Late Pleistocene ages (3.3-18.0 ka) rather than zero ages due to slight but measurable thorium contamination (~2-10 ppb, Table 2). Despite their boreholes being in close proximity, they also have differing ($^{230}Th/^{232}Th$) ratios (1.5-2.9). Holocene specimens yield ages that cluster between 5.67 and 6.36 ka, very similar to their radiocarbon dates (4260-6890 yrs BP). However, the low ($^{230}Th/^{232}Th$) ratios indicate significant thorium contamination, (three ratios between 17 and 20 and one of 5.7), and therefore the calculated ages are likely to be overestimates. The likely range of corrected ages calculated using the ($^{230}Th/^{232}Th$) detrital ratios from the modern samples (1.5-2.9) are shown in Table 3. True ages probably lie around 5.0 ka, although the shells are unlikely to all be exactly the same age.

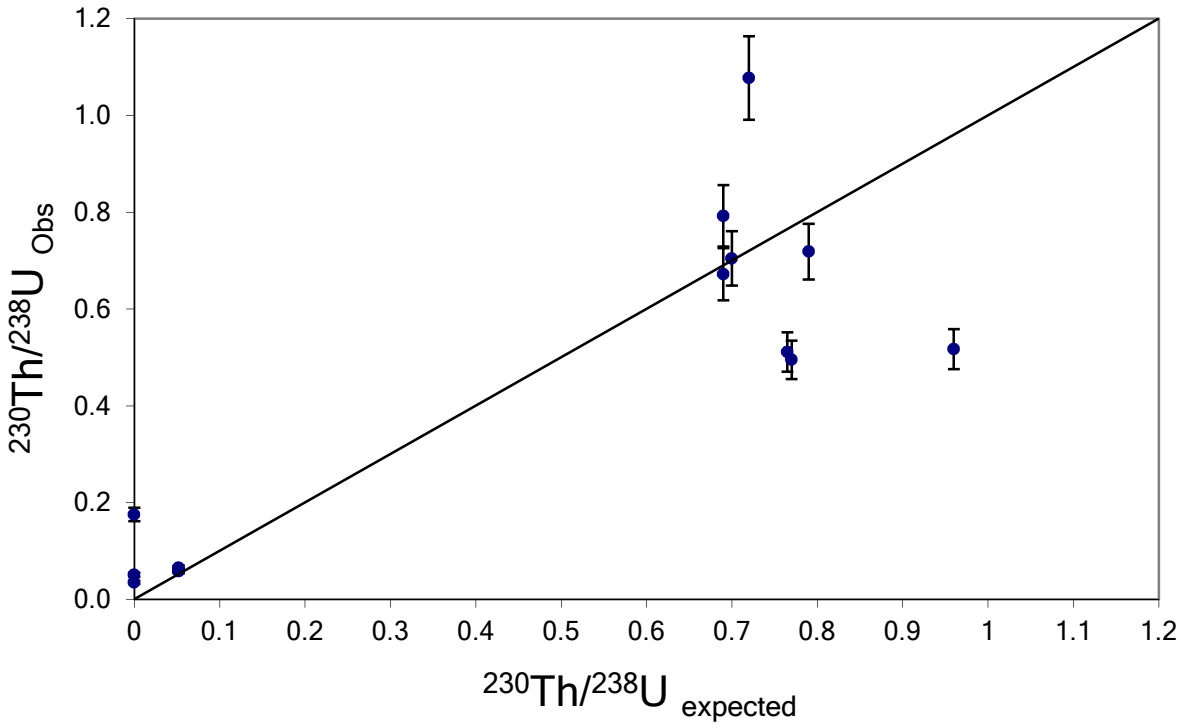


Fig. 6. Observed ($^{230}Th/^{238}U$) ratios vs ($^{230}Th/^{238}U$) ratios expected, based on U-series coral dates and stratigraphic evidence. Samples attributed to MIS 5a/c are assumed to be ~100 ka. Two of these lie within error of the 1:1 line.

Apparent ages of Pleistocene specimens range from ~64 ka to ~239 ka. Only two shells (L10 and L11 of MIS 5a/c age) yield dates compatible with their expected ages (98.1 and 103.8 ka respectively) assuming their true age is ~100 ka (MIS 5c). Two further MIS 5a/c shells (L8 and L9) produced ages that are much too old, 238.7 ka and 131.0 ka respectively. Although their ($^{230}Th/^{232}Th$) ratios are sub-optimal (~100), they are sufficiently high that age corrections for any feasible ($^{230}Th/^{232}Th$) detrital ratio would not exceed the 2σ age error limits and cannot explain the discrepancies between the measured and geological ages of these two samples. The older shells (L12 and L13, MIS 5e; L14, MIS 7) have apparent ages that are significantly too young (63.99 and 67.3 ka, 106.8 ka, and 67.4 ka respectively). The period 60-70 ka coincides with low global sea level, clearly demonstrating the unreliability of the dates.

Since the four 5a/c samples (L8-L11) can be considered to be approximately coeval in age, isochrons were constructed in ($^{230}Th/^{232}Th$) vs. ($^{238}U/^{232}Th$) and ($^{234}U/^{232}Th$) vs. ($^{238}U/^{232}Th$) space (not shown) to establish whether a common age could be derived. However, there was no significant correlation between ($^{230}Th/^{232}Th$) and ($^{238}U/^{232}Th$) and no meaningful ($^{230}Th/^{238}U$) value could be calculated, although there was a strong linear relationship between ($^{234}U/^{232}Th$) and ($^{238}U/^{232}Th$), with a regression line slope of 1.1075.

5. Discussion

Live Samples: Low U and Th concentrations (typically 50 ppb and 5 ppb respectively) in the modern shells relative to fossil samples (>1 µg g^{-1} and 10-350 ppb) demonstrate that these elements are only sparingly absorbed during life. The ($^{234}U/^{238}U$) ratios lie within error of the modern seawater value suggesting that uranium is absorbed from seawater during feeding rather than from the host limestone during boring. The presence of trace amounts of detrital thorium in the (zero age) modern shells is responsible for their calculated apparent ages of 4.96, 18.04 and 3.38 ka. Detrital thorium is a common

and serious problem when dating sub-aerial deposits by U-series methods although if the initial ($^{230}Th/^{232}Th$) activity ratio is known, as here, it is possible to correct for the excess thorium and calculate a true age. Usually, however, this ratio is unknown and a value of ~0.8 is often adopted, being the value derived from a contaminant having the average upper crustal $^{232}Th/^{238}U$ atomic ratio of ~4, (Wedepohl, 1995), and ^{230}Th in secular equilibrium with ^{238}U. However, the ($^{230}Th/^{232}Th$) ratios of 1.5-2.9 observed here correspond to Th/U atomic ratios in the contaminant of 1.1–2.1 rather than ~4, probably because the thorium derives from carbonate sediments which are rich in uranium (and consequently ^{230}Th) and relatively poor in ^{232}Th. Clearly it is inappropriate to use average crustal U/Th values to correct contaminated dates in this type of carbonate environment. The variation in initial ($^{230}Th/^{232}Th$) occurs despite the three live samples having been collected in close proximity from the same limestone block. Interestingly, the values encompass the empirical ratio of 1.7±0.7 reported by (Kaufman, 1993) from a range of carbonate materials around the globe. The lack of a single well constrained detrital ratio in our samples presumably reflects a diversity of local detrital sources.

Holocene samples: The four Holocene samples were recovered from limestone bedrock. They all have U levels more than an order of magnitude higher than modern shells (typically ~1 $\mu g\ g^{-1}$) and similar to Pleistocene samples (see below), suggesting that uptake occurs fairly rapidly (within a few thousand years) of the death of the organism. *Post-mortem* U uptake would not materially affect age estimates for uplifted shorelines provided it occurs shortly before or after relative sea level fall whilst the shells are either still submerged or remain in the swash zone, since the shells will remain close to contemporary sea level during uptake. Three of the four samples have ($^{234}U/^{238}U$) ratios that lie within error of seawater values (1.147) with one only outside the range at 1.136±0.005. These data suggest that significant uranium is indeed taken up from seawater whilst the shells remain in the swash zone following shoreline uplift, or following death and prior to emergence. Th concentrations are 2-10 times higher than modern samples but typically two to five times lower than Pleistocene samples. These relative values might mean that U uptake is a rapid event whereas Th uptake is a slower, more continuous, process. Alternatively, U uptake may be a semi-continuous process that eventually reverses following long exposure to sub-aerial

Pleistocene weathering, resulting in some uranium loss (such that concentrations fall towards Holocene values) but Th remains immobile within the shell.

Sample	(^{230}Th/^{232}Th)	Calculated Age (ka)	Corrected Age Range (ka)
L4	19.02±0.81	6.36±0.13	5.35-5.85
L5	5.73±0.24	6.21±0.11	3.00-4.60
L6	19.94±0.83	5.67±0.11	4.80-5.20
L7	17.48±0.73	5.77±0.10	4.80-5.25

Table 3. Detritally corrected ages for Holocene shells. Values for authigenic (^{230}Th/^{238}U) activity ratios are calculated using the equation: $(^{230}Th/^{238}U)_{auth} = (^{230}Th/^{238}U)_{meas} - (^{232}Th/^{238}U)_{meas} \times R_0.e^{-\lambda 230t}$ where R_0 is the initial (^{230}Th/^{232}Th) activity ratio, in this case the range of observed (^{230}Th/^{232}Th) values in the live-collected specimens.

The true ages of the Holocene lithophagids are broadly constrained by radiocarbon dates on shells from the same colony (4260-6890 calendar years BP, (Leeder, 2007; Pirazzoli et al., 1994)). However, if the radiocarbon dates were dead-carbon corrected, they would probably be significantly younger, possibly by 1000 years or so (Shaw et al., 2010), and a range of 3300 – 5900 years BP is likely to be more realistic. U/Th ages using measured (^{230}Th/^{232}Th) values from the modern samples to correct for detrital contamination lie in the range 3.0 – 5.9 ka (Table 3), compatible with that estimate. This level of agreement supports the inferred timing of the uplift event, bearing in mind that the shells may differ in age by many hundreds of years and possibly a few thousand years. U/Th dating may therefore be a useful dating tool for Holocene samples, particularly if future better understanding of initial (^{230}Th/^{232}Th) ratios in modern lithophagids were to allow more accurate correction of detritally contaminated samples. In this regard the method may be preferable to ^{14}C dating where a similar problem, that of dead carbon contamination, may be more difficult to characterise.

Pleistocene Samples: U concentrations in five of the seven Pleistocene samples lie between 1.10 and 1.58 µg g^{-1}, similar to Holocene values, whilst two are significantly higher. L12 and 12a have 2.48 and 2.68 µg

317 g^{-1} respectively and L8 has uranium levels almost an order of magnitude higher at 11.3 µg g^{-1}. Th
318 concentrations are generally >20<100 ppb except for L12a (151 ppb) and L8 (329 ppb). L8 also has the
319 highest ($^{230}Th/^{238}U$) ratio (1.0775), but overall there is no correlation between U or Th content and
320 ($^{230}Th/^{238}U$) (Fig. 4a, b). The absence of a positive relationship between U concentration and apparent age
321 might be construed as support for a geochemical model of early uranium uptake from seawater with
322 negligible subsequent migration (i.e. closed system behaviour). However, the ($^{234}U/^{238}U$) ratios do not lie
323 along the seawater evolution line (Fig. 5), implying that either the U in these shells has a non-marine
324 source, or the samples have not remained closed systems, or both. Since the evidence from modern and
325 Holocene samples strongly indicates an initial marine origin for the uranium, the most likely explanation
326 for the observed deviations is open system behaviour. Five ($^{234}U/^{238}U$) ratios lie above the marine
327 evolution line and two below. Those below (L12 and L14) have not simply experienced preferential ^{234}U
328 removal from damaged lattice sites during sub-aerial leaching of marine uranium from the shells as this
329 would cause apparent ages to be overestimated rather than underestimated as observed here. Both have
330 apparent ages between 60 ka and 70 ka (a global marine lowstand) whereas one sample is actually of MIS
331 5e age and the other MIS 7. Probably uranium has been derived, at least partly, from meteoric water with
332 ($^{234}U/^{238}U$) ratios lower than marine, and taken up either quasi-continuously or late in the shells' history
333 to achieve the observed ages and ($^{234}U/^{238}U$) ratios.
334
335 The actual ages derived for the Pleistocene shells will of course depend on the timing of U uptake
336 (whether from marine or meteoric sources) and its subsequent geochemical behaviour. Early uptake
337 followed by closed system conditions will produce accurate ages, continuous or late uptake,
338 underestimated ages, and early U uptake followed by later loss, overestimated ages. Here three ages are
339 too young (L12, L13, L14), two are compatible with the probable true (MIS 5c) age (L10, L11) and two
340 are too old (L8, L9). The two samples that yield plausible (MIS 5c) ages have calculated $(^{234}U/^{238}U)_{init}$
341 ratios of 1.1566±0.0059 and 1.1763±0.0066 respectively. Whilst 1.1566 is quite close to a marine
342 signature, 1.1763 is compatible only with meteoric water values and it is likely that one or both of these
343 shells have experienced geochemical disturbance. So although it is possible that the apparent accuracy of

the L10 age is real and the shell has only suffered minor isotopic alteration, probably it has experienced significant alteration and yields a plausible age only by chance. Two samples (L8 and L9) are older than their geological ages, the former by an entire glacial-interglacial cycle. This sample has by far the highest U and Th content (11 µg g^{-1} and 329 ppb respectively) which may reflect high early uptake of uranium and thorium followed by relatively recent uranium loss. This would account for the high ($^{230}Th/^{232}Th$) ratio of 113. L9 may also have suffered recent uranium loss since detrital thorium levels are insufficient ($^{230}Th/^{232}Th = 94$) to account for the upward age displacement of 30-50 ka to ~131 ka. It may be significant that the MIS 5e and MIS 7 sample ages are much younger than expected whilst two of the MIS 5a/c ages are much older, although this pattern is difficult to interpret.

There is a strong inverse correlation ($R^2 = 0.71$, $p<0.05$) between uranium concentrations and ($^{234}U/^{238}U$) for six of the seven shells (Fig. 7) and the y-axis intercept of 1.146 is very close to the uranium isotope composition of seawater. The negative slope indicates that any non-marine uranium taken up by the shells must have a ($^{234}U/^{238}U$) ratio below that of seawater. We currently have no uranium isotope data from local groundwaters, but alpha spectrometric analysis of a local vadose flowstone, formed on limestone bedrock and dated to 27.7+/-1.3 ka (1σ), showed $(^{234}U/^{238}U)_{init}$ to be 1.032+/-0.024; how representative this might be of local groundwaters over a glacial-interglacial timescale is unknown. The intersection of the regression line with the $(^{234}U/^{238}U)_{init}$ value of the dated flowstone occurs at a uranium content of ~7 µg g^{-1} (Fig. 7). If 1.032 is broadly representative of ($^{234}U/^{238}U$) ratios in groundwaters on the Perachora Peninsula through the mid-late Pleistocene, then the regression line approximates a mixing line between two uranium end members, seawater and groundwater. The local geology is very complex and highly tectonised and is dominated by Mesozoic and Neogene limestones and flysch deposits, with basic rocks and sandstones and phyllites occurring along the southwest coastal margin (IGME 1984). The whole-rock ($^{234}U/^{238}U$) is likely to be close to 1.00 and thus a groundwater ($^{234}U/^{238}U$) value of 1.032 would be compatible with a derivation from rocks that have been heavily leached over a prolonged period. One sample (L8) does not fit this pattern, having a ($^{234}U/^{238}U$) value of 1.168±0.006 and U concentration of 11.3 µg g^{-1}. These values might reflect a different geological origin for the U, or uptake might have

occurred at a time when higher U concentrations (enriched in ^{234}U due to recoil effects) had accumulated in the surface rocks due to enhanced weathering and limited removal by leaching.

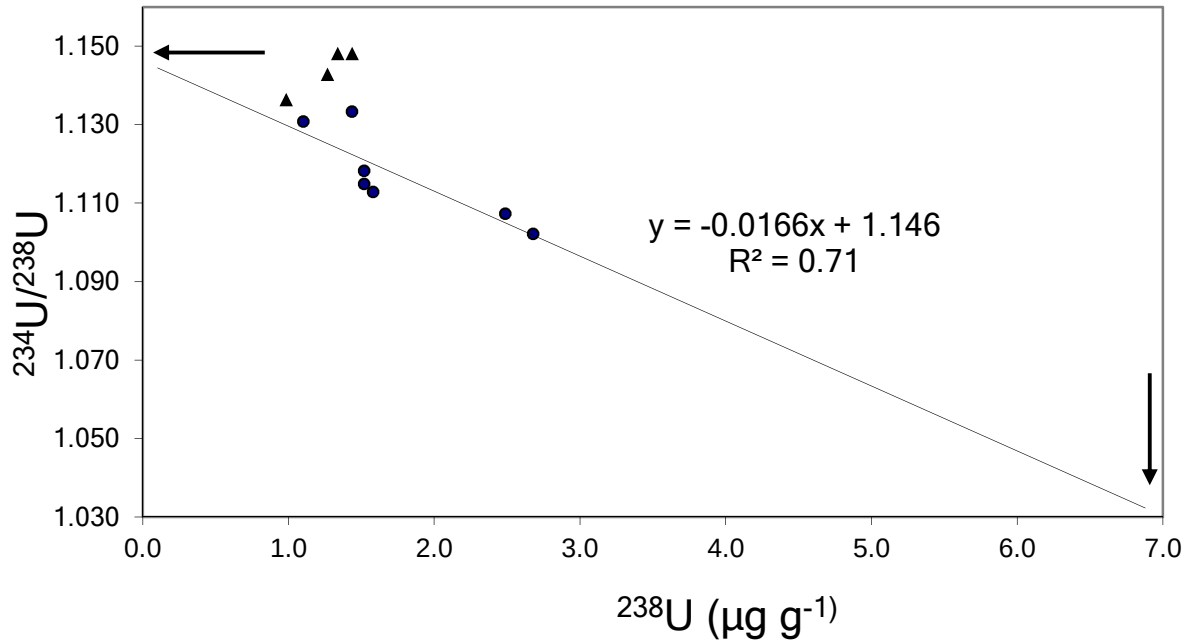


Fig. 7. ($^{234}U/^{238}U$) vs. U concentration for Pleistocene *L. lithophaga* shells (filled circles), excluding sample L8. These data may lie along a uranium mixing line between seawater (upper left arrow) and meteoric water (lower right arrow) end-members characterised by differing ($^{234}U/^{238}U$) signatures (see text). Solid triangles are Holocene shells which have uranium isotopic ratios close to the seawater value.

6. Open System Modelling

There is a strong positive correlation ($R^2 = 0.82$, $p<0.01$) between measured ($^{234}U/^{238}U$) and ($^{230}Th/^{238}U$) in the Pleistocene *L. lithophaga* shells (Fig. 8). This relationship is often seen in diagenetically altered reef corals, although the slopes in those cases are usually much steeper. U-series analyses of Pleistocene corals have shown that they frequently experience *post-mortem* isotopic disturbance and despite careful sample screening and selection, ($^{234}U/^{238}U$) ratios often lie significantly above (occasionally below) the marine evolution curve, the discrepancy increasing with age (Gallup et al., 1994; Stirling et al., 1995). Marine uranium isotope values have changed little during the Mid-Late Pleistocene (Henderson, 2002) and alpha-recoil processes, which are predictable and allow micro-scale redistribution of daughter isotopes from recoil-damaged lattice sites, have been suggested as a probable causal mechanism

(Henderson and Slowey, 2000; Henderson et al., 2001). Such isotopic redistributions lead to positive correlations between ($^{230}Th/^{238}U$) and ($^{234}U/^{238}U$) and cause divergence between calculated and true ages that increase with time (Stirling et al., 2001). Data from coeval samples often form quasi-linear arrays above the ($^{234}U/^{238}U$) evolution curve and numerical models have been developed to correct for recoil effects and retrieve true ages from affected samples (Thompson et al., 2003; Villemant and Feuillet, 2003). An empirical approach was adopted by (Scholz and Mangini, 2006; Scholz et al., 2004) which also allows for U uptake and loss, and they assumed that coeval subsamples of individual corals gain different amounts of uranium but with similar ($^{234}U/^{238}U$) ratios. ($^{230}Th/^{238}U$) and ($^{234}U/^{238}U$) are then positively correlated and a fitted regression (mixing) line through the data intersects the ($^{234}U/^{238}U$) marine evolution curve at the true ($^{230}Th/^{238}U$) ratio, thus providing a corrected age for the suite of samples. (Frank et al., 2006) reviewed these methods and found that both numerical models gave almost identical corrected ages for samples that had experienced only slight diagenetic alteration, although the Thompson et al. (2003) model performed rather better for older samples that were significantly altered. However, they were unable to test the approach of (Scholz et al., 2004) since their data lacked significant correlation between ($^{230}Th/^{238}U$) and ($^{234}U/^{238}U$).

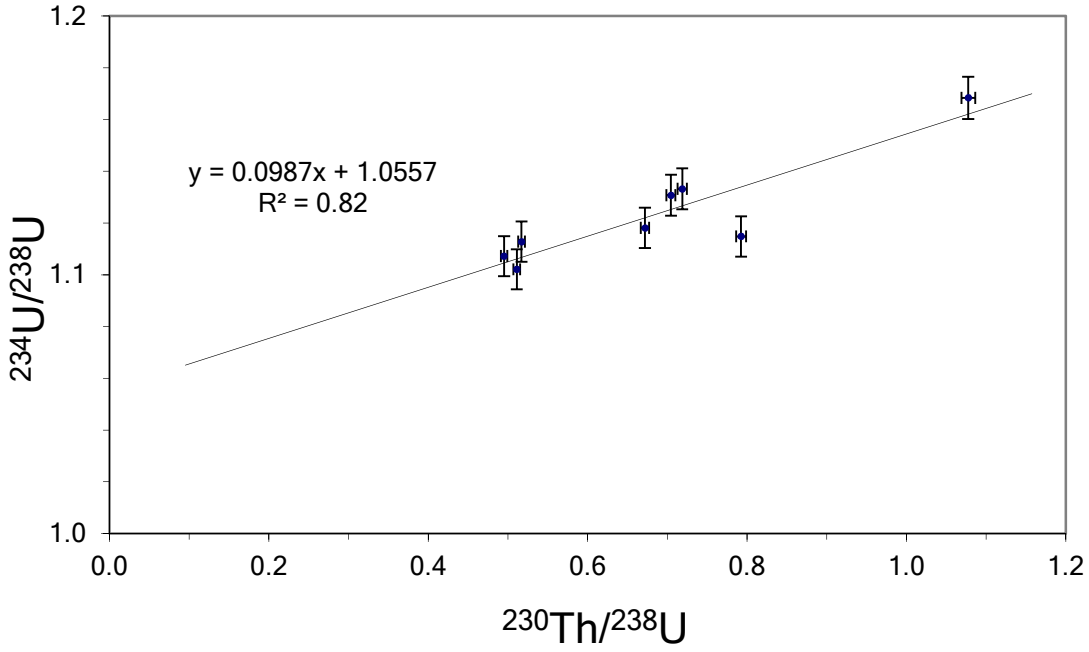
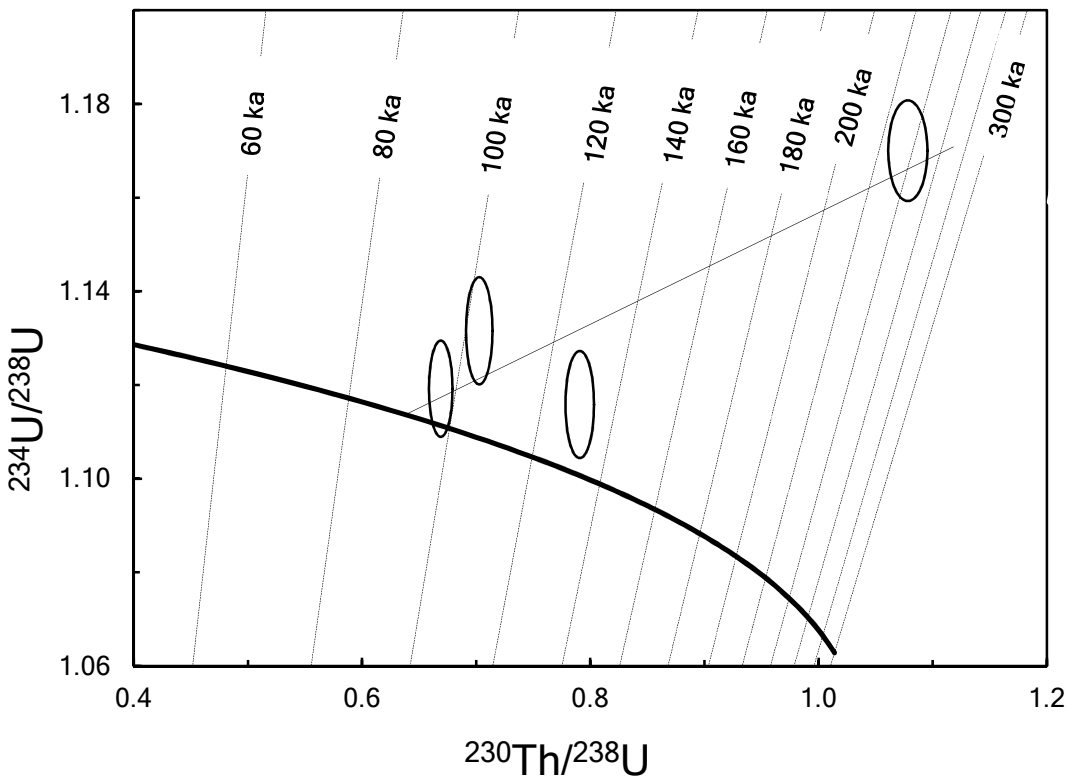


Fig. 8. ($^{234}U/^{238}U$) vs. ($^{230}Th/^{238}U$) for Pleistocene *L. lithophaga* shells. The strong correlation is indicative of *post-mortem* isotopic disturbance. A similar relationship is frequently observed in MIS 5e reef corals.

Unlike the coral samples, the lithophagid shells are neither precisely coeval nor spatially compact. However, to assess whether alpha recoil processes might have played a significant role in disturbing the shell ages we applied one of the models (Thompson et al., 2003) to our data. Recalculated ages are shown in Table 2**.** It is clear that these "corrected" ages do not correspond with the stratigraphic ages, although some are shifted in the right direction, and that, as expected, alpha recoil does not fully account for the observed isotopic disturbance. The four lithophagid samples of MIS 5a/c age are likely to be of similar age (i.e. broadly coeval), and their ($^{230}Th/^{238}U$) and ($^{234}U/^{238}U$) ratios are positively correlated ($R^2 = 0.79$). Following the approach of (Scholz et al., 2004), a regression line through these data intersects the marine curve at 90.3 ka (Fig. 9), which lies within the correct interglacial complex (MIS 5); however it corresponds to marine lowstand MIS 5b and is therefore implausible. The two MIS 5e samples plot far apart (Fig. 5) and could not form part of a linear array intercepting the marine curve near 120 ka. It therefore appears that the Pleistocene shells have experienced diagenetic processes more complex than alpha recoil or simple U uptake and subsequent loss, and that existing models are unable to retrieve meaningful ages from the current data.



425
426
427 Fig. 9. Plot of MIS 5a/c *L. lithophaga* data in ($^{234}U/^{238}U$) vs. ($^{230}Th/^{238}U$) space. The regression line
428 intercepts the ($^{234}U/^{238}U$) marine evolution curve at 90.3 ka (MIS 5b).
429
430 **7. Conclusions**
431 *L. lithophaga* shells show remarkably good mineralogical preservation over glacial-interglacial timescales
432 with little or no petrographic or XRD evidence of alteration in specimens as old as ~200 ka. U-series data
433 suggest that it may be possible to date emergent Holocene shells by the U/Th method, although
434 significant age correction is necessary because of detrital contamination. Successful correction depends
435 upon using realistic estimates of U/Th ratios in the contaminants rather than average crustal values which
436 are inappropriate for carbonate-dominated environments. U-series dating may, therefore, prove to be a
437 useful tool for constraining the age of uplifted Holocene shorelines in the Mediterranean. Despite their
438 almost pristine appearance, the evidence from our field area suggests that Pleistocene shells cannot be
439 reliably dated. They show unequivocal evidence of open system behaviour, there is little consistency in
440 isotope patterns between samples and in the absence of detailed understanding of the diagenetic processes
441 involved, correcting for the effects of isotopic disturbance is not currently possible. Such disturbance is
442 probably subject to many process controls, perhaps, *inter alia*, decay of intra-shell organic matter or

availability of transport pathways along mineralogical boundaries. The rate and extent of such isotopic turnover may be at least partially controlled by micro-environmental factors related to substrate weathering, aspect, slope angles and rainfall runoff. The evidence presented here shows that *L. lithophaga* boreholes apparently provide insufficient protection from meteoric waters for the shells to maintain closed-system conditions over prolonged periods of time (10^4-10^5 years). It remains possible that particularly sheltered borehole sites might contain geochemically closed-system shells but this has yet to be demonstrated. Since regular winter rainfall is part of the Mediterranean climatic regime, it seems likely that similar results could be expected from other parts of the basin. *L. lithophaga* shells, like most other mollusc shells and some *Cladacora* sp. corals in the Eastern Mediterranean, exhibit complex open system behaviour with respect to U-series isotopes, which precludes their use in constructing reliable chronologies for Mid-Late Quaternary tectonic and climatic events.

Acknowledgements: We gratefully acknowledge funding provided by NERC Grant IP-1143-1109 and thank Dr. W.G. Thompson for providing the spreadsheet for his open-system model. The manuscript was improved by the comments of an anonymous reviewer.

References

Andrews, J.E., Portman, C., Rowe, P.J., Leeder, M.R., and Kramers, J.D., 2007, Sub-orbital sea-level change in early MIS 5e: New evidence from the Gulf of Corinth, Greece: Earth and Planetary Science Letters, v. 259, p. 457-468.

Causse, C., Coque, R., Fontes, J.C., Gasse, F., Gibert, E., Benouezdou, H., and Zouari, K., 1989, 2 High-Levels of Continental Waters in the Southern Tunisian Chotts at About 90 and 150 Ka: Geology, v. 17, p. 922-925.

Causse, C., Ghaleb, B., Chkir, N., Zouari, K., Ben Ouezdou, H., and Mamou, A., 2003, Humidity changes in southern Tunisia during the Late Pleistocene inferred from U-Th dating of mollusc: Applied Geochemistry, v. 18, p. 1691-1703.

Dia, A.N., Cohen, A.S., O'Nions, R.K., and Jackson, J.A., 1997, Rates of uplift investigated through Th-230 dating in the Gulf of Corinth (Greece) (vol 138, pg 171, 1997): Chemical Geology, v. 143, p. 263-263.

El-Menif, N.T., Kefi, F.J., Ramdani, M., Flower, R., and Boumaiza, M., 2007, Habitat and associated fauna of Lithophaga lithophaga (LinnÃ© 1758) in the Bay of Bizerta (Tunisia): Journal of Shellfish Research, v. 26, p. 569-574.

Evelpidou, N., Vassilopoulos, A., and Pirazzoli, P.A., 2012, Holocene emergence in Euboea island (Greece): Marine Geology, v. 295, p. 14-19.

Frank, N., Turpin, L., Cabioch, G., Blamart, D., Tressens-Fedou, M., Colin, C., and Jean-Baptiste, P., 2006, Open system U-series ages of corals from a subsiding reef in New Caledonia: Implications for sea level changes, and subsidence rate: Earth and Planetary Science Letters, v. 249, p. 274-289.

Galinou-Mitsoudi, S., and Sinis, A.I., 1997, Population dynamics of the date mussel, Lithophaga lithophaga (L., 1758) (Bivalvia : Mytilidae), in the Evoikos Gulf (Greece): Helgolander Meeresuntersuchungen, v. 51, p. 137-154.

Gallup, C.D., Edwards, R.L., and Johnson, R.G., 1994, The Timing of High Sea Levels over the Past 200,000 Years: Science, v. 263, p. 796-800.

Hallam, A., and O'Hara, M.J., 1962, Aragonitic fossils in the lower carboniferous of Scotland: Nature, v. 195, p. 273-274.

Henderson, G.M., 2002, Seawater (U-234/U-238) during the last 800 thousand years: Earth and Planetary Science Letters, v. 199, p. 97-110.

Henderson, G.M., and Slowey, N.C., 2000, Evidence from U-Th dating against Northern Hemisphere forcing of the penultimate deglaciation: Nature, v. 404, p. 61-66.

Henderson, G.M., Slowey, N.C., and Fleisher, M.Q., 2001, U-Th dating of carbonate platform and slope sediments: Geochimica Et Cosmochimica Acta, v. 65, p. 2757-2770.

HillaireMarcel, C., Gariepy, C., Ghaleb, B., Goy, J.L., Zazo, C., and Barcelo, J.C., 1996, U-series measurements in Tyrrhenian deposits from mallorca - Further evidence for two last-interglacial high sea levels in the Balearic Islands: Quaternary Science Reviews, v. 15, p. 53-62.

Hudson, J.D., 1968, The microstructure and mineralogy of the shell of a Jurassic Mytilid (Bivalvia) Palaeontology, v. 11, p. 163-182.

Ivanovich, M., Vitafinzi, C., and Hennig, G.J., 1983, Uranium-Series Dating of Mollusks from Uplifted Holocene Beaches in the Persian Gulf: Nature, v. 302, p. 408-410.

Kaufman, A., 1993, An Evaluation of Several Methods for Determining Th-230/U Ages in Impure Carbonates: Geochimica Et Cosmochimica Acta, v. 57, p. 2303-2317.

Kaufman, A., Broecker, W.S., Ku, T.L., and Thurber, D.L., 1971, Status of U-Series Methods of Mollusk Dating: Geochimica Et Cosmochimica Acta, v. 35, p. 1155-&.

Kaufman, A., Ghaleb, B., Wehmiller, J.F., and HillaireMarcel, C., 1996, Uranium concentration and isotope ratio profiles within Mercenaria shells: Geochronological implications: Geochimica Et Cosmochimica Acta, v. 60, p. 3735-3746.

Leeder, M.R., Andrews, J. E., Collier, R. E., Gawthorpe, R. L., McNeill, L. C., Portman, C., Rowe, P. J., 2007, The Gulf of Corinth: Harpenden, Terra 164 p.

Leeder, M.R., McNeill, L.C., Collier, R.E.L., 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, v. 30.

Leeder, M.R., Portman, C., Andrews, J.E., Collier, R.E.L.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, v. 162, p. 549-561.

McLaren, S.J., and Rowe, P.J., 1996, The reliability of uranium-series mollusc dates from the western Mediterranean basin: Quaternary Science Reviews, v. 15, p. 709-717.

Morhange, C., Marriner, N., Laborel, J., Todesco, M., and Oberlin, C., 2006, Rapid sea-level movements and noneruptive crustal deformations in the Phlegrean Fields caldera, Italy: Geology, v. 34, p. 93-96.

Morton, B., and Scott, P.J.B., 1980, Morphological and Functional Specializations of the Shell, Musculature and Pallial Glands in the Lithophaginae (Mollusca, Bivalvia): Journal of Zoology, v. 192, p. 179-203.

Pirazzoli, P.A., Stiros, S.C., Arnold, M., Laborel, J., Laboreldeguen, F., and Papageorgiou, S., 1994, Episodic Uplift Deduced from Holocene Shorelines in the Perachora Peninsula, Corinth Area, Greece: Tectonophysics, v. 229, p. 201-209.

Reimer, P.J., and McCormac, F.G., 2002, Marine radiocarbon reservoir corrections for the Mediterranean and Aegean Seas: Radiocarbon, v. 44, p. 159-166.

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 10(5) years: An example from central Greece constrained by U-234-Th-230 coral dates from uplifted paleoshorelines: Journal of Geophysical Research-Solid Earth, v. 114.

Scholz, D., and Mangini, A., 2006, Estimating the uncertainty of coral isochron U-Th ages: Quaternary Geochronology, v. 1, p. 279-288.

Scholz, D., Mangini, A., and Felis, T., 2004, U-series dating of diagenetically altered fossil reef corals: Earth and Planetary Science Letters, v. 218, p. 163-178.

Shaw, B., Jackson, J.A., Higham, T.F.G., England, P.C., and Thomas, A.L., 2010, Radiometric dates of uplifted marine fauna in Greece: Implications for the interpretation of recent earthquake and tectonic histories using lithophagid dates: Earth and Planetary Science Letters, v. 297, p. 395-404.

Stewart, I., and VitaFinzi, C., 1996, Coastal uplift on active normal faults: The Eliki Fault, Greece: Geophysical Research Letters, v. 23, p. 1853-1856.

Stirling, C.H., and Andersen, M.B., 2009, Uranium-series dating of fossil coral reefs: Extending the sea-level record beyond the last glacial cycle: Earth and Planetary Science Letters, v. 284, p. 269-283.

Stirling, C.H., Esat, T.M., Lambeck, K., McCulloch, M.T., Blake, S.G., Lee, D.C., and Halliday, A.N., 2001, Orbital forcing of the marine isotope stage 9 interglacial: Science, v. 291, p. 290-293.

Stirling, C.H., Esat, T.M., Mcculloch, M.T., and Lambeck, K., 1995, High-Precision U-Series Dating of Corals from Western-Australia and Implications for the Timing and Duration of the Last Interglacial: Earth and Planetary Science Letters, v. 135, p. 115-130.

Thompson, W.G., Spiegelman, M.W., Goldstein, S.L., and Speed, R.C., 2003, An open-system model for U-series age determinations of fossil corals: Earth and Planetary Science Letters, v. 210, p. 365-381.

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, v. 167, p. 1237-1249.

Van Calsteren, P., and Thomas, L., 2012, Quantitation of protactinium, 231Pa in abyssal carbonate: Journal of Analytical Atomic Spectrometry, v. 27, p. 952-956.

Villemant, B., and Feuillet, N., 2003, Dating open systems by the U-238-U-234-Th-230 method: application to Quaternary reef terraces: Earth and Planetary Science Letters, v. 210, p. 105-118.

Wedepohl, K.H., 1995, The Composition of the Continental-Crust: Geochimica Et Cosmochimica Acta, v. 59, p. 1217-1232.

Highlights

- Uranium-thorium methods are used for the first time to date the boring marine mollusc *Lithophaga lithophaga*
- Uranium is taken up by the shells early *post mortem* from a marine source
- Later uranium isotope mobility interferes with accurate age determination
- Holocene specimens of *L. lithophaga* can probably be succesfully dated
- Pleistocene specimens cannot be succesfully dated