Radiometric dates of uplifted marine fauna in Greece

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Radiometric dates of uplifted marine fauna in Greece: implications for the interpretation of recent earthquake and tectonic histories

B. Shaw, Jackson, J., Higham, T., England, P., Thomas, A.

1   Abstract

In AD 365 a great $(M_w > 8)$ earthquake lifted up western Crete, exposing a shoreline encrusted by marine organisms, and up to 10 m of marine substrate beneath it. Radiocarbon ages determined for corals and bryozoans exposed between the paleo-shoreline and present sea level are consistent, within measurement error, with each other and with the date of the earthquake. But radiocarbon ages determined for the boring bivalve *Lithophaga lithophaga* found on the same substrate are at least 400 years, and up to 2000 years, older than the date of the earthquake that lifted them above sea level. These observations reveal two important effects that limit the use of radiocarbon lithophagid ages in tectonic and paleoseismological studies. The first is that the exceptional preservation potential of lithophagids allows them to remain intact and *in situ* long after natural death, while the substrate continues to be colonized until eventual uplift. The second, which we confirm with radiocarbon analysis of museum specimens of known age, is the incorporation of old (^{14}C-free) carbon into lithophagid shells from the limestone host rock into which the lithophagids bored. The two effects are both significant in Crete and central Greece, and can cause the radiocarbon lithophagid ages to be up to 2,000 years older than the uplift event which exposed them. Understanding these effects is important because lithophagids are far more abundantly preserved, and used to date uplift, than most other ma-

rine organisms. This study shows that they can rarely be used to distinguish uplift events, or date them to better than 1000 years, or even to distinguish whether observed uplift occurred in a single or in multiple events. After taking account of these uncertainties, the ages of the lithophagids are, however, consistent with the hypothesis that the highest prominent marine notches and exposed lithophagid holes within a few metres of sea-level in Greece formed when sea-level became relatively stable ~6,000 years ago, following rapid rise after the last glacial maximum.

2 Introduction

Although sea-level is rarely stable for long periods, its well-understood behaviour in the late Quaternary has allowed its use in countless studies of active tectonic processes and, in particular, its relative stability in the late Holocene has led to its widespread use as a datum in the investigation of past earthquakes in coastal regions (e.g. Wallace 1986; Yeats et al. 1996). These uses of sea-level as a datum are well illustrated in Greece, one of the fastest-deforming continental regions on Earth (McKenzie, 1978; McClusky, 2000), where uplift of the coastline is seen both in the footwalls of active normal faults in the Aegean Sea (e.g. Jackson et al. 1982; Armijo et al. 1996) and in the hanging wall of the subduction zone between the Aegean and Mediterranean (e.g. Laborel et al. 1979; Thommeret et al. 1981b; Pirazzoli et al. 1996). The rates of uplift in these circumstances are estimated either by the correlation of uplifted marine terrace sequences with the Late Quaternary sea-level curve (e.g. Armijo et al. 1996; De Martini et al. 2004; McNeill and Collier 2004) or, on a more recent time-scale, by the direct dating of uplifted marine organisms by radiometric methods (e.g. Laborel and Laborel-Deguen 1994; Laborel et al. 1979; Papageorgiou et al. 1993; Pirazzoli et al. 1996). The second of these techniques is the focus of this paper, which is concerned with factors that limit the

use and resolution of such radiometric dates, particularly for paleoseismological purposes (i.e. the association of particular uplift observations with particular historical earthquakes), and which have hitherto been little appreciated or understood.

This study arose from a forensic investigation of the great ($M_W > 8$) earthquake of AD 365 in the eastern Mediterranean by Shaw et al. (2008). This earthquake had long been suspected as the cause of a tilting of the coastline of SW Crete, uplifting a paleo-shoreline to a height of up to ~10 m (Pirazzoli, 1986; Pirazzoli et al., 1996; Stiros and Drakos, 2006). In an attempt to confirm that this uplift really occurred in a single event, rather than progressively over a long period, Shaw et al. (2008) obtained radiocarbon dates on uplifted marine organisms between the uplifted paleo-shoreline and modern sea level. They found that corals and bryozoans all gave radiocarbon ages consistent with uplift in a large historical earthquake in AD 365 (within errors, and after conversion from radiocarbon years to calendar years). But they also obtained 14 radiocarbon dates on uplifted *Lithophaga lithophaga*, a boring mollusc, all of which were substantially older than AD 365 (by up to 2,000 years, even allowing for errors), and which exhibited a much less consistent set of ages than the coral and bryozoan dates.

Lithophagids are widespread and abundant in the Mediterranean and Aegean Seas (Galinou-Mitsoudi and Sinis, 1995), and are frequently preserved in uplifted coastlines; much more so than corals and bryozoans. They are consequently much used to estimate uplift rates, and the discrepancy between their dates and those of corals and bryozoans revealed by Shaw et al. (2008) is therefore a serious concern, raising the question of the limits to which their ages can be used to constrain uplift rates or the timing of particular uplift events.

In this study we demonstrate the importance of two effects for the interpretation of radiometric dates obtained for such marine organisms. The first, indicated by the sequence of biological colonization of the marine substrate, is that the hard parts

of organisms can remain within the substrate for long periods after death, so their ages may not date the uplift event itself. The second effect is the incorporation of host-rock carbon into the shells of the lithophagids, which causes radiocarbon ages to be artificially old. We quantify these effects using radiocarbon and U-Th dates on samples from Crete, and radiocarbon dates of museum specimens whose age of collection and death are known. While lithophagid ages remain a valuable means of estimating average uplift rates over thousands of years, the age offsets of up to 2000 years that we demonstrate here make it unlikely that such ages can be used to reveal details of the uplift history. We illustrate these effects by considering Holocene rates of vertical movement in the extensional graben systems of the Gulfs of Corinth and Evia in central Greece.

3 Data

The central arguments of this paper relate to radiocarbon dates obtained from uplifted marine organisms in the western part of the island of Crete, which lies above the Hellenic subduction zone. A prominent paleo-shoreline fringes the coast of western Crete, reaching a maximum elevation of 10 m above present-day sea-level (Spratt 1865 and Fig. 1b). The samples discussed in this section were collected by Shaw et al. (2008) at a range of elevations between present-day sea level and this paleo-shoreline, and include corals (*Stenocyathus vermiformus, Caryophyllida (sp.)* and *Balanophyllia regia*), bryozoans (*Myriapora truncata*), and lithophagids (*Lithophaga lithophaga*).

Radiocarbon ages for these samples were determined in the Research Laboratory for Archaeology and the History of Art (RLAHA) in Oxford using standard techniques. The basis of the radiocarbon dating technique is widely known (Bronk Ramsey, 2008) and is extensively used for age determination of geological and archae-

ological carbonaceous materials between ∼55,000 BP and today. A correction is required, when dating marine organisms, to allow valid comparison of results with samples in equilibrium with atmospheric and terrestrial carbon reservoirs. There is a delay in the exchange of carbon between the atmosphere and ocean, but the most important influence is the mixing of surface waters with ^{14}C-depleted carbon from the deep ocean (Mangerud, 1972). On average, the modelled difference between the ^{14}C activity of the world ocean reservoir and the terrestrial reservoir is 400 ^{14}C years. Using the INTCAL marine calibration dataset (Hughen et al., 2004) and suitable software, it is possible to calibrate radiocarbon ages and thereby correct for the reservoir effect. The marine calibration curve is modelled upon the terrestrial calibration using a simple box diffusion model (Stuiver et al., 1986). Specific work in the Mediterranean area is reported by Siani et al. (2000) and Reimer and McCormac (2002). The data are summarised on the marine reservoir database (www.calib.org) and by Reimer and Reimer (2001). We calculated a value of 53±43 yr to account for the local reservoir offset from the modelled world ocean, using known-age data from the eastern Mediterranean, and this was used in the calibration of radiocarbon ages in this paper. The results of these analyses for the samples of Shaw et al. (2008) are displayed in Fig. 1 and Table 1.

In earlier studies of this uplifted shoreline, marine organisms (mostly encrusting algae and not corals, bryozoans or lithophagids) were collected at a number of locations close to the top of the paleo-shoreline and were radiocarbon-dated, largely by conventional (non-AMS) methods (Thommeret et al., 1981b,a; Laborel et al., 1979; Pirazzoli et al., 1982; Kelletat and Zimmermann, 1991; Pirazzoli and Thommeret, 1977). These measurements, which were recalibrated by Price et al. (2002) in consistency with the dates reported here, are also displayed in Fig. 1. The youngest calibrated ages, obtained from the encrusting algae (Thommeret et al., 1981b,a; Laborel et al., 1979; Pirazzoli et al., 1982; Kelletat and Zimmermann, 1991; Pirazzoli and

Thommeret, 1977), lie within ~200 years of AD 365, the date of a well-documented very large historical earthquake (Thommeret et al., 1981b; Pirazzoli et al., 1996; Ambraseys et al., 1995), consistent with the suggestion that at least the upper part of the exposed marine substrate below the paleo-shoreline was lifted up during that event.

In their more recent study, Shaw et al. (2008) found that 11 out of their thirteen new radiocarbon ages for corals and bryozons bracket AD 365 within their 2σ error bounds, and because the samples covered almost all of the range between present sea level and the paleo-shoreline (Fig. 1, Table 1), they concluded that *all* of the observed uplift occurred in a single event in AD 365.

Additional confirmation of the date of death of the corals comes from U/Th dating. Three of the coral samples were split into two pieces; one half was sent for radiocarbon dating, and the other half was dated using U/Th methods. In spite of a high initial Th concentration (probably due to incorporation of siliceous mud in the carbonate skeleton) and consequently relatively large error bounds, the U/Th ages were consistent with the radiocarbon ages, confirming that the radiocarbon ages obtained from the corals and bryozoans accurately record the date of death of the organisms (Fig. 2 and Table 2).

4   Causes of discrepent lithophagid ages

Shaw et al. (2008) also collected 14 samples of *Lithophaga lithophaga* which had been preserved in their boreholes between the top of the uplifted shoreline and present-day sea level (blue bars in Fig. 1a, blue dots in Fig. 1b, Table 1). *Lithophaga lithophaga* (Linnaeus, 1758) is a species of marine bivalve belonging to the mussel family (Mytilidae), which bores into calcareous substrates using acid secreted from its pallial gland (Jaccarini and Bannister, 1968; Yonge, 1955). It can live between

the sea surface and around 30 m depth, although the highest concentrations are found within the top few metres, and their upper limit conicides closely with sea level (Antonioli and Oliverio, 1996). Fig. 1c is a field photograph which shows the typical appearance of the uplifted paleo-shoreline. The exposed cliff-face below the raised shoreline is densely covered in the borings of *L. lithophaga* and, in some holes, shells can be found *in situ*.

Since the lithophagids collected in Western Crete grew on the same uplifted marine substrate as the corals and bryozoans whose ages closely concentrate near AD 365, their ages might also be expected to bracket the same date. All of the lithophagid ages obtained by Shaw et al. (2008) are older than AD 365, and are therefore consistent with uplift in the earthquake, but they have a much larger range (2107 years) than the range (640 years) of coral-bryozoan ages and, in addition, the average coral-bryozoan ages are also ∼500 years younger than the youngest lithophagid ages, suggesting a possible systematic offset in the lithophagid ages (Fig. 1a). We now investigate two possible reasons for the observed difference in coral-bryozoan and lithophagid ages.

4.1   Colonisation order and preservation potential

Lithophagids colonise calcareous substrates and excavate their own boreholes, beginning at the surface as juveniles and boring deeper into the limestone as adults. The entrances to the boreholes are therefore commonly narrower than the adult shell, which means that the shells are often difficult to dislodge after death, thereby greatly enhancing their preservation potential. Cross-cutting relationships between generations of lithophagids can be recognised in Kynos, on the southern coast of the Gulf of Evia, where later generations have bored into cement-infilled earlier holes (Figs. 3a,b) showing that the same area of cliff-face can be colonised repeatedly over

an extended period. In an example from western Crete, the shell of a lithophagid provided protection for another elongated bivalve species, which was found occupying the vacated shell (Figs. 3d,e). Many of the corals and bryozoans that were collected in western Crete were also found within the protected vacated boreholes of lithophagids (Fig. 3f), showing that there were generations of lithophagids present in the cliffs before the corals and bryozoans settled there.

By contrast, in every place that uplifted corals and bryozoans were observed, they were clearly late colonisers, belonging to the very last phase prior to uplift. They grew on top of all other encrusters and borers, and had a relatively low preservation potential because of their delicate, stick-like structure and because they attach to and protrude from the limestone substrate, making them much easier to dislodge than the lithophagid shells (Fig. 3f).

If the difference in colonisation time and preservation potential were the sole cause of the discrepancy in radiocarbon ages between the corals-bryozoans and the lithophagids, we might expect to see the date of uplift well constrained by the corals and bryozoans, whereas the lithophagids should have a wide range of ages, from about 6000 yr BP (when sea level reached relative stability near its present level following the last glacial maximum (Siddall et al., 2003)) to the date of uplift. The lithophagids do indeed display a much wider range of ages than the corals and bryozoans, but there is also an offset between the youngest lithophagid ages and the average coral-bryozoan ages of around 500 years. Colonisation sequence and preservation can explain the larger range of the lithophagid ages compared with coral-bryozoan ages, but cannot explain the systematic offset.

4.2   Incorporation of old carbon into shells

In general, there are two sources for the carbon that bivalves use to build their shells: metabolic carbon, which comes from food, and dissolved inorganic carbon, which comes from the surrounding sea water. Shell-building has been extensively studied in the edible mussel *Mytilus edulis*, which builds its shells from less than 10% metabolic carbon (Gillikin et al., 2006). *Mytilus edulis* is in the same family as *Lithophaga* and this value seems to be a reasonable average for bivalves generally, although the maximum observed proportion of metabolic carbon in a bivalve shell is 35% (Gillikin et al., 2007). The remainder of the shell carbon, and therefore the majority, comes from HCO_3^- and CO_3^{2-} in the water column.

A complexity arises in the case of lithophagids, because they bore chemically into their substrate, releasing bicarbonate ions whose ^{14}C activity reflects the age of the host rock, not the organism. If any of this carbon is incorporated into the lithophagid shell, then the proportion of ^{14}C to ^{12}C in the shell will be lower than a shell that had grown from seawater alone, resulting in an artificially old radiocarbon age. Thus, if the limestone substrate acts as a carbon source for their shells, those shells will have a radiocarbon age that is older than their true age. In a similar way, lacustrine molluscs can yield artificially old ages when radiocarbon-dated, if ^{14}C is diluted by dissolved bicarbonate from ancient limestone rocks in the catchment area of the lake (Deevey et al., 1954; Broecker and Kulp, 1956; Shotton, 1972).

In the next section, we investigate this effect using modern lithophagid samples.

4.3   Test using modern lithophagids

The simplest test of whether lithophagids have artificially old ages due to the incorporation of old, detrital carbon, would be to radiocarbon-date the shell of a live lithophagid collected from present sea level and compare its age directly with that

expected from modern atmospheric ^{14}C levels. This is complicated, however, by enriched levels of ^{14}C from nuclear testing that have entered the oceans, but at variable concentrations that depend on ocean depth and latitude (Toggweiler et al., 1989).

We therefore carried out a test using lithophagids that were collected alive, with a well-recorded collection date and location, prior to 1950. We located 4 museum specimens which were thought to have been collected alive from tectonically stable or subsiding areas (Table 3 and Fig. 4). Three of these samples were *Lithophaga lithophaga* shells from the central and western Mediterranean. The fourth sample was a *Lithophaga obesa* from the Red Sea, which had been entirely preserved in ethanol, including its soft tissues. All were analysed at the Scottish Universities Environment Research Centre (SUERC) at East Kilbride, and radiocarbon ages were corrected to obtain calibrated ages in the exactly the same way as for the Cretean samples. All four samples were extremely clean, articulated, with a complete periostracum and nacreous lustre inside the shell, suggesting that they were either alive or very recently dead when collected.

The calibrated radiocarbon ages of the museum samples are plotted relative to their date of collection (and we assume their date of death) in Fig. 4d. All of the modern *L. lithophaga* shells have ages that are offset from the date of death by approximately 900–1400 years. The date obtained from the *L. obesa* shell is also older than the date of death but, in contrast with the other modern samples, is offset by just 200 years.

The calibrated ages of the lithophagids collected in western Crete by Shaw et al. (2008) are also plotted at the bottom of Fig. 4d (on the horizontal axis) as open triangles relative to AD 365 (that is, AD 365 would plot at the zero or 'date of death'). The range of offsets from AD 365 (approximately 300–2800 years) obtained from these samples is shown as a grey region. All of the museum lithophagid samples

plot within this grey field. The Cretan coral and bryozoan data from Shaw et al. (2008) are plotted at the top of this figure (black triangles), and plot close to zero, showing that the coral and bryozoan ages are not significantly offset from AD 365.

The modern samples confirm that lithophagids can record an artificially old age when radiocarbon-dated. Intriguingly, the *L. obesa* age is offset by a much smaller amount than any of the *L. lithophaga* dates, which may be related to differences in their ecology. *L. obsea* preferentially bores into dead coral heads (Kleemann, 1994; Owada, 2006), which are likely to be very young, whereas *L. lithophaga* bores into a variety of carbonate substrates, from Mesozoic limestone to modern algal encrustations. The difference in age offset may therefore depend on the age of the substrate into which the lithophagid is boring, and the consequent depletion of that substrate's ^{14}C. We now apply these insights to the lithophagid ages from western Crete.

4.4 Assessment of host-rock carbon incorporated into lithophagid shells

In this section we investigate the possibility that the differences between the radiocarbon ages of the lithophagids from western Crete and the date of the earthquake that lifted them out of the water result from the incorporation of 'dead' carbon into their shells. Here we use the term 'dead' carbon to refer to a source of carbon containing no ^{14}C, such as would be the case if the lithophagid incorporated carbonate from the Mesozoic bedrock. We consider later the influence of incorporating carbon from Holocene marine encrustation.

In the absence of contamination, the age T of a sample is given by by

$$t = \frac{1}{\lambda} \ln \left(\frac{C_0}{C} \right)$$

where C_0 is the $^{14}C/^{12}C$ ratio of the medium in which the organism grew, C is the ratio now, and λ is $1/8033$ years^{-1}. With contamination or dilution of the measured $^{14}C/^{12}C$ by the host rock, the apparent age is

$$t_{app} \approx \frac{1}{\lambda} \ln \left(\frac{C_0}{C(1 - \gamma')} \right)$$

where γ' is the effective fraction of ^{14}C-free (or 'dead') carbon included, and

$$\gamma' = \gamma(1 - \exp(-\lambda T)),$$

γ is the fraction of host-rock carbon included in shell, and T is effective age of host rock at the time of inclusion.

Thus the difference between the apparent and real ages, Δ, is

$$\Delta \approx - \ln(1 - \gamma')/\lambda \tag{1}$$

If $\Delta = 500$ years, roughly the offset seen between the average age of the coral-bryozoan samples and the youngest lithophagid samples from Crete (see Fig. 1), then $\gamma = 6\%$ if the host rock is Mesozoic limestone ($T \approx \infty$). Even if $\Delta = 1000$ years, $\gamma = 12\%$. Thus only a small fraction of shell carbon must be sourced from the limestone substrate in order for the age offset of the lithophagid to be significant.

In fact, with one exception (sample 17020, Table 1) the age offsets for the lithophagids relative to the corals and bryozoans from Crete are smaller than $\sim$1600 years, and all the modern lithophagids have age offsets smaller than 1400 years. These differences are small compared with the decay constant for ^{14}C, so we may make use of the linear approximation that each 1% of 'dead' carbon incorporated into the sample is equivalent to an apparent increase in the samples age of 1% of the decay constant, or 80 years. Thus three of the modern lithophagid samples and

4 out of the 14 samples from Western Crete, show age discrepancies between about 800 and 1600 years, equivalent to an incorporation of 10–20% of dead carbon from the host rock.

We note, however, that a substantial subset of 7 of the 14 lithophagids from western Crete show smaller age offsets between 530 and 330 years. This could imply smaller contributions (4–7%) of dead carbon to their shells. But, alternatively, some of these samples may have incorporated carbon from a Holocene algal marine encrustation that commonly overlies the Mesozoic carbonate (as illustrated in Fig. 3f). This encrustation could not have formed before the sea surface stabilized near its present level at about 6kybp (Siddall et al., 2003), so its maximum age at the time of the AD 365 earthquake would have been about 4500 years and, assuming a constant rate of encrustation, its average age would have been about 2250 years. The average ^{14}C activity of this encrustation would therefore have been approximately 75% of the activity of the open ocean, so the influence on the apparent age of the lithophagids of incorporating 1% of carbon of this activity would be approximately one-quarter the influence of incorporating the same proportion of dead carbon. If, therefore, the lower range of age lithophagid offsets arises from the incorporation of carbonate from the Holocene encrustation, it would require a greater proportion (16–30%) of the lithophagid shell to be derived from the host rock. Thus contamination from younger encrustation as well as from Mesozoic limestone allows yet further spreading of lithophagid ages. More detailed analysis of the present dataset is not justified: most of the samples collected had probably bored through at least some encrustation into the underlying old limestone, but in some cases the encrustation had fallen off the cliff-face.

We have no objective way of distinguishing age offsets induced by the incorporation of dead carbon from those produced by the preservation of lithophagid shells *in situ* long after death. Indeed, both effects are likely to occur simultaneously.

The existence of a lower bound (~ 400 years) on the age offsets observed in Crete requires some dilution of environmental carbon by material from the host rock. The minimum proportion of host-rock material required to explain that offset is about 5% if all that material is carbon-dead. The age offsets on modern lithophagids require between 10% and 20% of dead carbon, which is comparable to the fraction estimated from the smallest lithophagid age offsets from western Crete if they were generated entirely by the incorporation of carbon from the Holocene encrustation.

Regardless of the details of their explanation, it must be accepted that there are offsets of up to 2000 years in the ages of lithophagids. We now consider the implications of these findings for tectonics and palaeoseismology.

5 Implications for tectonics and paleoseismology

In western Crete, the large amount of uplift in the single big earthquake of AD 365, confirmed by both radiocarbon dates and the physical appearance of the uplifted paleo-shoreline (Shaw et al., 2008), allows us to identify two effects that result in artificially old estimates of the date of that uplift event from lithophagid radiocarbon ages. The first is a combination of colonisation order and the high potential for lithophagid shells to be preserved *in situ* in their bore-holes long after their death. The second effect is the incorporation into the shell of ^{14}C-free carbon from the limestone substrate. The age offset from this effect alone is at least 500 years on Crete, and at least 800 years for the museum specimens. In this section we illustrate the implications of these effects in a different tectonic environment, in the extensional graben system of central Greece.

The Gulfs of Corinth and Evia in Central Greece (Fig. 5) are large-scale active normal-faulting systems (e.g. Goldsworthy et al. 2002). Uplift occurs in the footwalls of these faults during earthquakes with repeat times of roughly 200–300 years in

Corinth (Collier et al., 1998; Pantosti et al., 2004a) and 1000–2000 years in Evia (Pantosti et al., 2004b). Extension rates across the graben measured by GPS are consistent with these palaeoseismological estimates of repeat times (Avallone et al., 2004; Hollenstein et al., 2008). With maximum fault-segment lengths of about 20 km, the earthquakes are much smaller than the AD 365 Crete event, and are typically up to M_w 6.0–6.5, with perhaps just 10 cm uplift in each event (Jackson et al., 1982). The Late Quaternary rate of uplift in the Gulf of Corinth can be estimated from matching flights of uplifted marine terraces to sea-level stillstands, and from U/Th dating of corals found on those terraces (e.g. Armijo et al. 1996; De Martini et al. 2004; Dia et al. 1998; McNeill and Collier 2004).

A series of marine notches can also be observed in the footwalls of the recently active normal faults, particularly in the Gulf of Corinth (Fig. 5, photographs). The elevation of the highest notch varies from east to west, with the highest elevations ($\sim$10 m) associated with the fastest extension rates ($\sim$12 mm yr^{-1}) in the west; both are lower in the east ($\sim$3 m and $<$ 5 mm yr^{-1} respectively; e.g. Clarke et al. 1997; Goldsworthy and Jackson 2001; Hollenstein et al. 2008). The cliff faces beneath the notches are punctured by lithophagid borings, some of which have been collected and radiocarbon-dated to investigate uplift rates over the last few thousand years (Pirazolli et al., 2004; Mouyaris et al., 1992; Papageorgiou et al., 1993; Vita-Finzi, 1993; Keraundren et al., 1995; Stewart, 1996; Stewart and Vita-Finzi, 1996; Stiros et al., 1992; Pirazzoli et al., 1999).

Lithophagid holes and associated notches are also seen in the Gulf of Evia, to a lower maximum height of typically $\sim$1 m. Here, older lithophagid ages beneath higher younger ones have been used to infer subsidence followed by uplift at the same site over a few hundred years (Stiros et al., 1992; Pirazzoli et al., 1999). In the light of the insights from western Crete, it is not surprising that we see reversals in radiocarbon ages of lithophaga with elevation caused by prolonged and repeated

colonisation of an exposed substrate, and the examples in Figs. 3a and 3b were taken from this site. With lithophagid shells remaining intact and *in situ* for a thousand or more years after death, a complicated history of reversed vertical motions seems poorly supported by such evidence.

Goldsworthy and Jackson (2001) suggested that the highest notches and the highest exposed lithophagid boreholes in the Gulfs of Corinth and Evia were formed at about 6000 yr BP, when sea-level stabilised near its present level, having risen at very rapid rates of up to 1–2 m per century over the previous 10,000 years. If correct, this rule-of-thumb provides a very useful quick estimator of uplift in the late Holocene. In Fig. 5 we examine the extent to which this suggestion is compatible with published lithophagid ages.

In Fig. 5 conventional (i.e. uncalibrated) radiocarbon ages are plotted because the appropriate correction for reservoir effect is poorly known in the Gulfs of Corinth and Evia. The map shows the sample locations, identified as A–G on the plots of radiocarbon ages and in field photos. In the plots of radiocarbon age against elevation, the lithophagid ages are shown as red dots. The blue circles mark the elevation of the top of the highest notch or limit of lithophagid holes in each locality. At Lambiri, the top of the cliff sequence is buried beneath road talus, and is only known to be higher than 7 m. If we assume in each place that the highest notch or lithophagid holes formed at 6000 yr BP, the black line joining the blue circle to the origin represents the average, smoothed, long-term uplift rate. The lithophagid ages should plot to the left of this line. Some uncertainty arises because the first earthquake at a site may not have occurred immediately when sea-level stabilised, but will presumably have occurred somewhere between 6000 yr BP and in a following time interval corresponding to the average repeat time of earthquakes at that location. The grey triangles therefore bound the expected average uplift rates, based on the expected earthquake repeat times in the two Gulfs.

The majority of uncalibrated lithophagid ages plot either on top of, or to the left, of the estimated uplift curve, consistent with the suggestion that the highest notch formed at ~6000 yr BP. The spread of lithophagid ages relative to the expected age at that elevation (given by the black line) is large in places, with the oldest ages up to 9000 years BP (Fig. 5a,b,c). Some of this variation is expected if lithophagids are preserved *in situ* for centuries to milennia after death while the substrate is colonized by other organisms; but the oldest ages of 8,000–9,000 years cannot be explained in this way. At 8,000–9,000 years BP, before it reached relative stability near its present level ~6000 years ago, sea level was up to 25 m lower than today. At that level it would have been impossible for lithophagids to live at the position they now occupy on the substrate without uplift rates a factor of 3 or more faster than the Late Quaternary averages based on the correlation of terrace heights with marine stillstands, which would also be much faster than expected from fault slip-rates that are consistent with GPS and paleoseismology. These older ages, roughly 2,000–3,000 years beyond the expected 6,000 years BP maximum, suggest that the lithophagid age offset in the Gulf of Corinth due to the incorporation of ancient limestone substrate carbon into shells may be as much as 2,000–3,000 years.

6   Conclusions

The ubiquity of lithophagids in the Mediterranean, espcially the species *Lithophaga lithophaga*, together with their high potential for preservation, makes them very useful indicators of uplift in tectonically active areas. Quantifying that uplift requires some estimate of its age, and dates determined from radiocarbon ages on lithophagids have often been used for this purpose. The ocurrence of a single, large-amplitude uplift event of up to 10 m in western Crete, associated with a very large ($M_w \geq 8$) earthquake in AD 365, reveals two effects that limit the resolution

and applicability of radiocarbon lithophagid ages for tectonic and paleoseismological purposes.

The first effect is that the good preservation potential of lithophagids can cause them to be preserved *in situ* long after death, while the marine substrate continues to be colonized by other marine organisms, including other lithophagids. The second effect is a systematic error in the lithophagid age caused by the incorporation of 'dead' (i.e. ^{14}C-free) carbon into the shell from the host limestone into which it bored, which can lead to ages up to 1,000–2,000 years too old, even in museum specimens collected before the atmospheric testing of nuclear weapons. In western Crete the second effect is probably responsible for a minimum offset of about 500 years between the youngest lithophagid ages and the ages of corals and bryozoans that faithfully record the AD 365 uplift and were the last colonizers of the substrate.

These two effects mean that even where the uplift occurs in a single massive event, as in AD 365 in Crete, lithophagid ages alone are unlikely to constrain the age of the uplift to better than a thousand years, or even to demonstrate that it all occurred at once. In places like the Gulf of Corinth, where uplift occurs in events of much smaller magnitude ($\sim$10 cm *vs.* $\sim$10 m) separated by hundreds of years, lithophagid ages are clearly unable to distinguish individual uplift events for paleoseismological purposes. They can, however, be used to test (but not prove) the hypothesis that the highest uplifted lithophagid borings and marine notches in the coastal regions of central Greece were formed about 6,000 years BP, when sea-level became relatively stable near its present level, following a rapid riase at the end of the last glacial maximum. The available lithophagid ages in Greece are indeed consistent with that suggestion.

7 Acknowledgements

8 Tables

8.1 Cretan Samples

Labcode	Site	Height m	Material	^{14}C age BP	±	Calibrated range (68.2% prob.)	Calibrated range (98.4% prob.)	Ref
16743	PHA 1	3.5	coral (S)	1985	28	AD 395 – AD 522	AD 327 – AD 576	1
16744	PAL 6	1.6	*Lithophaga*	2396	30	BC 101 – AD 32	BC 165 – AD 84	1
16745	PAL 8	9.0	coral (B)	2019	28	AD 338 – AD 468	AD 275 – AD 538	1
16788	PAL 3	9.0	*Lithophaga*	2715	28	BC 486 – BC 366	BC 601 – BC 325	1
16991	PHA 3	3.0	coral (S)	2032	28	AD 326 – AD 451	AD 264 – AD 521	1
16993	KIR 1	2.2	*Lithophaga*	3401	31	BC 1366 – BC 1232	BC 1407 –BC 1146	1
17017	SFI 1	2.0	*Lithophaga*	2660	27	BC 416 – BC 261	BC 486 – BC 210	1
17018	PHA 2	3.5	*Lithophaga*	2390	27	BC 92 – AD 37	BC 157 – 85	1
17019	KOU 1	2.5	*Lithophaga*	2490	28	BC 219 – BC 72	BC 322 – BC 31	1
17020	SOU 1	2.9	*Lithophaga*	4293	30	BC 2480 – BC 2339	BC 2556 – BC 2278	1
17269	PAL 1	5.2	*Lithophaga*	2350	29	BC 37 – AD 81	BC 111 – AD 137	1
17270	SOU 1	6.5	*Lithophaga*	2403	28	BC 109 – AD 24	BC 168 – AD 75	1
17271	PAL 5	3.6	*Lithophaga*	2506	29	BC 252 – BC 93	BC 332 –BC 47	1
17272	PAL 7	6.0	*Lithophaga*	2904	29	BC 768 – BC 626	BC 791 – BC 527	1
17273	HSF 2	2.1	*Lithophaga*	2914	31	BC 780 – BC 646	BC 797 – BC 535	1
17330	KIR 2	3.2	*Lithophaga*	2339	29	BC 31 – AD 90	BC 101 –AD 146	1
17331	HSF 1	1.0	*Lithophaga*	2578	35	BC 339 – BC 206	BC 381 – BC 139	1
17669	CHS 1	3.3	bryozoans (My)	2129	27	AD 215 – AD 350	AD 151 – AD 401	1
17670	CHS 2	3.0	bryozoans (My)	2071	27	AD 280 – AD 405	AD 222 – AD 460	1
17671	CHS 5	2.5	bryozoans (My)	2019	27	AD 340 –AD 465	AD 277 – AD 536	1
17672	CHS 5	2.5	bryozoans (My)	2024	26	AD 335 – AD 459	AD 272 – AD 530	1
17673	CHS 7	6.0	coral (S)	2345	27	BC 33 – AD 83	BC 104 – AD 140	1
17674	AGM	3.0	coral (S)	1977	26	AD 409 –AD 531	AD 340 – AD 580	1
17675	SOU NB2	2.2	bryozoans (My)	2119	29	AD 230 – AD 360	AD 160 – AD 414	1
17676	GRAM 2	4.7	bryozoans (My)	1878	25	AD 514 – AD 630	AD 452 – AD 658	1
17677	GRAM 4	2.0	bryozoans (My)	2015	28	AD 342 – AD 472	AD 281 – AD 541	1
17678	PHA 2	3.4	coral (S)	2028	27	AD 331 – AD 455	AD 268 – AD 525	1

8.2   U/Th dating

Sample	C-14 age yrbp	Corrected radiocarbon date	U/Th age uncorrected yrbp	U/Th age corrected yrbp	U/Th age corrected date	+	−
AGM	1977 ±26	AD 340 – AD 580	2530 ±180	1840 ±320	AD 106	317	405
PAL 08	2019 ±28	AD 275 – AD 538	2040 ±90	1440 ±250	AD 514	247	333
PHA 01	1985 ±28	AD 327 – AD 576	1890 ±410	1060 ±510	AD 891	509	591

8.3   Museum specimens

Labcode	Collection site	Collection date	Species	^{14}C age yrbp	Calibrated date 68.2%	Calibrated date 95.4%	Source
SUERC-18952	Egypt	1934	*L. obesa*	638 ± 35	AD 1653–1805	AD1567–1860	CZM
SUERC-18953	Bay of Naples	1918	*L. lithophaga*	1875 ± 37	AD 511–638	AD 445–665	NHM
SUERC-18954	Sardinia	1905	*L. lithophaga*	1783 ± 37	AD 604–697	AD 550–764	NHM
SUERC-18955	Trieste	1890s	*L. lithophaga*	1515 ± 37	AD 864–994	AD 793–1030	NHM

CZM: Cambridge Zoology Museum, NHM: Natural History Museum, London

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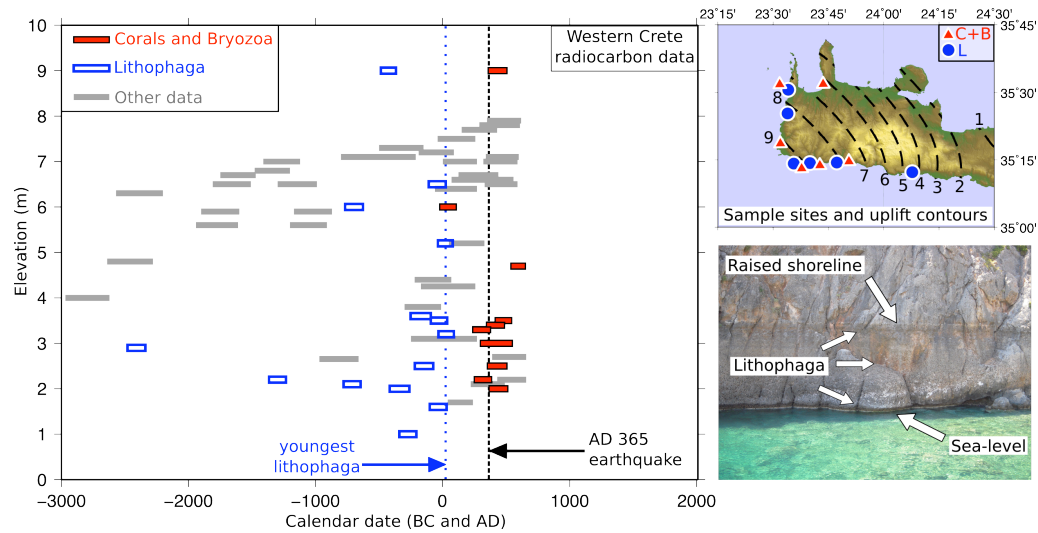
Figure 1: (a) Radiocarbon dates from Western Crete. Grey bars are radiocarbon dates obtained prior to the Shaw et al. (2008) study; see text for references. The youngest ages coincide with AD 365. Red bars are coral and bryozoan ages from Shaw et al. (2008), nearly all closely bracketing AD 365. Lithophagid dates (blue bars) are offset from the coral and bryozoan ages, and have a much larger range. All bars are 1σ errors. (b) Contours of uplift, in metres, of the AD 365 paleo-shoreline, with sample sites for corals and bryozoans (red) and lithophagids (blue). (c) The AD 365 paleo-shoreline on the south coast, marked by a white band of algal encrustation. The same white band is forming today at sea-level. Between the top of the shoreline and present sea-level, the cliff face is covered with lithophagid borings.
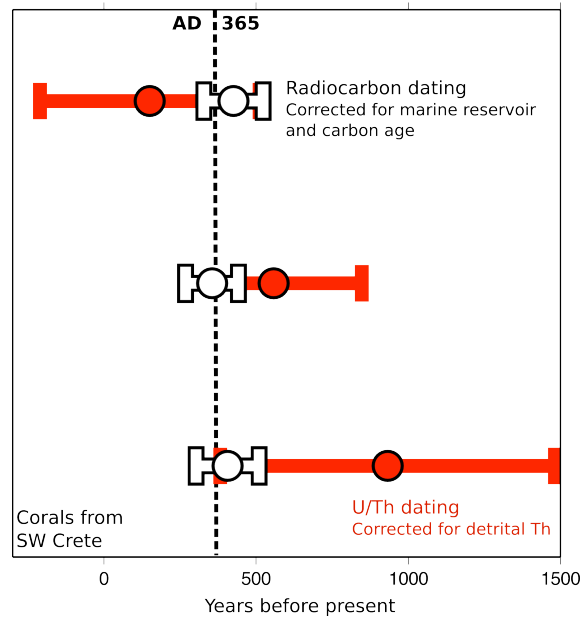
Figure 2: Radiocarbon (blue) and U/Th (red) dating of corals from Western Crete. Error bars are σ.
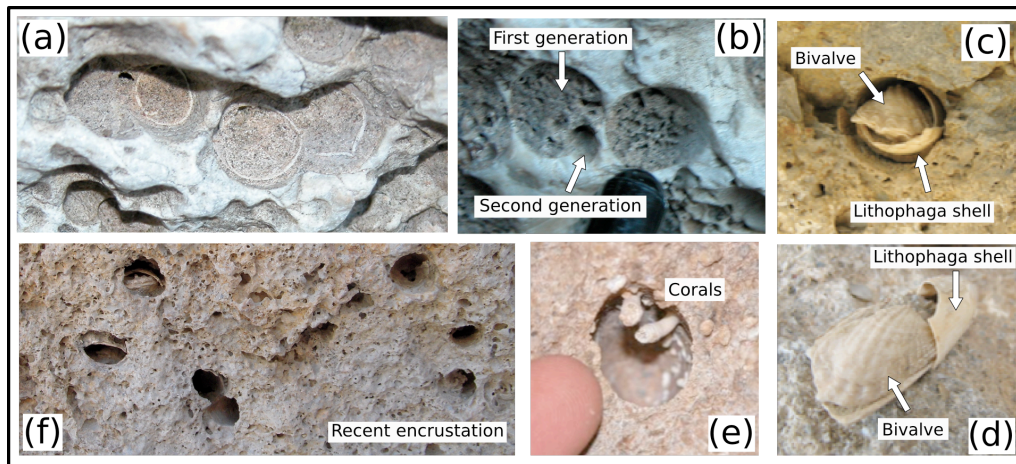
Figure 3: Repeated colonisation of lithophagid borings. (a) and (b) were taken at Kynos (see Fig. 6 for location), and show cross-cutting between lithophaga boreholes, with young shells bored into the infill of older holes, confirming that multiple generations of lithophagids lived on the cliff face prior to uplift. (c) shows lithophagids holes bored into recent algal encrustation in Crete, (d) and (e) show an elongated bivalve occupying the shell of an older lithophagid. (f) is a representative photograph of the habitat of the corals and bryozoans: in all cases they were the most recent colonisers, and in this case were found within a lithophagid borehole.
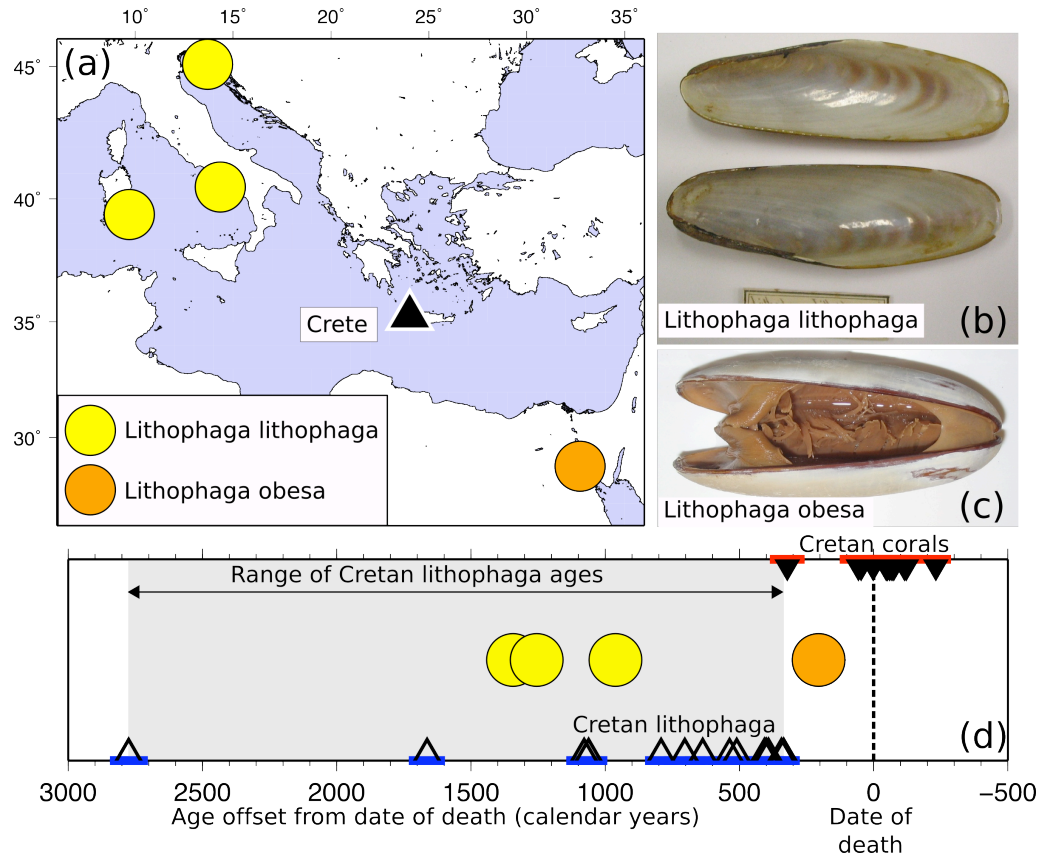
Figure 4: (a) Map showing the locations of *Lithophaga lithophaga* (yellow) and *Lithophaga obesa* (orange) museum samples collected from the Mediterranean and Red seas. (b) and (c) show photographs of one of the *L. lithophaga*, and the *L. obesa* samples. (d) Calibrated ages relative to the date of collection. If the museum lithophagid samples recorded the correct age, they would plot at zero. The *L. lithophaga* (yellow) are offset 1000–1400 years from the date of collection, whereas the *L. obesa* is offset only 200 years. The calibrated radiocarbon ages of the Cretan lithophagids from Shaw et al. (2008) are plotted as white triangles along the bottom of the figure relative to AD 365: if they correctly recorded the date of their uplift, they should plot at zero. The age offset of the museum lithophagid specimens plots within the range of lithophagid ages from Crete. The calibrated radiocarbon ages of the corals and bryozoans from Shaw et al. (2008) are plotted as black triangles at the top of the figure, again relative to AD 365. They plot at the origin, and therefore correctly record their date of uplift and death. (b) and (c) show photographs of one of the *L. lithophaga*, and the *L. obesa* samples.
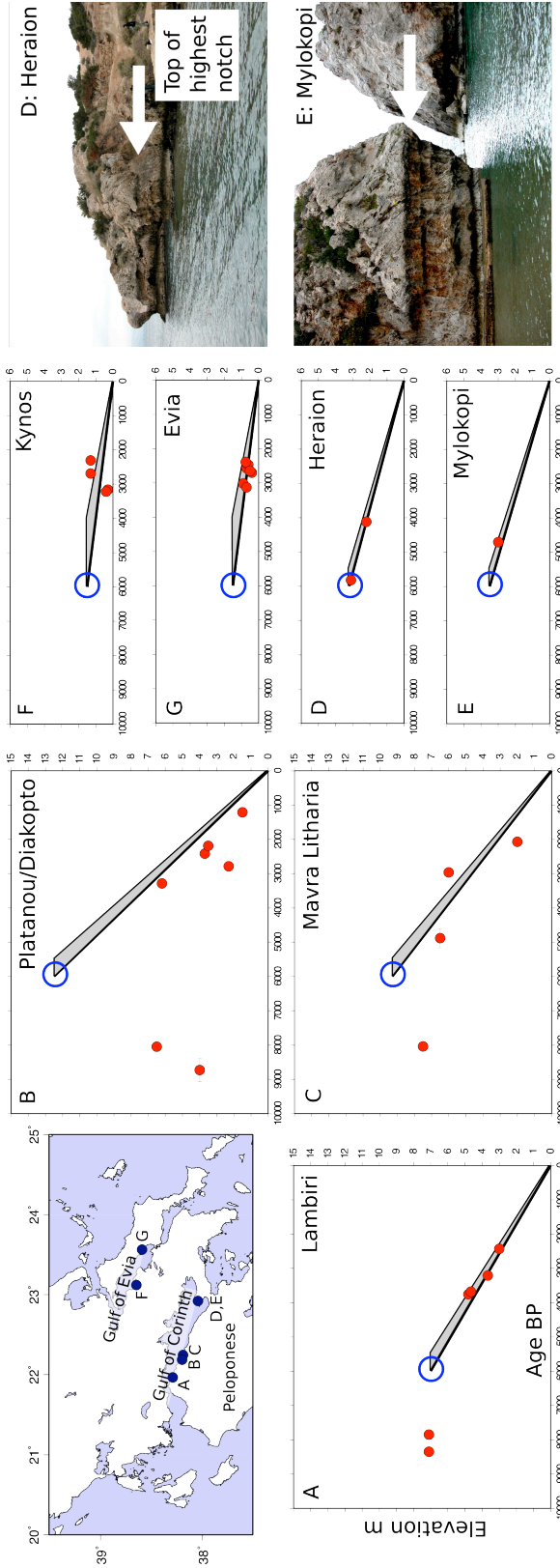
Figure 5: Conventional radiocarbon ages of *L. lithophaga* (red dots) collected from the Gulfs of Corinth and Evia plotted against elevation above present sea-level. The location of each plot,a nd of teh field photos, is identified by letter on the map. Blue circles mark the elevation of the top of the highest marine notch or boring in each locality. At Lambiri, the top of the cliff sequence is buried beneath road talus, and is only known to be higher than 7 m. If the highest notch formed 6000 years BP, then the black line represents the average uplift rate over that period. The grey triangle is the range of average uplift rates allowing for local earthquake repeat times (see text). Note that the lithophagid ages plot on, or to the left of, these lines. Field photos show multiple notches at Heraion and Mylokopi, with white arrows marking the position of the highest one.