

RELATIVE SEA-LEVEL CHANGES IN CRETE:

REASSESSMENT OF RADIOCARBON DATES

FROM SPHAKIA AND WEST CRETE

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BY

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1. SEA-LEVEL CHANGES IN CRETE

This article is concerned with the recognition and dating of Holocene-age uplift events which changed relative sea-levels in the coastal zone of Crete, an island located in the active Hellenic subduction arc of the southern Aegean Sea (Fig. 1). Our specific region of interest is the area of Sphakia, which is representative of this much studied coastline, which has almost the greatest density of evidence for sea-level changes of any coastline in the whole Mediterranean. We consider the effect of recent changes in the calibration of radiocarbon (¹⁴C) dates on our understanding of the history of changes in relative sea levels in the region, and their potential effect on human populations. We concentrate particularly upon the most recent of these events, which has been correlated with a major uplift affecting western Crete in later antiquity.

In southwestern Crete, a series of historic changes in relative sea level are recognizable by eight raised palaeoshoreline levels (I-VIII). Evidence for these shorelines is found all along the coast of west Crete, as a series of wave notches. At Moni Khrysoskalitissas the sequence is particularly clear. Here, there are eight superimposed levels associated with these successive events. At other sites, while all

eight sea levels are not identifiable, the depth intervals recorded between the different shoreline events are nearly constant, strongly supporting the notion that these levels form horizons which are essentially contiguous across western Crete. Table 1 records the readings of changes in sea level in Sphakia.²

These shorelines can be dated using radiocarbon analysis of the marine fauna which originally lived at the surface and which were later killed by changes in sea level. The conclusion of the analysis presented here is that a period of tectonic instability commenced around 4500 BP and lasted ca. 3500 years.³ During this time, brief falls and occasional rises of relative sea level occurred, each with a magnitude of 10-25 cm, separated by phases of tectonic quiescence of the order of 250 years.⁴

The existing consensus is that the modern sea level (Level I) was created by an event of enormous magnitude which caused an abrupt emergence of the earlier palaeoshoreline levels. A crustal block some 200 km in east-west length, including western Crete, was upwarped, while central and eastern Crete remained largely unaffected. The western end of the island was uplifted by as much as 9 m.⁵ The uplift in Sphakia ranged from 7 m at Poikilasion in the west to 3.50 m at Khora Sphakion and 2 m at Agia Marina in the east. Isobases for this uplift are shown on Fig. 1. The magnitude of this young crustal uplift is unique in the Mediterranean region, and is among the greatest historic uplift events in the world. This latest episode of relative sea-level change has previously been dated using radiocarbon to about 1530 years BP. We attempt to determine a more accurate date for this event, arguing that it did not occur, as is usually stated, in AD 365, but in the fifth or sixth centuries AD.

In the rest of this section, we outline the recording of data for sea-level changes in west Crete, and set this in the context of recent geological and

geomorphological work. Next we explain the principles behind the recorection of the radiocarbon data, to allow for isotopic fractionation, and the recalibration of the resulting data, to allow for the reservoir effect in ^{14}C in the ocean, and the different offsets from the average reservoir effect which are apparent in different seas (section 2).

We then analyse these recalibrated results, using Bayesian statistics, which are designed to establish statistically, rather than impressionistically, the probabilities of different calendar dates (section 3). We explore the implications of the new calendar dates for the creation of sea level I for three major coastal sites in Sphakia (section 4). A final section (5) offers some conclusions.

Holocene changes in sea level have been noted ever since antiquity. The geographer Strabo gave a lengthy discussion of changes in the relationship between the sea and the land: ‘When I was staying at Alexandria in Egypt, the sea about Pelusium and Mount Casius rose and flooded the country and made an island of the mountain.’ (i. 3. 17; cf. xvi. 2. 26) This was probably a tsunami that (temporarily) flooded the Nile delta. Strabo’s general explanation of this phenomenon invoked earthquakes, volcanic eruptions and upheavals of the sea-floor raising the sea level (i. 3. 4-20).

The observations and theories on relative sea-level changes became more systematic with the development of the modern disciplines of geology and geomorphology. The founder of modern geology, Charles Lyell, already by 1830 used archaeological evidence, the ruins of the temple of Serapis at Puteoli, to argue for (two) changes in relative sea level since antiquity.⁶ Studies of the historic and earlier Holocene sea-level changes in Crete started with the acute observations in the 1840s and 1850s by Raulin and Spratt.⁷ Spratt noted the remarkable changes in sea

level at Poikilasion, Agia Roumeli and Loutro and argued that the retreat of the sea must post-date the third century AD, when the landlocked Poikilasion was still listed as a 'landing place' among the coastal sites of the Mediterranean.

Later, Flemming made further observations in southwest Crete, as well as other parts of the Mediterranean.⁸ He attempted to date the sea-level changes by considering the ages of the affected archaeological sites, and concluded that in general the changes in the Aegean region occurred gradually, largely as a result of the steady rise of sea levels after the last ice age. The application of radiocarbon dating to fossil fauna raised out of the water by relative sea-level fall enabled independent dating of these events. Hafemann was the first to apply this technique in Crete.⁹ A more comprehensive study was undertaken by a French team, whose data were published in the 1970s,¹⁰ and synthesized by Pirazzoli and others.¹¹ The dating done by this team was challenged as part of a major study of Mediterranean ecological history by Grove and Rackham.¹² A team of German researchers undertook further work in Crete in the late 1980s.¹³

In 1988, Nemec and Postma studied the Lefka Ori piedmont, preserved between Khora Sphakion and Frangokastello, where they recognized: a) hanging Pliocene valleys indicative of a rapid relative fall of sea level by up to 450 m, greatest to the west; b) an early Pleistocene wave-cut platform raised several metres above the sea level; and c) a bajada-like array of Pleistocene alluvial fans whose progradation involved phases of deep fan-head trenching, by up to 75 m near Khora Sphakion, indicating major episodes of relative sea-level fall.¹⁴ The lower reaches of these alluvial fans, hardly active since the early Holocene climate change, are presently hanging a few metres above the sea, at the top of wave-cut coastal cliff. At the foot of the cliff, relicts of raised Holocene gravelly beaches are preserved in local niches.

The sedimentology of such a raised beach, in a coastal embayment just east of Khora Sphakion, was studied by Postma and Nemec.¹⁵

The Sphakia Survey has also made observations on relative sea-level changes at four locations in Sphakia: Agia Roumeli; Loutro; Frangokastello; and Agia Marina.¹⁶ (Fig. 2) At Agia Roumeli, on the east side of the river mouth, there is a doubly undercut cliff, ca 6 m high, which shows two raised beaches, at altitudes of 2.50 m and 6 m above sea level. On the southwest side of the Loutro peninsula we have noted raised barnacles and raised coral at heights of between 3.80 and 3.90 m. This observation is part of the evidence that there was once a shallow-water harbour on the west side of the peninsula (Site no. 5.11, Sector IV; photographs on website, n. 16).¹⁷ Five levels of raised shoreline are recognizable to the south and east of Agios Kharalambos in the vicinity of the Frangokastello fort (Site no. 8.50; photographs on website, n. 16; see Table 1 for details). And in the far east of the eparchy, at Agia Marina, we have noted prehistoric sherds (a conical cup and pithos base) cemented to a beachrock that must have been raised between 1.85 m and 2.60 m (Site no. 8.74; text and photographs on website, n. 16).

When studying sea-level changes at a particular coast, geologists and geomorphologists talk invariably about relative sea-level changes, that is, changes with respect to that particular coast. The relative rise or fall of sea level may be due to the sinking or uplift, respectively, of the coast as a result of local tectonics (crustal movements); or it may be due to global sea-level changes. Global sea-level changes are caused by two main factors: glacial, that is, the growth and melting of polar ice caps (e.g., the world ocean's water volume is still rising due to the last major deglaciation of Earth's northern hemisphere ca. 15,000 years ago); and geoidal, that is deformations in the earth's core and mantle, the breakup of continents and opening of

deep new basins that *drain* the world ocean, and the growth of mid-oceanic volcanic ridges and their collapse after cooling, which decreases or increases, respectively, the oceanic basin's capacity, or water-accommodation space.

Although glacial and geoidal changes may combine with the effect of local tectonic movements along many coasts, they are recognizable by being much more widespread. Some geologists believe that they are genuinely global, and have carried out large-scale compilatory studies to establish a general time curve of global sea-level changes, which would serve as a reference for the numerous marine transgressions and regressions recognized in the geological record. Such global time curves have been produced for the whole Cenozoic era (last 65 million years), Mesozoic era (230-65 million years ago) and Palaeozoic era (570-230 million years ago); the geological record from Proterozoic era is too sparse to allow a systematic compilation. Other geologists argue that glacial and geoidal effects, though widespread, are not uniform globally.¹⁸

The geological observations on the Quaternary changes in relative sea level in the Eastern Mediterranean led to an abandonment of Flemming's original gradualistic view. The current consensus is that the tectonic uplift at active plate margins, such as the Hellenic subduction arc, occurs in discrete and rapid events. The perfect preservation of Bryozoan shells on raised coasts supports this notion, because these and other fragile pieces of debris would hardly survive the abrasive wave action of a slowly advancing surf zone.¹⁹ In addition, radiocarbon dates of sublittoral bioconstructions at lower levels have yielded the same results as those from higher up, which suggests the sea-level change was virtually instantaneous. The notion of rapid uplifts is also in keeping with the geomorphological observation from the Lefka Ori piedmont and other parts of Crete, as well as wider in the Mediterranean region.²⁰

Offshore earthquakes, if they occurred, can be expected to have resulted in tsunami waves, and the sedimentary record of such catastrophic events is now beginning to be recognized in many onshore areas. At Phalasarna in northwestern Crete, for example, a thick layer of surficial sediment, presently vegetated and turned into soil, is claimed to be a tsunami deposit, as it appears to contain species of fossil fauna quite different from those present in the underlying marine strata deposited in normal nearshore conditions.²¹ Dramatic coastal changes occurred after the tectonic uplift of *c.* 1530 BP, including the formation of small atolls by calcareous algae over local shoals.²²

2. RECALIBRATION OF THE RADIOCARBON RESULTS

Radiocarbon dating has been used in Crete, and further afield in the Mediterranean, to determine the ages of marine faunal remains attached to raised palaeoshorelines, and to establish the time-sequence of the corresponding relative sea-level changes (n. 11). Several scholars have advanced a convincing case for the reliability of radiocarbon measurements undertaken on these fauna.²³ Vermetids such as *Dendropoma* sp. and algal reef-building organisms like *Neogoniolithon notarissi*, have been used for radiocarbon dating. The vermetids are intertidal and construct ledges near the mark of the tide. Pirazzoli et al. 1982 used them to date ancient shorelines and relative sea-level changes by correlating radiocarbon age with the elevation of the ledges themselves.

One potential problem associated with these radiocarbon determinations concerns the reservoir effect.²⁴ Radiocarbon ages of contemporaneous marine and terrestrial fossils differ, on average, by some 400 years because of delays in the exchange of CO₂ between the air and sea and the dilution effect of upwelled deep sea

water which is depleted in ^{14}C . Radiocarbon ages of marine organisms can be corrected using a marine calibration curve, which is modelled upon the terrestrial ^{14}C record using a simple box diffusion model. The model assumes a reservoir (seawater) age of about 400 years.²⁵ Local departures (termed ΔR) from this average can be established by measuring the radiocarbon activity of shells of known pre-nuclear age, or by dating pairs of contemporaneous marine and terrestrial fossils. ΔR is assumed to be time-independent as a first approximation.

For many years, there was only one reported value for ΔR in the Mediterranean, but Siani and others have recently reported from the Mediterranean a series of twenty-six radiocarbon determinations from shells of known age.²⁶ Reimer and McCormac have collated the available radiocarbon data, and reported a ΔR of 58 (± 85) ^{14}C years for use with the 1998 marine calibration curve.²⁷ They suggest there is no statistically significant difference between the ΔR value derived from Aegean Sea shells of pre-nuclear age and those measured for the seventh to eighth millennium BC. This information means that the existing data from Crete can now be corrected with increased confidence. We have therefore recalibrated the radiocarbon data associated with dates derived from Crete and Antikythira given in n. 11 for the chronology of the six main palaeoshorelines in southwest Crete, using the new ΔR value, and the calibration curve of Stuiver, Reimer and Braziunas (n. 25). (fig. 3)

The original published radiocarbon determinations were not corrected for isotopic fractionation at the time of measurement. During the passage of carbon through the different biosphere, biochemical processes fractionate the ratios of the ^{12}C and ^{14}C isotopes. Although radiocarbon laboratories now routinely correct for this fractionation, dates of marine carbonates were not always corrected, because the correction for fractionation (c. -400 yr) appeared to be approximately equal to that

applied to account for the ocean reservoir effect (c. +400 yr). We have corrected the original radiocarbon dates (BP) by adding 430 ^{14}C yrs to each; this being the recommended age correction for samples of marine HCO_3 and CO_3 .²⁸ The corresponding standard error on each radiocarbon determination was increased using:

$$(\Delta^{14}\text{C age})^2 + (20^{14}\text{C yrs})^2$$

where 20 yrs is the recommended 2.5‰ correction for isotopic fractionation.²⁹ We then used the Intcal98 marine calibration curve and the ΔR value of $58 (\pm 85)^{14}\text{C}$ yrs to recalibrate each date. The calibrated results are given in Table 2 and plotted in Figure 4.

3. IMPLICATIONS

The recalibrated radiocarbon dates overthrow the accepted correlations with the historical and archeological record. The latest tectonic uplift of Crete, marked by the abrupt fall of relative sea level and the establishment of the modern shoreline, was probably a single event. This event is usually said to be part of the so-called ‘early Byzantine tectonic paroxysm’.³⁰ Those interested in the archaeology and history of this region will naturally want to tie this event in to earthquakes known elsewhere in the Eastern Mediterranean and to the settlement history of the region.³¹ Until now, a major quake in AD 365 has always been invoked as the cause of the ‘tectonic paroxysm’. The quake is known to have affected a wide region from South Italy, to North Africa, Cyprus and Egypt.³² In particular there is specific, well-dated archaeological evidence from west Crete for destruction just after AD 361, which probably does date to the 365 event.³³ The problem with this ‘event’ is that scholars attribute to it evidence, both textual and archaeological, which in fact comes from other events years or even decades apart.³⁴ Such lumping of data is disastrous for

serious study of historical seismicity as it inflates the size of the damage area and hence the size of the event.³⁵

Moreover, there are other earthquakes attested archaeologically and historically from the fourth to seventh centuries, some of which may have affected south-west Crete.³⁶ In particular, there is archaeological evidence for quakes at Gortyn in AD 560, AD 620 and AD 670, and there is a report of a violent quake affecting Crete in AD 796.³⁷ Still other quakes known to have affected other parts of the Aegean; some of these might also have affected Crete.

So far, archaeologists and historical seismologists have thought that whatever precise date is ascribed to the creation of Level 1, the event must have been coseismic, and hence catastrophic. It might seem natural to assume that the elevation of coastline by up to 9 m must have been the result of a powerful earthquake, and hence very destructive locally, but this assumption is in fact highly questionable. Seismologists have recently started to study relative plate movements that are not accompanied by earthquakes; such movements used to escape attention, but are now measurable because of the availability of GPS data.³⁸ In particular, the movement west of Turkey (relative to Eurasia) is made possible by the so-called Hellenic Trench, a subduction zone to the west of Greece and Crete. (FIG. 5)

In essence, Turkey and Greece move south-west over the floor of the Mediterranean, the junction being known as the Hellenic Trench. The length of this junction, some 300 km, is the right length to have produced a maximum up-lift of 9 m.³⁹ (FIG. 6) The estimated movement of these countries over the last 100 years (an estimation that is again reliable because of GPS data), when fed into a mathematical model for predicting earthquakes, predicts far more major earthquakes than have actually occurred over that period. That is, about 90% of the movement is

accompanied by earthquakes, and the rest occurs by ‘creep’.⁴⁰ From this it follows that the creation of Level 1 might also have occurred without an earthquake: the evidence of fragile raised molluscs and of our statistical data alike support the idea that it was a single event, but that event could have been spread over a number of days, and might not have been accompanied by a catastrophic earthquake.

The time of this ‘tectonic paroxysm’ was originally estimated as 1850 BP (Laborel et al. 1979), but was subsequently reassessed as 1550 BP (Thommeret et al. 1981a), and finally as 1530 BP (Pirazzoli 1986). Our reanalysis of this data has first recorrected by taking account of isotopic fractionation, and second recalibrated by using the new marine reservoir ΔR value. This indicates a younger age for the latest Cretan uplift. The recalibrated time range bracketed by one standard deviation (68% confidence) is AD 405–615, which points to a date significantly later than the event of AD 365.

To take matters further, we have analysed the available radiocarbon data using a Bayesian approach to radiocarbon calibration.⁴¹ The Bayesian paradigm is outlined in a number of previous publications.⁴² Put simply, it involves the use of prior information as well as collected data to make inferences regarding the probability of certain events. There would appear to be considerable benefits of this approach to a discipline where relative sequences are often already known, as is the case in the Mediterranean sea level example. At the Moni Khrysoskalitissas site, for instance, there are eight superimposed raised shorelines representing each of the eight relative sea-level events which have been identified and dated (Table 2). Here we are interested in dating uplift events which can be cross-correlated across large distances and have well documented relative information available in the form of careful measurements by theodolite of metres above sea level and superimposition at key sites.

In essence the Bayesian method can be distilled to the following simple framework:

$$\text{Prior beliefs} \times \text{Standardised likelihood} = \text{Posterior beliefs}$$

In this statement the term ‘prior beliefs’ describe the belief attached to the unknown parameters before the data themselves are collected. The parameters in this case refer to the true calendar age associated with the material which has been radiocarbon dated (these are determination parameters, so there may be more than one radiocarbon determination for a specific determination parameter), or they can refer to the true age corresponding to the start or end date of a prehistoric phase of occupation (boundary parameters). A simple example of prior belief could be the relative sequencing obtained from careful stratigraphic excavation. This sequencing supports a prior belief that the upper level of an archaeological site is later in time than the lower level and that there is superimposition in the strata exposed. The ‘likelihood’ describes the relationship between the radiocarbon age and the true but unknown calendrical age by way of the model, which is the radiocarbon calibration curve. For a specific radiocarbon date, the likelihood will reflect how likely each value for the calendar age is along the calibration curve itself. The term ‘posterior beliefs’ describes the belief attached to the unknown parameters *after* the collection of the data.

This approach can be represented by inevitably complicated mathematics and the reader is referred to recent publications listed in the references for details. Software applications such as BCal enable the Bayesian method to be applied in a more straightforward manner.⁴³ BCal uses an MCMC (Markov Chain Monte Carlo) method to simulate a large number of possible scenarios which are randomly generated to take into account both the probability distributions of the calibrated radiocarbon ages themselves, and the prior beliefs which are attached to them. Posterior distributions are then produced from the simulations. It is this probabilistic evidence that we shall review and consider below.

We developed a calibration model (Figure 7) in BCal to evaluate the chronology of uplifted relative sea levels near Crete. In the model, certain mathematical symbols are used to describe these events. \square_n and \square_n represent the earliest and latest dates of the uplift event n . Each uplift event is represented by traces left by marine corrosion on the underlying rock, or by the remains of gastropod marine organisms whose rims contribute to bioconstruction of reefs beneath the highest wave notch. In western Crete there is continuity in lateral displacement of these uplifted loci. For each identified uplifted shoreline, the radiocarbon determinations were therefore assumed to be contemporary.⁴⁴ There is evidence to support this assumption. At different sites the depth intervals recorded between the different shoreline events are consistent with the isobases mapped in Fig. 1. Radiocarbon samples obtained from each notch are assumed to date the uplift event accurately, since the marine organisms dated would have died soon after the uplift took place. It is worthwhile pointing out that the majority of evidence strongly suggests that these phases of uplift are sudden and so the span of time represented by \square_n — \square_n is probably brief (above, n. 19). \square_8 represents the temporal boundary immediately prior to the uplift, while the latest temporal boundary of this level is represented by \square_8 (see Figure 7).

Before the analysis of the radiocarbon determinations, we hypothesized that the variation in certain radiocarbon determinations might be due to sample constituent or contamination problems.⁴⁵ We therefore ascribed a prior outlier probability of 10% to each radiocarbon determination⁴⁶ to account for potential variation due to sample constituents and possible trace recrystallisation of the sample carbonates, with the exception of MC2426 (40%), MC2279 (40%), 2276 (30%) and MC2103 (30%) for this reason. Outlier analysis is described by Christen in some detail.⁴⁷ Posterior probabilities were predominantly below the 10% prior specified, but the higher outlier determinations yielded significantly higher posterior probabilities, suggesting they

were real outliers (these four samples are denoted by a hash [#] in Table 3). We therefore removed them from further analysis. In the second run of the sampler without these outliers, one determination (MC2500) yielded a slightly higher posterior probability (16%), but the remainder suggested no outliers. (It should be noted that since this original work it has become clear that in future there is no need to remove the outliers; their effect on the posterior distribution is simply down weighted.)

The radiocarbon likelihoods for the ‘sea level 1’ dataset, as simulated in BCal, range between *ca.* AD 400—600 (Table 5). We also examined the group boundary parameters ($\Delta_n - \Delta_n$; early and late, as illustrated in Fig. 7) for the determinations from this uplifted shoreline. The most likely calendar date range (or ranges) for each parameter outlined in Figure 7 are represented by highest posterior density (HPD) regions. To determine the parameters for the uplift creating the present sea level, the HPD region for Δ_8 at 95%, for example, is AD 325 to AD 545, with a modal value of AD 425, which is the earliest probable date. The modal value is the calendar age associated with the highest probability. The other parameter, which gives the latest probable date of ‘sea level 1’ is represented by Δ_8 . The age range for this parameter is AD 435 to AD 685 probability with the modal value at AD 530.

In Figure 8, we plot the posterior probability distributions between the different sea-level parameters shown in Figure 7 to estimate the time elapsed between those events. The data associated with each figure are given in Table 4. With the exception of $\Delta_5 - \Delta_5$ (‘sea level 4’), they are unanimous in supporting a brief span of elapsed time for each dated uplifted sea level. There are at least two reasons why ‘sea level 4’ implies a longer span of time. The first is that the radiocarbon analyses genuinely attest to a slow phase of uplift. This longer time span is shown by the

range in radiocarbon determinations and calibrated age ranges for dated samples from this level. The second is that there are problems with some of the radiocarbon measurements such as contamination. Further research is required to resolve which, if either, of these alternatives is correct, or whether there are other explanations.

We estimated the span of time which is represented by the radiocarbon determinations within the parameters $\bar{\mu}_8$ to $\bar{\mu}_8$ ('sea level 1') as 1 to 137 years (68% probability), with 10 years the highest probability. This suggests that the radiocarbon data from this level are in close agreement and supports the interpretation that the marine organisms which were radiocarbon-dated ceased metabolising within a very brief span of time. This might be considered consistent with a sudden uplift event rather than a longer term changes, although in terms of radiocarbon precision it is not possible to quantify such potential brevity.

One question which arises concerns the effect on the posterior distributions of the large σ_R standard deviation (± 85 yr). We tested this effect by running subsequent iterations using a standard deviation of ± 0 and noted similar results to those obtained with the larger value, which suggests our results are robust and that the effect of this large uncertainty is not significant.

We also determined the elapsed time span between the establishment of each change in relative sea level. In other words, we wanted to know how much time elapsed between the changes in the relative sea levels in western Crete. The results are also listed in Table 4.

Finally, we determined the probability associated with specific calendar years being contained in the range $\bar{\mu}_8 - \bar{\mu}_8$ to ascertain whether AD 365 was associated with a higher probability of being the event date for the uplift. In Table 6, we show the results of this analysis. Also shown are the calculated probabilities associated with

other known historic earthquakes. AD 365 yields a probability of 0.11 of being contained within the range \square_8 — \square_8 . In other words, there is a 1 in 10 chance of 365 AD being the year of this event. Other historic events yield a higher probability, for example the earthquake attested at Gortyn in AD 560 has a probability of 0.4, or a 4 in 10 chance. The period AD 480-500 corresponds to the highest levels of probability (c. 0.65). It is also possible of course that the major uplift, which did not affect central Crete, has not been detected in the archaeological record.⁴⁸

The recalibration of radiocarbon dates corresponding with uplifted relative sea-level events in the late Holocene results in age ranges which are more recent than previously estimated. In particular, the creation of sea level 1 must be dated not to AD 365, but to AD 480-500 (0.65 probability).

4. THE RECALIBRATED DATES IN SPHAKIA

The recalibrated age of the establishment of the present-day sea level can now be correlated with other data for Sphakia. The *Stadiasmus Maris Magni*, a manual of probably second century AD date listing places where ships could put in to shore, includes three sites in Sphakia: Poikilasion, Tarrha and Phoinix (330-1, *GGM* i. 508-9).⁴⁹ The first two are said to have just landing places (ὄρμος), but Phoinix to have a harbour (λιμήν). If the tectonic uplift were coseismic, it would have damaged or destroyed many buildings, and coastal constructions could be seriously affected by possible associated tsunamis. At Phoinix we have observed some remains on the east side of the peninsula that may have been damaged in an earthquake, but we have not observed signs of massive damage. However, we have already suggested that the tectonic uplift was not necessarily associated with a catastrophic earthquake, and the

significant changes may be those associated with changes in the coast line. Relevant evidence from all three coastal sites has been collected by our surface survey.

Poikilasion (FIG. 9; PLATE 1)

The observation of the *Stadiasmus* about Poikilasion, at the mouth of the Trypiti Gorge, apparently predated the latest great uplift, when there was still probably a small beach extending inland some 20 m or so. As Spratt notes, there would have been ‘a narrow and well-sheltered inlet or creek, expanding immediately within its entrance, which would then form a natural harbour without any artificial aid’. Now boats cannot beach, and one has to disembark with some difficulty offshore.⁵⁰ In the mouth of the gorge we found pottery dating between Hellenistic and Late Roman (into the fifth century), which may be associated with the unloading of goods from passing boats (Sphakia Survey Site no. 1.01; photographs on website, n. 16). The settlement in this area lay about 1 km up the Trypiti Gorge on south-south-east facing slopes on its west side. The settlement’s major phase is Roman-Late Roman, and it seems not to have gone out of use even after the loss of its landing place. Pottery at the settlement continues into the sixth and even seventh centuries (Sphakia Survey Site no. 1.06; photographs on website, n. 16). The settlement’s economy was probably related to land-based activities (perhaps pastoralism and beekeeping), and hence was little affected by the uplift.

Tarrha (FIG. 10; PLATE 2)

At Tarrha (Agia Roumeli) the shoreline today is a straight beach, trending EW, with no protection for boats in stormy weather, but before the uplift (of ca 6 m here) it would have extended landwards ca 150 m in the lee of the cliff on the east side of the

river.⁵¹ On the southeast part of the site east of the river are traces of a long wall, with inner stretch 8.75 m long; there are two likely towers in this sector (Sphakia Survey Site no. 1.28; photographs on website, n. 16).⁵² We wonder if this was a fortification wall or a sea wall. The towers suggest fortification, but the wall runs round graves of the Greek and Roman periods, and it is unusual to defend graves in this way. In addition, at the west edge of the site the wall appears to terminate abruptly at a small cliff which would not deter any human foe. On the south part of the site there is a doubly undercut cliff, ca 6m high, which shows two raised beaches, at heights of 2.50 m and 6 m, and above the top of the cliff is a surf zone stopping some 5 m (horizontally) short of the wall. Before the great uplift, which raised this section of the coast by 6 m, the wall would have been regularly in the surf zone (though the state of preservation of wall makes it difficult to be certain on this point). The wall might have been designed to protect the site from the sea, and then maybe became redundant after the uplift.

Tarrha as a settlement, like Poikilasion, seems little affected by the uplift. The pottery from the part of the site east of the gorge river continues through Late Roman; though most of the datable material is fourth-fifth centuries, some could be sixth or even seventh century. Two basilicas existed at Tarrha. The first, underneath a Medieval church on the west side of the river, has a mosaic which is probably sixth century.⁵³ The other, on the east side of the river, was probably built after the uplift, because its footings would otherwise have been almost at sea level and inundated during storms.

Phoinix (FIG. 11; PLATES 3-4)

Further east, at Phoinix (Loutro), where the uplift amounted to ca 4 m, there was a shallow-water harbour on the west side of the peninsula. As is stated by Ptolemy (iii. 17. 3), writing in the second century AD, a harbour of Phoinix was to the west of the town of Phoinix. Because of the problem of clearance of rocks at the mouth of the harbour, it could take vessels with a draught of 2 m or less. Now, only spray from seawater reaches this elevated area during winter storms.

Phoinix was especially prosperous in the Roman-Late Roman periods (Sphakia Survey Site no. 5.11; photographs on website, n. 16). The area in use in the Classical and Hellenistic periods was limited to part of the southern section of the peninsula; in Roman-Late Roman times the area in use was both larger and more intensely exploited. By contrast, the main site of Anopolis, on the ridge 600 m above Phoinix, which had been the major site of the region from Archaic times onwards, was abandoned in the late Hellenistic period.⁵⁴ This pattern, of inland and upland sites giving way to settlements down on the coast in the Roman period, is familiar elsewhere on Crete and the Mediterranean.⁵⁵

In the case of Phoinix the harbours constituted a particular attraction. The ship carrying St Paul to Rome tried (in vain) to shelter there from a storm (Acts of the Apostles 27. 12) and a second century AD inscription refers to a ship engaged in the grain trade from Alexandria to Rome (*IC* xx. 7) successfully making use of the harbour.

Phoinix continued to flourish after the uplift. The loss of the shallow west harbour was perhaps not very significant overall. The use of the western area changed after the uplift, probably in the Late Roman period, with the building of two wells and three cisterns (Sector D). As there was no further building here, the water was presumably for arable or pastoral purposes. Instead, the focus of the peninsula

was increasingly on the east. The deep-water east harbour remained the only winter harbour on the south coast of Crete, and the amount of beach available there was actually enlarged by the uplift. The rich ceramic evidence from the peninsula runs right through Late Roman (into the sixth and seventh centuries) with no visible hiatus. No fewer than five Late Roman basilicas are known at this site, mostly in the eastern half of the peninsula (Sectors A and B). Some building damage may be visible on the east side of the peninsula, where part of a bath building slid down the slope, but the most dramatic tectonic event of historic times seems not to have had long-term consequences for the settlement.

5. CONCLUSIONS

The importance of collecting and analysing environmental (as well as archaeological, documentary, and local) evidence as part of the work of archaeological projects is clear. Unless basic information for changes in sea-level is reliably collected and dated, it is not possible to reconstruct the sequence of human occupation within a wider landscape.

We have used a Bayesian approach and new calibration data to examine the chronology of important episodes of relative sea-level uplift in western Crete, in order to make a historic assessment of their impact. The new ^{14}C calibrations suggest that the latest episode of allegedly coseismic activity, the so called ‘Early Byzantine Tectonic Paroxysm’, occurred somewhat later than previously thought. Single calibrated radiocarbon ages yield wide calendar ages. A re-analysis of the radiocarbon dates using a Bayesian approach suggests that the highest probability for the date of this critical event is associated with a later date (around AD 480—500), rather than AD 365, as previous scholars have suggested. The dates of previous

episodes of sea-level change are also somewhat later than previously determined, but interpreting these new ages in terms of human prehistory in the Crete region is beyond the scope of this paper. We have examined the implication of the sea-level event for later antiquity in the Sphakia region, but there are obvious wider implications for the archaeology of other regions bordering the Mediterranean. The new ^{14}C calibrations add welcome precision to the work of geomorphologists, and make possible a closer integration of different disciplines involved in understanding landscape history in the eastern Mediterranean.

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TABLE 1

Site and Photograph	Unspecified Level	Level I	Level II	Level III	Level IV
Poikilasion (Sphakia Survey Site no. 1.01)		+ ca 6 m (Spratt 1865: ii. 245-6, 20 feet) + 6.50 m/7 m (Laborel et al. 1979: no.44; Pirazzoli 1986: 36)			
Agia Roumeli (Sphakia Survey Site no. 1.28)	+ 3.60 m (Spratt 1865: ii. 249, ca 12 feet)	+ 2.50 m and + 6 m. East of the river mouth is a doubly undercut cliff (height, ca 6 m), which shows two raised beaches, at 2.50 m and 6 m (Sphakia Survey data)		+ 4.25 m (Laborel et al. 1979: no.45 700 m west of Ag. Roumeli, MC2102, 1860 \pm 70 BP; Pirazzoli et al. 1982: no.45, 1860 \pm 70 BP, shoreline III)	+ 2.50 m (Pirazzoli and Thommeret 1977 (n. 10), MC1378, MC1379, 2400 \pm 70 BP) ⁵⁶ + 2.50 m (Sphakia Survey data; cf. under Level I)
Agios Pavlos (Sphakia Survey Site no. 3.01)	+ 4.60 m (Laborel et al. 1979: no.46)				
Akr. Plaka					+ 4.25 m (Laborel et al. 1979: no.47; Pirazzoli et al. 1982: no.47, MC2106, 1980 \pm 70 BP, shoreline IV)
Kourta					+ 4.40 m (Laborel et al. 1979: no.48; Pirazzoli et al. 1982: no.48, MC2107, 2030 \pm 70 BP, shoreline IV)
Karavopetra					+ 4.40 m (Laborel et al. 1979: no.49)
Loutro (Sphakia Survey Site no. 5.11)	+ ca 4.10 m (Spratt 1865: ii. 252, 13 feet 6 inches) + 3.50 m	+ 3.50 m (Hafemann 1965 (n. 9): 656, H1890/1369, 1705 \pm 60 BP, explaining how			

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	(Flemming 1978: 414 no.127)	Spratt might have measured too high) ⁵⁷			
Akr. Mouros (Sphakia Survey Site no. 5.11, Sector D)	+ 3.80 m, 3.90 m (raised barnacles), 3.84 m (raised coral) (Sphakia Survey data) ⁵⁸				+ 3.70 m-3.80 m (Laborel et al. 1979: no.50; Pirazzoli et al. 1982: no.50, MC2108, 2080 \pm 70 BP, shoreline IV)
Ponda	+ 3.50 m (Laborel et al. 1979: no.51)				
Timios Stavros (Sphakia Survey Site no. 5.21)		+3.60 m (Laborel et al. 1979: no.52; Pirazzoli et al. 1982: no.52, undated, shoreline I?)			+ 3.10 m (Laborel et al. 1979: no.52; Pirazzoli et al. 1982: no.52, MC2104, 2050 \pm 70 BP, shoreline IV) + 2.65 m (Laborel et al. 1979: no.52; Pirazzoli et al. 1982: no.52, MC2103, 2610 \pm 70 BP, shoreline IV' or IVa)
Khora Sphakion (Sphakia Survey Site no. 6.12)		+ 3.30 m (Laborel et al. 1979: no.53) + 3.50 m (Flemming 1978: 414 no.126) Both presumably shoreline I			
Sphakia Beach	+2.10 m +2.40 m (Kelletat and Zimmermann (n. 13), 81-2) + 2.30 m + 2.38 m + 3.00 m + 3.08 m + 3.50 m (Postma and Nemec n. 15) ⁵⁹	+ 3.50 m (Postma and Nemec n. 15)			
Frango-kastello	+ 1.64 m + 2.16 m + 2.61 m	+ 2.81 m (Sphakia Survey data)			

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(Sphakia Survey Site no. 8.50)	+ 2.81 m (Sphakia Survey data). Cf. description in Kelletat and Zimmermann (n. 13), 77-80.	presumably shoreline I.			
Agia Marina (Sphakia Survey Site no. 8.74)		+ 2 m (Flemming 1978: 414 no.124) + ca 2 m. Outcrop + 2.60 m; undercut beachrock (fallen) at +1.85 m, with Prehistoric sherds cemented in before uplift (Sphakia Survey data). Both presumably shoreline I.			

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Lab code	Site	Sea level	m ASL	Model parameter	Material dated	CRA BP	Error	Recorrected age	Error	Ca 1 s
MC2238	Moni Khrysoskalitissas	1	7.9	\square_{47}	<i>Neogoniolithon</i> and <i>Dendropoma</i>	1550	80	1980	82	1
MC2110	Moni Khrysoskalitissas	1	7.8	\square_{46}	<i>Dendropoma</i>	1565	70	1995	73	1
MC2110I	Moni Khrysoskalitissas	1	7.8	na	<i>Dendropoma</i>	1595	70	2025	73	1
MC22110II	Moni Khrysoskalitissas	1	7.8	na	<i>Dendropoma</i> and calcareous algae	1555	70	1985	73	1
MC2114 ⁶⁰	Moni Khrysoskalitissas	1	6.5	\square_{45}	<i>Dendropoma</i>	1575	70	2005	73	1
MC2423 ⁶¹	Moni Khrysoskalitissas	1	7.1	\square_{44}	<i>Serpulorbis</i>	1565	70	1995	73	1
MC2422 ⁶²	Moni Khrysoskalitissas	1	6.6	\square_{43}	<i>Serpulorbis</i>	1595	70	2025	73	1
MC2435	Pharos*	1	2.7	\square_{42}	<i>Neogoniolithon</i> and <i>Dendropoma</i>	1490	70	1920	73	1
MC2430	Kamarela*	1	2.7	\square_{41}	<i>Neogoniolithon</i> and <i>Dendropoma</i>	1530	70	1960	73	1
MC2438	Kaminakia*	1	2.2	\square_{40}	<i>Neogoniolithon</i> and <i>Dendropoma</i>	1490	70	1920	73	1
MC2109	Peristerias	1	7.0	\square_{39}	<i>Dendropoma</i>	1580	70	2010	73	1
MC2195	Moni Khrysoskalitissas	2	7.7	\square_{38}	<i>Dendropoma</i> and calcareous algae	1710	80	2140	82	1
H6341	Phalarsarna	2	6.7	\square_{37}	<i>Neogoniolithon</i>	1680	30	2110	36	1
H6340	Phalarsarna	2	6.7	\square_{36}	<i>Neogoniolithon</i>	1760	45	2190	49	1
H6342	Phalarsarna	2	6.4	\square_{35}	<i>Neogoniolithon</i>	1870	50	2300	54	
MC2200	Phalasarna	2	6.6	\square_{34}	<i>Neogoniolithon</i>	1780	90	2210	92	
MC2102	Agia Roumeli	3	4.25	\square_{33}	<i>Neogoniolithon</i> (?)	1860	70	2290	73	20
MC2282	Moni Khrysoskalitissas	3	7.5	\square_{32}	<i>Dendropoma</i> and calcareous algae	1870	80	2300	82	40
MC2115	Ag. Theodoroi Island	3	3.1	\square_{31}	<i>Dendropoma</i>	1850	70	2280	73	
MC2116	Kamerelou	3	5.2	\square_{30}	<i>Dendropoma</i> and <i>Neogoniolithon</i>	1810	70	2240	73	
MC2101	Pevkoi	3	7.0	\square_{29}	<i>Dendropoma</i>	1850	70	2280	73	
MC2426 ⁶⁴	Phalasarna	3	2.1	\square_{28}	Coral	1660	70	2090	73	1
MC2193	Phalasarna	3	6.4	\square_{27}	Vermetids and <i>Neogoniolithon</i>	1875	100	2305	102	60
MC2105	Plakias Bay (SE of)	3	1.7	\square_{26}	<i>Dendropoma</i> (?)	1880	70	2310	73	40
MC1378 ⁶⁵	Agia Roumeli	4	2.5	\square_{25}	Vermetids and	2400	70	2830	73	7

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Serpulids										
MC1379 ⁶⁶	Agia Roumeli	4	2.5	\square_{b4}	Vermetids and Serpulids	2400	70	2830	73	5
MC2108	Cape Mouros	4	3.8	\square_{b3}	<i>Dendropoma</i> only	2080	70	2510	73	
MC2106	Akr. Plaka	4	4.25	\square_{b2}	<i>Dendropoma</i> only	1980	70	2410	73	170
MC2111 ⁶⁷	Moni	4	7.3	\square_{b1}	Melobesiees and <i>Dendropoma</i>	2225	70	2655	73	4
MC2272 ⁶⁸	Moni	4	7.2	\square_{b0}	<i>Dendropoma</i> and calcareous algae	2000	70	2430	73	19
MC2273	Moni	4	7.3	\square_{l9}	<i>Dendropoma</i> and calcareous algae	2250	70	2680	73	4
MC2274 ⁶⁹	Moni	4?	7.1	\square_{l8}	<i>Dendropoma</i> and calcareous algae	2280	70	2710	73	4
MC2500 ⁷⁰	Moni	4?	7.1	\square_{l7}	<i>Dendropoma</i> and calcareous algae	2500	70	2930	73	8
MC2107	Kourta	4	4.4	\square_{l6}	<i>Dendropoma</i> only	2030	70	2460	73	22
MC2104	Timios Stavros	4	3.1	\square_{l5}	<i>Dendropoma</i> only	2050	70	2480	73	24
MC2103 ⁷¹	Timios Stavros	4?	2.65	\square_{l4}	<i>Neogoniolithon</i> (?) not separated	2610	70	3040	73	9
MC2112	Moni	5	7.0	\square_{l3}	<i>Dendropoma</i> and calcareous algae	3000	70	3430	73	14
MC2275	Moni	5	6.8	\square_{l2}	<i>Dendropoma</i> and calcareous algae	3050	70	3480	73	14
MC2420 ⁷²	Moni	5	5.6	\square_{l1}	<i>Dendropoma</i> and calcareous algae	2830	70	3260	73	1
MC2113	Moni	6	6.7	\square_{l0}	<i>Dendropoma</i> and calcareous algae	3290	70	3720	73	15
MC2421	Moni	6	6.5	\square_b	<i>Dendropoma</i> and calcareous algae	3330	80	3760	82	18
MC2276 ⁷³	Moni	6	6.5	\square_8	<i>Dendropoma</i> and calcareous algae	2900	80	3330	82	1
MC2194	Phalasarna	6	5.9	\square_7	Vermetids and calcareous algae	3400	70	3830	73	19
MC2279 ⁷⁴	Phalasarna	6	5.9	\square_6	Vermetids and calcareous algae	2800	70	3230	73	1
MC2429	Phalasarna	6	5.6	\square_5	<i>Dendropoma</i> and calcareous algae	3420	90	3850	92	19
MC2424	Moni	7	6.3	\square_4	Lithophyllum	3870	90	4300	92	24
MC2425 ⁷⁵	Moni	7	6.3	\square_3	Calcareous algae	3880	90	4310	92	24
MC2428	Phalasarna	7	4.8	\square_2	<i>Dendropoma</i> , Lithophyllum and calcareous algae	3930	90	4360	92	26
MC2427	Phalasarna	8	4.0	\square_1	<i>Dendropoma</i> and calcareous algae	4200	90	4630	92	29

¹ Thanks to a generous permit obtained from the Greek Archaeological Service through the Canadian Archaeological Institute at Athens, researchers began working in Sphakia in 1987. The Survey is co-directed by Lucia Nixon and Jennifer Moody. Fieldwork was conducted in 1987-90, 1992; final site revisiting 1996; study seasons 1992-95, 1997-99.

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Special abbreviations:

Flemming 1978 = N. C. Flemming, 'Holocene eustatic changes and coastal tectonics in the northeast Mediterranean: Implications for models of crustal consumption', *Philosophical Transactions of the Royal Society of London*, 1362 (1978), 405-58

Laborel et al. 1979 = J. Laborel, P. A. Pirazzoli, J. Thommeret and Y. Thommeret, 'Holocene raised shorelines in western Crete (Greece)', in K. Suguio, T. R. Fairchild, L. Martin and J. M. Flexor (eds), *Proceedings 1978 International Symposium on Coastal Evolution in the Quaternary* (Sao Paulo, 1979), 475-501

Pirazzoli 1986 = P. A. Pirazzoli, 'The early Byzantine tectonic paroxysm', *ZfG* n. s. supp. 62 (1986), 31-49

Pirazzoli et al. 1982 = P. A. Pirazzoli, J. Thommeret, Y. Thommeret, J. Laborel and L. F. Montaggioni, 'Crustal block movements from Holocene shoreline: Crete and Antikythira (Greece)', *Tectonophysics*, 86 (1982), 27-43

Pirazzoli et al. 1992 = P. A. Pirazzoli, J. Ausseil-Badie, P. Giresse, E. Hadjidaki, and M. Arnold, 'Historical environmental changes at Phalasarna harbor, West Crete', *Geoarchaeology*, 7 (1992), 371-92

Spratt 1865 = T. A. B. Spratt, *Travels and Researches in Crete*, 2 vols (London, 1865)

Thommeret et al. 1981a = Y. Thommeret, J. Thommeret, J. Laborel, L. F. Montaggioni and P. A. Pirazzoli, 'Late Holocene shoreline changes and

seismo-tectonic displacements in western Crete (Greece)', *ZfG* n. s. supp. 40 (1981), 127-49

Thommeret et al. 1981b = Y. Thommeret, J. Thommeret, J. Laborel, L. F.

Montaggioni and P. A. Pirazzoli, 'Nouvelles données sur les rivages soulevés de l'Holocène dans l'ouest de la Crète', *Oceanis* 7 (1981), 473-80

ZfG = *Zeitschrift für Geomorphologie*

² For some illustrations of wave notches, see in the Sphakia Survey website (n. 16), Region 5 (mouth of the Aradena Gorge) and Site 8.50 (multiple wave notches just east of Frangokastello).

³ Pirazzoli et al. 1982, with further references in n. 11, is the starting point for our work. In this paper conventional radiocarbon ages are given as years BP, following the conventions outlined by M. Stuiver and H. A. Polach, 'Discussion: Reporting of ¹⁴C data', *Radiocarbon*, 19 (1977), 355-63. Calibrated radiocarbon ages are given as cal BC or cal AD.

⁴ Cf. O. Rackham and J. Moody, *The Making of the Cretan Landscape* (Manchester, 1996), 13-15, 195.

⁵ J. A. Gifford, 'The physical geology of the western Mesara and Kommos', in J. W. Shaw and M. C. Shaw (eds), *Kommos* 1.i (Princeton, 1995), pp. 30-87 at pp. 51-5, 71-80, modifies the model of Pirazzoli and others for central Crete.

⁶ *Principles of Geology* (1st edn; London, 1830-33), i. frontispiece and 449-59.

⁷ V. Raulin, *Description physique de l'île de Crète*, 2 vols plus Atlas volume (Paris, 1861), ii. 625-34 (based on field work in 1845); Spratt 1865, ii. 245-6, 249, 252 (field work of 1854).

⁸ Flemming 1978. N. C. Flemming and C. O. Webb, 'Tectonic and eustatic coastal changes during the last 10,000 years derived from archeological data', *ZfG* n. s. supp. 62 (1986), 1-29, extend the analysis to 1053 archaeological sites round the Mediterranean.

⁹ D. Hafemann, 'Die Niveauveränderungen an den Küsten Kretas seit dem Altertum', *Abh. der mathematisch-naturwissenschaftlichen Klasse 1965 no.12*, (Akademie der Wissenschaften und der Literatur [Mainz]. Wiesbaden, 1965), 607-88.

¹⁰ P. A. Pirazzoli and J. Thommeret, J., 'Datation radiométrique d'une ligne de rivage à + 2,5m près de Aghia Roumeli, Crète, Grèce', *C.R.Acad. Sc. Paris*, 284 no.14 (1977), 1255-8; Laborel et al. 1979; P. A. Pirazzoli, J. Thommeret, Y. Thommeret, J. Laborel and L. F. Montaggioni, 'Les rivages émergés d'Antikythira (Cerigotto): corrélations avec la Crète Occidentale et implications cinématiques et géodynamiques', in *Actes du Colloque 'Niveaux marins et tectonique quaternaires dans l'aire méditerranéenne (Paris 29.11.1980)* (Paris, 1981), 50-65.

¹¹ Pirazzoli et al. 1982 offer a synthesis in relation to southwest Crete; Pirazzoli 1986 gives an interpretation of the 'early Byzantine tectonic paroxysm'; P. A. Pirazzoli, 'Sea-level changes and crustal movements in the Hellenic arc (Greece): the contribution of archaeological and historical data', in A. Raban (ed.), *Archaeology of Coastal Changes* (BAR Int. Ser. 404; Oxford, 1988), 157-84, and 'Les ports antiques

soulevés de la Méditerranée orientale’, in *Geoarqueologia i Quaternari litoral*.

Memorial M. P. Fumanal (Valencia, 1999), 391-401, are more general syntheses.

¹² A. T. Grove and O. Rackham, *The Nature of Mediterranean Europe: An Ecological History* (New Haven, 2001), 43-4, recalibrated tsunami dates from Phalasarna which were suggested as being from the AD 365 event and arrived at a later date, AD 530 \pm 100 for the Great Uplift (0.95 probability).

¹³ D. Kelletat and L. Zimmermann, *Verbreitung und Formtypen rezenter und subrezenter organischer Gesteinsbildungen an den Küsten Kretas* (Essener Geographische Arbeiten 23; Paderborn: Schöningh, 1991). Cf. D. Kelletat, ‘The 1550 BP tectonic event in the Eastern Mediterranean as a basis for assuring the intensity of shore processes’, *ZfG* n. s. supp. 81 (1991), 181-94; id., ‘Perspectives in coastal geomorphology of western Crete, Greece’, *ZfG* n. s. supp. 102 (1996), 1-19.

¹⁴ W. Nemec and G. Postma, ‘Quaternary alluvial fans in southwestern Crete: sedimentation processes and geomorphic evolution’, in M. Marzo and C. Puigdefábregas (eds), *Alluvial Sedimentation* (International Association of Sedimentologists, Special Publication 17; Oxford, 1993), pp. 235-76. See also their reply to criticism in *Sedimentology*, 42 (1995), 531-49.

¹⁵ G. Postma and W. Nemec, ‘Regressive and transgressive sequences in a raised Holocene gravelly beach, southwestern Crete’, *Sedimentology*, 37 (1990), 907-20.

¹⁶ The Survey’s website is the best introduction to the work of the Survey: L. Nixon, J. Moody, S. Price and O. Rackham, ‘The Sphakia Survey: Internet Edition’ (2000), <http://sphakia.classics.ox.ac.uk/>; it includes a republication of the three main preliminary articles, and the site database (with photographs of all sites).

¹⁷ As was observed originally by R. M. Ogilvie, 'Phoenix', *Journal of Theological Studies*, n. s. 9 (1958), 308-14, a reference we owe to the indefatigable curiosity of Dr J. Wanklyn.

¹⁸ R. W. Fairbridge, 'Eustatic changes in sea level', *Physics and Chemistry of the Earth*, 4 (1961), 99-185; N.-A. Mörner, 'Eustasy and geoidal changes as a function of core/mantle changes', in Mörner (ed), *Earth Rheology, Isostasy and Eustasy* (Chichester and New York, 1980), 535-53. In relation to the Aegean sea, see K. Lambeck, 'Sea-level changes and shore-line evolution in Aegean Greece since Upper Palaeolithic times', *Antiquity*, 70 (1996), 588-611.

¹⁹ Thommeret et al. 1981a, 136, with fig. 8; P. A. Pirazzoli, 'Tectonic shorelines', in R. W. G. Carter and C. D. Woodroffe (eds), *Coastal Evolution: Late Quaternary Shoreline Morphodynamics* (Cambridge, 1994), pp. 451-76, at pp. 466-8; P. A. Pirazzoli, J. Laborel and S. C. Stiros, 'Coastal indicators of rapid uplift and subsidence: examples from Crete and other eastern Mediterranean sites', *ZfG* n. s. supp. 102 (1996), 21-35; P. A. Pirazzoli, 'Uplift of ancient Greek coastal sites: study methods and results', in S. Stiros and R. E. Jones (eds), *Archaeoseismology* (BSA Fitch Laboratory Occasional Paper 7; Athens, 1996), 237-44.

²⁰ P. A. Pirazzoli, J. Laborel and S. C. Stiros, 'Earthquake clustering in the eastern Mediterranean during historical times', *Journal of Geophysical Research*, 101 (1996), 6083-97; S. C. Stiros, M. Arnold, P. A. Pirazzoli, J. Laborel, F. Laborel and S. Papageorgiou, 'Historical coseismic uplift on Euboea Island, Greece', *Earth and Planetary Science Letters*, 108 (1992), 109-17.

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- ²¹ Pirazzoli et al. 1992; A. Dawson, 'The geological significance of tsunamis', *ZfG* n. s. supp. 102 (1996), pp. 199-210, at pp. 204-5. See further below, n. 48.
- ²² Kelletat 1991 and 1996 (n. 13).
- ²³ J. Laborel and F. Laborel-Deguen, 'Biological indicators of Holocene sea-level variations and of co-seismic displacement in the Mediterranean area', *Journal of Coastal Research*, 10 (1994), 395-415.
- ²⁴ For an introduction to this subject see T. Higham, 'Radiocarbon web-info' (1999), <http://www.c14dating.com>.
- ²⁵ M. Stuiver, G. W. Pearson and T. F. Braziunas, 'Radiocarbon age calibration of marine samples back to 9000 Cal Yr BP', *Radiocarbon*, 28(2B) (1986), 980-1021; M. Stuiver, P. J. Reimer and T. F. Braziunas, 'High-precision radiocarbon age calibration for terrestrial and marine samples', *Radiocarbon*, 40(3) (1998), 1127-51.
- ²⁶ G. Siani, M. Paterne, M. Arnold, E. Bard, B. Metivier, N. Tisnerat and F. Bassinot, 'Radiocarbon reservoir ages in the Mediterranean Sea and Black Sea', *Radiocarbon*, 42 (2000), 271-80.
- ²⁷ P. J. Reimer and F. G. McCormac, 'Marine reservoir corrections for the Mediterranean and Aegean seas'. Manuscript in preparation.
- ²⁸ This calculation follows M. Stuiver and H. A. Polach, 'Discussion: Reporting of ¹⁴C data', *Radiocarbon*, 19 (1977), pp. 355-63 at p. 358 and S. K. Gupta and H. A. Polach, *Radiocarbon Dating Practices at ANU* (Handbook, Radiocarbon Dating Laboratory, Research School of Pacific Studies, ANU; Canberra, 1985); see also discussion in Stiros et al. (n. 20); also, M. Arnold, E. Hadjidaki, L. F. Montaggioni, P. Giresse, J. Ausseil-Badie and P. A. Pirazzoli, 'The raised harbor of Phalasarna (West Crete): Archaeological, stratigraphic and radiometric data' (unpub. manuscript).

²⁹ Stuiver and Polach (n. 28); we are grateful for advice on this point to Dr Paula J. Reimer.

³⁰ Pirazzoli 1986.

³¹ For an introduction to archaeoseismology, see R. E. Jones and S. C. Stiros, 'The advent of archaeoseismology in the Mediterranean', in W. J. McGuire, D. R. Griffiths, P. L. Hancock and I. S. Stewart (eds), *The Archaeology of Geological Catastrophes* (Geological Society, Special Publication 171; London, 2000), 25-32. G. A. Carver and J. P. McCalpin, 'Paleoseismology of compressed tectonic environments', in McCalpin (ed.), *Paleoseismology* (San Diego etc., 1996), pp. 183-270, is also helpful.

³² F. Jacques and B. Bousquet, 'Le raz de marée du 21 Juillet 365. Du cataclysme local à la catastrophe cosmique', *MEFRA* 96 (1984), 423-61, presenting a maximalist view of the scope of this event. The evidence is reviewed more critically by E. Guidoboni, A. Contastri and G. Traina, *Catalogue of Ancient Earthquakes in the Mediterranean up to the 10th Century* (Rome, 1994), 267-74, and N. N. Ambraseys, C. P. Melville and R. D. Adams, *The Seismicity of Egypt, Arabia and the Red Sea: A Historical Review* (Cambridge 1994), 22-4. On Libya see more recently N. N. Ambraseys, 'Material for the investigation of the seismicity of Libya', *Libyan Studies*, 25 (1994), 7-22; D. White, 'Fresh reverberations from Cyrene's later antique earthquakes', in L. Bacchielli and M. B. Aravantinos (eds), *Scritti di antichità in memoria di Sandro Stucchi* (Studi Miscellanei 29; Rome, 1996), i, pp. 317-25 (references we owe to Dr A. Wilson). For a list of Greek earthquakes (not using the works cited above), see 'The telemetry seismological network of Geophysical

Department of Thessaloniki University, Greece’,

<http://geohazards.cr.usgs.gov/iaspei/europe/greece/the/>.

³³ S. C. Stiros and S. Papageorgiou, ‘Seismicity of western Crete and the destruction of the town of Kissamos at AD 365: archaeological evidence’, *Journal of Seismology*, 5 (2001), 381-97; Stiros, ‘The AD 365 Crete earthquake and possible seismic clustering during the fourth to sixth centuries AD in the eastern Mediterranean: A review of historical and archaeological data’, *Journal of Structural Geology*, 23 (2001), 545-62 (Kissamos and Eleutherna). See also Stiros, S. Papageorgiou and S. Markoulaki, ‘Καταστροφή των Κρητικών πόλεων το 365 μ.Χ.’, Πρακτικά Διεθνούς Συνεδρίου *Creta Romana e Protobizantina 2001*; A. G. Drakos and S. C. Stiros, ‘Ο σεισμός του 365 μ.Χ. από το θρύλο στην προσομοίωση’, Δελτίο Ελλ. Γεωλογική Εταιρεία 34.5 (2001), 1417-24.

³⁴ *IG* iv. 674 (republished by D. Feissel and A. Philippidis-Braat, ‘Inventaires en vue d’un recueil des inscriptions historiques de Byzance: III Inscriptions du Péloponnèse (à l’exception de Mistra)’, *Travaux et Mémoires*, 9 (1985), 267-395, at p. 274 no. 9) records restorations at Nauplion (AD 375-378) following ‘earthquakes and tsunamis (?)’, κατὰ σεισμούς καὶ τοὺς θαλαττίους / κατακλυσμούς ? ...] (We owe this reference to Mr G. Deligiannakis.) However, it is not possible to establish whether any of the events referred to are the major quake of AD 365.

³⁵ N. N. Ambraseys and D. P. White, *Seismicity of the East Mediterranean and Middle East I* (ESEE Research Report 96; Civil Engineering Department, Imperial College London, 1996), 10.

³⁶ Cf. Guidoboni et al. (n. 32); Ambraseys et al. (n. 32); G. Waldherr, *Erdbeben, das aussergewöhnliche Normale: zur Rezeption seismischer Aktivitäten in literarischen Quellen vom 4. Jahrhundert v. Chr. bis zum 4. Jahrhundert n. Chr.* (Geographica historica 9; Stuttgart, 1997).

³⁷ A. Di Vita, 'Earthquakes and civil life at Gortyn (Crete) in the period between Justinian and Constant II (6-7th century AD)', in Stiros and Jones (n. 19), 45-50; AD 796 (April) Theophanes 470.5-10: Guidoboni et al. (n. 32); Ambraseys et al. (n. 32), 26.

³⁸ A. R. Lowry, K. M. Larson, V. Kostoglodov and R. Bilham, 'Transient fault slip in Guerrero, southern Mexico', *Geophysical Research Letters*, 28 no. 19 (2001), 3753-6.

³⁹ The ratio of the slip in an earthquake to the length of the fault that slipped is usually between 1 part in 10^{-4} and one part in 10^{-5} , thus a slip of about 10 metres in an earthquake would imply a fault length of between 100 and 1000 km. Cf. C. H. Scholz, *The Mechanics of Earthquakes and Faulting* (Cambridge, 1994). We owe this point to Prof. Philip England.

⁴⁰ J. A. Jackson and D. McKenzie, 'The relationship between plate motions and seismic moment tensors, and the rates of active deformation in the Mediterranean and Middle East', *Geophysical Journal*, 93 (1988), 45-73; Jackson, 'Active tectonics of the Aegean region', *Annual Review of Earth and Planetary Sciences*, 22 (1994), 239-71; Jackson, 'Living with earthquakes: Know your faults', *Journal of Earthquake Engineering*, 5 special issue 1 (2001), 5-123, at pp. 86-8.

⁴¹ C. E. Buck, W. G. Cavanagh and C. D. Litton, *Bayesian Approach to Interpreting Archaeological Data* (Chichester, 1996).

⁴² C. E. Buck, C. D. Litton and A. F. M. Smith, 'Calibration of radiocarbon results pertaining to related archaeological events', *Journal of Archaeological Science*, 19 (1992), 497-512; Buck et al. (n. 41); C. E. Buck and J. A. Christen, 'A novel approach to selecting samples for radiocarbon dating', *Journal of Archaeological Science*, 25 (1998), 303-10; C. Bronk Ramsey, 'Radiocarbon calibration and analysis of stratigraphy: The OxCal program', *Radiocarbon*, 37 (1995), 425-30.

⁴³ C. E. Buck, J. A. Christen and G. N. James, 'An on-line Bayesian radiocarbon calibration tool', *Internet Archaeology*, 7 (2000):
<http://intarch.ac.uk/journal/issue7/buck/index.html>.

⁴⁴ The BCal calibration model was run three times with a Markov Chain Monte Carlo (MCMC) sampler of 50000 iterations collected at a sampling interval of 50 (see nn. 41 and 42) with a convergence checking of 4. As there were no significant differences between each run, we are confident in the reproducibility of the sampling in this dataset.

⁴⁵ The authors of the various papers from which the radiocarbon data were obtained had suggested that the dates might be problematic (see notes and references to Table 3).

⁴⁶ C. E. Buck, T. F. G. Higham and D. J. Lowe, 'Bayesian tools for tephrochronology', unpublished manuscript.

⁴⁷ J. A. Christen, 'Summarizing a set of radiocarbon determinations: a robust approach', *Applied Statistics* 43.3 (1994), 489-503.

⁴⁸ We note that D. Dominey-Howes, A. Dawson and D. Smith, 'Late Holocene coastal tectonics at Falasarna, western Crete: A sedimentary study', in I. S. Stewart

and C. Vita-Finzi (eds), *Coastal Tectonics* (Geological Society, Special Publications 146; London, 1998): 343-52) find no evidence of a tsunami dating around AD 365 in their analysis of putative tsunami deposits in Phalasarna harbour.

⁴⁹ On date, see J. Rougé, *Recherches sur l'organisation du commerce maritime en Méditerranée sous l'empire romain* (Paris, 1966), 24-5; cf. O. Cuntz, 'Der Stadiasmus Maris Magni', *Texte und Untersuchungen zur Geschichte der altchristlichen Literatur* 29 (1906), pp. 243-76, at pp. 243-53.

⁵⁰ Spratt 1865, ii. 244-6, who vividly describes the difficulty of landing there nowadays. The topography of the original beach is well illustrated in Pirazzoli 1999 (n. 11), 397 fig. 9.

⁵¹ A thick layer of sand has accumulated on both sides of the river; on the west side it is 2-3 metres thick near the coast. This postdates the Roman period (Archaic-Classical and Roman graves were excavated beneath 1.50 m of sand: I. Tzedakis, 'Δυτική Κρήτη', *A. Delt.* 25.2 (1970), Khron. 473; K. Davaras, 'Δυτική Κρήτη', *A. Delt.* 26.2 (1971), Khron. 511). In the region of Kommos there was also a sudden deposit of sand after the Hellenistic period, after two millennia of gradual deposit (Gifford, n. 5). It is tempting (though Gifford does not do so) to relate this to the sudden 2 m uplift in the area between 100 BC and AD 200, which might have caused a tsunami. The same might be true for Agia Roumeli.

⁵² Cf. J. Moody, L. Nixon, S. Price, and O. Rackham, 'Surveying *poleis* and larger sites in Sphakia', in W. G. Cavanagh, M. Curtis et al. (eds), *Post-Minoan Crete* (BSA Studies 2; London, 1998), pp. 87-95, at p. 89.

⁵³ We are grateful here to advice on dating from Prof. K. Dunbabin.

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- ⁵⁴ For discussion of the importance of different altitudes in Sphakia, see L. Nixon, J. Moody, S. Price, and O. Rackham, 'Rural settlement in Sphakia, Crete', in P. Doukellis and L. Mendoni (eds), *Structures rurales et sociétés antiques: Actes du colloque de Corfou 14-16 mai 1992* (Annales littéraires de l'Université de Besançon; Paris, 1994), 255-64; Moody and Nixon et al. (n. 52), 90-2.
- ⁵⁵ P. Brulé, *La piraterie crétoise hellénistique* (Paris, 1978), 148-56; I. F. Sanders, *Roman Crete to the Arab Period* (Warminster, 1982), 30-1; cf. E. Kirsten, *Das dorische Kreta* (Würzburg, 1942), 80-6 and A. Petropoulou, *Beiträge zur Wirtschafts- und Gesellschafts- geschichte Kretas in hellenistischer Zeit* (Frankfurt am Main, 1985), 133-4.
- ⁵⁶ Pirazzoli and others do not assign this reading to one of the later determined shorelines, but our recalibration of the data puts it firmly in level IV.
- ⁵⁷ Our recalibration of this datum is as follows: 2135±63BP, cal AD 175-425 (68.2 % probability), cal AD 60-550 (95.4% probability), which puts the reading firmly in Level I (cf. Table 2). However, the actual height of the reading is on the low side, and we have therefore excluded it from further analysis.
- ⁵⁸ It is unclear if these readings belong to Level I or to one of the lower levels. If the latter, then the depth of water in the pre-uplift harbour would be a little deeper than 2 m, but (because of the range of data for Level I from west and east of this site) not very much deeper.
- ⁵⁹ These figures are calculated from Postma and Nemec (n. 15), fig. 5 (Station 100).

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- ⁶⁰ Thommeret et al. 1981a: 142: Collapsed block. Pirazzoli et al. 1982: local collapse of 1.30 m.
- ⁶¹ Thommeret et al. 1981a: 142: Sublittoral fauna.
- ⁶² Thommeret et al. 1981a: 142: Sublittoral fauna.
- ⁶³ We have selected only three of the eight new data given in Kelletat and Zimmermann's publication because we have been unable to determine the relationship of the other data to specific sea levels.
- ⁶⁴ Thommeret et al. 1981a: 143: Sublittoral fauna.
- ⁶⁵ Pirazzoli et al. 1982: 35: Level 4'. The main vertical movement of Level 4 seems to have been preceded by 'ephemeral reversed displacements' (Pirazzoli et al. 1982: 32). These displacements are indicated by 4' or 4a.
- ⁶⁶ Pirazzoli et al. 1982: 35: Level 4'.
- ⁶⁷ This is identified as *Dendropoma* and calcareous algae, according to Pirazzoli et al. 1982: 34.
- ⁶⁸ Thommeret et al. 1981a: 142: slightly contaminated by younger material?
- ⁶⁹ Thommeret et al. 1981a: 142: slightly contaminated by younger material? So Pirazzoli et al. 1982: 35. Level 4'.
- ⁷⁰ Pirazzoli et al. 1982: 35: Level 4'.
- ⁷¹ Pirazzoli et al. 1982: 35: Level 4' or 4a.
- ⁷² Thommeret et al. 1981a: 142: collapsed block. Pirazzoli et al. 1982: local collapse of 1.30 m.
- ⁷³ Thommeret et al. 1981a: 142: slightly contaminated by younger material?
- ⁷⁴ Pirazzoli et al. 1982: 35: slightly contaminated by younger material?
- ⁷⁵ Thommeret et al. 1981a: 142: Sublittoral fauna; Level 6 (?). Thommeret et al. 1981b: 474 show that this sample was taken from around MC2424, and therefore belongs to Level 7.