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Late Holocene coastal tectonics at Falasarna, western Crete: a sedimentary study

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Abstract: The late Holocene sedimentary record of Falasarna Harbour, western Crete, includes detailed evidence of tsunamis and serves as an independent dataset to evaluate the magnitude and timing of coastal tectonic movements in an area affected by contrasting tectonic regimes. Analysis of a foraminiferal assemblage makes it possible to identify suites of tsunami-deposited sediments within normal sedimentary sequences. The palaeo-environmental record is then complemented with a sequence of raised fossil marine notches. The transitional boundary between marine and terrestrial sedimentation indicates tectonic uplift at *c.* AD 63–75 ± 90 radiocarbon years BP, which is in conflict with previously published interpretations. No sedimentary evidence can be found for a tsunami believed to be associated with a large uplift event during AD 365.

This paper presents the results of an investigation at Falasarna Harbour, western Crete, of sediments deposited by tsunamis reported to have occurred in the Aegean Sea region of Greece. Falasarna is located within an active extensional domain inboard of the compressional front associated with subduction of the Mediterranean plate, and, is therefore affected by different tectonic regimes. Any sedimentary evidence for tsunamis may help to shed light on the nature of coastal tectonic activity in this area.

Biostratigraphic (Foraminifera) and lithostratigraphic evidence was used to determine the palaeoenvironmental history of Falasarna. We show that, following the construction of the harbour, sedimentation progressed until the site was affected by tectonic movement. The sedimentological data indicate that the harbour of Falasarna was raised above sea level, as reflected by a change from marine to terrestrial conditions. The data do not preserve evidence for a large vertical coseismic displacement reported to have occurred in AD 365 (Pirazzoli 1986).

Tectonic setting

On a regional scale, the present form of the Aegean is the result of a set of complex interactions between phases of compressional and extensional tectonic normal faulting which result from the southward stretching and subsidence of the Aegean plate (Le Pichon & Angelier 1981; Mercier 1981). The Aegean region is composed of the Inner Hellenic Volcanic Arc and the Outer Hellenic Arc (with subducting trench system) (Fig. 1). The Outer Hellenic Arc forms part of a rigid body thrusting over the Mediterranean basins and is associated with the development of the accretionary complex and a compressional front located south of Crete at the junction between the African and European plates (Lallemant *et al.* 1994). The Falasarna study site lies within an active extensional domain inboard of the compressional front and is found at the western end of the island of Crete, the most prominent feature of the Outer Hellenic Arc and which has been affected by uplift during the Holocene. The uplift is related to the development of the compressional front and the accretionary wedge by underplating of sediments from the downgoing plate beneath the continental upper plate (Le Pichon & Angelier 1981; Lallemant *et al.* 1994).

Figure 1 provides a schematic representation of the main structural and tectonic components for the region in which Falasarna is located. It should be noted that the area to the south of western Crete is characterized by a series of E–W trending faults, whereas to the west of Crete, the main offshore faults trend N–S. To the NW of Crete, the orientation of submarine faults changes to NW–SE. Such radically different tectonic regimes in closely adjoining areas have prevailed since early Quaternary time (Angelier 1978); Jackson (1994) noted that the faults associated with the Outer Hellenic Arc are affected by normal, reverse and thrust movement. The area considered in this study is affected by both relatively shallow earthquakes associated with extensional faulting of the overriding

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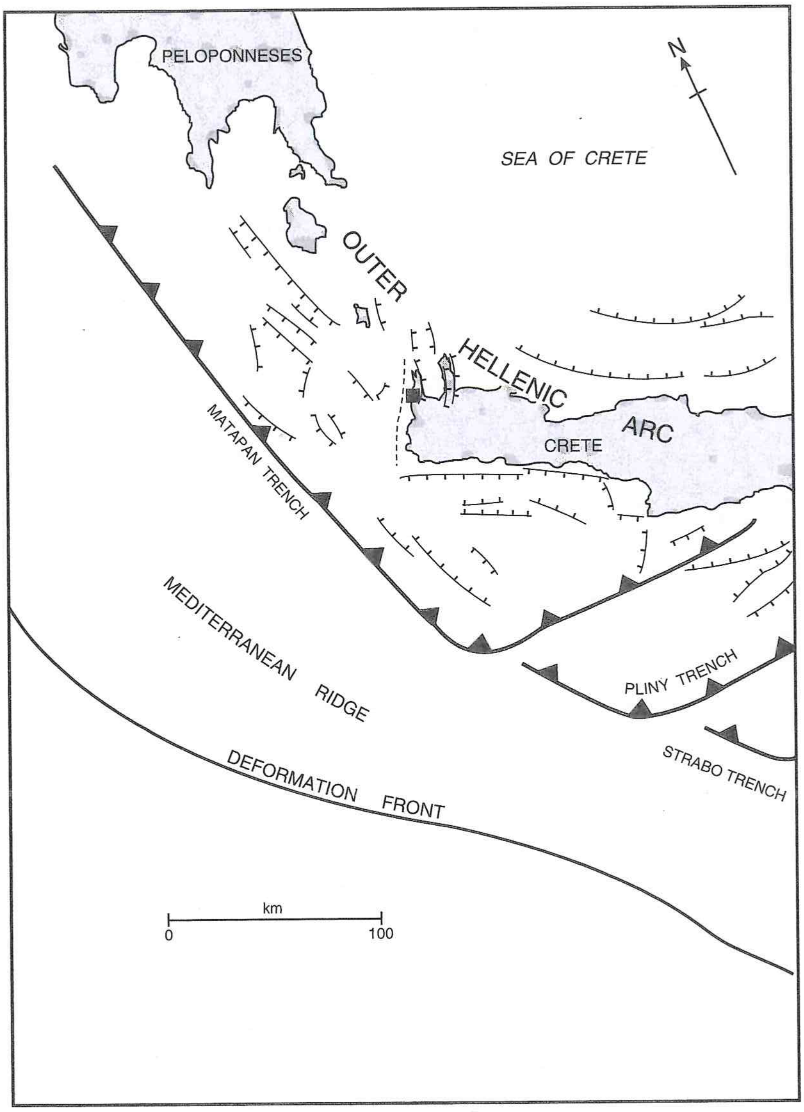

Fig. 1. Schematic representation of the main structural components of the Outer Hellenic Arc, subduction system and compressional front (Mediterranean Ridge and deformation front). Location of the study site is shown by the square.

upper-crustal plate and by deeper earthquakes associated with thrust movement of the subducting plate (Taymaz *et al.* 1990; Lallemant *et al.* 1994; Stewart, pers. comm. 1997).

Conceptual framework and methods

It has been reported that the harbour of Falasarna contains a record of late Holocene sedimentation and that the harbour sediments include deposits laid down by tsunamis which flooded the area in AD 66 and AD 365 (Pirazzoli *et al.* 1992). To elucidate the palaeoenvironmental history of this site, the lithostratigraphy of sedimentary sequences was investigated in five trenches excavated by the Greek Regional Archaeological Service at Falasarna. The elevation of all units was determined by instrumental levelling using a Zeiss Autoset Level. All levelling traverses were closed with no error greater than ±0.01 m. In the absence of a Greek Datum, present sea level was assumed to be true mean sea level, as tidal variations rarely exceed 10 cm (P. A. Pirazzoli, pers. comm., 1994). It is recognized, however, that sea-level variations as a result of tidal cycles, atmospheric conditions, the nature of the geoid, storminess and seasonality may result in variations of mean sea level approaching 50 cm (IAPSO 1985; Emery *et al.* 1988; Flemming & Woodworth 1988; Flemming 1992).

Variations in the stratigraphy based upon changes in clast content, colour, lithology, matrix, shell content, stone content, clast roundness, structure and texture were recorded. Contiguous 0.05 m bulk samples (125 cm^3) of sediments were collected successively through the sequence from the base to the top of each trench for laboratory investigation including detailed biostratigraphic analysis based on Foraminifera. Foraminifera counting was carried out using a VMT 12 microscope at $\times 1$ and $\times 4$ magnification. Reference was made to type collections at the Department of Micropalaeontology at the Natural History Museum, London, and the accounts of Sidebottom (1904–1909) and Cimerman & Langer (1991). Wherever possible, 300 individuals were counted in each sample to ensure statistical confidence. Particle size analysis was unsuccessful because detailed variations were obscured by the sample size adopted and since over 80% of the sediment is composed of marine biogenic $CaCO_3$ (Pirazzoli *et al.* 1992).

Falasarna Harbour, site description

Falasarna was a pirate port which operated between approximately the middle of the fourth century BC and the late first century BC (Hadjidaki 1988). The date at which the harbour became functional and the date at which it was finally abandoned are not known exactly (Hadjidaki 1988; Frost 1997), although the harbour was in existence by the time of Scylax of Caryanda in the middle of the fourth century BC (Hadjidaki 1988).

The harbour is situated next to the Bay of Livadi in an enclosed position behind the eastern side of Cape Kutri at the southern end of the Grammvousa peninsula in western Crete. It is an quadrangular artificial harbour cut into the surrounding Mesozoic limestone and Scylax referred to Falasarna's status as a closed harbour (Pirazzoli *et al.* 1992, p. 375). The main harbour is 100 m × 75 m in size and is divided from a secondary basin 50 m × 35 m lying immediately to the east by a complex of walls and buildings. The main harbour is connected to the sea at its western side by a channel which stretches 100 m to the present shoreline (Fig. 2). The ground surface within the main harbour is at an elevation of 6.6 m above sea level (m a.s.l.).

Hadjidaki (1988) suggested that Falasarna was probably destroyed by the Romans in 67 BC. She stated that the Romans sent Caecillius Metellus as a praetor to Crete to destroy a number of pirate strongholds. According to Pirazzoli *et al.* (1992), after its destruction the harbour rapidly filled with marine and terrestrial sediments and was inundated by tsunamis in AD 66 and in AD 365, when it was uplifted to 6.6 m a.s.l. by an earthquake on 21 July. There is no evidence at Falasarna of continued occupation after the destruction of 67 BC.

Sedimentology

In this paper only the results of the sedimentological analysis of Trench A are presented because this trench displays the clearest sedimentary record (Dominey-Howes 1996). Trench A is located within the main harbour basin (Fig. 2). The surface is at an elevation of 6.2 m a.s.l. and the base is at 4.6 m a.s.l. (Fig. 3). Five lithostratigraphic units occur within the sedimentary sequence.

The basal unit is a Foraminifera- and mollusc-rich, well-sorted fine to medium sand. The unit contains coarse rounded to angular grit. There are many small to medium-sized well-rounded to subangular limestone, sandstone and quartz clasts. The matrix contains many whole and comminuted marine molluscs. Many small subrounded pottery sherds are visible. Some crude horizontal bedding is apparent. The upper boundary of this unit is defined by an undulating unconformity. The basal unit is overlain by a mollusc- and Foraminifera-rich marine sand which contains rounded fine grit. The unit is further characterized by large numbers of whole and broken marine molluscs with no obvious orientation. Medium to large subrounded to subangular limestone and sandstone clasts and blocks (*a*-axis up to 10 cm) are present. There is no obvious bedding or structure, although clast *a*-axis tends towards the horizontal. The upper boundary of this unit is defined by an undulating unconformity. The middle unit is composed of a fine to medium-sized sand and grit and is further characterized by abundant well-rounded to subangular limestone and sandstone clasts. The smaller clasts are matrix supported whereas the larger blocks (*a*-axis from 20 cm) are clast supported. The *a*-axis of the clasts tends towards the horizontal although there is no other

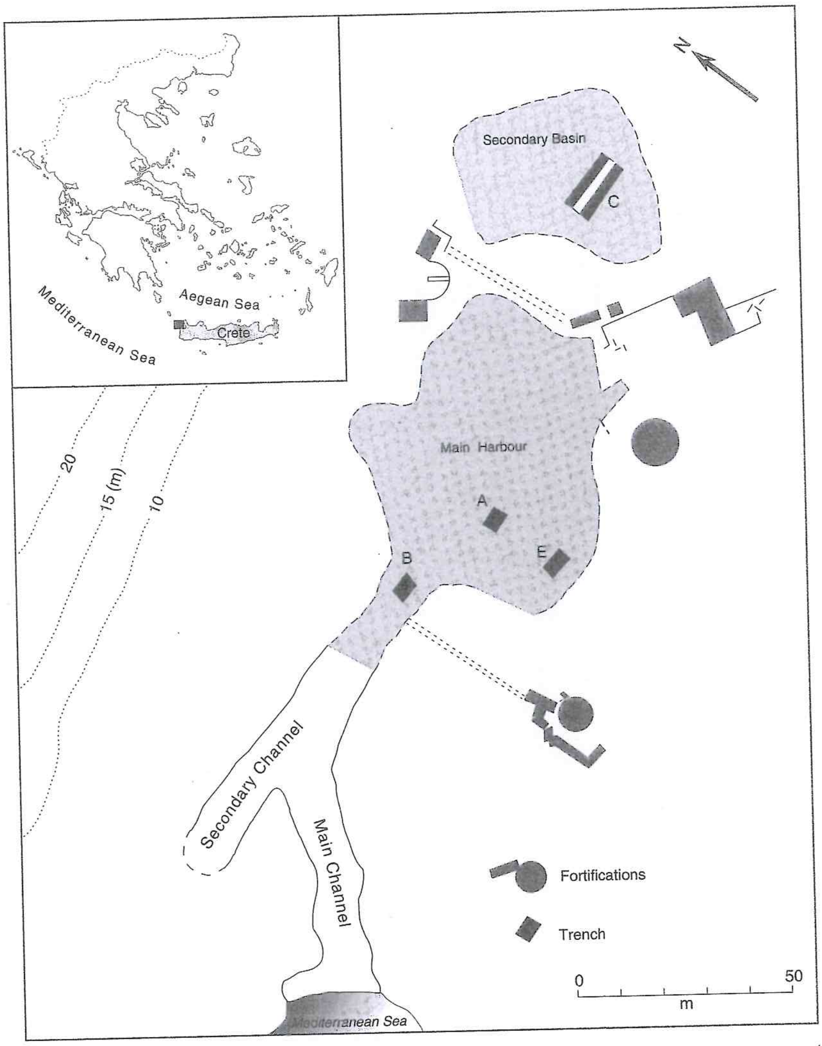

Fig. 2. Detail of Falasarna Harbour and the position of the trenches. This paper presents the results of only Trench A. Cape Kutri is located immediately to the north of the harbour. The main channel connects with the Bay of Livadi.

obvious bedding or structures. Both whole and comminuted molluscs are present, as are small rounded pottery sherds. This unit is conformably overlain by a red silty clay sand which extends to the surface of the trench. There are many small to large subrounded to very angular limestone, sandstone and quartz clasts which are matrix supported. A few broken marine molluscs are found towards the base of this unit and there is no apparent bedding or structure. This unit is interrupted by numerous subrounded limestone blocks at 5.70–5.90 m a.s.l. (Fig. 3). This unit represents the sediments reported to have been deposited by a tsunami in AD 365 (Pirazzoli *et al.* 1992). The *a*-axis of these blocks is up to 18 cm in length, and is approximately horizontal, and the blocks are matrix supported.

More than 5200 Foraminifera were extracted and identified from the Trench A sediments and 28 species were identified (Table 1). The number of individuals (300+) per sample is high from the bottom of the trench upwards as far as sample 14 (Table 1); between samples 15 and 20 it declines rapidly and remains low (nine individuals in sample 21 to four in sample 23). None is recorded from sample 24 upwards to the surface

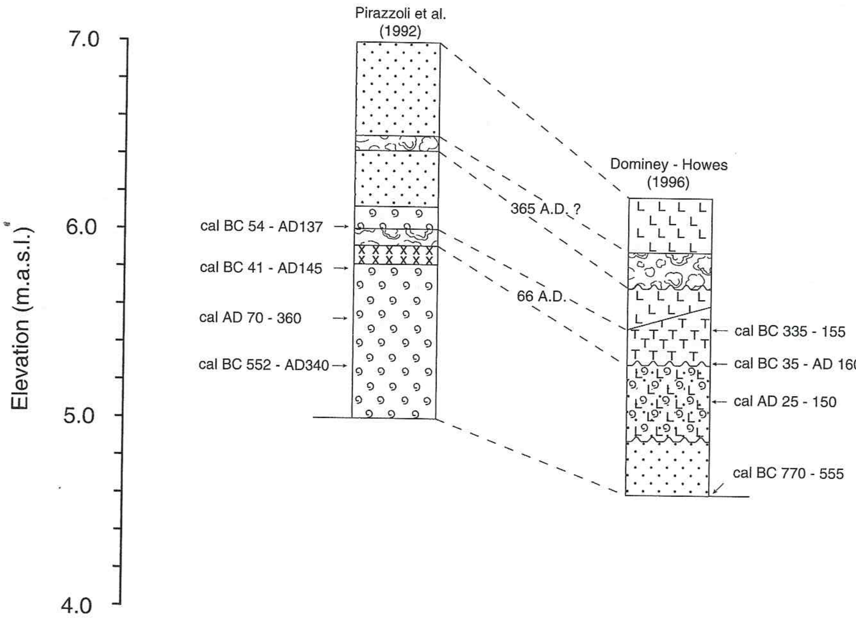

Fig. 3. Stratigraphy of Trench A according to the present authors and Pirazzoli *et al.* (1992). It can be clearly seen that the elevations of the base and top of Trench A vary between the two studies. (For a description of the lithostratigraphic units, refer to the text.)

of the trench. The assemblage of Foraminifera present in samples 1–17 is dominated by *Ammonia beccarii*, *Ammonia parkinsoniana*, *Ammonia tepida*, *Elphidium advenum*, *Elphidium crispum*, *Globigerina ruber*, *Quinqueloculina aspera*, *Quinqueloculina bicornis* and *Quinqueloculina vulgaris* (Table 1). These species make up 64% of the Foraminifera present within the Trench A samples. The rarest species of Foraminifera preserved are *Quinqueloculina jugosa*, *Lachlanella variolata* and *Triloculina tricarinata*, which constitute 0.4%, 1.6% and 1.8% of the total count, respectively.

The number of individuals per sample of *Cibicides advenum* increases from an average of six specimens per sample in samples 1–14 to an average of 11 specimens per sample in samples 15–20. Similarly, *Eponides repanda* increases from an average of 2.2 specimens per sample in samples 1–14 to seven specimens per sample in samples 15–20. It is also worth noting that there is an increase in the number of broken tests for all species from an average of 21% of tests in samples 1–14 and 21–23 to an average of 55% of tests in samples 15–20.

Pennate forms of Foraminifera total 555 specimens and the average percentage of broken tests is 26% in samples 1–14 and 21–23, compared with 83% in samples 15–20. The average percentage of broken centric forms in samples 1–14 and 21–23 is 21%, and in samples 15–20 is 18%. Therefore, a higher percentage of pennate to centric Foraminifera are broken in samples 15–20.

Table 2 gives the results of radiocarbon dating. The AMS (accelerator mass spectrometry) technique was used as no sample weighed more than 2.0 g. For the purpose of consistency all samples submitted for dating comprised specimens of the marine mollusc *Hydrobia acuta*. Calibration to calendar years was made by reference to the data of Stuiver & Braziunas (1993). The $^{13}C/^{12}C$ ratios are compared with those given as $-5 \pm 40‰$ for the eastern Mediterranean by Stuiver & Braziunas (1993). As they lie well within the -45 to $+35‰$ range (Table 2) the shell ages reported here are taken to be reliable.

Interpretation of palaeoenvironmental history

The most striking aspect of the lithostratigraphy of Trench A is that there is a clear change in the pattern of the sedimentation at *c.* 5.70 m a.s.l. and this change dates from AD 63 to AD 75 ± 90 radiocarbon years BP. The abrupt change of sedimentation is from marine conditions characterized by the deposition of Foraminifera–mollusc-rich sands to terrestrial silts and clay

Table 1. *Summary of Foraminifera identified in the Trench A samples*

Species	Sample unit number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Ammonia beccarii (Linnaeus)	18	21	23	7	31	24	24	27	32	24	14	17	20	22	19	17	24	12	3	2	3	1	1
A. parkinsoniana (d'Orbigny)	14	17	17	12	21	19	14	19	0	13	21	18	23	11	17	21	23	19	6	3	1	1	0
A. tepida (Cushman)	12	11	19	8	10	13	16	14	21	18	6	29	37	37	12	11	13	4	0	0	0	0	0
Asteriqerinata mamilla (Williamson)	0	5	0	0	7	9	0	0	12	0	0	7	0	0	6	8	7	3	0	0	0	0	0
Cibicides advenum (d'Orbigny)	0	0	6	0	0	13	9	7	0	14	0	6	11	16	11	19	15	8	0	0	0	0	0
C. Iobatulus (Walker and Jacob)	0	5	0	22	6	8	7	8	6	0	0	0	0	0	13	9	7	0	0	0	0	0	0
C. refulgens (Montfort)	8	12	11	11	11	9	7	12	11	9	9	14	14	6	17	14	15	6	3	0	0	0	0
Elphidium advenum (Cushman)	17	21	23	22	23	19	23	29	21	17	19	17	23	16	32	42	38	14	4	5	0	0	0
E. crispum (Linnaeus)	39	32	32	48	30	28	36	43	38	33	29	32	35	36	37	34	34	23	7	7	3	2	2
E. macellum (Fitchel and Moll)	21	17	18	0	25	24	7	13	0	18	0	19	0	24	0	0	7	0	0	0	0	0	0
Eponides repanda (Fitchel and Moll)0	0	0	0	0	5	8	0	0	5	0	0	0	7	6	12	14	7	6	0	0	0	0	0
Globigerina ruber (d'Orbigny)	13	16	19	7	22	14	13	19	18	12	7	12	11	21	19	14	12	14	2	0	1	0	0
Laclanella variolata (d'Orbigny)	0	0	2	2	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0
Lobatula lobatula (Walker and Jacob)	0	0	0	16	0	4	4	0	6	0	0	0	0	0	0	0	4	0	8	4	0	0	0
Nonion commune (Walker and Jacob)	7	5	6	8	7	8	9	3	6	11	3	6	0	0	0	0	8	3	0	0	0	0	0
Peneroplis pertusus (Forskall)	4	10	8	2	0	7	8	8	0	7	0	7	0	10	4	0	0	0	0	0	0	0	0
P. planatus (Fitchel and Moll)	6	0	11	5	5	9	11	12	11	9	5	11	7	7	14	9	9	7	1	0	0	0	0
Quinqeloculina aspera (d'Orbigny)	28	26	24	16	16	14	28	12	20	22	7	27	18	21	14	8	14	7	3	0	0	0	0
Q. bicornis (Walker and Jacob)	21	22	26	22	28	19	24	18	17	12	19	19	28	11	27	29	23	9	6	5	0	0	0
Q. cliarensis (Heron-Allen and Earland)	17	10	6	13	10	7	0	0	11	8	2	22	9	6	13	19	0	0	0	0	0	0	0
Q. jugosa (Cushman)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Q. seminula (Linnaeus)	14	16	12	16	0	8	8	11	11	12	0	0	13	17	0	10	0	0	0	0	0	0	0
Q. vulgaris (d'Orbigny)	27	26	16	24	19	8	19	12	16	13	11	12	12	10	8	0	14	12	2	2	0	0	0
Roslina globularis (Egger)	14	12	7	4	7	7	8	5	7	8	4	6	8	6	5	3	0	0	0	0	0	0	0
Spiroloculina ornate (d'Orbigny)	4	11	6	12	6	9	8	16	16	18	0	7	7	6	7	9	14	4	0	0	0	0	0
Triloculina laevigata (d'Orbigny)	8	0	0	6	0	4	9	0	5	0	0	0	4	0	0	0	0	0	0	0	0	0	0
T. oblonga (Montagu)	6	5	8	19	11	8	8	8	10	18	9	12	13	11	10	10	12	5	3	0	0	0	0
T. tricarinata (d'Orbigny)	2	0	0	0	0	0	0	4	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0
Total	300	300	300	300	300	300	300	300	300	300	165	300	300	300	300	300	300	156	48	28	9	4	4

Table 2. *^{14}C AMS dates of samples from Trench A*

Sample	Measured	Conventional	$^{13}C/^{12}C$ (‰)	Calibrated
Beat-81412	2460 ± 70	2870 ± 70	0.0	770–555 BC
Beta-81413	1900 ± 60	2270 ± 60	−2.4	AD 25–150
Beta-81414	1890 ± 90	2290 ± 90	−0.8	35 BC–AD160
Beta-81415	2110 ± 60	2530 ± 60	+0.7	335–155 BC

The dates are plotted on Fig. 3.

(with some sand). This change is sudden, as indicated by the boundary unconformity, and is thought to represent relative sea- and land-level changes associated with vertical coseismic deformation. The conditions in which the deposition of large, well-rounded to subangular limestone and sandstone blocks between 5.20 and 5.60 m a.s.l. were deposited are thought to be different from those that had operated during marine sedimentation. It is believed by the present authors that deposition of the larger blocks at this level probably relates to a high-energy low-frequency event such as a tsunami. The evidence to support this interpretation is described below.

Samples 15–20 in Table 1 correspond lithostratigraphically to the sediments ascribed by Pirazzoli *et al.* (1992) to a tsunami in AD 66 (Fig. 3). Sample 15 lies unconformably on top of the underlying sediments. The evidence provided by the Foraminifera shows clearly that the last episode of marine sedimentation within the harbour was probably during or just after the AD 66 tsunami event reported by Pirazzoli *et al.* (1992). There is no evidence for marine sedimentation taking place anywhere within the harbour after this event.

Of the Foraminifera recovered from Trench A, 64% belong to the *Ammonia*, *Elphidium* and *Quinqueloculina* genera (Table 1). According to Murray (1991), these three genera are all found together in the shallow inner-shelf region. The *Ammonia* and *Elphidium* genera are also representative of brackish conditions, but the presence of *Quinqueloculina* is representative of open marine-lagoonal conditions. Parker (1958) identified a 'typical' shallow-depth assemblage between 0 and 25 m, which he referred to as the 'bay–open marine' assemblage. The presence of the high numbers of *Ammonia*, *Elphidium*, Miliolidae and Peneroplidae indicate a clear shallow, fully marine (lagoonal) assemblage at Falasarna similar to that identified by Parker (1958).

Murray (1991) noted that *Cibicides* species range from the inner shelf (0–100 m) through the outer shelf (100–200 m) and in to the upper slope (200–2000 m or upper bathyal). *E. repanda*, however, was noted as characteristic of depth ranges from the outer shelf (100–200 m) to the abyssal plain (4000 m). Its presence may be the result of post-mortem transport processes operating from the outer shelf–bathyal–abyssal depths into the shallow marine–lagoonal sediments of Falasarna. However, the processes that resulted in the deposition of the higher numbers of *E. repanda* and *C. advenum* in samples 15–20, were markedly different from those normally operating and are equated with a tsunami because tsunamis occur less frequently than other high-energy phenomenon such as storm surges. A tsunami may also explain the rise in the percentage of broken pennate Foraminiferal tests from 21% to 83% in samples 15–20.

In laboratory experiments on the relative resistance of Foraminiferal tests to crushing, globular forms were more resistant than pennate forms (Wetmore 1987). Wetmore recognized that test strength is likely to be related to a complex set of factors such as general shape, character of partitions between chambers, the arrangement of chambers and test wall thickness. However, the strongest foraminiferal tests are those which belong to species that have biconvex to globular shapes and sutures which are only slightly depressed. Such a morphology, Wetmore believes, would allow a more uniform dispersion of compressive stresses associated with sediment impact in the marine environment. If pennate Foraminiferal forms are more susceptible to crushing (and breakage) associated with impact stresses, higher percentages of broken pennate forms in sediments thought to have been deposited during high-energy tsunami inundation would be expected. The data presented here support this hypothesis. Furthermore, such dramatic increases in the percentage of broken pennate forms of diatoms have been reported for tsunami-deposited sediments associated with the Storegga tsunami in Scotland (S. Dawson, pers. comm. 1995).

Radiometric dating of marine shells of the species *H. acuta* from the base of the Trench A (Fig. 3) gave a conventional radiocarbon date of 2870 ± 70 radiocarbon a BP (calibrated age 662 BC ± 70). This dates the onset of sedimentation within the harbour. A conventional radiocarbon date of 2270 ± 60 radiocarbon a BP (calibrated age AD 75 ± 60) has been obtained for sample 11 which comes from below the inferred AD 66 tsunami layer, and a conventional radiocarbon age of 2290 ± 90 radiocarbon a BP (calibrated age AD 63 ± 90) has been obtained for sample unit 16, which comes from within the proposed tsunami unit. These dates imply that the high-energy event which led to the deposition of the high percentages of broken (pennate) Foraminifera in samples 15–20 occurred between 35 BC and AD 160 (but probably between AD 63 and 75 ± 90).

The preceding interpretation strongly suggests that deposition of sediments associated with a tsunami of *c.* AD 66 appears to be preserved within the Trench A stratigraphy and it is also noted that no Foraminifera are recorded above sample 23. Most significantly, no Foraminifera are recorded in samples 24–28 which correlate with the sedimentary unit that according to Pirazzoli *et al.* (1992), had been deposited by a tsunami during AD 365.

The results of the present investigation broadly support the findings of a previous study by Pirazzoli *et al.* (1992) which sought to understand the palaeoenvironmental history of Falasarna. However, there are some discrepancies between the findings of the two investigations.

Pirazzoli *et al.* (1992) reported that the base of Trench A is at an elevation of 5.0 m a.s.l. and the surface is at 7.0 m a.s.l., whereas the present study gave elevations of 4.6 m a.s.l. and 6.2 m a.s.l., respectively (Fig. 3). There are four possible explanations for these variations. First, tectonic activity resulting in relative sea- and land-level changes could have occurred between the two successive phases of investigations, but such tectonic activity is not known to the present authors. Second, the elevations of the present authors could be erroneous. However, the closing error for the Trench A traverse was 0.01 m. Third, the elevations of Pirazzoli *et al.* (1992) could be incorrect. P. A. Pirazzoli (pers. comm., 1997) stated that as the trench elevations reported by him and his coworkers were calculated by the Regional Archaeological Service, significant error may have been introduced. Fourth, errors associated with the assumption that present sea level is true mean sea level may result in variations between successive phases of investigation of up to 50 cm.

The lithostratigraphy described in this paper is similar to that previously published, and the foraminiferal assemblages identified in the present investigation are similar to those with those identified by Pirazzoli *et al.* (1992), although those workers reported that Foraminifera are only present within the sediments from the base of Trench A only as high as the layer they ascribed to the AD 66 tsunami (sample 14 in Table 1). They stated that Foraminifera are not present in the AD 66 tsunami layer, although they reappear above this unit (e.g. from sample 21 onwards). This conflicts with the findings of the present investigation, perhaps because the earlier interpretation was based on just 15 samples taken at regular intervals between 5.2 and 6.6 m a.s.l. Finally, the calibrated age of 662 BC ± 70 for the base of Trench A contrasts with a date of 522–340 BC at ±1 SD for a sample 20 cm farther up the stratigraphic column reported by Pirazzoli *et al.* (Fig. 3), and suggests that the harbour may actually have been in existence two centuries earlier than proposed by Pirazzoli *et al.* (1992).

Discussion

In many parts of Crete, by mapping and dating sequences of uplifted, superimposed raised fossil marine notches, it is possible to identify those areas believed to have been affected by coseismic deformation associated with earthquakes (Spratt 1865; Flemming 1978; Pirazzoli 1986; Kelletat 1991). At Falasarna, a sequence of uplifted palaeo-shorelines suggests that a series of small, uniform episodes of subsidence occurred during the 2000–3000 years before *c.* 1530 ± 40 radiocarbon a BP (Pirazzoli *et al.* 1981, 1982, 1992; Thommeret *et al.* 1981; Pirazzoli 1986) (Fig. 4). Radiometric dates on these raised shorelines show ages which decrease with increasing altitude

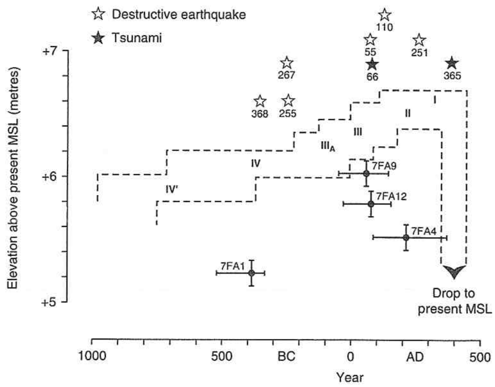

Fig. 4. Band of relative sea-level changes at Falasarna between 1000 BC and AD 500 compared with historically destructive earthquakes and tsunamis in western Crete. Radiocarbon dates for the shoreline displacements are shown in Table 3. (After Pirazzoli *et al.* (1992).)

Table 3. *Relative sea-level changes at Falasarna during historical times deduced from radiocarbon-dated shorelines.*

Shoreline	Elevation (m a.s.l.)	Displacement age →		
		a BP	Calibrated age range*	Inferred historical event
0	±0	1530 ± 40	AD 341–439	AD 365 (?)
I	+6.6 ± 0.1	1600–1710	AD 89–404	
II	+6.5 ± 0.1	1780–1800	16 BC–AD 169	AD 66 (?)
III	+6.35 ± 0.1	1880–1900	141 BC–AD 69	
IIIa	+6.25 ± 0.1	1950–1980	235–18 BC	
IV	+6.1 ± 0.1	2250–2300	728–378 BC	
IV[I]	+5.9 ± 0.1	2500–2610	991–759 BC	

The shoreline numbers correspond to those shown in Fig. 4. (Adapted from Pirazzoli *et al.* (1992)).
* Calibration according to Stuiver *et al.* (1986).

(Pirazzoli *et al.* 1992) (Table 3). The sedimentological analyses presented in this paper provide an independent record of late Holocene coastal tectonic movements.

From Fig. 4 and Table 3 the palaeo-shoreline data of Pirazzoli *et al.* (1992) imply that an earthquake subsidence occurred *c.* AD 66, which displaced the contemporary shoreline from +6.35 ± 0.1 to +6.5 ± 0.1 m. However, the sedimentology indicates a sudden change from marine to terrestrial conditions, which is believed to be associated with uplift of the harbour rather than subsidence. The sedimentology is thus in direct conflict with the geomorphological evidence.

The last major tectonic displacement determined from the shoreline data in Fig. 4 relates to the uppermost of the emerged notches at *c.* 6.5 m a.s.l. radiometrically dated at 1530 ± 40 radiocarbon a BP (Table 3). The stratigraphic record preserves no evidence of this event in the form of tsunami-deposited sediments. It is difficult to understand why the stratigraphy at Falasarna records no evidence of such a large displacement.

The implications of these findings are that, in general, it is difficult to correlate the very precise stratigraphic record with the raised palaeo-shorelines at Falasarna and in particular with the +6.5 m shoreline associated with the inferred AD 365 tectonic uplift. Furthermore, the sedimentology does not reflect the suggested pattern of Holocene coseismic tectonic movements deduced from uplifted shoreline features.

Conclusions

Data presented from Falasarna Harbour records a late Holocene palaeoenvironmental history which also contains detailed evidence of earthquake-related tsunamis. The results provide a useful independent dataset for evaluating the magnitude and timing of coastal tectonic movements in an area affected by contrasting tectonic regimes.

Sedimentation within the harbour began *c.* 662 BC ± 70, which is approximately two centuries earlier than previously reported. The results suggest that, on the basis of foraminiferal assemblage, assemblage variation and individual test preservation, it is possible to identify suites of tsunami-deposited sediments within normal sedimentary sequences. The evidence provided by the foraminifera shows clearly that the last episode of marine sedimentation within the harbour was during or just after the AD 66 earthquake–tsunami event. Consequently, the sedimentology strongly suggests tectonic uplift of the harbour *c.* AD 66, rather than subsidence, as inferred from the raised palaeo-shoreline data. Significantly, there is no bio- or lithostratigraphic evidence to infer sedimentary deposition associated with a tsunami reported to have been generated by a large vertical tectonic displacement *c.* AD 365. It is not possible to interrelate distinct sedimentary horizons with raised shoreline features at Falasarna which have previously been used to describe late Holocene coastal tectonic movements in this area.

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References

ANGELIER, J. 1978. Tectonic evolution of the Hellenic Arc since the Late Miocene. *Tectonophysics*, **49**, 23–36.

CIMERMAN, F. & LANGER, M. R. 1991. *Mediterranean Foraminifera*. Ceneter Sazu Paleotoski Institut Ivana Takovca, Ljubljana, **2**.

DOMINEY-HOWES, D. T. M. 1996. *The geomorphology and sedimentology of five tsunamis in the Aegean Sea region, Greece*. Unpublished PhD thesis, Coventry University.

EMERY, K. O., AUBREY, D. G. & GOLDSMITH, V. 1988. Coastal neotectonics of the Mediterranean from tide-gauge records. *Marine Geology*, **81**, 41–52.

FLEMMING, N. C. 1978. Holocene eustatic changes and coastal tectonics in the northeast Mediterranean: implications for models of crustal consumption. *Philosophical Transactions of the Royal Society of London, Series A*, **289**(1362), 405–445.

——1992. Predictions of relative coastal sea level change in the Mediterranean based on archaeological, historical and tide-gauge data. *In*: JEFTIC, L., MILLIMAN, J. D. & SESTINI, G. (eds) *Climatic Change and the Level of the Seas. Vol. I The Mediterranean*, 247–281.

—— & WOODWORTH, P. L. 1988. Monthly mean sea levels in Greece during 1969–1983 compared to relative vertical land movements measured over different timescales. *Tectonophysics*, **148**, 59–72.

FROST, F. J. 1997. Tectonics and history at Phalasarna. *In*: SWINY, S., HOHLFELDER, R. L. & WYLDE SWINY, H. (eds) *Res Maritimae: Cyprus and the Eastern Mediterranean from Prehistory to Late Antiquity*. Cyprus American Archaeological Research Institute, Monograph Series, **1**, 107–115.

HADJIDAKI, E. 1988. Preliminary report of excavations at the harbour of Phalassarna in western Crete. *American Journal of Archaeology*, **92**, 463–479.

IAPSO 1985. Changes in relative mean sea level. Working Party Report of the International Association for the Physical Sciences of the Ocean Advisory Committee on Tides and Mean Sea Level. *Eos Transactions, American Geophysical Union*, **66**, 754–756.

JACKSON, J. 1994. Active tectonics of the Aegean region. *Annual Review of Earth and Planetary Sciences*, **22**, 239–271.

KELLETAT, D. 1991. The 1550 BP tectonic event in the eastern Mediterranean as a basis for assessing the intensity of shore processes. *Zeitschrift für Geomorphologie, Supplementband*, **81**, 181–194.

LALLEMANT, S., TRUFFERT, C., JOLIVET, L., HENRY, P., CHAMOT-ROOKE, N. & DE VOOGD, B. 1994. Spatial transition from compression to transition in the western Mediterranean Ridge accretionary complex. *Tectonophysics*, **234**, 33–52.

LE PICHON, X. & ANGELIER, J. 1981. The Aegean Sea. *Philosophical Transactions of the Royal Society of London, Series A*, **300**, 357–372.

MERCIER, J. L. 1981. Extensional-compressional tectonics associated with the Aegean Arc: comparison with the Andean Cordillera of south Peru–north Bolivia. *Philosophical Transactions of the Royal Society of London, Series A*, **300**, 337–355.

MURRAY, J. W. 1991. *Ecology and Palaeoecology of Benthic Foraminifera*. Longman, Harlow, UK.

PARKER, F. L. 1958. Eastern Mediterranean Foraminifera. Swedish Deep Sea Expedition, **8**, 219–279.

PIRAZZOLI, P. A. 1986. The Early Byzantine tectonic paroxysm. *Zeitschrift für Geomorphologie, Supplementband*, **62**, 31–49.

——, AUSSEIL-BADIE, J., GIRESSE, P., HADJIDAKI, E. & ARNOLD, M. 1992. Historical environmental changes at Phalasarna harbor, West Crete. *Geoarchaeology*, **7**, 371–392.

——, THOMMERET, J., THOMMERET, Y., LABOREL, J. & MONTAGGIONI, L. F. 1981. Les rivages émergés d'Antikithira (Cerigotto): corrélations avec la Crete occidentale et implications cinématiques et geodynamiques. *Actes du Colloque Niveaux Marins et Tectonique Quaternaires dans l'Aire Méditerranéene*. University of Paris I, 49–65.

——, ——, —— & ——1982. Crustal block movements from Holocene shorelines: Crete and Antikythira (Greece). *Tectonophysics*, **86**, 27–43.

SIDEBOTTOM, H. (1904–1909). Report on the Recent Foraminifera from the coast of the Island of Delos (Grecian Archipelago). *Manchester Literary and Philosophical Society Memoirs and Proceedings*. **48**, 1–26; **49**, 1–22; **50**, 1–18; **51**, 1–28; **52**, 1–28; **53**, 1–32.

SPRATT, T. S. 1865. *Travels and Researches in Crete. Vol. 2*. J. van Voorst, London.

STUIVER, M. & BRAZIUNAS, T. F. 1993. Modelling atmospheric ^{14}C influences and ^{14}C ages of marine samples to 10,000 B.C. *Radiocarbon*, **35**, 137–189.

——, PEARSON, G. W. & BRAZIUNAS, T. 1986. Radiocarbon age calibration of marine samples back to 9000 cal yr BP. Radiocarbon, **28**, 980–1021.

TAYMAZ, T., JACKSON, J. & WESTAWAY, R. 1990. Earthquake Mechanisms in the Hellenic Trench near Crete. *Geophysical Journal International*, **102**, 695–731.

THOMMERET, Y., THOMMERET, J., LABOREL, J., MONTAGGIONI, L. F. & PIRAZZOLI, P. A. 1981. Late Holocene shoreline changes and seismotectonic displacements in western Crete (Greece). *Zeitschrift für Geomorphologie, Supplementband*, **40**, 127–149.

WETMORE, K. L. 1987. Correlations between test strength, morphology and habitat in some benthic Foraminifera from the coast of Washington. *Journal of Foraminiferal Research*, **17**, 1–13.