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Seismic coastal uplift in a region of subsidence: Holocene raised shorelines of Samos Island, Aegean Sea, Greece

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Abstract

At least three raised shorelines, micro-benches and notches, spanning a distance of more than 10 km and marked by a well-preserved marine fauna have been identified along the NW coast of Samos Island, Aegean Sea, and area hitherto assumed to be characterised by a Holocene marine transgression. These fossil shorelines are nearly horizontal, approximately 0.6, 1.1 and 2.3 m above sea level, and can be assigned to hitherto unnoticed earthquakes, which occurred approximately 500, 3600–3900 and possibly 1500 years ago. Some evidence of Quaternary and longer-term uplift has been found as well. The observed uplift may be related to a zone of intense seismicity and faulting following the Great Meander (Buyuk Menderes) River graben in Western Anatolia, but its structural explanation is not clear. New evidence indicates that the geomorphological evolution of Samos Island and of the wider Eastern Aegean is not simply a result of marine transgression and of regional-scale tectonics, but also of earthquakes, and that local-scale tectonics are responsible for the evolution and present-day morphology of at least a part of the coast of Samos Island, as well as of other Aegean coasts. © 2000 Elsevier Science Ltd All rights reserved.

Keywords: Fossil shorelines; Holocene; Samos Island

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1. Introduction

The East Aegean island of Samos, mostly known for muscat wine (used for the Christian communion) and as the native land of mathematician Pythagoras (6th c. BC) and astronomer Aristarchus (3rd c. BC), is located at the west edge of a zone of intense earthquakes and seismic faulting, along the Greater Menderes River (Saroglu et al., 1992; Figs. 1 and 2), which, in the early days of plate tectonics, was regarded as a micro-plate boundary (McKenzie, 1972).

The coasts in the wider region are characterised by submerged ancient ruins (Flemming, 1978; Fig. 1), indicating that, at least in the Late Holocene, its coastal morphology is controlled by marine transgression. In Samos, however, relics of uplifted notches and benches, testifying to fossil uplifted Holocene shorelines have been found and were examined in

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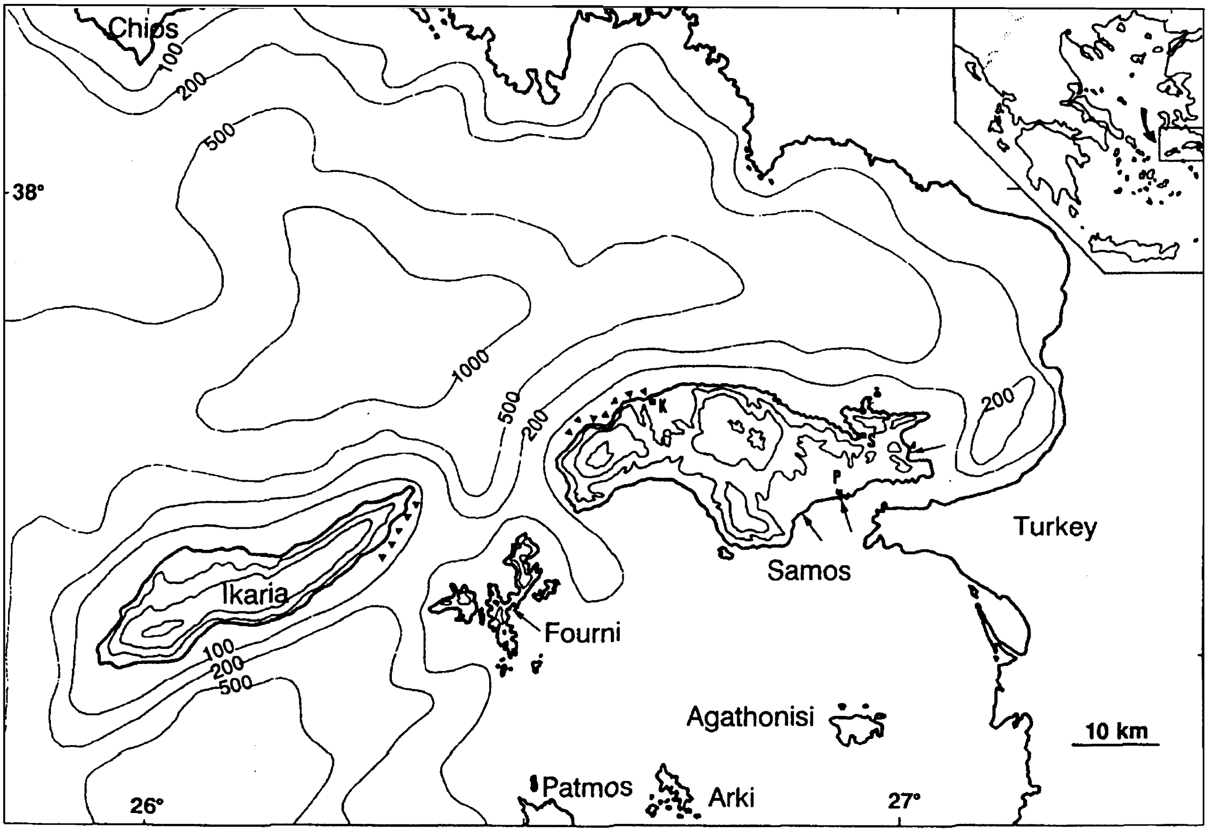

Fig. 1. Topography and bathymetry in the Samos-Ikaria area. Contours of 200, 500 and 1000 m are shown. Based on UNESCO (1981) and the 1:500,000 topographic map of the Hellenic Military Geographic Service. Solid triangles, coastal uplift; arrows, submerged archaeological sites; K, Karlovasi; S, Samos Town; P, Pythagorion.

September 1998 during a fieldtrip organised in the framework of the final meeting of the IGCP-367 project leaded by D. Scott (see Stiros, 1998).

The geographical distribution, morphology, biology and age of these raised shorelines, the first of this type to be identified in the wider area, as well as their structural and seismological implications, are the subject of this paper.

2. Physiography of the island

Samos Island, about 45 km long and covering a surface area of approximately 480 km^2, is located in the east-central part of the Aegean Sea. Straits less than 1.5 km wide and less than 30 m deep separate it from the West Anatolian coasts (Fig. 1), indicating that until the recent geologic past, Samos was connected with Western Anatolia (Western Turkey).

A marine basin, more than 1000 m deep, one of the deepest marine basins in the Aegean, is found north-west of Samos, and its bathymetric gradient is indicative of major normal fault controlling the NW and W coast of the island (Mascle and Martin, 1990). All along the other coasts, the bathymetric gradient is slight, and depths do not exceed 50–200 m (Fig. 1).

Samos is composed of three metamorphic massifs coinciding with topographic “highs”: Kerketeus Mt., 1433 m high, to the west; Karvounis (Ambelos) Mt., 1150 m high in the middle of the island; and the Zoodochos Pigi Massif, 433 m high, to the east. These three structural highs are separated by two

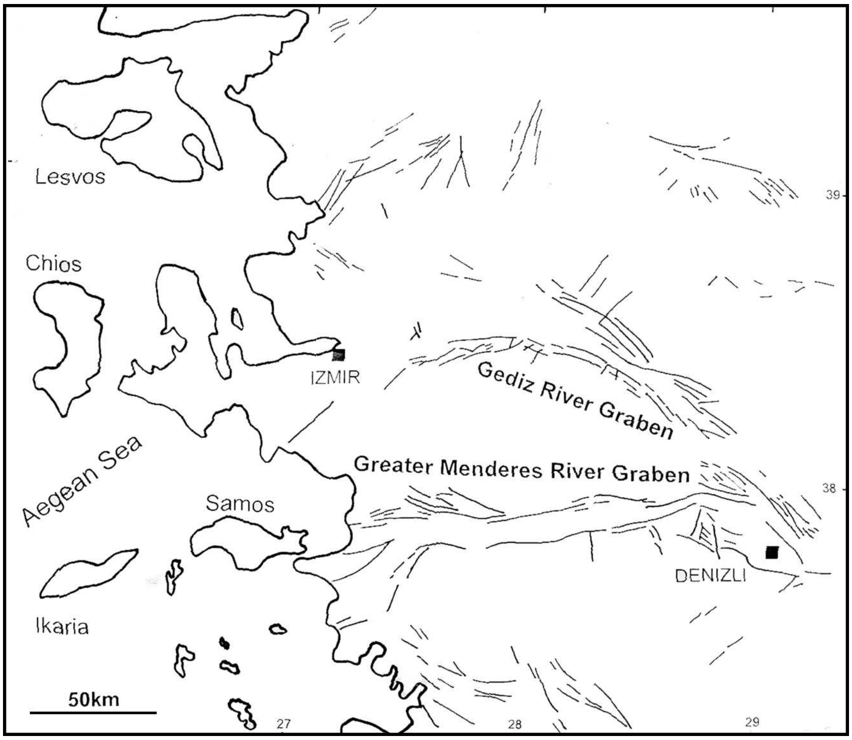

Fig. 2. A part of the map of active faults of Turkey by Saroglu et al. (1992), simplified. Note that Samos is located at the edge of a zone of active faulting along the Greater Meander (Buyuk Menderes) River Graben.

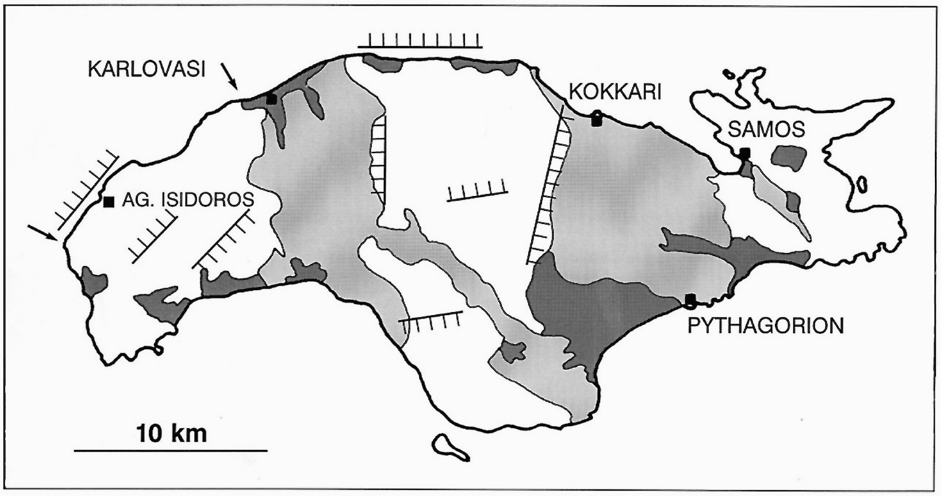

Fig. 3. Geology of Samos Island, simplified after Theodoropoulos (1979). Blanks, pre-neogene rocks, mostly schists and marbles, corresponding to the three topographic highs of the island; light shading, neogene sediments; dark shading, the Quaternary sediments. Major faults are shown. Two arrows indicate the east and west edges of the coast marked by raised beaches.

Neogene sedimentary basins coinciding with topographic "lows"; the Mytilinii Basin to the east, containing large quantities of the well-preserved Miocene mammals (Black et al., 1980; Solounias, 1981; Weidmann et al., 1984) and the Karlovasi Basin to the west (Fig. 3).

The northwestern part of the island is mountainous, and characterised by steep cliffs and highly-incised streams with fluvial terraces. The coastal topography gradient is high and coasts are mostly fault-controlled (Figs. 1 and 3). Only small beaches exist. The gradient of the topography decreases to the east and the southeastern part of the island is characterised by a low, smooth relief and karstic features, and a coastline marked by numerous coves and islets (a nearly ria-type shoreline). Lagoons and extended sandy or sand–gravel beaches developed along long-shore bars, especially along the swamps of the southern coast.

Data from nearby islands indicate that sea water around Samos is nearly tide-free (average tide range 5–10 cm, Hydrographic Service, 1991), whereas its average temperature ranges between 16 and 24°C (Hydrographic Service, 1987). Such conditions obviously permit the development of a thermophile coastal fauna and geomorphic features precisely defining sea level (Laborel and Laborel-Deguen, 1994).

Metamorphic rocks in Samos are mostly marbles and schists, whereas Neogene sediments correspond to two cycles of Miocene–Pliocene deposition and consist mainly of fluvial limestones, marls and breccia. A nappe of non-metamorphic rocks, consisting mostly of Mesozoic limestones and basic intrusive rocks, has been identified in the SW part of the island. Quaternary sediments, mainly recent scree and talus cones, torrential terraces, fillings of karstic depressions and alluvial deposits of coastal plains are limited in extent and are mostly found in the southern part of the island (Theodoropoulos, 1979). Marine sediments (with the exception of some beachrocks, Mourtzas and Stavropoulos, 1989) have not been reported from Samos.

From a structural point of view, as a first approximation, Samos Island can be regarded as an E–W trending anticline, somewhat connected with the normal faults of the northern coast. This type of structure is probably related to the last of a series of deformation phases that affected the island between the Upper Eocene and the Lower Miocene (Angelier, 1976; Papanikolaou, 1979). Normal faults dominate the landscape, and most of them should be active, as earthquakes and steep escarpments indicate. Furthermore, a high-gradient relief at the western part of the island, deeply-incised V-shaped valleys with rapids and waterfalls and active pools in the river beds testify to a young, tectonically-controlled relief (compare with Mayer, 1986), and not to a relief generated millions of years ago and subsequently controlled by karstic and exogenic processes, as Riedl (1989) suggested, based on a geomorphological study of the eastern part of the island.

3. Previous studies of coastal change

Archaeological studies, including underwater excavations, that were made at a number of sites (Fig. 1; Milojcic, 1961; Oekonomides and Drosogianni,1989; Simosi, 1991; M. Viglaki, unpublished data), provide evidence of quasi-submerged or submerged ancient remains, indicating that the SE part of the island has subsided in the last few thousand years.

On the contrary, raised Holocene shorelines were identified on the northwestern coast of Samos and have been presented as evidence of an uplift in a normal faulting environment, not corresponding to the footwall of a major normal fault (see Stiros, 1988 and below).

Based on a subsequent, independent field examination of the coasts of Samos, Mourtzas and Stavropoulos (1989) reported relicts of tilted raised shorelines (notches and platforms) at the northwestern corner of the island, as well as another raised beach: 0.2 m high on the southernmost coast. In combination with field observations of beachrocks, but in the absence of any ^{14}C or other (archaeological, etc.) dating, these authors concluded that the island consists of at least four tectonic blocks moving up and down independently, with an amplitude of up to 10 m since a postulated Flandrian transgression (7000–5000 BP).

4. Study methods

The details of our method have been explicitly analyzed in Stiros et al. (1992); Laborel and Laborel-Deguen (1994); Pirazzoli et al. (1996a); Pirazzoli (1996) and are only quickly reviewed here. Our study of fossil Holocene shorelines of Samos was interdisciplinary, and included a topographic–geographic study, a biological study, sampling and radiometric analyses, as well as observations of sea-water energy.

The aim of the topographic–geographic study was to identify, map, compare and correlate fossil and active notches and benches on the base of their geographical distribution, morphology, elevation and biological signature.

The aim of the biological study was to identify various exposed marine species, determine their relationship with present and fossil sea-level, and whether their fossilisation was a slow or rapid, conspicuously seismic, process. The biological study in particular, is based on the concept of biological zonation. Biological studies summarised in Laborel and Laborel-Deguen (1994) reveal that the spatial distribution of the littoral fauna and flora of the rocky Mediterranean and other shores can be described as three superimposed sub-horizontal belts, namely the supralittoral, midlittoral and infralittoral zones.

These belts are identified on the basis of their degree of exposure to the air, their biomass (number and quantity of species they contain) and their bio-erosive and bio-constructive role. The *supralittoral* zone is never submerged but is regularly moistened by spray. The *midlittoral* zone is submerged at close intervals by waves and tides. Algae and limpets are the most usual species of this zone. The width of this zone depends on the tidal range and the exposure of the site. In nearly tideless waters (for instance in most of the Aegean Sea and the Mediterranean) and sheltered coasts, this zone does not exceed a few tens of centimetres in width and is usually characterised by intense erosion. Finally, the *infralittoral* zone is found below the midlittoral zone and extends to a depth of 25–35 m. It is always submerged, and only rarely (between waves) is its uppermost part exposed to the air. The upper part of this zone, up to a few metres wide, is densely populated by brown algae, vermetids, Clionid boring sponges, sea urchins, the rock-boring pelecypod *Lithophaga lithophaga,* etc. This zone is characterised by an alternation of zones of bio-construction (mainly algal and vermetid reefs) and intense bio-erosion (by sea urchins, *Lithophaga*, Cliona, etc.). Because of the striking difference in their amount and type of biomass, the limit of the last two zones is very characteristic, and has been regarded as the Biological Mean Sea Level (BMSL); a level that in favourable circumstances can locally be identified as a nearly horizontal line with an accuracy of up to 10 cm.

Changes in the sea level are followed by a vertical shift of coastal biological zones, for various species try to adapt to the new sea level, usually colonising a zone previously confined to species of another zone, and abandoning parts of, or the whole of the zone in which they were previously living. Depending on the amplitude and velocity of the sea-level shift, the new zones may be partly or totally printed over the old ones, or they may permit signs of the older zonation to be conserved. In the case of a seismic land uplift of an important amplitude (i.e. larger than the amplitude of the mid-littoral zone), for instance, the shifting of the biological zoning is a momentary process, and the upper parts of the infralittoral zone cross the midlittoral zone without being subject to the intense erosion of this zone, as would be the case for a small-scale or slow lowering of the sea level. Hence, signs of the fossil BMSL can be recognised, and the vertical shift of the biological zoning (i.e. relative sea-level drop) can be estimated as the difference in elevation between the fossil BMSL and its modern counterpart with an accuracy of up to 10 cm.

Finally, the age of representative marine fossils was determined by the radiocarbon analyses of selected samples. These samples were collected from micro-reefs, so it was possible to analyse them with conventional radiocarbon techniques at the Lyon Centre for Radiocarbon Measurements at Claude Bernard University, Lyon 1, France. Results are calculated using a reservoir effect correction factor of 320 ± 25 yr; this estimate is documented in Stiros et al. (1992) and is also adopted here to comply with results obtained in many other parts of the Aegean and the Eastern Mediterranean (see Pirazzoli et al., 1996b).

The results of field observations and laboratory analyses were subsequently used to identify fossil shorelines and their characteristics.

5. Holocene uplifted shorelines

Relicts of fossil shorelines can be observed at the NW, mountainous part of the island, along a high-gradient, quasi-linear, fault-controlled coast, along a distance of approximately 10 km. The first signs are

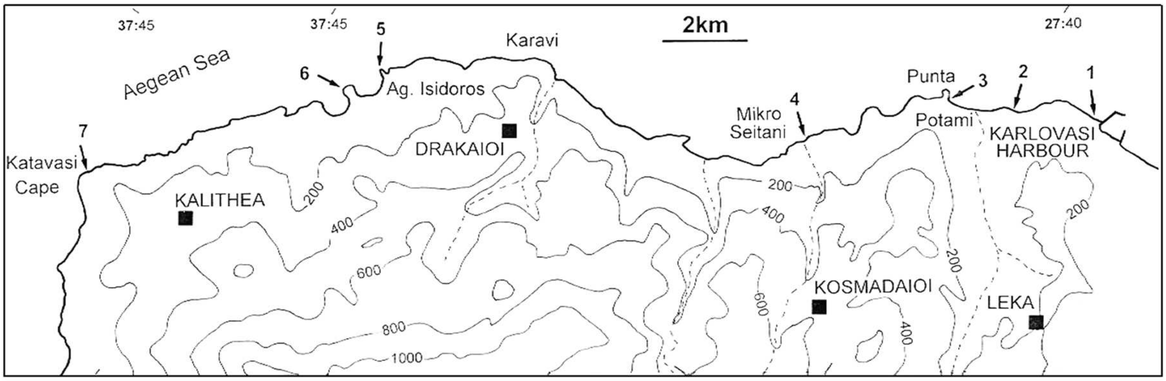

Fig. 4. Raised beaches at NW Samos. Location map and topography. Numbers with arrows correspond to sites mentioned in the text.

visible directly west of the Karlovasi harbour, at the boundary of the Karlovasi Neogene Basin, and can be followed as nearly continuous marks on the rocks, up to approximately 1 km west of the Katavasi Cape (Figs. 1 and 4).

Marine notches and micro-platforms cut in marbles (Figs. 5 and 6), as well as marine fauna, especially micro-reefs of *Dendropoma petraeum* (Fig. 7) and other Vermetids (Fig. 8), testify to at least three fossil shorelines up to approximately 2.5 m high. Rather dubious, geomorphological signs of intermediate shorelines have also been recognised locally.

The signs of elevated shorelines are locally interrupted where lithological conditions are unfavourable for their formation and preservation (usually anisotropic and heterogeneous marbles). Their lateral continuity along a distance of approximately 10 km was, however, confirmed by examination by boat.

West of the Katavasi Cape, due to the unfavourable coastal lithology, only some dubious and erratic signs of raised shorelines can be traced along a distance of a few kilometres; farther west the coastal morphology gradually changes to a low-gradient coast with no signs of exposed former shorelines. This type of coast characterises the whole southern and eastern part of the island, where submerged ancient ruins are found (see above and Fig. 1).

East of Karlovasi Harbour, the sandy beach along the Karlovasi Neogene Basin, does not permit tracing of the eastern limit of uplift. The change in morphology and geology, however, may indicate that the zone of coastal uplift ends close to the harbour. In a few sites along the northern coast east of Karlovasi, isotropic and homogenous calcareous hard rocks outcrop, but they preserve no signs of fossil uplifted or submerged shorelines.

The best exposures of these shorelines are found in the following sites.

5.1. West edge of Karlovasi Harbour (site 1 in Fig. 4)

On the rocks directly west of the Karlovasi Harbour signs of notches, at least 2 m high, though not well developed, can be observed all along the coast towards Potami Beach.

5.2. White (St. Nicholas) Chapel at Potami Beach (site 2 in Fig. 4)

On the beach directly east of the White (St. Nicholas) Chapel at Potami (site 2), a well-preserved colony of vermetids (mainly *Vermetus triqueter*) has built a thin reef capping slabs of beachrock, up to the height of 50 cm above sea level (Fig. 8). These species live in the infralittoral zone, and they do not represent good indicators of sea level. However, as they are confined to the lower part of the beachrock slabs, their upper part is likely to correspond to the sea level of the period they were living.

On the nearby rocks, remains of vermetids (colonies of *Dendropoma petraeum*and isolated *Vermetus triqueteur*) were found at two distinct levels: 0.6 and 1.1 m high on average, on coastal rocks. They certainly correspond to two fossil shorelines.

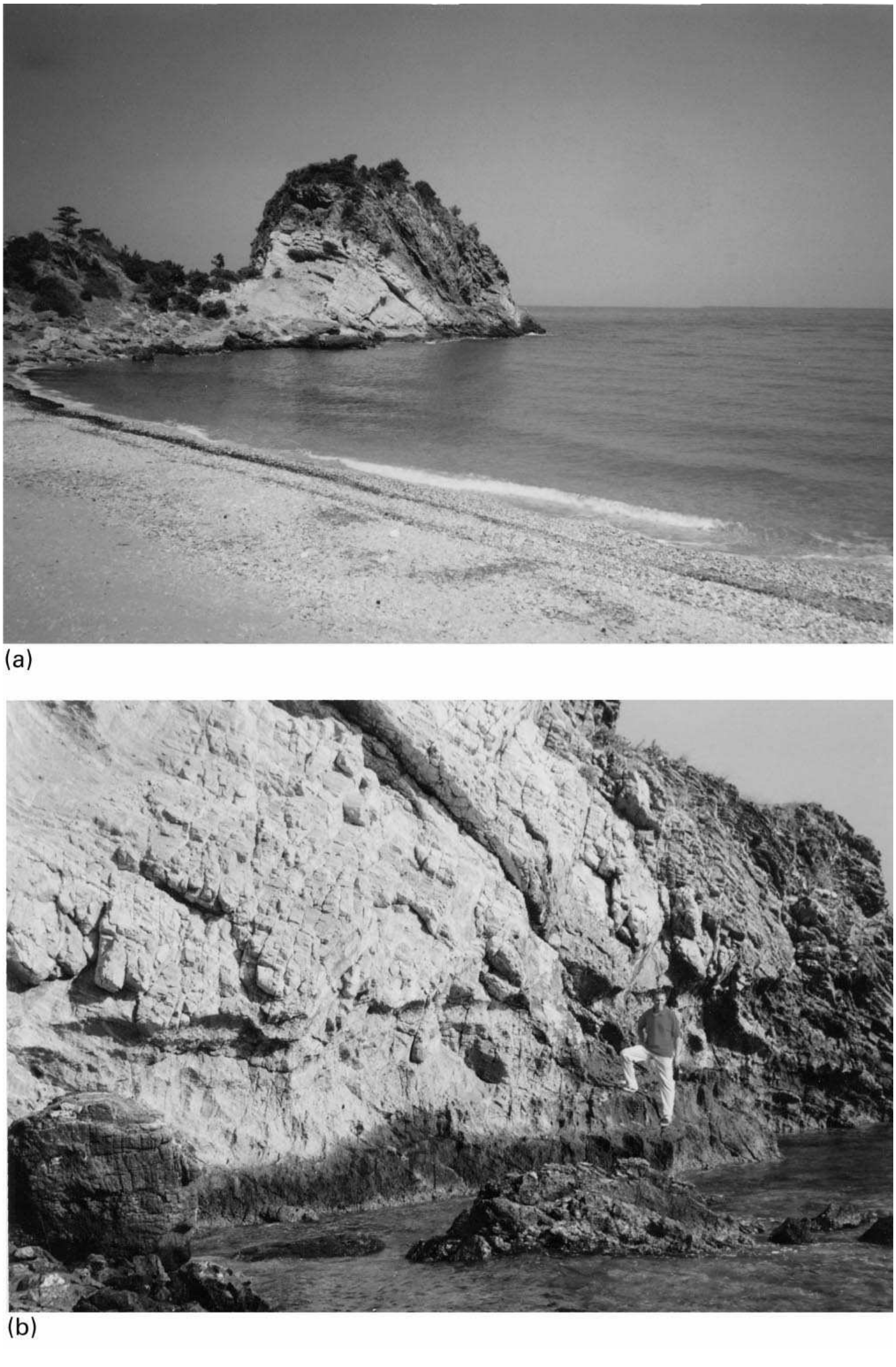

Fig. 5. a: Punta Promontory, near Karlovasi. Marbles preserve traces of at least three fossil shorelines. b: Raised shorelines at Punta. C. Morhange's feet are on the two low benches (about 0.6 and 1.1 m in altitude) and head is at the elevation of the upper notch (approximately 2.3 m in altitude).

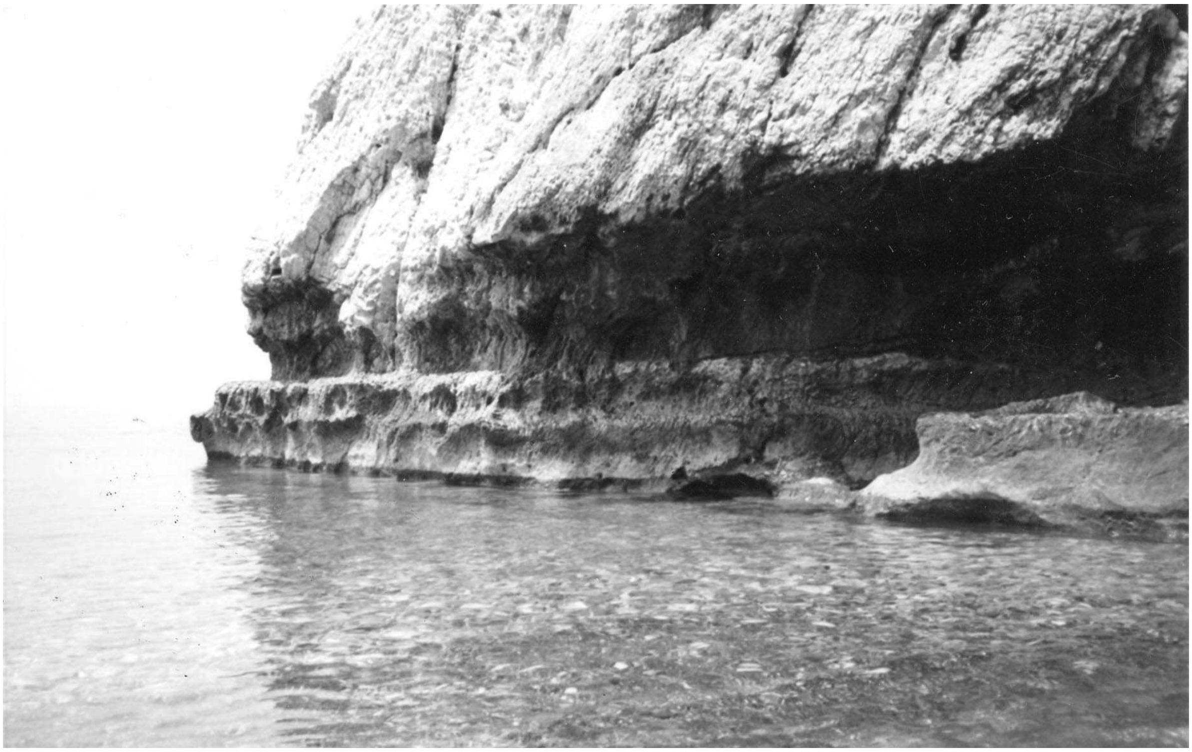

Fig. 6. Mikro Seitani Cove: two coastal platforms and a notch above them testify to the three fossil Holocene raised beaches.

5.3. Punta Promontory (site 3 in Fig. 4)

Along parts of the eastern side of the Punta Promontory, at the western edge of Potami Beach (Fig. 5a), there is clear geomorphological evidence of at least three fossil shorelines: two benches, 0.6 ± 0.2 m and 1.1 ± 0.2 m above sea level, and a narrow notch at a height of 2.3 ± 0.2 m (Fig. 5b). The lithology is non-uniform even at the scale of a few metres, so these features disappear at the tip of the cape, but reappear on the coast west of the promontory.

No biological traces have been found on these two benches, but remains of two polystromatic colonies of *Dendropoma petraeum*, 0.7 ± 0.2 m and 1.1 ± 0.2 m above sea level, respectively, have been found at the eastern edge of the Punta Promontory. These two colonies clearly correspond to two fossil shorelines, geomorphological evidence of which consists of the two adjacent benches.

5.4. Mikro Seitani Cove (site 4 in Fig. 4)

In this spot, the two benches are at a slightly higher (about 20–30 cm) level, probably due to higher wave energy. The 1.5 m high platform, in particular, looks like a former surf bench, locally more than 1 m wide, and forms an arch at the cape of the eastern edge of this cove (Fig. 6). The corresponding sea level in such a case should be identified at a level of at least 20–30 cm lower than the bench rims (Pirazzoli, 1996, pp. 31–33). The upper notch, although not well developed, is also clear at this spot, at the height of approximately 2.4 ± 0.2 m above sea level (Fig. 6).

5.5. Aghios Isidoros Cove (sites 5 and 6 in Fig. 4)

At Aghios Isidoros, the pattern of fossil shorelines is somewhat diffuse and apparently different from other sites. Between sites 5 (shipyards for traditional wooden boats) and 6, the major part of the coast is marked by a flat bench made of cemented material, on top of which

Fig. 7. An extremely well-preserved fossil micro-reef of *Dendropoma petraeum* at Aghios Isidoros, testifying to the coastal uplift of approximately 0.6 m, which occurred 500 yr ago. Such micro-reefs reveal that *Dendropoma petraeum* are confined to a narrow band, about 15 cm below mean sea level. They are therefore accurate indicators of the biological active and fossil mean sea level (see Laborel and Laborel-Deguen, 1994).

extremely well-preserved colonies of *Dendropoma petraeum,* up to 0.6 m high can be found (Fig. 7).

On the small cape can be found two notches: a lower one, which is well developed (about 40 cm deep); and an upper one, less well-developed, with their vertex at the height of 0.50–0.70 and 1.10–1.30 m, respectively, can be found. Locally, on a vertical rock face *Lithophaga lithophaga* holes, with their top forming a nearly horizontal line about 1.20–1.30 m can be observed. Finally, at site 5, on the rocks at the far east edge of the cove, a narrow notch, about 2.4 m high can be observed.

5.6. Katavasi Cape (site 7 in Fig. 4)

Some signs of elevated fossil shorelines, up to 1.5 m high, can be observed at the cliffs of the west side of Katavasi Cape. Due to the local lithology, these traces are diffuse, and disappear farther west.

6. Samples and radiometric data

The details of samples collected and dated from the raised shorelines are shown in Fig. 1. Samples Ly-6729 and Ly-6730 were collected from the eastern side of the base of the rocky promontory of Punta, from elevations approximately 0.70 and 1.10 m (site 3 in Fig. 4a). These fossils represent the eroded bases of two well-developed *Dendropoma petraeum* colonies and correspond to the two platforms observed at this spot; hence, they define with a ±10 cm accuracy the fossil mean sea level (see Fig. 7; Laborel and Laborel-Deguen,

Fig. 8. Details of the raised vermetid micro-reef capping at about +0.5 m a beachrock slab, on the beach east of the White (St. Nicholas) Chapel. The Vermetid layer consists mostly of *Vermetus triqueter*. Such a gregarious association of many *Vermetus triqueter* in a micro-reef is unusual, this species is usually solitary (Photo E988 by PAP).

1994), and also provide a lower boundary for the age of corresponding shorelines.

Samples Ly-6731, Ly-6732 and Ly-6733 come from Aghios Isidoros, from the beach between sites 5 and 6. The first two of these samples were collected from the 0.6-m high fossil shoreline. Ly-6731 is an isolated vermetid (*Serpulorbis*), whose time span is small (about 10 yr) and hence dates precisely the fossilisation of the corresponding shoreline. Sample Ly-7632 was collected from a height of 0.6 m from the base of a well-developed colony of *Dendropoma petraeum* (see Fig. 7), and hence can provide a lower boundary for the age of the 0.6-m high fossil shoreline. Sample Ly-6733 comes from a *Murex* cemented at a height of 2.0 m above the active platform on rocks with signs of raised shorelines at site 5, but it cannot be easily attributed to any specific one. It is a rather fragile, short-living (up to 10 yr) species, brought to the coast after its death by waves (a tsunami?) or human action, and cemented on the active beach of this period. This may have happened when the sea level was at a height of approximately 2.0 m above the active platform. Hence, this fossil may correspond to the 2.3–2.5-m high fossil level seen at a number of places (Punta, Mikro Seitani, etc.).

7. Interpretation

7.1. Geographical distribution of raised shorelines

Macroscopic examination of the coast by boat and detailed study of various spots, some of which are discussed above, reveal that in spite of some local variations in the type and number of former shorelines (mainly due to variations in lithology) and their height (mainly due to variations of the hydraulic energy of the coast), at least three main shorelines, 0.6 ± 0.2, 1.1 ± 0.2 and 2.3 ± 0.2 m high can be traced along a distance of over 10 km along the NW coast of Samos, between the Karlovasi Harbour and Katavasi Cape. These shorelines do not continue much farther east or west, for their traces are not observed in sites where lithological conditions are unfavourable for their formation and preservation.

7.2. Evidence of seismic uplift

There is evidence that the three fossil shorelines, up to 2.3 m high, identified along the NW coast of Samos, originate from tectonic land uplift at a scale of about 10 km and do not represent relicts of climatic sea-level oscillations or regional tectonic events:

First, they are confined to a geographically limited area, about 10 km wide, and they correlate with a major tectonic feature: the footwall of a major normal fault controlling the coast of the island, as can be deduced from bathymetry and topography (Fig. 1). On the contrary, a few tens of kilometres away, along the SE coast of the island, there is archaeological evidence of a coastal subsidence (see above).

Second, they formed during a short time interval, between approximately 2000 BC and AD 1500, a period during which no significant global or regional relative sea-level fall is reported (Pirazzoli, 1991).

There is biological and geomorphic evidence that observed uplifts were episodal and conspicuously seismic: preservation of fossil isolated species of the infralittoral zone (*Vermetus triqueteur, Serpulorbis*) on raised shorelines suggests that these species crossed the mid-littoral zone, a zone of intense bioerosion, quickly. This indicates a relatively very rapid drop in sea level, provided that these species did not develop into an endobiotic environment or were not preserved by sedimentation (Laborel and Laborel-Deguen, 1994; Pirazzoli et al., 1996a). If the rate of uplift was slow (millimetres or centimetres per year) these fragile remains would be altered and destroyed in a few years by mid-littoral bioerosion, which is generally considered to proceed at a rate of at least 1 mm/yr (Torunski, 1979).

The lower two fossil benches, on which isolated Vermetids can be identified, therefore originate from seismic uplift. The upper notch may also provide some direct evidence of episodic land uplift. It is very narrow, at least locally (for instance at Punta (Fig. 5b) and Aghios Isidoros, indicating that it was formed during a stillstand of the sea level. If its uplift was associated with a gradual, relatively slow sea-level drop, its shape would have been modified by erosion, and its lower part would have been obliterated (see Pirazzoli 1986b; Pirazzoli et al., 1996a). Apart from that, it is difficult to imagine effects other than earthquakes that can produce the uplift of a 10-km long coastal segment in this region.

7.3. Dating of the seismic uplifts

Samples Ly-6732 and especially Ly-6729 date the base of the lower vermetid "reef" (Fig. 7) at AD 1040-1284 and AD 720-972, respectively, providing a lower boundary for the land uplift: dated samples do not correspond to a single layer of fossils, but rather, a mixture of layers, and hence they do not determine the last days of the reef, but the average age of the earliest and the latest layers of the fossils sampled. The land uplift is, however, dated precisely by sample Ly-6731 (isolated vermetid) at AD 1306–1467 (2-sigma confidence interval, Table 1). The radiometric ages estimated for these three samples are consistent with the field and biological evidence (see Fig. 9).

Similarly, sample Ly-6730 dates the vermetid colony related to the second (upper) platform, 1.1–1.5 m in altitude at 973–773 BC, and hence provides a lower boundary for the uplift that fossilised this platform. Samples Ly-6732 and Ly-6729, which are related to the conspicuously younger (lower), 0.6-m shoreline, provide an upper boundary for this uplift. Hence, the land uplift which caused the fossilisation of the 1.1-m shoreline occurred between 973–773 BC and AD 720–972/1040–1284 (see Fig. 9). Finally, sample Ly-6733 indicates that the 2.3–2.5 level is likely to date at 1867–1601 BC.

A more precise, though tentative estimate of the uplift of the second platform can be obtained on the base of the assumption of a constant average uplift rate, an hypothesis not unreasonable for many coastal seismic uplifts (Shimazaki and Nakata, 1980; Thatcher, 1984). A straight line describing the mean uplift rate and connecting the oldest and youngest precisely dated uplift events intersects the interval of uplift of the second platform, which is defined by upper and lower boundaries. This defines the likely period of this earthquake at approximately 2000–1100 yr BP (Fig. 9).

7.4. Correlation with historical seismicity

Samos is reported to have been shaken in the historical period and the present century by numerous earthquakes of magnitude higher than 6 (at least six earthquakes during the 19th century, and two earthquakes during the present century: 1904, $M = 6.8$; 1955, $M = 6.9$), but its seismic history remains nearly unknown: For the period up to 1800, there is historical evidence of only three earthquakes: in circa 200 BC, in AD 47 and in 1751 (Guidoboni et al., 1994; Stiros, 1995; Papazachos and Papazachou, 1997).

The available information for the earthquake at circa 200 BC comes from an inscription commemorating the work of a doctor to heal wounds of earthquake victims, while for the AD 47 event information comes from two inscriptions commemorating the reconstruction of a certain temple destroyed by the earthquake. The 1751 event is reported to have caused considerable damage to the island and the Turkish coast opposite (Guidoboni et al., 1994; Papazachos and Papazachou, 1997). There is also some poor evidence for an earthquake in 1476 that devastated Samos and was one of the reasons which forced the Genovese, at this time the rulers, and most of the inhabitants to abandon the island to the Turks and emigrate to Chios Island nearby (see Noos, 1976). This possible earthquake excellently correlates with the coastal uplift dated to AD 1306–1467.

Concerning the older coastal uplift events, any correlation with historical earthquakes can only be tentative, for their dating is imprecise. No reports of seismic coastal change are available, while many unnoticed earthquakes seems to have hit Samos during this period.

Consequently, the uplift of the upper (older) platform may correlate with both the event circa 200 BC and the AD 47 event. However, from the graph of Fig. 9 it seems plausible that the seismic uplift occurred at a later period, at around 1500 BP. Interestingly, this period is broadly consistent with a period during which a series of 4th–6th century coastal uplifts of unprecedented scale have been identified in the Eastern Mediterranean (Pirazzoli, 1986a; Pirazzoli et al., 1996b).

8. Quaternary uplift

Signs of Quaternary fossil shorelines in Samos are scarce. Between Punta and Aghios Isidoros there are level surfaces, some of them at an altitude of approximately 20 m. At Aghios Isidoros, along the beach east of the cove, the 20-m surface is well developed, though covered by terrestrial material (Fig. 10). The constant height along strike of this level, as well as

Table 1
^{14}C ages and calibrated ages for samples from two sites (Datings by J. Evin (1994), Centre de datation par le radiocarbon, University Claude Bernard, Lyon-1, France.)

Sample	Location	Material	Elevation	^{14}C age	Cal age[a]	1-sigma interval	2-sigma interval
			(m)				
Ly-6729	Potami (Punta)	*Dendropoma*	0.7 ± 0.2	1485 ± 45	cal AD 843	AD 783–902	AD 720–972
Ly-6730	Potami (Punta)	*Dendropoma*	1.1 ± 0.2	2970 ± 45	cal BC 837	BC 902–800	BC 973–773
Ly-6731	Ag. Isidoros	*Serpulorbis*[b1]	0.5 ± 0.1	895 ± 50	cal AD 1406	AD 1339–1437	AD 1306–1467
Ly-6732	Ag. Isidoros	*Dendropoma*[c2]	0.6 ± 0.1	1170 ± 50	cal AD 1180	AD 1089–1237	AD 1040–1284
Ly-6733	Ag. Isidoros	*Murex*	2.0 ± 0.3	3760 ± 50	cal BC 1721	BC 1771–1662	BC 1867–1601

[a] Based on Stuiver and Reimer (1993) and a correction factor of −80 ± 25 yr (see Stiros et al., 1992).δ^{13}C estimated: 0‰ POB.
[b] Isolated vermetid.
[c] Base of vermetid reef on coastal platform.

marine conglomerates exposed at a road cutting at Aghios Isidoros indicate that these levels originate from a marine terrace. Along the path from Potami to Mikro Seitani, about 200 m east of this cove, a rather poorly-consolidated sandstone, covering a surface of a few square metres exists at a height of about 20 m on a sub-vertical fault surface. This deposit is likely to correspond to a fossil beach deposit.

No evidence for the age of the 20-m shoreline exists. However, based on the assumption that the uplift rate was constant and that approximately 1 m of uplift has occurred in approximately 1500 yr (see above), the age of this shoreline can be estimated roughly as late Pleistocene.

There is some evidence that this uplift reflects a longer-term effect. The relief in this area is very

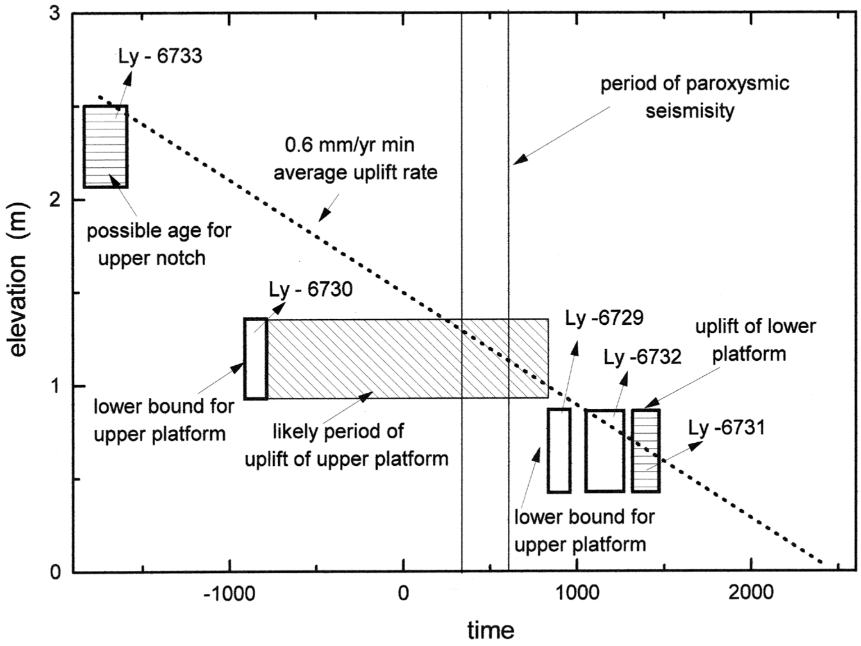

Fig. 9. Radiocarbon ages versus elevation of samples of Table 1. Boxes indicate the radiocarbon age and elevation uncertainties of the samples analysed. The horizontal box with thin lines and shading indicates the interval during which the upper platform was fossilised. Interestingly, the average uplift rate defined by the upper notch and the lower platform crosses the rectangle of the likely period of upper platform, at an interval coinciding with the period of paroxysmic seismicity in the Eastern Mediterranean (bounded by two vertical lines). The line of average uplift is however crudely drafted and cannot readily be used to estimate recurrence intervals of earthquakes.

different from the other parts of the island: the gradient is high, and the streams are deeply incised with rapids and falls. Furthermore, this area corresponds to the footwall of a major normal fault, as bathymetry and topography indicate (Fig. 1). This type of relief can be considered to be the result of recent land uplift (for instance see Mayer, 1986). No direct evidence of this assumed long-term uplift has been found, for local lithology and topography do not preserve stratigraphic or geomorphic signs of fossil shorelines. A similar situation was observed also along the northwest Aegean coasts (Olympus and Pelion Mts. coasts), where the long-term uplift is well documented but the associated biological, geomorphological and sedimentological remains are confined to an altitude of up to 20 m and the latest Quaternary (Stiros et al., 1994).

9. Implications for the seismic risk

Available radiometric data constrain the timing of at least two seismic uplifts. The most recent one was dated to AD 1306–1467 (but it may have possibly occurred in AD 1476, see above), with an older one having possibly occurred between the 4th and 6th century. If an intermediate shoreline, poor evidence of which is locally preserved, is also taken into account, the available data may indicate that the average repeat time of seismic coastal uplifts is about 1000 yr. This estimate, however, is very crude.

Earthquakes responsible for coastal uplift documented here, would have been extremely strong, associated with very high seismic accelerations, especially close to the raised shorelines, and they should have left their signature on the occupation history of the island. The offset of the drums of the Heraion (6th c. BC) monumental temple in Samos (Fig. 11) may originate from such an earthquake (Stiros, 1996).

In any case, new evidence indicates that the seismic risk in Samos, till recently based on a poor historical record is rather underestimated, especially in the western part of the island: According to the official Seismotectonic Map of Greece (IGME, 1989), intensities of the order of IX are reported in the eastern part of the island and only intensities of the order of VII in its western part, close to the raised beaches.

10. Structural implications

Raised shorelines in normal faulting terrains are usually explained as the elastic or isostatic uplift of the footwall of major, normal active faults (Jackson and McKenzie, 1983). As a first approximation, this appear to be the likely explanation for the case of Samos as well: the topography and bathymetry gradients of the NW part of Samos and of the NE part of the adjacent Ikaria island seem to be controlled by a major normal fault or a normal fault zone (Fig. 1; Mascle and Martin, 1990).

However, raised shorelines of Pliocene to Holocene age have been found only along the NE of Ikaria, i.e. along the two rims of the minor graben separating Ikaria from Samos (Fig. 1). This evidence casts doubt on whether coastal uplift in the study area is controlled by footwall uplift of major normal faults (see also Stiros, 1988). A similar conclusion was obtained also for the North Aegean (Stiros, 1991).

A possible alternative explanation for the coastal uplift in Samos and Ikaria may provide the hypothesis of Mariolakos and Papanikolaou (1981/1982) for a strike-slip fault separating these two islands; a result consistent with the interpretation of seismic reflection profiles (Mascle and Martin, 1990). Another possibility is that the coastal uplift at the NW part of Samos accommodates deformation from the tectonically and seismically active fault zone along the Greater Meander River (Fig. 2). The North Aegean Trough, which abuts to the west to the fault-bounded, uplifting coast of Thessaly (Olympus Mt.), may provide a parallel to this type of deformation (Stiros et al., 1994).

Whatever the causes of the uplift are, the coastal topography of Samos (and probably of other Aegean islands as well) is to a major degree controlled by tectonic processes at a scale of up to a few, or a few tens of kilometres. Hence, earlier hypotheses of a regional-scale tectonic (see Mercier, 1979 and references therein) or climatic (for instance, Pfannenstiel, 1944 and subsequent work) control of the Aegean islands are not supported by new evidence; a conclusion broadly consistent with the results of Jackson et al. (1982) and Jackson and McKenzie (1983).

The possible seismic uplift in the 4th–6th century is also of much interest, for it may indicate that the 4th–6th c. AD clustering of earthquakes and coastal seismic uplifts observed in an

Fig. 10. Aghios Isidoros. Black arrow points to fossil *Dendropoma petraeum* micro-reefs on a coastal platform, uplifted approximately 0.6 m following an earthquake of the 14th or 15th century. White arrows point to a level surface about 20 m high, which corresponds to a marine terrace.

Fig. 11. The only surviving column of the Heraion temple, near Pythagorion, constructed in circa 530 BC. Displacement of the drums testifies to rocking caused by high seismic accelerations (see Stiros, 1996), similar to those expected to have been produced by earthquakes responsible for the coastal uplift of the Karlovasi area.

East-Mediterranean scale (Pirazzoli, 1986a; Pirazzoli et al., 1996b) extends also to the central-east Aegean. This may signify that the Greater Meander River fault-zone has accommodated some of the deformation produced at nearby plate boundaries, for instance at the junction between the East Anatolian and the Dead Sea Faults. This emphasises the importance of the Great Meander River fault-zone in the structural evolution of the area; a point first noticed by McKenzie (1972).

11. Implications for coastal marine biology

The degree of preservation of the micro-reef of *Dendropoma petraeum* at Aghios Isidoros (Fig. 7) is really exceptional, and clearly discloses that these species are confined to a very narrow (10–15 cm wide) band just below the mean sea level. Hence, such species can unambiguously define both the fossil and active sea-levels. The micro-reef of *Vermetus triqueter* at site 2 (Fig. 8) is also quite unusual, for such vermetids are usually solitary. Hence, the identification of other, similar micro-reefs may lead to erroneous conclusions on the fossil sea level: Micro-reefs of *Vermetus triqueter*, which may live at any depth in the infralittoral zone, may be confused with *Dendropoma petraeum,*which, in contrast, live very close to sea level.

The development of vermetid micro-reefs along the Samos coasts may also indicate that its waters are somewhat warmer than the 16–24°C values, estimated by the Hydrographic Service (1987).

12. Conclusion

The fossil shorelines of Samos reported here, testify to a number of repeated major palaeo-seismic events, which, apart from their possible impacts on the inhabitation history of the island, have contributed in the shaping of a part of its coasts. In addition, these raised shorelines provide some constraints to the understanding of the palaeogeography of the region and of the mechanism of the structural evolution of the Aegean back-arc basin.

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