Recent Uplift Rates at Perachora Peninsula, East Gulf of Corinth, Greece, based on Geomorphological – Archaeological Evidence and Radiocarbon Dates*

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ABSTRACT: The broader area of the Gulf of Corinth has been tectonically active and is characterized by high seismicity. Almost all the cities around the Gulf have suffered from numerous earthquakes since ancient times. This region and especially its eastern part is well known for its archaeological sites dating back to prehistoric times There is evidence of seismic destruction in a lot of these, leading one to conclude that the seismicity rates have remained high since ancient times.

Detailed geomorphologic investigations and mapping carried out in the coastal region of the southern Perachora peninsula showed that active tectonism has left its imprints on the coastal environment in the form of uplifted wave-cut benches and terraces, beachrocks, notches and sea caves.

The archaeological evidence, findings and indications of destruction by earthquakes, the geomorphologic observations carried out on coastal landforms, the absolute and relative dates and the obtained uplift rates, were all correlated in order to understand the vertical movements that have taken place in this region.

Three radiocarbon dates were obtained from different levels of a notch and consolidated beach material, and were correlated with other available dates and geomorphological observations, assigned to coseismic movements giving an average rate of uplift for the Holocene period of 1.5 to 2.0 mm/yr and for the Upper Pleistocene 8 to 14 mm/yr depending on the sea level curve used.
Key-words: *Coastal Geomorphology, Geoarchaeology, Radiocarbon dating, Holocene, uplift rates, Perachora Peninsula, Greece*.

ΠΕΡΙΛΗΨΗ: Η ευρύτερη περιοχή του Κορινθιακού κόλπου χαρακτηρίζεται απο έντονη τεκτονική και σεισμική δραστηριότητα απο αρχαιοτάτων χρόνων. Η πλειονότητα των πόλεων της περιοχής αναφέρεται ότι επλήγησαν απο πολλούς σεισμούς. Στην περιοχή του ανατολικού Κορινθιακού κόλπου υπάρχουν πολλές αρχαιολογικές θέσεις που χρονολογούνται ακόμη και απο τους προϊστορικούς χρόνους στις οποίες υπάρχουν ενδείξεις σεισμικών καταστροφών, γεγονός που οδηγεί στο συμπέρασμα ότι η σεισμικότητα παραμένει υψηλή από αρχαιοτάτων χρόνων.

Πραγματοποιήθηκε λεπτομερής γεωμορφολογική χαρτογράφιση του νοτίου τμήματος της χερσονήσου της Περαχώρας με έμφαση στις θαλάσσιες γεωμορφές όπως αναβαθμίδες, παράκτιους πάγκους, ακτολίθους, θαλάσσιες εγκοπές και σπήλαια. Οι αρχαιολογικές ενδείξεις και τα ευρήματα για σεισμικές καταστροφές, οι παράκτιες γεωμορφολογικές παρατηρήσεις, οι απόλυτες και σχετικές χρονολογήσεις και οι υπολογισθέντες ρυθμοί ανύψωσης συσχετίστηκαν με σκοπό να κατανοηθούν οι κατακόρυφες κινήσεις που έλαβαν χώρα στην περιοχή μελέτης.

Ειδικότερα τρείς ραδιοχρονολογήσεις που έγιναν σε δείγματα που συλλέχθηκαν απο διαφορετικά επίπεδα μιάς θαλάσσιας εγκοπής καθώς και απο συνεκτικοποιημένο παράκτιο υλικό έδωσαν ηλικίες 11,200-10,00, 8,600-7,400, 5,300 – 4,700 έτη π.Χ. και συνδυάστηκαν με άλλες υπάρχουσες χρονολογήσεις και γεωμορφολογικές παρατηρήσεις.

Τα ανωτέρω επέτρεψαν να υπολογισθούν μέσοι ρυθμοί ανύψωσης για το Ολόκαινο της τάξης 1.5-2.0 mm/yr και για το Ανώτερο Πλειστόκαινο 8 - 14 mm/yr εξαρτώμενες απο την χρησιμοποιηθείσα καμπύλη στάθμης θάλασσας.
Λέξεις-κλειδιά: *παράκτια γεωμορφολογία, γεωαρχαιολογία, ραδιοχρονολόγηση, Ολόκαινο, ρυθμοί ανύψωσης, χερσόνησος της Περαχώρας, Ελλάδα*.

INTRODUCTION

The landscape of Greece reflects its recent tectonism and high seismicity. The Gulf of Corinth, (Fig. 1) a 130 km long, WNW-ESE trending structure, is the most active tectonic area of continental Greece. Its overall form comprises an asymmetric half-graben with uplifted southern coasts and submerged northern ones, a characteristic example of neotectonic processes whose resultant landforms have become the object of various studies (VITA-FINZI & KING, 1985; ARMIJO *et al*., 1996)

Several studies have been carried out in this area, investigating the vertical land movements and examining the reactivation of the existing faults. The dominant vertical movement of the area is uplift. In the Perachora Peninsula, east Gulf of Corinth, uplifted coastal features and Tyrrhenian terraces, corresponding to the interglacial stage 5e, up to 100m high (IGME, 1984), are observed.

VITA-FINZI & KING (1985) used recent earthquakes, historical and archaeological data and ^{14}C dates from

* Πρόσφατοι ρυθμοί ανύψωσης στη χερσόνησο της Περαχώρας, Ανατολικός Κορινθιακός κόλπος, σύμφωνα με γεωμορφολογικές-αρχαιολογικές ενδείξεις και ραδιοχρονολογήσεις ^{14}C.

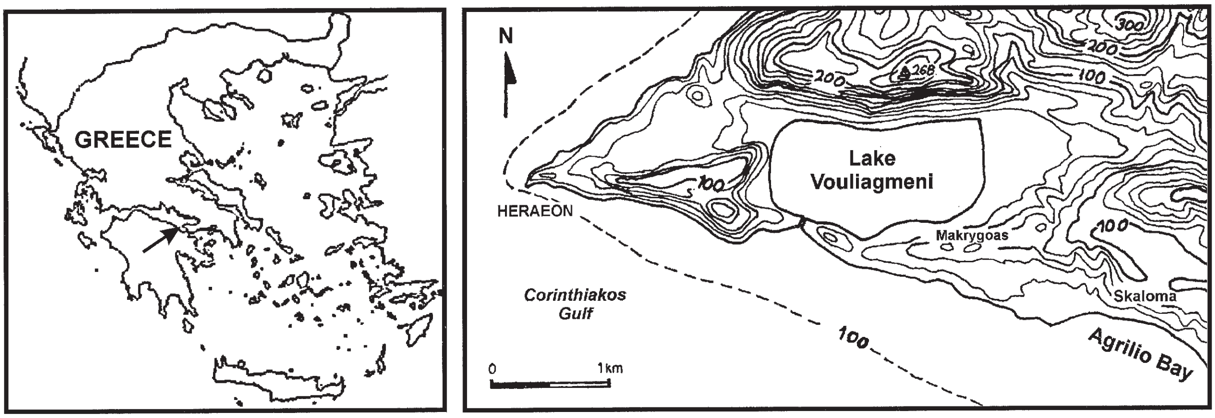

Fig. 1.Topogaphic map of the Perachora Peninsula. Left drawing shows the location of the study area in Greece.

mollusks collected from fossil shorelines in order to describe the evolution of faulting in this area. COLLIER *et al*. (1992) by dating uplifted marine sediments in the area of eastern Gulf of Corinth, presented uplift rates for the upper Pleistocene to Holocene of the order of 0.3 mm/yr. PIRAZZOLI *et al*. (1994) by using ^{14}C dates from the Perachora peninsula concluded that the average uplift rate during the Holocene was faster than the rate of 0.5mm/yr for the last interglacial period. Moreover, STEWART and VITA-FINZI (1996) reappraised the shoreline data of VITA-FINZI (1993) and PIRAZZOLI *et al*. (1994) and proposed an average Holocene uplift rate of 0.75 mm/yr. DIA *et al*. (1997) performed 230Th dating of coral samples from raised terraces at elevations 7 to 65 m above p.m.s.l. and estimated a mean uplift rate of 0.3 mm/yr over the last 350 ka.

COLLIER *et al*. (1998) performed palaeoseismological trenching at Skinos fault, one of the main faults of the area, and deduced recurrence average intervals of 330 yrs for the last 2000 yrs and vertical displacement rates of 0.7-2.5 m. The same repeat rates for strong earthquakes in this area were also suggested by VITA-FINZI & KING (1985) while PIRAZZOLI *et al*. (1994) proposed that uplift movements have occurred in increments of 0.8 ±0.3 m with return periods of the order of 1600yrs.

Taking into account the complexity of the tectonic regime of the area which has left its imprints on the coastal features, detailed coastal geomorphological mapping with ^{14}C dating was performed and correlated with geo-archaeological observations in order to determine uplift rates and to draw conclusions about the palaeoseismic history and palaeogeographic evolution of the area.

TECTONICS OF THE REGION AND GEOLOGICAL SETTING

The configuration of the Gulf of Corinth is controlled by a series of major normal faults that bound the high relief along the southern coast and enter towards the east into the sea, having an average E-W strike and a dip to the north. On the northern side, there are smaller antithetic normal faults dipping south. The eastern extremity of the Gulf of Corinth is more complex. There, the main active normal faults strike northeast and dip north like the main faults of the south coast of the gulf, but there are also major faults that dip to the south.

The broader area of the Peninsula of Perachora is affected by intense tectonism (Fig. 2) likewise, Lake Vouliagmeni owes its formation to this activity. The primary faults have ENE-WSW directions dipping to the NNW and WNW-ESE directions dipping to the SSW. This region is tectonically very complex as it is influenced by positive or negative land movements depending on the identity of each re-activated fault. Therefore, the activation of the submarine faults extending offshore along the NW and SW shores may cause the emergence of land, while the re-activation of faults north of Mount Gerania may cause land subsidence. The Holocene re-activation of these faults is verified by the presence of a fresh scarp at their bases, exceeding 10m at some places.

The alpine basement of the Perachora Peninsula belongs to the Boeotian zone (Geologic Map of IGME, Perachora sheet, 1984) (Fig. 3). The older formations outcropping in the study area are Triassic - Lower Jurassic grey thick-bedded to massive limestones, overlain by Upper Jurassic composite volcano - sedimentary series consisting of mainly basic rocks and including sandstones, rhyolites with calcarenite lenses, and Lower Cretaceous Boeotian flysch, a rhythmic series of mainly radiolarites and intercalations of red pelites, marly limestones and sandstones. On top of it, is the Maestrichtian flysch, a rhythmic series consisting of sandstone and calcarenite-rudite intercalations.

The alpine basement is overlain by Upper Pliocene marine deposits composed mainly of conglomerates, marls and sandstones. The Pleistocene deposits are abundant in the area. From Cape Heraeon area to Agrilio Bay, Upper Pleistocene deposits, consisting of conglomerates, sandstones, marls and calcarenites are found,

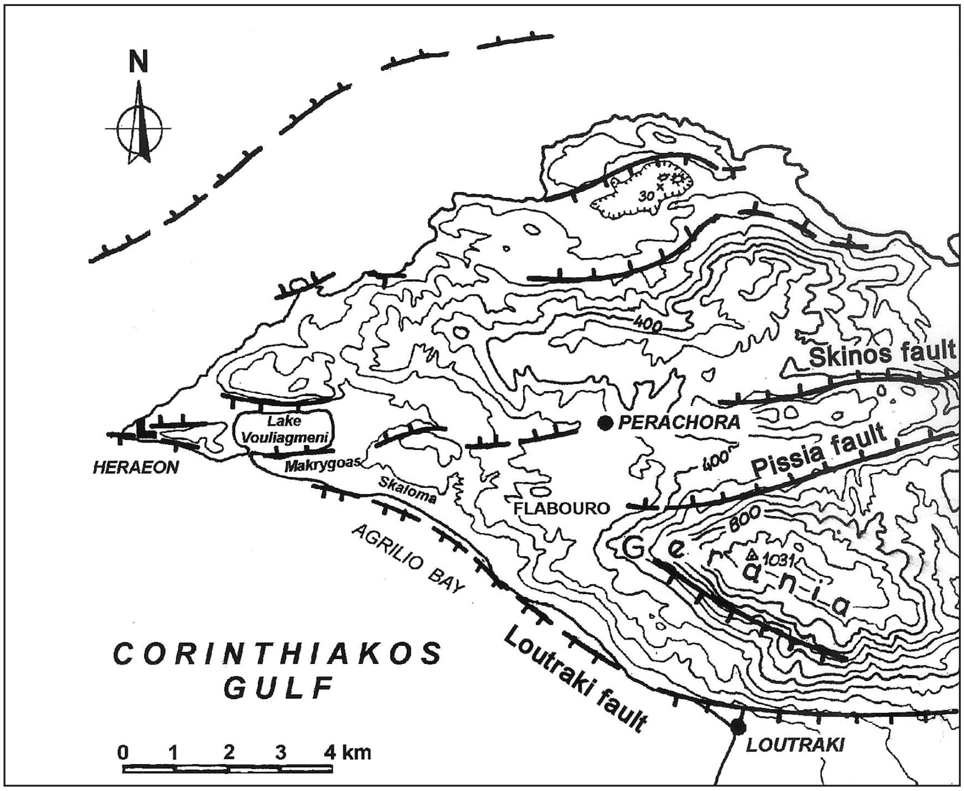

Fig. 2. The main faults of the study area.

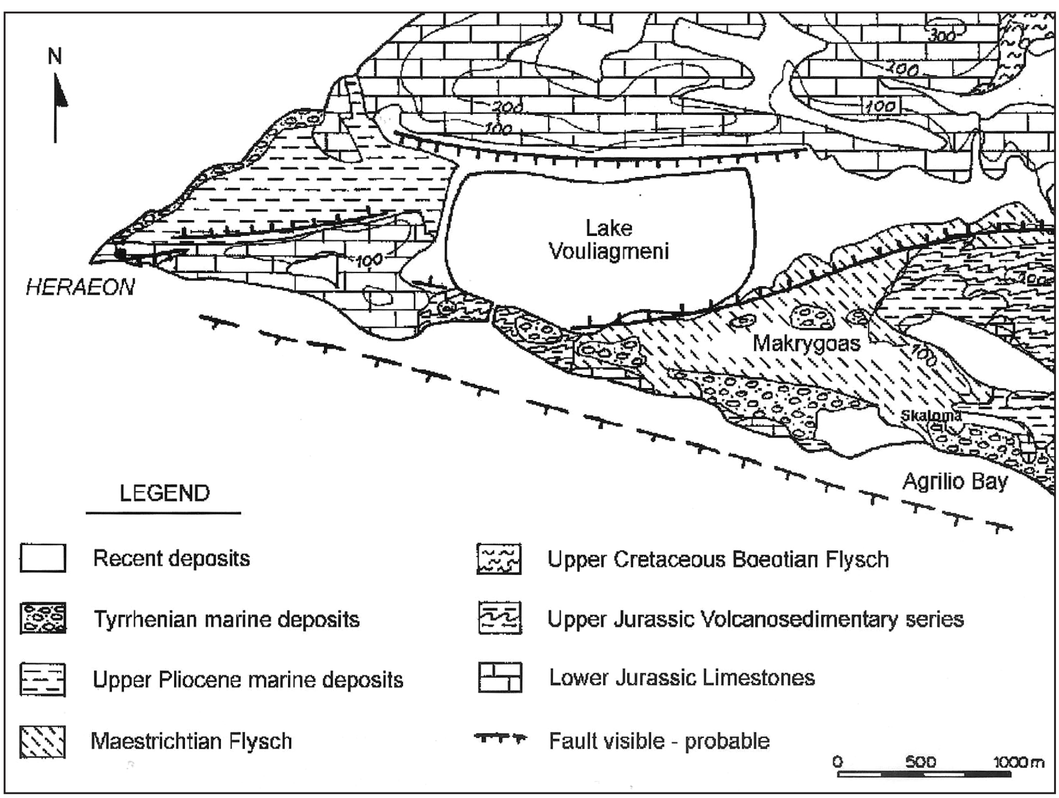

Fig. 3. Geologic map of the Perachora Peninsula.

reaching a height of 28 m. (Mitzopoulos, 1933; Marcopoulou-Diakantoni, 1983). Vita-Finzi & King (1985), assigned an age of 31,820 to 36,180 yrs BP, while Vita-Finzi (1993) dated them as Tyrrhenian at 134±3Ka by U/Th. In the Makrygoas area, southeast of Lake Vouliagmeni, marine deposits were observed capping hills whose elevations reach 100 m.; according to the geologic map of IGME their age is Tyrrhenian, corresponding to the interglacial stage 5e. In a recent paper Morewood and Roberts (1999), ascribe the higher levels of these Tyrrhenian surfaces to older interglacial sea level stands, 7e and 9c. The terrestrial deposits consist of consolidated cones and talus material. The Holocene deposits are composed of talus cones, screes, colluvials, fluvio-torrential and coastal sediments.

Based on the raised Tyrrhenian deposits and the coastal features of the study area, it becomes evident that the prevailing tectonic movement is positive (emergence) during the Late Pleistocene and Holocene periods.

HISTORICAL AND INSTRUMENTAL SEISMICITY OF THE AREA

Apart from archaeological evidence, historical reports and information as well as instrumentally recorded earthquakes prove that the broader area of Perachora Peninsula has suffered the consequences of the occurrence of many catastrophic shocks originated from the active tectonism of the area.

Concerning the evaluation of historical seismicity, the archaeological sites, excavations and findings are of great help. Although the main archaeological site of the area is the city of Corinth, located outside the study area, other important places also exist:

On both sides of the entrance to Lake Vouliagmeni, on a narrow neck of land between Lake Vouliagmeni and the sea, extends a partly submerged Early Helladic settlement (Fig. 4a). It was one of the largest settlements of its time probably inhabited by fishermen. Several phases of occupation have been excavated, having an Early Helladic (EH) age (5,200 BP – 4,000 BP) while the last one is of Archaic (2,500 BP) age, (Fossey, 1969, 1973). According to the excavator, the site was firstly constructed at the lowermost part of the neck, about 5,500yrs BP. The site was forced to be abandoned and moved uphill, about 4,600 to 4,000 yrs BP, indicated by a thick destruction layer produced by the debris of the constructions of the previous periods. Contemporaneous to this layer, are two retaining walls found along the shores of the lake. The settlement continued at the new site for a long time and during the Archaic period it was moved again at the earlier lower parts by the sea and the lake.

The small harbour of Heraeon is situated on the westernmost end of the Perachora Peninsula, just west of Lake Vouliagmeni. The ruins of the sanctuary of Hera are found there. The harbour area was excavated and studied by the British Archaeological School of Athens (Payne, 1940; Blackman, 1966). The sanctuary, located at the head of the harbour, is believed to have been founded in the 8th BC century. There is evidence that the area of Heraeon has suffered by a number of earthquakes, (Payne, 1940; Blackman, 1966). The first one occurred at the end of the 8th BC century when the sanctuary of Hera was moved west due to destruction. Another destruction occurred in the 6th BC century, dated by the sherds found in a landslide west of the harbor. In the middle of the 4th BC century, the whole of the harbour was remodeled. In the early Roman period, the northern part of the sanctuary was covered by debris from a landslide. In the 2nd A.D. century, an earthquake was responsible for the destruction of the sanctuary of Hera.

Other archaeological sites are: the excavations located at Makrygoas at elevations of about 20m and the partly submerged ancient foundations around the western and northern shores of Lake Vouliagmeni.

Evidence of catastrophic events, come also from historical reports and contemporaneous descriptions and recordings. These events are of 420, 227BC and 77, 524, 543, 580, 1858, 1887, 1928 and 1981AD, (Galanopoulos, 1961; Jackson *et al*., 1982; Vita-Finzi & King, 1985; Makropoulos *et al*., 1989; Ambraseys & Jackson, 1990, 1997; Guidoboni, 1994; Ambraseys & White, 1997; Papazachos & Papazachou, 1997).

The correlation of these earthquakes with the rupture of particular faults in the examined area is not always possible even for the recent events. Recent research work associate some of them with the reactivation of the big offshore fault, located NW of the Perachora Peninsula, like the earthquakes of 227 BC, of the 6th AD century and of 1928 (Jackson *et al*., 1982; Ambraseys & Jackson, 1990; Hubert *et al*., 1996). Evidence also exists that this particular fault must have been reactivated after the 9th AD century (Gaki-Papanastassiou *et al*., 1996; Maroukian *et al*., 1997).

The most recent earthquakes that provided valuable information about the tectonic movements at Perachora peninsula are those of 1981. These shocks consisted a sequence of quakes of the Alkyonides gulf and caused heavy damage in the areas of eastern Corinth gulf. The first two occurred during the night, 4 February 20:53 and 25 February 02:35, and the third 7 days later, 4 March 21:58. The heaviest destruction by the first two events was in the villages in the southern part of the gulf, while the last one in the villages near the northeast coast. As a result of the first two events, a surface trace of a normal fault was observed, along the northern coast of the Perachora peninsula. It extended for about 15 Km dipping north, with throws of about 60-70cm on the average (Jackson *et al*., 1982; King *et al*., 1985). Small magnitude ruptures were also observed at the faults around the study area. Since these events occurred at night, it was

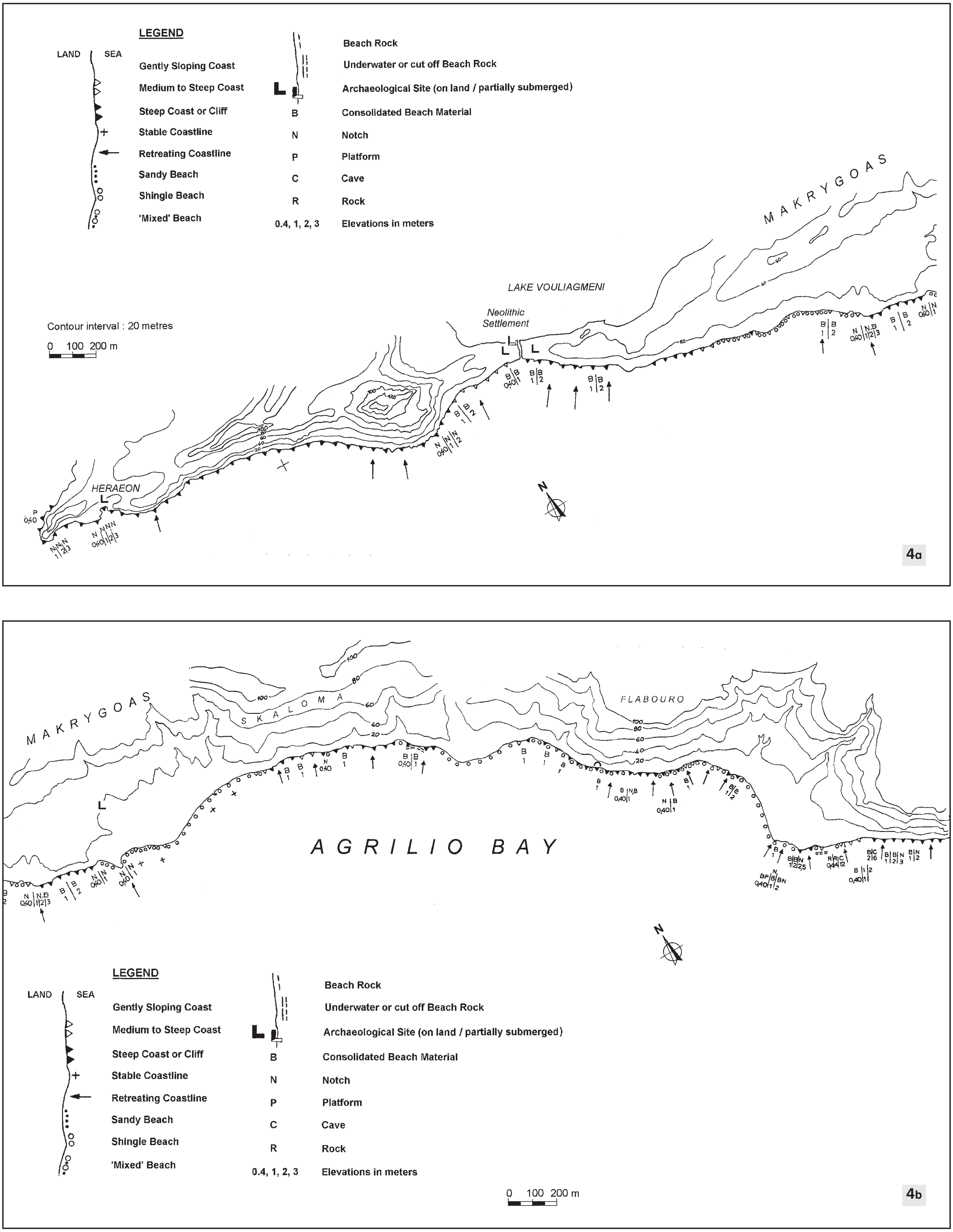

Fig. 4a, b. Geomorphologic map of the southern coastal zone of Perachora Peninsula.

impossible to judge how much of the faulting was attributed to both events or to only one of them, although there followed extensive subsequent work (TAYMAZ *et al*., 1991). The relation between the third event and the surface breaks on a south dipping fault at the eastern end of the gulf near Kaparelli, was obvious. JACKSON *et al*., (1982) implied that the Perachora peninsula had risen as a result of the motion on the submarine fault extending offshore the peninsula along the NW and SW shores, that was thought to have moved in the first event. VITA-FINZI and KING (1985) reported that the peninsula sank, as this fault did not move. Along the southern coast of the peninsula the subsidence was of the order of 0.2 to 0.3 m. Almost 10 years later PIRAZZOLI *et al*. (1994) maintained that the coastal zone showed no evidence of significant perturbation. HUBERT *et al*. (1996) indicated that the subsidence in the region was probably much less than the changes reported. The latter researchers by modelling the vertical motions associated with the first two events showed that they were produced by rupture of the two on land faults, Pissia and Skinos faults, located north of Mount Gerania and not with the activation of the submarine fault extending offshore Perachora. More precisely, they concluded that the first shock was considered to have moved the southern fault (Fig. 2) and the second event the northern one.

GEOMORPHOLOGICAL STUDY OF THE AREA

Coastal geomorphological mapping was realized at a scale of 1:5,000 in the broader area of Lake Vouliagmeni (Fig. 4a, b) which included the determination of palaeo-coastline features such as uplifted wave-cut benches or platforms, marine terraces, beachrocks or consolidated beach material, caves and notches which correspond to former sea levels.

Specifically, Upper Pleistocene marine deposits, are found in the areas of Skaloma and Makrygoas at elevations of up to 100 m (IGME map) while in the coastal zone NE of Cape Heraeon marine deposits dated to 31,820-36,180yrs BP, (VITA-FINZI & KING, 1985) reach up to 28 m. Old sea caves are found at elevations ranging from 4 to 12 m while borings of Lithodomus Lithophaga on limestones are observed at various elevations. In the area of Makrygoas palaeocliffs are located at 18-20 m and 40 m.

The most characteristic features along the narrow coastal zone in this area are the beachrocks or consolidated beach material found at elevations of up to 3 m and forming four step-like levels at heights of 3, 2, 1 and 0.4 meters with a variance of 0.1 m. The extent of the 0.4 m and 1 m beachrocks is greater and they are found along a significant portion of the coast from Lake Vouliagmeni to Flabouro while the 2 and 3 m beachrocks are observed locally. A small but constant increase of the heights of the beachrocks toward cape Heraeon is also observed.

Fig. 5. Beachrocks at elevations of 1 and 2 m west of the entrance of Lake Vouliagmeni. The latter includes sherds of the nearby prehistoric (Early Helladic) settlement. In the background the uplifted notches at Cape Heraeon are also visible. In the upper right hand corner a sea cave at 6m is noticeable.

Fig. 6. Prehistoric (Early Helladic) settlement remains overlying beachrocks along the shores of Lake Vouliagmeni located at 1.4 to 1.6 m a.m.s.l.

Fig. 7. Marine notches curved on limestones at 0.4 m and 1 m above p.m.s.l. near the ancient harbour of Heraeon.

The 2.0 m beachrock at the entrance of Lake Vouliagmeni, includes in its upper portions archaeological sherds derived from the nearby prehistoric (Early Helladic) settlement providing an indirect age of this coastal feature

Fig. 8. The 2.1 m notch at Flabouro filled with consolidated beach material (a) which covers reddish terrestrial breccia (b).

(Fig. 5). In addition sherds were also found in the 0.4m beachrock which extends underwater down to a depth of 1.5 m and a distance of 10m from the shore.

Furthermore, the existence of a beachrock along the shores of Lake Vouliagmeni at 1.4-1.6 m underlying the Early Helladic settlement strata denotes that the beachrock formation is older than the settlement (Fig. 6).

A second prominent coastal feature is the marine notches carved on limestones at the same elevations with the beachrocks or a little higher (Fig. 7). More precisely, in the area of Cape Heraeon there exist notches at elevations of 3, 2, 1 and 0.4 m. These are the most prominent and are easily distinguishable all along the study area. However at some locations, like cape Heraeon, another one at 1.6m is also noticeable (PIRAZZOLI *et al.*, 1994; KERSHAW & GUO, 2001). The exact elevation of these notches depends on seasonal, meteorological, tidal variations and coastal configuration. Consequently a variance of ±0.2m should be taken into account on all the aforementioned elevations. It should be noted that the mean tidal range in this area doesn't exceed 0.08m (HHS, 1991).

The presence of submarine notches at depths 5.5m and 9m on limestones in the area of Cape Heraeon is noteworthy. Inside Lake Vouliagmeni only one notch at 1.2 m is observed without any signs of borings, although traces of Lithodomus Lithophaga are found at a height of 4m near the southern shore of the lake.

PIRAZZOLI *et al.* (1994), dated the notches of the Heraeon area at 3, 2 and 1.6 m to 4,440 - 4,320 yrs BC, 2,440 - 2,260 yrs BC and 190 - 440 yrs AD respectively.

The most important coastal geomorphological site is located in the Flabouro area and it permitted to get a better understanding of the paleogeographical evolution of the coastal area of southwest Perachora Peninsula. The site combines the existence of a well formed notch with consolidated beach material partly filling it (Fig. 8). The notch is carved in limestone, its lower edge being at 1.60 m, the highest at 2.7 m and the mean at 2.1 m. Shells of Lithodomus Lithophaga taken from borings at a height of 2.1 m were radiocarbon dated from Geochron Laboratories, USA and the obtained age was 10,680±160 yr. (^{13}C corrected). The date has been corrected for ^{14}C changes in the atmosphere and calibrated to a calendar age by using the program OxCal, ver3.5 of the University of Oxford, which incorporates the InCal Calibration Curve (STUIVER *et al.*, 1998). Following this the calibrated calendar age is 11,200-10,00 yrs BC with a 95.4% probability. Near the lower edge of the notch at ~1.6m, the remains of a bivalve shell were collected and ^{14}C dated at 6,070±100 yr (^{13}C corrected), calibrated to calendar age of 5,300 – 4,700 yrs BC. This notch was partly filled by consolidated beach material having a thickness of about 0.7 m (1.30 - 2.00 m). This formation included large well-rounded pebbles in a matrix of finer sandy material with remains of marine shells. Shells from a height of 1.4 m were radiocarbon dated and the obtained age was 8,850±230 yr (^{13}C corrected) calibrated to calendar age of 8,600-7,400 yrs BC. Further west, near the mouth of Flabouro torrent a similar formation was observed at the same elevation, having a width of at least 10 m. Underneath this formation an older deposit was observed composed of terrestrial breccia and having reddish color without any marine inclusions, showing that the area was land during a time period between 11,200 - 7,400 yrs BC.

UPLIFT RATES

By dating the coastal features, derived from the vertical tectonic movements, it is possible to obtain uplift rates. Utilizing, however, directly the elevations of the dated samples at age-elevation plots, no conclusion is possible to be reached. It is therefore necessary to make some elevation corrections by using existing sea level curves.

It is generally acceptable that sea level rose rapidly at the end of the last glacial period till the middle Holocene (~6,500 yrs BP) and then this rate diminished significantly. This is shown by published sea level curves which although differ in data and geographical locations present slightly different results (SHEPARD, 1963; AHARON & CHAPPELL, 1986; CHAPPELL & SHACKLETON, 1986; FAIRBANKS, 1989; WARNE & STANLEY, 1995; etc.). These curves show that the rates of the rapid sea level rise are of the order of 7.5-9.5 mm/yr which later slow to 0.7-0.9 mm/yr.

In the case of the eastern Mediterranean and particularly in Greece there are varying views about the Holocene sea level rise. Among the proposed curves is that of FLEMMING & WEBB, (1986) based on data from coastal archaeological sites located in the Mediterranean area and covers the time period of the last 10,000. However, if data covering only the broader area of Peloponnesus are used, then only the time period of the last 7,000 yrs could be reached. WARNE and STANLEY, (1995) used radiocarbon dated worldwide sedimentary sequences of Late Pleistocene to Holocene age underlying modern delta plains. LAMBECK (1996) provides sea-level curves for the Aegean sea region, for the past 20,000, taking into account eustatic and isostatic corrections.

In order to obtain uplift rates, three (3) samples of shells of Lithodomus Lithophaga and other mollusks were selected from the area of Skaloma and dated. The obtained rates are presented in Table 1, together with other radiocarbon dates published in other studies. All the samples were collected from Heraeon, Lake Vouliagmeni and Flabouro, which are sites of the southern coast of Perachora covering a strip of 8Km. However the available dates covering the last 36,000 yrs are not continuous at all. The gap of data that is observed between 30,000 yrs BP and the early Holocene (10,000 yrs BP) should be attributed to the very low sea level stands of the last ice age. Whatever notches or other coastal features were formed during this period should be found drowned at various depths. The presence of two notches at depths of 5.5 m and 9.0 m at Heraeon could belong to that period.

In Table 1 the corrected ^{14}C dates are listed together with the present elevation of the dated fossils and the corrected elevations according to the sea level curves of SHEPARD (1963); FLEMMING & WEBB (1986); WARNE & STANLEY (1995) and LAMBECK (1996) for the Holocene. These 5 sets of data are presented in Fig. 9(a-e). It is also important to note that the corrected elevations are strongly depended on the sea level curve that is used, influencing the obtained rate of uplift. By using the SHEPARD (1963) sea level curve the obtained rate of uplift is about 1,4 mm/yr for the Holocene and about 8,0 mm/yr for the previous period. (Fig. 9b). The sea level curve by FLEMMING & WEBB (1986) gave for the Holocene a rate of 1,4 mm/yr (Fig. 9c), LAMBECK (1996) 1,1 and 14,0 mm/yr. (Fig. 9d) and WARNE & STANLEY (1995) 1,0 and 9,0 mm/yr (Fig. 9e).

The rates for the Holocene are comparable with 0,75mm/yr obtained in the broader area of Perachora Peninsula from STEWART and VITA-FINZI (1996).

A slightly lower rate is derived from the curve of FLEMMING & WEBB (1986), which stands for the whole Mediterranean and has a smaller gradient than that of Peloponnesus used in this study.

DISCUSSION AND CONCLUSIONS

The broader area of Perachora Peninsula is characterized by intense tectonic and seismic activity with a general uplift trend during the Late Pleistocene and Holocene periods. Combining the tectonism of the area with sea level changes of this period, coastal geomorphologicl observations, archaeological evidence and radiocarbon dates, we can draw several conclusions and reconstruct the palaeogeographic evolution of the study area.

The tectonic graben of Lake Vouliagmeni was a bay in Tyrrhenian times and took its present form at the end of the last glacial period. The coastline has not moved significantly during the periods 40,000 - 30,000 yrs BP and the Holocene, as all the dated sites are located along a narrow strip near today's shoreline. During the period 30,000-10,000 yrs BP sea level had dropped considerably,

TABLE 1
List of ^{14}C dated samples with their present and corrected elevations and sources.

LOCATION	PRESENT ELEVATION (m)	MEAN CALIBRATED ^{14}C AGE (yrs BP)	Shepard (1963)	Flemming & Webb (1986)	Lambeck (1996)	Warne & Stanley (1995)	SOURCE
Lake Vouliagmeni	23.5	32,060	-	-	-	-	1
Heraeon	23	33,580	-	-	-	-	1
-//-	20	31,820	-	-	-	-	1
-//-	8	32,440	-	-	-	-	1
-//-	1.7	6,760	11.7	8.7	9.2	6.1	2
-//-	1.7	7.720	16.7	11.2	26.7	9.7	1
-//-	1.7	7,625	15.6	10.2	21.9	8.5	2
-//-	1.7	7,540	15.1	9.9	20.8	8.4	2
-//-	1.4	1,540	2.3	2.5	2.4	3.0	3
-//-	3.1	6,260	11.7	9.1	8.1	6.8	3
-//-	2.2	4,185	5.4	5.8	4.2	4.2	3
Flabouro	7.5	36,180	-	-	-	-	1
-//-	1.6	6,950	13.6	8.9	18.6	6.6	4
-//-	1.4	9,950	33.4	15.1	46.4	21.4	4
-//-	2.1	12,350	57.1	----	72.1	49.1	4

^{14}C 1: VITA-FINZI & KING (1985); 2: VITA-FINZI (1993); 3: PIRAZZOLI *et al*. (1994); 4: this paper.

more than 100 m below the present one, and the coastline had moved farther to the south.

The abandonment of the Early Helladic settlement site and the shift uphill is related with the occurrence of a strong earthquake which submerged the site as the destruction layer and the retaining walls show. This shock happened in the period between 4,600 – 4,000 yrs BP, while sea level was still rising. The successive retaining walls proved to be insufficient to protect the site from the rising sea level and the citizens moved farther uphill far from the invading sea. In Archaic times, the area was uplifted enough and permitted the citizens to return again near the shore.

The general uplift rates for the Holocene are found to be about 1.0-1.4 mm/yr, depending on the sea level curve used for the elevation corrections. This means that the kind of sea level curve used, for such short time periods is of prime importance in the determination of vertical movement rates for a given area. It should be noted that uplift rates show general trends when we deal with long periods of time. As these periods become shorter, it is possible to get faster or slower rates, which reflect time intervals of different tectonic activity. In areas of intense activity, caused by a number of differential movements of faults, like Perachora Peninsula, and in times of fast sea level changes the correlation of these two factors becomes extremely complicated and even impossible as in the case of the notch and the consolidated beach material filling it at Flabouro.

The notch comprises an evolutionary signature during the Holocene. Around 12,000 years ago, when sea level was at about 50m below the present one, the formation of the notch occurred. The height of the notch, which is about 1.1m, should have taken a few hundred years to form. There followed a period of intense tectonic uplift which overcame the rising sea level indicated by the presence of the terrestrial reddish deposit (Fig. 8b). Around 9,000 years ago sea level reached the notch again partly filled it and covered the terrestrial material. The presence of bivalve shells at the base of the notch dated at 7,000 years BP indicates that sea level was at that elevation, 1.6m or higher, at that time and was eroding the older beach and terrestrial material. All of the above are found a few meters above present sea level.

The existence of archaeological Early Helladic sherds in the beachrocks south of Lake Vouliagmeni permits us to continue to reconstruct the coastal evolution of the study area. Between 6.000 BP and the deposition of the Early Helladic shells in the 2 m beachrocks, (~4,000BP) sea level rose by about 0.5 m, which is not consistent with the global sea level curve and the estimated rates of uplift. This could only be explained by a local tectonic subsidence, shown by the partly submerged archaeological site. Taking into account the estimated uplift rates of 1.0 to 1.4 mm/yr and assuming that this event happened during a time period of 1,000 to 1,500 yrs, this gives an uplift of 1.0 to 1.6 m, indicating a parallel subsidence rate of about 0.5 to 0.7 mm/yr. This different vertical movement is very normal as the reactivation of the different faults of the area the site could have undergone subsiding movements. Therefore the uplift rates are increased, reaching rates of about 1.5 to 2.0 mm/yr

The increased rate of uplift during the period 20,000 to 10,000 BP which also corresponds to high seismicity rates, could be attributed to the hydro-isostatic effect representing the loading of the ocean basins by the melting water after the last glacial period. Similar results have also been concluded by McGuire *et al*. (1997), for increased volcanic activity in the Mediterranean.

Using the estimated uplift rates of 1.5 to 2.0 mm/yr, and an uplift/subsidence ratio of 1/2.5 to 1/3 (Stein & Barrientos, 1985; King & Elis, 1990) a fault slip rate of 5.0 to 7.0mm/yr is obtained. This slip rate for the Holocene period is also in good agreement with the slip rate of 6-8mm/yr, obtained for a time period of 350 Kyr, of the big offshore fault located north of the Perachora Peninsula mainly responsible for the uplift of a major part

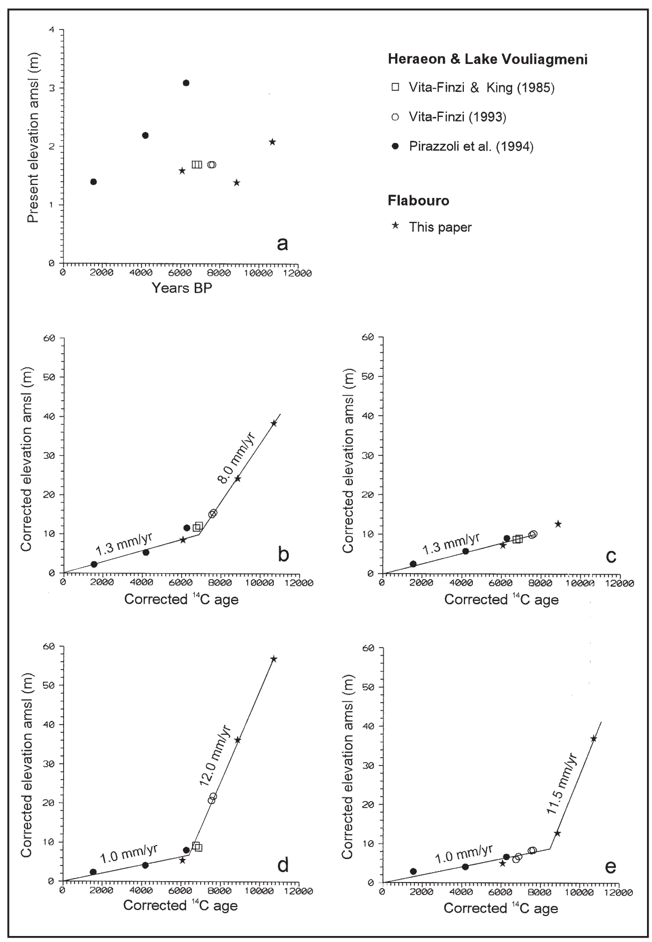

Fig. 9a. Plot of corrected ^{14}C age versus present elevations a.m.s.l. of all the samples. b, c, d, e. Plots of corrected ^{14}C age versus corrected elevations a.m.s.l. of samples according to the sea level curve for the Holocene of Shepard (1963), Flemming & Webb (1986), Warne & Stanley (1995) and Lambeck (1996) respectively.

of the southern Gulf of Corinth (Armijo *et al*., 1996).

It is interesting to note the difference in the rates between the Holocene and the Upper Pleistocene periods. This suggests that the big faults do not have stable rates of movements and they differ considerably in time. This is also indicated from the archaeological and historical evidence for catastrophic earthquakes as well as from the instrumentally recorded events which represent paroxysmic and quiescence periods of seismic activity of the order of hundreds of years.

All of the above permit us to maintain that the estimated uplift rate of 1.5 to 2.0 mm/yr is a minimum one, meaning that tectonism has surpassed eustatism in the last 6,000 yrs. The obtained uplift rates were reached by combining the complex active tectonism resulting in various significant landforms, the archaeological observations and the absolute dating and therefore could be considered as a reliable approach for this interesting area.

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