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Recognition of past earthquakes along the Sparta fault (Peloponnesus, southern Greece) during the Holocene, by combining results of different dating techniques

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Abstract

Sparta fault is an impressive landform, located on the eastern front of Taygetos mountain, southern Greece. Detailed morphotectonic observations on this fault suggest that it should be active at least since Early Quaternary. However, according to the current seismological knowledge, this region is characterized by very low seismicity. The only reported earthquake to have occurred in this area is that of 464 B.C., a destructive event that devastated the whole city of Sparta. In order to get information on the occurrence of past earthquakes during the Holocene, results of different independent dating works that have performed along the Sparta fault were used. These researchers confirm the existence not only of the 464 B.C. earthquake but also of several more that occurred at ca. 3900 B.C., 2500 B.C. and 2000 B.C., 550 A.D. and 1000 A.D. The events that occurred at 2500 and 464 B.C. should correspond to major events of magnitude of the order of 7, which ruptured the entire length of the fault, while these at 3900 B.C., 2000 B.C., 550 A.D. and 1000 A.D., to smaller events of magnitude 6–6.5. The return periods of strong earthquakes along the Sparta fault is estimated to be around 2000 years, but within these periods events of smaller magnitude that ruptured segments of the fault have also occurred.

Keywords: Sparta fault; Morphotectonics; Dating techniques; Palaeoearthquakes; Holocene

1. Introduction

Greece is among the most seismically active countries in Europe, where destructive earthquakes are frequent and have left their imprints on the natural environment. In order to get information on the occurrence of strong events that happened in the last millennia, geomorphological markers of past earthquakes could be identified, correlated and dated. This will not only improve our knowledge of the past seismicity but also the seismic hazard estimation of the area.

Taygetos mountain is the highest in Peloponnesus (2409 m) while its eastern front having a N–S direction and a length of 60 km, is one of the most impressive landforms of Greece, bounded by several active fault segments. The southern one, known as the Sparta fault, has a length of more than 22 km and is located just 5 km west

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of the famous ancient city of Sparta (Fig. 1a). Morphotectonic observations conducted along this fault suggest that this should have been tectonically active not only during the Holocene but since Late Quaternary (Armijo et al., 1991; Maroukian et al., 1999). On the other hand, various seismological studies have shown an absence of intense and continuous activity for the last 25 centuries. However, during the 6th and 5th centuries B.C., disastrous earthquakes are reported, with that of 464 B.C. being the most destructive one that devastated the ancient city of Sparta.

In order to identify past earthquakes related with the Sparta fault, results of several researches that have been carried out in the area during the last years were correlated. It is important to mention that these methods did not have as main target the recognition of palaeoearthquakes. More specifically results have been used from studies:

- performed on alluvial fans of Taygetos mountain. The results suggested periods of extensive sediment supply corresponding to phases that increased the shape of the alluvial fans (Pope and Millington, 2000, 2002; Pope et al., 2003);
- that assessed the earthquake slip history on different places of the Sparta fault by determining ^{36}Cl exposure ages as a function of height on the scarp (Benedetti et al., 2002);
- on palaeoseismological trenching (Papanastassiou et al., 2002);
- which dated destruction layers in archaeological excavations in the city of Sparta (Papanastassiou et al., in preparation).

The compilation of the results of the different works gave dates of palaeoearthquakes at several points covering the entire length of the Sparta fault. This permitted to draw conclusions on the seismic history of the fault as well as its segments and to estimate the magnitude of the individual palaeoearthquakes. This has a significant implication on the long-term seismicity and deformation of the area.

2. Geology and tectonics

The broader area of Sparta is characterised by the mountain massif of Taygetos, to the west, and Parnonas, to the east, with an asymmetric valley in between where the Eurotas river flows from north to south (Fig. 1a). The basement of Taygetos mountain mainly consists of Permian to Lower Triassic phyllites stratigraphically overlain by crystalline limestones, dolomites, schists and flysch up to Oligocene age (Ionian zone). Further north, the phyllite—quarzite series overlain by Mesozoic limestones and dolomites (Tripolis zone) and Cretaceous limestones (Pindos zone) is thrust over these formations. Along the basin of the Eurotas, Pliocene–Pleistocene lacustrine deposits and fanglomerates as well as Quaternary alluvial and colluvial deposits and screes occur.

The area has been affected by major normal faults running NNW–SSE which in Taygetos dip eastwards and in Parnonas westwards resulting in the formation of an asymmetric graben where Eurotas river is situated. In Taygetos, recent tectonism is more active. The surficial expression of Sparta fault is more pronounced due to the recent tectonic activity and resistant lithology. Apart from the main fault system, there is a secondary one, perpendicular to the primary, having an ENE–WSW strike. This system has affected the flow of Eurotas river and several of its tributaries.

3. Morphotectonics of Sparta fault

This morphotectonically significant area has been studied by several researchers (Dufaure, 1975; Armijo et al., 1991; Maroukian et al., 1999). After the results of the aforementioned studies the most important morphotectonic characteristics of the Sparta fault are as follow.

Taygetos, has a prominent relief ranging between 300 and 2400 m. Its eastern front represents one of the most impressive normal fault systems in Greece. It has a length of 60 km, trending NNW–SSE and dipping to the east. It consists of several segments, the southern one being the Sparta fault, a normal pure dip-slip fault (Fig. 1a). It has a direction of N30°W, a length of more than 22 km and a dip of 40° towards the east. Based on geological and morphological characteristics, Sparta fault appears to be composed of two successive segments with an en echelon geometry, with surface lengths of 14.5 and 7.5 km, north and south, respectively. The mountain front is entrenched by deep gorges, the longitudinal profiles of the torrents issuing from the Taygetos have steep gradients and at their exit

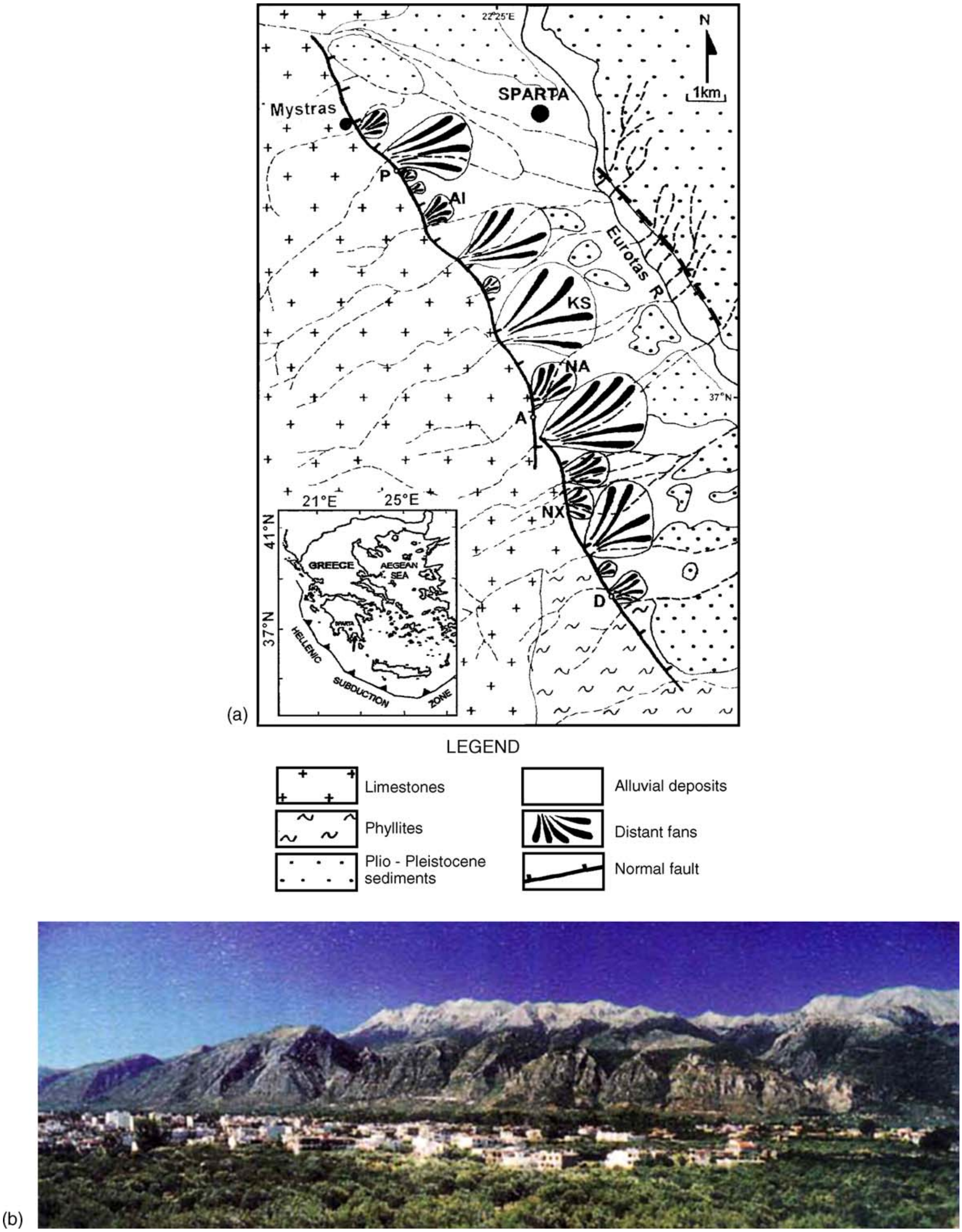

Fig. 1. (a) Simplified lithological-geomorphic map of the Sparta fault. The different sites discussed in the text are also shown. Inset shows the location of the study area. P: Parori, AI: Agios Ioannis, KS: Kalyvia Sokhas, NA: North Anogia, A: Anogia and NX: is North Xirokambi site. (b) General view of the Sparta fault zone, east front of Taygetos mountain, showing trapezoidal facets and truncated valleys with deep gorges.

from the mountain, most of them exhibit several knickpoints. The majority of them could have been formed after each reactivation of the fault and have heights of 2–10 m.

Moreover, the mountain front is characterized by impressive triangular and trapezoidal facets placed between the gorges (Fig. 1b). The older ones at the top have a mean slope of 20°, the middle ones 30° and the lower ones 40°. Furthermore, at the contact of the mountain front with the alluvial fans, an impressive fault scarp is observed reaching in the central part of the fault a height of 12 m, progressively decreasing towards the faults ends. At the base of the front, steep talus and scree slopes are observed. The alluvial fans are less extensive and less cohesive, exhibit steeper slopes and overlie the lower parts of the older large Parnonas fans coming from the east. At least two fan generations are observed, the older one having a morphologic slope of 3° and the more recent one 3–6° located further west in contact with the Sparta fault zone. In natural vertical sections on the older fans, sedimentation phases of repeated fining upwards breccia can be identified that could be linked with previous earthquakes. At many locations along the fault plane, remnants of tectonic breccia are still visible while in other places the fault has truncated old, consolidated scree material which in the form of prisms comes into direct contact with the fault plane.

4. Seismicity

The existence of important old settlements in this area (Ancient Sparta, Byzantine Mystras) and numerous other archaeological sites provides a good knowledge of the history of the area and consequently offers a more or less complete understanding of the historical seismicity. Various seimological studies (Galanopoulos, 1961; Guidoboni et al., 1994; Papazachos and Papazachou, 2002) have shown an absence of intense and continuous activity for the last 25 centuries. However, during the 6th and 5th centuries B.C., disastrous earthquakes are reported (550, 496, 464 and 412 B.C.). Among them, that of 464 B.C. was the most destructive and devastated the ancient city of Sparta, killing more than 20,000 people and causing great social upheaval, as many historians testify (Thucidides, Pausanias, Ephoras, Diodoros of Sicily, Cicero, Strabo, Pliny the Elder, Ploutarch and Aristophanes). After a detailed morphotectonic study of the eastern Taygetos front Armijo et al. (1991), attributed this earthquake to the most recent reactivation of the Sparta fault.

The fortified city of Mystras, an important Byzantine city, is located on a small hill at the northern end of Sparta fault. It was founded in the 13th century A.D. and flourished for two centuries as a political and cultural center of Peloponnesus. There is no information for any severe destruction of the city due to earthquakes, meaning that no strong events occurred in the area after its establishment.

The existing instrumental earthquake catalogues (Makropoulos et al., 1989; Papanastassiou et al., 2001; Papazachos and Papazachou, 2002) and the Annals of the Institute of Geodynamics of Athens, depict that the seismicity of the area is low and, compared to other places of Peloponnesus, is quite negligible (Fig. 2). Papanastassiou (1999) and Papanastassiou et al. (2000) studied the seismicity of the last 100 years and the hazard assessment of the broader area of Mystras–Sparta. Among the different aspects of their work, they examined the earthquakes that have affected the region of Sparta by the kind of the reported damages and the distribution of the macroseismic information. These authors document that among the many felt earthquakes only two moderate ($M \leq 5.0$) events could have been originated by an activation of a nearby source possibly located either in Taygetos or Parnonas.

5. Methods and data used in this study

During the last years, some independent studies have been performed in the area of Sparta fault, either trying to recognize palaeoearthquakes or to examine the evolution of the alluvial fans of Taygetos and to recognize periods of intense deposition. In Fig. 1a are shown the location of the places that were studied with the different methods and are discussed in the text.

5.1. Analysis of Upper Quaternary sediments

The pattern of erosion or deposition of the landscape is attributed mainly to climatic changes, tectonic movements and human activity. Pope and Millington (2000, 2002) and Pope et al. (2003) attempted to reconstruct the types of Late Pleistocene and Holocene erosion and deposition in the piedmont zone of the Sparta basin by using proxy evidence from the alluvial fans of Taygetos. They analysed iron (Fe) oxides within the B horizons of soils developed on the top

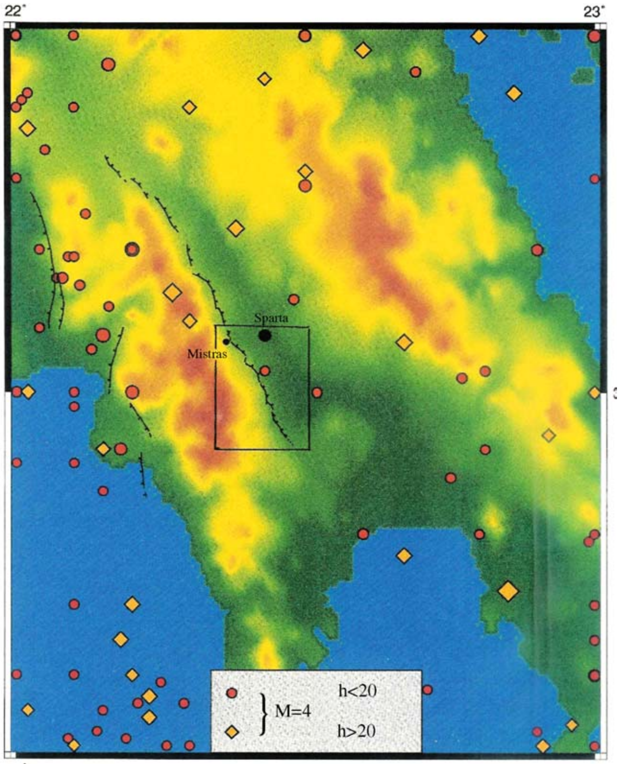

Fig. 2. Spatial distribution of the earthquakes ($M \geq 4$), recorded in the period 1900–2000, in the broader area of Sparta. Circles represent epicenter of earthquakes with depths < 20 km, while diamonds earthquakes with depths > 20 km. The main faults on the both sides of Taygetos mountain are also shown. The box indicates the location of Fig. 1a.

of the alluvial fans and from the cut-and-fill terraces located in front of the Sparta fault by performing mineral magnetic and extractable iron (Fe_d) analyses. The magnetic and Fe_d data, the morphological evidence, and the TL dating of coarse silt/fine sand facies in the fan trench sequences, suggested periods of extensive sediment yield corresponding to phases that increased the shape of the alluvial fans as they progressively shifted towards the basin. Following this procedure, they examined the alluvial fans of (Fig. 1a): Agios Ioannis (AI), Kalyvia Sokhas (KS), North Anogia (NA) and North Xirokambi (NX). The former three fans are located in the northern segment of Sparta fault, while the latter fan in the southern segment (Fig. 1a). The analyses revealed that the fans have undergone some distinctive phases of major active deposition during the examined period. In particular, for the Holocene they found that the first one happened at ca. 4500 B.P., the second phase no later than 3400 B.P., the third no later than 2400 B.P. and the last one no later than 1450 B.P. A synthesis of the results obtained by Pope et al. (2003) is represented in Fig. 3. Given the poor knowledge of the tectonic activity within the Sparta basin and the lack of evidence of strong earthquakes during the Holocene in this area, they attributed the increased deposition rate of the two oldest phases to climatic reasons and for the last two exclusively to agricultural causes like the clearance of large tracks of forest during the Classical and the Early Hellenistic period (500–150 B.C.) and to the burning of forests during Late Roman to Early Byzantine times (200–650 A.D.). The accelerated deposition during the periods 3400 and 2400 B.P. have been systematically observed in all the studied fans, while that of the period of 4500 B.P. occasionally at all the fans. The last period of high sedimentation rate at 1450 B.P. has been mainly observed on the fan of Kalyvia Sokhas (KS in Fig. 1a) while minor deposition has been detected in all fans located to the north. Pope et al. (2003) also revealed that during the Neolithic period (8–5 Ka B.P.) and 5.9 Ka B.P. they noticed occasional short-lived deposition, while during the Late Byzantine period (ca. 1000 years A.D.) there was minor deposition in all the fan systems.

In addition to climatic reasons or anthropogenic interventions we re-interpret their results suggesting the tectonic activity (viz., strong morphogenic earthquakes, sensu Caputo, 1993) as a likely cause for increased phases of deposition. Following a strong earthquake, landslides and rock falls from the mountain face are usual phenomena (Keefer, 1984).

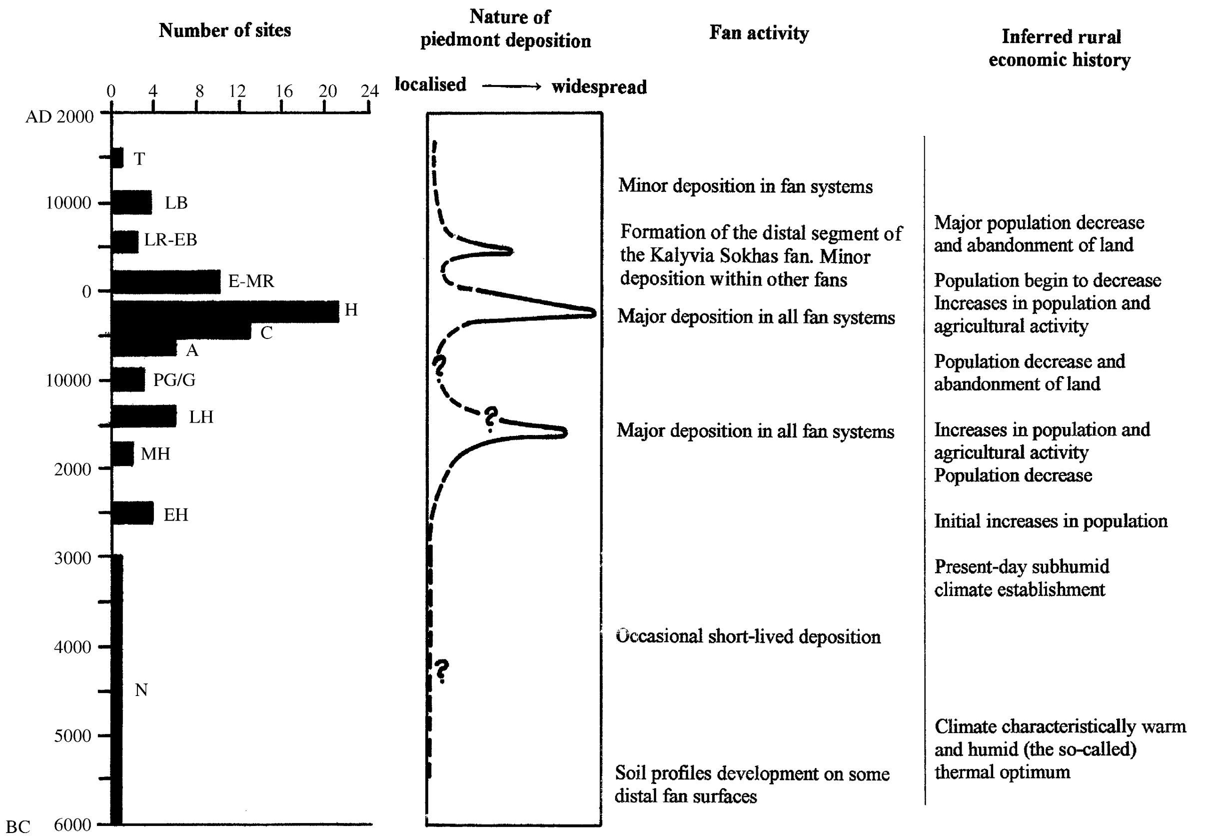

Fig. 3. Relationship between the number of sites, nature of piedmont deposition and inferred rural economic history within the Sparta basin between the Neolithic and modern periods (Pope et al., 2003). The number of sites relates to those recorded within the catchments of drainage basins, which feed the investigated fans and those on the floor of the Sparta basin. N: Neolithic; EH: Early Helladic; PG/G: Protogeometric and Geometric; A: Archaic; C: Classsical; H: Hellenistic; E-MR: Early to Middle Roman; LR-EB: Late Roman to Early Byzantine; LB: Late Byzantine and (T) is Turkish period.

Moreover, the subsequent uplift of the mountain block increases the erosion rates achieved by the torrents thus increasing the sedimentation rates on the alluvial fans.

5.2. Cosmogenic dating of fault scarps

Recently, the cosmogenic dating is employed for estimating landform ages. It is based on the generation of rare isotopes within minerals produced by cosmic rays. Benedetti et al. (2002) have used cosmogenic ^{36}Cl concentrations to assess the earthquake slip history on two different sites of the Sparta fault: Anogia and Parori (A and P in Fig. 1a), by determining ^{36}Cl exposure ages as a function of height on the scarp. ^{36}Cl is produced primarily through interactions of cosmic rays and neutrons with Ca in the scarp limestone ($CaCO_3$). Since the upper parts of the scarp have been exposed for a longer period of time, they have the highest ^{36}Cl concentrations which decrease towards the base. Their results indicate that the central part of the fault (Anogia) ruptured at 4500, 5900, 8400 and 12,900 B.P., while the northern part (Parori) at 2800 ± 300, 4000, 4500 and 5900 B.P.. The observed slip per event is 1.2, 1.8, 2 and 2 m for Anogia and 2, 2.1, 2.1 and 2 m for Parori sites, respectively.

The most recent and penultimate events, those of 2800 and 4000 B.P., are not observed on the Anogia surface. However, the authors found evidence of small fault scarps (total offset 2–3 m), cutting the slope 10–20 m below the main scarp. Therefore, it is likely that these two events bypassed the main scarp at Anogia. Moreover, at Parori the top 2.7 m were extremely weathered and were not sampled. This could explain the absence of the earliest event of 12,900 B.P. detected at Anogia, or this part of the scarp could correspond to the 8.4 Ka event also observed at Anogia.

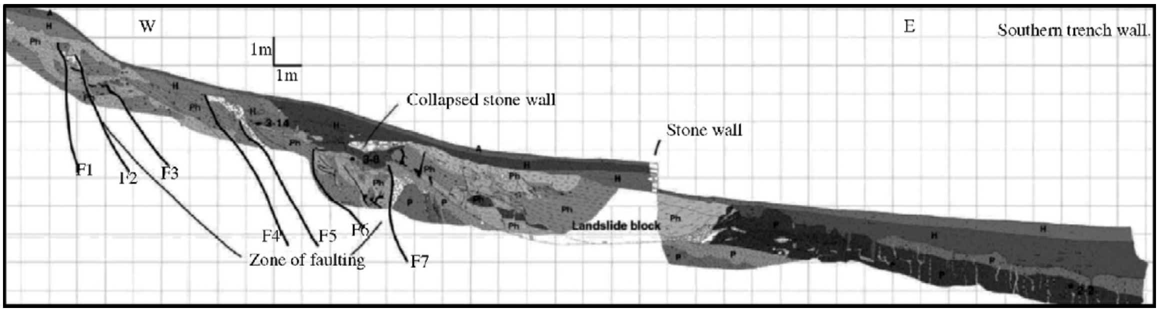

Fig. 4. Log of the western sector of the Sparta trench, southern wall, reverse image. Ph: Phyllite basement, P: Pleistocene layer, CW: colluvium wedges, H: Holocene colluvium layers. A is the modern soil. Numbers indicate position of dated samples. (Papanastassiou et al., in preparation).

5.3. Palaeoseismological investigation

Papanastassiou et al. (2002) presented results from palaeoseismological trenching in the area. The trace of the Sparta fault runs along the steep contact between Alpine bedrock at the footwall and Quaternary units in the hangingwall, usually at a height of several tens of meters from the border of the plain. This made very difficult the task of locating appropriate sites for trenching in order to have a clear stratigraphy of both footwall and hanging wall. The only possible area was at the southern end of the fault, near the village of Dafni (D in Fig. 1a) where the morphology is less steep as the bedrock consists of phyllites (Fig. 1a). In this site, the main geomorphic fault trace is paralleled by a compound scarp, displacing Upper Pleistocene and Holocene deposits. In spite of the high level of human modification for agriculture purposes, since the area is covered by olive orchards, a place was selected where a scarp of 2.5 m high and length of 500–600 m is prominent. Its height decreases towards the south and disappears after 300 m in the nearby valley, covered by younger fan deposits. Immediately north of the selected area the scarp is about 4–5 m height. A 70 m long trench was excavated with a maximum depth of 5 m and logged with a total station at a scale of 1:20.

Trench walls could be separated into three completely different sections: the western part characterized as the zone of normal faulting, the central part where a large landslide is exposed and the eastern one showing typical alluvial fan stratigraphy. A 20–30 cm thick active soil is developed at the top of the trench with a thin humic layer on top. In the upper part of the trench and especially at the eastern end, archaeological potsherds and bricks were found.

In the western part (Fig. 4), the zone of normal faulting having a length of 13 m, several fault strands (F1–F7) can be distinguished. On these strands clear offsets of the upper surface of the bedrock (Ph) are measured, having displacements of the order of several decimetres. The easternmost strand (F7) is a major tectonic contact between the bedrock (Ph) and the Pleistocene (P) sediments showing a visible throw of 2 m, while it clearly depicts characteristic that is a part of a fault plane having direction N5°W and dip 53°NE. Colluvium layers (H1–H4) cover the faulted phyllite bedrock. Located on this deformed part of the trench, these layers are not continuous for a sufficient length and it is very difficult to correlate them in space. It is also important the existence of several remaining parts of colluvium wedges (CW1–CW3), infilling of fractures and fissures along the fault strands as well as a collapsed stone wall. Datable organic material, mainly charcoal fragments were found and dated with ^{14}C method.

In the central part of the trench, extending for about 12 m and having a thickness of 3 m (Fig. 4), a large block of phyllite bedrock (Ph) has slipped over Upper Pleistocene (P) layers. In the upper part, over the slide block, a cultural layer and active soil (A) have been deposited. The starting point of the landslide in the west is well correlated with the fault strand that has been interpreted and discussed earlier as a tectonic contact between the bedrock and the Pleistocene sediments.

The eastern part of the trench exposes a typical alluvial fan stratigraphy. A hard Upper Pleistocene layer (P), with an age of 36.9 ± 0.6 Ka B.P., containing several vertical veins filled with clay-rich material occupies the lower part. Over this layer some colluvium layers (H2–H4) exist.

The results for past earthquakes gave evidence for the 464 B.C. event, while the best estimate for the date of the landslide which is contemporaneous with the collapsed wall, is between 990 and 1165 A.D.

Fig. 5. Archaeological excavation in the city of Sparta. Leaning and fallen walls are clearly seen.

5.4. Archaeological survey

The city of Sparta, capital of the kingdom of Lacedemonians, is well known among the important cities of ancient Greece, even since prehistoric times owing to the famous poet Homer who mentioned it in "Iliad". However, ruins and remnants of that epoch and the following ancient Greek periods, when the city was in power and glory, are few due to the total destruction by the Romans. The city was rebuilt and grew during the Byzantine period. In the 13th century A.D., the city of Mystras was founded on a small hill at the northern end of Sparta fault. For two centuries it was the political and cultural center of Peloponnesus. Nevertheless, it continued to be occupied till the end of the previous century, even though its importance was greatly subdued.

In the city of Sparta, several archaeological excavations have opened in the last years, mostly in the northern part of the city, just south of the existing ruins of the ancient citadel and theatre. In these digs (Fig. 5) signs of destruction are frequent (layers of fire, leaning walls, fallen stones, etc.) at a depth of ca. 2 m below the present-day surface. Their cause is attributed either to an earthquake or to enemy invasion, like that of 7–8th A.D. of races coming from the north. (Personal communication with the archaeologists of the local Ephory.) Samples of charcoal from the destruction levels were also selected and dated, giving dates of 405–570, 370, 650–705 and about 600 A.D. These ages were correlated with the archaeological evidence of destruction, concluded that a damaging earthquake likely occurred in Sparta sometime in the 6th or 7th century A.D. (500–600 A.D.).

6. Discussion–conclusions

Different investigation methods applied in the area of Sparta, dealing with palaeoseismological aspects and sedimentation rates, have been correlated in order to estimate the date and the size of past earthquakes. Table 1 summarizes the results of all the used methods. The location of the sites where the different methods have been applied is listed in the left column of the Table from north to south. The location of every site in relation to the segments of the fault (northern and southern) is also shown. The dates given for every site are also depicted, while uncertainties for the earthquake occurrence are also given.

These independent studies attain some common ages especially by correlating the palaeoseismological results with the depositional periods (5.9, 4.5, 4–3.4, 2.4, 1.45, and 1 Ka B.P., corresponding to calendar dates of 3900 B.C., 2500 B.C., 2000–1400 B.C., 464 B.C., 550 A.D. and 1000 A.D.). The question that arises is which of these ages could correspond to dates of possible strong palaeoearthquakes?

For those of 2500 B.C., 464 B.C., 550 A.D. and 1000 A.D., there is strong evidence that they correspond to palaeoevents, as these dates coincide with those obtained from the palaeoseismological method and with the periods of increased sedimentation.

In particular, that of 2500 B.C. is very well correlated with the growth of the largest free-face of the Sparta fault at both sites of Parori and Anogia and to intense sedimentation in all the fans of the area. For the 464 B.C., the date

Table 1
Synopsis of the obtained dates from all the methods

LOCATION	SEGMENT	DATING TECHNIQUE	DATES in Ka BP: 6 5 4 3 2 1 0 / CALENDAR DATES in Ka: 4 3 2 1 BC 0 AD 1 2
SPARTA Archaeological Excavation	NORTH	^{14}C	←→
PARORI Fault scarp	NORTH	^{36}Cl	↔ ↔ ↔ ←——→
AGIOS IOANNIS Fan	NORTH	Mineral magnetic analysis, TI	——→| ←→ |← |← |← ?
KALYVIA SOKHAS Fan	NORTH	Mineral magnetic analysis, TI	——→| ←→ |← |← |← ?
NORTH ANOGIA Fan	NORTH	Mineral magnetic analysis, TI	——→| ←→ |← |← |← ?
ANOGIA Fault scarp	NORTH	^{36}Cl	↔ ↔ ? ?
NORTH XIROKAMBI Fan	SOUTH	Mineral magnetic analysis, TI	——→| ←→ |← |← |←↔
DAFNI Palaeoseismological trench	SOUTH	^{14}C	←→ ←→
CALENDAR DATES of MAJOR EVENTS in yrs			3900 BC, 2500BC, 2000BC, 464BC, 600AD, 1100AD

The location of the sites where the different methods have been applied is listed in the left column from north to south. The location of every investigated site in relation to the two segments of the fault (northern and southern) is also given. The dates given for every site are also shown. The symbol '?' represents an uncertainty of the earthquake occurrence, that '|←' or '→|' represents upper or lower time limit determination and those '↔', '←→' small or large time intervals.

of the earthquake reported by the historians, together with the indications of the growth of the fault scarp and the intense sedimentation in all the fans of the area, is also evidenced in the palaeoseismological trench. Consequently it is confirmed that the 464 B.C. earthquake was a real catastrophic event and was produced by the rupture of the Sparta fault. For the 550 and 1000 A.D. dates, these are well correlated with increased sedimentation rates and are confirmed by archaeological and palaeoseismological trenches.

Concerning the date of 2000–1400 B.C., an earthquake is confirmed in the northern segment by the palaeoseismological indications at 2000 B.C. (Benedetti et al., 2002). Major deposition in all the fan systems is clearly observed by Pope et al. (2003) (Fig. 4) that occurred about 600 years later, at 1400 B.C. and attributed to climatic reasons. A question also arises for the date of 3900 B.C. Although this corresponds to an increase of the fault's height at the northern segment, it is not paired by an increase in sedimentation rate. Given the accuracy of the paleoseismological method, these dates (3900 and 2000 B.C.) are retained as events that ruptured only the northern segment.

Regarding the seismic events of 550, 496, and 412 B.C., which are referred by the historians to have affected the city of Sparta, these were not directly detected by the used methods in this study. Nevertheless, we recall that all these events as well as that of 464 B.C. occurred very close in time. In this period the highest sedimentation rate was observed in all the fans (Pope et al., 2003), while the raise of the fault scarp is assigned at 800 ± 300 B.C. (Benedetti et al., 2002). Both observations suggest that these events really occurred and could be correlated with a rupture of the Sparta fault, but it is not possible to estimate their magnitude.

Aside from the assessment of the time of the confirmed past earthquakes, it is important also to investigate the amount of slip per event, the slip rate and the recurrence time. These are the major parameters, along with fault length, that define the seismic fault behaviour for hazard purposes. As the earthquakes of 2500 and 464 B.C. are traced at all the investigated sites along the fault, this is an indication that the entire fault length of 22 km was ruptured during these earthquakes. Given that the displacement produced by these events was of the order of a couple of meters (2.1 m after Benedetti et al., 2002) and following the proposed relationships correlating the magnitude of an earthquake with the ruptured length of the fault or the maximum vertical displacement (Wells and Coppersmith, 1994; Pavlides and Caputo, 2004) it is estimated that the magnitude of these events was of the order of $M \sim 7.0$, meaning that these were major earthquakes.

The events of 3900 and 2000 B.C. were recorded only in the northern segment of the fault scarp. Given that the observed scarp displacement is 1.8 m and applying the above mentioned formulae, a magnitude of about 6.5 is estimated. In addition to these dates, there are two more, those of 600–700 and 1100 A.D. The first one observed mainly in the northern segment of the study area, and more specifically in the archaeological trenches in the city of Sparta and in the fan of Kalyvia Sokhas. The second observed in the southern segment and particularly in the palaeoseismological trench. For both dates, Pope and Millington (2000, 2002) and Pope et al. (2003) observed minor deposition in all the fans, but Benedetti et al. (2002), have not found any vertical displacement. Given that the cosmogenic method has a vertical resolution of 10–20 cm for fault displacement, it is assumed that during these events the whole fault ruptured but the displacement was less than 20 cm. Following the equations of Pavlides and Caputo (2004), which correlate earthquake magnitude and vertical displacement, it is concluded that these two events should be of smaller magnitude of the order of $M \sim 6.0$, in accordance with our knowledge that earthquakes in Greece with magnitudes $M > 6.0$ are usually accompanied with surface faulting. Moreover, given that the second event was accompanied with a landslide observed into the palaeoseismological trench, the obtained magnitude is also in accordance with the magnitudes given by Keefer (1984), capable to trigger a landslide.

Sometimes, for seismic hazard purposes, it is important to know for a given fault the maximum expected magnitudes. Pavlides and Caputo (2004) proposed worst case equations derived from the upper envelopes of their regression diagrams. The corresponding magnitudes differ from the previously estimated, being greater by the amount of 0.2–0.4. In the same concept, Papanastassiou et al. (2000) computed values of ground acceleration for the area of Mystras based on various modes of rupture of the Sparta fault. Their results suggest that for some types of unilateral rupture, where a directivity of the energy radiation is prominent, the obtained ground acceleration values were higher than those proposed for the area by the Greek Seismic Code. It is evident that such expected greater magnitudes are of great importance for seismic hazard preparedness purposes.

In addition to the identification of the dates (3900 B.C., 2500 B.C., 2000 B.C., 464 B.C., 550 A.D. and 1000 A.D.) and the magnitudes (between 6.0 and 7.0) of the past earthquakes on the Sparta fault, it is also important to estimate recurrence intervals for them. By taking into account all the available information, like dates, magnitudes and length of rupture, it is concluded that Sparta fault behaves in a complex way. The determined major events those of 2500 and 464 B.C., occurred at time interval of about 2000 years. Within these periods, events of smaller magnitude occurred (600 and 1100 A.D.) and ruptured distinct segments of the fault. By using only the major events slip, a rate of the order of 1 mm/a is obtained.

Concerning the elapsed time period after the last major event of 464 B.C. and the recurrence interval (2000 years), one could wonder for the delay of a strong earthquake along the Sparta fault during the last 2500 years. There are two possible solutions: either that a major event is imminent on the fault or the smaller events of 600 and 1000 A.D. released the accumulated stress and the fault is in the preparation process now to build up stress. Recent studies have shown that seismic quiescence in a fault zone has been attributed to stress relaxation due to preseismic sliding. Such relaxation extends in an area larger than the rupture zone of the oncoming mainshock (Kato et al., 1997).

This study points out the importance of correlating different methods in order to reconstruct the dates of occurrence of past earthquakes in an area. Through the compilation of the results of different works, dates of palaeoearthquakes from several points covering the entire length of the Sparta fault were obtained. This led to formulate common ages of palaeoevents, to draw the seismic history of the fault and to estimate in the most accurate way the magnitude of individual earthquakes. This has a significant implication on the long-term seismicity and deformation of the area.

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References

Armijo, R., Lyon-Caen, H., Papanastassiou, D., 1991. A possible normal fault rupture for the 464 B.C. Sparta earthquake. Nature 351, 137–139.

Benedetti, L., Finkel, R., Papanastassiou, D., King, G., Armijo, R., Ryerson, F., Farber, D., Flerit, F., 2002. Post-glacial slip history of the Sparta fault (Greece) determined by ^{36}Cl cosmogenic dating of limestone fault scarps: evidence for non-periodic earthquakes. Geophys. Res. Lett. 29 (8), 871–874.

Caputo, R., 1993. Morphogenic earthquakes: a proposal. Bull. INQUA, Neotectonic Commission, Stockholm, pp. 16, 24.

Dufaure, J.J., 1975. La relief du Peloponnese. These Letters. Universite Paris IV, p. 1422.

Galanopoulos, A., 1961. A Catalogue of Shocks with Io = VI for the Years Prior to 1800. National Observatory of Athens, Seismological Institute.

Guidoboni, E., Comastri, A., Traina, G., 1994. Catalogue of Ancient Earthquakes in the Mediterranean Area up to the 10th Century. Editrice Compository Publ., Rome.

Kato, N., Ohtake, M., Hirasawa, T., 1997. Possible mechanism of precursory seismic quiescence: regional stress relaxation due to preseismic sliding. Pure Appl. Geophys. 150, 249–267.

Keefer, D., 1984. Landslides caused by earthquakes. Geol. Soc. Am. Bull. 95, 406–421.

Makropoulos, K., Drakopoulos, J., Latoussakis, J., 1989. A revised earthquake catalogue since 1987. Geophys. J. Int. 98, 391–394.

Maroukian, H., Papanastassiou, D., Gaki-Papanastassiou, K., 1999. Palaeogeographic evolution and seismotectonic implications of the broader area of Eurotas River (Greece) during the Quaternary. Z. Geomorphol. 118, 135–146.

Papanastassiou, D., 1999. Seismic hazard assessment in the area of Mystras-Sparta, south Peloponnesus, Greece, based on local seismotectonic, seismic, geologic information and on different models of rupture propagation. Nat. Hazards 18, 237–251.

Papanastassiou, D., Gaki-Papanastassiou, K., Maroukian, H., Karimbalis, E., Makaris, D., 2000. Implications of morphoIogy and seismicity on the hazard assessment in the ancient monument of Mystras in southern Peloponnesus, Greece. Annales Geologiques des Pays Hellenique 39, 157–173.

Papanastassiou, D., Latoussakis, J., Stavrakakis, G., 2001. A revised catalogue of earthquakes in the broader area of Greece for the period 1950–2000. Bull. Geol. Soc. Greece 34 (4), 1563–1566.

Papanastassiou, D., Sieh, K., Yule, D., Gaki-Papanastasssiou, K., Meyer, B., Vrenzou, E., 2002. Seismological and archaeological trenching to detect past earthquakes: a case study from the area of Sparta, Peloponnesus, Greece. In: Proceedings of the Ninth International Symposium on Natural and Man-made Hazards, Antalya, Turkey, October 3–6, 2002 (Abstract).

Papanastassiou, D., Sieh, K., Yule, D., Gaki-Papanastassiou, K., Meyer, B., Maroukian, H., in preparation. Palaeoseismological trenching and archaeological evidence for past earthquakes on the Sparta fault, Peloponnesus, Greece.

Papazachos, B., Papazachou, C., 2002. The Earthquakes of Greece. Ziti Publ., Thessaloniki, p. 304.

Pavlides, S., Caputo, R., 2004. Magnitude versus faults' surface parameters: quantitative relationships from the Aegean region. Tectonophysics 380, 159–188.

Pope, R., Millington, A., 2000. Unravelling the patterns of alluvial fan development using mineral magnetic analysis: examples from the Sparta basin, Lakonia, southern Greece. Earth Surf. Process. Landforms 25, 601–615.

Pope, R., Millington, A., 2002. The role of alluvial fans in mountainous and lowland drainage systems: examples from the Sparta basin, Lakonia, southern Greece. Z. Geomorph. N.F. 46 (1), 109–136.

Pope, R., Wilkinson, K., Millington, A., 2003. Human and climatic impact on late Quaternary deposition deposition in the Sparta basin piedmont: evidence from alluvial fan systems. Geoarcheology 18 (7), 685–724.

Wells, D.L., Coppersmith, K.J., 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area and surface displacement. Bull. Seism. Soc. Am. 84 (4), 974–1002.