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Paleoseismicity of the Kaparelli fault (eastern Corinth Gulf): evidence for earthquake recurrence and fault behavior

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ABSTRACT

The Kaparelli Fault was activated during the 1981 Gulf of Corinth earthquake sequence, producing extensive ground deformation. The main purpose of this work was to identify and date previous Late Quaternary faulting events and to resolve slip on the main trace of the Kaparelli normal fault prior the 1981 seismic event by means of paleoseismological trenching. The identification of paleoseismic events is based on the recognition of colluvial deposits, fissure fills and displacements of key stratigraphic horizons.

The three excavated trenches exposed evidence of at least three events in the past 10.000 years, prior to the 1981 earthquake sequence. The two most recent events were identified in two of the trenches. Calibrated radiocarbon age distributions are used directly from organic-rich soil horizons in order to estimate the recurrence interval of past seismic events. Radiocarbon dating results from two of the trenches constrain the timing of the recognized faulting events, based on colluvial sedimentation and fissure fills, from 9490-9250 BP and 7150-7430 BP to 5710-5570 BP and 1390-1060 BP. These colluvial deposits and fissure fills are associated with successive earthquake events.

The Kaparelli fault comprises many different fault strands and segments consisting in this way a complex fault zone. Displacement per event on different fault segments varies from 0.7 m to 1 m. The vertical displacement associated with the interpreted paleo-earthquakes at the trench site is on the order of 2.7 m, while the average slip rate is estimated at ca. 0.3 mm/a. A non-systematic variation in recurrence interval, as well as a characteristic earthquake behavior for Kaparelli fault is implied by the present available radiometric dates.

KEY WORDS: *active fault, trenching, paleoseismological dating, recurrence interval, Corinth Gulf, colluvial deposits.*

RIASSUNTO

Paleosismicità della faglia di Kaparelli (Golfo di Corinto orientale): evidenza di terremoti ricorrenti e comportamento della dislocazione.

La faglia di Kaparelli si è attivata durante la sequenza sismica del Golfo di Corinto inducendo un'estesa deformazione superficiale. Il presente lavoro si è posto come obiettivo principale quello di identificare e datare, mediante l'analisi paleosismologica di depositi colluviali, riempimenti di fessure e dislocazioni di orizzonti stratigrafici di riferimento, individuati all'interno di tre trincee esplorative appositamente scavate, i precedenti eventi sismici tardo-quaternari, così da poter definire l'entità della dislocazione tettonica lungo il tracciato principale della faglia.

L'analisi paleosismologica svolta sulle sezioni esposte all'interno delle trincee ha messo in evidenza gli effetti di almeno tre terremoti, succedutosi negli ultimi 10.000 anni prima del 1981; gli effetti prodotti dai due eventi più recenti sono stati riconosciuti in due delle trincee. La datazione al radiocarbonio (date calibrate) di orizzonti di suolo sepolti e il riconoscimento di episodi di fagliazione, anche in rapporto a episodi di colluviazione e al riempimento di fessure associati ad eventi sismici successivi, ha consentito di riferire i tempi di ritorno degli eventi stessi agli intervalli 9490-9250 BP/7150-7430 BP e 5710-5570 BP/1390-1060 BP.

La faglia di Kaparelli si compone di un gran numero di diramazioni e segmenti differenti che formano nel loro insieme una zona di faglia complessa. I valori della dislocazione tettonica per singolo evento, registrati in corrispondenza di segmenti diversi, variano tra 0,7 m e 1 m. Il rigetto verticale associato ai paleo-terremoti, interpretati nel sito di scavo delle trincee, è risultato dell'ordine di 2,7 m, mentre lo slip rate medio è stato stimato in circa 0,3 mm/a. I dati radiometrici disponibili, come anche il comportamento caratteristico del terremoto, indicano una variazione non-sistematica dei tempi di ritorno.

TERMINI CHIAVE: *faglia attiva, trincea; datazione paleosismologica, tempo di ritorno, Golfo di Corinto, depositi colluviali*.

INTRODUCTION

The Gulf of Corinth, located in central Greece, is one of the most tectonically active and rapidly extending regions (6-15 mm/a) in the world (fig. 1a, inset). Extension has a roughly N-S direction as indicated by both geodetic (CLARKE *et alii*, 1997) and fault-slip analysis (DOUTSOS & KOKKALAS, 2001). The southern side of the Gulf of Corinth is bounded by a series of major north-dipping normal fault zones, forming a complex asymmetric half-graben (DOUTSOS & KOKKALAS, 2001; MORETTI *et alii*, 2003). These E-W striking normal faults, which have a length of several tens of kilometres, typically have an impressive morphotectonic expression on the southern border of the Gulf (ROBERTS & KOUKOUVELAS, 1996), while some antithetic faults, less developed, are also visible at the northern edge of the gulf. One of these south dipping faults is the Kaparelli Fault (KF; fig. 1, a and b).

During February and March 1981, two earthquake sequences occurred in the eastern part of the Gulf of Corinth. Structures within this part of the Gulf comprise a complex array of onshore and offshore faults bounding a half-graben separating the Perachora peninsula from the rest of Central Greece (LEEDER *et alii*, 2002). The first sequence of earthquakes (Ms: 6.7-6.4) generated north-dipping surface normal faulting along the southern edge of the Gulf of Perachora, while the second sequence with a main shock of Ms: 6.4 created south-dipping surface faulting along the northern side of the gulf in the area

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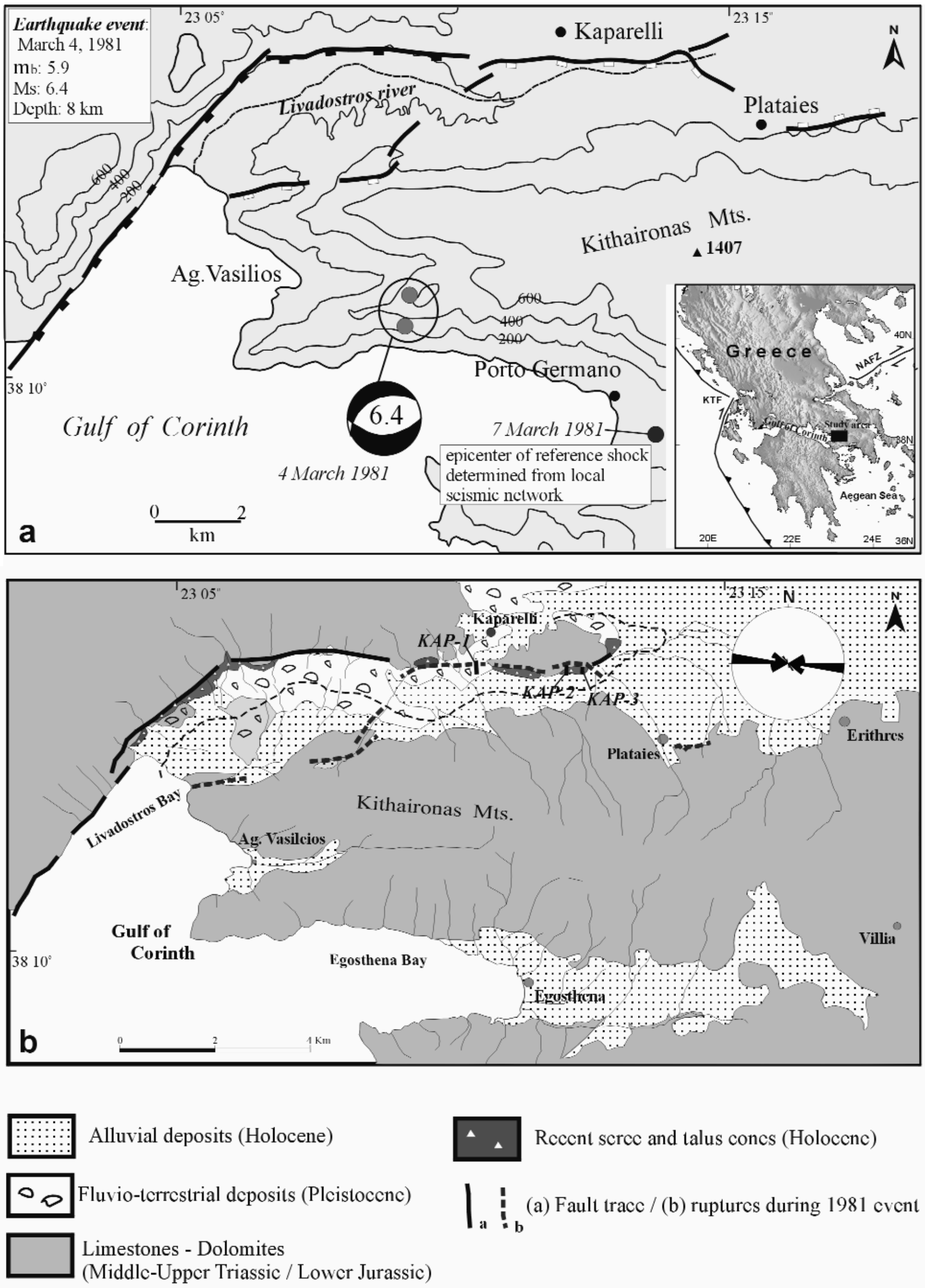

Fig. 1 - a) Simplified map of the eastern Gulf of Corinth highlighting major faults and the position and magnitudes of the mainshocks of the 1981 earthquake (relocated epicenters and hypocentral parameters from JACKSON *et alii*, 1982). Faults with white colored teeth correspond to fault segments activated during 1981 earthquake; *b*) Simplified geological map of Kaparelli area with the location of the paleoseismological trenches.
– a) *Rappresentazione schematica del Golfo di Corinto orientale nella quale sono riportate le faglie principali nonché l'ubicazione e la magnitudo delle scosse principali del terremoto del 1981 (epicentri e parametri ipocentrali rilocalizzati da* JACKSON et alii, *1982). Le faglie indicate dalle linee con i dentini bianchi corrispondono ai segmenti attivati durante il terremoto del 1981;* b) *Rappresentazione schematica dell'area di Kaparelli con l'ubicazione delle trincee paleosismologiche.*

of Kaparelli and Plataies (figs. 1 and 2; PAPAZACHOS *et alii*, 1981; JACKSON *et alii*, 1982). Earthquake ruptures occurred both along the boundary between Triassic limestones and alluvial deposits (fig. 2b), as well as alluvial fan deposits and colluvial deposits at the base of a well defined compound scarp (fig. 2a), generally reactivating pre-existing E-W striking faults.

Paleoseismological studies through trenching investigations of fault colluvial tectono-stratigraphy can facilitate to extend historical seismological data and thus are a valuable method that can provide data regarding the occurrence of destructive prehistoric earthquakes (MCCALPIN, 1996; PAVLIDES *et alii*, 1999). Paleoseismology is the study of the location, timing and size of prehistoric earthquakes (SOLONENKO, 1973; SIEH, 1978; WALLACE, 1981; MCCALPIN, 1996) and tries to interpret geological evidence created during individual paleoearthquakes. Paleoseismology uses geomorphological and geological evidence of past seismic shaking and/or ground rupture to extend earthquake studies. It differs from more general active tectonic studies in its focus on the almost instantaneous deformation of landforms and sediments during earthquakes (ALLEN, 1986). In the past decade, data collected in some detailed paleoseismic studies have been used to develop important new concepts about the earthquake generation process.

Recently there has been an increasing interest also in Greece in defining specific seismic events with the use of trenching excavation. The first paleoseismological studies in Northern Greece showed varied recurrence intervals like in Mygdonia basin (1000 yr), in Kozani-Grevena (3500 yr) and Thessaly plain (>2000 yr), (PAVLIDES *et alii*, 1992; CHATZIPETROS & PAVLIDES, 1994; CAPUTO *et alii*, 2004), in contrast to the short recurrence intervals estimated for the Atalanti fault (PANTOSTI *et alii*, 2004) the south Alkyonides fault zone (PANTOSTI *et alii*, 1996; COLLIER *et alii*, 1998), and the Eliki fault zone (KOUKOUVELAS *et alii*, 2001; PAVLIDES *et alii*, 2004), showing past events during historical times with recurrence intervals <800 yr. Some of the data results appearing in this study have been already included in a recent review article about the paleoseimological study in Greece (CHATZIPETROS *et alii*, 2005).

The present study provides information on the seismic history of the Kaparelli normal fault (KF) by means of trenching techniques, tectonostratigraphy of fault colluvial sequences and radiocarbon dating. Knowledge of timing, location and slip distribution of past earthquakes is critical to understand the long-term behavior of the KF and to attempt to forecast future large earthquakes.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The roughly E-W trending KF is a segment of the greater Plataies-Avlona-Oropos fault zone which extends from the eastern part of the Gulf of Corinth to Evia Island. The KF comprises three main fault segments that are clearly expressed at the surface by nearly continuous scarps. The footwall of the northwest strand of the KF reaches c. 600 m and is composed of Triassic-Jurassic limestones of the Pelagonian zone (IGME, 1984). The hangingwall of the KF forms a topographic low and contains a maximum of c. 230 m of fluvio-terrestrial deposits of probable Pleistocene age, as well as Holocene alluvium and recent scree (fig. 1b). Sediments in the hanging wall of the westernmost fault segment dip towards the fault.

The two segments of the KF that ruptured during the third event of the February-March 1981 Alkyonides seismic sequence (JACKSON *et alii*, 1982) form a left-stepping en echelon geometry, while the third north-western strand of the KF did not rupture during the March 4th event (fig. 1). The mean co-seismic ground offset was approximately 0.70 m, with maximum offsets larger than 1 m, whereas the slip vector was approximately 200°-220°/60°-70° (JACKSON *et alii*, 1982; MOREWOOD & ROBERTS, 2001).

Normal faulting extending for approximately 10-12 km with an E-ENE/W-WSW trend, dipping to the south, appeared at the surface in the Livadostros Valley after the shock of March 4th. The surface breaks of March 4 th consist of two continuous fault segments (JACKSON *et alii*, 1982; PAVLIDES, 1993). The first lies immediately south of Kaparelli village and forms a continuous limestone scarp for about 5 km. Freshness and existence of zones with different color argue that a 3-5 m high scarp is the cumulative effect of past earthquake events. Recent displacements on this segment average 0.6-0.7 m, as it is clearly visible by a discontinuous basal strip of fresh bedrock exposed at the base of the scarp. At its eastern end the surface rupture turns abruptly from an E-W to a SE-NW direction (PAVLIDES, 1993) and crosses the recent alluvial sediments of Livadostros Valley floor. Although fault scarps are visible within the footwall block of the E-W trending Kaparelli fault, which continues eastwards, they seem not to be reactivated at the surface. The second fault segment lies along the north-western slope of Kithaironas Mt., south of Livadostros River, which dips also to the south, and it extends down to the coast (Livadostros Bay; fig. 2b). A series of discontinuous cracks with a NE-SW direction

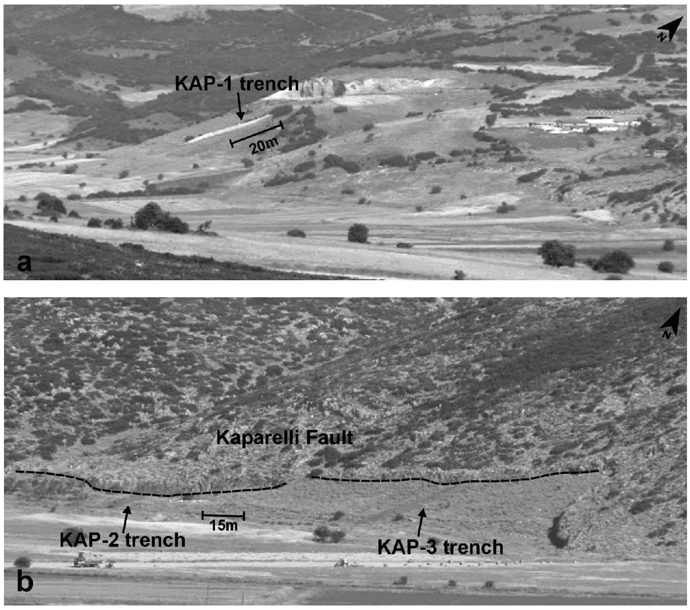

Fig. 2 - Aerial side views of trenching sites in Kaparelli area: *a*) location of KAP-1 trench; *b*) locations of KAP-2 and KAP-3.
– *Vedute aeree oblique dei siti di trincea nell'area di Kaparelli:* a) *ubicazione della trincea KAP-1*; b) *ubicazione delle trincee KAP-2 e KAP-3.*

crosses the gorge of Livadostros River forming a step-over zone between the two segments (fig. 2b).

Recently, BENEDETTI *et alii* (2003), using ^{36}Cl cosmic ray exposure dating on the 3-5 m high limestone scarp of Kaparelli fault, suggested that the fault has ruptured three times prior the 1981 event at 20±3 ka, 14.5±0.5 ka and 10.5±0.5 ka and ceased its activity in the last 10 thousand years.

TRENCH SITE SETTING AND METHODS

Three trenches were excavated during May-June 2002 across the Kaparelli fault scarp, sampling a fault segment with a length of 3 km. They are oriented perpendicular to the fault strike and are designated from west to east as KAP-1, KAP-2 and KAP-3. They are located mainly in deformed Holocene colluvium, (KAP-2, KAP-3) or fluvial deposits (KAP-1), in contact with bedrock limestone or Pleistocene fluvial deposits, respectively (fig. 1b; figs. 2a and b).

The trenches revealed excellent exposures of deformed late Holocene sediments. The lithology of the faulted slope comprises, in general, a typical colluvial succession in front of the fault scarp, which is composed mainly of unconsolidated sub-angular limestone fragments and soil (debris element), which includes occasionally tile fragments and rare charcoal. The colluvial deposits preserve high repose angles on the order of 30-45°, as observed inside the trenches (fig. 3a; figs. 4 and 5). The wash element facies, which lie directly above the debris element, declines gradually to lower angles mainly due to the higher percentage of matrix and less coarse lithofacies, suggesting high rates of slope degradation (KOKKALAS & KOUKOUVELAS, 2005).

The trenches were 15 to 20 m in length and 2-4 m in depth and started from the last reactivated fault scarp and extended southward, with the KAP-1 as the only

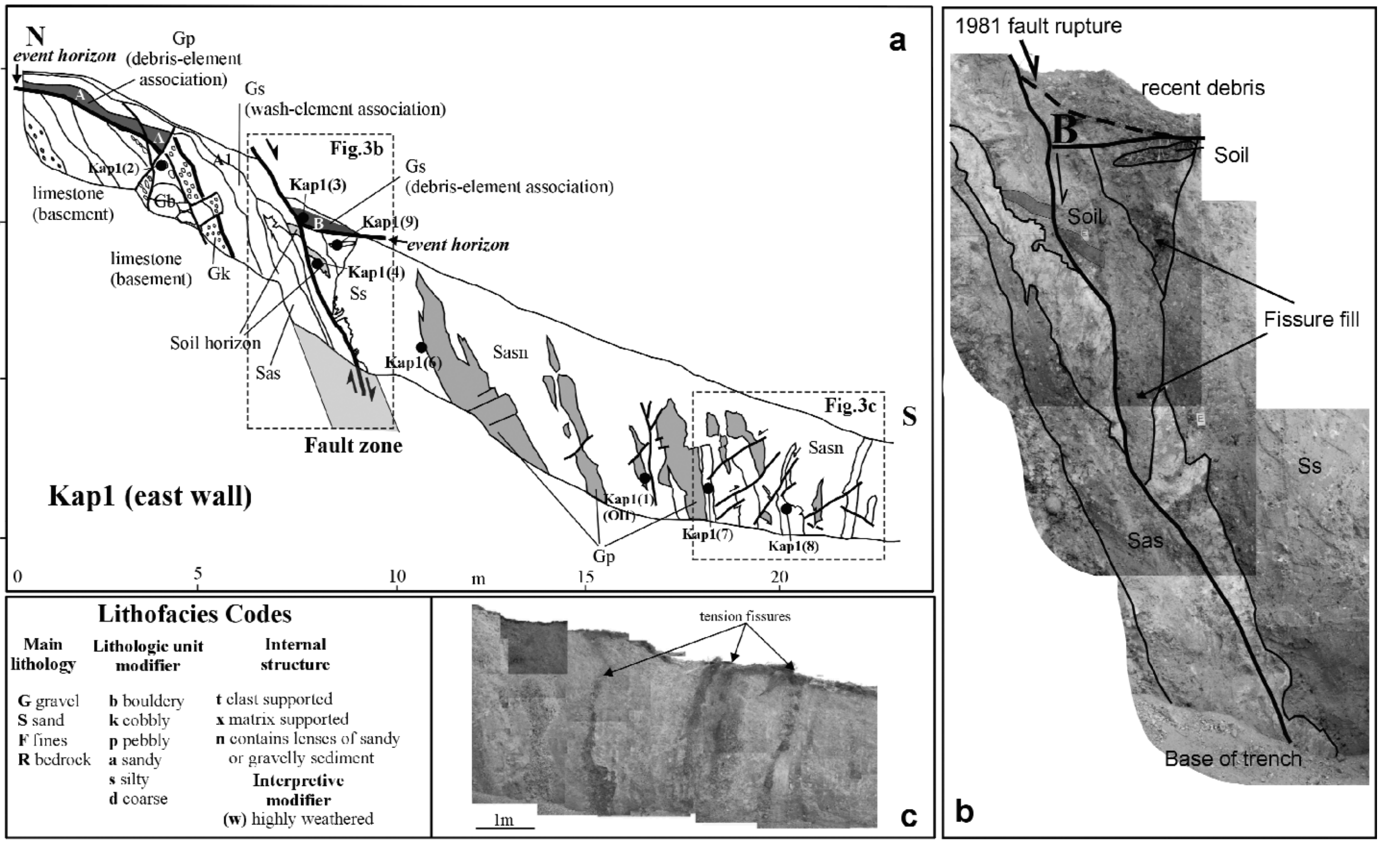

Fig. 3 - a) East wall of trench KAP-1. Capital letters within colluvial units show which units were deposited following the first (A) or second (B) faulting event. Lithofacies codes after NELSON (1992); *b*) Detailed view of 1981 rupture surface and accompanying fissure fills as identified in the trench; *c*) Fissures fills in the downslope area of the main fault trace.
– a) *Parete est della trincea KAP-1. Le lettere maiuscole all'interno delle unità colluviali mostrano quelle unità depositate per effetto del primo (A) e del secondo evento di fagliazione. I codici delle litofacies seguono quanto proposto da* NELSON *(1992)*; b) *Veduta di dettaglio della superficie di rottura del 1981 e delle fessure riempite ad essa associate, identificate nella trincea*; c) *Riempimenti di fessure nell'area a valle del tracciato di faglia principale.*

exception since it crossed the 1981 fault rupture (figs. 3, 4 and 5). Walls of the trenches were scraped clean, gridded with string on the east wall (1×1 grid cells) and logged in detail, at a scale of 1:20. Faults and contacts were etched into the wall and marked with painted nails to enhance their visibility in the photographs. The walls of all trenches were photographed, cell-by-cell, while they were locally cleaned and the photographs were mosaiced to provide a complete unobstructed view of the entire trench wall. The wall that was mapped in each trench was chosen as to preserve the best stratigraphy, and exhibiting faulting events with clear marker horizon displacements.

EVIDENCE OF FAULTING

The ground surface at the time of a paleoearthquakes is termed as an «event horizon» (see PANTOSTI *et alii*, 1993). An event horizon is stratigraphicaly defined by either scarp-derived colluvium that buries the pre-faulting surface and/or by unconformities that develop as a result of warping and subsequent deposition. Therefore, the number of event horizons should equal the number of paleoearthquakes or similarly, the number of discrete colluvial wedges represents deposition following a surface-rupturing event.

Commonly used indicators of event horizons include liquefaction, upward terminations of faulting and abrupt changes in deformation between units (e.g. MCCALPIN, 1996). All these, taken alone, might also be explained by off-fault seismic sources or fault creep. Lines of paleoseismic evidence that may be unique to coseismic rupture and not creep include fissure fills and colluvial-wedge deposits (STENNER & UETA, 2000; KELSON & BALDWIN, 2001). For this reason the colluvial wedge model is applied for the paleoseismic investigation of the three trenches in the Kaparelli Region assisted also by other characteristic observations such as, upper terminations of secondary faults, fissure fills or striking difference between deformed and less deformed units.

TECTONOSTRATIGRAPHY

TRENCH KAP-1

Trench KAP-1 was excavated in fluvial fan deposits and exposed a ca. 4 m deep section of unconsolidated well-stratified silty-sand unit with conglomerate intercalations, in the southern part of the trench (fig. 3, a and c). The northern part of the trench comprises a moderate-dipping non-typical colluvial association which is subdivided, based mainly on its lithology (grain size), matrix

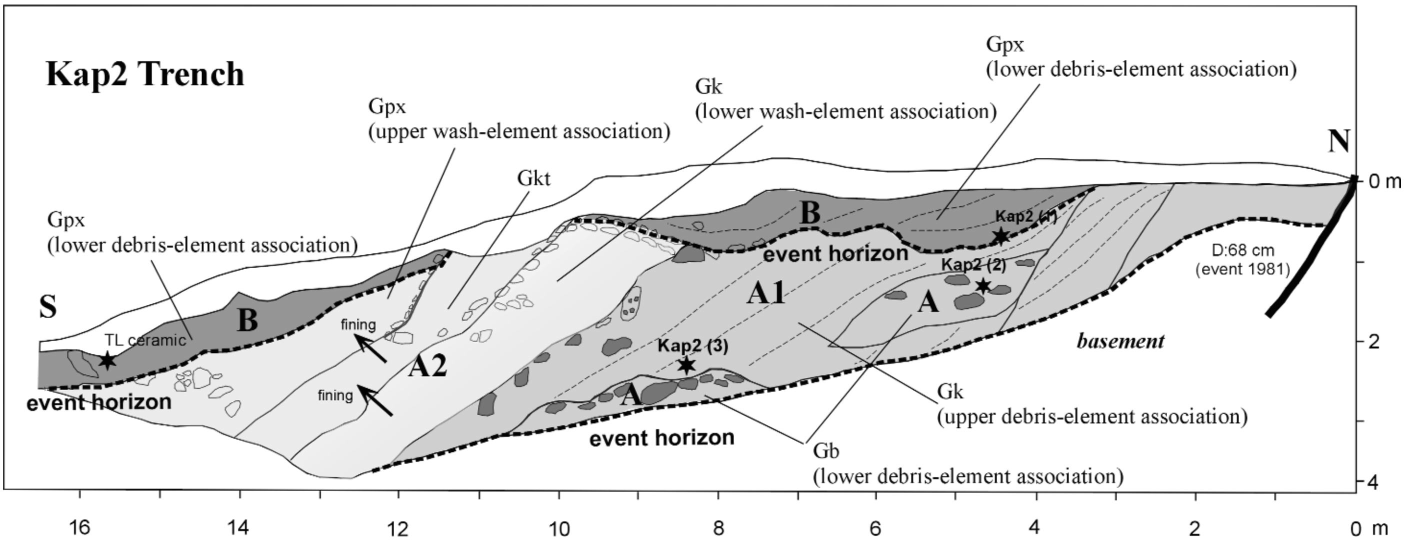

Fig. 4 - West wall of trench KAP-2 with the interpreted event horizons (lithofacies codes as explained in fig. 3).
– *Parete ovest della trincea KAP-2 con gli orizzonti degli eventi intepretati (codici delle litofacies come in fig. 3).*

and proximity to the fault scarp, into two subunits: (1) a lower part corresponding to a debris element association (fig. 3a, unit A) and (2) an upper part, poorly developed, classified as a wash element association (A1). The debris element is a pebbly-cobbly gravel bed, containing clasts up to 20 cm in length. Above this, lithofacies are getting much thinner consisting mainly of silty sand with sparse pebbles. This wash element association, which is about 0.5 m thick, is not well developed, probably due to erosion, and is lying on the slope surface of the debris element. Below these units (A & A1), a complex assemblage of weathered basement blocks, up to 50 cm in length, as well as poorly sorted conglomerate beds of probable fluvial origin is lying, restricted mainly in the base of the colluvium. The fact that the backhoe excavator couldn't dig easily any further below the sedimentary units, indicates that we reached the bedrock at the base of this trench. High-angle normal synthetic and antithetic fault strands displace these units, as well as the debris element of the overlying colluvium, showing a complex geometry. These sequences (Gb, Gk below A unit in fig. 3a) are probably related to another fault segment, further north close to the reactivated 1981 segment. It is possible that previous interaction of these faults caused the rotation of alluvial fan deposits seen in the trench.

The 1981 Kaparelli fault trace in KAP-1 trench is identified as a 2-3m wide high-angle fault zone containing small step faults that is bounded by tension fissures on its down-slope side (see fig. 3, b and c), where highly rotated bed units are observed. As in fault zones that have been subjected to more than a few reactivations, the zone in the trench consists of a complicated assemblage of sheared «in situ» deposits, material that has fallen into fissures in intact blocks, plus $CaCO_3$ precipitated by circulation of meteoric water, partly disaggregated blocks and material washed into depressions by running water, during the development of the colluvial wash element. Many pebbles have been dragged along the fault planes and some layers appear to be warped (fig. 3b). A thin key-bed soil horizon is displaced along the fault surface, showing a vertical offset of ca. 50 cm. (fig. 3b) The lower part of this key-bed horizon [sample Kap1(4)] has been dated to 3760-3620 BC (calibrated age).

The hangingwall block of the reactivated fault strand comprises a strongly rotated (>60^0) sedimentary sequence, which consists of silty-sand with pebbly gravel bed intercalations. This rotation may have been achieved with fault interaction and formation of a restraining overlap zone (see also RYKKELID & FOSSEN, 2002) during cumulative fault deformation.

The stratigraphic evidence of paleoearthquake events in the hanging wall block is represented by a series of nested crack fills (fig. 3, a and c). Soil samples taken from these fissure fills gave an age range from 5480 BC to 5200 BC [samples Kap1(1) and Kap1(8)]. Thus, either the fissures were still open when the material was deposited as crack fill, so the seismic event was a bit older than the age of the fill, or the material has been already deposited atop of the alluvial fan deposits and then down-dropped into the fissures, implying that the cracks are coeval or young. The uppermost parts of the trench are disrupted in places probably by erosion or human activity and a more detailed and careful soil analysis is needed in order to study the recent faulting process in detail.

Due to the lack of significantly coarse scarp-derived colluvial deposits in KAP-1 trench, it seems probable that the surface rupture event did not form large high angle free faces but rather less than meter scale normal faulting combined with a complex pattern of fissure opening, as it is observed in the south part of the trench. Also the absence of thick paleosol beds in the trench log suggests that periods of slope stability and soil formation (lasting from some hundreds years to 1 kyr) had not existed, implying a more or less continuous seismic activity of the area, or very intense erosion.

The age range covered by the sediments within the trench is 7430-7150 BP (soil fissure fill in fluvial sediments) to 1270-1060 BP (fig. 3a, sample Kap1(3), unit B; base of the younger colluvial wedge). This small-scale colluvial wedge (unit B, fig. 3b) adjacent to the surface rupture trace of the 1981 event corresponds to a strong event

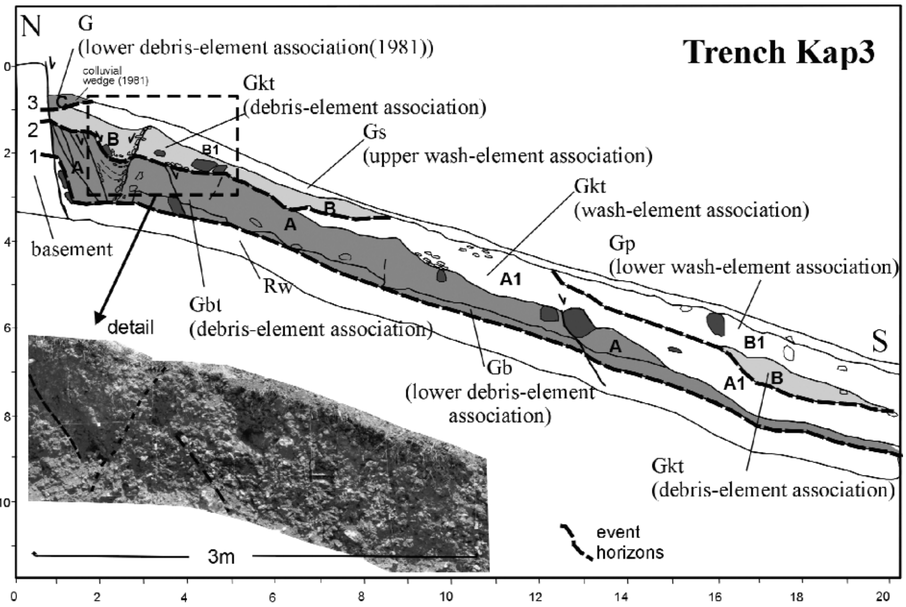

Fig. 5 - East wall of trench KAP-3 with the event horizons and a photomosaic in more detail (lithofacies codes as explained in fig. 3). – *Parete est della trincea KAP-3 con gli orizzonti degli eventi e un fotomosaico di maggior dettaglio (codici delle litofacies come in fig. 3).*

prior the 1981 earthquake, bracketed by the age of the underlying soil bed horizon (fig. 3a, sample Kap 1(4), 3760-3620 BC), which possibly represents an age limit of the underlying fissure fill caused by a possible earlier event (event 5?; fig. 6) and an age obtained from a sample within unit B (fig. 3a; 680-890 AD, sample Kap1(3)].

Trench KAP-2

The KAP-2 trench is ca. 16 m long, 3 m deep and 2 m wide (fig. 4) and exposes a typical colluvium succession, composed mainly by sub-angular limestone fragments and soil, which include occasionally tile, fragments, and some charcoal.

The lower (A) and upper debris-element facies (A1) associations of the lower colluvium are distinguished by their position in the wedge next to the scarp and their lithology, and by the proportion of basement blocks, coarse angular clasts and fine-grained sediments. The upper debris-element facies (A1) consists of lithofacies that are thinner, more laterally extensive and contain smaller and more dispersed blocks and clasts than the lithofacies of the lower debris element. No datable material could be collected at the base of this colluvium. Thus, a sample near the base of the older debris element indicates that, at 2σ, age ranges from 7540-7300 BC (9490-9250 yr BP), implying a seismic event before this age. This event can be possibly correlated with the suggested ~10 Ka BP event of Benedetti *et alii*, (2003).

Above this association lies a subunit (A2), which comprises a less wedge-shaped assemblage of lithofacies deposited on the sloping surface of the debris element. It is finer grained than the upper debris element and the internal bed contacts are more nearly parallel. The percentage of matrix increases upwards from 10% in the lower beds to 40% in the upper beds, while the clast size decreases significantly. This fact, as well as its position relative to the underlying debris element, suggests that the unit is a wash element association. Overlying this wash element and above an erosional surface is a second colluvial wedge (B) that is finer grained than the first, eroded in its upper part and more laterally extensive. The results from a soil sample taken at the base of this colluvium indicate that, at 2σ, the age ranges from 560-690 AD (1390-1260 BP). It is possible that some of the events identified in KAP-1 trench could not be detected in this trench due to unfavourable deposits (homogenous colluvium), as well as erosional activity.

Trench KAP-3

The trench KAP-3 is ca. 30 m long, 3 m deep, 2 m wide and it exposes identical lithological units and similar paleoseismological results with the trench KAP-2 (fig. 5). Two older well-developed colluvial wedges (fig. 5, units A and B) and a younger wedge adjacent to the fresh fault scarp were identified (fig. 5, unit C). The colluvial deposits from the successive events are deposited on the sloping surfaces of the earlier colluvium wash element (A1) or directly above the debris element. This causes the younger wedge to extend, after every event, farther downslope from the fault, and get thinner and less wedge-shaped (see also Ostenaa, 1984).

Of particular interest for understanding the seismic history on the KAP-3 trench is a small-scale graben formed between the main fault trace and an antithetic normal fault (see detail in fig. 5). The synthetic fault strands extend up to the second event horizon (base of colluvium B) in contrast to the antithetic fault, which crosses the debris element of the younger colluvial wedge (B) and extends no higher than the base of a wash element association (B1) probably related to the colluvial wedge B (fig. 5). Age determinations of this trench are not yet available.

RADIOCARBON DATING

Table 1 shows the results for 6 samples of soil that were submitted for radiocarbon dating. Dating of samples was performed in the Center for Applied Isotope Studies, University of Georgia. Radiocarbon ages were calibrated to calendar ages using the program OxCal ver. 3.5 (Ramsey, 1995, 2000) that uses the atmospheric data of STUIVER *et alii* (1998). These samples were chosen from locations that are in the vicinity of the debris associations. Samples from the uppermost part of the sections were excluded because they might be too young in age and thus their dating would have been unreasonable due to uncertainties in calibration.

Dating soils, involves uncertainties discussed in the following. When a soil is buried, rejuvenation of ^{14}C activity by the addition of fresh organic material is prevented and at that point in time the soil organic matter has an apparent mean residence time. Thus, the date of burial is derived by the subtraction of the apparent mean residence time from the measured ^{14}C date. A ^{14}C date for a buried soil provides therefore a maximum estimate of the time elapsed since burial and permits only a minimum estimate of the period of time since the beginning of soil formation. Some of the common problems in the ^{14}C dating are a) uncertainties associated with the degree of development of the soil and weather or not it was in equilibrium prior to burial, b) young root penetration and concentration in buried soil horizons, which will tend to rejuvenate the buried soil organic matter, c) the possibility of an ageing effect from infinitely old carbon present in the soil mineral matter and d) the possibility of some disturbance and/or erosion of soils during or after the burial.

DISCUSSION

Based on colluvium tectono-stratigraphy, fissure fills, small displacement of some key horizons, and fault upper terminations, we examined the seismic faulting record (paleoearthquakes) of the Kaparelli fault, prior to the 1981 earthquake event. Although recent studies suggest that the Kaparelli fault ceased its activity in the last 10 thousand years (BENEDETTI *et alii*, 2003), our data provide evidence for younger displacements across the fault, which occurred during the Holocene.

Thus, based on radiocarbon dating of soils, we identified at least three events that occurred in the last 10 ka (fig. 6). We consider the strongest evidence for paleoearthquakes to be the existence of successive colluvium wedges and fissure fill facies deposited adjacent to the main fault trace, as material can be shed off a newly exposed fault scarp relatively quickly, with high rates of degradation (see KOKKALAS & KOUKOUVELAS, 2005).

Our preliminary results from the two trenches show that the age range for the colluvial sedimentation and fissure fill formation is at 9490-9250 BP [Kap2(3)], 7150-7430 BP [Kap1(1) & Kap1(8)], 5710-5570 BP [Kap1(4)], and 1390-1060 BP [Kap1(3) & Kap2(1)], providing evidence for at least three strong earthquake events during this periods (tab. 1 and fig. 6), although these dates cannot be correlated and confirmed yet with radiocarbon dating results from the KAP-3 trench, which is still under way. Expected dating results from additional samples collected in KAP-1 and KAP-3 trench will determine time brackets between the past seismic events more accurately and will also confirm the possible fourth event (fig. 6, event 5).

In the first trench (KAP-1) the last 1981 event is clearly shown within a greater fault zone of ~3m width, where tilted (50°-70°) sediments (clay, sand, colluvial wedges and soil) are strongly rotated possibly by previous tectonic events. The average displacement per event as indicated by displacement of key marker beds in the trenches is 0.75±0.16 m. Furthermore, the colluvium thickness observed in the trenches is ca. 2.7 m (trench KAP-2) and with age bracketing of the samples an average slip-rate of 0.28-0.29 mm/yr can be estimated. Taken into account the whole tectonic history of Kaparelli fault, there is evidence of six seismic events at the Kaparelli fault, in the last 20 Ka prior the 1981 event (BENEDETTI *et alii*, 2003 and this study), which yields a long term mean recurrence of 3.35 Ka. However the recurrence time is variable ranging from 1.4 to 5.5 Ka (fig. 6). The standard deviation (σ) of recurrence series is 1.66 Ka which defines a coefficient of variation of 0.49, typical of paleoearthquake sequences. Additionally, only for the paleoseismicaly identified events, we estimated a non systematic short term recurrence interval with a mean of 2.52 Ka and standard deviation of 1.3 Ka, although a clustering of events seems to occur in present times. The coefficient of variation remains also close to 0.51.

TABLE 1

Dates of Radiocarbon samples from Kaparelli trenches (Results from the Center for Applied Isotope Studies, University of Georgia).
– *Datazioni al radiocarbonio dei campioni provenienti dalle trincee scavate attraverso la faglia di Kaparelli.*

Sample	**Laboratory**	**Description**	**h^{13}C**	**^{14}C Age**	**[1]Calibrated Age (at 95% C.I.)**
No	*No*		*(‰)*	*Years BP*	*Calendar Years*
Kap1(4)	11002	soil	-10,88	4.870±40	***3760-3620 BC (85,8%)***
					3580-3530 BC (9,6%)
Kap1(8)	11003	soil	-23,47	6.280±40	***5340-5200 BC (75,8%)***
					5180-5140 BC (11,7%)
					5130-5070 BC (7,9%)
Kap1(3)	11004	soil	-21,55	1.250±40	***680-890 AD (95,4%)***
Kap1(1)	11005	soil	-14,28	6.390±50	***5480-5300 BC (95,4%)***
Kap2(3)	11006	soil	-21,88	8.330±50	***7540-7300 BC (86,8%)***
					7270-7240 BC (1,5%)
					7230-7180 BC (7,1%)
Kap2(1)	11007	soil	-23,39	1.410±40	***560-690 AD (95,4%)***

[1] Calibrated age is the intercept of the mean ^{14}C age with the calibration curve of STUIVER *et alii* (1998).

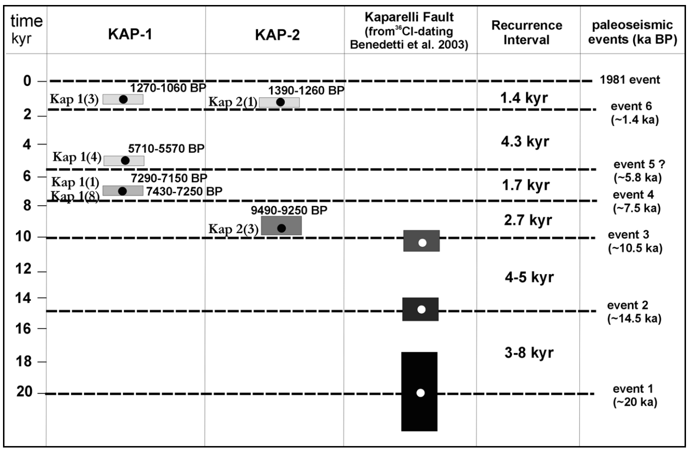

Fig. 6 - Summary of C^{14} dating results and correlation of possible earthquake events in the Kaparelli fault.
– *Sommario delle date C^{14} e correlazione dei possibili eventi sismici associati alla faglia di Kaparelli.*

Vertical slip on Kaparelli fault associated with the seismic events that were determined by BENEDETTI *et alii* (2003) is between 0.6 and 2.1 meters, while the most recent events determined by our study show values of 0.7 to 1 m. Thus, slip history yields an integrated rate of ca. 0.2 mm/yr from ^{36}Cl cosmogenic dating, while independently from our radiocarbon dating we estimated also a slip rate in the same order (0.28-0.29 mm/yr). Taken also into account the whole fault history in the last 20 Ka a reasonable average vertical slip rate of ca. 0.30 mm/yr can be estimated.

At least two individual paleoearthquakes, occurring prior to the 1981 event, have been also recognized in the antithetic, north-dipping, Skinos fault (Bambakies site), south of Kaparelli, by PANTOSTI *et alii* (1996). In this site the 1981 rupture produced average vertical displacements of 0.6-0.7 m (maximum 1.3 m), showing similar offset to Kaparelli fault. One of the events in Skinos trenching site, which is assigned to occur after A.D. 590 (PANTOSTI *et alii*, 1996), could be correlated with one of the events reported in our study [Kap2(1) sample, A.D. 560-690].

This is another significant aspect for understanding the fault behavior in the broader area of Gulf of Corinth. It seems that during some seismic sequences both north and south dipping normal faults can be ruptured synchronously. This was also confirmed by the most recent event of 1981, as well as possibly in the penultimate event around 1400 yr BP (~590 AD).

CONCLUSIONS

1) Paleoseismological results across the Kaparelli fault suggest a continuous seismic activity in the last 10000 years. Stratigraphic record shows at least three, possibly four, events during the last 10 Ka, prior the 1981 event. The age estimates that constrain these events are mainly radiocarbon ages of soil and charcoal from post-faulting colluvial deposits and fissure fills.

2) Colluvial tectonostratigraphy and analysis of displacements on soil horizons suggest surface rupturing events with vertical displacements on the order of 0.7-1 meters.

3) Preliminary results from paleoseismic data indicate probably a non-systematic recurrence interval with a mean value of 2.52 Ka (s.d. ±1,3 Ka) for the south dipping Kaparelli fault, during the last 10 Ka.

4) Minimum colluvial vertical thickness in KAP-2 trench is about 2.7 m and the calibrated age of its lower part is 7540-7300 BC (86,8%, at 2σ; tab. 1) suggesting an average vertical slip rate of ca. 0.29 mm/yr. This suggests that over the last 20.000 yr the slip rate of the fault hasn't changed significantly.

5) At least one of the events at ~1400 yr BP may have ruptured both the south dipping Kaparelli and north dipping Schinos faults synchronously, resembling in this way the recent activity of 1981 earthquake sequence.

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