LOW SLIP-RATE FAULTS AROUND BIG CITIES: A CHALLENGING THREAT. THE AFINDAI FAULT AS A CASE STUDY FOR THE CITY OF ATHENS.

I. D. Papanikolaou[1,2], D.I. Papanikolaou[1] and E.L. Lekkas[1]

[1] *Natural Hazards laboratory, Department of Dynamic, Tectonic and Applied Geology, Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, Panepistimioupolis Zografou, 157-84 Athens, Greece.*

[2] *Benfield-UCL Hazard Research Centre, Department of Earth Sciences, University College London, Gower Str. WC1E6BT London, UK.*

Email: i.papanikolaou@ucl.ac.uk, dpapan@geol.uoa.gr, elekkas@geol.uoa.gr

ABSTRACT :

Low slip-rate faults tend to have large recurrence intervals and are usually regarded that they represent a low hazard probability. However, when these faults neighboring a large city, the risk becomes high. The Afidnai fault is a low slip-rate fault that bounds the northern edge of the Athens Plain and represents such an example. Due to the long recurrence intervals these faults are often absent from the historical catalogues, therefore are usually excluded from the seismic hazard assessment. In such cases only geological data can extend the history of a fault back in time, depicting the long-term deformation pattern of slip. Offset Pleistocene terraces have been used to calculate a long-term throw-rate of 0.1 to 0.3 mm/yr for the Afidnai fault, depending on our location along strike the fault. Based on a worst-case scenario the 14 km long Afidnai fault can generate events of the maximum magnitude (M=6.4), about every 2000 years. Considering that the completeness of the historical record in Greece for such magnitude events is about 200 years, it is evident that it represents only a small fraction of the mean earthquake recurrence interval of the Afidnai fault. The Afidnai fault is a typical case study concerning the threat posed by low slip rate faults around big cities and priorities should be given in tracing and assessing such structures worldwide. In such cases, paleoseismology and earthquake geology have an important role to play.

KEYWORDS: Attica, recurrence intervals, seismic hazards, Greece

1. INTRODUCTION

The slip–rate of a fault is a fundamental parameter that governs earthquake occurrence and is a critical tool for assessing the seismic hazard in an area. For example as slip rates decrease average recurrence intervals tend to increase (e.g. **Cowie and Roberts 2001**). Therefore, low slip rate faults due to their long recurrence intervals are often absent from the historical catalogues and thus are usually excluded from the traditional seismic hazard assessment. Where earthquake recurrence intervals on specific faults are commonly several hundred to several thousand years, the time period covered by the historical record in many cases is shorter than the earthquake recurrence interval for some faults (**Yeats and Prentice 1996; Machette 2000**). There are several examples that verify the incompleteness and inhomogeneity of the historical record, for whatever reason, even in countries like Greece, which maintain some of the longest and best-constrained historical catalogues worldwide. For example, the 1995 (Ms=6.5) Kozani-Grevena, damaging earthquake in Greece (e.g. **Ambraseys 1999**), occurred in a region characterized as aseismic, according to the existing hazard maps, despite the fact that geologic data indicate repeated Late Pleistocene-Holocene slip, but with long (10^3 yrs) recurrence intervals. Following the Kozani Grevena event, the National Seismic Code re-assessed the damaged area as an area of higher risk (e.g. **E.P.P.O. 1995; E.P.P.O.-A.C.E.G. 2001**). It is clear that there are other gaps in the earthquake record and will only be noticed following future earthquakes, or preferably after studies of geological data concerning active faulting.

Low slip-rate faults tend to have large recurrence intervals and thus are usually regarded that they represent a low hazard probability. However, when these faults are neighboring a large city, the risk becomes high. The recent neighboring Athens 1999 moderate (Ms=5.9) event that ruptured a previously unknown fault and resulted in 143 fatalities and about 3.5 billion euros of total economic loss (representing about 3% of the GDP) is such an example (**POMONIS 2002**). The latter demonstrates the importance of tracing and evaluating such structures. The Afidnai fault which is used as a case study in this paper is a similar low slip-rate fault that bounds the northern edge of the Athens Plain and represents such an example.

In such cases only geological data have the potential to extend the history of slip on a fault back in time (**YEATS AND PRENTICE 1996**), a time span that generally encompasses a large number of earthquake cycles depicting the long-term deformation pattern of slip. Indeed, geological data are of decisive value in the estimation of the maximum potential earthquake for a given seismogenic structure and is performed using: a) empirical relations between rupture parameters (surface length and displacement) and magnitude and b) the integrated evidence of recurrent coseismic events over a geological time interval (**MICHETTI ET AL. 2005**). Following such geologically based fault-specific approaches we try to define for the Afidnai fault: a) the maximum expected earthquake magnitude and b) estimate the mean recurrence interval based on long-term geological rates.

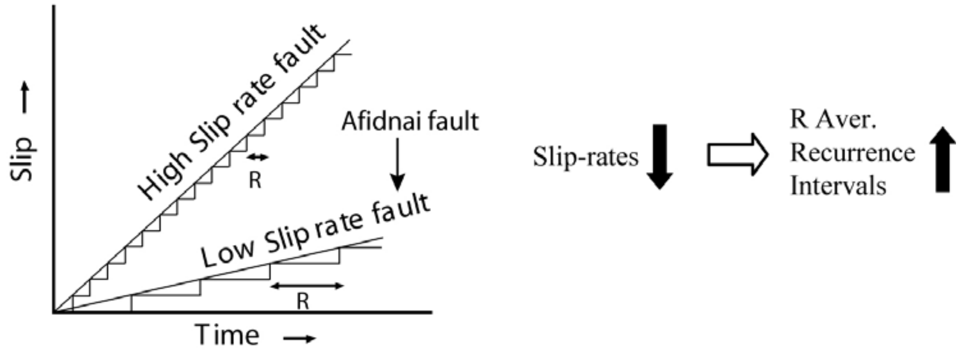

Figure 1 The slip–rate of a fault is a fundamental parameter that governs earthquake occurrence (e.g. **COWIE AND ROBERTS 2001**). For example as slip rates decrease average recurrence intervals tend to increase and several times are longer than the period covered by the historical record. This is why low slip-rate faults are often absent from the historical catalogues and thus from the seismic hazard assessment.

2. GEOLOGICAL AND TECTONIC STRUCTURE IN NE ATTICA

The NE Attica is divided by a major NNE-SSW detachment fault that separates the metamorphic units to the east from the unmetamorphic units to the west (Figure 2) and continues to the southwest into the plain of Athens approximately along the Kifissos River (**PAPANIKOLAOU ET AL. 1999**). This detachment was active in Late Miocene-Early Pliocene, produced several hundred meters of debris-flow deposits and caused the uplifting of the metamorphic units from the deeper part of the lithosphere (**PAPANIKOLAOU AND ROYDEN 2007**), where the metamorphism took place in Eocene-Oligocene times (**LOZIOS 1993**). This detachment also separates the E-W trending faults towards the western part from the NW-SE trending less active faults towards the eastern part (**PAPANIKOLAOU AND LOZIOS 1990**). It is important that the set of E-W trending active normal faults in northern Attica is constrained exclusively within the non-metamorphic Alpine units and that these faults taper out to the east as approaching the detachment zone. Therefore, the detachment indirectly seems to have a significant effect on the neotectonic structure, influencing the geometry, style and intensity of deformation (**PAPANIKOLAOU AND PAPANIKOLAOU 2007**). The post-Alpine sediments of the area comprise Late Miocene – Pliocene continental deposits and minor outcrops of Pleistocene and Holocene alluvial (**METTOS 1992**). The older sediments comprise a clastic tectonosedimentary formation that outcrops in the area of Kapandriti and in the area between Aghios Stefanos and Afidnai, forming a NE-SW zone of debris-flow deposits that are several hundred meters thick (**PAPANIKOLAOU AND PAPANIKOLAOU 2007**). On top of this breccio-conglomerate formation outcrop a few hundred meters thick lacustrine limestones that are found unconformably overlying the metamorphic basement. Finally, recent alluvial sediments are limited in thickness and are observed only in some small narrow bands along the coastline (Oropos, Kalamos, Marathon) and in the Afidnai basin.

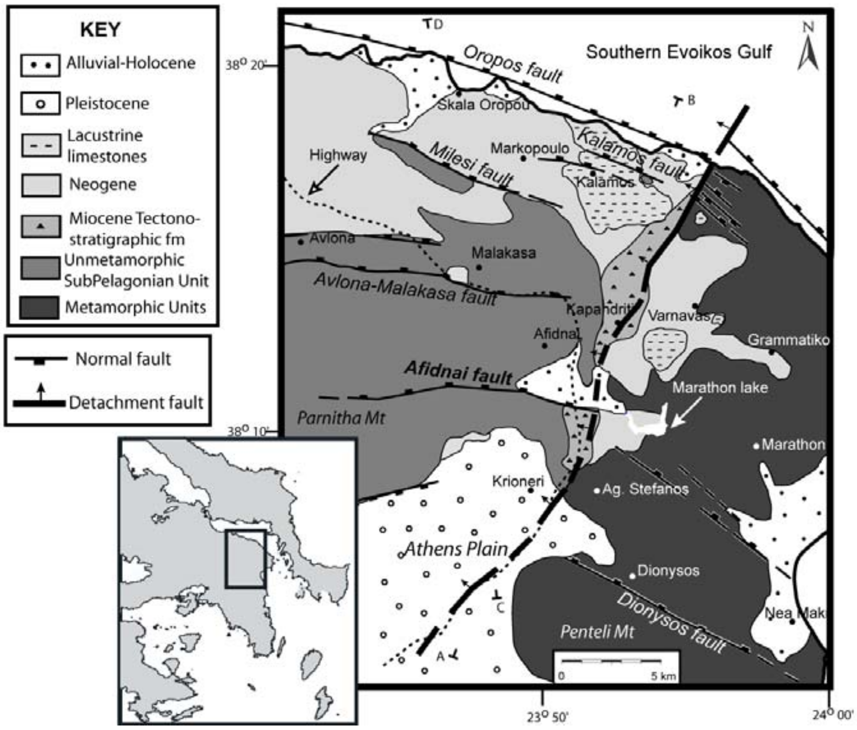

Figure 2 Geological map of NE Attica (**PAPANIKOLAOU AND PAPANIKOLAOU 2007**).

3. THE AFIDNAI FAULT

3.1. Geometry, geomorphology and drainage pattern

The Afidnai fault is a E-W trending normal fault, which downthrows to the north. This fault does generate an impressive morphological footprint and bounds the Afidnai Quaternary basin. Even though no post-glacial scarps have been identified, there are signs in the geomorphology and drainage, attesting to its recent activity. The drainage basins of the Kifissos and predominantly of the Charadros river are highly asymmetric due to the activation of the Afidnai fault (Figure 3). In particular, the Charadros river is clearly deflected into a fault parallel flow direction due to the subsidence within the Afidnai hangingwall. Moreover, the Charadros drainage divide is located only several hundred meters southwards from the Afidnai fault in its footwall, but several kilometers northwards from the fault trace in its hangingwall (Figure 3). The proximity of the footwall watershed to the fault trace is due to the tilted footwall. The tilted footwall results into southward flow directions that drain the footwall away from the hangingwall towards the Kifissos river and are perpendicular to the fault. On the other hand, headward erosion within the footwall catchments drain across the fault into the hangingwall producing also fault perpendicular flow directions, but these are limited in length. Therefore, there is a combination of fault parallel and fault perpendicular flow that is characteristic of active normal faulting settings (**GAWTHORPE AND HURST 1993; ELIET AND GAWTHORPE 1995**).

The Afidnai plain is a local base level. The short distance of the drainage divide on the footwall of the Afidnai fault from the fault trace shows that the dominant route for sediments to enter the adjacent basin in the hangingwall is via short, steep footwall catchments. Indeed, **ROUBANIS (1961)** reported that in the Afindai plain close to the railway station, the Late Pleistocene-Holocene sediments are about 30 m thick, whereas recent drillings for water withdrawal also showed that the alluvial-Quaternary thickness does not exceed 80 m. Therefore, the volume of sediment supply into the Afidnai basin is restricted, resulting into a basin of limited extent and thickness. On the other hand, the limited thickness and spatial distribution of the Quaternary sediments also imply that this base level is recently established, indicating that this fault is relatively young (Early? -Middle Pleistocene fault) that is also in agreement with the paleogeography of the Athens Plain (**PAPANIKOLAOU ET AL. 2004**).

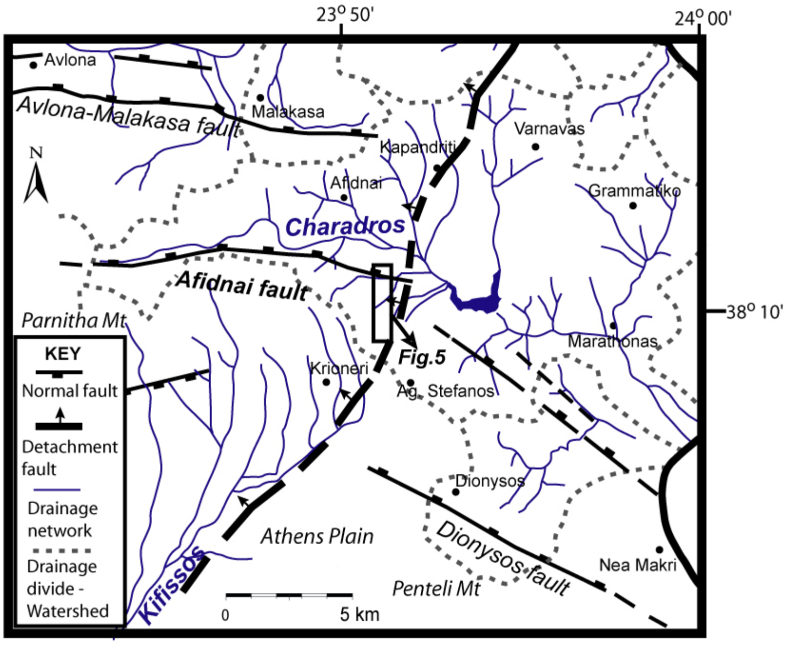

Figure 3 Map showing the drainage network, the drainage divide, the active normal faults and the detachment fault in NE Attica.

In conclusion, it is argued that the Afidnai fault is active due to: i) its geometry (~E-W trending fault parallel to all other major regional active faults, see **MARIOLAKOS AND PAPANIKOLAOU 1987, PAPANIKOLAOU ET AL. 1988** and compatible with the regional ~N-S stress field, **GANAS ET AL. 2004**), ii) its morphological expression (Figure 4, Figure 5, Figure 6, Figure 7), iii) the fact that it bounds a Quaternary basin, and iv) its drainage pattern.

3.2. Deformation rates (Slip-rate)

The lack of characteristic stratigraphic horizons and postglacial scarps limits our ability to calculate accurately the finite throw or the throw-rate. However, the study of geomorphic features, such as terraces/planation surfaces, can provide us with a first order pattern of displacement. In Early? -Middle Pleistocene the Kifissos river basin was formed, producing what is today known as the Athens Plain (**PAPANIKOLAOU ET AL. 2004**). However, one important modification that occurred since Middle Pleistocene concerns the initiation of activity and/or the speeding up of the Afidnai fault. This fault constrained the northern edge of the Athens plain as well as its drainage basin. The asymmetry of the Kifissos drainage basin, where most channels flow from Partnitha Mt to the southeast (Figure 3), illustrates nicely this recent fault tilt. Also in Middle Pleistocene thick fans and terraces were formed (**PAPANIKOLAOU ET AL. 2004**). These planation surfaces observed up to the area south of Krioneri are now offset by the Afidnai fault and have been used in order to estimate the throw-rate of the fault. Figure 5a shows nicely the influence of the fault activity into the slope map. Between the two plains of Athens and Afidnai, slope values exceed 10%, reaching up to 84%. Due to the dense vegetation cover of the Parnitha national park and the highly disturbed topography from the existing old clay quarries west of the Athens-Thessaloniki highway, we focused our terrace mapping mostly east of the highway, where geomorphology is still relatively undisturbed, even though we are aware that we are closer to the eastern tip of the fault, rather than to the center of it.

Detailed 1:5000 mapping of the planation surfaces on the northern edge of the Athens Plain revealed the presence of the main fault at the base of the hillside and two secondary faults on the footwall of the main fault (Figure 4, Figure 5b). It is unclear whether the secondary faults are still active or that activity may have shifted to the lower major fault, following a progressive hangingwall directed migration within the fault zone (e.g. **STEWART AND HANCOCK 1994**). The Afidnai fault separates the major Athens plain from the minor Afidnai-Lake-Marathon

Plain. The present day Afidnai basin on the immediate hangingwall of the Afidnai fault lies at 270 ±10 m, whereas the northern edge of the Athens basin is at 390 ±10 m, implying a minimum finite throw of 120 m (Figure 6). Half of this throw is accommodated by the main fault at the base and the other half from the two secondary faults towards the footwall, which are probably linked at depth with the main fault (Figure 6). Considering an Early Pleistocene age (between 1.0 to 1.5 Ma) of the planation surface, we calculate a long-term throw-rate of 0.08-0.12 mm/yr. However, this rate is extracted from a locality, which is closer to the eastern tip of the fault, rather than to the center of it (Figure 7). The latter suggests that we may underestimate the rate towards the center of the fault (**PAPANIKOLAOU AND ROBERTS 2006**), because fault slip and slip-rates vary along strike the fault and increase systematically along strike from zero at the fault tips, to maxima towards its center (e.g. **COWIE AND SCHOLZ 1992**). The latter can be nicely observed on the panoramic view of the fault, showing how displacement progressively decreases to minima as approaching the eastern tip of the fault (Figure 7). The same is also revealed by the gradual decrease in the slope values towards the eastern tip (Figure 5a). Considering that the finite throw towards the center of the fault is about 3 times higher ~360 m, (see also **GANAS ET AL. 2005** who calculate a 350 m relief based on DEM analysis) and that the sedimentation in the hangingwall is minimal, the maximum rate is about 0.30 mm/yr. Following the above discussion, we estimate a mean rate of 0.15-0.20 mm/yr for this fault.

Figure 4 Satellite view of the Afidnai fault geometry, showing the main (P1) and the secondary (P2, P3) fault planes.

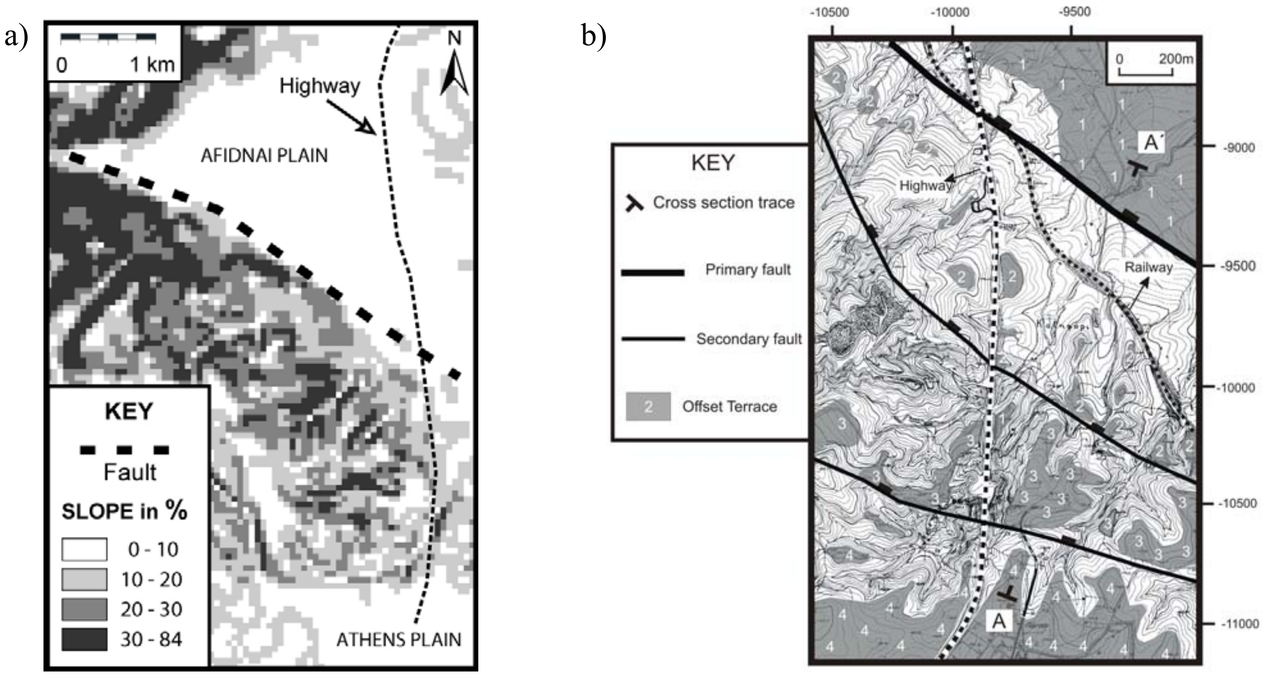

Figure 5. a) Slope map in %, b) 1:5000 scale map showing the offset terrace (numbering 1 to 4) and the traces of the major and the secondary faults towards the eastern part of the Afidnai fault (for location see Figure 3).

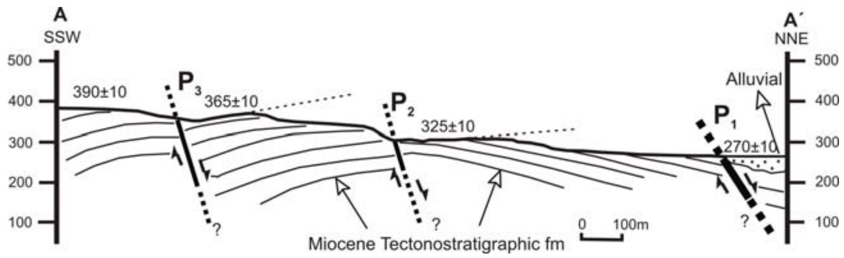

Figure 6 Cross section based on the 1:5000 map (Figure 5b), showing the offset terrace and the displacement produced by the major and the secondary fault planes.

Figure 7 Panoramic view of the Afidnai fault geometry (photo from Kapandriti) showing the displacement variation along strike the fault. Displacement decreases to minima as approaching the eastern tip of the fault.

4. DISCUSSION

The worse case scenario implies the rupture of the entire 14 km long Afidnai fault. Based on the equation between Magnitude (M) and surface rupture length (SRL) of the worldwide dataset of **WELLS AND COPPERSMITH (1994)**, this fault can generate a M=6.4 event. A similar magnitude (Ms=6.5) is also calculated based on **PAVLIDES AND CAPUTO (2004)** empirical relationships from normal faulting events of the Aegean, which may be more representative of the local geotectonic conditions. **GANAS ET AL. (2005)** estimated the fault as 11 km and calculated a similar Magnitude (Ms=6.4). Considering a mean slip-rate in the order of 0.15-0.20 mm/yr and that all slip is released in earthquakes of the maximum magnitude (M=6.4), therefore assuming a worst-case scenario, we calculate a recurrence interval of about 2000 years. The Afidnai example shows how geological data can provide an estimate both for the maximum expected earthquake and the average recurrence interval, even for low slip-rate faults. The characteristics of the Afidnai fault are summarized in Table 1.

Table 1 Data for the Afidnai fault

Length	Mmax (Maximum Expected Magnitude)	Mean slip-rate	Average Recurrence Interval	Completeness of the historical record for shallow events (h<60km)
14 km	6.4 (**WELLS AND COPPERSMITH 1994**) 6.5 (**PAVLIDES AND CAPUTO 2004**)	0.15-0.20 mm/yr	~ 2000 yrs	M>6.5 since 1845 M>7.3 since 1500 (**PAPAZACHOS ET AL. 2000**)

Following the historical catalogue, no large events (M>6.5) or severe damages have been recorded in the study area (**GALANOPOULOS 1955; PAPAZACHOS AND PAPAZACHOU 1997**). Only one event has been recorded, in 1705 (**AMBRASEYS AND JACKSON 1997**), but there is uncertainty concerning both the magnitude (M~6.4 according to **PAPAZACHOS AND PAPAZACHOU 1997**) and predominantly the epicentral area. Minor damages were inflicted both to the towns of Athens and Chalkida, so that researchers place the epicenter towards the NE flanks of the Parntitha mountain. It is possible that the Afidnai fault could have ruptured during the 1705 event; however the limited data extracted from the historical record cannot confirm or deny such an interpretation (e.g. it could be also the Malakasa-Avlona or even the Milesi fault). If this fault indeed ruptured in 1705, then the probability for a future event in the near future generated by this source is rather negligible. The historical record in Greece is considered complete for shallow events (h<60km) for M>6.5 since 1845 and for M>7.3 since 1500 (**PAPAZACHOS ET AL. 2000**). Therefore, it is also possible that an earthquake of M=6.4 could have occurred before the year 1845 and for several reasons has not been recorded. Taking into account that the completeness of the historical record for such magnitude events covers time periods of a few hundreds years and definitely shorter than 500 years (e.g. **PAPAZACHOS ET AL. 2000**), it is evident that the recurrence interval is only a fraction of the completeness period. Therefore, either this fault has not been activated in historical times or it was activated, but for whatever reason such an event was not recorded in the historical catalogues.

In 1999, the city of Athens experienced a moderate event (Ms=5.9) that resulted in 143 fatalities and about 3.5 billion euros of total economic loss (including 130 million euros of insured loss) (**POMONIS 2002**). This earthquake ruptured a previously unknown fault shorter than the Afidnai fault that was located within the Plain of Athens and represents the costlier natural disaster as well as the bigger insured loss recorded in the modern Greek history. The latter demonstrates the importance of tracing and evaluating such structures. The city of Athens rests both towards the eastern tip and the footwall of the Afidnai fault, implying that a possible rupture of this fault is expected to cause a lot of disturbance, but minor to moderate damage to the city of Athens. This is because: a) the offset towards the city of Athens is expected to be small and b) the Athens Plain will be uplifted. On the other hand, the Afidnai plain may experience severe damages not only because it is closer to the fault trace and located on the subsiding block, but also because it is founded on recent unconsolidated Quaternary deposits.

5. CONCLUSIONS

The 14 km long Afidnai fault bounds the northern edge of the Athens Plain, separates it from the secondary Afidnai Plain and constitutes a potential threat for the city of Athens. Drainage basins due to the fault activity are highly asymmetric, producing a combination of fault parallel (E-W) and fault perpendicular (N-S) flow directions. Based on offset Pleistocene terraces we calculate a long-term throw-rate of 0.1 to 0.3 mm/yr for the Afidnai fault, depending on the actual terrace Pleistocene age estimates and our location along strike the fault. Based on a worst-case scenario, the Afidnai fault can generate events of the maximum magnitude (M=6.4), about every 2000 years. Considering that the completeness of the historical record in Greece for such magnitude events does not exceed 200 years, it is evident that it represents only a small fraction (~10%) of the mean earthquake recurrence interval of the Afidnai fault.

Most of these low slip-rate faults are absent from the historical records and thus are not considered in the traditional seismic hazard assessment. This implies an even higher hazard because these faults have not been activated recently and thus maybe entering towards the end of the seismic cycle, so that a rupture is imminent. The Afidnai fault is a typical case study concerning the threat posed by low slip rate faults around big cities and priorities should be given in assessing such structures worldwide. Therefore, paleoseismology and earthquake geology have a fundamental role to play by tracing and evaluating such structures.

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