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Slip distribution of strong earthquakes in the Aegean Sea and the surrounding lands

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Abstract

The slip distribution of strong earthquakes, which occurred in the Aegean Sea and the surrounding land area, is examined based on studies conducted by us or published in the literature. This region has suffered the occurrence of strong events (i.e. Kozani 1995; Aighio 1995; Athens 1999), which produced high-quality data to study their source process and variation of slip on their fault plane. We comparatively present the methods and data sets used, as well as their results and difficulties in their application imposed by the present seismological and geodetic networks. We also compare the fault dimensions estimated from the slip distribution studies with those calculated from empirical relations based on field observations of surface fault traces or on the spatial distribution of aftershocks. In many cases, the latter are found to be inadequate to predict the observed levels of strong ground motion. Therefore, the source process of a larger set of events has to be studied in order to derive more realistic regional scaling relations of earthquake rupture models to be used in the prediction of strong ground motion for engineering design purposes.

Introduction

Slip models of past earthquakes observed in different seismotectonic regimes show that the spatial variation of slip on the ruptured fault plane is of fundamental importance for the realistic simulation of strong ground motion. During the last two decades, seismologists have done a large amount of work to investigate the rupture process of large earthquakes and to estimate the distribution of slip on their fault surfaces. Most of these studies are based on the inversion of long period data, i.e. teleseismic and regional broadband seismographic records, although recent studies additionally combine data obtained at close to the source distances, such as strong motion recordings, GPS and SAR interferometry data. The incorporation of such data in the studies of the distribution of coseismic slip on the ruptured fault planes allows more insight into the rupture process. Nevertheless, the published literature suggests that the variable slip models derived from long-period data can be used successfully in the prediction of higher-frequency ground motions (Sommerville et al., 1999).

The Aegean Sea and the surrounding lands have long been recognized as areas with the highest seismicity in Europe. Despite the often occurrence of moderate to large magnitude earthquakes, slip distribution studies concerning Aegean earthquakes started only a few years ago. The first articles that appeared in the literature incorporated basically seismological and geodetic data and forward modeling of the observed displacement fields, which involved uniform slip distribution models. More recent studies include advanced inversion techniques and are capable of revealing the possible inhomogeneous distribution of slip. The resulting slip distribution models are found to be of great importance, not only for understanding the earthquake process, but also from the engineering point of view.

The objective of the present paper is to present a review of recent publications on the slip distribution of catastrophic earthquakes, which occurred in the Aegean Sea and the surrounding lands during the last few years.

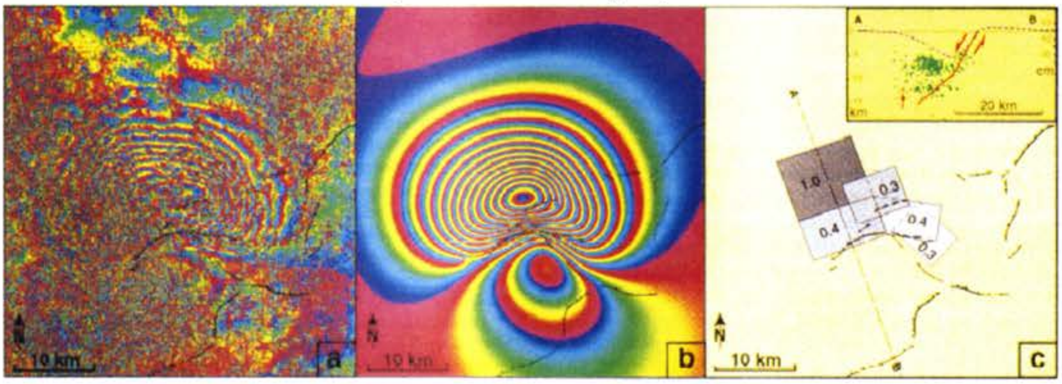
Kozani-Grevena earthquake (13 May 1995, M_w=6.6)

The 1995 Kozani-Grevena earthquake occurred on May 13, 1995 in north-central Greece, a region of low historical and instrumental seismicity. Extensive damage was caused in many villages, while the two large towns of the area, Kozani and Grevena, were more moderately affected. The earthquake caused surface breaks, which were mapped in detail during field studies conducted a few days after the earthquake (e.g. Pavlides et al., 1995; Meyer et al., 1996).

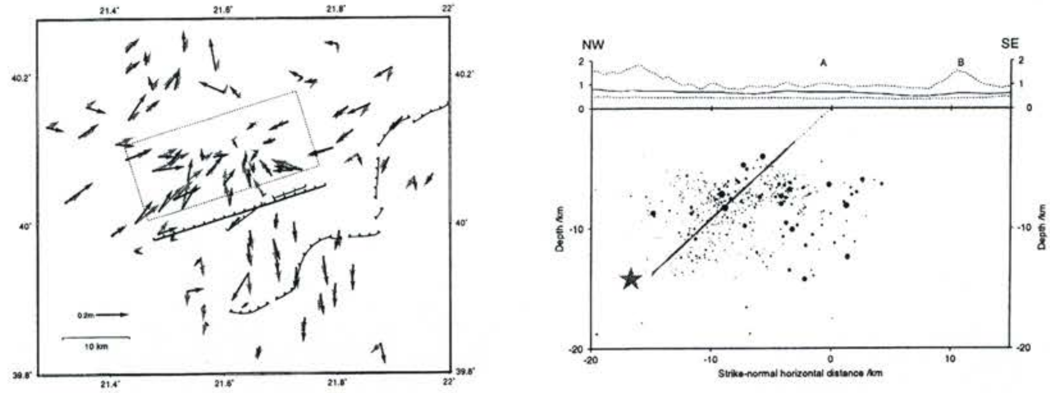
The first article regarding the source model of the Kozani-Grevena event was published by Meyer et al. (1996). The authors used InSAR data in combination with morphologic and tectonic observations in order to constrain the fault model of the examined event. The interferogram, computed from ERS-1 SAR scenes, revealed eleven main concentric fringes (Figure 1a), which outline a kidney-shaped area of subsidence of 400 km^2 with maximum of about 30 cm. The interferogram also revealed a zone of uplift reaching ~5 cm high (2 fringes), 5 km south of Palaeochori. Meyer et al. (1996, 1998a) performed forward calculations of the observed displacement field (Figure 1b) using the code of Okada (1985). Their best fault model was found by trial and error and consists of normal faulting on rectangular planes intersecting the surface at the traces of the mapped faults (Figure 1c). The main fault (10 km long) coincides at the surface with the trace of the Palaeochori fault and experienced 1 m of uniform slip at depths ranging from 9 to 15 km, where the dip of the fault model was taken equal to 40°. At shallower depths, slip decreases rapidly to 5 cm within the 4 km near the surface, while a steeper dip of 60° is required to model the InSAR displacement field. This main rectangular plane released about 80% of the total moment, while the rest is assigned to three smaller planes with W-NW strikes, located at the eastern termination of the activated area.

In another article, Clarke et al. (1997) investigated the coseismic displacement field of the Kozani-Grevena earthquake by comparing triangulation surveys of a geodetic network made in 1984-1986 and a post-earthquake survey of the same network with GPS made in 1995. The authors inverted the computed horizontal displacements for the focal parameters by assuming that the surface deformation is equivalent to that caused by uniform slip on a rectangular dislocation in elastic half-space (Okada, 1985). They found a moment tensor (strike=253°, dip=43°, rake=-95°), which compares well with that of the CMT (strike=252°, dip=41°, rake=-87°). They also employed additional parameters in their inversions in order to permit along strike variation of slip. The results showed that such an increase of parameters does not improve the goodness of fit between synthetic and observed data nor does it change the slip model significantly. Consequently, their final single rectangular fault model was assigned uniform slip of about 1m throughout its surface (27x11 km). The projection of the fault model of Clarke et al. (1997) (dotted line) and its trace at the surface (heavy ticked line) are shown in Figure 1d along with the observed (black) and modeled (gray) horizontal displacements, as well as the observed surface ruptures (light ticked lines) and the Dheskati/Servia fault scarps (light toothed lines). A cross section through the mid-point of the fault model is presented in Figure 1e. The upper edge of the fault plane was located at a depth of 2.8 km, which implies that the seismogenic fault of the 1995 Kozani-Grevena earthquake was a blind one, in accordance with the distribution of aftershocks.

KOZANI – GREVENA EARTHQUAKE
(13 MAY 1995 – M_w 6.6)



Meyer et al. (1996, 1998)



Clarke et al. (1997)

Figure 1: *Fault models for the 1995 Kozani-Grevena earthquake (a, b, c from Meyer et al., 1996; e, d from Clarke et al., 1997). a) Computed interferogram. Each fringe corresponds to 28 mm of displacement. b) Synthetic surface displacement field c) Fault model by Meyer et al. (1996, 1998a). Average slip is displayed for each fault plane. A cross section of the fault model is displayed on the inset. d) Projection of the fault model (heavy ticked line) of Clarke et al. (1997). Black and gray arrows correspond to observed and modeled horizontal displacements, respectively. Observed surface ruptures (light ticked line) and Dheskati/Servia fault scarps (light toothed lines) are also shown. e) Cross section of the model of Clarke et al. (1997). Star denotes the projection of the hypocenter into the section, A shows the locations of observed ground ruptures and B the location of the Dheskati fault.*

Meyer et al. (1998b) argued that the model proposed by Clarke et al. (1997) is inconsistent with important tectonic, seismological and geodetic observations provided by SAR interferometry. For example the WSW extension of the fault model towards the Meso- Hellenic trough is not justified neither by the SPOT satellite imagery nor the field observations of surface faulting. Furthermore, they claim that the length of the fault model proposed by Clarke et al. (1997) is large, resulting in a significant overestimation of the seismic scalar moment compared to that of the Harvard's CMT solution. In order to strengthen their argument, Meyer et al. (1998b) used the model of Clarke et al. (1997) to forward model the surface displacement field, which they compared with the observed InSAR displacement field (Meyer et al., 1996, 1998a). They showed that the model parameters of Clarke et al. (1997) result in many more fringes and in a much longer along-strike subsidence zone compared to the information extracted by the SAR interferometry.

Clarke et al. (1998) replied to the comments of Meyer et al. (1998b) through a new paper. They argued that the main difference of their model and the model of Meyer et al. (1996, 1998a) lies in the position of the western end of the rupture and they explained that their choice was based on the characteristic "toeing-in" displayed by the observed horizontal displacements. Nevertheless, they add that slightly shorter faults (lengths down to 20 km) can be accommodated by the GPS data with only a slight increase in misfit.

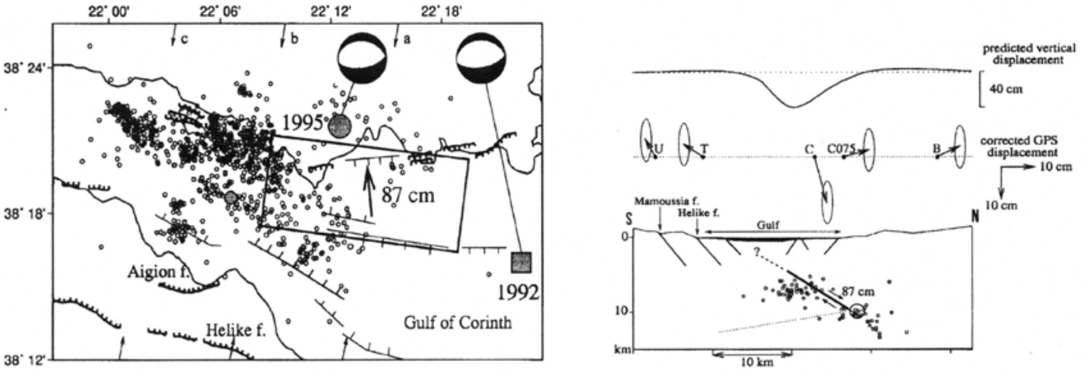
Aighio Earthquake (15 June 1995, M = 6.2)

The Aighio earthquake occurred on July 15, 1995 and had magnitude of **M** 6.2. Its epicenter was located within the Gulf of Corinth, around 15 km northeast of the town of Aighio. The earthquake caused the death of 26 people in two multistory building collapses and extensive damage in the town of Aighio and the surrounding villages, as well as in several sites located at the northern part of the Gulf. The fault plane solution showed normal faulting, while field observations indicated subsidence at the coasts in both sides of the epicentral area.

The rupture process of the Aighio earthquake was investigated by Bernard et al. (1997) who incorporated, either directly or indirectly, all the available data from seismology (local, regional and teleseismic of the mainshock and of aftershocks), geodesy (GPS and InSAR) and tectonics. They estimated the focal mechanism of the event from teleseismic data (strike=277°, dip=33°, rake=-77°) and relocated the hypocentral depth at 10 km based on S-wave polarization data. Based on direct observations of the GPS displacements, which display a well-resolved 7cm northward motion above the hypocenter, they suggested the north-dipping low angle nodal plane of the focal mechanism as the one that ruptured.

In order to investigate the fault model of the Aigio earthquake, Bernard et al. (1997) inverted GPS and InSAR data using an inversion program of Briole et al. (1986), which is based on a least-square minimization algorithm developed by Tarantola and Valette (1982). The authors concluded that the SAR interferometry data are not self-constraining as they can be explained by both the north dipping and the south-dipping fault planes suggested by the focal mechanism of the event. Therefore, their final model, which includes north-dipping faulting, greatly depends on the GPS measurements. Bernard et al. (1997) performed several inversion tests and in combination with the seismological data they proposed their final model of dimensions 9x15 km and uniform slip of 0.87 m (Figure 2). The fault was located around 10 km E-NE of the town of Aighio and experienced upward and southwestward rupture propagation resulting in directivity effects towards the south. This directivity was further assessed by the teleseismic data and the large acceleration recorded within the town of Aighio. The duration of the rupture was estimated to be 4-5 sec, implying a mean rupture velocity of 2.7±0.3 (~80% of the S-wave velocity), considering the 12 km length from the hypocenter to the furthest point of the activated fault area.

AIGHIO EARTHQUAKE
(15 JUNE 1995 – M_w 6.2)



(a) (b)

Bernard et al. (1997)

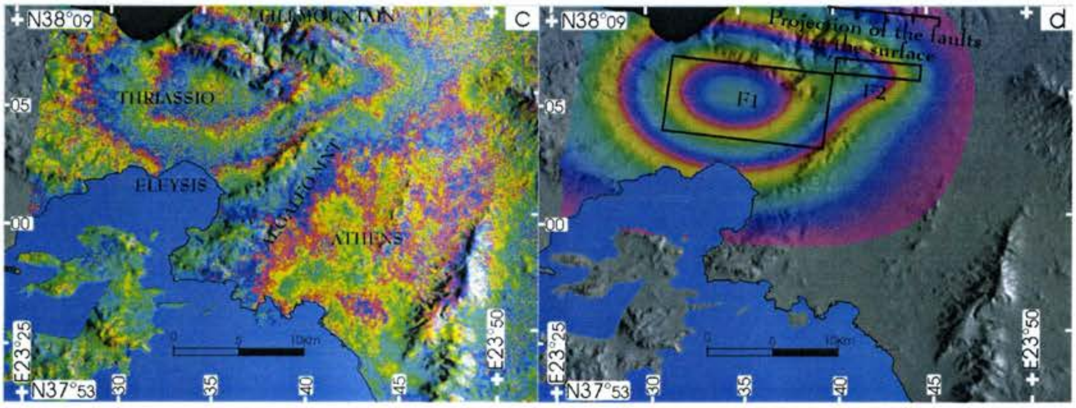
Figure 2: *Fault model for the 1995 Aighio earthquake taken from Bernard et al. (1997) a) Surface projection of the fault model (rectangle). Large dot, small dot and square denote the epicenter locations of the 1995 mainshock, its largest aftershock and the relocated 1992 Galaxidi epicenter. Onshore and offshore fault locations taken form Armijo et al. (1996) and Papanikolaou et al. (1996), respectively, are also depicted as ticked lines b) Cross section of the proposed fault model. Predicted vertical displacement (top) and GPS inferred displacement vectors and their error ellipses (center) are also depicted. Large circle denoted the hypocenter and small circles the aftershock locations.*

Athens earthquake (7 September 1999, M_w=5.9)

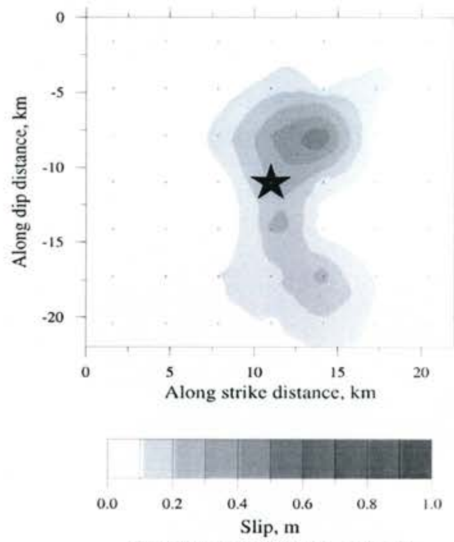
The Athens earthquake (M_w 5.9) occurred on September 7, 1999, a few kilometers away from the center of the Greek capital. Despite its moderate magnitude, the earthquake caused the death of 143 people and extensive damage in the N-NW part of Athens. The fault mechanism of the event, computed from teleseismic waveform modeling (Louvari and Kiratzi, 2001) showed normal faulting (strike=115°, dip=57°, rake=-80°), while aftershock distribution studies (Papadopoulos et al., 2000; Papazachos et al., 2001) identified the southwest-dipping fault plane as the one that ruptured.

Kontoes et al. (2000) investigated the fault model of the Athens earthquake through the use of ERS2 SAR interferometry data. They computed the coseismic interferogram of the event and revealed an asymmetric surface displacement field (Figure 3a, left part) consisting of two concentric fringes (equivalent to 56 mm of subsidence). The asymmetry was observed at the E-SE part of both fringes, towards the meizoseismal area. Kontoes et al. (2000) inverted the InSAR displacements assuming dislocations in an elastic half space (Okada, 1985). The employed inversion code was developed by Briole et al. (1986) and is based on the least squares approach proposed by Tarantola and Valette (1982).

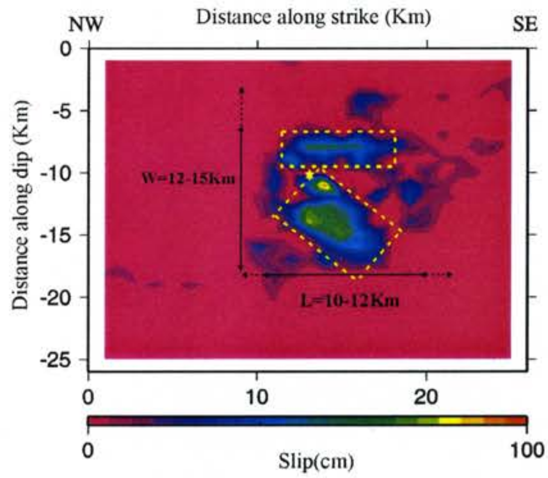
ATHENS EARTHQUAKE
(7 SEPTEMBER 1999 – M_w 5.9)



(a) Kontoes et al. (2000)



(b) Baumont et al. (2002)



(c) Roumelioti et al. (2002)

Figure 3: *Fault models for the 1999 Athens earthquake a) Computed coseismic interferogram (left part) and fault model (rectangular) with resulting synthetic surface displacement field (right part) taken from Kontoes et al. (2000) b) Slip distribution model from Baumont et al. (2002) c) Slip distribution model from Roumelioti et al. (2002). In the last two figures star denotes the hypocenter location.*

A secondary fault was found to be necessary in order to adequately fit the asymmetry at the eastern end of the fringe pattern. Therefore, the final model proposed by Kontoes et al. (2000) consists of two fault planes (Figure 3a, right part). The main plane is located at NW extension of the Fili fault, has a length of 7-11 km and experienced more than 3 m of uniform slip at a depth ranging from 6 to 16 km. The secondary plane is located east to the main plane and intersects the surface ~3 km north to the Fili fault.

Baumont et al. (2002) proceeded further into the investigation of possible inhomogeneous distribution of slip on the fault plane. They used regional broadband seismological data from the mainshock and its aftershocks to estimate the apparent source time functions of the examined event at different azimuths relative to the epicenter. The computation of the source time functions was performed through an empirical Green's function approach, which includes deconvolution of the records of a small earthquake, having hypocenter and focal mechanism similar to that of the mainshock, from the corresponding records of the mainshock. The deconvolution was performed iteratively in the time domain, using only the most energetic phases, i.e. the Rayleigh and Love waves. The resulting apparent source time functions were inverted using a damped-least square inversion scheme with inequality constraints. The final slip distribution model of Baumont et al. (2002) is presented in Figure 3b. The activated area was found confined into a 10x20 km area, with average slip amplitude of 25 cm. The slip is concentrated in two elongated patches, with amplitudes reaching locally 60 cm. The total rupture duration was found to be 5-6 sec.

The regional broadband records of the Athens earthquake were also used by Roumelioti et al. (2002a) to investigate the rupture process of the event. The authors applied a similar methodology to that of Baumont et al. (2002), which includes inversion of the source time functions of the examined event. Roumelioti et al. (2002a) also estimated the source time functions through an empirical Green's function approach, although they performed the deconvolutions in the frequency domain and used the phases of body-waves, as well as surface waves. The employed inversion procedure was originally proposed by Mori and Hartzell (1990) for local earthquakes and extended to regional distances by Dreger (1994) and involves inversion of the source time functions shapes. The resulting slip distribution model of Roumelioti et al. (2002a) is shown in Figure 3c. The ruptured area is confined to 10x10 km and the slip is mainly concentrated in two slip patches. In order to test the credibility of the slip model, Roumelioti et al. (2002a) incorporated it in forward simulations of the surface displacement field, which they compared with the interferogram of Kontoes et al. (2000). The forward simulations showed that the model adequately explains the InSAR data and that the shallow slip patch might be responsible for the observed asymmetry at the eastern end of the observed fringe pattern.

Conclusions – Discussion

We presented a synopsis of studies regarding the fault models and slip distribution of destructive earthquakes, which occurred in the Aegean area during the last few years (1995 Kozani and Aighio and 1999 Athens earthquakes). The set of the so far examined events is very small and therefore does not allow the investigation of systematic features in the rupture process of the Aegean earthquakes. Nevertheless, some general results can be drawn:

- There is some indication that the dimensions of the source models inferred from the inversion of seismological and geodetic data are in some cases significantly different from those expected, according to empirical relations applicable to the Aegean or the aftershock distribution studies. For example, the length of the fault responsible for the Athens earthquake is estimated to be ~15 km based on information other than the slip distribution models. Even though it is possible that there are areas of very low slip, which can not be well resolved by the inversion studies, and which could lead to an increase of the dimensions of the proposed slip models, the latter might be more appropriate for simulations of strong ground motion in the near-fault region as they are expected to be more realistic representations of the high-frequency radiation area.

- Inversions of regional broadband data from the 1999 Athens earthquake imply a large amount of downward rupture propagation. This style of rupture propagation was not expected for an earthquake in the Aegean area and could not be inferred by the event's aftershock distribution studies. This result points out the importance of conducting slip distribution studies, in combination with the routine aftershock distribution studies, in order to understand the true nature of earthquake faulting.
- Although inhomogeneous distribution of slip was only investigated for the Athens earthquake, the results are indicative of the degree of potential impact of the source in the near-field distribution of damages, even in cases of moderate magnitude earthquakes.

The aforementioned results can only be considered as indications, as it is possible that they will change as more earthquake slip models are investigated and new information comes to light.

Studies of the spatial and temporal distribution of slip during large earthquakes in Greece have significantly lagged, compared to other regions of the world where multiple data sets are routinely combined and inverted for such purposes. This delay brings to the surface the problem of optimum instrumentation, as many of the difficulties faced in slip distribution studies rise from inadequacies of the permanent networks established in the broader region. The prevailing seismological point of viewing the problem requires modern instruments, which ensure reliable broadband recordings and the highest possible dynamic range. On the other hand, engineers need to have larger densities of recording instruments to adequately describe the damaging nature of strong motion. Nevertheless, according to the international literature (Sommerville et al., 1999 and references therein), both very low and high frequencies are of crucial importance in slip distribution studies.

Low frequencies can provide reliable information on the rough characteristics of the rupture process and usually can be easily obtained from permanent global teleseismic networks. Regional broadband networks can also provide valuable information on the low-frequency content of an earthquake. Therefore, the recent establishment of the regional broadband network of the National Observatory of Athens consists a significant step towards the increase of slip distribution studies in the Aegean area. The importance of the regional broadband network is even more important in the case of the Aegean, where the location of a large number of active faults at the sea area does not allow their monitoring with strong motion instruments.

The slip distribution models derived from low frequencies have an intrinsic incapability to resolve small-scale heterogeneities on the fault plane. In order to gain more insight into the rupture process of the Aegean earthquakes denser networks of near-fault recording stations are required. Even the most recent papers deal with slip models inferred only from low-frequency data. The omission of higher frequency data in past studies is mainly due to the difficulties in the accurate description of the complicated geological structure of the area and the lack of absolute trigger time in strong motion accelerographs. Furthermore, the permanent strong motion network rarely provided good azimuthal coverage, essentially surrounding the source. Although geodetic data are often proven to act as compensating factor for the lack of adequate strong motion recordings, the need for modernization of the permanent strong motion network remains commanding.

Acknowledgements

This work was partially funded by OASP of Greece (Project 20246 –2000) and by the Science for Peace Project (Seis- Albania – 972342 and GSRT Project 1868). We also thank D. Baumont and his co-authors for allowing us to use their results prior to publication.

References

Armijo, R., B. Meyer, G. King, A. Rigo and D. Papanastassiou (1996). Quaternary evolution of the Corinth rift and its implications for the late Cenozoic evolution of the Aegean, *Geophys. J. Int.* **126,** 11 – 53.

Baumont, D., F. Courbouleux, O. Scotti, N. Melis and G. Stavrakakis (2002). Slip distribution of the M_w 5.9, 1999 Athens earthquake inverted from regional seismological data, *Geophys. Res Lett.*, in press.

Bernard, P., P. Briole, B. Meyer, H. Lyon-Caen, J.-M. Gomez, C. Tiberi, C. Berge, R. Cattin, D. Hatzfeld, C. Lachet, B. Lebrun, A. Deschamps, F. Courbouleux, C. Larroque, A. Rigo, D. Massonnet, P. Papadimitriou, J. Kassaras, D. Diagourtas, K. Makropoulos, G. Veis, E. Papazisi, C. Mitsakaki, V. Karakostas, E. Papadimitriou, D. Papanastassiou, G. Chouliaras and G. Stavrakakis (1997). The M_S=6.2, June 15, 1995 Aigion earthquake (Greece): evidence for low angle normal faulting in the Corinth rift, *Journal of Seismology* **1,** 131 – 150.

Briole, P., G. De Natale, R. Gaulon, F. Pingue and R. Scarpa (1986). Inversion of geodetic data and seismicity associated with the Friuli earthquake sequence (1976 – 1977), *Annales Geophysicae* **4,** 481 – 492.

Clarke, P. J., D. Paradissis, P. Briole, P. C. England, B. E. Parsons, H. Billiris, G. Veis and J.-C. Ruegg (1997). Geodetic investigation of the 13 May 1995 Kozani – Grevena (Greece) earthquake, *Geophys. Res. Lett.* **24,** No 6, 707 – 710.

Clarke, P. J., D. Paradissis, P. Briole, P. C. England, B. E. Parsons, H. Billiris, G. Veis and J.-C. Ruegg (1998). Reply, *Geophys. Res. Lett.* **25,** No 1, 131 – 133.

Kontoes, C., Elias, P., Sykioti, O., Briole, P., Remy, D., Sachpazi, M., Veis, G. and I. Kotsis (2000). Displacement field and fault model for the September 7, 1999 Athens earthquake inferred from ERS2 satellite radar interferometry, *Geophys. Res. Let.* **27,** No 24, 3989-3992.

Meyer, B., R. Armijo, D. Massonnet, J. B. de Chabalier, C. Delacourt, J. C. Ruegg, J. Achache, P. Briole and D. Papanastassiou (1996). The 1995 Grevena (Northern Greece) earthquake: Fault model constrained with tectonic observations and SAR interferometry, *Geophys. Res. Lett.* **23,** No 19, 2677 – 2680.

Meyer, B., R. Armijo, D. Massonnet, J. B. de Chabalier, C. Delacourt, J. C. Ruegg, J. Achache, and D. Papanastassiou (1998a). Results from combining tectonic observations and SAR interferometry for the 1995 Grevena earthquake: a summary, *J. Geodynamics* **26,** No 2 – 4, 255 – 259.

Meyer, B., R. Armijo, D. Massonnet, J. B. de Chabalier, C. Delacourt, J. C. Ruegg, J. Achache, and D. Papanastassiou (1998b). Comment on "Geodetic investigation of the 13 May Kozani-Grevena (Greece) earthquake by Clarke et al., *Geophys. Res. Lett.* **25,** No 1, 129 – 130.

Okada, Y. (1985). Surface deformation to shear and tensile faults in a half space, *Bull. Seism. Soc. Am.* **75,** 1135 – 1154.

Papadopoulos, G. A., Drakatos, G., Papanastassiou, D., Kalogeras, I. and G. Stavrakakis (2000). Preliminary results about the catastrophic earthquake of 7 September 1999 in Athens, Greece, *Seism. Res. Let.* **71,** 318 –329.

Papanikolaou, D., G. Chronis, V. Lykousis, D. Sakellariou and I. Papoulia (1996). Neotectonic structure of the west Korinthiakos gulf and geodynamical phenomena induced by the Egion earthquake, in *International Scientific Symposium, Earthquake, 6.1R, Egio Earthquake,* extended abstract (in Greek), Aighio.

Papazachos, C. B., Karakostas, B. G., Karakaisis G. F. and Ch. A. Papaioannou (2001). The Athens 1999 mainshock (M_w=5.9) and the evolution of its aftershock sequence, *Proc. 9th International Conference of the Geological Society of Greece*, September 2001, Athens, 1581-1586.

Pavlides, S. B., N. Zouros, A. Chatzipetros, D. Kostopoulos and D. M. Mountrakis (1995). The 13th May 1995 Western Macedonia, Greece, Kozani Grevena Earthquake; preliminary results, *Terra Nova* **7,** 544 – 549.

Roumelioti, Z., D. Dreger, A. Kiratzi and N. Theodoulidis (2002a). Slip distribution of the September 7, 1999 Athens earthquake inferred from an empirical Green's function study, *Bull. Seism. Soc. Am.*, in print.

Roumelioti, Z., A. Kiratzi, D. Dreger and N. Melis (2002b). Broadband analysis of the source process during the 26 July, 2001 Skyros (Greece) earthquake, *in preparation.*

Sommerville, P., K. Irikura, R. Graves, S. Sawada, D. Wald, N. Abrahamson, Y. Iwasaki, T. Kagawa, N. Smith and A. Kowada (1999). Characterizing crustal earthquake slip models for the prediction of strong ground motion, *Seism. Res. Let.* **70,** 59 – 80.

Tarantola, A. and B. Valette (1982). Generalized nonlinear inverse problem solved using the least squares criterion, *Reviews Geophys.* **20,** 219 – 232.