Geophysical Research Letters, **24**(6), 707–710, March 1997.

Geodetic investigation of the 13 May 1995 Kozani – Grevena (Greece) earthquake

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Abstract. The $M_s = 6.6$ 13 May 1995 Kozani – Grevena earthquake struck a region of low historical seismic activity which includes a 10-year-old triangulation network in northern Greece. After the earthquake, monuments from this network were occupied with GPS to measure co-seismic displacements. Inversion of the co-seismic displacement field to yield a source mechanism is achieved by use of a hybrid simplex – Monte-Carlo method which requires no *a priori* constraints. The model focal mechanism agrees well with the global CMT solution and locally observed aftershocks, but implies a significantly higher scalar moment than do seismological or SAR interferometry studies, and has a longer fault length than the model based on SAR interferometry.

Introduction

The Aegean region is the most seismically-active part of Europe (Figure 1) and exhibits a variety of tectonic styles. Within the central Aegean and mainland Greece, the predominant mechanism is that of north–south extension revealed by normal-faulting earthquakes, whereas in the northern Aegean it is strike-slip motion related to the termination of the North Anatolian Fault [*Taymaz et al.*, 1991]. Seismicity decreases to the north of these areas.

The 13 May 1995 Kozani – Grevena earthquake of magnitude $M_s = 6.6$ ($M_0 = 7.6 \times 10^{18}$ Nm, Harvard CMT) struck western Macedonia (Figure 1), a region previously thought to have low seismic risk [*Papazachos*, 1990]. No obvious surface break was found so it was not possible to locate the fault plane *a priori*. However, the CMT solution was almost purely normal [J.H. Woodhouse, pers. comm.] and the majority of the severe damage and ground cracking [*Pavlides et al.*, 1995] lay to the south of the epicentre (Figure 1). The region contains normal faults that have cut Miocene and older structures of the Mesohellenic Trough during Holocene time [*Pavlides et al.*, 1995; *Hatzfeld et al.*, 1997]. Since the nearby Servia fault dips to the north-west, it was tentatively assumed that the 1995 fault was associated with the north-west–dipping nodal plane and a plan of site occupation was designed accordingly. This assumption was later confirmed by the aftershock sequence [*Hatzfeld et al.*, 1997].

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Geodetic Measurements

The most recent geodetic survey of the area was made during the period 1984–1986 by the Hellenic Military Geographic Service (HMGS), using horizontal and vertical triangulation with some electronic distance measurement for scale control. The formal errors of this survey are estimated by HMGS to be 15 mm for the horizontal component and 25 mm for the vertical, although the true errors are likely to be larger. Five days after the event we began to re-occupy concrete pillars (Figure 1) from the HMGS survey, using a mixture of Ashtech LM-XII and Z-XII and Trimble 4000SST dual-frequency GPS receivers. Ninety-one sites within 30 km of the epicentre were occupied for 2–3 hours on at least one occasion each. Several of these sites were occupied for longer periods on two or three occasions to provide a basis for future measurement of post-seismic strain. In addition, continuous observations were made at three sites during the week-long campaign in order to monitor any short-term deformation, and at the Dionysos mobile SLR site (near Athens) in order to tie the campaign coordinates to the ITRF93 reference frame.

The observations were processed using version 3.4 of the Bernese GPS Processing Software [*Rothacher et al.*, 1993], and as an independent check, with the Ashtech GPPS package. The Bernese solution is used hereafter as it is considered to be more accurate. The Bernese processing used the ionosphere-free L3 phase combination, with precise satellite orbits in ITRF93 obtained from the Centre for Orbit Determination in Europe. Correlations of observations between baselines and frequencies were modelled correctly, and tropospheric zenith delays were estimated for all stations

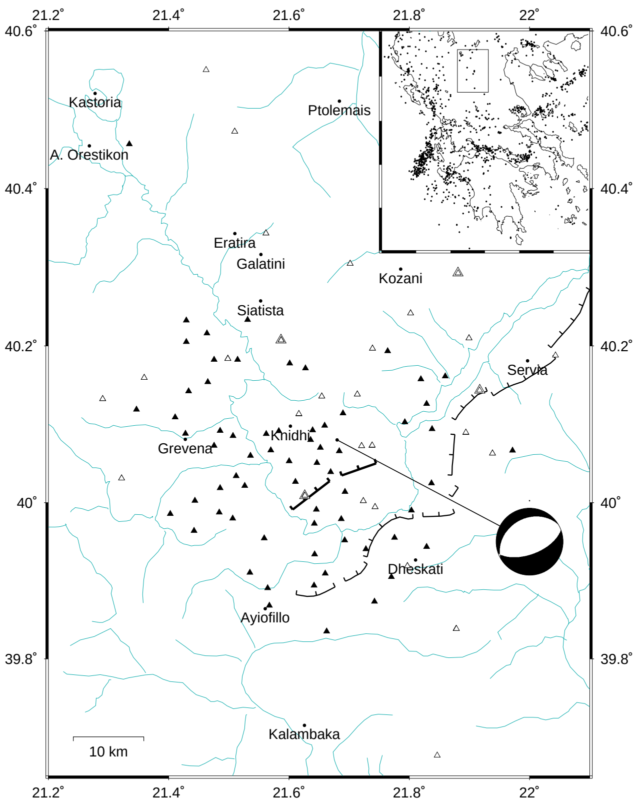

Figure 1. Location of the 13 May 1995 Kozani – Grevena earthquake (Harvard CMT solution), showing existing fault scarps (light ticked line), surface ruptures (heavy ticked line) [*Hatzfeld et al.*, 1997, and observations of the authors], and drainage. Sites in the coseismic GPS survey are shown as triangles: open triangles denote sites also in the post-seismic network and nested triangles denote continuously-occupied sites. Inset shows $M_b \geq 3.5$ earthquakes above 30 km depth in the ISC catalogue 1964–1994, with the study area outlined.

within fixed six-hour windows. Because of the short occupation times and high level of apparent ionospheric noise, it was not possible to resolve ambiguity parameters. Daily network solutions were combined using the network adjustment software L3D [*Cross*, 1990] to yield a set of campaign coordinates with estimated precision 10 mm in the horizontal and 21 mm in the vertical. Coseismic site displacements were obtained by differencing the epoch coordinates with the HMGS coordinates, subject to a global translation to bring them from the GGRS87 reference frame [*Veis and Paradissis*, 1990] to ITRF93.

Inversion method

We solved for the focal parameters by assuming that the surface deformation was equivalent to that caused by uniform slip on a rectangular dislocation in an elastic half-space [*Okada*, 1985]. Synthetic experiments with both gridded networks and our actual distribution of observations showed that the problem is strongly non-linear, with many closely-spaced local minima. We therefore seek the global minimum by a refinement of the downhill simplex method [*Press et al.*, 1992, and references therein]. A simplex is a hypervolume whose vertices are described by $n+1$ vectors whose components are estimates of the n parameters we wish to determine. The simplex method collapses this volume towards a point that represents a local minimum in the penalty function to be minimised (in this case the r.m.s. misfit of observed displacements to those of the model dislocation). Because the minimum found depends on the starting values given to the simplex, we performed 1000 simplex inversions with the vertices of the starting simplexes chosen randomly from the possible range of the parameters. Physically unreasonable minima are later rejected, and the lowest remaining minimum is retained. Synthetic experiments [*Clarke*, 1996] have shown that this method recovers the 'true' parameters reliably for gridded and actual network geometries.

Although the local GGRS87 reference frame is nominally parallel to the ITRF93 and has the same scale, the sparseness of scale and azimuth control in the HMGS survey obliged us to solve for global rotation and scale change parameters in addition to network translation parameters. This was incorporated in the simplex inversion for the fault parameters.

Results

We used only the horizontal displacements because the precision of the vertical measurements is much lower. Eight sites out of 91 were rejected, either because they were in the far field and so do not contribute to the solution, or because they had anomalous displacements when compared with neighbouring sites. The best minimum found has the source parameters shown in Table 1 and scale and rotation terms of less than 2 p.p.m., well within likely systematic errors of the triangulation survey. The r.m.s. residual to the solution is 47 mm, similar to the expected noise of the data, confirming that site instability problems and secular strain do not adversely affect our dataset. It is not significantly reduced by the inclusion of extra parameters to model either the antithetic fault suggested by the aftershock studies [*Hatzfeld et al.*, 1997] or additional shallow, steep fault segments to bring the fault plane up to the surface, as suggested by *Hatzfeld et al.* [1997] and *Meyer et al.* [1996]. The addition of parameters permitting along-strike variation of slip does not reduce the r.m.s. residual or result in significant change of slip, so constant slip along the entire 27 km length of the fault plane is compatible with the dataset. In contrast, models based on SAR interferometry [*Meyer et al.*, 1996], which have a shorter fault length, show significant systematic residuals to the geodetic monument displacements near the eastern and western ends of our fault and a significantly higher r.m.s. residual. We conclude that our dataset does not require a model more complex than a single long fault plane with constant slip. We have confirmed this model by an independent inversion using a repeated linearised least-squares method based on that of *Tarantola and Valette* [1982]. Observed and model horizontal displacements are shown in plan view in Figure 2, and a profile perpendicular to strike is given in Figure 3.

Discussion

The focal mechanism compares well with that of the CMT. The fault angles and location are well-resolved and consistent with the body-wave studies aftershock distribution observed by *Hatzfeld et al.* [1997] (Figure 4), and with the positions of observed ground cracks. Our estimate of 2.8 km for the minimum depth of faulting is consistent with the fact that the region is covered by poorly consolidated Neogene sediments, and the estimates of minimum and maximum depth are consistent with both the aftershock depths and hypocentral depth of 11 km [*Hatzfeld et al.*, 1997]. The significant difference between geodetic and seismological studies lies in the scalar moment. As our estimates of fault length, dip and minimum and maximum depth are compatible with the aftershock studies, and our estimate for the average slip on the fault plane is tightly constrained by displacements close to the fault, we conclude that the moment must be considerably higher than the seismically estimated value. The slip magnitude we find is close to that for the main fault segment of *Meyer et al.* [1996], and the prime cause of our higher scalar moment is the greater fault length required by our observations. The scatter of local minima found by our inversion algorithm indicates that our estimate of scalar moment is closer to the minimum than the maximum permitted

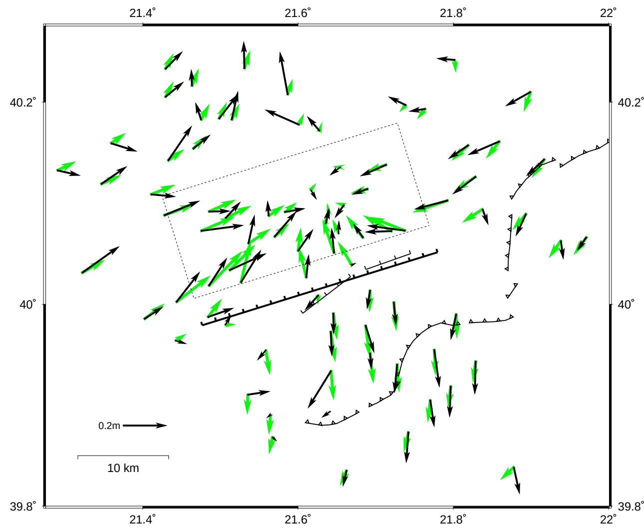

Figure 2. Observed (black) and modelled (grey) horizontal site displacements for the 13 May 1995 Kozani – Grevena earthquake. The surface projection of the model fault scarp is shown as a heavy line with ticks on the downthrown side. In the forward model, displacement directions in the near field of the fault are characteristic of the fault slip, strike, rake, length and position. The observed surface ruptures (light ticked line) and Dheskati/Servia fault scarps (light toothed line) are also shown.

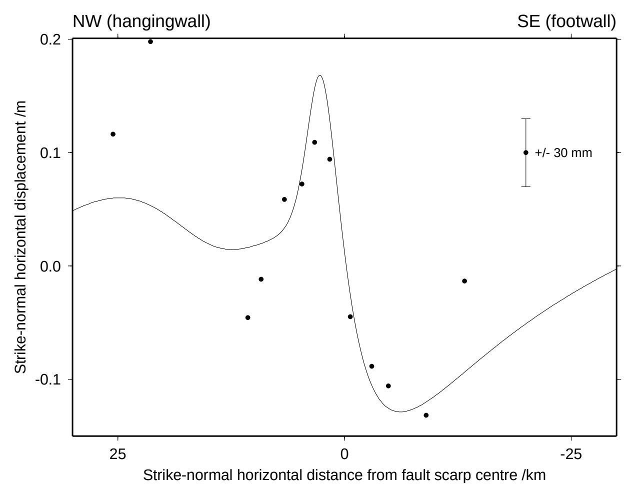

Figure 3. Observed (dots) and modelled (solid line) horizontal site displacements along a profile normal to strike, for the 13 May 1995 Kozani – Grevena earthquake. Displacements from sites up to 3 km either side of the centre line are included. The sample error bar is 30 mm (twice the formal error quoted by HMGS). The magnitude and shape of the forward model curve are characteristic of the fault slip, dip, and minimum and maximum depths.

Table 1. Source parameters of the 13 May 1995 Kozani – Grevena earthquake .

	Scarp Lat,Lon	Length	M_0 / N m	Strike	Dip	Rake	Dmin	Dmax
Seismic	40.18°, 21.66° [a]	25 [b]	6.2×10^{18} [c]	252° [c]	41° [c]	-87° [c]	5 [b]	15 [b]
Geodetic	40.02°, 21.63°	27.1	16.3×10^{18} [d]	253°	43°	-95°	2.8	13.5

[a]Hypocentre relocated by *Hatzfeld et al.* [1997], projected up-dip to surface.
[b]From aftershock locations [*Hatzfeld et al.*, 1997].
[c]From P- and SH-waveform modelling, centroid depth 11±1 km [*Hatzfeld et al.*, 1997].
[d]Based on total slip of 1.2 m.

All lengths and depths are in km. Lamé parameters $\lambda = \mu = 3.23 \times 10^{10}$.
Scale change: -1.9 p.p.m.; rotation: -1.7 p.p.m. (*i.e.* clockwise).
r.m.s. residual of observed displacement components to model displacement components 47 mm.

value [*Clarke*, 1996]. The total effect of foreshocks and aftershocks may add as much as 25% to the seismological moment, but the cause of the remaining difference remains unresolved.

The geodetic displacements clearly constrain the fault scarp to be north of the Dheskati Fault. The lack of surface expression of our model fault scarp (Figure 4) is a result of the soft surficial Neogene sediments, and also implies that it is younger than the Dheskati and Servia Faults, which have cumulative displacements sufficient to expose basement rocks in their footwalls.

Acknowledgments We thank all those who helped us during the May 1995 GPS campaign, including S. Bourne, R. Cattin, R. Davies, S. Felekis, A. Huber, I. Hunstad, J. Hyde, K. Kamberos, E. Kounenaki, G. Mandas, A. Marinou, A. Michopoulos, M. Tsoulakis, M. Vourvakis and the people of Paleokastro. We are grateful to Ashtech Europe and the NERC Geophysical Equipment Pool for the loan of additional GPS equipment. Fieldwork was supported by NERC grant GR3/10178. Denis Hatzfeld provided useful preprints, and James Jackson and Mike Leeder provided geological insight in the field. P.J.C. acknowledges receipt of a NERC research studentship. We thank John Beavan, Denis Hatzfeld and an anonymous reviewer for their helpful criticism.

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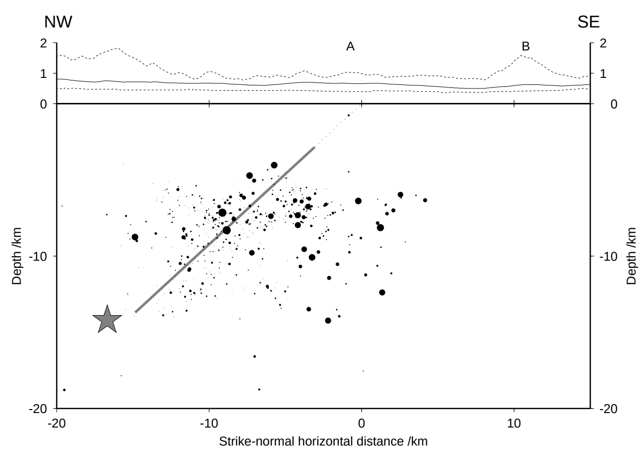

Figure 4. Cross-section through the mid-point of the model fault plane perpendicular to strike, showing the locations of ground ruptures (A), the Dheskati Fault (B), the model fault plane (solid grey line), and aftershocks within 10 km along strike of the model scarp centre (taken from *Hatzfeld et al.* [1997]). The main shock lies 8 km NE of the plane of this section, but its projection along strike into the section is shown by a star. A topographic profile (vertical exaggeration ×2) is above, showing minimum, mean and maximum heights within 10 km either side of the profile.

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