Reply to: 'Comment on "Geodetic investigation of the 13 May 1995 Kozani – Grevena (Greece) earthquake" by Clarke *et al.*' by Meyer *et al.*

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In our paper [*Clarke et al.*, 1997], we sought a simple model to explain horizontal geodetic displacements obtained using a combination of triangulation and GPS observations, which show a high degree of coherence throughout the network. We inverted the displacements and obtained a single-dislocation model that is consistent with much of the tectonic and seismological information reported elsewhere [*Pavlides et al.*, 1995; *Hatzfeld et al.*, 1995; *Meyer et al.*, 1996; *Hatzfeld et al.*, 1997]. *Meyer et al.* [1997] criticise our paper on two main grounds: (1) that we have inconsistently used tectonic data to arrive at our conclusions, and (2) that our conclusion is incorrect because it disagrees with some of the tectonic and SAR observations.

The first criticism is based on a misinterpretation of our paper: *Meyer et al.* [1997] state that we used their observations of the fault scarp to fix the position of the fault. Our inversion used only the GPS–triangulation relative site displacements, without any *a priori* constraints, to obtain a source mechanism which we showed to be consistent with the CMT fault plane solution and areal extent of the aftershock distribution [*Hatzfeld et al.*, 1997]. At no point did we use any observations of the fault scarp, either those of *Meyer et al.* [1997] or our own, as constraints. *Meyer et al.* [1997] also object to our statement that surface breaks could not be used to locate the fault plane *a priori*. We adhere to this view because the 2–4-cm scarps described by *Meyer et al.* [1997] are insignificant compared both with the slip at depth (∼1 m) and with surface breaks associated with similar magnitude earthquakes elsewhere [*e.g.* the 1981 Gulf of Korinthos earthquakes, *Jackson et al.*, 1982].

Meyer et al. [1997] comment, at greater length than we could [*Clarke et al.*, 1997, p. 709] on the discrepancy between our solution from the horizontal surface displacements and that obtained from SAR interferometry. We agree with them that there are significant differences, but disagree with them in their implicit assumption that the SAR interferometry is necessarily correct and the GPS–triangulation solution incorrect. We emphasise that the critical displacement differences discussed in our paper and below are large (100 – 200 mm)

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compared with the uncertainty in relative positioning of the initial triangulation (30 – 50 mm, equivalent to an angular uncertainty of 2 p.p.m. over 20 km).

The principal difference between the fault models proposed by *Clarke et al.* [1997] and *Meyer et al.* [1996] lies in the position of the western end of the rupture (Fig. 1). The two studies agree with each other and with the seismological evidence [*Hatzfeld et al.*, 1997] as to the dip, down-dip extent and eastern termination of the rupture, and as to the slip vector of the earthquake. The positions of the ends of the rupture are constrained, in the GPS–triangulation solution, by the characteristic "toeing-in" displayed by the horizontal displacements shown by *Clarke et al.* [1997] (Fig. 2, see also Fig. 2 in this paper). Our best-fitting solution (47 mm r.m.s. misfit) yielded a fault length of 27 km but slightly shorter faults (down to c. 20 km) can be accommodated by the horizontal displacement data with only a slight increase in misfit (51 mm r.m.s.). However, the 22-fault model of *Meyer et al.* [1996], with r.m.s. misfit to our observations of 64 mm, has large systematic residual displacements near the ends of the rupture (Fig. 2). Synthetic experiments show that our conclusion is unaffected by possible scale errors in the original triangulation.

Figure 1.

Figure 2.

Meyer et al. [1996] give no quantitative estimate of the misfit between the observed SAR interferometric fringes and those predicted by their 22-segment model. We note, however, that any such quantity would not cast light on the discrepancy between their model and that of *Clarke et al.* [1997], because the SAR data are largely incoherent at the western end of the fault and thus provide little constraint on displacement in the locality where our horizontal displacements disagree with the conclusions of *Meyer et al.* [1996].

We do not regard it as improbable, as *Meyer et al.* [1997] apparently do, that the geodetically-determined scalar moment of an earthquake should exceed that determined seismically. We point out that several other geodetic studies, including those using SAR interferometry or shorter-term geodetic observations [*e.g. Stein and Barrientos*, 1985; *Briole et al.*, 1986; *Lundgren et al.*, 1993; *Bernard et al.*, 1997], have revealed excesses of geodetic scalar moment over seismic scalar moment.

We thus do not accept the conclusion of *Meyer et al.* [1997] that the GPS–triangulation solution is incorrect, or "blind". The differences between the GPS–triangulation and SAR interferometric models arise primarily in the region where the horizontal displacement data are self-consistent but the SAR data have poor coherence. We prefer to accept that there is an important discrepancy between the results of two methods using different types of data — each of which has limitations — and hope that pointing out this discrepancy may eventually lead to an improved understanding, both of the methods and of the distribution of strain before, during and after earthquakes.

References

Bernard, P., et al., The M_s = 6.2, June 15, 1995 Aigion earthquake (Greece): Evidence for low angle normal faulting in the Corinth rift, *J. Seismol.*, *1*(2), 131–150, 1997.

Briole, P., G. de Natale, R. Gaulon, F. Pingue, and R. Scarpa, Inversion of geodetic data and seismicity associated with the Friuli earthquake sequence (1976–1977), *Annales Geophysicae*, *4*(B4), 481–492, 1986.

Clarke, P., D. Paradissis, P. Briole, P. England, B. Parsons, H. Billiris, G. Veis, and J.-C. Ruegg, Geodetic investigation of the 13 May 1995 Kozani – Grevena (Greece) earthquake, *Geophys. Res. Lett.*, *24*(6), 707–710, 1997.

Hatzfeld, D., et al., The Kozani–Grevena (Greece) earthquake of May 13, 1995, M_s = 6.6. Preliminary results of a field multidisciplinary survey, *Seis. Res. Lett.*, *66*, 61–70, 1995.

Hatzfeld, D., et al., The Kozani–Grevena (Greece) earthquake of 13 May 1995 revisited from a detailed seismological study, *Bull. Seismol. Soc. Am.*, *87*(2), 463–473, 1997.

Jackson, J., J. Gagnepain, G. Houseman, G. King, P. Papadimitriou, C. Soufleris, and J. Virieux, Seismicity, normal faulting and the geomorphological development of the Gulf of Corinth (Greece): the Corinth earthquakes of February and March 1981, *Earth Planet. Sci. Lett.*, *57*, 377–397, 1982.

Lundgren, P., S. Kornreich Wolf, M. Protti, and K. Hurst, GPS measurements of crustal deformation associated with the 22 April 1991 Valle del la Estrella, Costa Rica earthquake, *Geophys. Res. Lett.*, *20*(5), 407–410, 1993.

Meyer, B., R. Armijo, J. de Chabalier, C. Delacourt, J. Ruegg, J. Acache, P. Briole, and D. Papanastassiou, The 1995 Grevena (Northern Greece) Earthquake: Fault model constrained with tectonic observations and SAR interferometry, *Geophys. Res. Lett.*, *23*(19), 2,677–2,680, 1996.

Meyer, B., R. Armijo, J. de Chabalier, C. Delacourt, J. Ruegg, J. Acache, and D. Papanastassiou, Comment on "Geodetic investigation of the 13 May 1995 Kozani – Grevena (Greece) earthquake" by Clarke *et al.*, *Geophys. Res. Lett.*, (this issue), 1997.

Pavlides, S., N. Zouros, A. Chatzipetros, D. Kostopoulos, and D. Mountrakis, The 13 May 1995 western Macedonia, Greece (Kozani Grevena) earthquake; preliminary results, *Terra Nova*, *7*(5), 544–549, 1995.

Stein, R., and S. Barrientos, High angle normal faulting in the intermountain seismic belt: Geodetic investigation of the 1983 Borah Peak, Idaho, earthquake, *J. Geophys. Res.*, *90*(B13), 11,355–11,366, 1985.

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Figure Captions

Figure 1. (a) Surface projection (dotted rectangle) and scarp location (heavy ticked line) of the single fault segment obtained by *Clarke et al.* [1997], compared with the mainshock location (grey star) and aftershock locations (black dots) [*Hatzfeld et al.*, 1997].
(b) As (a) for the 22-segment fault model of *Meyer et al.* [1996], scarp locations not shown for clarity.

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Figure 2. Horizontal site displacements observed by *Clarke et al.* [1997] (black arrows) and horizontal displacements predicted by the model of *Meyer et al.* [1996] (grey arrows). Note the large systematic differences between the actual displacements and those predicted by the SAR model beyond the eastern and western ends of the rupture determined by GPS–triangulation (solid circles).

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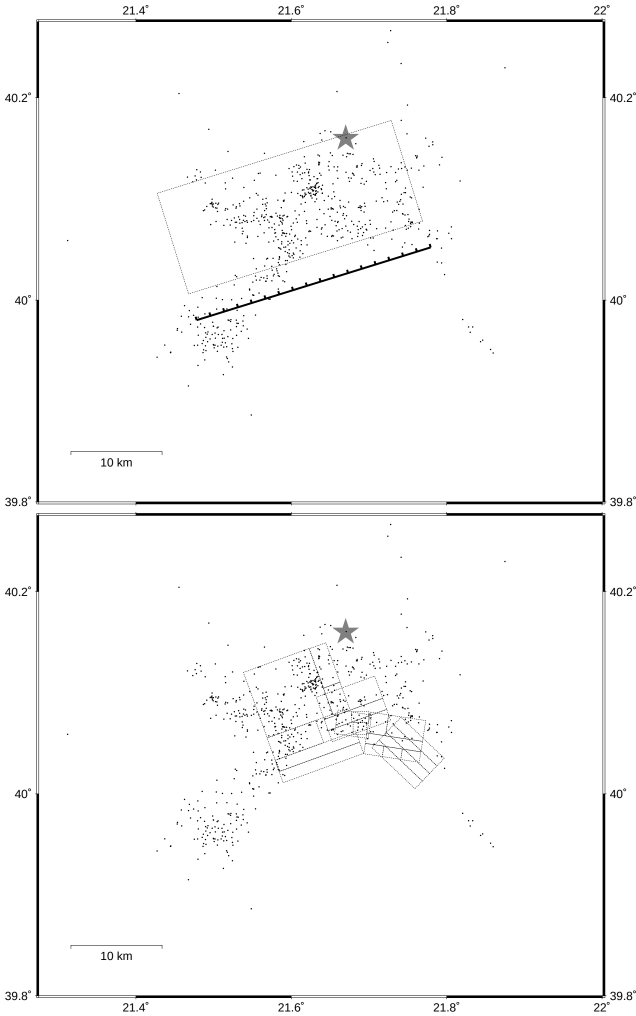
Figures



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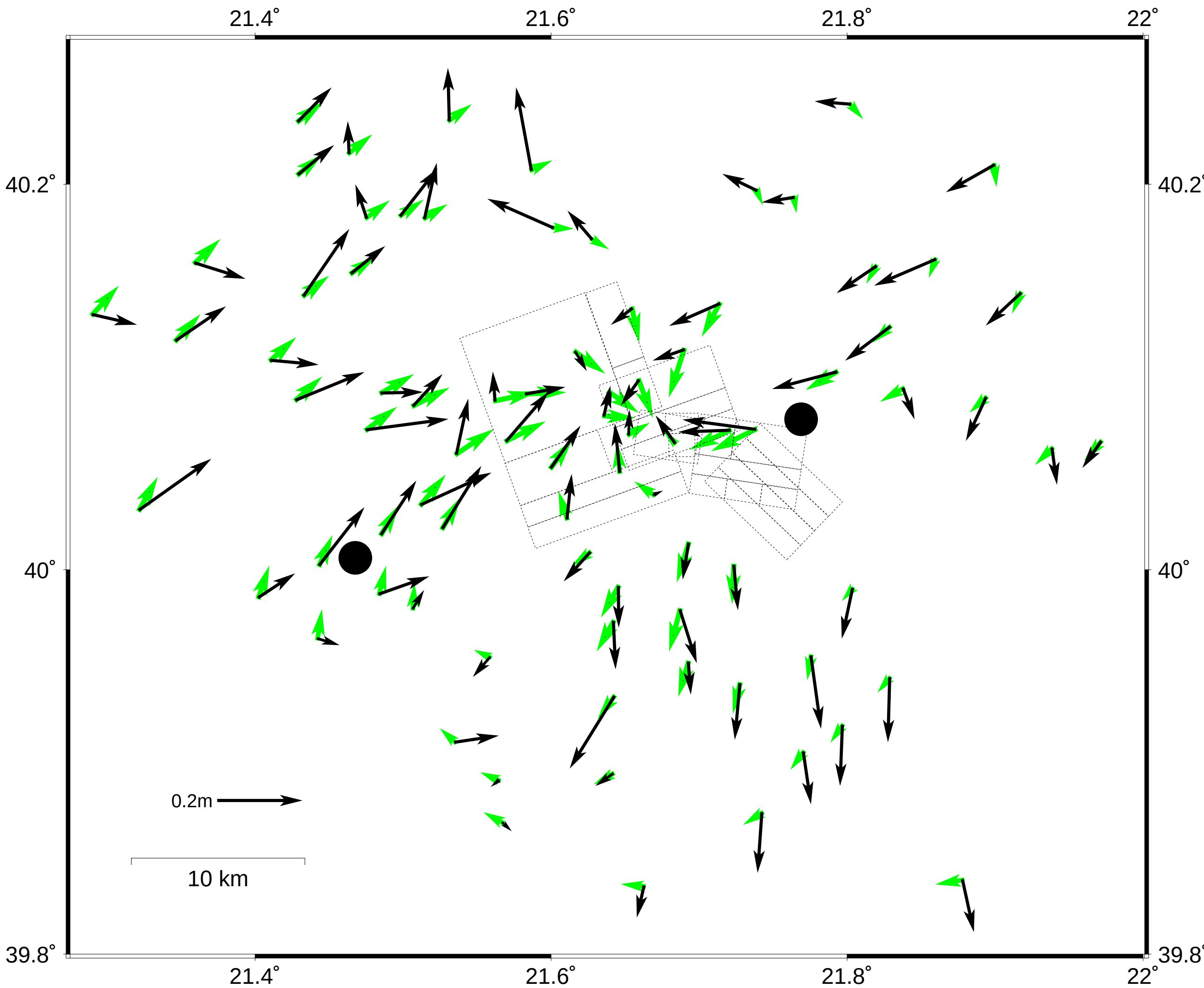

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