

## The 1995 Grevena (Northern Greece) Earthquake: Fault model constrained with tectonic observations and SAR interferometry

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**Abstract.** After the 1995 Grevena  $M_s = 6.6$  event in northern Greece, we mapped the earthquake fault break in detail. The surface break is small (8-12 km long, 4 cm slip) compared to the moment release of the event. However, the morphologic and tectonic study of the active faults, in the field and using the SPOT satellite imagery, suggests that the earthquake ruptured part of a much larger fault system including interconnecting segments. We used SAR interferometry of the satellite ERS-1 imagery to characterize the coseismic displacement field. This shows a kidney-shaped zone of subsidence reaching 30 cm flanked by an uplift zone reaching 5 cm. We reproduce this field using dislocations in an elastic half-space and our observations of the fault system. This requires 1 m slip from 4 to 15 km depth on a main normal fault segment dipping NNW. Our preliminary model includes significant NE-dipping scissors faulting at the eastern end of the rupture, clearly seen in the interferograms.

### Introduction

A  $M_s = 6.6$  earthquake occurred on May 13, 1995 in north-central Greece, a region with low historical and instrumental seismicity [Papazachos and Papazachos, 1989]. After the event several teams conducted field studies including tectonics, geodesy and seismology [Hatzfeld et al., 1995; Pavlides et al., 1995]. The results pose stimulating tectonic and mechanical problems. The observed surface break is compatible with the Harvard CMT solution and corresponds to normal faulting with NW-SE extension, but this contrasts with the dominant NE-SW extensional regime in the nearby Aegean domain (Fig. 1). The CMT scalar moment of  $7.6 \times 10^{18}$  Nm is significantly larger than expected from the relatively small extent of both the aftershock zone and the surface break. Surprisingly, the 1995 surface break involves relatively minor faults; the event apparently did not rupture the larger faults in the area.

Here we show the preliminary results of a study combining morphologic and tectonic observations of the major active faults and of the earthquake break with the coseismic surface deformation deduced from Synthetic Aperture Radar (SAR) interferometry. We use this information to constrain the earthquake faulting, which we treat as dislocations in an elastic half-space. We can resolve in some detail the rupture parameters on a multisegment fault system. Although not

unique, we consider that the combined use of geological, seismic and radar data reduces the range of possibilities and is more likely to approximate reality than using any one technique alone.

### Earthquake surface break and major faults

The structure and morphology of the region struck by the 1995 earthquake is dominated by the NW-SE trending Hellenic fold-thrust belt, with two parallel basins corresponding to broad synclines separated by a mountain range (Fig. 1). The cities of Kozani and Grevena are in the Fiorina-Kozani basin and the larger Meso-Hellenic Trough, respectively, which are at about 600 m altitude and are filled with Miocene-Quaternary continental clastics [IGME, 1983]. The intervening Vourinos Range, reaching 2000 m, is mainly formed by a conspicuous ophiolitic complex overthrust on Pelagonian basement [Moores, 1969]. By contrast, most of the Pleistocene and Holocene strain is controlled by few prominent normal faults dipping chiefly northwest and striking NE-SW, thus cutting nearly orthogonally the earlier Hellenic structure. The largest newly-formed normal faults have interrupted both basins, opening a passage for the Aliakmon river to cross the Vourinos Range (Fig. 1).

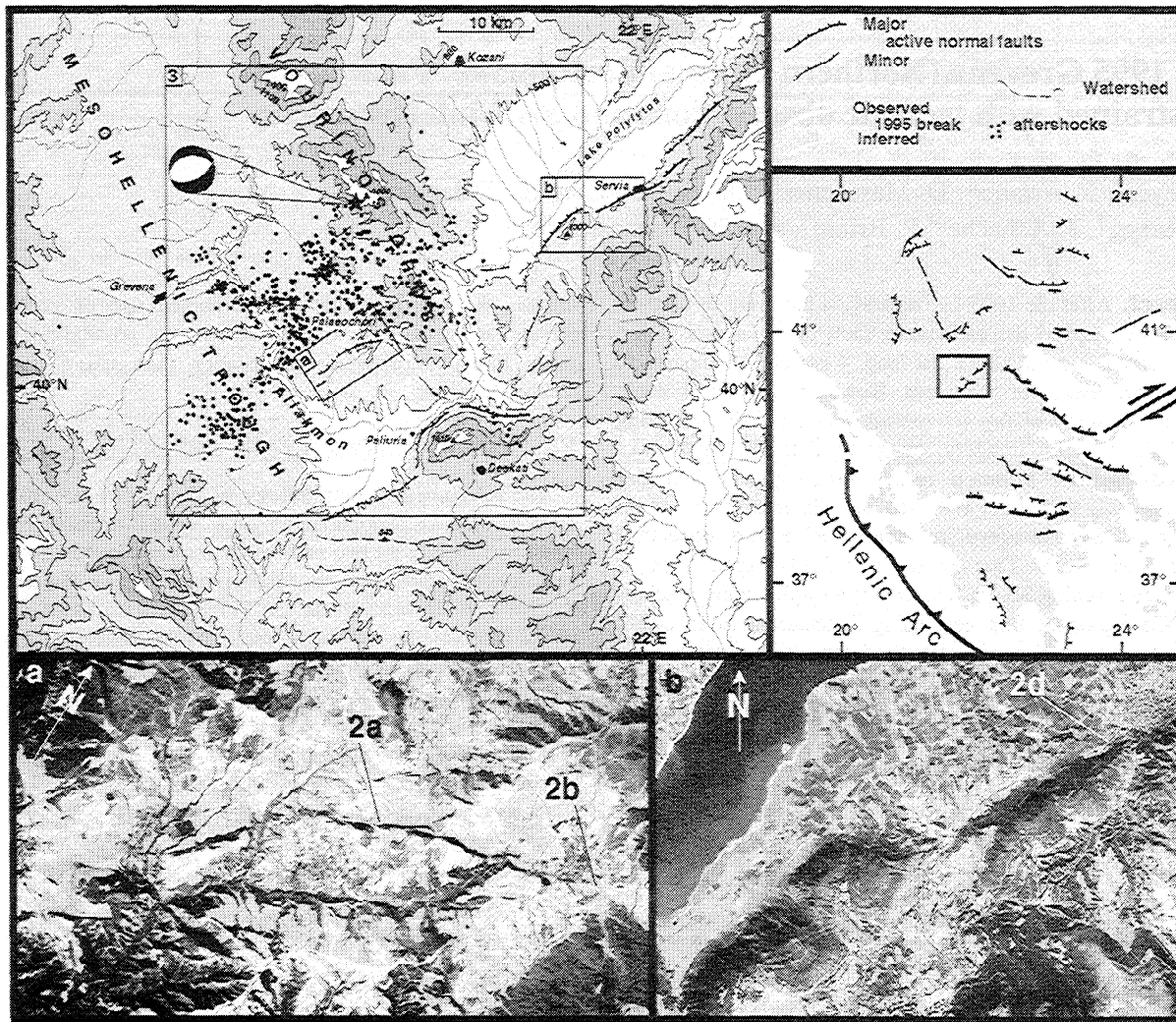
Three to seven days after the 1995 earthquake, we scrutinized in the field all the major faults in the Kozani-Grevena area. Although non-tectonic slumps, fissures and landslides were abundant throughout most of the region [Pavlides et al., 1995], we found that unequivocal tectonic rupture was limited to a fairly continuous break along a pre-existing, minor normal fault (topographic relief  $\leq 50$  m) within the sediments of the Mesohellenic Trough (Fig. 1a). The fault strikes  $N70^\circ E$  on the average, and the observed near-surface dip is  $70^\circ$  due northwest (Fig. 2b). The break, which we followed and mapped in detail for 8 km south and SW of Palaeochori, consisted of open fissures and small scarps with 2-4 cm down-to-the-northwest, normal slip (Fig. 2a). Local witnesses confirm that the break (which crossed dirt roads and wheat fields) formed during the main event. North and NE of the main fault segment are two less clear, en échelon, segments with the same strike and dip. The larger one (4 km long) cuts across ophiolitic rocks northeast of Palaeochori (Fig. 1). There are also some small, oblique, E-W to NW-SE striking faults on the western side of the Vourinos Range southeast of Palaeochori. Based on indirect evidence (i.e., numerous small slumps over the fault zone) we infer that part of these segments may also have ruptured during the main event. However, we did not find any sign of tectonic rupture east of these faults, across the Vourinos Range.

The total length of the break is therefore at least 8 km (and possibly 12 km) along a northwest-dipping en échelon normal fault system, which we shall refer to here as the Palaeochori Fault. Its trace lies about 15 km south of the main shock

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**Figure 1.** Active faulting in the Kozani-Grevena area mapped with panchromatic SPOT imagery and fieldwork. Topography from 1:250,000 scale maps. 1995 earthquake epicenter, fault plane solution and aftershocks from Hatzfeld et al. [1996]. Boxes give location of Fig. 3 and of SPOT enlargements. Right inset shows tectonic framework. (a) The 1995 earthquake broke the small NW-dipping Palaeochori normal fault. (b) Western two right stepping segments of the much larger Servia Fault. Note the semi-elliptical shape of the hangingwall basin outlined by the 500 m elevation contour. Lower-case letters indicate location of photographs in Fig. 2.

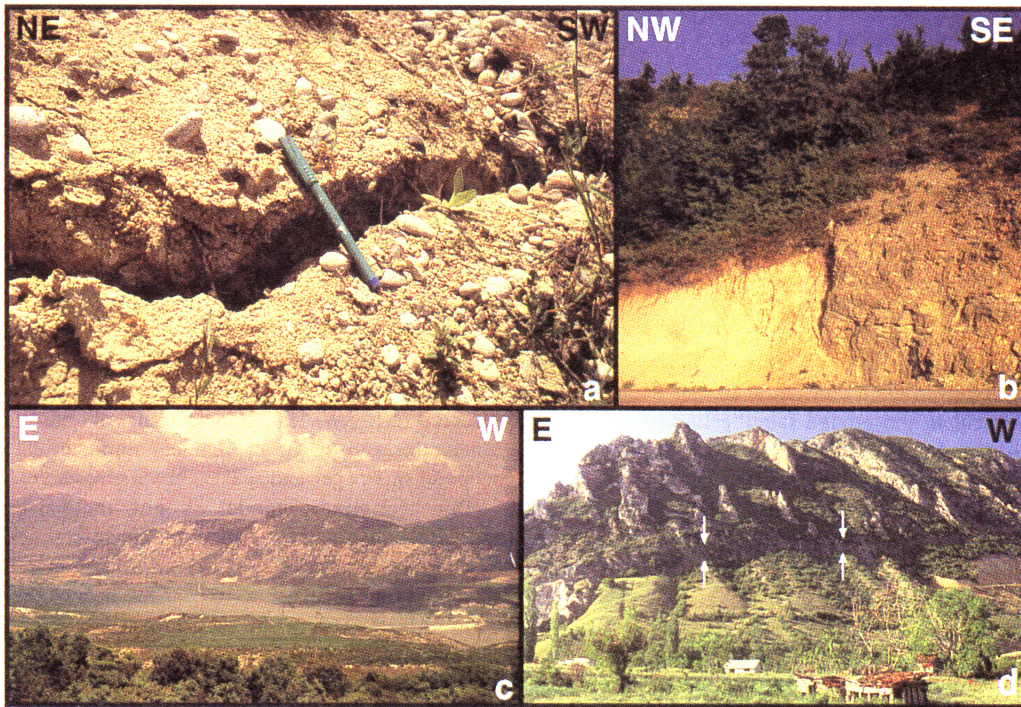
epicenter and south of the main cluster of aftershocks (Fig. 1). Both the geometry of the observed break and its location with respect to the mainshock and aftershocks favor rupture on the northwest-dipping nodal plane of the focal mechanism (strike  $N263^\circ$ ; dip  $38^\circ$ , Fig. 1). The slip at the surface, however, is less than expected for the moment release of the 1995 event.

The Palaeochori Fault is part of a larger fault system with similar average strike and dip including the Paliuria and Servia faults, which form a left-stepping en échelon system linked by smaller segments striking N-S to  $N40^\circ E$  (Fig. 1). The Servia Fault is composed of three main segments with a total length of about 35 km. Normal slip on the Servia Fault has caused the southeastward tilt and offset of the pre-extensional sediments south of Kozani, forming the characteristic flexed hangingwall basin with semi-elliptical shape seen in the morphology (Fig. 1). Taking into account the overall flexure of geological markers, the probable maximum throw across the Servia Fault is in the range of 1000-2000 m, and the structural offset along the Vourinos Range across the Paliuria Fault is probably similar (Fig. 1).

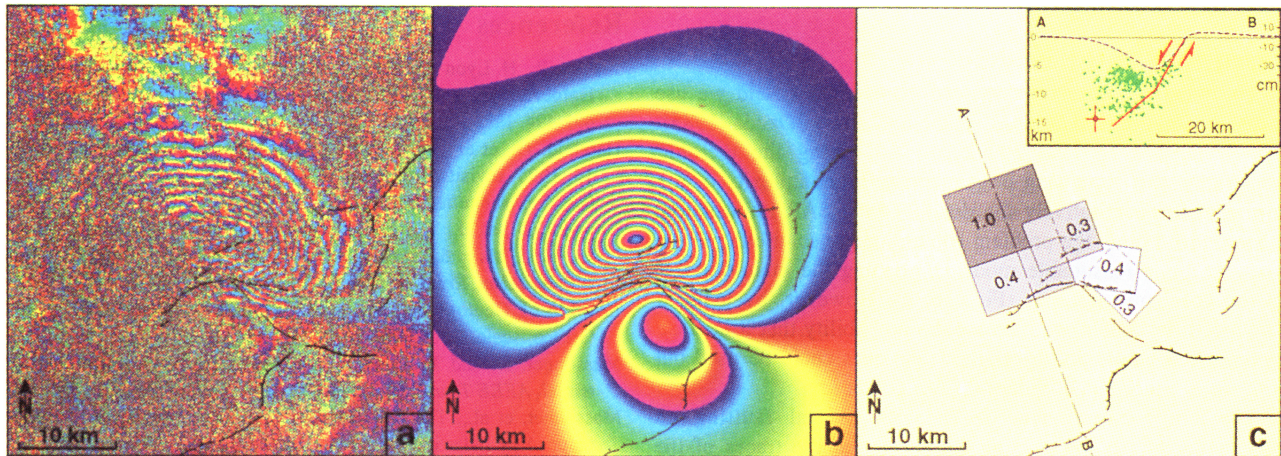
The morphological evidence for young Quaternary slip is particularly clear along the Servia Fault footwall. The faceted NW-facing mountain front is more than 400 m high, cut into Mesozoic limestone, and capped by pre-extensional Neogene sediments (Figs. 1b, 2c). Steep slopes reaching  $40^\circ$  form the lower half of the front. Large exposed fault planes indicate  $60^\circ$  northwestward dip on the average, with nearly pure dip-slip normal faulting. At the base of the front there is a conspicuous scarp 10 to 20 m high, similar to fault scarps found in limestone fronts in other regions of Greece and interpreted to be mainly of Holocene age (Fig. 2d) [Armijo et al., 1992]. This suggests that the Servia Fault has average Holocene slip rate in the range of 1-2 mm/yr, and that it is capable of  $M \approx 7$  earthquakes every 1000-2000 years (rupture 35 km long, 15 km wide, with 2 m slip per event). Although the morphologic evidence along the Paliuria Fault is less clear, probably because of the different lithology, its slip rate and seismic potential may be comparable.

The 1995 earthquake break along the subdued Palaeochori Fault thus reveals reactivation of part of a much larger fault





**Figure 2.** Palaeochori Fault: (a) Detail of the 1995 break across talus, with 4 cm throw down-to-the-NW and 2 cm horizontal extension. (b) Cross-section of the Palaeochori Fault, with Quaternary fill in the hangingwall (left) and gently SE-dipping Miocene (?) sand and gravel layers in the footwall (right). The earthquake en échelon fissures are visible on the pre-existing 70° SW dipping fault plane with throw of 4 cm. Servia Fault: (c) Western end of the northwest-facing range front fault, and of the flexed hangingwall basin with Polyfytyos lake. Note the southeastward tilt of the footwall surface, which is capped with pre-extensional sediments. (d) Scarp 10-20 m high (arrows) at the base of the limestone front near Servia.



**Figure 3.** (a) Interferogram describing surface displacement between 16/11/93 and 05/10/95, with altitude of ambiguity of 126 m and error of less than 2 mm. Each fringe represents 28 mm displacement. Unit vector from ground to satellite [east, north, up] is [0.402, -0.083, 0.912]. (b) Synthetic fringes. (c) Fault model with average displacement (in m). The two patches with 0.4 m have variable slip, see text. Inset section: Modeled Palaeochori fault and surface vertical displacement (in cm, segmented). Main shock with error bars and aftershocks (over 14 km wide band) from Hatzfeld et al. [1996].

system with interconnecting segments at a range of scales. The system has developed recently (Plio-Quaternary?) across the older Hellenic structure, suggesting that it is in the process of growing. To explore the 3-D geometrical and mechanical relationships between the different elements of the developing system, we use the surface displacement field determined with the SAR interferometry.

### Displacement observed by SAR interferometry

To describe the surface displacement field we used interferometric fringes generated by comparing radar images acquired at different times by the European ERS-1 satellite in C-band (56 mm wavelength). The images were combined two-by-two using the Digital Elevation Model (DEM) elimination

method [e.g., Massonnet et al., 1993] which reveals fringes corresponding to contours of equal change in satellite to ground distance (i.e., range). We selected 8 ERS-1 SAR scenes and of the 28 possible pairs we retained 10 that ensured moderate topographic residuals. This is because their altitudes of ambiguity (i.e., the altitude of unmodelled topography required to create one spurious fringe [Massonnet and Rabaute, 1993]) are much higher than the rms accuracy of 8 m of the DEM, which was obtained from a couple of stereometric SPOT scenes. From these 10 pairs we produced five interferograms with good coherence spanning periods of 2-3 years and the date of the earthquake. The others were used to check error budgets for atmospheric propagation problems.

The interferogram selected for this study is the least sensitive to topography (Fig. 3a). It contains mostly coseismic deformation, with eleven main concentric fringes depicting the surface displacement in the ground-satellite line of sight. The fringes are sharp and well-determined on the non-cultivated slopes of the Vourinos Range. Surprisingly, although much more blurred, the fringes are also distinguishable on the plains of the Mesohellenic Trough. That some coherence remains in this area, despite intense agriculture, may be due to stable field borders which survive annual plowing.

The interferogram outlines a kidney-shaped area of subsidence of 400 km<sup>2</sup> with maximum of about 30 cm. The interferogram also reveals a zone of uplift reaching ~5 cm high (2 fringes) 5 km south of Palaeochori. There is a marked N-S asymmetry in the average spacing of the fringes and the subsidence maximum is closer to the southern edge of the subsidence. Half of this southern edge coincides with the break observed along the Palaeochori Fault. However, a significant part of the area of subsidence bypasses the Palaeochori break to the southeast, toward the Paliuria Fault. Within this part a set of converging fringes 3 km SE of Palaeochori indicates local scissors faulting.

## Discussion of the model

To model the coseismic surface displacement field we use a dislocation embedded in an elastic half space [Okada, 1985]. We proceeded by trial and error integrating the tectonic constraints and increasing progressively the complexity of the model to fit quantitatively the details of the SAR information. As we have noted, the problem has no unique solution, and we show here one reasonable model explaining the main features of the coseismic faulting (Fig. 3b, c). However, by using a range of information we increase the probability that it is close to reality. We note that inversion techniques could be used but less easily incorporate widely differing data sets.

The fringe pattern can be fit with normal faulting on rectangular planes intersecting the surface at the traces of the mapped faults. The western half of the subsidence area requires that the Palaeochori Fault has a steeper dip near the surface than at depth. We take 60° dip from the surface to 9 km depth, and a dip of 40° down to 15 km. Average slip is 1 m at depth, but it has to decrease rapidly to 5 cm within the 4 km near the surface. The eastern part of the subsidence area requires rupture of the two ENE-dipping faults southeast of Palaeochori. For the southern one, which parallels the structure of the Vourinos, we take dip of 60° and average slip of 0.3 m within a patch not reaching the surface, from 2 to 10 km depth. For the northern one we take the same dip but reaching to the surface with slip that tapers from 0.6m to 0.1m to the ESE, in agreement with the scissors faulting seen in the interferogram (Fig. 3a).

The model explain well the kidney shape of the hangingwall fringes, their number and the local gradients. It

also reproduces satisfactorily the bulge in the footwall. The small break observed along the Palaeochori Fault is the surface expression of larger slip on the same structure at depth. However, to fit in detail the complexities in the best defined part of the fringes requires slip reaching the surface on the minor fault segments where the surface break in the field was less certain, NE and SE of Palaeochori. In any case the eastern part of the 1995 rupture appears to splay into several segments as it enters the Vourinos Range. This implies scissors faulting and probably reactivation, under extension, of a patch of an old Hellenic thrust plane with NW-SE strike and NE dip. The 1995 rupture along the Palaeochori Fault mimics the bend in the geometry of the Paliuria Fault farther south. This suggests that the former is possibly encountering the same mechanical obstacles as the latter as it propagates across the Vourinos structure. This geometry implies some amount of stretching directed NE-SW. A full account of the details of the kinematics and of the mechanical implications is out of the scope of this paper and will be given elsewhere.

Our preliminary model is not inconsistent with the mainshock hypocenter and with the aftershock distribution. Taking shear modulus of 33 GPa, the model yields total seismic moment of  $6.4 \times 10^{18}$  Nm, nearly the same as the CMT. About 80% of the total moment is released by slip on the Palaeochori Fault and 45% on its 40° dipping part, in agreement with the long-period fault plane solution. Further work is needed to resolve better the model with additional tectonic and seismological constraints.

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