Earthquake sources retrieved from intensities: seven successes in Greece

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ABSTRACT
Our source inversion technique (*KF*) gives an answer to an important hazard issue: the lack of knowledge of most fault-sources of earthquakes of the pre-instrumental epoch, because we retrieve the sources only from intensity. (*KF* was validated by comparing the sources we found with those known from instrumental measurements). Our cost function is the sum of the squared residuals (field intensities-minus-computed ones) and a genetic algorithm is used to find its minimum. Our inversions are automatic, do not use starting models nor constraints. The macroseismic patterns of 9 earthquakes of the Hellenic area were inverted, in the Marie Curie Project TOK-DEV at ITSAK, with the purpose of validating *KF* also in Greece. In seven cases, the found sources were close to the instrumental ones: Stivos (M6.5, 06.20.1978) and its foreshock (M5.8, 05.23.1978); Kozani (M5.5, 10.25.1984), Kalamata (M6.0, 09.13.1986), Almyros, (M6.5, 09.07.1980), Aeghio (M6.5, 06.15.1995), Sophades (M7 04.30.1954).

Keywords:Greece Intensity Historical earthquakes Kinematic function Source inversion

1. INTRODUCTION

We developed a technique to invert the kinematic function *KF* (Sirovich, 1996) to retrieve the fault-sources of earthquakes of the pre-instrumental epoch from good-quality macroseismic intensity data. *KF* simulates body waves (SH, plus the horizontal component of SV) and bases on the representation theorem (Aki and Richards, 1980) in the high-frequency approximation (Madariaga and Bernard, 1985) in relatively far-field conditions. This approximation works satisfactory even at distances of the order of the wavelength (Madariaga and Bernard, 1985; Spudich and Frazer, 1984). Thus, in Alpine contexts, we treat field intensities at maximum distances of the order of 80-100 km from the macroseismic epicentre. Since *KF* produces non-dimensional values, empirical equation (2) in Pettenati and Sirovich (2003) is employed to obtain intensities. Our inversions use a genetic algorithm with niching (NGA, Levine, 1996).

The cost function of our inversion is the sum of the squared differences between the experimental intensities and the computed ones. NGA uses a set of sub-populations (deme) to explore the relative minima of the multi-modal space of parametres, to find out the absolute minimum. It is important to remember that NGA doesn't start from any input model; thus, subjectivity is avoided. See Gentile et al. (2004) and Sirovich and Pettenati (2004) for details.

A final validation of the method was published in 2007 (Pettenati and Sirovich, 2007) using three well-recorded California earthquakes with good intensity data. Satisfactory solutions were achieved also in Norway (Bungum et al., 2009) and in Italy (Sicily region: Sirovich and Pettenati, 2001; Veneto region: Sirovich and Pettenati, 2004; Campania: Pettenati and Sirovich, 2006).

We eliminated subjectivity also from isoseismals, presenting a new natural-neighbor (n-n) interpolation, which doesn't use input parametres (Sirovich et al., 2002). We chose to round the real values to the closest integers; for example, the isoseismal of VI degree follows the 5.5 limit of the interpolation. The macroseismic data of the Institute of Engineering Seismology and Earthquake Engineering of Thessaloniki ITSAK were used (Papazachos et al., 1997) in the MMI scale.

We show here that our technique works well also in Greece. In fact, we compared the sources of nine earthquakes in the last sixty years in Greece, which we obtained from our inversion, with those already known from instrumental measurements independently from our study. In particular, for this kind of validation we used the Papazachos and Papazachou (1997) catalog and the other papers cited below. As intuitively guessed from Fig. 1 (the Sophades, 1954 earthquake is still missing from the figure), the nine earthquakes treated fall in different tectonic contexts, from the rather strong seismic activity to the northeast, still influenced by the North Anatolian Fault, in the area of the Mygdonian Graben, close to the Langada Lake and Volvi, with its extensional regime and normal structures in the Halkidiki peninsula, to the complicated structure of the Hellenic Trench, which connects the Dinarides and the Hellenides chains with the Turkish Taurides; not to mention the internal Hellenides, where most of the principal structures trend NW-SE and experienced extensional tectonics from the late Miocene at least to the Oligocene. This is a well-stocked sample of earthquake mechanisms for our inversion experiments.

2. VALIDATION OF THE INTENSITY INVERSION OF NINE EARTHQUAKES

The choice of the Greek earthquakes to be studied followed these criteria:

1) reasonably homogeneous intensity distributions in the field (i.e. 'enough' regular decrease with distance); not many spots with numerous positive or negative anomalies, nor statistical outliers, because extensive local effects prevent reliable inversions, since they reflect spuriously on the retrieved source;
2) inland events, because we need complete intensity fields; this was a hard condition for Greece;
3) no destructive foreshocks or aftershocks close in time to the principal event, to avoid spurious damage increase caused by different shocks, possibly with different mechanisms;
4) seismic moments Mo within the calibration range of our semi-empirical model (2.7 1024≤Mo≤2.2 1026 dyne cm, see Sirovich et al., 2001, table 1).

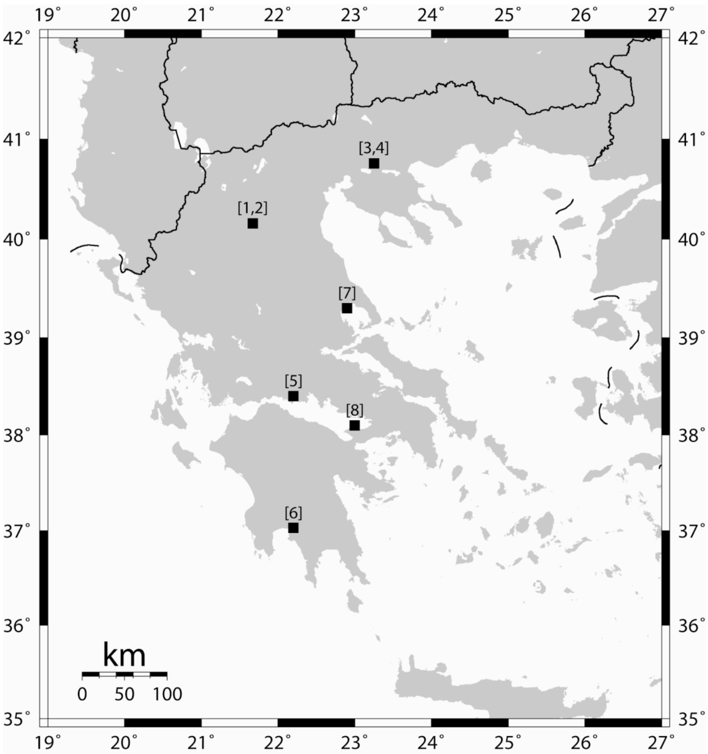

Figure 1. Locations of eight out of the nine earthquakes studied in the Hellenic Region (the 9th case, the Sophades, 1954 earthquake is still missing from the figure).

Eight earthquakes met approximately the preceding criteria (see the location numbers in Fig. 1; one was added at the last minute): 1. Kozani 05.13.1995 M6.6; 2. Kozani 10.25.1984 M5.5; 3. Stivos 06.20.1978 M6.5; 4. Stivos 05.23.1978 M5.8; 5. Aeghio 06.15.1995 M6.4; 6. Kalamata 09.13.1986 M6.0; 7. Alkyonides 02.24.1981 M6.7; 8. Almyros 07.09.1980 M6.5 (see the location numbers in Fig. 1); 9. Sophades (04.30.1954 M7; location not shown). Kozani is in western Macedonia, Stivos in its central part close to Thessaloniki. The Kalamata earthquake occurred in the southern Peloponnese and the others (5, 7, 8 and 9) in Attica and Central Greece. As said in the Introduction, we validate our inversions by comparing the sources and fault mechanisms retrieved from intensities with those obtained from instrumental data, independently from our study. In particular, subjectivity was eliminated from the comparisons between different fault-plane solutions, by using a new algorithm, which computes the disorientation (i.e. rotation to overlap) between one double couple and another one; in our case: the inverted mechanism and the instrumental one taken as reference. Our algorithm doesn't use quaternion as Kagan did (1991), but solves the problem by simple linear algebra (Pettenati and Cavallini, 2005).

2.1. Results

First, we removed the statistical outliers from all intensity data-sets by the Chauvenet method (Pettenati and Sirovich, 2003). Then, we inverted these data-sets. The results are in Table 1 (the 9th case, Sophades 1954, is discussed later). The inverted fault-plane solution is perfectly validated if the disorientation angle with the reference is zero. But the choice of the maximum allowed disorientation is not trivial. Consider that a rotation of 90º is needed to change a pure strike-slip mechanism into a pure dip-slip one. Then, 45º could be taken as the maximum angle for a validated solution, but 44° would be a very weak evidence. We chose the 36º limit because it was the median of the 24 disorientations we had in our data set of 24 comparisons from the following sequences: Sumatra 2004-2005 (Pettenati and Cavallini, 2005), Irpinia 1980 (Pettenati and Sirovich, 2006) and the present ones. We agree on that it is an arbitrary choice, however.

Table 1, summarizes the principal results of the present inversions (Sophades is discussed later): the retrieved fault-plane solutions, FPS; the instrumental FPSs taken as reference; the differences of our Seismic moments (Mo, dyne cm) and epicentral coordinates (km) with the reference ones. You can see that for six earthquakes (refer to the shaded boxes; seven with Sophades, see later) the disorientation angles show validation. Kalamata 09.13.1986 is at the limit of 36º, but new informations from Geology and Seismic exploration (Fountanoulis, 2008; Garcia and Slejko, 2009; Nicolich written communication, 2010) suggest a rotation of the strike of the rupture of this earthquake toward 357° (from the instrumental result of 6º; see Table 1). In fact, the causative fault coincides with the eastern border of the Kalamata-Kyparissia Graben, which trends a little bit more NNW than toward NNE (see Table 1 and Figures 2a-2b). If one accepts this small strike correction, the disorientation becomes 8º. It is worth mentioning that Kalamata was a difficult inversion because one part of the intensity field is lacking due to the presence of the sea. Perhaps this is also the reason for the 16.5 km difference between the two epicentres. From Figure 2a you see that the instrumental epicentre (CMT, 22.2°E – 37.03°N) falls inland; ours (Figure 2b) is close to the eastern border of the Messiniakos Gulf (along the flank of the graben). As in Figures 3b and 4, in Figure 2b we show the projection of the line source (in this case with asymmetric nucleation); conceptually, in the *KF* model the source is a rupture plane of unit width, however. See that the line source is aligned with the eastern flank of the graben.

In conclusion, we consider Kalamata 09.13.1986 an acceptable validation.

Then, the high disorientation angle of Kozani 05.13.1995 (40º) is due to our dip angle, which is too steep (87º see Table1). This inversion was complicated by the presence of a VI degree area along the valley of the Haliacmon River, suggesting a significant sub-event or regional site effects there. Let us mention, however, that the second deme of the genetic inversion found a fault-plane solution compatible with the instrumental ones, but with a relevant epicentral difference.

We come now to the Stivos 06.20.1978 earthquake. As you can see in Figs. 3a and 3b, the inverted fault-plane solution (white for the intrinsic ±180° ambiguity of the rake angle in the *KF* model) matches well the available reference solutions, and also the synthetic intensity field is well balanced.

Table 1. Principal results of the inversions of the eight earthquakes of Fig. 1 (see the 9th case later).

Earthquake	FPS from inversion [°]	reference FPS (instrumental) [°]	γ [°]	Δ (MoIn - Mo*KF*) [dyne cm]	Δ (EpicIn - Epic*KF*) [km]
Kozani 05.13.1995	77,87,-73 242,32,-63*	240,31,-90§	40	-2.21 10^{25} -3.87 10^{25}	14.8¢ 16.4¢
Kozani 10.25.1984	230,66,-86$	/	32	/	/
Stivos 06.20.1978	282,37,-94	286,43,-88§	6	-2.44 10^{25}¥	3.5£
Stivos 05.23.1978	289,45,-89	265,40,-83	27	1.7 10^{24}§	8.3£
Aeghio 06.15.1995	259,53,-91	272,30,-78#	20	3.16 10^{25}§#	8.5#
Kalamata 09.13.1986	357,72,-87	6,40,-100#	36	-3.09 10^{25}§#	16.5#
Alkyonides 02.24.1981	252,76,-57	246,42,-99#	43	-1.69 10^{25}§#	7.9#
Almyros 07.09.1980	231,45,-84	261,50,-90#	33	-1.57 10^{25}§#	1.1#

Notes to Table1:

Shaded boxes show acceptable matches (validations).

FPS: fault-plane solution, shown in the following order: strike, dip, rake angle (±180° for intrinsic ambiguity in the *KF* model).

γ: disorientation angle (rotation between our FPS and the reference one).

Δ: difference between:

MoIn = instrumental seismic moment; Mo*KF* seismic moment from *KF* inversion.

EpicIn = instrumental epicentre; Epic*KF* epicentre found by our *KF* inversion.

§ CMT Harvard (fault-plan solution), in Rumelioti et al. (2007).

£ CSEM Centre Seism. Euro-Mediterranéen (epicentre coordinates) in Rumelioti et al. (2007).

¥ Rumelioti et al. (2007).

¢ Hatzfeld et al. (1997).

Papazachos and Papazachou (1997).

§# CMT Harvard in Papazachos and Papazachou (1997).

$ The reference data of Kozani 10.25.1984 were not available, those of Kozani 05.13.1995 were taken as reference.

* the 2nd solution is shown here from our 4-deme inversion (see text).

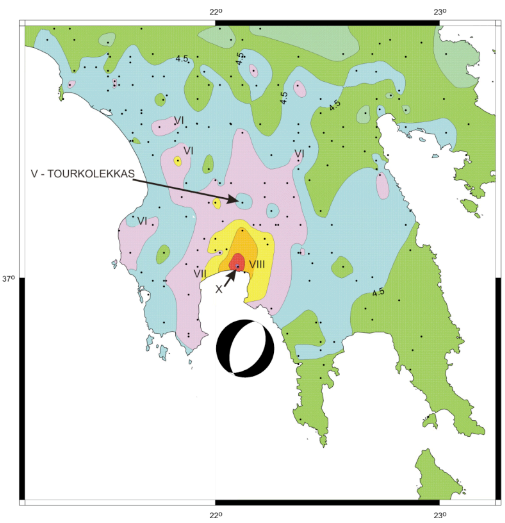

Figure 2a. Experimental isoseismals (n-n contour) of Kalamata, 1986, with the fault-plane solution by Papazachos and Papazachou (1997).

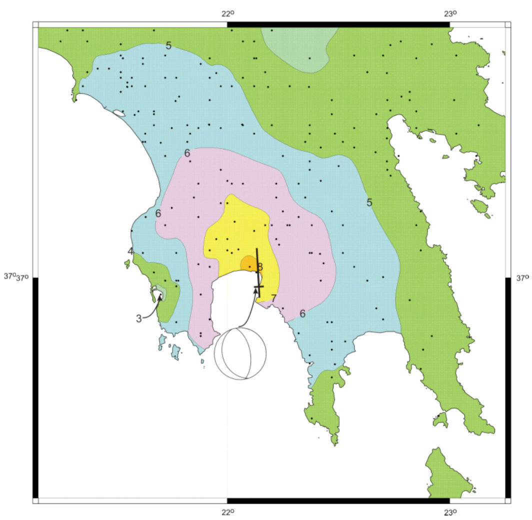

Figure 2b. Synthetic intensities and faul-plane solution of Kalamata, 1986 from the best fitting source in the *KF* inversion.

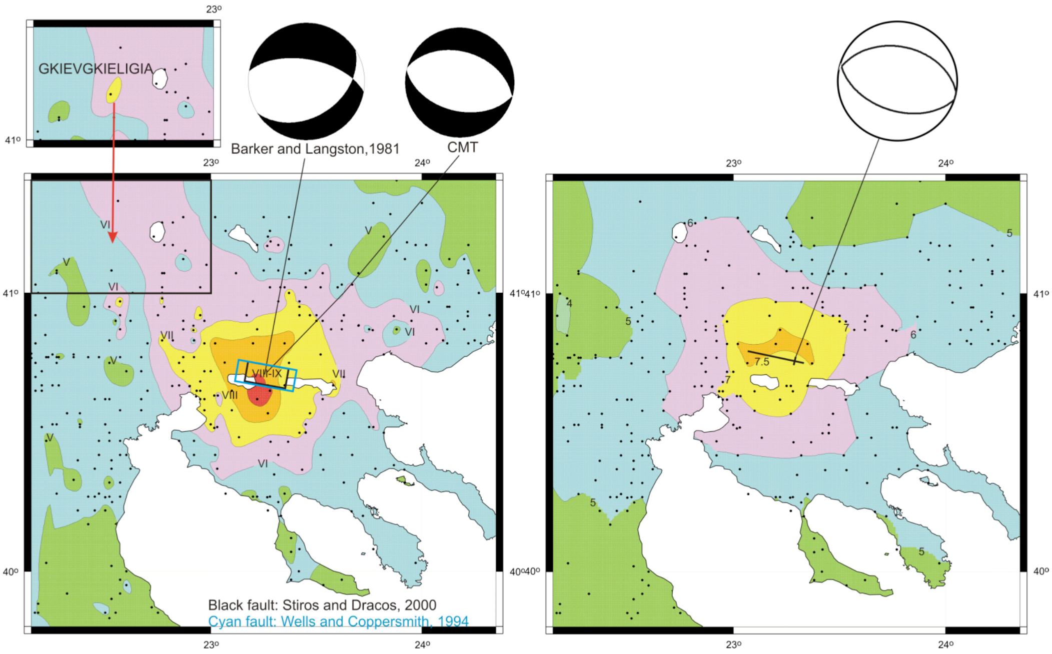

Figure 3a. As in Fig. 2a for Stivos 06.20.1978. Gkievgkieligia is a statistical outlier

Figure 3b. As in Fig. 2b for Stivos 06.20.1978.

Very recently, we performed also the inversion of the Sophades, 1954 M7 earthquake of April 30, 1954. As said, these results are not in Table 1. The reference values for this experiment were also taken from Papazachos and Papazachou (1997): epicentre 39.28°N – 22.29°E, strike angle 246°, dip 44°, rake -88° (see Figure 4.1). Our epicentral coordinates retrieved by *KF* are: 39.26°N – 22.40°E, FPS is: strike angle 245°, dip 41°, rake -95°.

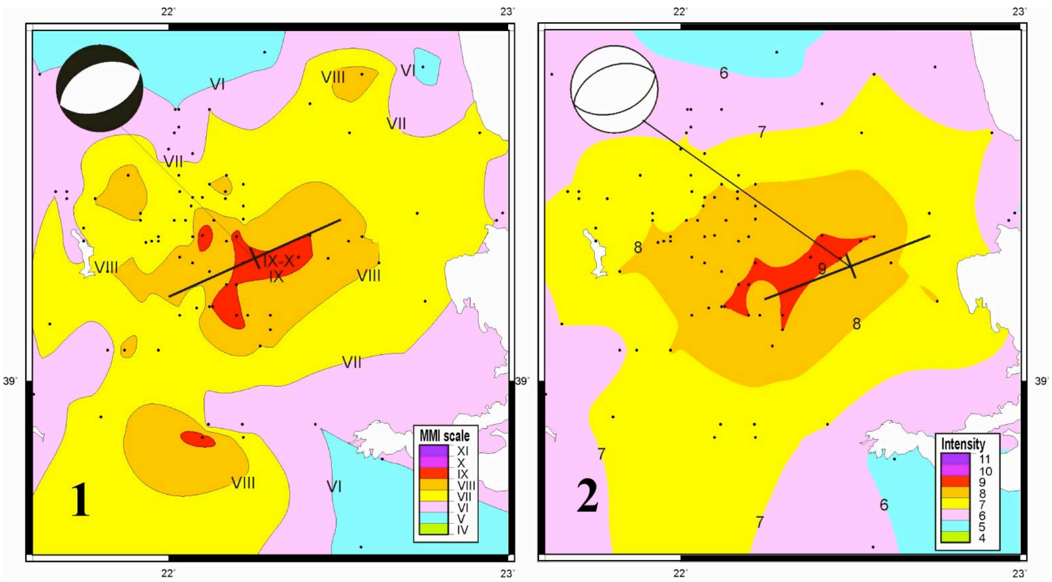

Figure 4. As in Figures 2a and 2b. **1**) Experimental isoseismals of Sophades, 1954, with the fault-plane solution by Papazachos and Papazachou (1997). **2**) Synthetic intensities and faul-plane solution from the best fitting source in the KF inversion.

In our opinion, the match between the synthetic intensities in Figure 4.2 and those observed in the field (Figure 4.1) is very good; almost perfect if you omit that site of IX degree in the left lower corner of the figure (that site is not a statistical outlier, however). The only relevanti misfit is in the location of the inverted epicentre (see Figure 4.2), but we had no time to go deeper in this matter.

3. EMPIRICAL CALIBRATION OF *KF* FOR DETERMINISTIC SCENARIOS IN GREECE

After these inversions, we performed the new calibration of *KF* in Greece. In fact, the values radiated by our model to the sites are non-dimensional (Sirovich, 1996) and need to be calibrated with empirical intensities. In the past, we did this in California (Sirovich et al., 2001) and the calibration worked well also in Italy. In Norway, with the Moho interface at about 40 km depth, we were obliged to perform a new calibration (Pettenati et al., 2005; Bungum et al., 2009). So, we used the new results obtained in Greece to produce the local calibration of Fig. 5.

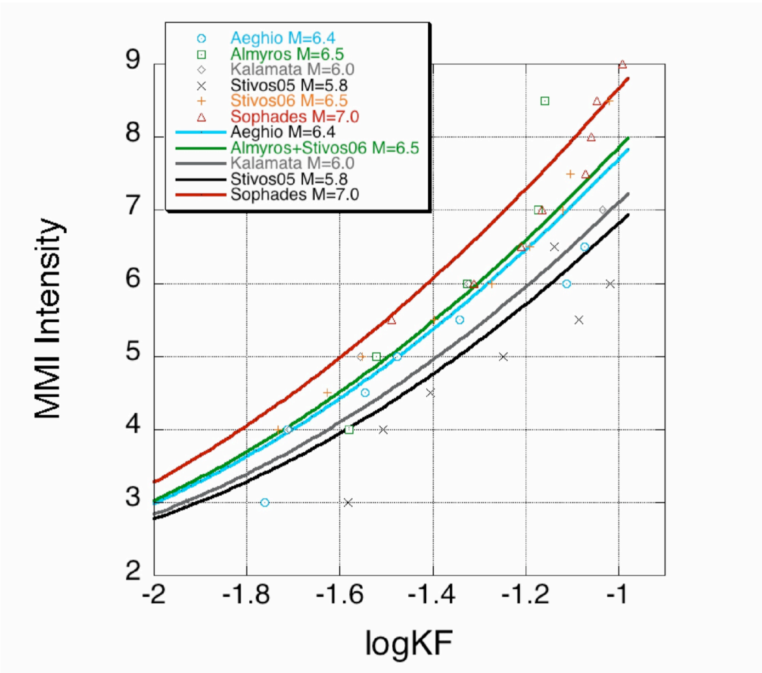

Figure 5. Empirical calibration of the *KF* values (log) produced by the model at the sites where intensities were observed in the field. The six successful results of Table 1, plus Sophades 04.30.1954 M=7 were used.

As seen from it, we used the six successful results of Table 1, plus the striking result obtained for the Sophades 04.30.1954 M=7 earthquake. Note that - according to Physics - in the figure the correlations do scale themselves according to the M size, from M5.8 (black) to M7 (red). The new Eqn. (1) can be used in Greece both for inversions of pre-instrumental destructive earthquakes (the original strategic target of *KF*) and to calculate deterministic parametric scenarios of intensity (a new application; see Sirovich and Pettenati, 2009).

$$I = 0.259 - 3.613 LogKF - 0.067 LogM_0 + 1.853 LogKF^2 + 0.743 LogKF LogM_0 + 0.049 LogM_0^2 \quad (1)$$

4. DISCUSSION AND CONCLUSIONS

The use of the *KF*-intensity calibration from five California earthquakes (Sirovich et al., 2001) allowed us to obtain acceptable inversions also in Greece. But Eqn. 1 is differente from Eqn. 2 of the preceding authors. Thus, in the future we will repeat the present inversions hoping to improve the present results and, however, future inversions and scenarios will be done with Eqn. 1. It is worth mentioning that the present Eqn. 1 is closer to Eqn. 2 by Sirovich et al. (2001) than to Eqn. 4 by Pettenati et al. (2005) from Norwegian earthquakes. This is coherent with the three tectonic

environments, with the Scandinavian Crust being thicker than the others.
As the reader understood, we made many efforts to avoid subjectivity in the treatment of intensity. Our most recent tool, the disorientation angle test, also goes in this direction.
Intensity has a long story, it is one of the earliest concepts which made its way into seismology, but we think that - when treated with modern techniques - it can still give interesting results (not only for improving the knowledge of earthquakes of the pre-instrumental epoch, but also for future damage scenarios). For example, in our opinion Figures 3 and 4 show stricking results. Consider that the sources of these earthquakes were already well known from seismograms, but think about the very poor knowledge that we have about hundreds of destructive earthquakes of the past centuries in countries were historical information is available, or could be extracted from archives. By the way, we are aware that the *KF* model is simplistic, from the point of view of the modern quantitative seismology, but we could not risk to overparameterize it because the intensity datum is not so rich as the instrumental ones. Then, do not forget that in most regions the seismic hazard is controlled by the source characteristics of ancient earthquakes, which are most often unknown. The *KF* inversions proved to be useful to give a contribute in this matter, also because they are sometimes able to retrieve the fault-plane solution, a task which seemed impossible with no instrumental measurements available.
In conclusion on the inversions, the present results along with the four inversions validated in California (Pettenati and Sirovich, 2003, Pettenati and Sirovich, 2007), the validations of the two earthquakes of 1980 and of 1694 in Irpinia, Italy (Pettenati and Sirovich, 2006), the good one in Cansiglio 1936, Italy (Sirovich and Pettenati, 2004) and the results in Norway (Bungum et al., 2009), confirm the interest of our method to improve the knowledge of the sources of old earthquakes in particular in the Old World.
Finally, this paper and the companion one (proc. #1810) suggest that *KF* can find application also for hazard scenarios, both in terms of intensity and low-frequency particle displacements. In particular, after the good results obtained using *KF* in the inverse mode for Stivos 1978 and Sophades 1954 (but we like also our result for Kalamata 1986), and after our experiments of scenarios south of San Francisco (Sirovich and Pettenati, 2009), in Los Angeles (Sirovich et al., 2009) and in Italy, we hope to be allowed to use *KF* in the direct mode to forecast deterministic scenarios also in Greece.

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