Journal of Seismology **4:** 365–375, 2000.

Source properties of the 1997–98 Central Italy earthquake sequence from inversion of long-period and broad-band seismograms

Andrea Morelli[1], Göran Ekström[2] & Marco Olivieri[1]
[1]*Istituto Nazionale di Geofisica, Rome, Italy;* [2]*Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts*

Received 18 March 1999; accepted in revised form 23 December 1999

Key words: body waves, Central Apennines, extensional tectonic regime, focal depths, seismic moment tensors, source mechanisms, source time functions, surface waves

Abstract

We study source properties of the main earthquakes of the 1997–98 Umbria-Marche (central Italy) sequence by analysis of regional-distance and teleseismic long period and broadband seismograms recorded by MEDNET and IRIS/GSN stations. We use a modified Harvard centroid-moment tensor (CMT) algorithm to allow inversion of long period waveforms, primarily Rayleigh and Love waves, for small earthquakes ($4.2 \leq M_W \leq 5.5$) at local to regional distances ($\Delta < 15°$). For the seven largest earthquakes ($M_W > 5.2$) moment tensors derived from local and regional data agree well with those determined using teleseismic waveforms and standard methods of analysis. We also determine moment tensors for a foreshock and 12 other aftershocks, that were too small for global analysis. Focal depth and rupture propagation are analyzed for three largest shocks by inversion of teleseismic broadband body waves. The earthquakes are generally located at shallow depth (5 km or shallower) and are characterized by normal faulting mechanisms, with a NE-SW tension axis. The presumed principal fault plane dips at a shallow angle towards the SW. Only one of the events analyzed has an entirely different faulting geometry, indicating instead right-lateral strike-slip motion on a plane approximately E-W, or left-lateral faulting on a N-S plane. The other significant exception to the regular pattern of mechanisms is represented by the March 26, 1998, event, located at 51 km depth. Its connection with the shallow earthquake sequence is unclear and intriguing. The time evolution of the seismic sequence is unusual, with the mainshock accounting for only approximately 50% of the total moment release. The broadband teleseismic waveforms of the main, September 26, 09:40, earthquake are very complicated for the size of the event and suggest a complex rupture. In our favored source model, rupture initiated at 5 km depth, propagated updip and was followed, 3 seconds later, by a shallower subevent with a slightly rotated mechanism.

Introduction

A series of earthquakes hit the regions of Umbria and Marche, in central Italy (Figure 1), starting in 1997, with a $M_W = 4.5$ foreshock on September 4, followed on September 26 by two events with $M_W = 5.7$ and $M_W = 6.0$ just 9 hours apart. Over the next 30 days or so, four more events with magnitudes larger than 5 followed (Ekström et al., 1998). The earthquakes were the most damaging to strike in Italy since the 1980 Irpinia event and have been well studied (see for instance the studies by Amato et al., 1998; Basili et al., 1998; Cello et al., 1998; Cinti et al., 1998; Ekström et al., 1998; Hunstad et al., 1998; Olivieri and Ekström, 1999; Pino et al., 1999; Stramondo et al., 1999; and papers in this special issue). The earthquakes fit well into the known seismotectonic regime of the central Apennines, a region undergoing extension (see Figure 1) and subject to normal faulting earthquakes with maximum magnitudes, known from historical and instrumental catalogs (Boschi et al., 1997), of around 6.0.

Previous studies have shown that the 1997 events of the seismic sequence can be associated with a NW-

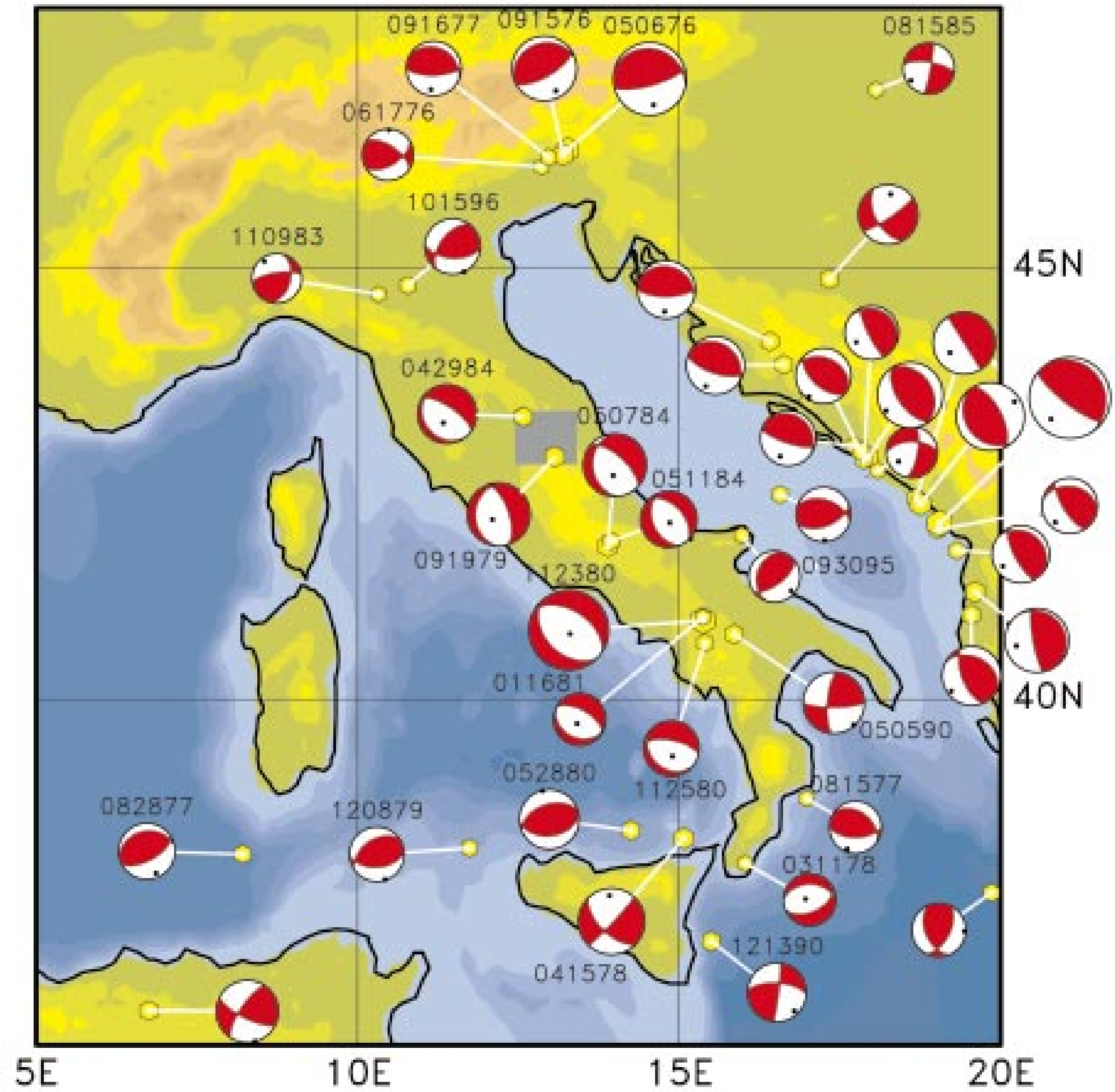

Figure 1. Source mechanisms for major earthquakes in Italy and the surrounding region since 1976 and before September 1997 (Harvard CMT Catalog). The box marks the epicentral area of the Umbria-Marche 1997–98 earthquake sequence studied. The numerical labels indicate dates (month, day, year) for italian earthquakes.

SE elongated fault zone with a length of about 40 km (Amato et al., 1998). The three largest shocks appear to have ruptured different, parallel, segments of this fault zone. Moment tensors, calculated by Ekström et al. (1998) show normal faulting mechanisms with NE-SW tension axes, in agreement with the aftershock distribution at depth, which also identifies a plane dipping to the SW. The inversion of teleseismic broadband P waveforms reveals that the rupture of the mainshock nucleated at depth and propagated updip and towards the north (Olivieri and Ekström, 1999), as confirmed by the aftershock distribution (Amato et al., 1998) and the modeling of regional waveforms (Pino et al., 1999). The mainshock appears to have a complex rupture history, with two subevents about 3 seconds apart and a total duration of about 7 seconds (Olivieri and Ekström, 1999). The waveforms are consistent with seismic ruptures confined to the top 5–7 km of the crust. Slip has been observed in the field on bedrock fault surfaces, but was attributed to secondary reactivation of old faults by gravitational movements (Basili et al., 1998; Cello et al., 1998; Cinti et al., 1998). ERS-SAR differential interferometry and GPS data detected maximum horizontal displacement of about 14 cm, and vertical subsidence up to 25 cm (Stramondo et al., 1999; Hunstad et al., 2000) which can be fit by a model with slip confined to the shallowest 6.5–7 km and suggest that rupture stopped very close to the surface. The moment tensors calculated by inversion of long period waveforms recorded at regional distance for the main shocks, a foreshock, and aftershocks with moment magnitude as small as $M_W = 4.2$ (Ekström et al., 1998), show a remarkable consistency, indicating high coherence of the faulting process.

After a decrease in seismic activity, other significant shocks ($M_W \geq 4.5$) struck the same area in 1998, first in February and then in another crisis in March-April. Among these earthquakes, the strongest had magnitude 5.3, and was unexpectedly located in the mantle.

In this paper we expand on our previous studies of the earthquake sequence (Ekström et al., 1998; and Olivieri and Ekström, 1999). We add the events of 1998 to the general analysis, and address their relation with the earlier shocks. We extend the previous discussion on source characteristics and focal depths of the main earthquakes by interpreting seismological observations in view of newly available results of geodetic data modeling (Hunstad et al., 2000; Stramondo et al., 1999).

The technique of computation of seismic moment tensors by inversion of surface waves that we use has been previously employed by Arvidsson and Ekström (1998) to study seismic sequences in North America and Greece. We apply it here to a different receiver geometry, where nearly-realtime seismograms from closer seismographic stations are available (station AQU is less than 100 km from the epicentral area). Our goal is then also to test robustness and celerity of the regional CMT algorithm in view of its systematic the robustness and celerity of the regional CMT algorithm in view of its systematic application in a rapid-response manner.

Data and methods

We calculate seismic moment tensors by inverting long period seismograms. This is routinely done on a global scale by several research groups for events with magnitudes greater than approximately 5.5 (e.g., Ekström, 1994; Sipkin, 1994; Kawakatsu, 1995). The Harvard centroid moment tensor (CMT) method (Dziewonski et al., 1981; Dziewonski and Woodhouse, 1983) fits seismograms in two frequency bands. For moderate earthquakes, only long period body waves, low-pass filtered at 45 s, are matched, while for large earthquakes, with magnitude above $M_W = 6.0$, also mantle waves ($T > 135$ s) are included. Synthetic seismograms are computed by superposition of normal modes calculated for PREM (Dziewonski and Anderson, 1981) with corrections for 3D mantle structure. The CMT method has proved to be very reliable, and has produced an extensive global catalog of earthquake source mechanisms that is widely employed to characterize and quantify the seismic release of stress in active regions (e.g., Pondrelli et al., 1993). The magnitude threshold – about $M_W = 5.2$ – is determined by the signal to noise ratio at the seismic frequencies of interest at teleseismic distances.

In order to lower the magnitude of the earthquakes that can be studied, we need to use data characterized by higher signal to noise ratio. This can be accomplished by analyzing intermediate period ($35 - 135$ s) surface waves recorded at shorter epicentral distance (as shown, for instance, by Fukushima et al., 1989; Patton and Zandt, 1991; Romanowicz et al., 1993; Ritsema and Lay, 1993; Thio and Kanamori, 1995; Arvidsson and Ekström, 1998). At close distance, the seismogram is not yet dispersed and is dominated by the fundamental mode surface wave arrival (Figure 2), making it impossible to isolate the long period body waves used in the standard Harvard CMT algorithm (Dziewonski et al., 1981; Dziewonski and Woodhouse, 1983) and thus calling for a modification of the processing scheme. At larger epicentral distance it would also be convenient to model the fundamental mode surface waves for smaller magnitude earthquake analysis, because they have large amplitudes, but this has always proved to be difficult because of the high sensitivity of these waves to the usually poorly known heterogeneous structure of the crust and litho-

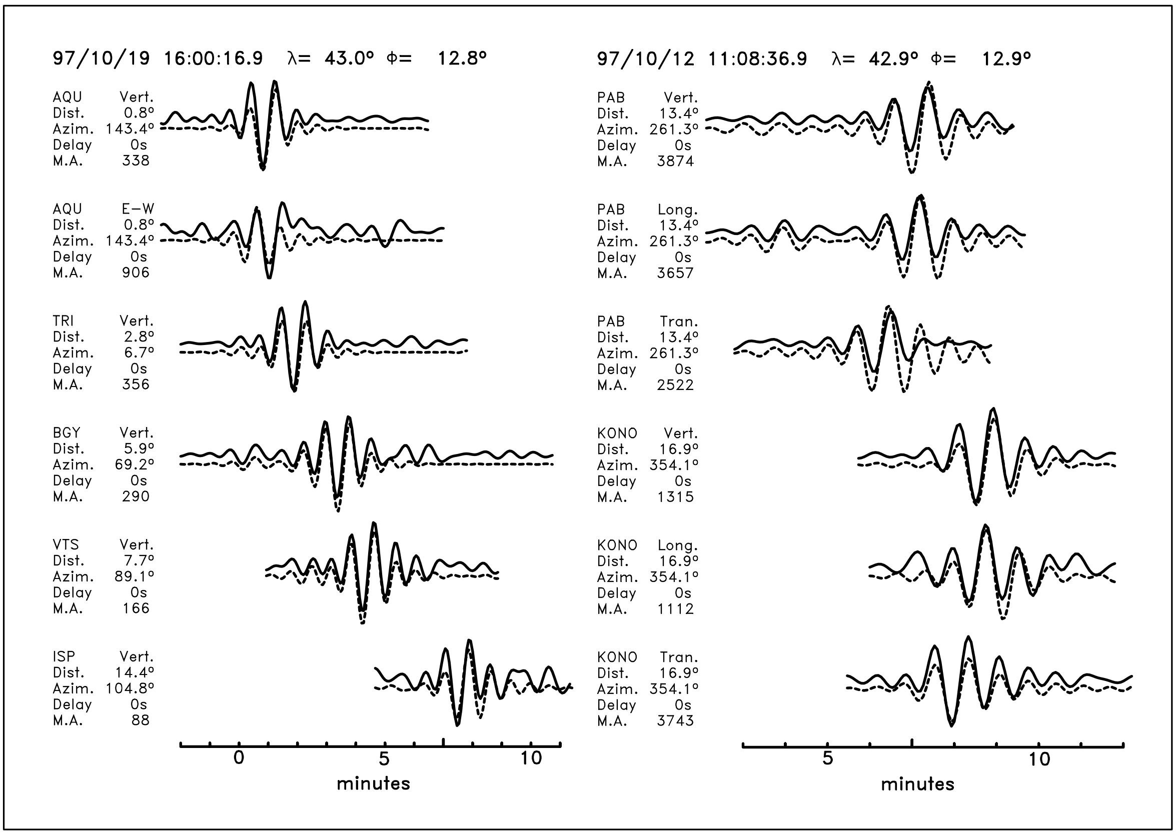

Figure 2. Left panel: example of waveforms recorded at regional distance for one of the smallest ($M_W = 4.2$) events analyzed. Right panel shows seismograms at two stations at farther distance (PAB in Spain, and KONO in Norway) for the October 12, $M_W = 5.2$, event. Each trace is labeled with station code (capital letters), component (vertical, longitudinal, or transverse), epicentral distance, and azimuth. Continuous lines plot filtered observed ground motion; dotted lines show synthetic seismograms calculated after inversion for source mechanism.

sphere where they propagate. Our approach follows the modified Harvard CMT algorithm described by Arvidsson and Ekström (1998) and Ekström et al. (1998). The complete waveform is included in the inversion. Higher order modes are computed as in the standard Harvard method by normal mode summation in a three-dimensional Earth model, but fundamental Love and Rayleigh modes are dispersed according to the high-resolution phase velocity maps by Ekström et al. (1997), which provide a global representation of heterogeneous wave propagation with unprecedented detail. The method was used in the preliminary analysis of the sequence by Ekström et al. (1998). We primarily use data from the very-broadband seismographic stations of the MEDNET Network (Figure 3), but also from the IRIS Global Seismic Network.

A new data retrieval system had just been activated and was operational during the 1997 central Italy earthquake sequence. This allowed timely computation of source mechanisms. The automatic system at the MEDNET data center is triggered by the occurrence of an earthquake and dials up field stations to retrieve waveform data for analysis (Mazza et al., 1998). The actual computation of regional moment tensors is not automatic, but it can in principle be run by an operator within approximately 30–45 minutes of the earthquake occurrence. The source mechanisms we present here have been revised and are based on an enriched dataset; however, they differ only slightly from those computed immediately following the events. A more detailed report of the robustness and effectiveness of the rapid regional moment tensor analysis, applied to the whole Mediterranean area for a longer time period, will be presented elsewhere.

Details of the earthquake source – such as source depth, source time function, and direction of rupture propagation – can be calculated by analysis of broadband P wavetrains recorded at teleseismic distance. The results shown here were obtained using the method of Ekström (1989), which was previously ap-

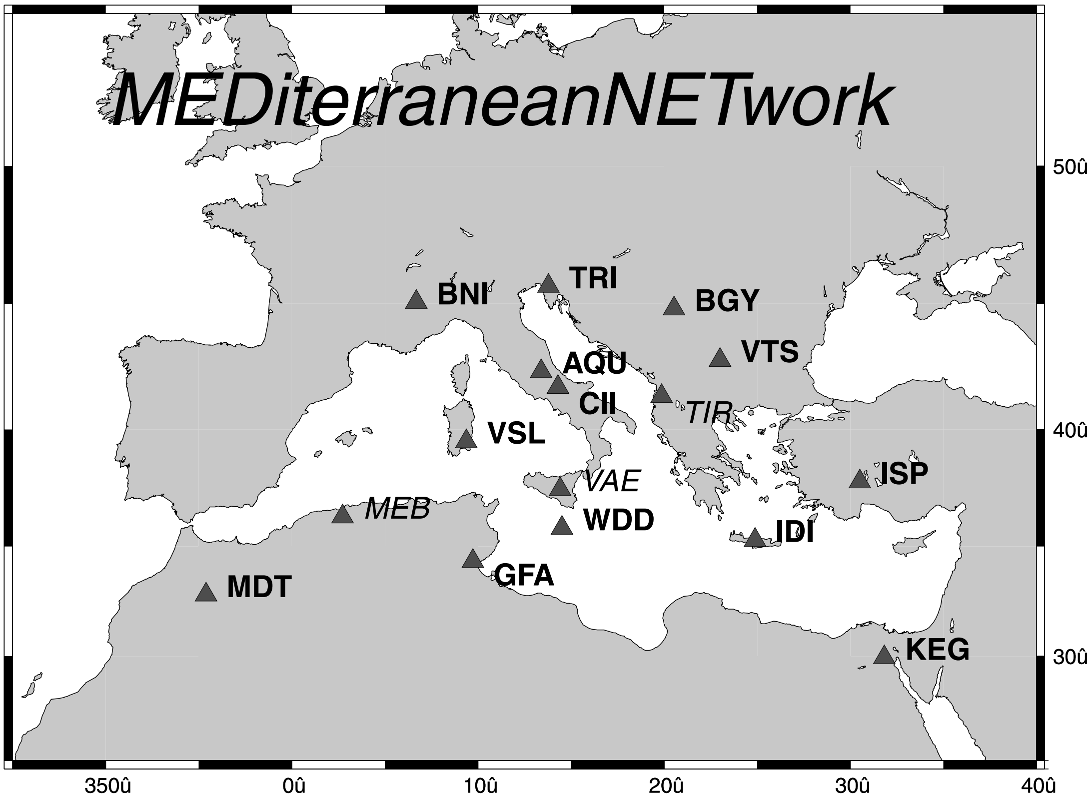

Figure 3. Map of stations of the Mediterranean very-broadband seismographic network MEDNET. Stations MEB (Medea, Algeria), TIR (Tirana, Albania) and VAE (Valguarnera, Sicily, Italy) were not operational during years 1997 and 1998.

plied to events in the central Italy sequence by Olivieri and Ekström (1999). The displacement pulses, filtered between 1 and 25 s, are fit using ray theory synthetic seismograms calculated in the Earth model PREM (Dziewonski and Anderson, 1981) with an appropriate crustal velocity model for the source region given by a 7 km thick shallow layer with $V_P = 5.15$km/s and $V_S = 2.71$ km/s overlying a 23 km thick layer with $V_P = 6.3$ km/s and $V_S = 3.31$ km/s.

Source parameters

The double-couple components of the moment tensors for all the earthquakes of the sequence that we studied are shown in Figure 4, using the usual convention of shading compressional quadrants of the lower hemisphere of the focal sphere. Source parameters are listed in Table 1. Only one focal plane per earthquake is recorded in the table for clarity: for all but two of the events we list the plane dipping to the SW and corresponding to the inferred orientation of the fault plane of the main event, described in the Introduction. Hypocentral depths of these events are in the shallow crust, except for the puzzling March, 26, 1998, event, located in the mantle at 51 km. The moment tensor inversion is not very sensitive to source depth, which we fix at 10 km in the analysis for the crustal events. The actual depth is better determined by the teleseismic broadband analysis, discussed below.

Regional centroid moment tensors for the 1997 events of the sequence have been published by Ekström et al. (1998). The shocks which followed in 1998, after a quiescence lasting a few months, were also strong: three had a magnitude larger than 5, were strongly felt and caused limited damage. The 1998 events did not modify two distinctive characteristics of this sequence: the uniformity of source geometries and the unusual time evolution, already apparent

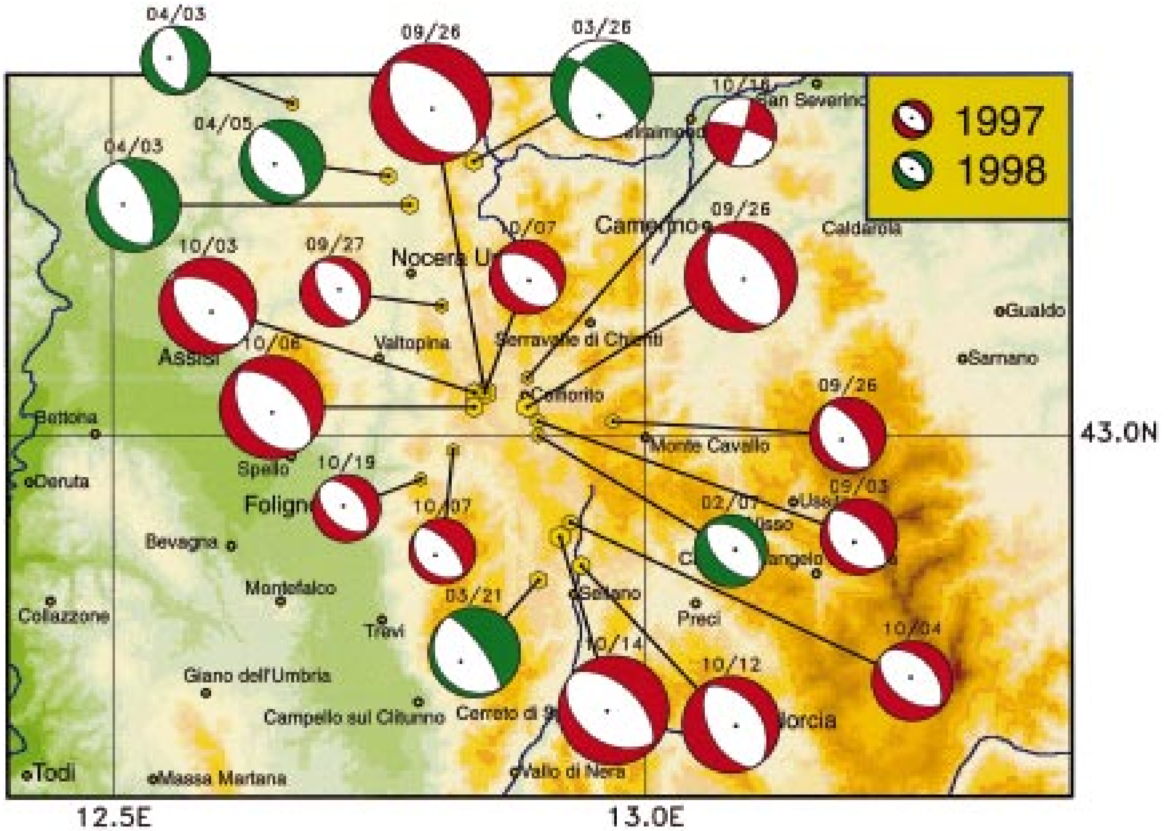

Figure 4. Moment tensor solutions for all the events analyzed (see Figure 1 for location). Double couple components of the moment tensors are shown. Each solution is labeled by its date (month and day). The radius of each focal sphere is proportional to the moment magnitude. Compressional quadrants are shaded in different colors to distinguish between 1997 and 1998 events.

in the first month of the sequence. With the exception of the March 26, 1998, $M_W = 5.3$ event, the new source mechanisms share the normal faulting geometry, with NE-SW extension, of previous events. The April, 1998, events are located at the NW end of the NW-SE trending epicentral area. It appears that the reactivation of the sequence can be directly connected to the stress regime responsible for the first month of earthquake activity, modified by the occurrence of previous earthquakes.

The time evolution of stress release of the sequence does not follow the common pattern of a mainshock followed by aftershocks with decaying frequency and magnitudes. Figure 5 shows this behavior by a graph of the scalar moments of the events, resulting from our analysis, as a function of days preceding and following the September 26, 1997, main shocks, and the cumulative moment released. Only the events that we have analyzed (with moments greater than approximately $2 \cdot 10^{22}$ dyne cm) are included. Even though the late events contribute less than 10% to the total moment release, they nevertheless raise questions concerning the character of mutual interaction and stress diffusion among different fault segments (see Cocco et al., 2000). Similar irregularities, and late reactivation of seismogenic structures, during an earthquake sequence, have been observed in other instances and in other areas of Italy, such as Western Sicily (Belice, 1968; see Anderson and Jackson, 1987) and the Eastern Alps (Friuli, 1976; see Pondrelli et al., 2000).

Figure 5 also shows the (approximate) minimum moment ($M_0 = 1 \cdot 10^{24}$ dyne cm) for an earthquake to have globally well recorded body waves, and to be studied using the standard Harvard CMT algorithm. The seven largest events of the Umbria-Marche sequence are included in the Harvard CMT Catalog (Dziewonski et al., 1998) and a comparison is therefore possible, as shown in Figure 6. The agreement is excellent, and it is slightly less than so only

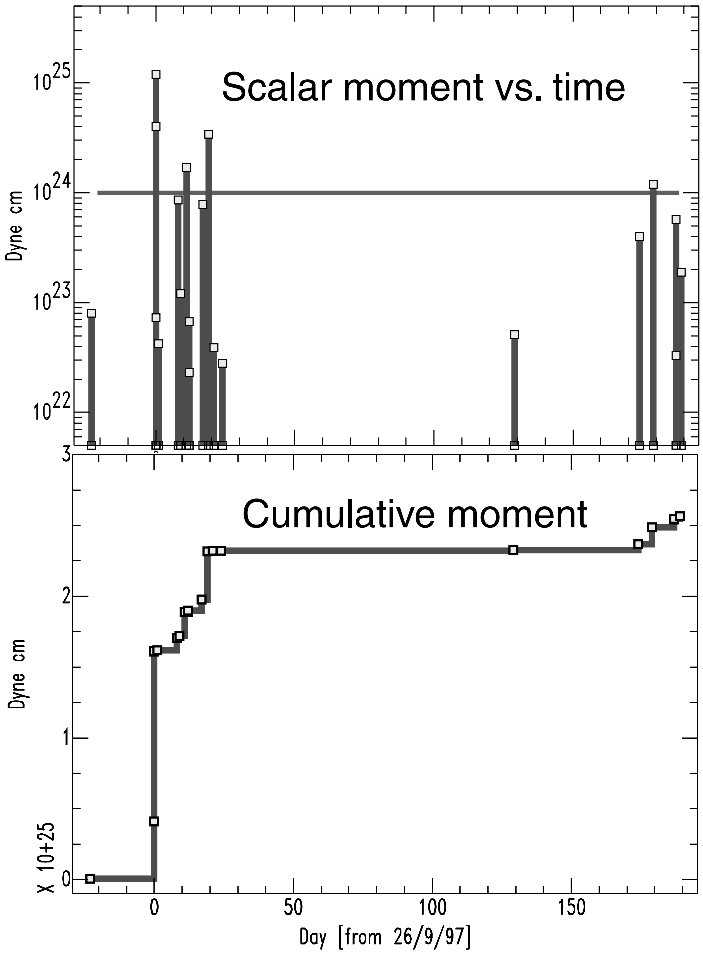

Figure 5. Scalar moments as a function of time. The dashed line in the top panel (corresponding to about 10^{24} dyne cm) represents the current approximate threshold for global centroid moment tensor analysis. Only events analyzed in this study are included (approximately above $2 \cdot 10^{22}$ dyne cm).

for the smallest of the events (100397 and 101297), which approach the minimum moment threshold for global analysis. We conclude that the regional CMT technique gives comparable results to those of the well-established, standard CMT analysis, at the same time allowing a considerable lowering of the energy threshold for events that can be studied.

Figure 6 gives an empirical, but conservative, estimate of the errors involved in our moment tensor inversion. Solutions in the two rows have been computed using partly different stations (local and regional-distance ones are only included in the regional CMT) and completely different portions of the seismograms (only body waves are used in the standard CMT inversion, while the regional technique is dominated by fundamental mode surface waves). As mentioned in section 2, synthetic seismograms are calculated following different approaches. We therefore think that the comparison, shown in Figure 6, is a significant measure of reliability of centroid moment tensor solutions.

The results of broadband modeling for the three strongest shocks are reported in Figure 7, which summarizes findings by Olivieri and Ekström (1999). Shaded radiation patterns correspond to mechanisms determined by the broad band inversion, and are super-

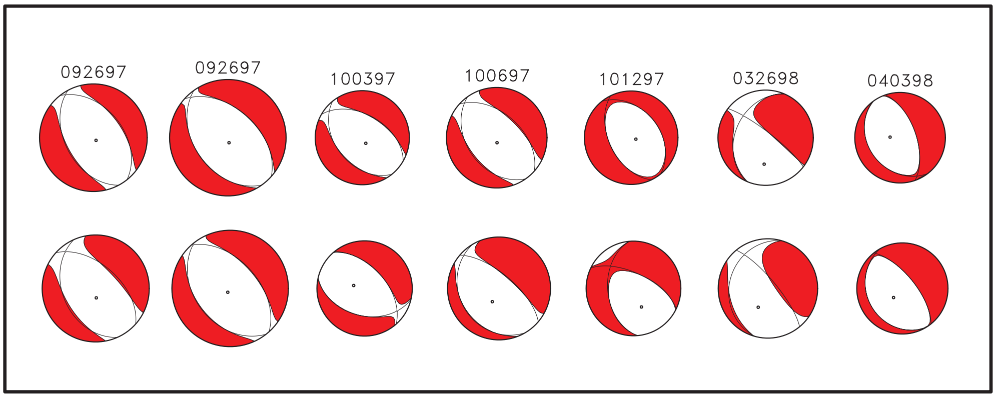

Figure 6. Comparison of regional CMTs (top) with CMT solutions from the Harvard catalog (bottom). Full moment tensors are plotted by grey shading. Best-fitting double couple solutions are shown by lines. Each earthquake is labeled with its date (see Table 1). The radius is proportional to magnitude.

Table 1. Earthquake focal parameters for the 20 strongest shocks of the sequence

Date	Time (UT)	Strike	Dip	Rake	M_0 dyne cm	M_W
09/03/97	22:07	137°	30°	–88°	8.0 · 10^{22}	4.54
09/26/97	00:33	152°	46°	–83°	4.0 · 10^{24}	5.67
09/26/97	09:40	144°	42°	–80°	1.2 · 10^{25}	5.99
09/26/97	13:30	147°	29°	–88°	7.3 · 10^{22}	4.51
09/27/97	08:08	148°	55°	–89°	4.2 · 10^{22}	4.35
10/03/97	08:55	141°	43°	–74°	8.6 · 10^{23}	5.23
10/04/97	16:13	125°	49°	–99°	1.2 · 10^{23}	4.66
10/06/97	23:24	145°	40°	–80°	1.7 · 10^{24}	5.42
10/07/97	01:24	126°	26°	–102°	2.3 · 10^{22}	4.18
10/07/97	05:09	141°	42°	–77°	6.7 · 10^{22}	4.49
10/12/97	11:08	154°	51°	–82°	7.8 · 10^{23}	5.20
10/14/97	15:23	122°	38°	–100°	3.4 · 10^{24}	5.62
10/16/97	12:00	287°	80°	175°	3.9 · 10^{22}	4.33
10/19/97	16:00	128°	44°	–103°	2.8 · 10^{22}	4.24
02/07/98	00:59	138°	55°	–84°	5.1 · 10^{22}	4.41
03/21/98	16:45	137°	15°	–97°	4.0 · 10^{23}	5.00
03/26/98	16:26	204°	38°	–21°	1.2 · 10^{24}	5.32
04/03/98	07:26	142°	30°	–106°	5.7 · 10^{23}	5.11
04/03/98	07:59	152°	33°	–108°	3.3 · 10^{22}	4.28
04/05/98	15:52	138°	31°	–98°	1.9 · 10^{23}	4.79

imposed on nodal lines representing the mechanisms from long period CMT analysis. For two of the events (September 26, 00:33, and October 14) the agreement between the different determinations is very good. They also show rather similar source time functions, with 5 seconds duration. The September 26, 09:40UT, event is shown to have a more complex source, with two subevents – the second being delayed by about 3 seconds – and having a rotated source mechanism. The first sub-source also shows evidence for rupture directivity up dip and to the north.

The earthquake of March 26, 1998, with moment magnitude 5.3, was located at a depth of 45 km based on local and regional travel times. The broadband analysis of this event (Figure 8) results in a depth of 51 km and a source mechanism consisting of a combination of normal faulting and strike-slip, with a NE-SW tension axis. The source duration is short compared to the other events, about 1 second, but this is not unusual for mantle earthquakes. This events also lacked aftershocks.

Discussion

With the exception of the March, 26, 1998, event, all earthquakes of the Umbria-Marche sequence were shallow. Data recorded by a dense temporary network, promptly installed after the main shocks (Amato et al., 1998), show that the aftershocks are located in the top 7–8 km of the crust, and delineate a SE-dipping fault plane. Stramondo et al. (1998) inverted SAR differential interferometry and GPS data for the two principal events of September 26, and inferred a maximum fault depth of 6.5–7 km, with a centroid of slip distribution located about 3–4 km below the surface. Their slip distribution has non-negligible values at shallow

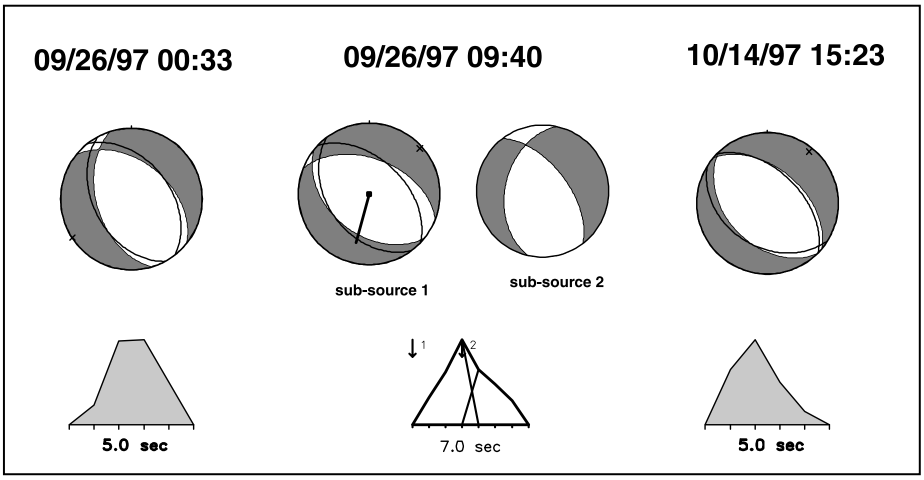

Figure 7. Broadband modeling of the three largest events of the sequence. For each event both the mechanism (above) and the source time function (below) that best fit the data are plotted. Shaded areas represent the preferred broad-band solution while the superimposed lines are the best double couple nodal planes of the CMT solutions. For the 9:40 event, the two sub-sources are displayed.

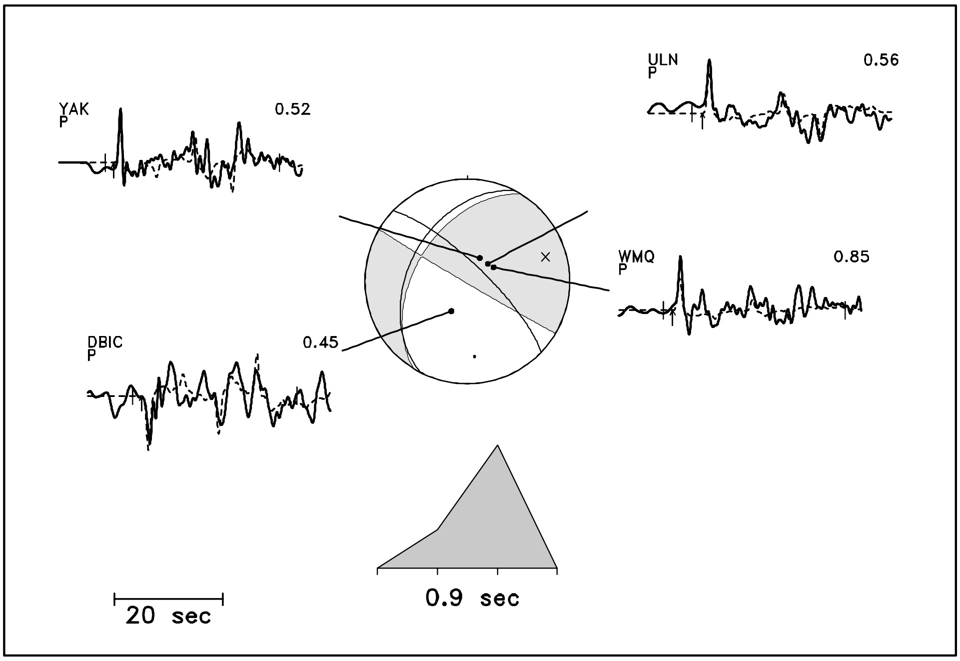

Figure 8. Broadband modelling of the mantle earthquake (26/03/1998). Synthetic seismograms (dashed) are calculated for our preferred source model. The lower hemisphere projection of the focal mechanism is presented together with the source time function. Dots plotted on the focal mechanism indicate the take-off points for each event-station ray path.

depths (< 1 km), but does not involve surface faulting. In agreement with Cinti et al. (1999) they suggest that the rupture stopped very close to the surface. This view is also consistent with seismological estimates. Broad band modeling for the two September, 26, events (Olivieri and Ekström, 1998) shows a best-fitting focal depth – to be interpreted as location of the centroid of moment release – of about 2 to 4 km. Short-period hypocentral determination puts the depth of nucleation at 6 km. This is in agreement with the model proposed by Olivieri and Ekström (1998), in which the first subsource nucleates at about 5.3 km and propagates updip with a velocity of about 1.3 km/s for 4 s, stopping at a shallow depth beneath the surface.

Figure 4 shows the remarkable consistency of source geometries for the events of the sequence. The only exceptions to the uniform normal faulting pattern are represented by the deeper, March 26, 1998, event and by the strike-slip mechanism of October 16, 1997. This shows that, at least down to $M_W = 4.2$, the individual events of the sequence ruptured structures with highly similar orientations. The largest earthquakes fit well in a model of elastic interaction in which each mainshock promotes the subsequent ruptures, but Coulomb stress modeling fails to explain some of the shocks close to the the major earthquakes of the sequence (Cocco et al., 2000). The strike-slip event can be interpreted as occurring on a structure which cuts the principal NW-SE striking normal fault system, a view supported by presence of significant shear structures in the region (Cello et al., 1998).

Subcrustal earthquakes have previously been observed in the northern-central Apennines (Selvaggi and Amato, 1992) but the March, 26, 1998, event is the strongest, and the southernmost, to be recorded to date. These intermediate-depth earthquakes have been postulated to be related to a descending lithospheric slab (Selvaggi and Amato, 1992) which is clearly imaged by tomographic models (Piromallo and Morelli, 1997). Both long period and body waveform inversion agree on a mechanism with normal and strike-slip components, and with a tension axis roughly orthogonal to the Apenninic chain. This would suggest the presence of tensile stress environment in the slab. The timing of this event is rather puzzling. It is in fact difficult to understand that stress changes originating by the shallow seismic activity could propagate to 45 km depth in 6 months. However, its occurrence during the shallow seismic sequence raises another point of interest for future research.

The technique for computation of centroid moment tensors by inversion of intermediate period surface waves recorded at regional distance (Arvidsson and Ekström, 1998; Ekström et al., 1998) has shown to be flexible, fast, and reliable. It allows for the computation of moment tensors for earthquakes with moment magnitude between 4.2 and 6.0, analyzing seismograms recorded at regional – down to less than 100 km – and teleseismic distance. Provided that they cover a fair azimuthal range, as few as 3 stations at distances of the order of 100's of kilometers were sufficient. Good agreement is found with the more established and known standard Harvard technique. The ability of calculating robust solutions also for intermediate magnitude earthquakes proves to be important for the study of complex sequences, such as the 1997-98 Umbria-Marche, and for the seismotectonic study of regions, such as the Mediterranean, where large earthquakes are not frequent. We plan to apply it routinely to the study of Italian and Mediterranean seismicity.

Acknowledgements

We wish to acknowledge discussions, suggestions, advice, and support of Enzo Boschi and Adam Dziewonski. We thank Salvatore Mazza and Silvia Pondrelli for their assistance in data retrieval and processing. One of us (M.O.) thanks the EPS Department of Harvard University for its hospitality. This work was partly funded by NSF Grant EAR-98-05172.

References

Amato, A., Azzara, R., Chiarabba, C., Cimini, G.B., Cocco, M., Di Bona, M., Margheriti, L., Mazza, S., Mele, F., Selvaggi, G., Basili, A., Boschi, E., Corboulex, F., Deschamps, A., Gaffet, S., Bittarelli, G., Chiaraluce, L., Piccinini, D. and Ripepe, M., 1998, The 1997 Umbria-Marche, Italy, earthquake sequence: a first look at the main shocks and aftershocks, *Geophys. Res. Let.* **25**, 2861–2864.

Anderson, H. and Jackson J., 1987, Active tectonics in the Adriatic region, *Geophys. J. R. Astr. Soc.* **91**, 937–983.

Arvidsson, R. and Ekström, G., 1998, Global CMT Analysis of Moderate Earthquakes $M_W \geq 4.5$, using Intermediate Period Surface Waves, *Bull. Seism. Soc. Am.* **88**.

Basili, R., Bosi, F., Galadini, F., Galli, P., Meghraoui, M., Messina, P., Moro, M. and Sposato, A., 1998, The Colfiorito earthquake sequence of September-October 1997: surface breaks and seismotectonic implications for the Central Apennines (Italy), *J. Earthquake Eng.* **2**, 1–12.

Boschi, E., Guidoboni, E., Ferrari, G., Valensise, G. and Gasperini, P., 1997. *Catalogo dei forti terremoti in Italia dal 461 a.C. al 1990*, Istituto Nazionale di Geofisica-SGA, Roma, pp. 644.

Cello, G., Deiana, G., Mangano, P., Mazzoli, S., Tondi, E., Ferreli, L., Maschio, L., Michetti, A.M., Serva, L. and Vittori, E., 1998, Evidence for surface faulting during the September 26, 1997, Colfiorito (Central Italy) earthquakes, *J. Earthquake Eng.* **2**, 303–324.

Cinti, F.R., Cucci, L., Marra, F. and Montone, P., 1999, The 1997 Umbria-Marche (Italy) sequence: relationship between ground deformation and seismogenic structure, *Geophys. Res. Let.* **26**, 895–898.

Cocco, M., Nostro, C. and Ekström, G., 2000, Static stress changes and fault interaction during the 1997 Umbria-Marche earthquake sequence, *J. of Seism., this issue.*

Dziewonski, A.M. and Anderson, D.L., 1981, Preliminary reference Earth model (PREM), *Phys. Earth Planet. Int.* **25**, 289–325.

Dziewonski, A.M. and Woodhouse, J.H., 1983, An experiment in the systematic study of global seismicity; Centroid moment tensor solutions for 201 moderate and large earthquakes of 1981, *J. Geophys. Res.* **88**, 3247–3271.

Dziewonski, A.M., Chou, T.-A. and Woodhouse, J.H., 1981, Determination of earthquake source parameters from waveform data for studies of global and regional seismicity, *J. Geophys. Res.* **86**, 2825–2852.

Dziewonski, A.M., Ekström, G. and Maternovskaya, N., 1998, Centroid-moment tensor solutions for October–December, 1997, *Phys. Earth Planet. Int.*, **109**, 93–1050..

Ekström, G., Tromp, J. and Larson, E.W., 1997, Measurements and global models of surface waves, *J. Geophys. Res.* **102**, 8137–8157.

Ekström, G., Morelli, A., Boschi, E. and Dziewonski, A.M., 1998, Moment tensor analysis of the central Italy earthquake sequence of September-October 1997, *Geophys. Res. Lett.* **25**, 1971–1974.

Fukushima, T., Suetsugu, D., Nakanishi, I. and Yamada, I., 1989, Moment tensor inversion for near earthquakes using long-period digital seismograms, *J. Phys. Earth* **37**, 1–29.

Kawakatsu, H., 1995, Automated near-realtime CMT inversion, *Geophys. Res. Lett.* **22**, 2569–2572.

Hunstad, I., Anzidei, M., Cocco, M., Baldi, P., Galvani, A. and Pesci, A., 2000, Modeling coseismic displacement during the 1997 Umbria-Marche earthquake (central Italy), *Geophys. J. Int.* submitted.

Mazza, S., Morelli, A. and Boschi, E., 1998, Near real-time data collection and processing at MEDNET, *EOS Trans. Am. Geophys. Soc.* **79**, F569.

Olivieri, M. and Ekström, G., 1999, Rupture depths and source processes of the 1997–1998 earthquake sequence in Central Italy, *Bull. Seismol. Soc. Am.* **89**, 305–310.

Patton, H.J. and Zandt, G., 1991, Seismic moment tensors of western U.S. earthquakes and implications for the tectonic stress field, *J. Geophys. Res.* **96**, 18245–18259.

Pino, A., Mazza, S. and Boschi, E., 1999, Rupture directivity of the major shocks in the 1997 Umbria-Marche (Central Italy) sequence from regional broadband waveforms, *Geophys. Res. Lett.* **26**, 2101–2104.

Pondrelli, S., Morelli, A. and Boschi, E., 1993, Seismic deformation in the Mediterranean area estimated by moment tensor summation, *Geophys. J. Int.* **122**, 938–952.

Pondrelli, S., Ekström, E. and Morelli, A., 2000, Seismotectonic reevaluation of the 1976 Friuli, Italy, seismic sequence, *J. of Seism.* in press.

Ritsema, J. and Lay, T., 1993, Rapid source mechanism determination of large ($M_W \geq 4.5$) earthquakes in western United States, *Geophys. Res. Lett.* **20**, 1611–1614.

Romanowicz, B., Dreger, D., Paysanos, M. and Urhammer, R., 1993, Monitoring strain release in central and northern California using broadband data, *Geophys. Res. Lett.* **22**, 1643–1646.

Sipkin, S.A., 1995, Rapid determination of global moment tenson solutions, *Geophys. Res. Lett.* **21**, 1667–1670.

Stramondo, S., Tesauro, M., Briole, P., Sansosti, E., Salvi, S., Lanari, R., Anzidei, M., Baldi, P., Fornaro, G., Avallone, A., Buongiorno, M.F., Franceschetti, G. and Boschi, E., 1999, The September 26, 1997, Colfiorito, Italy, earthquakes: modelled coseismic surface displacement from SAR interferometry and GPS, *Geophys. Res. Lett.* **26**, 883–886.

Thio, H.-K. and Kanamori, H., 1995, Moment tensor inversion for local earthquakes using surface waves recorded at TERRAscope, *Bull. Seism. Soc. Am.* **85**, 1021–1038.