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Moment tensor analysis of the central Italy earthquake sequence of September–October 1997

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Abstract.
The larger earthquakes in the Umbria–Marche (central Italy) seismic sequence of September–October 1997 are analyzed using long-period seismograms from the Mediterranean seismographic network (MEDNET) and additional data from the global seismographic network (GSN). We modify the Harvard centroid-moment tensor (CMT) algorithm to allow moment tensor inversion of long-period waveforms, primarily Rayleigh and Love waves, for small earthquakes at local to regional distances ($\Delta<15°$). For the three largest earthquakes ($M_W>5.5$) in the sequence, moment tensors have previously been determined using teleseismic waveforms and standard methods of analysis; our results agree well with those of earlier studies. We determine additional moment tensors for the largest foreshock and 10 aftershocks with $M_W>4.2$. The earthquakes are characterized by normal faulting mechanisms, with a NE–SW tension axis, and the presumed fault plane dips towards the SW. Only one of the fourteen events studied has a different faulting geometry, indicating instead right-lateral strike-slip faulting on a plane oriented approximately E–W, or left-lateral faulting on a plane oriented N–S. The September 26 mainshock (09:40 UT) accounts for only approximately $\sim$50% of the total moment release in the sequence.

Introduction

On September 26, 1997, two moderate (M_W=5.7 and M_W=6.0) but severely damaging earthquakes struck central Italy close to the town of Colfiorito near the border between the provinces of Umbria and Marche. The earthquakes were the most damaging to have occurred in Italy since the 1980 Irpinia (M_W=6.9) earthquake. The two earthquakes were part of a sequence which started with a M_L=4.7 foreshock on September 3, and which continued into October with strong aftershock activity, including a third damaging event (M_W=5.6) on October 14.

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The epicentral area is located in the central portion of the Apennines, a fold and thrust belt characterized by Quaternary extensional tectonics and a diffuse pattern of seismicity. The area has experienced destructive earthquakes in the past but none are known in the immediate vicinity of the 1997 sequence. Previous focal mechanisms show consistent extensional deformation, with an average direction of T axes around 40° [*Pondrelli et al.*, 1993].

The purpose of this paper is to determine the geometry of earthquake faulting in the 1997 sequence, and to provide robust estimates of the scalar moments of the events. These basic source parameters are of importance for investigations of the unusual spatial and temporal distribution of seismicity in this sequence which have already been noted (e.g., A. Amato et al., The 1997 Umbria-Marche, Central Italy earthquake sequence: a first look to main shocks and aftershocks, submitted to *Geophysical Research Letters*, 1998).

The three largest earthquakes in the Umbria–Marche seismic sequence have $M_W>5.5$, and were well recorded at seismographs around the world. In the hours following the two main events on September 26 (00:33 UT and 09:26 UT), seismograms were collected by various organizations through dial-up communications and via the global Internet, and moment tensors were determined and disseminated by Harvard University, United States Geological Survey, and the Earthquake Research Institute in Japan using established procedures [*Ekström*, 1994; *Sipkin*, 1994; *Kawakatsu*, 1995]. The remaining earthquakes in the sequence were generally too small to be analyzed by these standard methods.

For events with $M_W<5.5$, moment tensor analysis using teleseismic data is difficult. Both the modeling of broad band P and S waves and the inversion of the complete long-period bodywave wavetrain are limited by the level of seismic noise at typical GSN observatories. It generally becomes necessary to analyze the local and regional wavefield in order to determine focal mechanisms and scalar moments for earthquakes with $M<5.0$. Several methods for moment tensor analysis at short distances have recently been proposed and implemented, following the deployment of arrays of broadband seismometers in many different parts of the world. The

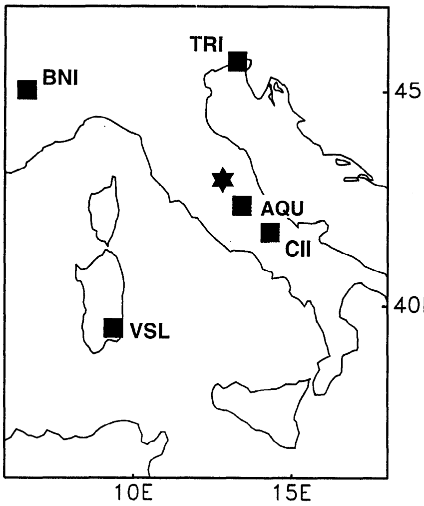

Figure 1. Map showing the location (solid star) of the September–October 1997 Umbria–Marche earthquake sequence in central Italy. Also shown are the locations (solid squares) of the five closest MEDNET stations. The stations AQL, TRI, and VSL were particularly useful in the analysis.

main challenge associated with the analysis of regional and local data, as compared with teleseismic data, is the significant regional variability of wave propagation. This complicating factor is, however, most pronounced at short periods; at long periods the wavefield remains relatively simple.

The Umbria–Marche sequence was well recorded on several MEDNET stations [*Boschi and Morelli*, 1994] located at distances of 80–1000 km from the epicentral area (Figure 1). In this study, we modify the standard Harvard CMT algorithm [*Dziewonski et al.*, 1981] to analyze the long-period waveforms recorded at these and additional GSN stations, and present focal mechanisms for the larger earthquakes in the sequence.

Method and Analysis

The CMT method is based on the linear relationship which exists between the observed long-period wavefield and the six independent elements of the moment tensor. The standard CMT algorithm matches the observed long-period ($T>$ 45 s) seismograms, which contain all body wave phases that arrive before the fundamental mode surface waves, with synthetic seismograms calculated by the summation of the Earth's normal modes. An iterative inverse procedure, which minimizes the misfit between observed and model seismograms, leads to an estimate of the moment tensor elements and a centroid location, which together provide the point source parameters which best predict the observed waveforms.

We make three modifications to the standard algorithm in order to apply it to data recorded at shorter distances: (1) The complete waveform, including the fundamental mode surface wave, is included in the inversion. Indeed, it is impossible to separate the surface waves from the body waves at long periods and short distances. (2) The dispersion effect of lateral heterogeneity on the fundamental mode surface waves is calculated from the global phase velocity maps of *Ekström et al.* [1997]. (3) The long-period cut-off period is shifted from 45 s to 35 s. This improves the signal-to-noise ratio of the data used in the inversion.

As a result of these modifications, our extended CMT method becomes similar to the regional centroid-moment tensor method developed and applied to earthquakes in the western US by *Ritsema and Lay* [1995]. These authors point out that at short distances the surface waves, which dominate the long-period seismogram, are not much distorted by the dispersion along the source–receiver path since propagation delays are very short. The correction for lateral variations in phase velocity (modification (2) above) is primarily important for longer paths ($\Delta>5°$). When the hypocenter is well known, the phase and amplitude of the surface waves can therefore be mapped into a source geometry without ambiguity. A limitation of our method is that the source excitation is calculated in the Earth model PREM [*Dziewonski and Anderson*, 1981], and not in a local velocity model. The thickness and structure of the crust in the central Apennines is, however, not sufficiently dissimilar from PREM to cause significant changes in the excitation of surface waves at the periods that we are considering ($T>35$ s). Since the long-period waveforms have limited sensitivity to the source depth, we fixed the depths of all events at 10 km, based on preliminary broadband modeling of the teleseismic P waves (M. Olivieri and G. Ekström, manuscript in prepa-

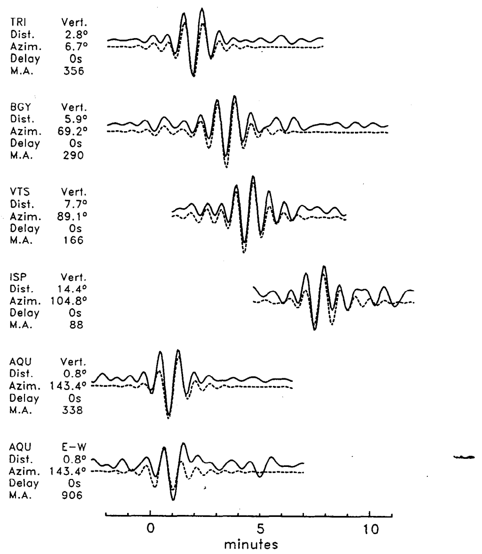

Figure 2. Comparison of observed (solid line) long-period waveforms and synthetic seismograms (dashed line) calculated for the CMT results determined for the for the M_W=4.3 aftershock on October 19. Long-period seismograms for MEDNET stations TRI (Trieste), BGY (Belgrade, Yugoslavia), VTS (Vitosha, Bulgaria), ISP (Isparta, Turkey), and AQU (Aquila) are shown, with the corresponding synthetic waveforms. The component, distance and azimuth to the station from the earthquake are given, as is the maximum amplitude in digital counts. The low-pass filter used in the CMT algorithm is not causal, which explains why the nearly monochromatic wave packets commence before the earthquake origin time.

Table 1. Earthquake Parameters

Date	Time (UT)	Strike	Dip	Rake	M_0 dyne-cm	M_W
09/03	22:07	137°	30°	−88°	$0.80 \cdot 10^{23}$	4.54
09/26	00:33	152°	46°	−83°	$0.40 \cdot 10^{25}$	5.67
09/26[a]	00:33	156°	38°	−71°	$0.38 \cdot 10^{25}$	5.66
09/26	09:40	144°	42°	−80°	$1.20 \cdot 10^{25}$	5.99
09/26[a]	09:40	142°	39°	−87°	$1.14 \cdot 10^{25}$	5.98
09/26[b]	09:40	143°	36°	−86°	$1.26 \cdot 10^{25}$	6.00
09/26	13:30	147°	29°	−88°	$0.73 \cdot 10^{23}$	4.51
09/27	08:08	148°	55°	−89°	$0.42 \cdot 10^{23}$	4.35
10/03	08:55	141°	43°	−74°	$0.86 \cdot 10^{24}$	5.23
10/04	16:13	125°	49°	−99°	$0.12 \cdot 10^{24}$	4.66
10/06	23:24	145°	40°	−80°	$0.17 \cdot 10^{25}$	5.42
10/07	01:24	126°	26°	−102°	$0.23 \cdot 10^{23}$	4.18
10/07	05:09	141°	42°	−77°	$0.67 \cdot 10^{23}$	4.49
10/12	11:08	154°	51°	−82°	$0.78 \cdot 10^{24}$	5.20
10/14	15:23	122°	38°	−100°	$0.34 \cdot 10^{25}$	5.62
10/16	12:00	287°	80°	175°	$0.39 \cdot 10^{23}$	4.33
10/19	16:00	128°	44°	−103°	$0.28 \cdot 10^{23}$	4.24

Only the nodal plane dipping towards SW is given.
[a]Standard CMT solution [*Dziewonski et al.*, 1998].
[b]Solution obtained using only AQU, TRI, and VSL.

ration, 1998) and aftershock locations (A. Amato, personal communication, 1998).

Seismograms for all earthquakes in the sequence with M_L>3.5 were collected from MEDNET and additional stations. For the largest event, a total of 122 seismograms from 42 stations were used in our inversion. For the smaller events we relied mainly on three MEDNET stations with relatively low noise levels: Villasalto (VSL; Δ=4.4°), L'Aquila (AQU; Δ=0.8°), and Trieste (TRI; Δ=2.7°; operated by University of Trieste and Osservatorio Geofisico Sperimentale). Two other MEDNET stations in Italy, Calitri (CII; Δ=1.7°) and Bardonecchia (BNI; Δ=4.9°) were less useful due to their higher noise levels. Figure 2 shows examples of waveform fits for one of the smallest earthquake (October 19, 1997) analyzed using the extended CMT method.

As a test of the performance of our method, we analyzed the largest event using a reduced data set consisting of seismograms only from the three stations AQU, VSL and TRI. We obtained essentially the same source parameters (see Table 1) as for the complete data set. For the two main events on September 26 our results are also very similar to those obtained in the standard CMT analysis [*Dziewonski et al*, 1998] using long-period body wave data recorded at teleseis-

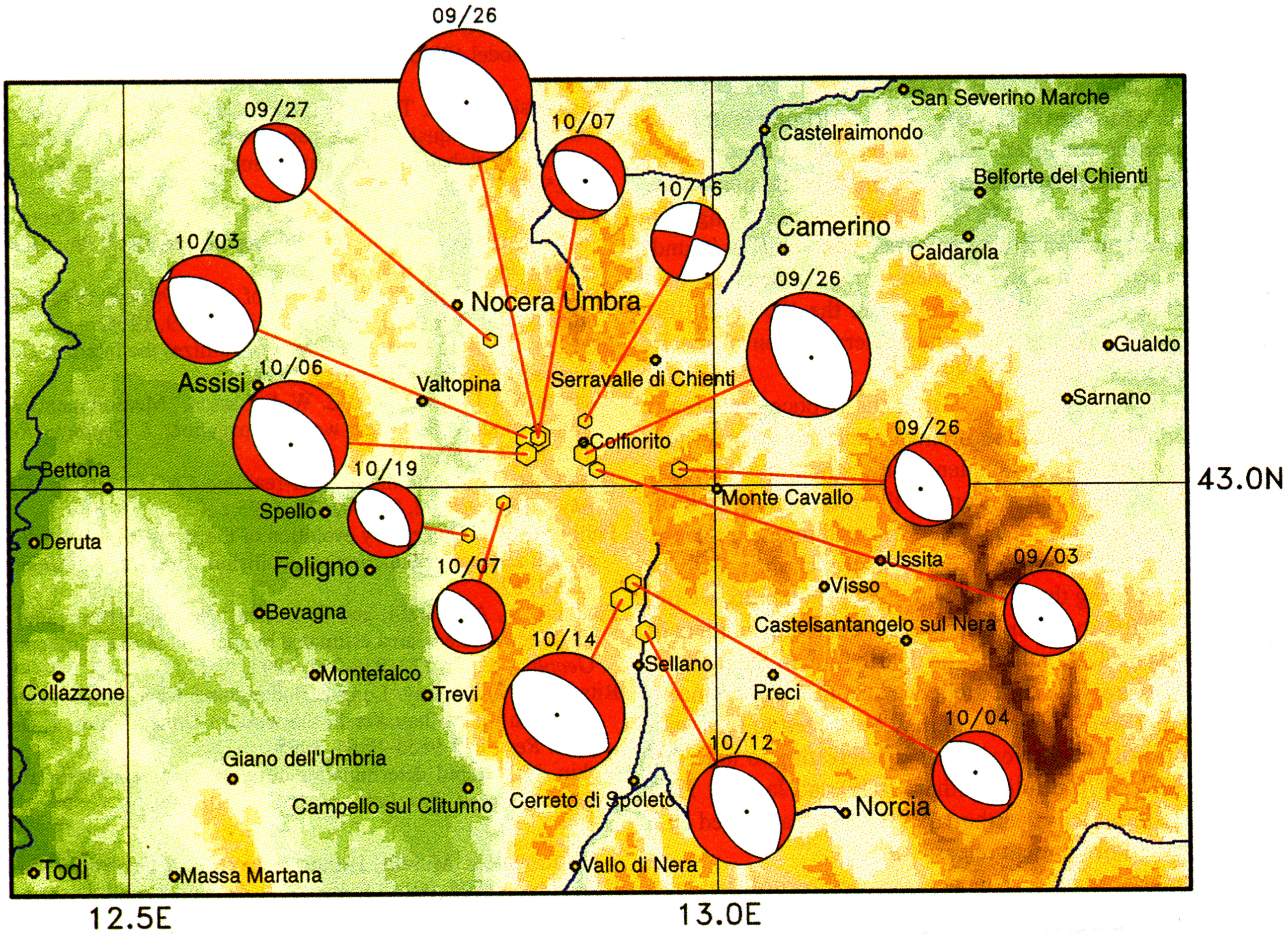

Figure 3. Map of the epicentral area, showing the focal mechanisms of the earthquakes analyzed in this report. The focal mechanisms are shown in lower hemisphere projection, with red color indicating tension at the source. Only the 'best double-couple' part of the moment tensors are shown, as the non-double components were small and most likely insignificant. The epicentral locations (A. Amato, personal communication, 1998) of the events are indicated by hexagons.

mic distances. The fault geometries agree to within 12°, and the scalar moments differ by less than 10% (see Table 1). We believe that the actual uncertainties in our calculations are similar in magnitude to theses differences, and that the comparison suggests that the results obtained from regional data are robust. The results of the moment tensor analysis are summarized in Table 1 and Figure 3. The non-double couple component of the moment tensors was small (<15%) for all events analyzed. Geological, macroseismic, and aftershock data strongly suggest that the SW-dipping nodal plane is the fault plane in the larger events, and only the SW-dipping plane is listed in Table 1.

Discussion

The focal mechanisms for 13 of the analyzed earthquakes indicate normal faulting on NW–SE striking fault planes with tension axes oriented in the range 40°–60°, roughly perpendicular to the strike of the Apennines. This geometry is consistent with tectonic models relating the crustal extension to rotation of the Adriatic microplate [e.g., *Anderson and Jackson*, 1987] or to flexural extension of the upper part of the mountain chain [*Philip*, 1987].

Only one of the larger aftershocks in the sequence was found to have a focal geometry which is significantly different from that of the main event. This earthquake, on October 16, has a strike-slip mechanism corresponding either to right-lateral faulting on an E–W striking fault, or left-lateral faulting on a N–S striking plane. A N–S striking fault plane for this event is consistent with the geological observations of significant shear structures of a similar orientation in the region [e.g., *Cello et al.*, 1997]. However, E–W striking seismogenic structures may also be expected to exist at boundaries between sub-parallel segments of the Apenninic normal faults as observed, for example, for the 1990 and 1991 Potenza earthquakes at the southern termination of the Irpinia earthquake [*Ekström*, 1994].

The strain release in the crust in the hypocentral area is proportional to the seismic moment, and the moment tensor. In most earthquake sequences the strain is completely dominated by the largest event of the sequence, which often accounts for more than 95% of the total moment release. Summing up the moment released in the Umbria–Marche sequence, omitting the main event on September 26, we obtain 1.12×10^{25} dyne-cm, nearly identical to the moment of the main event, 1.20×10^{25}. The distribution of the moment release in several events of moderate size instead of concentrating it in a single large event may be related to the structural complexity of the region. It is interesting to note that both the May 1976 Friuli (northern Italy) and January 1968 Belice (western Sicily) earthquakes were characterized by a similar pattern of moment release.

The Umbria–Marche sequence was well recorded at teleseismic and regional distances. The application of an enhanced version of the Harvard CMT algorithm to the smaller events of the sequence has shown that robust results for fundamental source parameters can be obtained from the relatively sparse distribution of MEDNET stations in and around Italy. Events as small as M_W=4.2 were successfully analyzed, where this moment magnitude on average corresponds to an ING magnitude of M_{ING}=3.7. By further extending the period range of the analysis to shorter periods (~25 s), and considering data from a somewhat denser Italian broadband network, it is likely that moment tensors could routinely be derived for earthquakes in and around Italy with $M_{ING} \geq 3.5$.

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