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Short Notes

Rupture Depths and Source Processes of the 1997–1998 Earthquake Sequence in Central Italy

by Marco Olivieri and Göran Ekström

Abstract The focal depths and the rupture processes of four moderate earthquakes, which occurred in central Italy during 1997 and 1998, are investigated using broadband teleseismic data. The earthquakes, the largest with M_W = 6.0, caused significant damage in the epicentral area and are part of an unusual sequence of moderate-sized earthquakes to strike the central Apennines. For three of the events, the waveforms are found to be consistent with seismic ruptures confined to the top 5 to 7 km of the crust. Directivity effects are evident in the waveforms of the largest earthquake, and waveform inversion suggests an upward rupture with a horizontal component oriented toward the north. One earthquake (M_W = 5.2) is confirmed from waveform modeling to have occurred at 50 km depth. This is the first event of this magnitude to have been located in the mantle beneath the Apennines.

Introduction

The seismicity of the Apennines is historically high and characterized by moderate and large earthquakes occurring in the crust beneath the crest of the mountain chain. Focal mechanisms of larger earthquakes indicate primarily normal dip-slip motion on faults with strikes parallel to the mountain chain (Valensise *et al.,* 1993). In September and October of 1997, and continuing into 1998, a seismic sequence occurred in the central part of the Apennines. It consisted of three main earthquakes with magnitudes between 5.6 and 6.0 and numerous aftershocks and caused extensive damage in the provinces of Umbria and Marche (Amato *et al.,* 1998). The focal geometries and seismic moments of the mainshocks and several large aftershocks have been studied by Ekström *et al.* (1998), and the events are characterized by normal faulting mechanisms with a tension axes oriented in the azimuth range 40° to 60°.

The epicenters of the two first large events, on 26 September at 00:33 UT (M_W = 5.7) and 09:26 UT (M_W = 6.0), have been located within 2 km of each other near the town of Colfiorito (see Fig. 1). The third large earthquake (M_W = 5.6) occurred on 14 October, approximately 15 km south of Colfiorito and outside the area of principal aftershock activity following the earlier events.

After months of declining aftershock activity, the region again experienced several events with magnitudes 4.5 $\leqq M \leqq$ 5.2 in March and April of 1998. The largest (M_W = 5.2) occurred approximately 20 km north of Colfiorito. The hypocenter determined by Istituto Nazionale di Geofisica (ING) locates the event in the mantle, at approximately 45 km depth.

The macroseismic observations and aftershock distributions for the three largest events suggest differences in their rupture characteristics. The first main earthquake in the sequence (26 September, 00:33) was followed by aftershocks mostly concentrated southeast of the mainshock epicenter, while the second (26 September, 09:40) was followed by aftershocks mainly toward the north and northwest (Amato *et al.,* 1998). The second event also caused most of the destruction northeast of the epicenters. The third main event (14 October) was felt in much of southern Italy, in contrast to the earlier two large events, and most of its aftershocks locate to the southeast of the epicenter (Amato *et al.,* 1998).

Following the deployment of portable stations by ING and other groups, it was seen that most of the aftershock activity was confined to depths shallower than 10 km, with a majority of the events occurring shallower than 6 km. Estimates for the hypocentral depths for the main events based on the ING national network and various local deployments are 6.9 ± 1.1 km, 8.0 ± 3.6 km, and 6.3 ± 0.4 km (Amato *et al.,* 1998). The observation that the earthquakes may have caused small amounts of surface displacement on mapped faults (Cinti *et al.,* 1998) also suggests that the ruptures may primarily have been directed upward. If the slip area is confined between the hypocentral depth and the Earth's surface, this would imply that the ruptures are shallower than many that have been reported for earlier events of similar size in the Apennines. For example, average depths for the moment release have been estimated from waveform modeling for the 1980 Irpinia (M_W = 6.9) earthquake at around 10 km

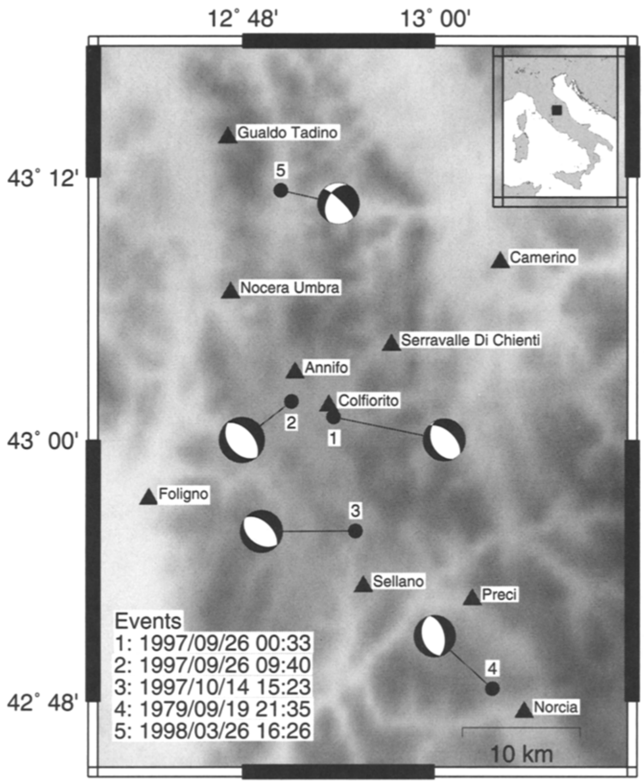

Figure 1. Map of the epicentral area showing the locations and the CMT focal mechanisms for the five earthquakes discussed in this report. The focal mechanisms are shown in lower hemisphere projection, with black color indicating tension at the source. The darker grays of the background correspond to higher elevations.

[for example, by Westaway (1992) and Giardini (1990)]; for the 1980 Lazio-Abruzzo ($M_W = 5.7$) earthquake at 10 km (Westaway *et al.,* 1989); and for the 1990 Potenza ($M_W = 5.4$) earthquake at 11 km (Ekström, 1994). In addition, centers of slip distributions have been estimated from aftershock locations for the 1984 Perugia ($M_W = 5.7$) earthquake at around 5 km (Haessler *et al.,* 1988) and for the 1979 Norcia ($M_W = 5.8$) earthquake at 6 km (Deschamps *et al.,* 1984).

In this report, we investigate the basic rupture characteristics of the larger events in the Umbria sequence using teleseismic data. The main objective is to determine the depth distribution of slip in the larger events and to examine possible evidence for rupture directivity. Our main result, that these earthquake ruptures are confined to the top few kilometers of the crust, motivated us to re-examine the focal depth of the $M_W = 5.6$, 1979 Norcia earthquake, the most recent earlier earthquake to have caused damage in the region.

Data and Analysis

We use data recorded on the IRIS Global Seismographic Network and model teleseismic *P*-wave phases using the method of Ekström (1989). In this algorithm, the teleseismic broadband waveforms are used in an inversion for focal mechanism, source depth, source time function, and the direction of rupture propagation. The inversion is stabilized by inclusion of long-period estimates of the point-source moment tensor elements (together with their covariance matrix) obtained from a standard Harvard centroid-moment tensor (CMT) analysis (Dziewonski *et al.,* 1981). The joint analysis will therefore preferentially produce source models that are compatible with both the broadband teleseismic waveforms and the long-period data used in the CMT analysis.

The waveforms used in the analysis are filtered to resemble broadband displacement pulses by deconvolution of the instrument transfer function. The displacement pulses are filtered between 1 Hz and 25 sec to remove long-period background noise and high-frequency signals that we do not model. Synthetic *P*-wave seismograms are calculated using ray theory in the Earth model PREM (Dziewonski and Anderson, 1981). Reflections and conversions near the source are included in the calculation using a layer matrix method for a flat-layered crustal model consisting of a 7-km-thick shallow crustal layer ($V_P = 5.15$ km sec^{-1}, $V_S = 2.71$ km sec^{-1}) overlying a 23-km-thick second crustal layer ($V_P = 6.30$ km sec^{-1}, $V_S = 3.31$ km sec^{-1}) and a standard mantle. This model is a good approximation for the crustal structure beneath the Central Apennines (G. Selvaggi and M. Di Bona, personal comm., 1998). All modeled crustal earthquakes were found to be located in the shallow layer.

Event 1: 26 September, 00:33 UT

We edited all available teleseismic *P* waves for the event and selected nine records with a good azimuthal distribution and high signal-to-noise ratio (Fig. 2a). We find it preferable to select a subset of good records from the total set available, particularly when the signal-to-noise ratio is low and it becomes difficult to pick onset times. Even at the best stations, the signal level for the *P* displacement pulse is low, around 1 μ at most stations. Qualitative characteristics make it clear that the source is very shallow: a very brief initial downward swing corresponding to the direct *P*, and the broad and larger upswing caused by the surface-reflected phases *pP* and *sP*. The point source inversion finds a best-fitting solution at 1.5 km depth with a source duration of 5.0 sec. The focal mechanism is very similar to the CMT solution assumed *a priori* (Fig. 2a). The preferred source depth is stable when the damping toward the CMT solution is reduced.

The fits to the waveforms are adequate, but generally not as good as for many other continental events of similar size that have been modeled using the same method (Ekström, 1987). We do not fully understand why this is so, but one possibility is that the submoho structure beneath the Apennines introduces phase conversions and complexity in the teleseismic waveforms.

In order to estimate the uncertainty in our depth estimate, we calculate the data misfit for a range of depths and

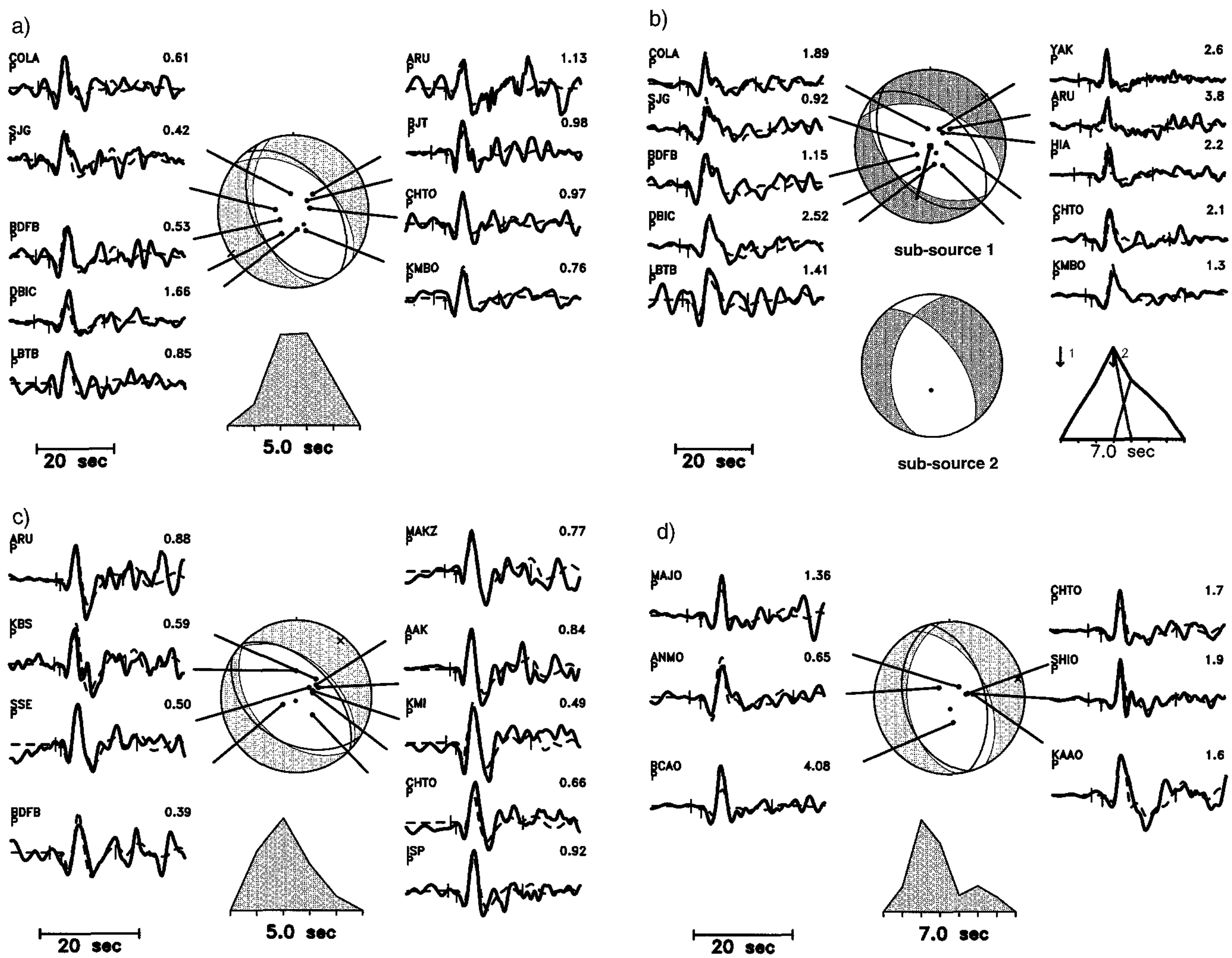

Figure 2. Observed (solid) and synthetic (dashed) seismograms calculated for our preferred source models. For each event, the lower hemisphere projection of the focal mechanism is presented together with the shape and the duration of the source time function. The shaded radiation pattern corresponds to the mechanisms determined in the broadband analysis of the *P* waves. The second set of nodal lines corresponds to the best double couple of the long-period CMT solution. Dots plotted on the focal mechanism indicate the take-off points for each event-station ray path. The arrow indicates the picked *P*-wave arrival time, and the solid vertical lines, indicate the portion of the waveform used in the inversion. The maximum amplitude in each pair is indicated in microns. (a) The 26 September, 00:33 UT earthquake. (b) The 26 September, 09:40 UT earthquake. We show the mechanisms of both subsources, and the projection of the directivity vector for the first subsource is also shown. The source time function shows the contributions of each subsource. (c) The 14 October earthquake. (d) The 19 September 1979 earthquake.

also inspect the corresponding waveforms (Fig. 3a). This is done by keeping the depth fixed and inverting for the focal mechanism and the source time function. The misfit curve has a well-defined minimum and the misfit grows rapidly for depths shallower than 1.5 km. The fit deteriorates more slowly for greater source depths, but a clear misfit in the onset of the up-swing becomes apparent for depths greater than 4 km. We therefore believe that the center of slip is located in the depth range 1 to 4 km.

No clear variability in the width and amplitude of the waveforms as a function of azimuth or take-off angle is apparent in the data, and we do not achieve any reduction in misfit when we include simple source directivity in the inversion, which also results in a negligible rupture velocity.

Event 2: 26 September, 09:40 UT

Approximately 9 hours after the 00:33 event, a second, stronger earthquake occurred a few kilometers to the northwest. Two observations suggest a complex rupture process for the 09:40 event. First, there are visible differences in the

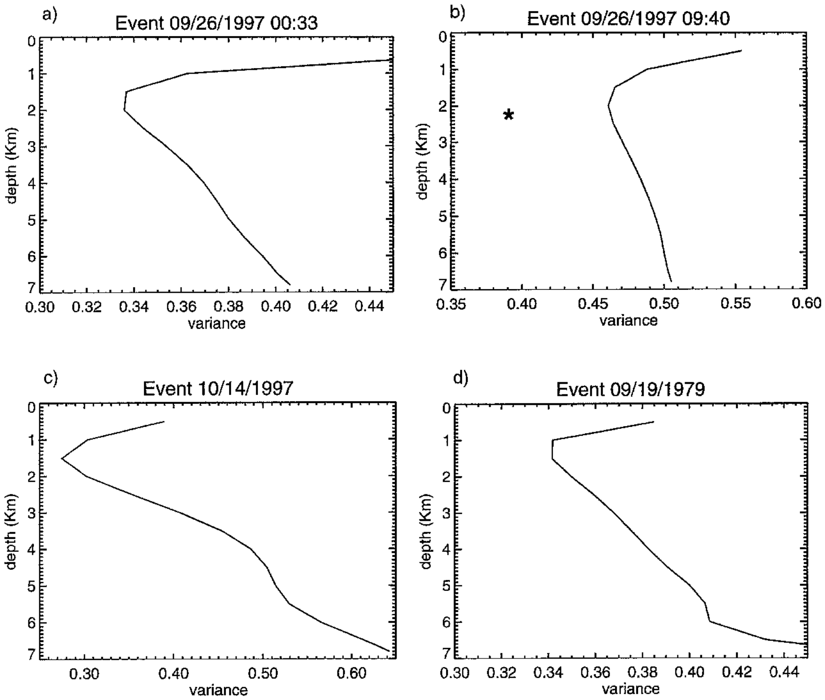

Figure 3. The residual variance after fitting the selected broadband records is plotted as a function of the depth for each of the four crustal earthquakes. (a) The 26 September, 00:33 UT earthquake. (b) The 26 September, 09:40 UT earthquake. The curve corresponds to the inversions for a single point source of 7-sec duration. The star indicates the misfit of our preferred solution obtained inverting for two separated subsources. (c) The 14 October earthquake. (d) The 26 September 1979 earthquake.

Table 1

Source parameters. For event 2, both the subsource parameters are listed.

Date	Strike	Dip	Slip	Preferred Depth (km)	Depth Range (km)	M_0 (dyne-cm)	Duration (sec)
09/26/97 00:33	163°	49°	−66°	1.5	1 ÷ 4	0.39×10^{25}	5.0
09/26/97 09:40	129°	43°	−77°	5.3*		0.51×10^{25}	4.0
	193°	43°	−47°	1.75†		0.39×10^{25}	4.0
10/14/97 15:23	126°	39°	−95°	1.5	1 ÷ 5	0.33×10^{25}	5.0
09/19/79 21:35	174°	43°	−73°	1.4	1 ÷ 5	0.77×10^{25}	5.0
03/26/98 16:26	122°	89°	138°	50.9	47 ÷ 55	0.11×10^{25}	0.9

*Nucleation depth of the first subsource.

†Depth of the second subsource while the centroid depth for the combined source is 2.0 km and its range of depth is 1 ÷ 5 km.

widths and amplitudes of the *P* phases recorded in opposite azimuths with respect to the epicenter (Fig. 2b). For example, the *P* wave at the station ARU (Arti, Russia), located in the northeastern quadrant with respect to the earthquake, is much compressed compared to the phase recorded at DBIC (Ivory Coast) in the southwestern quadrant. Second, the analysis of the regional body waveforms collected by the MEDNET stations in the distance range 80 to 400 km suggests the presence of two subsources (N. A. Pino and S. Mazza, unpublished manuscript, 1998).

Our attempt to invert the source parameters for a simple point source resulted in a preferred depth of approximately 2 km. The depth versus misfit (Fig. 3b) curve indicates that the likely centroid depth lies in the range 1 to 4 km. The point source solution does not generate synthetic waveforms that provide a good fit to the pulse widths noted above, and we initially attempted to invert the data using a propagating point source representation. In this case, the source is allowed to propagate in an arbitrary direction during the period of moment release. Such a source model allows us to fit the different pulse widths, but the resulting directivity vector has an unrealistic value of 8 km sec^{-1}. In addition, this solution does not model the phase following the large upward *pP–sP* phase that is apparent especially at BDFB, DBIC, COLA, and SJG with a delay of about 6 to 7 sec from the initial *P*-wave onset. After many attempts, we found that the noticeable discrepancies between data and synthetics generated by a single point source could be overcome in part by splitting the moment release in two separate subsources. A two-source model increases the number of free variables of the problem, and it becomes impossible to constrain all variables from the waveform data. We choose instead to combine a forward modeling approach, fixing some of the variables *a priori,* and inverting for the remaining subset of variables. We will not in this way find a unique solution, but we may be able to explore solutions that are consistent with the observations and that are simultaneously supported by other lines of evidence. Our assumed solution initiates at 6 km depth and has a directivity vector oriented toward the north and up-dip. A second subsource initiates 3 sec after the first subsource at 2 km depth, and we keep the depth of this event fixed in the inversion and do not allow it to have a separate directivity vector. The simultaneous inversion of the moment releases, focal mechanisms, source depth, and source directivity gives our preferred solution, shown in Figure 2b. The first subsource nucleates at 5.3 km and has a directivity vector with up, north, and east components (1.36, 2.29, 0.60) km sec^{-1}. The second subsource has a source depth of 1.75 km.

The proposed two-source model gives a 20% better fit to the data than the single point source (Fig. 3b). In particular, we obtain a good fit to the larger phase that is the result of the interference of the *pP* and *sP* phases of the first source and the direct *P* of the second one, for the stations COLA and YAK. Our source model generally reproduces well the waveform broadening of the southwestern stations. At stations SJG and BDFB, the second compressional arrival, which could not be modeled with a single source, is now well reproduced. The worst agreement is found at LBTB, but this is also a station with high background noise. The centroid depth of moment release for the combined sources is 2.0 km.

Event 3: 14 October, 15:23 UT

The third large event of the sequence occurred on 14 October, nearly 3 weeks after the two mainshocks. We selected nine *P*-wave records to model for this event and obtained a point source depth of 1.5 km (Fig. 2c). The depth–misfit diagram (Fig. 3c) indicates that the earthquake had its center of moment release in the depth range 1.0 to 5.0 km. Though the observation that this event was felt in a large part of southern Italy could suggest a southward rupture directivity, we find no evidence in the *P* waves supporting this. This is not necessarily surprising because the earthquake was relatively small.

The 19 September 1979 Norcia Earthquake

The shallow source depth obtained for the three main events of the 1997 Umbria earthquake sequence motivated us to examine the depth of the 19 September 1979 Norcia earthquake. This event was located approximately 30 km to the south of the 1997 sequence and had a similar magnitude to those of the mainshocks.

To model the source parameters, we use the few digital data available for 1979 from the GDSN network. Broadband waveforms, not directly recorded at that time, were reconstructed by splicing together data from short- and long-period channels using the technique of Choy and Boatwright (1981). Our data set consists of six reconstructed broadband *P* waveforms, with a relatively poor azimuthal distribution (Fig. 2d). The inversion yields an optimal depth at 1.4 km. The depth–misfit curve suggests that the center of moment release lies between 1.0 and 5.0 km.

Discussion

The broadband modeling for the three main earthquakes of 1997 and the 1979 Norcia earthquake lead to estimates of the slip centroids in the depth range 1.4 to 2.9 km. For very shallow sources ($h < 4$ km), the precise estimation of depth using teleseismic *P*-wave modeling is difficult. The time delay between the direct and reflected phases is short, of the order of 1 sec, and most of the waveform is therefore shaped by the complex superposition of direct and reflected phases. In addition, the selection of the arrival time of the direct phase can easily influence the depth determination. Based on the misfit curves shown in Figure 3, and qualitative aspects of the corresponding waveform fits, we believe that it is unlikely that the slip and moment centroids are deeper than 4 km for any of the four events.

The reported hypocentral depths for the Umbria events are deeper than 6 km (Amato *et al.,* 1998); we also obtain depths greater than 5 km when we pick onset times of *P* and *pP* on the raw broadband seismograms and directly estimate the depths of rupture nucleation. This implies that the ruptures in these events primarily extended upward. The modeling of the *P* waves only directly support this for the largest earthquake. This is not surprising, because for moderate and shallow earthquakes, it is generally difficult to isolate the effect of directivity from the complexity introduced by the local structure and the variable rate of moment release.

Geodetic investigations support the unusually shallow source depths obtained from the broadband *P* waves. Stramondo *et al.* (1998) modeled the ground deformation caused by the first two main earthquakes using ERS-SAR interferograms and GPS displacement vectors. The SAR image shows a narrow, elongated depression with a strike consistent with the orientation of the fault strike. The width of the depression provides a strong constraint on the down-dip width of the slipped portion of the fault. The preferred model of Stramondo *et al.* (1998) puts the slip centroids for the two events between 3 and 4 km depth.

The 26 March 1998 Mantle Earthquake

Six months after the largest events of the sequence, an $M_W = 5.2$ occurred approximately 20 km to the north of Colfiorito and was felt throughout central Italy. The event was located at 45 km depth and therefore belongs to the class of mantle earthquakes identified by Selvaggi and Amato (1992) beneath the central and northern Apennines and associated by them with a buried lithospheric slab. The 1998 event is the largest such event identified, and we were able to model a small number of teleseismic *P* waves to confirm the mantle depth.

Figure 4 shows the resulting waveform fits. The reflected arrivals are well separated from the direct *P*, and although there are several unmodeled details in the seismograms (in particular at the station WMQ), we believe that we have properly matched the main arrivals. The focal mechanism corresponds to a combination of strike-slip and normal faulting with a tension axis approximately perpendicular to the Apenninic chain. This is in agreement with previous focal mechanisms reported by Selvaggi and Amato (1992), who noted a change from compressional mechanisms beneath the northern Apennines to extensional ones beneath the central portion of the mountain chain.

Conclusions

Waveform modeling of teleseismic *P* waves provide strong evidence that the main moment release and slip in recent major earthquakes in central Umbria is concentrated at very shallow depth in the crust. This may be contrasted

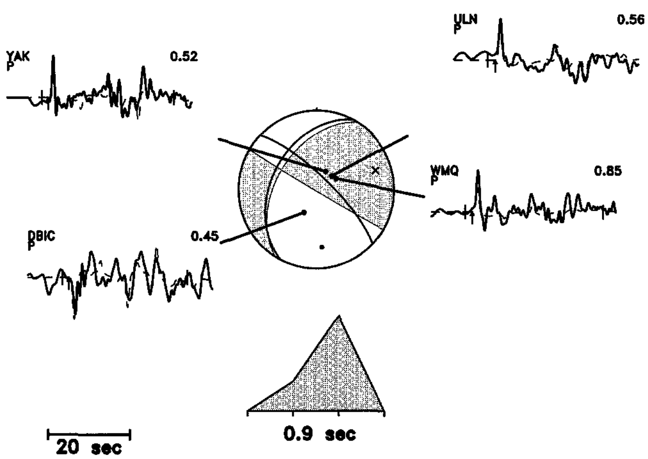

Figure 4. Fit of waveforms for the 19 March 1998 mantle earthquake. The preferred focal mechanism (shaded radiation pattern) is rotated with respect to the CMT best double couple. The CMT solution produces adequate fits to the broadband waveforms but predicts amplitudes that are too small for the direct *P* arrival.

with the situation in the southern Apennines where earthquakes of similar size appear to have ruptured a thicker portion of the crust. It is noteworthy that the central Apennines have not generated very large earthquakes in the past (Boschi *et al.,* 1995) and that this may be related to a thinner seismogenic portion of the crust.

Although the slip is confined to the top few kilometers of the crust both by the seismological observations and by geodetic data, it is unclear how the surface cracking and small fault offsets observed after the earthquakes (Cinti *et al.,* 1998) relate to the slip on the primary fault planes. More detailed studies of the near-field seismological data, geodetic data, and local geology should lead to a better understanding of the shallow termination of the seismic ruptures for the 1997 earthquakes.

The 26 March 1998 mantle earthquake is the largest mantle earthquake recorded beneath the Apennines. The timing of this event with respect to sequence of crustal earthquakes is intriguing, as is its relationship with the crustal extension of the Apennines.

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