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Mainshocks and aftershocks of the 2002 molise seismic sequence, southern Italy

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Abstract

In October and November 2002, the Molise region (southern Italy) was struck by two moderate magnitude earthquakes within 24 hours followed by an one month long aftershocks sequence. Soon after the first mainshock (October 31st, 10.32 UTC, M_w 5.7), we deployed a temporary network of 35 three-component seismic stations. At the time of occurrence of the second main event (November 1st, 15.08 UTC, M_w 5.7) the eight local stations already installed allowed us to well constrain the hypocentral parameters. We present the location of the two mainshocks and 1929 aftershocks with $2 < M_L < 4.2$. Earthquake distribution reveals a E-trending 15 km long fault system composed by two main segments ruptured by the two mainshocks. Aftershocks define two sub-vertical dextral strike-slip fault segments in agreement with the mainshock fault plane solutions. P- and T-axes retrieved from 170 aftershocks focal mechanisms show a coherent kinematics: with a sub-horizontal NW and NE-trending P and T-axes, respectively. For a small percentage of focal mechanisms (∼10%) a rotation of T axes is observed, resulting in thrust solutions. The Apenninic active normal fault belt is located about 80 km westward of the 2002 epicentral area and significant seismicity occurs only 20-50 km to the east, in the Gargano promontory. Seismic hazard was thought to be small for this region because neither historical earthquake are reported in the Italian seismic catalogue or active faults were previously identified. In this context, the 2002 seismic sequence highlights the existence of trans-pressional active tectonics in between the extensional Apenninic belt and the Apulian foreland.

Introduction

On October 31st (10.32 UTC), 2002, a Mw 5.7 earthquake struck the Molise region in Southern Italy. Due to the moderate magnitude of the event, only few villages were affected by damages and only one building fully collapsed. Sadly this building was an operating school where 29 people died: 26 of them were children's. The totally unexpected casualties became a tragedy and a shock for the Italian community. Seismic hazard for the region had not been previously retained high and the earthquake was mostly unexpected by seismologists. The reason was that neither historical or instrumental events had been previously reported in seismic catalogues for that area. In fact, the main faults responsible for the large devastating events of the past are located about 80 km to the West, along the Apennines (CPTI, 1999; Chiarabba et al., 2005), and to the East in the Gargano promontory (Figure 1). Moreover, background seismicity of the past 20 years occurred mostly at the border of the main active normal faults located along the chain. A more

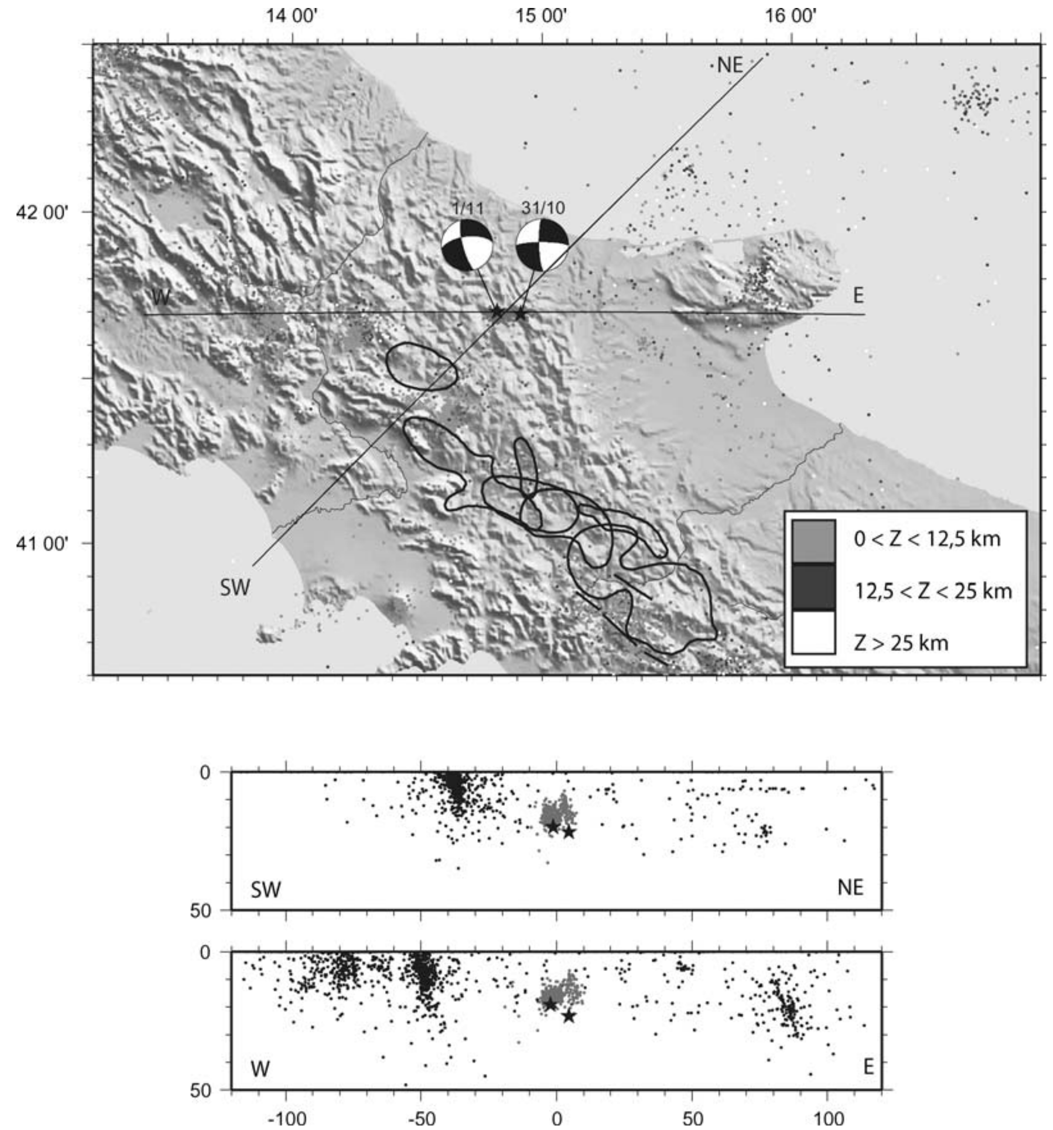

Figure 1. Map view of the background seismicity of the southern Apennines preceding the Molise seismic sequence (Chiarabba et al., 2005). The CMT solutions of the two main shocks (black stars) and aftershocks (red circles) are plotted. The black heavy lines are the isoseismals of X degree for the main historical events occurred in southern Apennines. The thin black lines are the traces of vertical sections. On the SW-NE and W-E sections, the Molise seismic sequence (red circles) is superimposed to the background seismicity (black circles).

diffuse seismicity is located in the Gargano promontory mostly at mid to low crustal depths. As clearly shown in Figure 1, the 2002 seismic sequence occurred in an area featuring no significant seismicity in the past years.

A few hours after the first main event, a temporary seismic network was installed in the epicentral region (Figure 2).The network was partially operating on November 1st, when a second Mw 5.7 event (15.08 UTC) occurred about 8 km faraway. In a few days after the two shocks, the seismic network was completed with up to 35 three-components digital seismic stations covering an area of about 1600 km^2. The entire sequence has been real-time monitored by a digital telemetered local network consisting of 7 stations. P- and S-wave arrivals were read on about 10,100 digital waveforms for a total of 1929 selected events. Hypocentral locations were obtained by using an optimized 1D velocity model and focal mechanisms are computed from P-wave polarities. In this paper,

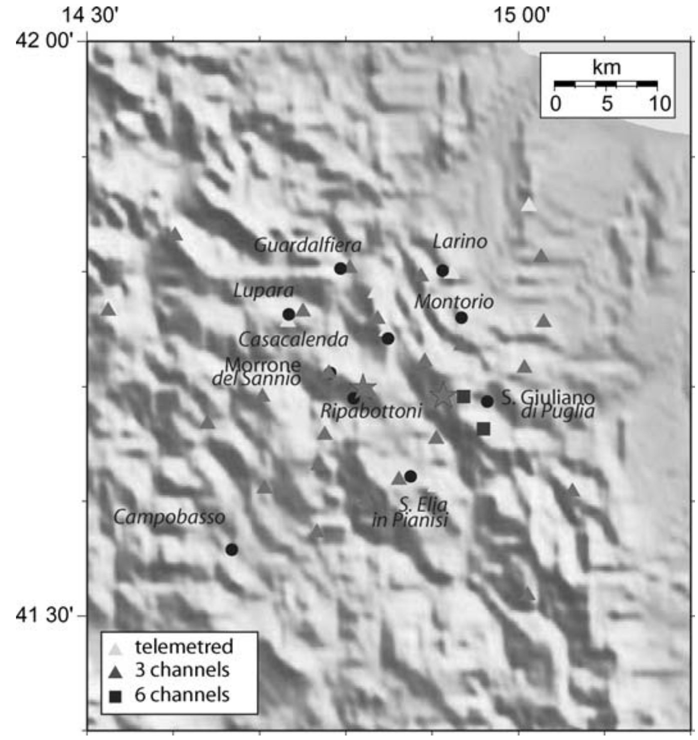

Figure 2. Map of the 33 seismic stations installed during the seismic sequence. Yellow indicates the telemetered stations, red the 3 channels stand alone stations equipped with velocimeters while blue indicates the 6 channels stand alone stations (velocimeters and accelerometers).

we analyze the seismic sequence by presenting and discussing the aftershocks spatial distribution and the geometry and kinematics of the fault system.

Seismic data and 1D velocity model

The temporary seismic network consists of 35 three-components digital stand alone stations equipped with velocimeter and accelerometer (Figure 2). All stations had been set for continuous recording. In addition, 7 seismic stations had telemetric connection by radio link to a mobile center to follow the real-time evolution of the sequence. The network operated for one month and acquired more than 100 Gb of data. The continuously recorded data were processed to detect the local events by using an algorithm based on STA/LTA thresholds and optimized for local regions (see Piccinini et al., 2003). We selected 1929 events recorded at almost all the stations. Magnitude of the events ranges between 2.0 and 4.2. P- and S-wave arrival times were read on the digital waveforms and weighted following 4 classes of reading accuracy (see Table 1).

The recorded waveforms show the complexity of the deep structure. The seismograms clearly show on the vertical and horizontal components an intermediary phase between P and S arrivals (Figure 3).The investigation of this phase is behind the scope of this paper but, basing on the observation of the almost constant delay time between this secondary phase and the direct S wave arrival, we speculate that this phase might be an S to P conversion at a discontinuity shallower than the hypocentral depth.

In order to constrain earthquake locations, we have inverted P- and S-wave arrival times to retrieve the 1D velocity model and station corrections. Arrival times for selected events that have hypocentral errors less than 2 km and more than 20 phases were inverted by using the Velest code (Kradolfer, 1989). The a priori starting model was chosen considering the available

Table 1.

Weight	Time uncertainty (s)
0	<0.02
1	0.02–0.05
2	0.05–0.1
3	0.1

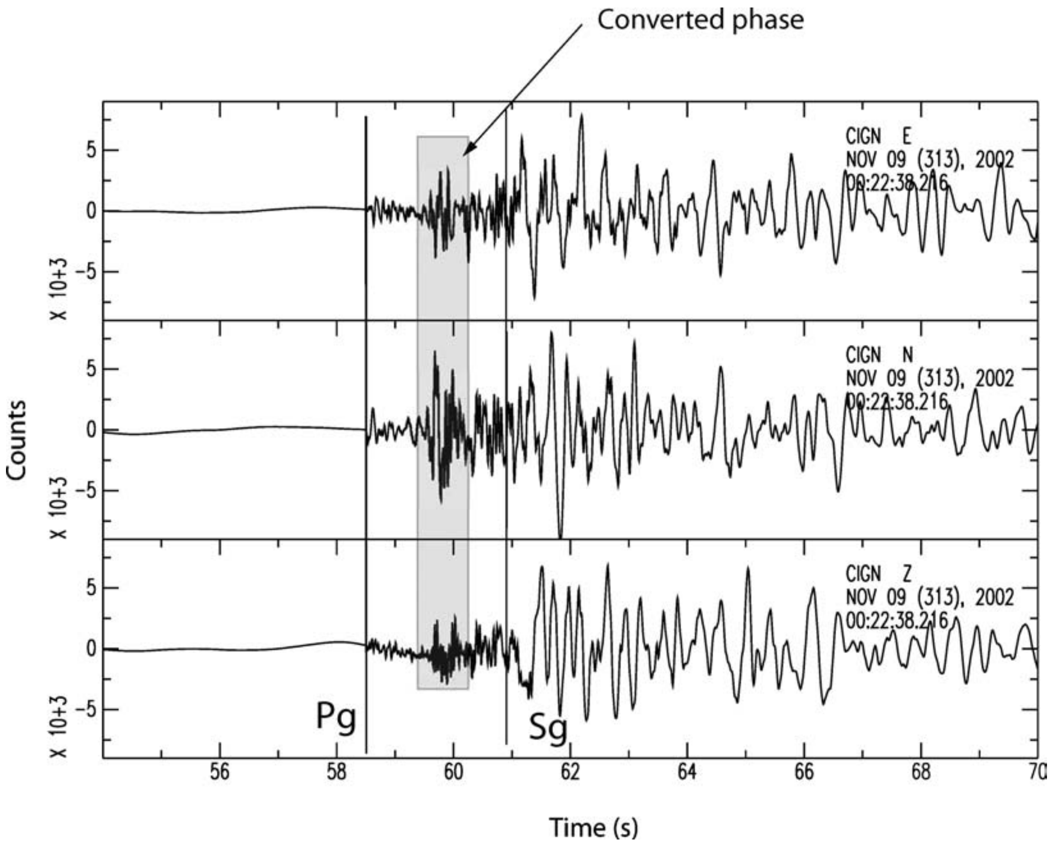

Figure 3. Local earthquake recorded at three-component station CIGN where it is possible to note the S-to-P conversion between the P and S onset.

information on the local structure, on geologic and deep well data (Mostardini and Merlini, 1986). We varied the starting V_p values to explore different 1D solutions around the a priori model. The optimum model has been computed after 4 iterations achieving a final *rms* of 0.3 s (Figure 4A).

The high V_p layer between 4 (5.2 km/s) and 11 km (6.4 km/s) depth is possibly interpreted as the Apulian limestone platform. Sharp velocity discontinuities are observed both above and below this layer, reflecting shallow sediments ($V_p = 2.9$ km/s) and the deeper transition to the metamorphic basement. We computed the V_p/V_s ratio for locating events from the Wadati diagram obtaining a value of 1.85 (Figure 4B).

Mainshocks

The two Mw 5.7 main shocks have been located (Table 2)by using the 1D model showed in Figure 4A and data from the national and regional permanent seismic networks. For the November 1st event, we add the arrival times at 8 local stations of the temporary network already installed. Then, hypocentral errors areof the order

Table 2.

Yr	M	D	H	Min	Lat^	Lon^	Depth^	Mw*	Strike*	Dip*	Rake*
2002	10	31	10	32	14.913	41.692	22.30	5.7	178	80	−10
2002	11	1	15	08	14.820	41.820	19.08	5.7	165	76	−29

^This study.
*INGV-Harvard European-Mediterranean Regional Centroid-Moment Tensors Project.

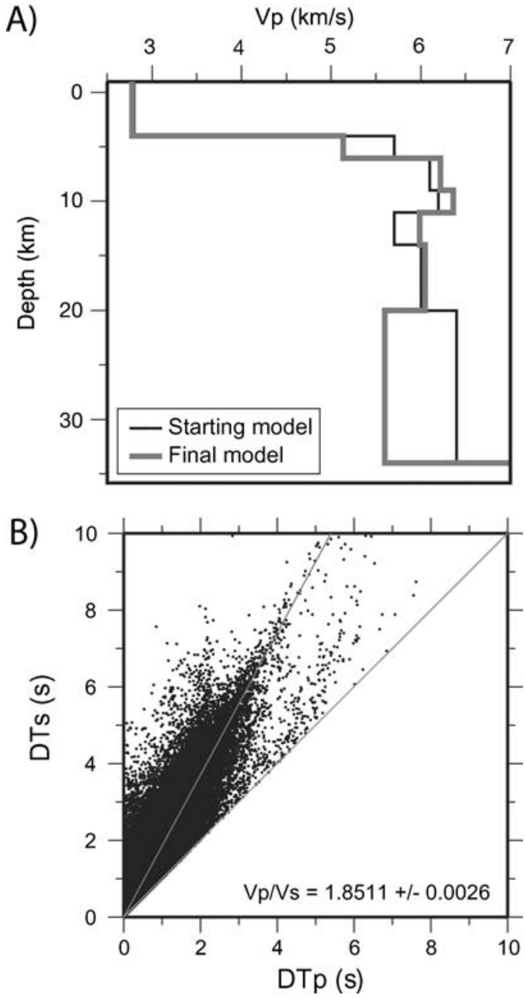

Figure 4. (A) One-dimensional velocity model used to locate the seismicity. (B) Wadati diagram for the Vp/Vs ratio.

of 2 and 1 km in horizontal and 5 and 2 km in depth for the first and second mainshock, respectively. Hypocentral depths are unusually high: 18–22 km depth, for both events. The deep location of the hypocenters is consistent with macroseismic data, aftershock distribution and preliminary analysis of seismic waveforms. CMT focal solutions show that both the events occurred on nearly vertical strike slip faults, with P and T axes NW and NE-trending, respectively. The aftershock distribution constrains the mechanism to right lateral slip on the E-W fault plane. The October 31st has a pure strike slip solution on the nearly vertical E-W plane, while the November 1st event appears to have a minor compressional component on a E-trending 80°N dipping plane, resulting in a transpressional mechanism.

The waveforms recorded at close distance show a certain amount of source complexity for the November 1st main shock (Figure 5).A very emergent low frequency onset preceded the later arrivals (0.3–0.9 s) of high frequency high amplitude P-wave. This complexity can be attributed to either the structure traveled by the wave field or to a slow rupture that undergoes some acceleration as rupture proceeds. This latter hypothesis may explain why the onset of the rupture is deep (18 km) while most of the preliminary models for coseismic deformation (Di Luccio et al., 2004; Giuliani et al., 2004) require a shallower source. We hypothesize that the slow initiation at depth was followed by the rupture of a more competent patch of the fault at shallower depths (10–14 km depth).

Aftershocks distribution

A total of 1929 aftershocks has been located with the optimized velocity model using the Hypoellipse location code (Klein, 1989). Owing to the huge number of data, the hypocentral determinations are well constrained, with errors which are less than 0.5 km on average. In Figure 6we show a seismicity map where it is possible to appreciate the 15 km long E-W trending fault system activated in 2002. The first and the second mainshock ruptured the eastern and western segments of the structure, respectively. The second event occurred at the western border of the fault system imaged by aftershocks distribution. The observation that its aftershocks concentrated to the east, suggests an eastward directivity of the rupture.

Vertical sections of aftershocks show the geometry of the fault system at depth (Sections a, b and c in Figure 6). The most striking observation is the absence of seismicity in the upper 8–10 km. Most of the aftershocks occurred at mid-crustal depth in between the two mainshocks. The eastern segment is almost vertical, with aftershocks confined between 20 and 8 km depth. The western segment has a 75° N-directed dip, with aftershocks between 20 and 10 km. Both mainshocks are located at the base of the aftershocks.

Focal mechanisms of aftershocks are consistent with the focal mechanisms of the mainshocks. Fault plane solutions are well constrained (classes A-A in the convention of the Fpfit program, see Reasemberg and Oppenheimer, 1985) for 170 events with more than 20 polarities. P axes are sub-horizontal with a general NW trend. T axes are broadly NE trending and show two main plunges: Sub-horizontal, strike slip motion,

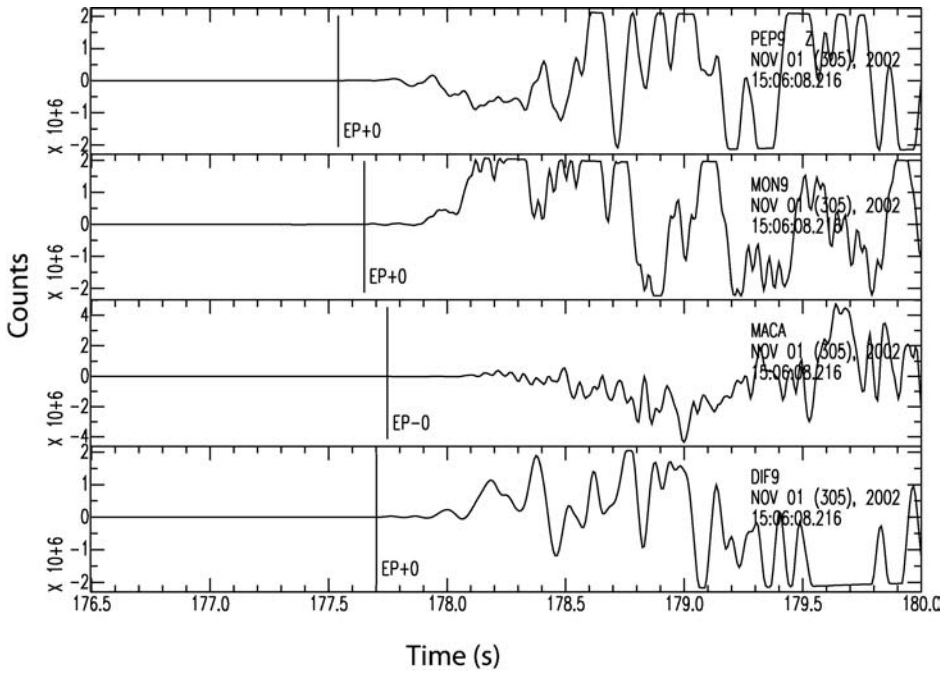

Figure 5. First seconds of the waveform of the November 1st 2002 mainshock recorded at four stations next to the epicenter. The seismograms are expressed in counts versus time (s).

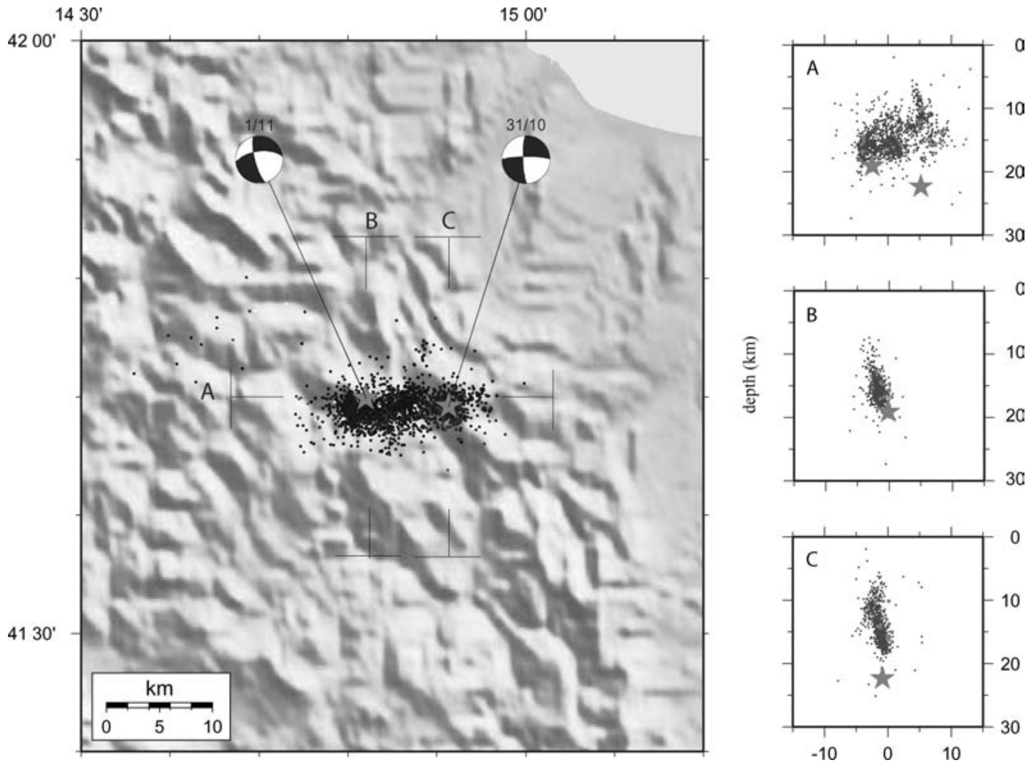

Figure 6. (a) Epicentral map of the seismic sequence. Pink stars and red circles indicate the mainshocks and the aftershocks with magnitude equal or grater than 4.0, respectively. The CMT solutions of mainshocks are shown. The black lines are the strikes of sections a, b and c. E-W (6a) and N-S (6b and 6c) vertical cross sections across the fault system.

and sub-vertical, thrust motion. We divided the fault system in blocks 4 km large and computed the average directions of P and T axes within each block with at least four axes with plunge less or equal to 30 degrees (Figure 7).The average is weighted with the cosine of the plunge. We observe that P-axes are roughly parallel along the fault system, NW-trending and with a plunge less than 30 degrees. T axes are NE-trending and exhibit two predominant plunges: Less than 30 degrees coherent with strike slip solutions and around 60 degrees testifying the presence of some inverse solutions.

Discussion and conclusions

The Molise 2002 sequence originated at mid-crustal depths on dextral E-W trending strike slip faults. Two mainshocks nucleated at about 18–22 km of depth and ruptured two 5–7 km long fault segments, at a distance in space of ≈6 km from each other and of a couple tens of hours in time. Aftershocks clustered on a total 15 km long fault system and highlighted a nearly vertical structure. Hypocentral depths are deeper than those usually found (≈14 km) in the southern Apennines normal fault belt (Chiarabba et al., 2005).

The geologic structure of the region is fairly known due to the availability of commercial seismic profiles and consists of a 6–7 km thick limestone layer of the Apulian platform underlying a 4 km thick pile of Cenozoic terrigenous sediments (Improta et al., 2000). The Meso-cenozoic cover lays above sedimentary Paleozoic and metamorphic rocks of the Adria continental lithosphere. The computed P-wave velocities model (Figure 4A), shows two sharp discontinuities interpreted to lie at the top (V_p decreases upward from 5.6–5.9 km/s to less than 3.0 km/s) and at the base, of the

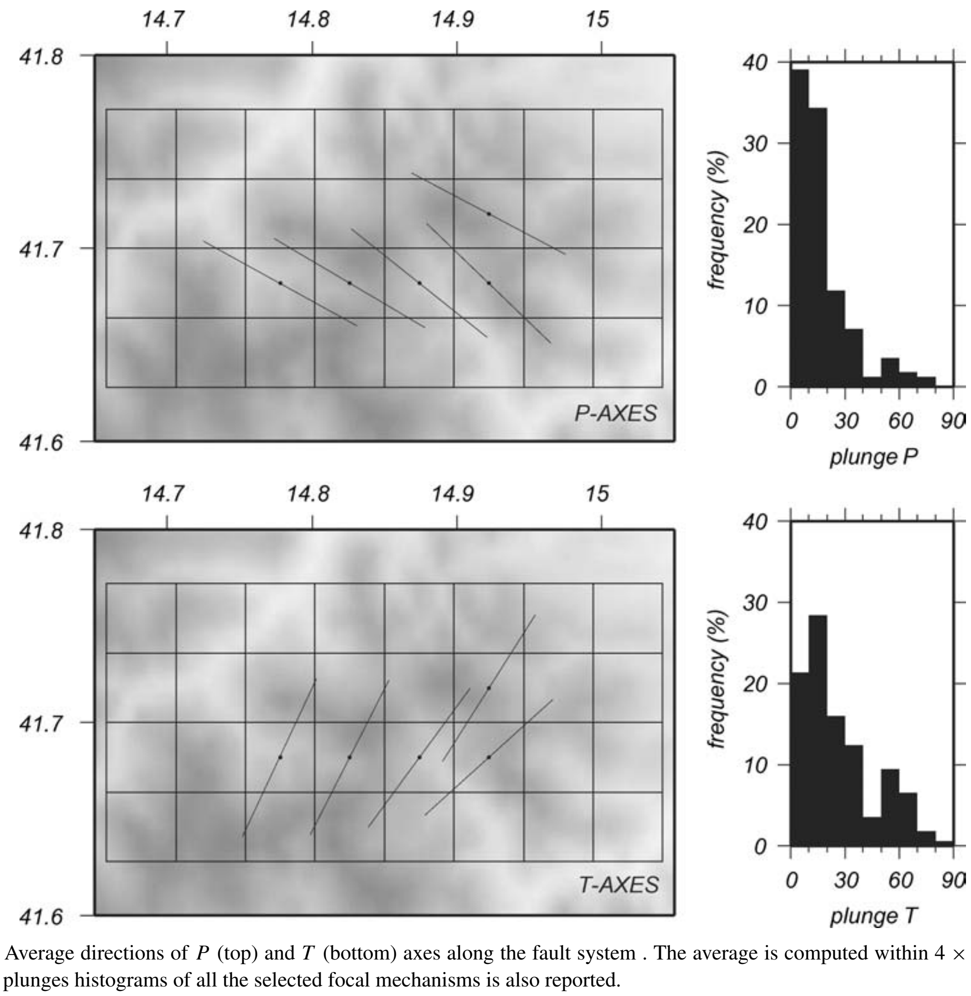

Figure 7. (a) Average directions of P (top) and T (bottom) axes along the fault system . The average is computed within 4 × 4 km cells. (b) The P and T plunges histograms of all the selected focal mechanisms is also reported.

Apulian platform (V_p decreases from 6.2–6.4 to 5.9). A clear converted phase between the P-wave and the S-wave arrivals was already observed for the aftershocks of the nearby Potenza 1991 earthquake (Demanet et al., 1998). For the Molise aftershocks, this phase is even more pronounced. We interpret the observed phase as a S-to-P conversion at the Apulian limestone top. Further studies are however needed to model this arrival and to define the geometry of this velocity discontinuity. Hypocentral depths indicate that earthquakes originated mostly within the metamorphic basement of the Adria lithosphere flexured beneath the Apennines belt and only slightly propagated within the upper Mesozoic cover.

Focal mechanisms and CMT solutions show right lateral strike slip movements on E-W right-lateral adjacent faults. A minor thrust component is revealed by aftershocks, indicating a rotation of the T and the null axes from the vertical to the horizontal plane. Since the P axes are stable and sub-horizontal while the extension axes varies from sub-horizontal to sub-vertical, we argue that the horizontal NW-trending compression prevails in the local stress. The comparison with the kinematics of the adjacent seismically active regions indicates that the direction of P axes is consistent with the compression observed in the adjacent Gargano promontory (Pondrelli et al., 2002). Conversely the direction of T axes agrees with the NE-trending extension of the Apennines belt.

Some similarities can be found with the 1990–1991 Potenza earthquakes (M_w 5.7 and M_w 4.8, respectively). In fact, the main events of the Potenza sequence ruptured at mid-crustal depth within the Apulian basement, on E-W-trending right lateral strike slip fault. In both cases we observe strike slip mechanisms testifying a shear zone located in between the extensional inner chain of the Apennines to the west, and the Apulian foreland, to the east. While the seismic features are reasonably well revealed by mainshocks and aftershocks for both the sequences, their relation to the seismotectonics of the region is still unclear and the role of these deep strike slip structures in the deformation style of the area need further studies.

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