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EXPRESS LETTER

Seismic moment tensors of the April 2009, L'Aquila (Central Italy), earthquake sequence

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SUMMARY

On 2009 April 6, the Central Apennines were hit by an $M_w = 6.3$ earthquake. The region had been shaken since 2008 October by seismic activity that culminated in two foreshocks with $M_w > 4$, 1 week and a few hours before the main shock. We computed seismic moment tensors for 26 events with M_w between 3.9 and 6.3, using the Regional Centroid Moment Tensor (RCMT) scheme. Most of these source parameters have been computed within 1 hr after the earthquake and rapidly revised successively. The focal mechanisms are all extensional, with a variable and sometimes significant strike-slip component. This geometry agrees with the NE–SW extensional deformation of the Apennines, known from previous seismic and geodetic observations. Events group into three clusters. Those located in the southern area have larger centroid depths and a wider distribution of T-axis directions. These differences suggest that towards south a different fault system was activated with respect to the SW-dipping normal faults beneath L'Aquila and more to the north.

Key words: Earthquake source observations; Seismicity and tectonics; Europe.

INTRODUCTION

The Italian Apennines are seat of extensional deformation, concentrated along the inner part of the mountain belt. This phenomenon is a relict of the process, driven by the rolling back subduction of Adriatic plate, that lead to the opening of the Tyrrhenian back-arc basin (Faccenna *et al.* 2004). This NE–SW trending extension reaches velocities up to 3 mm yr^{-1} (D'Agostino *et al.* 2008). Seismic activity is well known, both historically and instrumentally, and it is spread along the whole length of the mountain chain. Seismic hazard is high all along the Apennines (MPS Working Group 2004). Typically, earthquakes along Central–Southern Apennines show normal faulting mechanisms and focal depths in the upper 15 km of crust (Vannucci *et al.* 2004). The most recent examples are the 1915, $M = 6.9$ Avezzano event (Amoruso *et al.* 1998); 1930, $M = 6.7$ and 1980, $M = 6.9$, Irpinia events (Pino *et al.* 2008); the 1979, $M_w = 5.9$ Valnerina quake (Boschi *et al.* 2000); the 1997–1998 Umbria-Marche sequence, that included two events with $M_w = 5.7$ and 6.0 (Ekström *et al.* 1998). Another recent sequence—2002, $M_w = 5.7$, S. Giuliano di Puglia twin events—showed instead strike-slip character. It was located off mountain chain, and it has been attributed to deformation within the Adriatic Plate descending beneath the Apennines (Di Luccio *et al.* 2005).

On 2009 April 6, an $M_w = 6.3$ earthquake occurred in Central Italy, with shallow hypocenter located at the outskirts of the city of L'Aquila, in the Abruzzo region, causing extensive damage and casualties (Fig. 1). It followed a seismic activity that initiated in October 2008 and culminated with the $M_w = 4.4$ event of March 30, and the $M_w = 4.2$ earthquake, a few hours before the main shock (Supporting Information, Fig. S1 and Tables S1–S3; Chiarabba *et al.* 2009). Thousands of aftershocks have been recorded. Seismic activity in this region had been scarce during past few decades, with only three seismic swarms in 1985 (M_l 4.2), 1994 (M_l 3.9) and 1996 (M_l 4.1) as reported in *Catalogo della Sismicità Italiana* (CSI, Castello *et al.* 2007). Historical records show instead the occurrence of destructive events, with at least two of them—in 1461 and 1703—reaching intensities up to X (Gruppo di Lavoro CPTI 2004). The epicentral area had been identified before the earthquake as a region of higher-than-average earthquake probability, in particular along the Apennines axis (Faenza *et al.* 2003; Akinci *et al.* 2009).

Here, we report on source geometries of the L'Aquila seismic sequence. We computed 26 moment tensor solutions using the same technique we apply to maintain the European-Mediterranean regional centroid moment tensor (RCMT) catalogue (Pondrelli *et al.* 2006, and references therein; www.bo.ingv.it/RCMT). They are greatly in agreement with seismotectonics of the region.

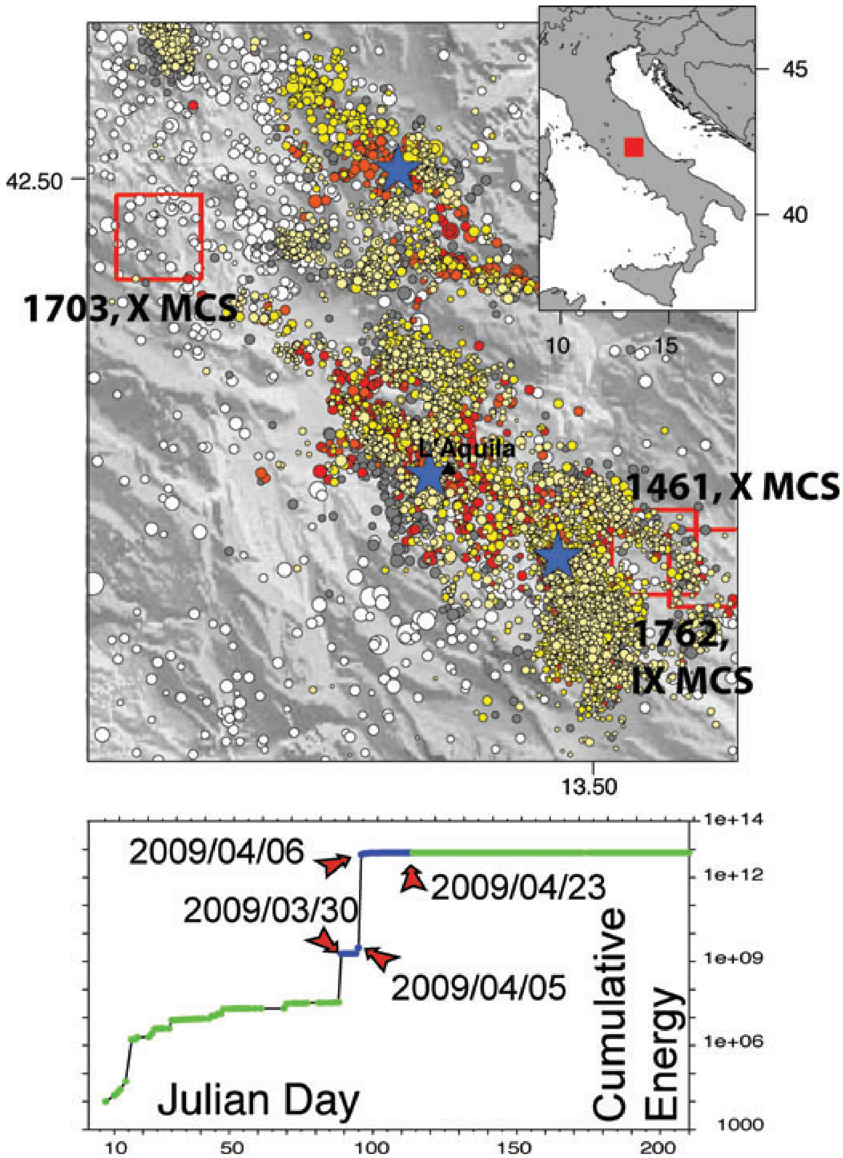

Figure 1. Map of the seismic sequence. Blue stars—events of the sequence with $M_l > 5.0$; red square—historical seismicity with $I_{\max} > 7.5$ (Gruppo di Lavoro CPTI 2004); white circles—previous seismicity (Castello *et al.* 2007); grey circles—events from 2009 January to April; red circles— seismicity from April 6 to 9; orange—from 9 to 11; yellow—from 11 to 30; light yellow—from May 1 to July 27 (Chiarabba *et al.* 2009). Lower plot: cumulative seismic energy release (joule) from January to July 2009. Upper right: Italy map with L'Aquila as a red square.

Comparing definitive to Quick RCMTs computed immediately after the earthquakes, we found really smaller adjustments to quick determinations. This highlights the robustness of RCMT solutions, considering that timely publication of moment tensors for main events of a sequence is a functional tool to support ongoing studies as complex source description and hazard update.

RCMT SOLUTIONS: DATA ANALYSIS

We compute seismic moment tensors using an extension of the global CMT scheme, based on fitting fundamental-mode Rayleigh and Love waves recorded at regional distance (Arvidsson & Ekström 1998). This process is particularly appropriate to study intermediate-magnitude events, and produces robust seismic moment tensors and M_w, fully compatible with other source parameters (e.g. Global CMTs; Ekström *et al.* 2005). We use three-component seismograms, low-pass filtered with cut-off frequencies ranging from 1/30 to 1/50 Hz, depending on magnitude, to select the broadest spectrum with good signal-to-noise ratio. When signal-to-noise ratio allows it, long-period body waves are added in the inversion, as for nine of the 26 RCMTs computed for this sequence (Fig. S1 and Table S2). Data retrieval and pre-processing are done automatically, however each inversion is always controlled and reviewed by an operator. We commonly use 5–15 stations with a distance range between 3° and 15°, belonging to MedNet and GEOFON networks. Located closer to the source region, these stations are the most useful to study European-Mediterranean smaller magnitude events, and provide good azimuthal coverage. When new seismograms from other networks become available through ORFEUS (www.orfeus.org) or IRIS (www.iris.edu), we revise and update the solutions. Here we present the definitive RCMTs for 26 events with an M_w between 3.9 and 6.3, including the two greater foreshocks of March 30 and April 5

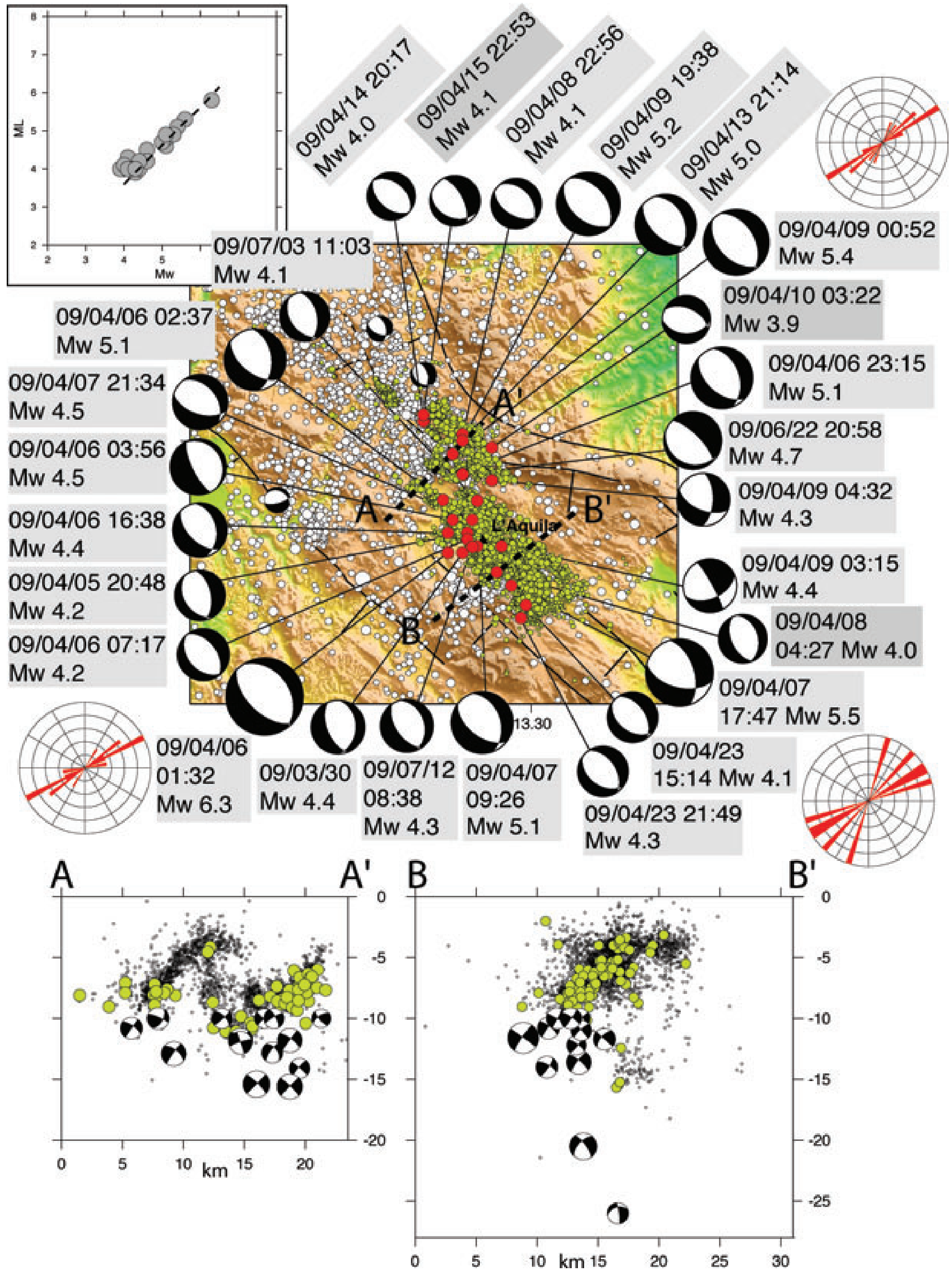

Figure 2. RCMTs with their epicenters (in red) and the smaller magnitude seismicity of the sequence (in yellow, Chiarabba *et al.* 2009). In the background (white dots) previous seismicity (CSI, Castello *et al.* 2007) and previous available RCMTs (small focal mechanisms, Pondrelli *et al.* 2006; http://www.bo.ingv.it/RCMT/Italydataset.html). Sections at the bottom (corresponding to AA' and BB' in map): the sequence events in yellow ($M \geq 3.0$) and black ($M < 3.0$), with all RCMTs. In section AA', the northern seismicity is reported; in section BB', the shallower seismicity belong to central cluster whereas deeper events are from the southern cluster. Upper left: M_1 versus M_w in comparison to the regression line for these magnitudes (Gruppo di Lavoro CPTI 2004). Upper right, lower left and right rose diagrams: they represent respectively the different T-axes distribution in the three areas where seismicity occurred.

(Tables S1–S3). NW–SE striking extensional moment tensors dominate, with tensional axes oriented between 40° and 60° (Fig. 2). Only in a few cases, a pronounced strike-slip component characterizes the source geometry as for the April 7, 17:47 aftershock. Most of these solutions have 'A' quality flag, that means greatest stability (see Pondrelli *et al.* 2006, for quality evaluation); only six smaller magnitude events have a 'C' flag because their inversion required to fix the location (Table S2). Centroid depth of all solutions is in general agreement with preliminary locations; only two cases have a final location 5 km deeper with respect to initial one. Most events have the typical depth, within the top 15 km, of seismic sequences occurred previously in the Apennines. Only a few of them are deeper, down to 26 km, mainly those located southward and with a more prominent strike-slip component (Tables S1–S3). A comparison with solutions produced by other groups with other techniques (www.csem-eu.org; TDMT on earthquakes.rm.ingv.it) shows an unquestionable similarity of focal geometries. Our M_w values are in good agreement with those from other agencies, mainly for greater events and have a regular behaviour respect to ML (Fig. 2).

Comparing definitive RCMTs to QRCMTs computed (when $M > 4.0$) within 1 hr after the earthquake occurred, we found really small rotation to principal axes needed to overlap the two solutions. This quantification, done computing the Kagan angle (Kagan 1991) for each QRCMT–RCMT couple, does not exceed the 25° (nearly the 50 per cent of the dataset has a value lower than 10°) when values lower than 30° represent a great level of similarity (Table S3). These results promote the robust reliability of QRCMTs, at least for the Central Mediterranean, where on-line seismograms ensure a fast and good azimuthal coverage.

RCMT SOLUTIONS IN A SEISMOTECTONIC FRAMEWORK

The extensional geometry of mechanisms of L'Aquila earthquakes is the same of other important seismic sequences along the Apennines, such as the 1980, $M = 6.9$, Irpinia earthquake and the Umbria-Marche seismic sequence in 1997–1998. The seismic sequence started beneath the city of L'Aquila and spread along a 40 km area into three main clusters (Figs 1 and 2). This migration of hypocenters was also seen in the 1997–1998 Umbria-Marche sequence. The foreshocks, the main shock and most of the activity of the first 3 days are part of the central cloud of seismicity, located beneath the town. The seismic activity that preceeded the sequence and the two main foreshocks also occurred in this area. All RCMTs of this central cluster have a shallow centroid depth (within 14 km; shallower events in section BB' of Fig. 2). The northern seismicity cluster activated just after the main shock ($M_w = 5.1$ on April 6, at 23:15 hours; Table S1) and continued with its northernmost expression with the two M_w 4.0 and 4.1 events on April 14 and 15. Depths for two of these events exceed 15 km (section AA' of Fig. 2). The southern seismicity cluster started later, with the M_w 5.5 aftershock, on April 7. Here are located the deepest events of the sequence, with hypocentral centroid locations deeper than 20 km and characterized also by a consistent strike-slip component (deeper events in section BB' of Fig. 2). The T-axes distribution is NE–SW, roughly perpendicular to the Apennines, in the central and northern seismicity clusters, whereas the southern one is more heterogeneous (Fig. 2).

The location and focal mechanism for the main shock suggest that this event occurred on the Paganica fault, a 10–15 km length, NW–SE striking, SW-dipping structure previously identified in the field (Vezzani Ghisetti 1998). The geometry of this fault is in agreement with our source parameters (see sections of Fig. 2). This hypothesis was supported also by aftershock distribution (Chiarabba *et al.* 2009), DinSAR analysis (Atzori *et al.* 2009), geodetic and geological surveys (Anzidei *et al.* 2009; Emergeo Working Group 2009). The northern cluster of the sequence shows a distribution that may be in agreement with an activation of the Campotosto fault, another normal fault, NNW–SSE striking and SW dipping (Boncio *et al.* 2004; Galli *et al.* 2008). Also our focal mechanisms are in agreement with the geometry of this fault. The southernmost cluster, where events with deeper location and with a greater strike-slip component are located, has a less-clear geometry and appears to be connected to a different system of faults. In this area, previous studies identified the NNW–SSE Mt. Ocre fault system (Salvi *et al.* 2003). Because of its strike direction, it could be related to the shallower present-day seismicity that at south aligns along a NNW–SSE trend. Deeper events, characterized also by a greater strike-slip component have probably occurred within the Adria plate. Deeper events also showed relevant strike-slip components in previous Apenninic seismic sequences, such as in the 1997–1998 Umbria-Marche sequence (Ekström *et al.* 1998). This is an important observation because it is common to take into account shallow normal faulting solutions near the axis of the Apennines chain and deeper strike-slip solutions further east (e.g. in the 2002 S. Giuliano di Puglia sequence; Di Luccio *et al.* 2005), not solving the doubt if this change is related to a lateral and/or vertical variation. Minor strike-slip components for deeper events of this sequence right under the belt axis may indicate that a contemporaneous lateral and vertical change in the stress field occurs. This distribution of deformation styles is also interpreted as the extension is working mainly within the thrust and fold belt, while deeper the deformation occurs within the Adria plate located beneath the chain.

CONCLUSIONS

We computed seismic moment tensors for 26 events with M_w between 3.9 and 6.3 belonging to the 2009 L'Aquila (Central Italy) seismic sequence. RCMTs gave immediately the indication that this seismicity, from the seismotectonic point of view, is similar to previous extensional activity occurred along this mountain belt, also in the vertical distribution of hypocenters and deformation styles. NW–SE striking focal planes agree with mapped faults of the region, allowing to infer which tectonic structures have been activated. For some events a relevant strike-slip component is observed, mainly when the hypocenters are deeper. This occurs mainly at south with respect to the entire activated region.

Seismotectonic analysis of the ongoing seismic sequence has been supported by the prompt availability of RCMTs, quick solutions first and definitive solutions successively. Our results provide crucial information for a number of ongoing studies about different aspects of the seismic sources. We conclude on the feasibility and importance of application of our inversion scheme for the early and reliable analysis of seismic sequences.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Figure S1. Data (blue) and syntethics (red) for some of seismograms used for the inversion of the main shock and two aftershocks. For the main shock also two examples of body and surface waves inverted together are shown, filtered at 40–150 s and 50–150 s, respectively. For the aftershocks, the bandpass filter used is reported with the station name together with distance and azimuth. Different filters mean different noise-to-signal ratio, related to minor magnitudes and different location and depths.

Table S1. Centroid locations and difference from preliminary information (dlat, dlon, ddep), preliminary M_l (INGV), M_w computed for events reported here (R, RCMT) and those computed by other agencies (G, global CMT catalogue; E, ETHZ; U, USGS from www.emsc-csem.org; T, TDMT from earthquake.rm.ingv.it).

Table S2. Qf is the quality flag (Pondrelli *et al.*, 2006), data used (S, only surface waves; C, body and surface waves; '*' for RCMT recovered later), focal plane parameters and *T*- and *P*-axes directions.

Table S3. Comparison between QRCMT and definitive solutions. Kagan angle (Kagan, 1991) is the minimum rotation angle to overlap a QRCMT to its RCMT. Also *P*-, *T*- and N-axes rotation needed to obtain the same result are reported, together with variation in M_w and hypocentral depth between QRCMT and definitive RCMT.

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