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The 2009 L'Aquila (central Italy) M_W6.3 earthquake: Main shock and aftershocks

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[1] A M_W 6.3 earthquake struck on April 6, 2009 the Abruzzi region (central Italy) producing vast damage in the L'Aquila town and surroundings. In this paper we present the location and geometry of the fault system as obtained by the analysis of main shock and aftershocks recorded by permanent and temporary networks. The distribution of aftershocks, 712 selected events with $M_L \geq 2.3$ and 20 with $M_L \geq 4.0$, defines a complex, 40 km long, NW trending extensional structure. The main shock fault segment extends for 15–18 km and dips at 45° to the SW, between 10 and 2 km depth. The extent of aftershocks coincides with the surface trace of the Paganica fault, a poorly known normal fault that, after the event, has been quoted to accommodate the extension of the area. We observe a migration of seismicity to the north on an echelon fault that can rupture in future large earthquakes. **Citation:** Chiarabba, C., et al. (2009), The 2009 L'Aquila (central Italy) M_W6.3 earthquake: Main shock and aftershocks, *Geophys. Res. Lett.*, *36*, L18308, doi:10.1029/2009GL039627.

1. Introduction

[2] On April 6th 2009 (1:32 UTC, 3:32 local time), a Mw6.3 earthquake struck central Italy, devastating the L'Aquila town and surrounding villages of the Abruzzi region, causing 300 deaths and leaving sixty thousand homeless. This region of central Apennines has one of the highest seismic hazard in Italy [*Akinci et al.*, 2009, and references therein]. Many destructive earthquakes are filed in the historical catalogue [*Gruppo di Lavoro CPTI*, 2004]. The last dramatic event was the M_W 6.7, 1915 Avezzano earthquake [*Amoruso et al.*, 1998], located about 30 km to the south–west, that caused about thirty thousand deaths. Large earthquakes originate mainly on a narrow belt along the central Apennines (Figure 1a), accommodating a NE-trending extension, with a rate of about 3 mm/yr [*D'Agostino et al.*, 2008], progressively thinning the Apennines thrust and fold belt. The normal fault system is elongated NW–SE and composed of adjacent, west-dipping, and echelon fault segments [*Amato et al.*, 1998; *Boncio et al.*, 2004; *Chiaraluce et al.*, 2004]. While the northern portion is almost continuously releasing seismicity, the central part, i.e., the Abruzzi region, was silent during the past decades, with only few and sparse events occurring around the main faults [*Bagh et al.*, 2007; *De Luca et al.*, 2009]. The extension in this region is accommodated by two sub-parallel sets of faults, the eastern and western normal fault systems [see *Boncio et al.*, 2004], which include several Quaternary normal faults with clear signature at the surface and paleoseismological evidence of Holocene surface faulting earthquakes [*Pantosti et al.*, 1996; *Galadini and Galli*, 2000; *Papanikolaou et al.*, 2005; *Roberts and Michetti*, 2004]. The deep geometry of most of these faults is poorly constrained by sub-surface data [*Boncio et al.*, 2004].

[3] After the 2009 M_W6.3 event, two additional earthquakes, M_W 5.6 and M_W 5.4, occurred at the edges of the main structure, raising concern that additional M > 6 shocks could develop on one of the adjacent seismogenic faults [*Galli et al.*, 2002].

[4] In this study we use data from permanent and temporary seismic networks to define the space-time evolution of the seismicity, providing accurate earthquake locations and the geometry of faults that accommodate the extension in this portion of the Apennines. Our results yield basic constraints to kinematic and dynamic source models and to statistical analysis of earthquake occurrence in the region.

2. Data Analysis

[5] We use data from the INGV national and regional permanent networks and some of the temporary stations deployed soon after the main event (see the auxiliary material, Figure S1).[2] These networks were strongly improved in the last few years [*Amato and Mele*, 2008; *De Luca et al.*, 2009] and are now capable of resolving details on the active faults at depth.

[6] Until May 15, more than 6,000 aftershocks were located by the surveillance duty. We selected and relocated about 3200 events recorded by at least 10 seismic stations (see the auxiliary material). Then, the $M_L \geq 2.3$ aftershocks have been carefully reanalyzed yielding high quality picks from digital recordings at three-component seismic stations. The final dataset consists of 17497 P- and 10815 S-wave arrivals from 712 earthquakes at 81 seismic stations located within 100 km from the epicentral area.

[7] Earthquakes are located with the Hypoellipse code [*Lahr*, 1989] and a 1D velocity model optimized for the region (Table S2 of the auxiliary material). The locations for

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[2]Auxiliary materials are available in the HTML. doi:10.1029/2009GL039627.

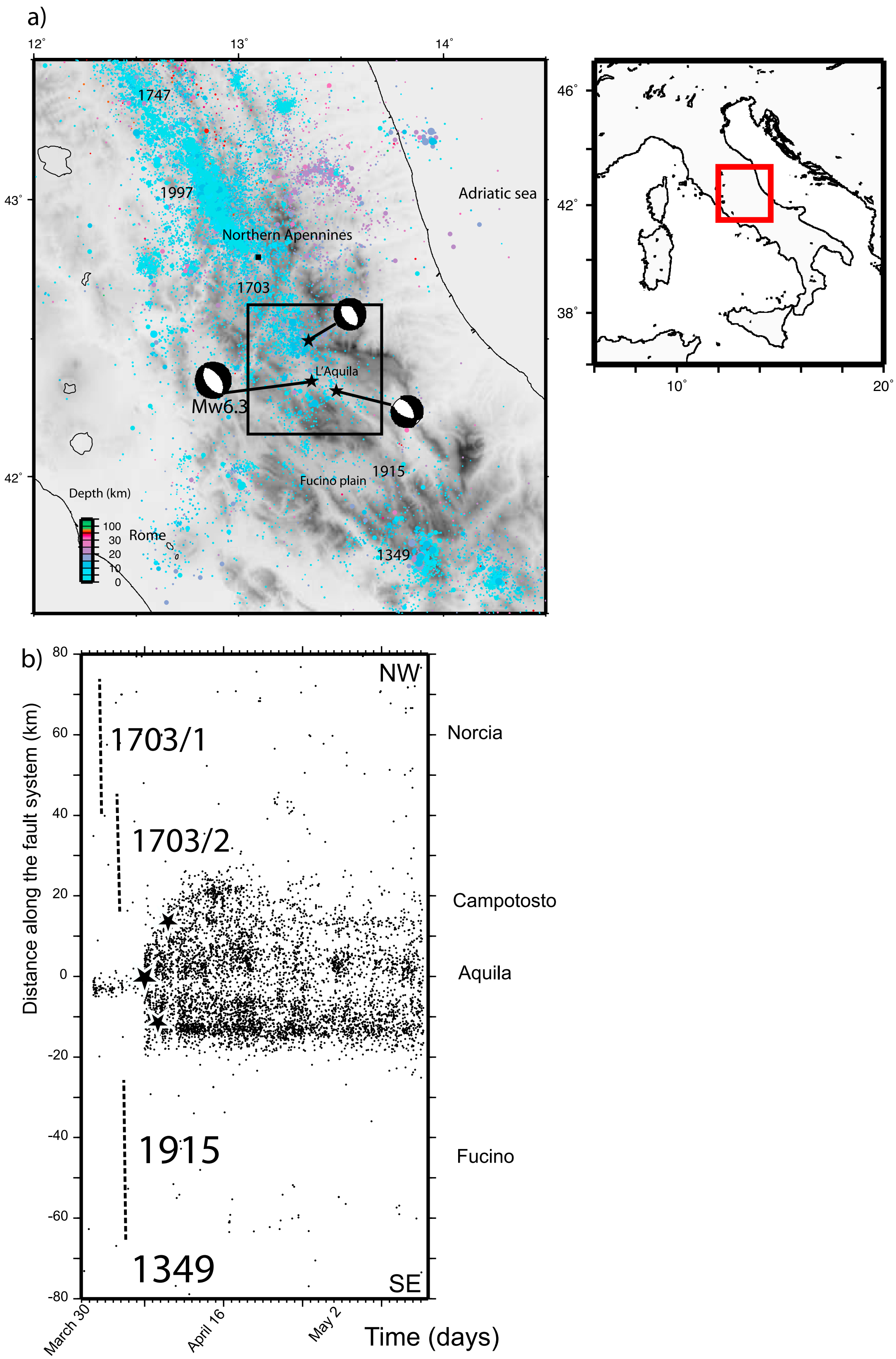

Figure 1. (a) Map of instrumental seismicity in the period 1980–2009, from the CSI catalogue. The L'Aquila sequence occurred in a silent region at the southern end of the Northern Apennines extensional belt. The stars indicate the three $M_L > 5$ earthquakes and the box is the area shown in Figure 2, focal mechanisms from the RCMT catalog (www.bo.ingv.it/RCMT). (b) Space time distribution of the seismicity along this portion of the NW-trending extensional belt from April 2009. The dates of the most recent historical events are reported for each segment. (c) M_L vs. time for the sequence starting at the end of March. The violet points are the 712 aftershocks re-analyzed in this work.

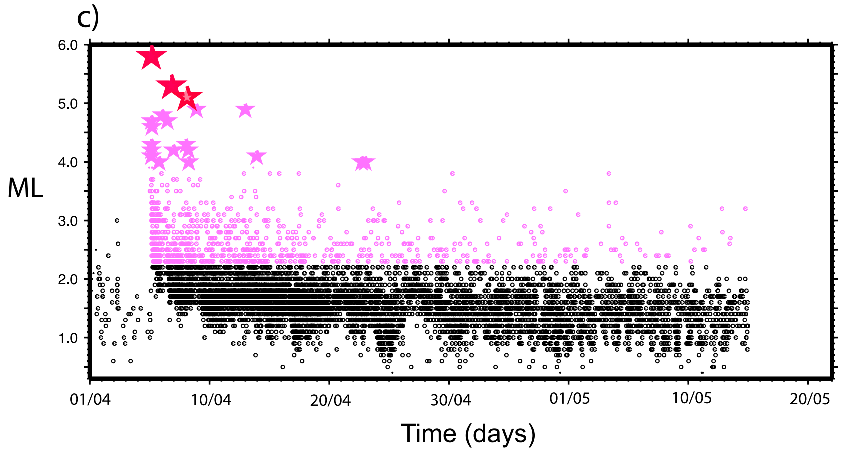

Figure 1. (continued)

the $M_L \geq 4.0$ aftershocks are reported in Table S1 of the auxiliary material. The final locations have formal errors less than 1.0 kilometer.

3. Temporal Evolution of the Sequence

[8] The April 6th, 2009 main shock was preceded by a long sequence of foreshocks, which started several months before, culminating with a M_L4.1 shock on March 30. We show in Figures 1b and 1c the magnitude distribution and the space-time evolution of the 2009 sequence using all the earthquakes located by the INGV National Seismic Network (RSN) from March 30 to May 15 (about 3200 events, see the auxiliary material). In the week before the April 6th event, a cluster of small magnitude earthquakes occurred close to the main shock location. Four hours before the main event, a M_L3.9 foreshock occurred (fortunately spurring part of the population to pass the night outside buildings). The main shock rupture activated a NW–SE trending, ~15–18 km long fault. In the first three days after the main event, we note a migration of seismicity from the main structure northward (Figure 1b), culminated with a Mw5.4 aftershock on April 9th. In the following week, seismicity continues migrating, spreading from the main fault plane to an adjacent, laterally offset, normal fault located to the north, and toward the southern termination of the main fault (Figure 2a). During the following month, seismicity spread along a 40 km long fault system, showing an Omori-like temporal decay (Figure 1).

4. Main Shock and $M_L \geq 4$ Shocks

[9] The main event has a pure normal faulting mechanism (www.bo.ingv.it/RCMT). Its location, obtained integrating arrival times at all the available permanent stations including the accelerometric network managed by the Dipartimento di Protezione Civile (DPC) (79 P-wave observations within 130 kilometers from the epicenter) is at 9.5 km depth and at distance of about 2 kilometers from L'Aquila town center (Figure 2). The earthquake had an initial emergent onset followed by a more energetic pulse after about 1 second. The hypocenter computed with the first P-wave readings is relative to the emergent onset that appears as a small prelude of the main dislocation. The aftershocks clearly define an 15–18 km long, NW-trending and ~45°SW-dipping fault, located above 10 depth, with a seismicity cut-off at 2 km depth (sez-2 in Figure 2b). The main shock hypocenter is located at the base of the aftershocks and close to the northwestern border of the fault. This suggests that the fault has both up-dip and southward directivity, in agreement with the peak ground motion pattern observed at the INGV and accelerometric DPC network, with the observed damage distribution and directivity analysis (N. A. Pino, personal communication, 2009).

[10] The second large event is the M_W 5.6 April 7 (17:47) shock that occurred a few kilometers to the south of the main event, at a depth of 15 km (Table S1 of the auxiliary material), well constrained by the use of P- and S-wave arrivals at 8 close temporary stations installed after the main event. The focal mechanism has a not negligible strike slip component. Only a few aftershocks followed this event, and they are located around the ruptured patch (sez-3 in Figures 2b and 2c). The geometry of this fault, barely illuminated by aftershocks, is still uncertain since the shallower earthquakes located above the hypocenter occur on the fault plane of the M_W6.3 event, with ~5 km gap in between.

[11] A third large event is the Mw 5.4, 9th of April shock that is located on a fault offset from the main plane by a few kilometers northward. Focal mechanisms show a pure normal solution. The hypocenter is at about 11 km depth and its aftershocks define a steep SW-dipping plane (sez-1 in Figure 2b). Differently from the April 6 main shock, there are no events in the top 6 km of the fault, although its upper continuation is consistent with the surface trace of the Laga Mts. fault [*Boncio et al.*, 2004].

[12] The other $M_L \geq 4$ earthquakes occurred close to and at the same depth of the main event, except a very shallow aftershock located at 2.3 km depth (Table S1 of the auxiliary material).

5. Discussion and Conclusion

[13] The aftershock data clearly show the location and geometry of the fault ruptured by the L'Aquila earthquake (Figures 2 and 3). The rupture developed on a planar, ~45°, SW-dipping fault evident from 10 to 2 km depth. The seismicity cutoff at 2 km depth (Figure 2) suggests that the upper portion of the fault did not slip much, in agreement with the limited extent of surface breaks mapped by geologists

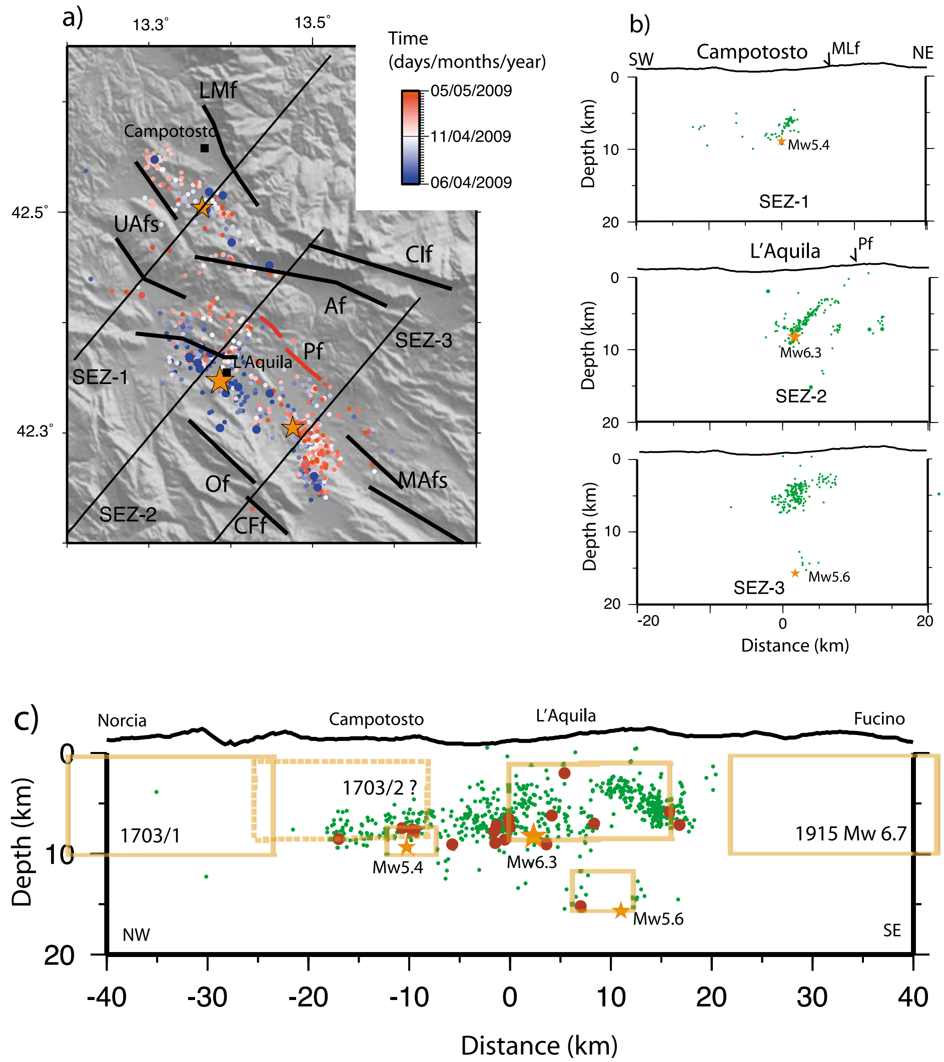

Figure 2. (a) Map of the 712 relocated events, with a color code indicating time after the main event. The dashed lines are the traces of vertical sections shown in Figure 2, and the solid lines are the mapped Quaternary faults [*Barchi et al.*, 2000]: (LMf, Laga Mts. fault; UAfs, Upper Aterno fault system; Af, Assergi fault; CIf, Campo Imperatore fault; MAfs, Middle Aterno valley fault system; OPf, Ovindoli Pezza fault; CFf, Campo Felice fault; Of, Ocre fault; Pf, Paganica fault). The box is a projection of the ruptured main fault. (b) Vertical sections across the Laga Mts. fault (SEZ-1) and the Paganica fault (SEZ-2, and SEZ-3). The fault geometry is consistently defined by the largest aftershocks. (c) Vertical section along the fault system, showing the geometry of the ruptured faults. Red dots are the $M_L \geq 4.0$ earthquakes. The 1703 and the 1915 earthquakes occurred at the north and southern border of the Paganica fault.

[*Emergeo Working Group*, 2009]. In the southern portion of the fault, the seismicity distribution is cloudy (sez-3 in Figure 2b), suggesting a change in the fault plane orientation along strike or, more likely, the transition to a more distributed deformation on several small faults.

[14] The extent of aftershocks near the surface coincides with an active fault recognized in the field that has a poorly constrained geometry, lateral continuity and doubtful seismogenic role (the Paganica fault of *Bagnaia et al.* [1992] or the "Aquilano s.l." fault of *Boncio et al.* [2004]). This poorly known fault is located close to other larger Quaternary faults previously considered to be the main seismogenic sources of the region [*Barchi et al.*, 2000; *Galadini and Galli*, 2000; *DISS Working Group*, 2005].

[15] Most of the aftershocks occur on the main fault plane around three patches that, we hypothesize, accounted for the largest slip during the main shock (the main asperities, see Figure 3). The aftershock data suggest a size of $\sim 10 \times 6$ km^2 for the main ruptured patch, whereas the second shallower patch is smaller, $\sim 5 \times 5$ km^2. The third patch is smaller and located northward of the first two. There is also a small volume around the main shock hypocenter where aftershocks are absent, probably around the fault portion where the initial onset of the rupture developed. All the largest magnitude events ($M_L \geq 4.0$) originate at about 11–8 km depth (excluding the 7th April event), and most of them around this volume that can be a compliant part of the fault plane, surrounded by the main asperities. The hypothesized asperity location well agrees with the maximum slip areas defined by DinSAR models [*Atzori et al.*, 2009].

[16] Macroseismic intensities assigned by immediate surveys in the epicentral area [*Camassi et al.*, 2009] are

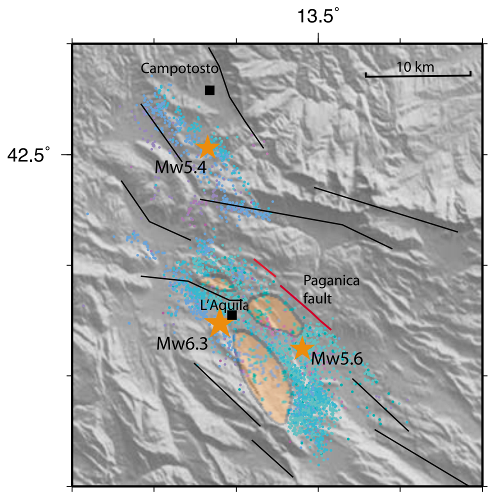

Figure 3. Map of the 3200 relocated events (see the auxiliary material) showing that aftershocks originate around three main patches that ruptured during the M_W 6.3 event (orange shaded zones).

comparable with those reported for historical earthquakes (the 1461 and the 1703 events). We infer that the repetition of similar earthquakes on the same fault ruptured in 2009 is very likely. DinSAR data clearly show that the creation of the intermountain L'Aquila basin is well correlated with the activity of the Paganica fault [*Atzori et al.*, 2009], whose geometry at depth is well constrained by our data. The expression of this fault at the surface is feeble, confirming that the present-day active extension in the Apennines is accommodated by young and not obvious faults (as for the Irpinia 1980 and Colfiorito 1997 cases [*Pantosti and Valensise*, 1990; *Chiaraluce et al.*, 2005]). In this scenario, the role of the large normal faults, mainly mapped by geomorphologic approach, still needs to be understood. Are they representing potential structure for M > 6.5 earthquakes, or do they include fossil or creeping segments? The present observation that the Paganica fault is accommodating the extension in the central Apennines area (3–5 mm/yr according to *D'Agostino et al.* [2008]) poses unambiguous evidence that at least some of the mapped faults are no longer active.

[17] One further issue raised by the earthquake is whether or not subsequent large shocks should be expected. The catalogue of historical earthquakes reports several multiple events in the Apennines, with elapsed times between events spanning from hours to a few years [*Gruppo di Lavoro CPTI*, 2004]. The 2009 aftershock data allow us to define the fault geometries and hence to infer the relationship with adjacent fault segments ruptured during past events (the 1915 Fucino earthquake to the south and the 1703 Upper Aterno to the north, see Figure 2c). The space-time distribution of seismicity shows a clear northward migration occurred soon after the main event and then ceased after about one week. The absence of seismic release in the upper 6–7 kilometers on the northern segment (Figure 2b) could be an indication for a future large shock. However, this area experienced a large earthquake in 1703 and frequent microseismicity in the last 30 years (Figure 1a) that probably decrease the seismic potential. A worst-case scenario could be a jump of activity in the southern portion of the central Apennines fault system, to the south of the 1915 Fucino earthquake, silent since 1349, where the accumulated strain is remarkable [*D'Agostino et al.*, 2008] and could turn to a large event. The recent seismicity in this southern portion is scarce [*Chiarabba et al.*, 2005; *Bagh et al.*, 2007], similarly to what observed before the 1997 and 2009 normal faulting events in central Italy.

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