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The Amatrice 2016 seismic sequence: a preliminary look at the mainshock and aftershocks distribution

Michele M.*, Di Stefano R., Chiaraluce L., Cattaneo M., De Gori P., Monachesi G., Latorre D., Marzorati S., Valoroso L., Ladina C., Chiarabba C., Lauciani V. and M. Fares.

Istituto Nazionale di Geofisica e Vulcanologia
maddalena.michele@ingv.it

Abstract

Three damaging earthquakes occurred in Central Italy between August and October 2016 leaving almost 30,000 homeless. The first event is a Mw 6.0 occurred on August 24th at 01:36 UTC close to Accumoli village; two months later, a Mw 5.9 on October 26th at 19:18 UTC happened 3 km West of Visso and finally a Mw 6.5 on October 30th at 06:40 UTC, 6 km North of Norcia, which is the largest earthquake recorded in Italy since the Mw 6.9 1980 Irpinia event. This paper focuses on the seismicity distribution observed from the beginning of the sequence until the 15th of September 2016, almost six weeks before the occurrence of the largest event. We relocated the aftershocks of the Mw 6.0 Amatrice 2016 main event by inverting, with a non-linear probabilistic location method, P- and S-arrival time readings produced and released in near real-time by the analyst seismologists of INGV on 24H duty in the seismic monitoring room. Earthquake distribution shows the activation of a normal fault system with a main SW-dipping fault extending from Amatrice to NW of Accumoli village for a total length of 40 km. Toward north, in the hanging-wall volume of the main fault, the structure becomes more complex activating an antithetic fault below the Norcia basin. It is worth nothing that below 8-9 km of depth, the whole fault system has an almost continuous sub-horizontal layer interested by an intense seismic activity, about 2 km thick.

Key words: Earthquake, Normal fault; Seismic sequence, Central Apennines.

I. Introduction

On the 24th of August, 2016 at 01:36 UTC a Mw 6.0 earthquake struck a region of Central Italy, severely damaging tens of villages and causing several fatalities. The seismic sequence, including a Mw 5.4 (UTC 2016-08-24 02:33:34) aftershock, produced hundreds of earthquakes per day until the middle of September when the seismicity rate (Ml >= 1.5) decreased from ~500 earthquakes/day to about 100. Two months after, on October 26th a Mw 5.9 earthquake occurred 14 km NNE of Norcia preceding the largest event of the sequence, a Mw 6.5 on 30th October at 06:40 UTC, 6 km North of Norcia. This ensuing phase of the sequence, enlighten a ~15 km long sector toward N-NW of Norcia and reactivated the northern sector of the previously activated fault system.

In this paper we focus on the analysis of the events related to the first part of the 2016 Central Italy sequence. The so called Amatrice sequence is located along the Apenninic sector extending across the Olevano-Antrodoco-Sibillini (OAS) [Centamore et al., 2009] tectonic alignment, a major inherited thrust front (NNE-trending), along which the Umbria-Marche and the Latium-Abruzzi domains come into contact. This is a tectonically active sector undergoing post-orogenic Quaternary extension, as expressed at surface by a set of NNW–trending normal faults [Pizzi and Galadini, 2009 and references

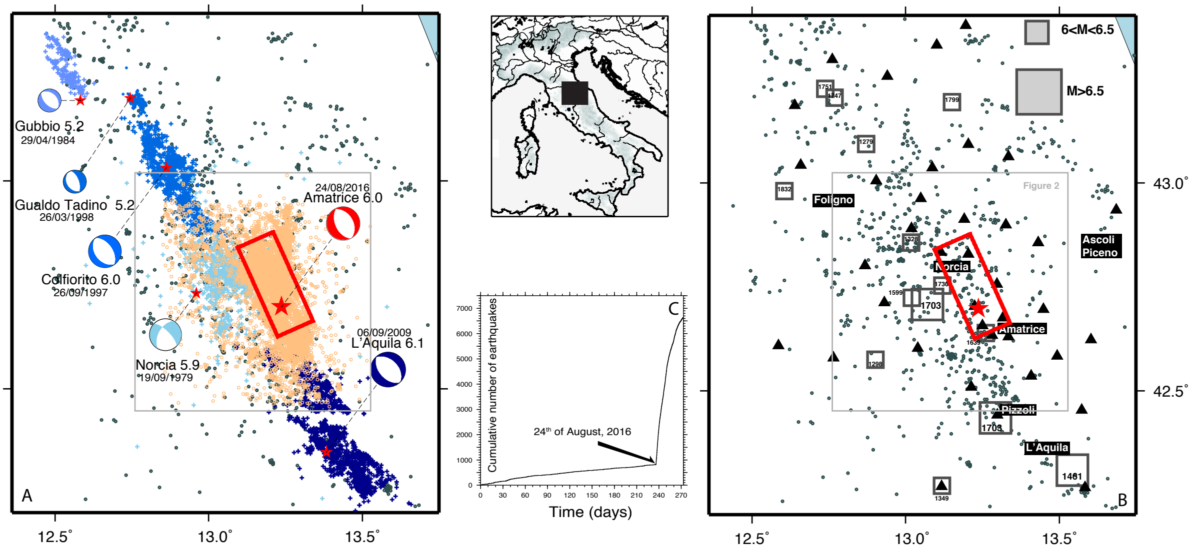

Figure 1. *Map of the study area. (A) Red stars = Mw ≥5.0; colored crosses= instrumental seismic sequences distinguished by colors; red box = Amatrice Mw 6.0 slip [Tinti et al., 2016]. (B) Black triangles = seismic stations; squares = historical earthquakes. (C) Cumulative number of earthquakes from 2016/01/01 to 2016/09/30. Grey small circles in A and B are background seismicity from 2016/01/01 to 2016/08/23 (http://iside.rm.ingv.it/iside).*

therein] and by the occurrence of a series of moderate magnitude historical and instrumental earthquakes (Figure 1A-B).

From 1984 a series of four seismic sequences activated a 150 km long and continuous sector of the chain with 5<Mw<6.1 events occurring on SW-dipping normal faults [Chiaraluce, 2012]. The Amatrice sequence is bounded to the north by the 1997 Colfiorito [Chiaraluce et al., 2003] and to the south by the 2009 L'Aquila [Valoroso et al., 2013] sequences.

As observed for other moderate-large earthquakes in the Apennines [Amato and Ciaccio, 2012], but differently from the 1997 Colfiorito [Ripepe et al., 2000] and the 2009 L'Aquila sequence [Lucente et al., 2010], the Amatrice earthquake was not forerun by a *standard* foreshock sequence. The background seismicity recorded in the area from January 1st 2016 to the Mw 6.0 of August 24th does not show any consistent variation in the monthly and/or daily seismicity rate with respect to the previous years, as observed by the space-time distribution (Figure 1B and 1C) of the events occurring in the epicentral area from 1st January 2016 until the day before the mainshock (23rd of August). The nearest historical event is the Mw 6.2 1639 one [Rovida et al., 2016], which seriously damaged the urban center of Amatrice and surrounding villages, while the largest one, hitting the region, occurred in 1703 when a sequence characterized by multiple-ruptures with two main events occurred within one month (in January and February with Mw 6.9 and Mw 6.7, respectively) [Rovida et al., 2016]. The first event has been associated to the Norcia Fault System by Galli et al. [2010]. In this paper we re-located the aftershock sequence of the Amatrice sequence covering a time window from the 24th August Mw 6.0 event to September 15th 2016, to reconstruct the first order geometry of the activated fault system. We used seismicity distribution also to investigate the main fault geometrical continuity between the two main patches ruptured during the Mw 6.0 mainshock, as identified by Tinti et al. [2016].

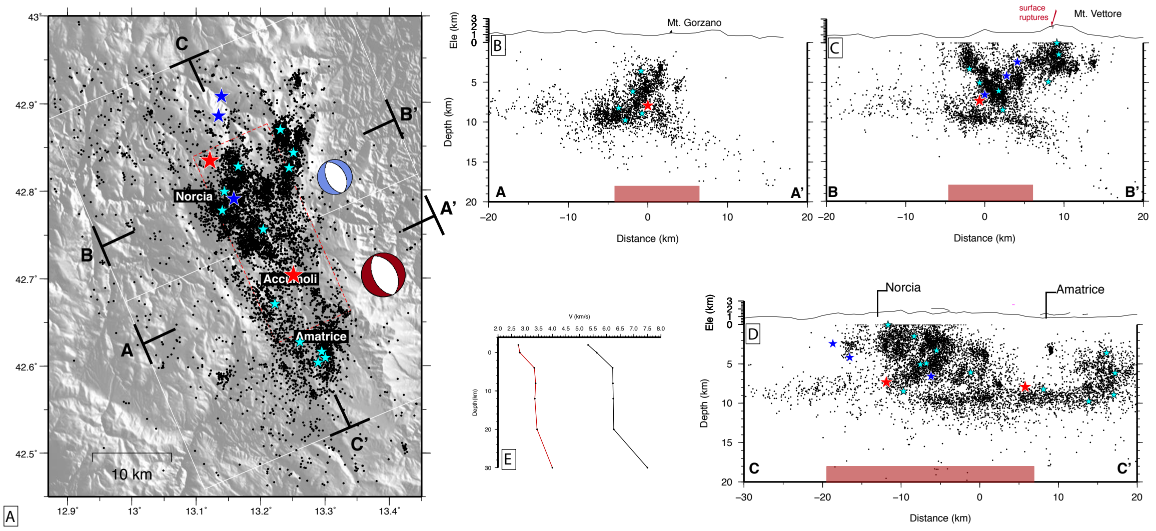

Figure 2. *Map view of the relocated aftershocks (black dots). Mw 6.0 and Mw 6.5 locations (red star); Mw 5.4 (2016/24/08), Mw 5.4 (2016/10/26) and Mw 5.9 (2016/10/26) locations (blue stars); aftershocks Mw > 4 location (light blue). Mw 5.4 (2016/24/08) and Mw 6.0 time domain moment tensors (blue and red beach balls). White boxes represent the thickness of vertical sections reported in Figure B and D, red box = Amatrice Mw 6.0 slip [Tinti et al., 2016]. (B): aftershocks distribution with depth, centered on the Mw 6.0. (D): aftershocks distribution with depth, centered on Mw 5.4 (2016/08/24). (C): aftershocks distribution along strike (155°). (E): 1D velocity model used for the locations (De Luca et al., 2009). Red bars below sections are the extension of the slip.*

II. Data and Methods

We re-located the aftershock sequence by inverting P- and S-wave arrival times, identified by the seismologists on duty in the seismic monitoring room of the INGV. Data are promptly released thanks to standard web-services giving direct access to the real time database [Pintore et al., 2016]. We analyzed the background seismicity and aftershocks occurring in the period from 2016/01/01 to 2016/09/15, recorded by the National Seismic Network (RSN, INGV), and the National Accelerometric Network (RAN, Civil Protection Department), plus 12 additional stations installed soon after the mainshock [SISMIKO Team, 2016]. The velocity model used for the location is a 1D gradient interpolated from the 1D velocity model of De Luca et al. [2009], in order to avoid seismicity scattering where velocity discontinuities were present (see Figure 2E). The 10,788 available earthquakes were relocated with a non-linear inversion code [NonLinLoc; Lomax et al., 2009] that provides a comprehensive description of the location uncertainties. To reduce systematic delays due to the use of a 1D velocity model we also used 143,825 P- and 116,824 S- arrival-times to calculate and apply stations corrections. Vp/Vs ratio was kept fixed to 1.85 (calculated with the Wadati method [1931]) only for the Mw 6.0 and the Mw 5.4 (Table 1). After applying the following quality selection criteria: i.e., RMS (Root mean square) ≤ 0.5 s; Erh (error of the horizontal components) ≤ 1.5 km ; Erz (error of the vertical component) ≤ 2.0 km; Gap (azimuthal coverage of the stations around the event) ≤ 180° and Nph (number of phases) ≥ 10, we ended up with a final catalogue composed by 8,340 well constrained events. Location statistics are reported in Table 2.

	Lat (°N)	Lon (°E)	Depth (km)	Nph	RMS (s)	Gap (°)	Erh (km)	Erz (km)
Mw 6.0	42.704	13.251	7.93	119	0.41	32.04	0.34	2.47
Mw 5.4	42.793	13.162	6.84	113	0.30	29.20	0.14	1.34

Table 1: *Mw 6.0 and Mw 5.4 location parameters: Lat (latitude), Lon (Longitude), Depth (Hypocentral depth), Nph (number of phases used for the location), Gap (stations azimuthal coverage around the event), Erh (error of the horizontal component), Erz (error of the vertical component).*

III. Results

In Figure 2 we show the aftershock distribution in map view and along three vertical cross sections where we project all the seismicity occurring within the two volumes highlighted in Figure 2A. Cross section AA′, centered on the Amatrice mainshock (Mw 6.0), shows aftershocks occurring between ~2 km and ~8 km of depth along a structure dipping ~54° to the SW. The mainshock is located at the lower tip of the fault, where the fault itself intersects a sub-horizontal seismicity layer located at about 9 km depth. The main fault seems to be roughly aligned with the Mt. Gorzano Fault outcrop (Figure 2B). Minor structures, identified by hypocenters alignments and a diffused seismicity, are visible in the footwall of the main fault. Section BB′, centered on the Mw 5.4 aftershock (UTC 2016-08-24 02:33:34), shows the presence of shallow seismicity up to 1 km or less. An antithetic structure is well imaged by hypocenters distribution in the 1-7 km depth interval, dipping at ~47° to the NE. The Mw 5.4 aftershock is located at the lower tip of this structure even if present data do not constrain the rupture plane. Close to the Mt. Vettore fault system, conversely, our locations seem not to show a clear continuous west dipping alignment. The sub-horizontal layer at about 8-9 km is still present in this portion of the fault system as confirmed by the along strike section CC′ (Figure 2D). The CC′ section also shows a lack of seismic activity in a large area of about 4x10 km^2 located right above the Amatrice mainshock. Furthermore, we observe that the October 26th Mw 5.9 is located in the northernmost and shallower portion of the entire fault system, while the October 30th Mw 6.5 event occurs at the northern termination of the sub-horizontal layer as activated up to the end of October 2016 (blue stars in Figure 2). Figure 3 shows the distribution of earthquakes with depth within layers of 1.5 km (between 0 and 6 km depth) to 4 km of thickness. We also show the hypocenter location of the Mw 6.5, Mw 5.9 and Mw 5.4 events of the following part of the seismic sequence. From 0 km down to 3 km of depth, seismicity is mostly confined to the WNW of the OAS and is distributed along two branches roughly diverging toward NNW. Earthquakes hypocenters within the first 1.5 km well correspond to the traces of the Mt. Vettore and Norcia fault systems, reported in blue [EMERGEO Working Group, 2016]. The western branch seems to correspond to the aftershocks related to the antithetic fault reported W of Norcia (cross-section BB′ in Figure 2). The position of this seismicity in map at increasing depths, from the trace of the Norcia fault toward NE, is due to the dip direction of the fault itself observed in cross section (Figure 2B). No seismicity is observed for this structure below 8 km depth: this lower limit coincides with the depth of the Mw 5.4 (Table 1).

	mean	median	σ
RMS (s)	0.09	0.09	0.04
Nph	26.56	25.00	11.19
Gap (°)	81.58	75.21	29.44
Erh (km)	0.21	0.14	0.19
Erz (km)	0.89	0.78	0.42

Table 2: *Location statistics: mean value, median value and standard deviation of statistics distribution. RMS: root mean square, Nph: number of phases, Gap: stations azimuthal coverage around the seismic event, Erh: error of the horizontal component, Erz: error of the vertical component.*

A different behavior is observed for the seismicity around the Mt. Vettore fault system. Here, the clusters of seismicity do not show the same directional migration. A third cluster of seismicity appears from 3 km downward in between the two faults. Below 4 km depth, seismicity is also present to the SE of the OAS and Gran Sasso (GS) oblique thrusts and of the mainshock, close to the Mt. Gorzano Fault [EMERGEO Working Group, 2016]. From 6 to 8 km of depth, the NW-SE alignment showed by seismicity distribution and striking between 140-150° is consistent with the Mw 6.0 and the Mw 6.5 locations. A continuous distribution of earthquakes crossing the OAS and the GS from Amatrice to Norcia is present only below 8 km corresponding to the abovementioned horizontal alignment.

IV. Discussion and conclusions

We analyzed the distribution of ~8,000 events occurred during the first 20 days of seismic activity after the Mw 6.0 Amatrice earthquakes. The events relocation performed with nearly real time data allow us to depict the first order geometry of the activated fault system. The sequence extends for about 40 km along a strike parallel to the axis of the Apennines, from about 5 km SE of Amatrice to about 10 km NW of Norcia, crossing two of the most important regional tectonic features of the Central Apennines, the OAS and the GS oblique thrust fronts. The Mw 6.0 Amatrice mainshock is located in between these two lineaments at a depth of ~8 km, below both the thrust surfaces [Bigi et al., 2013]. In map, the south-eastern seismicity is confined SE of the OAS, between the Mt. Gorzano and the GS thrust with depths ranging from 2.5 km to 8 km, depicting the main rupture fault with a dip of about 54° SW (Figure 2A). The fault plane imaged by the seismicity in this area is geometrically compatible with the surface outcrop of the Mt. Gorzano fault to which the 1639 Me 6.2 earthquake is associated [Lavecchia et al., 2002; Boncio et al., 2004, Pizzi et al., 2009]. In the north-western sector, the aftershocks are confined between the Mt Vettore fault system to the NE, and the Norcia fault system to the SW with depth ranging from the surface to about 8 km depth. Our locations clearly show a NE-dipping seismicity alignment associated to the Mw 5.4 aftershock, whose shallower part seems to correspond to the antithetic fault bounding the western flank of the Norcia basin. On the other hand, the seismicity close to Mt. Vettore shows no clear alignment from surface to depth nor a clear geometrical continuity with the main fault SE of the OAS. The seismicity around Mt. Vettore, in fact, seems to be more fragmented and organized in clusters, suggesting the possibility that such clusters might be related to several minor structures (plate 3-4 km and 4-5 km in Figure 3), though any inference in this sense needs further and more precise investigations. A sub-horizontal layer of seismicity is almost continuously distributed at about 8-10 km depth from south of Amatrice to Norcia. This feature, already observed in the Apennines [De Luca et al., 2009] is not an artifact either because the 1D model does not have a discontinuity at 8-10 km depth (see Figure 2E), and because we used a global search location method. A real feature, reported in Figure 2D, is also the lack of seismicity corresponding to the southernmost slip patch that Scognamiglio et al., [2016] refers to the Mw 6.0 event. It is worth noting that the subsequent major events (Mw 5.4, Mw 5.9 on Mw 6.5) occurred at the end of October partly insisted on the same fault already imaged by the previous seismicity enlarging its extend. By comparing the three-dimensional seismicity distribution with the known structural features of the area, we suggest that the OAS and GS oblique thrusts [Centamore et al., 2009; Di Domenica et al., 2014] might

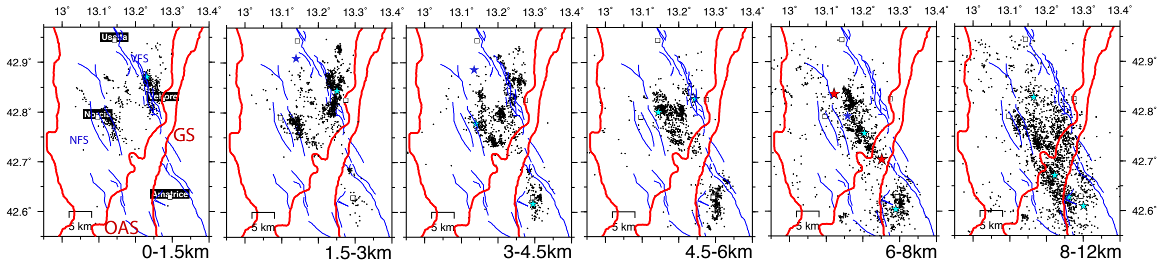

Figure 3. *Map view of relocated aftershocks, divided in 6 planes, corresponding to the ranges of depth 0-1.5 km, 3-4.5 km, 4.5-6 km, 6-8 km, and 8-12 km. Blue lines represent the faults mapped by EMERGEO Working Group (2016) while red lines represent thrust front traces (modified after Centamore et al., 2009). GS = Gran Sasso thrust front, OAS = Olevano-Antrodoco-Sibillini thrust front, NFS Norcia fault system and VFS Vettore fault system. Red stars represent the Mw 6.0 and Mw 6.5 locations, blue stars represent the Mw 5.4 (2016/08/24), Mw 5.4 (2016/10/26) and Mw 5.9 (2016/10/26) locations, light blue stars represent Mw > 4 locations.*

have played an important role influencing the activation of the Amatrice 2016 fault system separating two domains with strongly different seismicity distribution. This interference might have induced a sort of multiple segmented activation. Such hypothesis is similar to the activation model proposed by Chiaraluce et al., [2005] for the Colfiorito-Sellano 1997-1998 seismic sequence and was already mentioned related to the Norcia fault system for the 1703 earthquake [Blumetti, 1995; Galadini et al., 2000] and, more in general, for the NW-SE-trending normal fault propagation [Tavarnelli et al., 2004; Pizzi and Galadini, 2009]. We thus argue that though the mainshock activated both the Mt. Gorzano fault and the Mt. Vettore fault system, according to the slip model by Tinti et al. [2016], this happened by a transfer of stress across the above mentioned regional scale compressive structure.

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