# BOLLETTINO SISMICO ITALIANO: ANALISYS OF EARLY AFTERSHOCKS OF THE 2016 MW 6.0 AMATRICE, MW 5.9 VISSO AND MW 6.5 NORCIA EARTHQUAKES IN CENTRAL ITALY

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The Amatrice-Visso-Norcia seismic sequence is the most important of the last 30 years in Italy. The seismic sequence started on 24 August, 2016 and still is ongoing in central Apennines. At the end of February 2017 more than 57,000 events were located, 80,000 events up to the end of September 2017 (Fig. 1). The mainshocks of the sequence occurred on 24 August 2016 ($M_w$ 6.0 and $M_w$ 5.4), 26 October 2016 ($M_w$ 5.4 and $M_w$ 5.9), 30 October 2016 ($M_w$ 6.5), 18 January 2017 (four earthquakes $M_w \geq 5.0$).

In this seismic sequence, all the waveforms recorded by temporary stations deployed by the SISMIKO emergency group (stations T12**; Moretti *et al.*, 2016) where available in real-time at the surveillance room of INGV. Because of the high level of seismicity and the dense seismic network installed in the region, more than 150 events per day were located at the end of February 2017; still 60 events per day were located up to the end of August 2017.

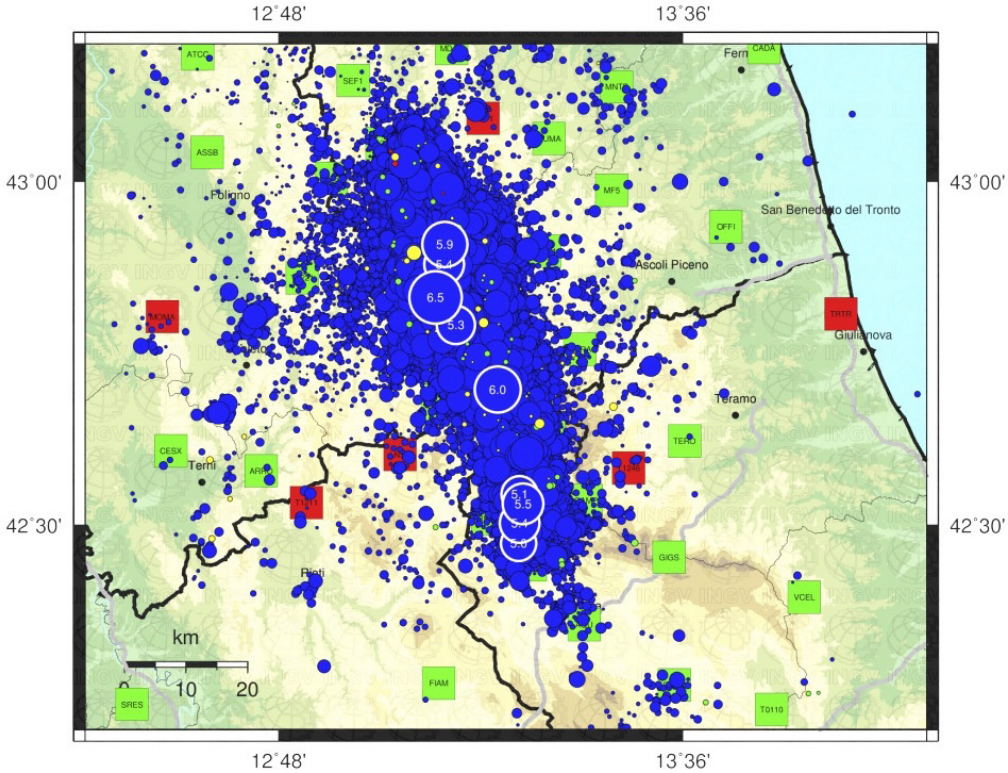


Fig. 1 - Map of the seismicity of the Amatrice-Visso-Norcia seismic sequence (AVN.s.s) from August 24th, 2016 to September 30th, 2017.

The Amatrice-Visso-Norcia is the most important seismic sequence since 2015, the time when the analysis procedures of the BSI group (Bollettino Sismico Italiano) were revised (Nardi *et al.*, 2015). BSI is now available every four months on the web: bulletins contain revised earthquakes (location and magnitude) with $M_L \geq 1.5$, quasi-real time revision of $M_L \geq 3.5$ earthquakes and phase arrivals from waveforms recorded on seismic stations available from the *European Integrated Data Archive* (EIDA), (Mazza *et al.,* 2012).

These last procedures allow the integration of signals from temporary seismic stations (Moretti *et al.*, 2014) installed by the emergency group SISMIKO (Moretti and *Sismiko working group*, 2016), even when they are not in real time transmission, if they are rapidly archived in EIDA, together with real time signals from the seismic stations of the permanent INGV network.

The analysis strategy of the BSI group for the Amatrice -Visso - Norcia seismic sequence (AVN.s.s in the following) was to select the earthquakes located in the box with min/max latitude: 42.2/43.2 - and min/max longitude: 12.4/14.1 to prepare a special volume of BSI on the seismic sequence.

For the earthquakes belonging to the AVN.s.s we used specific rules and duty timing, different from the standard analysis of the remaining Italian seismicity. We still revised within 48h from their occurrence all the 275 earthquakes (up to September 24, 2017) belonging to the AVN.s.s, with $M_L \geq 3.5$ (137 of them have also an Mw estimation from Time Domain Moment Tensor). Besides we revised location and magnitude of all the earthquakes in the sequence box, but with $M_L \geq 2.3$. This choice depends on the elevated number of events recorded at the INGV integrated seismic network, up to 80,000 until now (Fig. 2).

Moreover we defined a plan for the review of the early aftershocks, stressing our interest and focusing our analysis on the early aftershocks immediately following the major mainshocks ($M_w$ 6.0 e 5.4 of August 24, $M_w$ 5.4 e 5.9 of October 26, $M_w$ 6.5 of October 30, 2016 and the events $M_w \geq 5.0$ of January 18, 2017).

The first hours after a mainshock are the most critical for seismic surveillance. In fact in INGV seismic surveillance room, the hours immediately following the strongest earthquakes of the 2016 AVN.s.s have been the most critical because the frequency of seismic events was greatest and the personal on duty was not sufficient to follow it. Indeed the locations of the

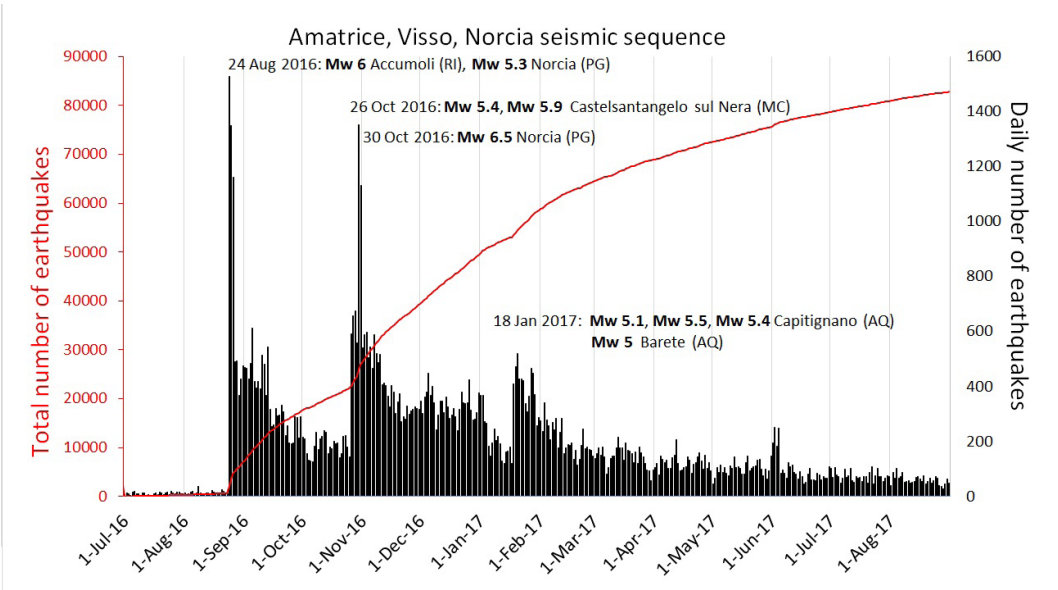


Fig. 2 - Daily number of located earthquakes of the AVN.s.s (black) and cumulated number of earthquakes (red).

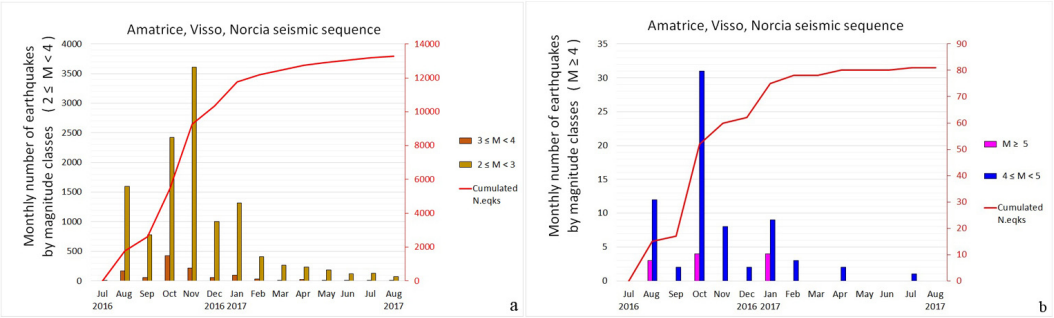


Fig. 3 - a, b: Monthly number of earthquakes of the AVN.s.s, per classes of magnitude with 2 ≤ ML < 4 (a) and with ML ≥ 4 (b). The red lines show the cumulated number of earthquakes.

early aftershocks give very important clues on the initial fault activation and are fundamental to understand the physical mechanisms of earthquake triggering (i.e. Peng *et al.,* 2006; Peng and Zhao, 2009; Tang *et al.*, 2014, Wu *et al.*, 2017). During the 2016-2017 seismic sequence we developed new tool to better evaluate the local magnitude (ML) of the earthquakes (Bono, personal communication) giving to the personnel on duty in the surveillance room and also to the analysts of the Bollettino Sismico Italiano the opportunity to revise the values of the Wood-Anderson amplitudes picked by the automatic system (Earthworm) (Figs. 3a and 3b).

In Marchetti *et al.* (2016) we published preliminary analysis on the completeness and hypocenters distributions of all the events between 00:00 and 08:00 UTC of August 24$^{th}$, 2016. We compared the seismicity analyzed by the seismologists of the surveillance room in Rome, with the earthquakes revised by the analysts of the Bollettino Sismico Italiano. In particular, we revised all automatic locations performed by the Earthworm system (Pintore *et al.*, 2016). In these eight hours of the first day of AVN.s.s the surveillance room located 133 events while the BSI located 408 events.

We already started the review of the days following the 2016 $M_w$ 6.0 Amatrice, $M_w$ 5.9 Visso and $M_w$ 6.5 Norcia and $M_w \geq 5$ Campotosto earthquakes. These "special days of analysis" include August 24, 25, 26, October 26, 27, 30 and 31, November 1 and January 18. The automatic locations produced by the Earthworm system, resolvable by the analysts, are about one per minute. For each day, the revision of the analysts increases the number of located earthquakes by a factor of three, on average (Tab. 1).

Tab. 1 - State of the art of Amatrice-Visso-Norcia seismic sequence analysis by BSI Group, up to September 30, 2017.

| | Surveillance room | BSI | Total |
|---|---|---|---|
| From 08-24-2016 to 08-31-2017 | 76820 | 9177 | 80462 |
| 08-24-2016 | 355 | 1122 | 1477 |
| 08-25-2016 | 467 | 807 | 1274 |
| 08-26-2016 | 377 | 771 | 1148 |
| 10-26-2016 | 249 | 314 | 563 |
| 10-30-2016 | 469 | 880 | 1349 |

For the earthquake location we are using all the temporary stations deployed by SISMIKO emergency group (stations T12**; Moretti *et al.*, 2016). Thanks to special procedures, introduced to study the sequence, the analysts can read signals from all the seismic stations available in the archive EIDA (European Integrated Data Archive, eida.rm.ingv.it/). We had the chance to look at all the waveforms of the sequence and could recognize peculiar aftershocks with a strong