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Spatial variation of the *b*-value observed for the periods preceding and following the 24 August 2016, Amatrice earthquake (M_L6.0) (Central Italy)

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Abstract

This paper deals with a preliminary spatial and temporal analysis of the b-value variability, observed in the area where the August 2016 Amatrice earthquake (M_L6.0) occurred. With comparison of the pre- and post-periods of the mainshock, an investigation of anomalous zone of b-values was performed aiming to find possible links with barriers and/or asperities in the crustal volume where seismic sequence was developed. Preliminary results show an area with high b-value (b=1.6) where the mainshock originated. Conversely, two low b-value (b=0.8) volumes are located at the border of the seismogenic structure. The location of these two areas is consistent with a preliminary fault slip inversion, suggesting the presence of two highly stressed patches of co-seismic deformation located NW and SE of the mainshock, with a high potentiality to rupture causing a possible moderate or larger event: the first one in the North (Norcia), the second one in South, next to the area of Amatrice and Campotosto.

I. INTRODUCTION

On 24 August 2016 1:36:32 (UTC) a local magnitude 6.0 earthquake, 8 km deep, occurred in Central Italy, close to Accumoli, a village in the area located between two towns: Norcia and L'Aquila. It ruptured a SW dipping, NNW-SSE trending fault segment. The mainshock has triggered a strong sequence of aftershocks (blue colour in Figure 1) that involved a portion of the Apennine chain along an axis of about 50 km (from Ussita village till Campotosto Lake) and about 15 km deep. The spatial aftershock distribution suggests the activation of different fault segments (Mt. Vettore fault segment and several other antithetical structures dipping towards NE) following the main shock occurred on 24 August, 2016. The area affected by the Amatrice earthquake sequence is located in a portion of the Central Apennines with a complex tectonic setting. An extensional tectonic regime, with several major Quaternary normal faults oriented along the axis of the whole Apennines (NW-SE), is superimposed on an inherited thrust sequence. This is mainly made of the Umbria-Marche Carbonatic-Mesozoic sequence (North-western half) and of Latium-Abruzzi flysch tertiary sequence (South-eastern half), split by the inactive thrust of Sibillini Mts. (Olevano – Antrodoco line). The Quaternary normal faults border the Laga Mt., the Vettore Mt., the Norcia basin and the nearby Quaternary intermountain basins. Despite its moderate extent, the Amatrice earthquake claimed 309 lives; the town of Amatrice was destroyed entirely as well as many surrounding villages. The area had been affected by a destructive earthquake in 1639 (Amatrice, Io 9-10 MCS, M_w6.2) which caused 500 fatalities.

Recently, Central Italy has been struck by two strong mainshocks: one occurred in 1997, Colfiorito earthquake with M_w6.0 (Umbria-Marche region) and the other one in 2009, L'Aquila earthquake with M_w6.3 (Abruzzo region).

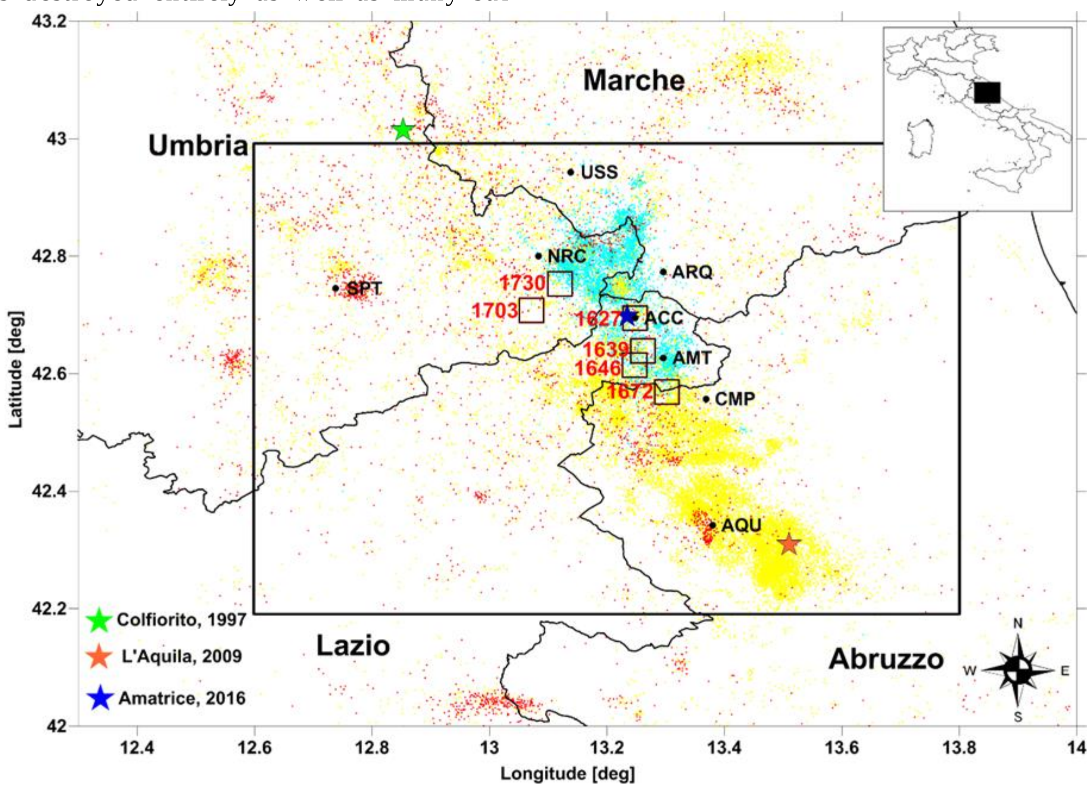

Figure 1. *Shallow seismicity map (M_w≥1.4) for the Central Apennines region (April 16, 2005-September 16, 2016). Historical seismicity (CPTI15 release 1.5, Rovida et al. 2016) is highlighted by black squares (the numbers are referred to the years of occurrence). The main shocks of the 1997 Colfiorito, 2009 L'Aquila and the recent 2016 Amatrice are shown as green, red and blue stars, respectively. The seismicity of three analyzed time periods is reported in different colors: the first* one in red, the second one in yellow and the *last in blue (see for details Table 1). The black box highlights the area under study (i.e., 12.6°E–13.8°E, 42.2°N–43.0°N). Black dots are the main towns: AQU=L'Aquila, CMP=Campotosto, AMT=Amatrice, ACC=Accumoli, ARQ=Arquata del Tronto, NRC= Norcia, USS=Ussita.*

Spatial and temporal variations of *b*-value of the *Gutenberg-Richter* (*G-R*) relation (1944), have been extensively studied for various tectonic regimes. This parameter depends on the stress regime, the tectonic character of the region, the heterogeneities of materials, and the temperature [i.e., Scholtz, 2015].
These factors can cause, locally, changes in the *b*-value compared to the global average value (assumed equal to 1).

Low *b*-values have been correlated with areas of asperity, locked part of a fault where the nucleation of earthquakes is likely to happen [*Schorlemmer et al.*, 2004, *Schorlemmer* and *Wiemer*, 2005, *Torman et al.*, 2012].

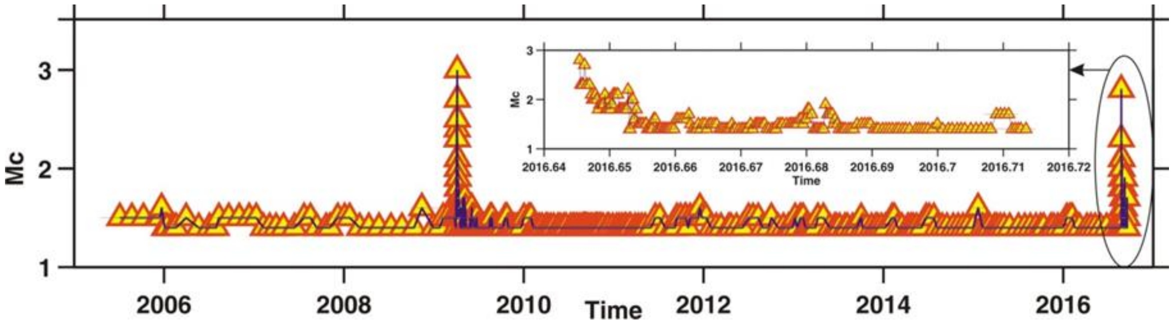

Figure 2. *Plot of M_c with time for all the analyzed period (April 16, 2005-September 16, 2016). In the upper right corner, the M_c zoom for the 2016 Amatrice sequence is depicted in the inset box (August 24-September 18, 2016).*

Recently a few authors have found that *b*-value in the continental crust decreases down to a depth corresponding to the transition between brittle and ductile material; below this depth the *b*-value was observed strongly increasing [i.e., *Mori and Abercrombie*, 1997; *Spada et al.*, 2013; *Scholtz*, 1968 and 2015]. High *b*-values have been correlated with the highest slip during large earthquakes [*Görgün et al.*, 2009; *Sobiesiak et al.*, 2007]. Moreover, they were even associated with the presence of fluids in the aftershock areas, facilitating the evolution of the sequence itself. The occurrence of a strong aftershock may be due to the upwelling of deep fluids which can reduce the effective stress and then trigger an earthquake [*Wand and Manga*, 2009]. A few authors highlighted that many aftershock sequences were mainly distributed in high pore pressure areas and their spatio temporal distribution could had been related to the transport of fluids. Such analysis was conducted in Italy for both sequences like the one in 1997 (Colfiorito) and the sequence in 2009 (L'Aquila) [*Malagnini et al.*, 2012; *De Gori et al.*, 2012; *Miller et al.*, 2004] and in some other countries: 1992 Landers earthquake [*Bosl and Nur*, 2002], the aftershocks of northern Chile's 1995 Antofagasta earthquake [*Shapiro et al.*, 2003] and aftershocks following the 2008 Wenchuan *Ms* 8.0 earthquake occurred in China [*Liu et al.*, 2013].

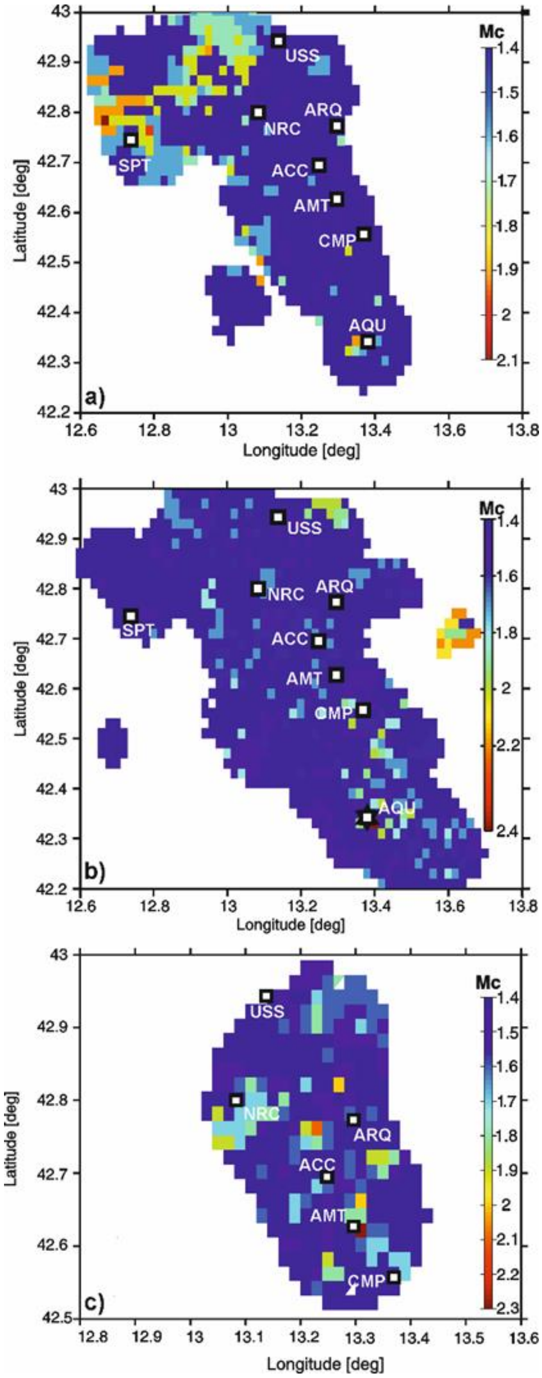

Figure 3. *Maps of completeness magnitude for each period (I-II-III in Table1). White* squares *are the main towns shown in Figure 1 as black dots.*

The spatial variation of *b*-value of the *Gutenberg-Richter* (G-R) relation in the area hit by the sequence, before and after the Amatrice earthquake, is investigated in the present work. The aim is to understand the meaningful variations of *b*-value that could be linked with the stress accumulated within an asperity placed along or around a fault surface. The period before the Amatrice mainshock includes the seismic sequence of L'Aquila earthquake in 2009

The technique employed in this paper has been already applied by the authors in different tectonic areas [*Murru et al.*, 1999, 2004, 2005; *Montuori et al.*, 2010; *De Gori et al.*, 2012].

II. DATA AND ANALYSIS

The data used in this study (April 16, 2005 to September 18, 2016) are drawn from the Italian Seismic Instrumental and Parametric Database (ISIDE) provided by INGV. An area containing 27,223 events having magnitude $M_L \geq 1.4$ and depth ≤30 km was selected (see black box in Figure 1). The first step was to calculate the magnitude of completeness (M_c) which is an important parameter when estimating *b*-values [*Wiemer* and *Wyss*, 2000]. M_c is computed as a function of time by sliding the time windows, each containing 150 earthquakes and stepping by 5 events (Figure 2). M_c values, for the whole period analyzed, change from 1.4 to 1.9, except for two periods of time correlated with two strong events occurred in April 2009 (L'Aquila) and in August 2016 (Amatrice), where M_c reaches the value of about 3.0. In the early hours of a seismic sequence may be very difficult to detect small shocks; this may lead, as a consequence, to an increase of the magnitude of

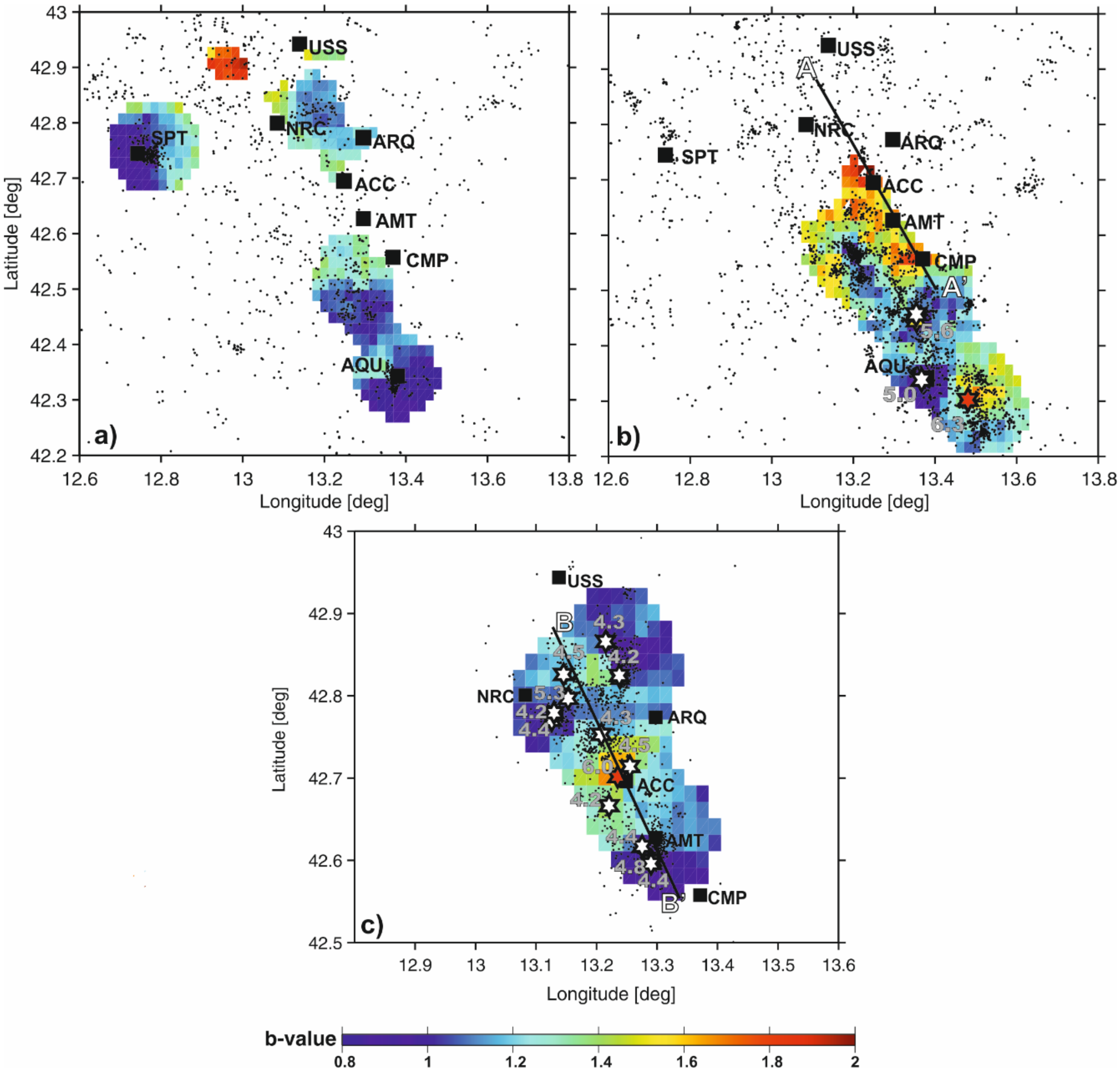

Figure 4. *Maps of b-values for the three periods shown in Table 1. a) I period ($M_c \geq 1.7$); b) II period ($M_c \geq 1.9$); c) III period ($M_c \geq 2.1$). The AA' and BB' lines indicate the b- value cross-sections of Figures 5a and 5b, respectively. In Figure 4b the red star is related to the 2009 L'Aquila earthquake, while the white stars indicate the strongest aftershocks of the sequence. Figure 4c shows the 2016 Amatrice aftershocks (white stars) with $M \geq 4.2$ and the location of the mainshock (M6.0) (red star). Black squares are the main towns.*

completeness [*Enescu et al.*, 2007].

Afterwards the catalog was split into three periods (Table 1). The first one ranges from

2005 to the time just before the L'Aquila mainshock that occurred in April 2009. The second one includes the aftershocks sequence of L'Aquila earthquake (the first month is not included in the analysis) and the seismicity occurred just before the Amatrice earthquake The last time period spans from the Amatrice aftershocks sequence (a few hours following the mainshock) to the end of the dataset (September 16, 2016).

The beginning of the last two periods does not coincide with the occurrence of two mainshocks because it has been preferred to take into consideration the periods when the completeness magnitude reaches stable values.

M_c has been then recalculated as a function of space for each considered period (Figure 3), by using the best combination method in software package Zmap [*Wiemer*, 2001].

By mapping M_c, the range of magnitudes, as well as the spatial extent in which these magnitudes are reported completely, can be determined [Wyss and Stefansson, 2006]. In Table I has been also reported the M_c and the number of events with $M>M_c$ contained in each period.

Once the M_c value has been calculated, the mapping of the *b*-value in space has been drawn for the three catalogs. A grid of 2 km spacing and a fixed number of events (N=80) for each node has been employed. The sampling volumes are cylinder-shaped with horizontal axes and radii inversely proportional to the seismicity density. We only plot events within a maximum cylinder radius ranging from 1.0 to 6 km for the first and second periods, from 1.0 to 5 km for the third one (Figure 4).

The maximum likelihood estimation method is used to determine *b*-values [*Aki*, 1965].

Table I: *Time periods choose for the analysis. M_c and events in each period are also reported*

	Periods	M_c	N events
I	16/ 04/ 2005 06/ 04/ 2009	1.7	1187
II	08/ 05/ 2009 23/ 08/ 2016	1.9	2803
III	24/ 08/ 2016 18/ 09/ 2016	2.1	1234

In order to analyze the *b*-value in depth, the earthquakes are projected onto vertical cross-sections along the strike of the fault (Figure 4 and Figure 5). The node separation for these cross sections was 2 km and samples of N=60 were considered. The maximum radius considered for these cross sections is 5 km for both time periods. To estimate the statistical meaningful of the *b*-value, the method of *Shi and Bolt* (1982) was employed.

To measure the confidence limits of the *b*-value anomalies for the sections, the Utsu's test [*Utsu*, 1992] was then employed.

III. RESULTS AND CONCLUSIONS

Maps of the spatial distribution of the *b*-value are shown in Figure 4.

For the first period (Figure 4a) the lowest *b* value (*b* about 0.8) is found in the area where the L'Aquila mainshock was nucleated. The decrease in *b*-value could be correlated with fault asperity (*Görgün*, 2013). Similar low *b* values (~0.8) has been observed in a region SW of Spoleto (SPT). The *b* parameter, between Norcia (NRC) and Campotosto (CMP), varies from 1 to 1.4 and it is very high (~2) in the northern part of the area.

Table II: *Mainshock and aftershocks occurred during the 2016 Amatrice sequence (24/08/2016-18/09/2016). The time is reported in UTC.*

Time yyyy/ mm/ ddhh:mm	Lon (°E)	Lat (°N)	M_L
2016/ 08/ 24 01:36	13.234	42.698	6.0
2016/ 08/ 24 01:37	13.253	42.712	4.5
2016/ 08/ 24 01:56	13.275	42.614	4.4
2016/ 08/ 24 02:33	13.154	42.794	5.3
2016/ 08/ 24 04:06	13.125	42.769	4.4
2016/ 08/ 24 11:50	13.146	42.819	4.5
2016/ 08/ 24 17:46	13.222	42.663	4.2
2016/ 08/ 25 03:17	13.208	42.753	4.3
2016/ 08/ 25 12:36	13.290	42.596	4.4
2016/ 08/ 26 04:28	13.290	42.600	4.8
2016/ 08/ 28 15:55	13.238	42.820	4.2
2016/ 09/ 03 01:34	13.13	42.775	4.2
2016/ 09/ 03 10:18	13.215	42.866	4.3

Figure 4b shows the aftershocks sequence of L'Aquila earthquake and the seismicity before the mainshock of the Amatrice earthquake. In the same figure, the epicenter of the L'Aquila mainshock is also plotted. With respect to the previous period, an increase of the *b*-value in an area between Campotosto (CMP) and Accumuli (ACC) is clearly seen; at the same time, a decreasing of *b*-value is found to the West of Campotosto and Amatrice (b~0.9), where most of seismicity is concentrated.

Figure 4c shows the distribution of *b*-value calculated using Amatrice aftershocks (Table II). The *b*-values in aftershock zone vary between 0.8 and 1.6. The highest *b*-values, are found near the mainshock epicenter, which is reported only for comparison. Lowest *b*-values are found in the SE (Amatrice and Campotosto) and in the N-NE (between Arquata del Tronto and Ussita) of the mainshock epicenter.

To define the distribution of *b*-value anomalies in depth, before and following the mainshock of Amatrice earthquake, the *b*-value analysis has been performed on the cross sections AA' and BB', projecting the seismicity within 10 km on each side of the cross sectional plane (Figures 4b and 4c).

Section AA' (Figure 5a) shows an area of anomalous high *b*-value (2.1±0.25) located around Accumoli area, between 6 and 12 km depth. A well-defined variation from high to low *b*-value, both vertically and laterally can be observed in the area between Accumoli (ACC) and Campotosto (CMP). It may be interpreted as a transition from brittle to ductile behaviour. The low *b* anomaly (about 0.9) observed below Amatrice (AMT) could be considered as a asperity zone located at the border of the area where the Amatrice earthquake was nucleated. The *p* test [Utsu, 1992] has been employed to quantify the statistical significance of the anomalous areas. The result of this test suggests that the hypothesis that the examined samples have the same *b*-values, can be rejected as it is not statistically significant at the 99% level (left bottom panel in Figure 5a).

Figure 5b shows a region at the SE of the Amatrice mainshock hypocenter of high b-value (1.65±0.2) around 10 km. Above Amatrice and Norcia areas are clearly evident two zones with low b-values (0.8±0.1) where the majority of aftershocks with M>4.2, occurred in this period, are concentrated.

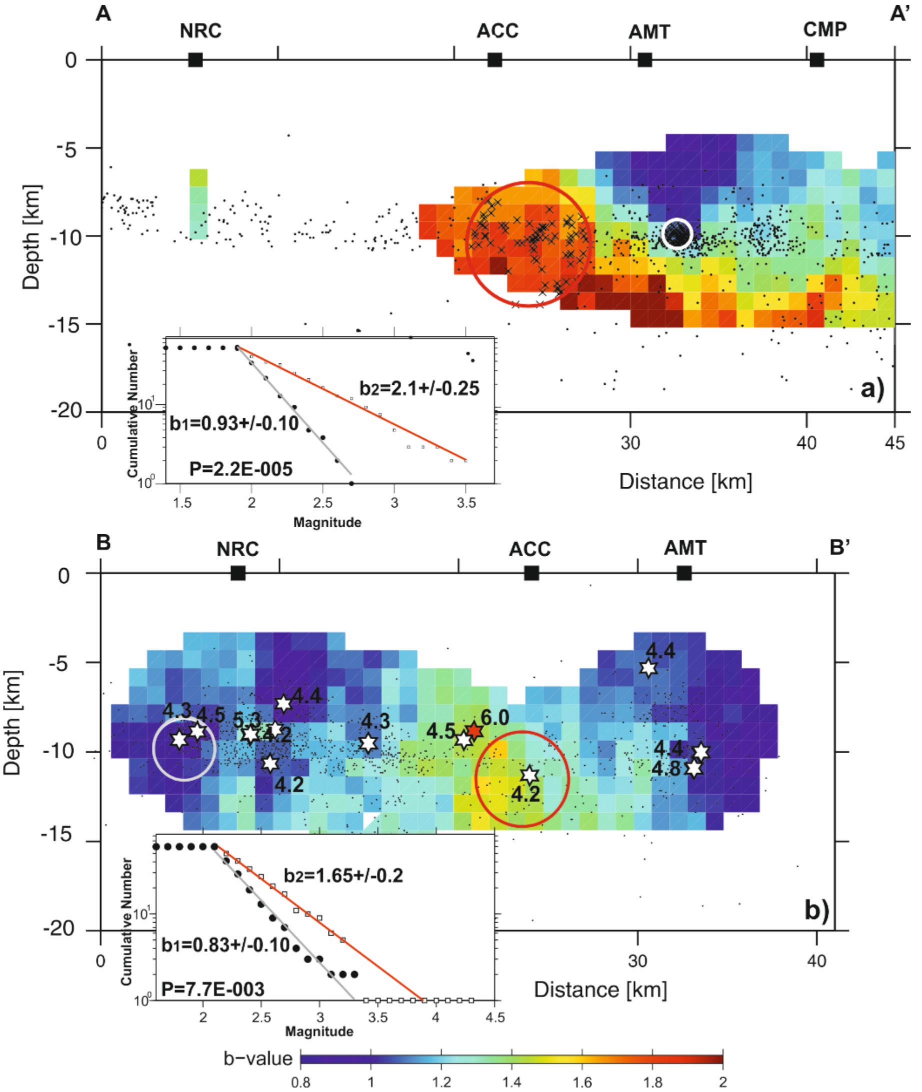

Figure 5. *Cross-sections of the distribution of b-values along the profiles shown in Figures 4b and 4c. (a) AA' cross-section. (b) BB' cross-section. The red and grey circles represent the volumes of high and low b-values used to calculate the FMDs. The white stars represent the aftershocks occurred during the Amatrice sequence. The red star is related to the 2016 Amatrice mainshocks.*

The probability that the two samples with high and low b-values belong to the same population is P= 7.7E-003, according to the Utsu test.These results well match a preliminary fault slip inversion that suggests the presence of two highly stressed patches of co-seismic deformation located SE and NW of the hypocenter which ruptured with the mainshock of 24 August [*Gruppo di lavoro INGV sul terremoto di Amatrice*, 2016]. Such patches, which are correlated to low *b*-values may have high potentiality to rupture causing a possible moderate or larger event (*Görgün*, 2013; *Tormann et al.*, 2013 and reference therein).

During the review process a strong event (M_w6.5) occurred on 30 October 2016 (06:40:17 UTC) 5 km from Norcia (42.84°N-13.11°E) and 9 km depth. This event was preceeded by two other strong shocks (magnitude M_w5.4 and M_w5.9) on 26 October 2016, between Norcia and Ussita. The M_w6.5 Norcia earthquake is the most powerful earthquake striking Italy since the 1980 M_w6.9 Irpinia event. Interestingly, the Norcia earthquake is located at the border which delimits the low *b*-value area highlighted by our analysis below Norcia (Figure 4c and 5b),The analysis performed so far and described in this paper is still in progress and will be improved by extending the period of aftershocks to map the distribution of the *b*-value along the fault planes responsible both the M_L6.0 Amatrice and M_w6.5 Norcia earthquakes. The future results will be compared with other multidisciplinary studies to better understand the earthquake occurrence in this area. This analysis suggests that monitoring the evolution of *b*-value might be useful for the evaluation of seismic hazard and earthquake forecasting.

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