

# Changes in seismic attenuation due to fracturing and fluid migration during the 2016-2017 Central Italy seismic sequence

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## Key points:

- 4D imaging of seismic scattering and absorption, before and during the 2016-2017 Amatrice-Visso-Norcia (Central Italy) seismic sequence
- Scattering imaging is highly influenced by lithological and structural features of the Central Apennines
- High-absorption anomaly is spatially related to deep CO<sub>2</sub>-bearing fluids, migrated along the fault network during each seismic sequence

**Abstract**

The Amatrice-Visso-Norcia seismic sequence struck Central Italy across the Apenninic normal faults system in 2016. Fluids likely triggered the sequence and reduced the stability of the fault network following the first earthquake (Amatrice,  $M_w6.0$ ), with their migration nucleating the Visso ( $M_w5.9$ ) and Norcia ( $M_w6.5$ ) mainshocks. However, both spatial extent and mechanisms of fluid migration and diffusion through the network remain unclear. High fluid content, enhanced permeability and pervasive microcracking increase seismic attenuation, but each process contributes to different attenuation mechanisms. Here, we measured and mapped peak delay time and late-time coda attenuation, using them as proxies of seismic scattering and absorption before and during the sequence. Structural discontinuities and lithology control scattering losses at all frequencies, with the highest scattering delineating carbonate formations within the Gran Sasso massif. The Monti Sibillini thrust marks the strongest contrasts in scattering, indicating a barrier for northward fracture propagation. Before the sequence, low-frequency high-absorption anomalies distribute around the chain axis. A single high-absorption anomaly bounded north by the Monti Sibillini thrust develops NNW-SSE across the seismogenic zone during the sequence. This spatial expansion appears related to the deep migration of  $CO_2$ -bearing fluids across the strike of the fault network from a deep source of trapped  $CO_2$  near the Amatrice earthquake. Migration develops primarily during the Visso sequence, followed by diffusion across the fault zones during the Norcia sequence. High-scattering and high-absorption focus below the carbonates south of Norcia during the sequence, mapping the progressive northern permeation of the seismogenic zone from south to north.

**Plain Language Summary**

Central Italy is characterized by significant seismic sequences, as the one of the 2016-2017 across the Apennine Chain, known as the Amatrice-Visso-Norcia sequence. Fluids migrating in the fault system have been already recognized as the trigger of this seismicity. However, the migration between the

faults of this mountain belt is not clear yet. Seismic attenuation (a description of how the seismic wave is losing energy during its path) can help in understanding the interaction between fluids and the fractures (e.g., faults). Here, we are looking at two seismic sequences, one between 2013 and 2016 (pre) and one during the 2016-2017 sequence. We applied two different techniques, the peak delay time and the coda attenuation, that describe the amount of fractures and the presence of fluids in the medium, respectively. In our results, the former is controlled by the presence of faults and fractures in the lithologies, as the high scattering around the Gran Sasso massif, which is highly fractured. The coda attenuation imaging is showing, at different time periods, how the deep-CO<sub>2</sub> fluids migrated in each seismic sequence, focusing along the Central Apennine chain at the end of the Norcia mainshock.

## 1. Introduction

Between August and October 2016, 25,600 earthquakes ( $0.1 < M < 6.5$ ) struck the Central Apennines chain in Central Italy (Chiaraluce et al., 2017). Eight events had  $M_w > 5.0$ , with three mainshocks occurring near Amatrice ( $M_w$  6.0, August 24, 2016), Visso ( $M_w$  5.9, October 26, 2016) and Norcia ( $M_w$  6.5, October 30, 2016). The Amatrice-Visso-Norcia sequence (AVN) developed on the NNW-SSE-trending normal fault systems of Mt. Vettore (north) and Mt. Gorzano (south), activating a 70 km x 10 km area trending parallel to the major axis of the central Apennines (Improta et al., 2019). The fault mechanisms were consistent with the extension of the central Apennines, which coexists with the opening of the Tyrrhenian back-arc basin (Chiaraluce et al., 2017). Digital seismic networks were deployed immediately after the Amatrice earthquake, recording events with  $M > 0.1$ , and making the AVN the best-monitored earthquake sequence striking Italy. The AVN has been modelled as a cascading rupture triggered by fluids entering the fault systems (Walters et al., 2018). Multiple mainshock sequences are common features in the Apennines (Improta et al., 2019 and reference therein). This phenomenon is a consequence of the complex interactions between adjacent faults and triggering processes that include static and dynamic stress transfer between faults, pores fluid pressure

85 migration and co-seismic release of a deep source of trapped CO<sub>2</sub> (Chiarabba et al., 2009a; Malagnini  
86 et al., 2012; Miller et al., 2004).

87 Seismic waves lose their energy when travelling through complex fluid-filled fault networks  
88 (Sketsiou et al., 2021). Seismic attenuation tomography has thus the potential to image the effect of  
89 increased fluid content and migration. Chiarabba et al. (2009a) used P- and S-wave attenuation to  
90 track fluid migrations across the Central-Northern Apennines fault networks, identifying them as the  
91 driving mechanism of the cause of the 1997 Umbria-Marche seismic sequence. Sketsiou et al. (2021)  
92 imaged total attenuation across the Pollino range (Southern Italy), identifying two fluid reservoirs  
93 hosting fluids that laterally migrated at depth, producing the 2010-2014 Pollino seismic sequence  
94 (Brozzetti et al. 2017, and references therein). Waves attenuate due to scattering and absorption (Sato  
95 et al., 2012). The increase of seismic absorption relative to scattering losses and of their frequency  
96 dependence supports the inference of fluids permeating faults during the AVN (Akinci et al., 2020).

97 Scattering and absorption can be mapped in space using two seismic attributes:

98 (1) the peak delay time, defined as the time difference between the S-wave arrival and the maximum  
99 amplitude of the event (Takahashi et al., 2007)

100 (2) the attenuation of coda waves ( $Q_c^{-1}$ ). Coda waves are wave-trains coming after the S wave-  
101 packet, and  $Q_c$  quantifies the decay rate of the coda envelope with increasing lapse time from the  
102 origin time of the earthquake (Aki and Chouet, 1975).

103 At crustal-scale and in the far field, peak delay measures multiple forward scattering due to random  
104 inhomogeneities (Takahashi et al., 2007; Calvet et al., 2013). The Markov approximation (Saito et  
105 al., 2002) can model its variations in space and frequencies at frequencies higher than 1 Hz. Takahashi  
106 et al. (2007) first used peak delay times to map volcanic areas in northeast Japan. High peak delays  
107 mark fractured volumes across the Pyrenees (Calvet et al., 2013), the eastern portion of the Siletz  
108 terrane in the Western US (De Siena et al., 2016), and the Vrancea region in Romania (Borleanu et  
109 al., 2017). Within fault networks, peak delay increases are visible at all frequencies when waves cross



fractured geological volumes, as the carbonates of the Pollino seismic gap, in Southern Italy (Napolitano et al., 2020).

Single scattering, multiple scattering and diffusion can model coda wave envelopes depending on frequency, lapse time and scale of the heterogeneities encountered during propagation (Sato et al., 2012). At late lapse times, coda waves can enter the diffusive regime, where coda attenuation is theoretically equal to absorption ( $Q_c = Q_i$  - Shapiro et al., 2000). Calvet and Margerin (2013) demonstrate that this assumption is valid for an onset time of the coda of 80s and epicentral distances between 0 and 90 km across the Pyrenees.  $Q_c^{-1}$  strongly depends on frequency in active tectonic regions (Sato et al., 2012). At low frequencies, high  $Q_c^{-1}$  anomalies map surface geology and sedimentary basins in the Pyrenees (Calvet et al., 2013), the Alps (Mayor et al., 2016) and Vrancea (Borleanu et al., 2017). At higher frequencies, the change in coda composition from surface to body waves can increase depth sensitivity (Mayor et al., 2016; De Siena et al., 2016; Gabrielli et al., 2020). This effect appears predominant when measuring  $Q_c^{-1}$  across volcanic structures, as at Mount St. Helens volcano (US). Here, low-frequency waves map the shallowest, most-heterogeneous volcanic structures, while deep feeding systems appear as high- $Q_c^{-1}$  anomalies at higher frequencies (De Siena et al., 2016; Gabrielli et al., 2020).

High peak delays and high  $Q_c^{-1}$  detect intrusions in mountain chains (Calvet et al., 2013) and magmatic systems (De Siena et al., 2016). These parameters are reliable marker of fluid-induced fracturing leading to earthquakes at the regional scale (Borleanu et al., 2017). In fault networks like those ruptured by the AVN, Napolitano et al. (2020) found that high-scattering and high-absorption patterns obtained by increasing frequencies map the migration of the historical seismic events from the 16<sup>th</sup> century up to the Pollino seismic sequence. This work supported the view that lateral fluid migrations cause the sequence (Brozzetti et al., 2017, and references therein). However, the temporal potential of joint scattering and absorption mapping in fault networks is still unexplored.

In this study, we measure and map peak delays and  $Q_c^{-1}$  in the 2D space. Due to the consistent spatial extent of the earthquakes, we repeat the mapping in time using data recorded:

- 1) between 2013 and 2016 (hereafter, pre-sequence), before the first mainshock of August 24, 2016,  $M_w$ 6.0 Amatrice earthquake;
- 2) between August 2016 and January 2017 (hereafter, sequence) using data from the entire AVN;
- 3) during three different periods starting from the three main shocks: Amatrice (August 24, 2016 - October 26, 2016), Visso (October 26, 2016 - October 30, 2016) and Norcia (October 30, 2016 - January 18, 2017).

We offer insight into fluid migration and expansion processes leading and controlling a seismic sequence using peak delay and coda attenuation as frequency-dependent proxies of scattering loss and absorption.

## 2. Geological and seismological background

The Central Apennines is governed by the opening of the back-arc Tyrrhenian basin (west), the eastern migration of the compressive front, and the lithospheric plate's flexural retreat dipping below the Italian peninsula (Di Luccio et al., 2010). The Western Tyrrhenian is marked by thin crust (25 km), high heat ( $> 200 \text{ mWm}^{-2}$ ), and positive gravity anomalies. Most of the Quaternary volcanoes and the geothermal areas (such as Larderello, Amiata, Campi Flegrei and Vesuvius) are activated by the perturbation of the mantle wedge (Ventura et al., 2007). On the contrary, the eastern part of the Adriatic Sea is marked by low heat flow and negative gravity anomalies. The average crustal thickness is thicker, around 35 km (Carminati and Doglioni, 2012).

The Central Apennine region is mainly composed of thrust sheets imbricated toward the Adriatic Sea, having a NW-SE trend, and creating a contact between the Meso-Cenozoic carbonate succession and the Miocenic flysch (Billi and Tiberti, 2009, and references therein). The sequence of carbonate rocks and terrigenous units can be traced from the surface to a depth of 8-10 km moving from east to west (Billi and Tiberti, 2009, and references therein). The Monti Sibillini thrust (also known as Olevano-Antrodoco thrust) in the southern sector of the Umbrian Arc has a NNE-SSW trend and it is causing the Sabina Miocene pelagic sediments to overthrust the Lazio - Abruzzi carbonate platform (Billi and

161 Tiberti, 2009). The Laga Formation (consisting of Messinian siliciclastic foredeep deposits) overlies  
162 both the Triassic - Miocene Lazio - Abruzzi platform and the Umbria - Marche pelagic succession  
163 (**Figure 1**) (Di Bucci et al., 2021, and references therein). Further east, the contact between the Laga  
164 Formation and the carbonate platform coincides with the E-W thrust of the Gran Sasso chain, bounded  
165 by the Monti Sibillini thrust to the west and the Morrone thrust to the east (Billi and Tiberti, 2009).  
166 Large intermountain basins as those of Amatrice, Norcia and Castelluccio are filled by Plio-  
167 Quaternary continental sediments (**Figure 1**). They formed due to Plio-Quaternary NW-SE striking  
168 normal faulting, which dissects the Apennine chain and partly reactivates the pre-existing older  
169 thrusts (Improta et al., 2019 and references therein).

170 Seismicity in the Apennines concentrates along the chain axis and manifests itself through swarms  
171 and sequences with events of magnitudes up to 7 and depths shallower than 10-15 km. The  
172 mainshocks have dip-slip, normal focal mechanisms consistent with ruptures along NW-SE striking  
173 fault planes moving in response to a NE-SW extension (Montone and Mariucci, 2016). Although  
174 some mainshocks nucleate in the crystalline basement underlying the chain at about 10 km depth,  
175 there are records of earthquakes in the overlying carbonates and sedimentary sequences. Seismic  
176 activity in the Central Apennines is modulated by deep-derived CO<sub>2</sub>-rich fluids, with gas releases  
177 triggering earthquakes (Miller et al., 2004; Di Luccio et al., 2010; Malagnini et al., 2012; Chiodini et  
178 al., 2004, 2020). Chiodini et al. (2020) show a record of 10 years (2009-2018) of tectonic CO<sub>2</sub>  
179 emissions compared with seismic activity in the Central Apennines (Italy), where devastating  
180 historical earthquakes (such as the 1461 event of L'Aquila, the 1703 event of Norcia - Montereale -  
181 L'Aquila and the 1915 M<sub>w</sub> 7.0 of Avezzano) occurred. Chiaraluce et al. (2007) and Collettini et al.  
182 (2008) reported overpressurized fluids in the deep wells of San Donato and Santo Stefano in the  
183 Apennines. Miller et al. (2004) propose that the 1997 Colfiorito aftershocks were caused by a co-  
184 seismic release of trapped high-pressure CO<sub>2</sub>. Chiarabba et al. (2009b) observed high velocity ratios  
185 during the foreshocks and aftershocks of the L'Aquila 2009 sequence (M<sub>w</sub>6.1), which allowed them  
186 to mark zones of high pore pressure and fluid enrichment. Malagnini et al. (2012) and Di Luccio et

187 al. (2010) showed that the diffusion of pore fluid pressure during the L'Aquila earthquake was caused  
188 by the activation of different fault segments visible through the spatial migration of seismic activity.  
189 In the Apennines, earthquakes with  $M > 5.5$ -6 often rupture the surface so that fluids circulating in the  
190 shallower crust can enter and interact with the fault zone (Amoruso et al., 2011; Doglioni et al., 2014).  
191 The Central Apennines host large aquifers in the carbonate formations, such as the Gran Sasso  
192 (Amoruso et al., 2011) and the Nuria-Velino-Giano (Devoti et al., 2018) aquifers. The Gran Sasso  
193 aquifer registered short and mid-term changes in groundwater hydrodynamics (Amoruso et al., 2011)  
194 after the 2009 L'Aquila seismic event. The Gran Sasso aquifer has an extension of 700 km<sup>2</sup>, bounded  
195 by the Laga Formation to the north and east and by the low-permeable alluvial deposits to the west  
196 and south. The perennial groundwater reserves in this aquifer are estimated in the order of 10<sup>10</sup> m<sup>3</sup>,  
197 with a mean thickness of 1 km (Amoruso et al., 2011 and references therein). The 2016 Amatrice-  
198 Norcia seismic sequence generated an uplift of the water level both near the Gran Sasso (~1.8 m;  
199 Devoti et al., 2018) and as far as 100 km away from the mainshock area (up to 80 cm; Barberio et al.,  
200 2017). The Mounts Nuria-Velino-Giano hydrological complex is located ~40 km southwest of the  
201 Gran Sasso aquifer and has an outcropping area of about 1000 Km<sup>2</sup> (Chiodini et al., 2011 and  
202 references therein). It is bordered by low-permeability deposits and by the Mt. Sibillini thrust  
203 (Chiodini et al., 2011). Chiodini et al. (2011) performed a hydrogeochemical study of the Gran Sasso  
204 and Nuria-Velino-Giano aquifers to investigate the presence of a deep CO<sub>2</sub> source in the epicentral  
205 area of the 2009 L'Aquila seismic sequence. Both aquifers showed an increasing influx of fluids rich  
206 in deep CO<sub>2</sub> before and during the seismic sequence. Thus, deep high-pressure gas traps played a role  
207 in the generation of the L'Aquila seismic sequence, as previously modelled for the Colfiorito seismic  
208 event (Miller et al., 2004). Tomography images suggest that such traps occur at the base of the  
209 Apennine seismogenic layer, i.e., at the boundary between the upper and lower crust (at 10-15 km  
210 depth - Chiarabba et al., 2020).  
211 AVN is ~30 km north of the L'Aquila area and ~50 km south of the hypocenter of 1997,  $M_w$ 6.0  
212 Umbria-Marche seismic sequence. The seismicity in this sector of the chain is associated to the Mt.

Vettore normal fault segments and the Mt. Gorzano fault (Monti della Laga fault system) (Buttinelli et al., 2018; Carminati et al., 2020; Brozzetti et al., 2019). The AVN ruptures the seismic gap between the 1997-98 Colfiorito (Chiaraluce et al., 2004) and the 2009 L'Aquila seismic sequences (Chiaraluce et al., 2011).

### 3. Data and Methods

#### 3.1 Seismic dataset

In the present study, we merged weak and strong-motion data from the AVN using earthquakes with magnitudes between 2.8 and 6.5. We selected earthquakes having a maximum depth of 20 km, keeping source-station distance within 100 km. The pre-sequence dataset comprises ~6000 waveforms recorded at 47 seismic stations (**Figure 2a**). The complete data set for the AVN contains ~22000 waveforms recorded at 156 seismic stations (**Figure 2b**).

Strong ground motion data were registered by the accelerometric stations of the Italian strong motion network (RAN). Broadband weak-motion seismological stations are part of the Digital Seismic Network run by the Istituto Nazionale di Geofisica e Vulcanologia. The weak- and strong-motion accelerograms were downloaded from the Italian ACcelerometric Archive (ITACA) website, the European Strong Motion (ESM) database and the European Integrated Data Archive (EIDA) repository. The strong ground motion network is equipped with a three-component Kinometrics EpiSensor (FBA-3200 Hz) with a full-scale range of 1 or 2 g, combined with an ETNA 18 bits or K2-Makalu 24 bits digitizers. The weak-motion seismograms are corrected for instrument response. All the stations that registered only one seismic event were removed. The waveforms with P-wave travel times higher than 35 s were discarded from the database to constrain propagation within the crust. Waveforms with spikes, telemetry gaps and wave arrivals in the coda of the horizontal components of ground motion were manually removed. The dataset comprises seismograms with signal to noise ratio of the selected coda window higher than two. The P- and S-wave arrivals were picked manually

on each seismogram of the final dataset. The final dataset comprises ~4100 waveforms for the pre-sequence and ~13900 for the AVN.

The final AVN dataset has been further divided into three time periods, each following a mainshock recorded in 2016:

- 1) Amatrice sequence, comprising ~3600 waveforms recorded between August 24 and October 26, 2016
- 2) Visso sequence, comprising ~1630 waveforms recorded between October 26 and October 30, 2016
- 3) Norcia sequence, comprising ~8700 waveforms recorded between October 30 and January 18, 2017.

Our study covers an area of 200 km x 220 km (lon: 11.85° - 14.25°; lat: 41.7° - 43.7°) and it is divided into 30x30 regularly spaced nodes. The seismograms were filtered with a band-pass Butterworth filter (4<sup>th</sup> order) in four frequency bands (1 – 2 Hz, 2 – 4 Hz, 4 – 8 Hz, and 8 – 16 Hz) centered at a frequency ( $f_c$ ) equal to 1.5, 3, 6 and 12 Hz. A Hilbert transform has been applied to compute the envelopes, which were then smoothed with a moving window of duration eight times the central frequency's inverse.

The open-access code Murat2D previously applied in volcanic (De Siena et al., 2016, 2017; Gabrielli et al. 2020) and tectonic settings (Borleanu et al., 2017; Napolitano et al., 2020) is used to perform all the analyses. The code is applied to datasets spanning five time frames: the pre-sequence (2013 – 2016), the AVN and the three subsequences after the mainshocks (from August 24, 2016, to January 18, 2017). Peak delay and  $Q_c^{-1}$  maps are interpreted separately and jointly in their parameter space (De Siena et al., 2016).

### **3.2 Peak delay measurements and mapping**

Seismic waves broaden in heterogeneous media due to multiple forward scattering. The delay between the S-wave onset and the maximum of the envelope increases with source-receiver distance

(Takahashi et al., 2007; Calvet and Margerin, 2013). The dependence of the peak delay time ( $t^{PD}(r)$ , in seconds) from hypocentral distance ( $R_{Hypo}$ , in km) is expressed by:

$$\log_{10} t^{PD}(f) = A(f) + B(f) \cdot \log_{10} R_{Hypo} \quad (1)$$

where  $A(f)$  and  $B(f)$  in Eq. (1) are the coefficients of the resulting linear fit.

We selected seismograms with an  $R_{Hypo}$  between 20 and 100 km. For waveforms with  $R_{Hypo} < 20$  km, the envelope broadening caused by the source duration prevails over scattering effects (Takahashi et al., 2007). Measured peak delay times (black circles) and their dependence on hypocentral distance are presented for the frequency band 1.5 Hz in **Figure S1**. The difference between the measured peak delay time of the  $i$ -th waveform ( $t_i^{PD}(f)$ ) and the theoretical peak delay at the corresponding hypocentral distance (Eq. 1) gives the amount of scattering accumulated along the raypath:

$$\Delta \log_{10} t(f) = \log_{10} t_i^{PD}(f) - \log_{10} t^{PD}(f) \quad (2)$$

Positive values of  $\Delta \log_{10} t(f)$  represent high-scattering zones and heterogeneous portions of the crust. In contrast, negative values mark low-scattering zones interpreted as rigid and compact crustal areas (Takahashi et al., 2007). We mapped S-wave peak delays assuming source-receiver sensitivity on rays and using a standard regionalization approach (Takahashi et al., 2007). **Figure S2** shows the ray coverage for both pre-sequence and AVN datasets. The ray coverage is dense in the central sector of the map; however, peak delay values spike in regions of low ray coverage. To avoid these trade-offs in areas surrounding the seismogenic zone, we removed from the maps all nodes crossed by less than ten rays (**Figure S3** - Calvet et al., 2013). The final maps are frequency-dependent, but we assume no dependence on depth, as the earthquake dataset is entirely within the crust. At different frequencies (wavelengths), we map heterogeneities of different dimensions.

### 3.3 Coda attenuation measurements and mapping

Aki and Chouet (1975) show that the power spectral energy density ( $E(t,f)$ ) is a function of the lapse time from the earthquake's origin time ( $t$ ):

$$E(t, f) = S(f) t^{-\alpha} \exp\left(\frac{-2\pi f t}{Q_c}\right), \quad (3)$$

where  $S(f)$  includes both source and site terms and  $Q_c^{-1}$  is the frequency-dependent inverse coda quality factor.  $\alpha$  is equal to 3/2 if propagation is constrained within a single layer characterized by an anisotropic multiple scattering regime (Paasschens, 1997; Calvet et al., 2013).  $Q_c^{-1}$  is computed by linearizing Eq. (3). The linearization is computationally faster than non-linear grid-search algorithms (e.g., Napolitano et al., 2020). The two approaches provide equivalent results when the signal-to-noise ratio is higher than three and for coda windows longer than 10 seconds (Sketsiou et al., 2020, and references therein).

Taking the logarithm of Eq. (3) and rearranging the terms, we can measure  $Q_c^{-1}$  using a straight-line fitting:

$$\frac{\ln[E(t,f) \cdot t^\alpha]}{2\pi f} = \frac{\ln[S(f)]}{2\pi f} - \frac{1}{Q_c} t \quad (4)$$

The  $Q_c^{-1}$  analysis window starts at twice the arrival time of the S wave and lasts 20 seconds. **Figure S4** shows source-station measurements (black dots) and fitted (red line)  $Q_c^{-1}$  obtained using the AVN dataset at 1.5 Hz. To image seismic absorption in the 2D space, we applied an inversion scheme (De Siena et al., 2017) based on sensitivity kernel functions valid in the multiple-scattering regime (Del Pezzo et al. 2018 – see **Figure S5**). We discuss the uncertainties relative to the onset of diffusion, the theoretical background, and assumptions behind the use of coda sensitivity kernels, the inversion strategy and resolution tests in the Supplementary Material Text and **Figures S6-S9**.

#### 4. Results

For both the peak delay and  $Q_c^{-1}$  spatial variation, the results are shown between 12.5° E – 13.7° E and 42.15° N – 43.48° N, a zoom of the central part of the area in **Figure 2a, b**. Areas of high resolution for peak delays and  $Q_c^{-1}$  are defined using hit counts (**Figure S3**) and the results of the checkerboard tests (**Figures S7-S9**), respectively. We present the separate spatial variations of peak delay and  $Q_c^{-1}$  using two different sets of maps (**Figures 3,4**). The final interpretation is performed after separating measurements in their parameter space (**Figures 5** – De Siena et al., 2016)



#### 311 **4.1 Spatial variations of peak delays**

312 **Figures 3** show the spatial variation of the peak delay parameter (from here, scattering losses) as  
 313 defined in Eq. (2) obtained at 1.5 Hz for the pre-sequence, the AVN and the three sub-sequences. The  
 314 maps show the absolute value of the frequency-dependent peak delay,  $t^{PD}(f)$ : low and high scattering  
 315 are the values below and above the 1.0 s, which is the average peak delay of the area. The results at  
 316 higher frequencies are shown in **Figures S10-12**. High and low scattering losses correspond to hot  
 317 (red) and cold (blue) colors, respectively. The pre-sequence and sequence maps (**Figures 3a,b**) show  
 318 low scattering in the contact zone between the Meso-Cenozoic carbonate succession and the Miocenic  
 319 flysch (Di Luccio et al., 2010). At higher frequencies (**Figures S11-12**), a high-scattering anomaly  
 320 appears west of the mountain range. The primary scattering contrast defines the Gran Sasso formation  
 321 in the pre-sequence, with low scattering northeast of the massif (Laga Formation domain) and high-  
 322 scattering values southwest of it (L'Aquila basin) (**Figures 3a,b**).

323 We observe variations in scattering attenuation over different periods. During the pre-sequence, a  
 324 low-scattering anomaly marks the northernmost area of the modelled fault planes. The area is  
 325 characterized by high-scattering values during the Amatrice and Visso sequences and returns low  
 326 scattering during the Norcia sequence. This area is delimited to the south by a thrust parallel to the  
 327 Monti Sibillini thrust (**Figure 1**). Before the Amatrice earthquake, the area intersected by the AVN  
 328 was marked by low scattering values (**Figure 3b**). During the Amatrice sequence, the southeastern  
 329 part of the epicentral area becomes a low scattering region, while scattering increases northwest. In  
 330 general, scattering losses increase and expand toward the epicentral area during the AVN. They  
 331 progressively reach the southwestern patch of the Amatrice fault rupture area, spreading across the  
 332 dense fault network west of Norcia during the Visso and Norcia sequences (**Figures 3a,b**).

333

#### 334 **4.2 Average and spatially varying $Q_c^{-1}$**

335 We report the frequency-dependent average  $Q_c^{-1}$  and their relative standard deviation for the pre-  
 336 sequence and the AVN datasets in **Table 1**. These values are obtained from the best fit line of Eq.

(4).  $Q_c^{-1}$  decreases with frequency, as expected in tectonically active regions (de Lorenzo et al., 2013; Akinci et al., 2020). Assuming a frequency-dependence given by  $Q_c^{-1} = Q_0^{-1} \cdot f^{-\eta}$ ,  $Q_c^{-1} = (0.0075 \pm 0.0007)f^{(-0.74 \pm 0.10)}$  for the pre-sequence and  $Q_c^{-1} = (0.0076 \pm 0.0005)f^{(-0.76 \pm 0.07)}$  for the AVN. While these values are comparable with those reported across the Apennines (de Lorenzo et al., 2013; Sketsiou et al., 2021), the frequency-dependent  $\eta$  parameters correspond to the upper limit of the range found by de Lorenzo et al. (2013) for the Central Apennines (0.65-0.75). In the assumption that  $Q_c^{-1} = Q_i^{-1}$  at late lapse time (Calvet and Margerin, 2013), we compare the results of **Table 1** with the  $Q_i$  calculated with the MLTWA by Akinci et al. (2020), who estimate  $Q_i(f) = (110 \pm 13)f^{0.9 \pm 0.2}$ . Both  $Q_0$  and  $\eta$  are within the uncertainties obtained with our method:  $Q_c(f) = (131 \pm 10)f^{(0.76 \pm 0.07)}$ .

**Figure 4a,b** present the spatial distribution of the  $Q_c^{-1}$  at 1.5 Hz obtained over the five periods. The average  $Q_c^{-1}$  decreases with increasing frequency using all datasets, showing more intense spatial variations at lower frequencies. The maximum  $Q_c^{-1}$  values are 0.015 at 1.5 Hz (**Figures 4a,b**) and 0.0027 at 12 Hz (**Figure S15**). At lower frequencies (1.5 - 3 Hz), there is a clear difference in the anomaly patterns between the pre-sequence and the 2016-2017 dataset (**Figures 4a and S13a**) and the individual seismic sequences (**Figures 4b**). High-absorption anomalies are widespread before the Amatrice mainshock and focus on the fault zones during the AVN. The L'Aquila-Gran Sasso sector shows a drastic decrease in attenuation during the AVN. The diffuse high absorption across the fault network during the pre-sequence shifts further north after the Amatrice mainshock. High absorption focuses on the dense fault network south of Norcia and the fault planes after the Visso mainshock (rectangles in **Figure 4a,b**). After the Norcia mainshock, the NNW-SSE-trending high-absorption anomaly expands across the Central Apennines range, bounded north and south by the Monti Sibillini and Gran Sasso thrusts, respectively (**Figure 1**). The dense fault network south of Norcia shows a substantial decrease of absorption at the end of the AVN compared to the Amatrice and Visso periods. We identify a similar trend at high frequencies (**Figures S13-15**), with a more focused high anomaly during each seismic sequence.

### 362 **4.3 Parameter separation maps**

363 Scattering and absorption measurements are combined by separating the spatially dependent  
 364 measurements in color-coded ensembles (**Figure S16**). To do so, we removed the average values of  
 365 peak delay and  $Q_c^{-1}$  at different frequency band from each single measurement of the datasets in each  
 366 grid cell (De Siena et al., 2016; Napolitano et al., 2020). We plotted on a graph the relative variation  
 367 of  $Q_c^{-1}$  on the horizontal axis and of  $\Delta \log_{10}(t)$  on the vertical axis (**Figure S16**) and presented in four  
 368 quadrants with different colors. In this way, we provided a visual presentation of combined absorption  
 369 ( $Q_c^{-1}$ ) and scattering (peak delay) attenuation patterns, characterizing each block in the map with the  
 370 corresponding color.

371 Each color is an interpretation of the structures and their content in fluids as follows:

- 372 **1.** HS-HA (red): high scattering and high absorption define a fractured medium saturated in fluids;
- 373 **2.** LS-HA (orange): low scattering and high absorption describe a compact medium filled in fluids;
- 374 **3.** HS-LA (light blue): high scattering and low absorption characterize a dry and fractured medium;
- 375 **4.** LS-LA (green): low scattering and low absorption represent a dry and compact zone medium;
- 376 **5.** white marks areas with a level of discrimination less than 1% of the maximum variations.

377 The parameter maps at 1.5 Hz (**Figures 5a, b**) show two HS-HA anomalies NW and SE of the AVN  
 378 epicentral areas in all periods. These anomalies coincide with the areas ruptured by the 1997 Umbria-  
 379 Marche and the 2009 L'Aquila seismic sequences, with the patterns remaining relatively stationary  
 380 during the AVN. Comparing the pre-sequence and sequence maps at 12 Hz shows the most significant  
 381 temporal differences in patterns (**Figures 5, 6**). Before the sequence, the HS-HA are diffused and  
 382 comprise the Visso and Norcia epicenters and the areas ruptured by the 1997 Umbria Marche  
 383 (Colfiorito) and the 2009 L'Aquila sequences. Instead, there is a sharp separation between HS and  
 384 HS-HA in the south and LS-HA in the north during the sequences. The boundary between zones is at  
 385 a latitude of  $42.7^\circ$  N, corresponding to the lithological differences between the Umbria Marche and  
 386 the Lazio-Abruzzi domains and part of the Monti Sibillini thrust.

## 5. Discussions

We discuss peak delay and  $Q_c^{-1}$  variations in space and time separately (**Figures 3,4**) and then use the parameter separation maps (**Figure 5**). These variations are investigated as a function of time and space for the pre-seismic and seismic periods. Spatial differences between the pre-seismic and the seismic phases characterize different processes, including fluid flow, crack opening/closure and crack density, pore pressure variations (compaction/dilatation), lithological contrasts and existing fault networks.

### 5.1 Peak Delay (scattering) patterns

At all frequencies and for all sequences, a low-scattering NNE - SSW directed anomaly coincides with the Monti Sibillini thrust, including the Flysch of Laga Formation. Thus, the thrust appears as a low-scattering barrier for northern propagation of fluid-induced seismicity (Improta et al., 2019). High-scattering losses correspond to the carbonatic Gran Sasso massif and the L'Aquila basin (Chiaraluce et al., 2011), where the 2009 L'Aquila seismic sequence nucleated. These losses mark high velocity and density contrasts, high density of cracks and fractures, and basins in the upper part of the crust (Borleanu et al., 2017). The correspondence between high scattering and carbonate rocks fractured by historical sequences is analogue to that observed across the Lauria Mountains in Southern Italy (Napolitano et al., 2020).

Considering the relationship with the Gran Sasso and the Monti Sibillini thrust (**Figures 3a,b**), peak delays appear primarily sensitive to the existing structural elements (Calvet et al., 2013; De Siena et al., 2016) as the pre-existing thrust and active faults. This inference is supported by the spatial correlation with the velocity model of the Central Apennines of Chiarabba et al. (2020a). The authors show lateral heterogeneity across the Monti Sibillini thrust, with high  $V_P$  and  $V_P/V_S$  anomalies consistent with the high-scattering Lazio - Abruzzi domain and low  $V_P$  and  $V_P/V_S$  in the northern portion corresponding to the low-scattering Umbria - Marche domain.

411 Peak delays patterns change less than  $Q_c^{-1}$  patterns before and during the AVN at all frequencies  
 412 (**Figures 3a,b** and **S10-12**). However, while high-scattering anomalies appear diffuse before the AVN  
 413 at 1.5 Hz, they focus on a narrow NW-SE-striking band just south of the fault planes during the  
 414 sequence (**Figure 3a**). Moving from the Amatrice to the Norcia sequences (**Figure 3b**), the high-  
 415 scattering anomaly progressively expands from the southern fault plane to comprise the dense fault  
 416 network located immediately to the SW of the modelled faults (red boxes in **Figure 3b**). We interpret  
 417 this change in scattering attenuation as evidence of micro-fracturing processes within this network  
 418 the fault network, lacking evidence of significant lithological change. This inference is supported by  
 419 the higher-frequency peak delay maps (**Figures S11-12**).

## 420 **5.2 Coda $Q$ (absorption) patterns**

421 The sparse distribution of the high-absorption anomalies during the pre-sequence becomes a  
 422 continuous NW-SE-striking pattern focused on the seismogenic zone during the AVN (**Figure 4a**).  
 423 Spatial variations of high-absorption patterns are a manifestation of increased fluid content, with  
 424 fluids expanding across the seismogenic zone with each sequence (**Figure 4b**). Fluids migrate across  
 425 the faults at seismogenic depths (8-12 km), where the main events of the AVN occurred. Pastori et  
 426 al. (2019) observed a reorientation of cracks from seismic anisotropy caused by overpressurized fluids  
 427 trapped in the fault zones in the preparatory phase of the Norcia mainshock. The rock formations on  
 428 the western side of the fault system are heavily fractured, and apparently, they channeled and trapped  
 429 fluids. High-absorption anomalies focus primarily west of the activated fault system during the AVN  
 430 (**Figure 4b**). They mark the extension of the highly fractured and fluid-filled zones and the area of  
 431 maximum displacement recognized by Brozzetti et al. (2019) for the Monte Vettore fault.  
 432 Our observations are consistent with the results from geochemical and geophysical studies that infer  
 433 the critical role of CO<sub>2</sub>-rich deep fluids in the seismogenesis and evolution of seismic sequences  
 434 across the Apennines (Miller et al., 2004; Di Luccio et al. 2010; Terakawa et al., 2010; Malagnini et  
 435 al. 2012; Chiodini et al. 2004, 2020; Chiarabba et al., 2020b; Barberio et al., 2017). These studies

436 evidence a relation between CO<sub>2</sub> release and seismicity rates and locations (Miller et al., 2004;  
437 Chiodini et al., 2020). Such CO<sub>2</sub> is supposedly released from the mantle and accumulates at the  
438 boundary between the lower and upper crust. Here, overpressurized reservoirs develop, sealed by 10-  
439 12 km deep evaporitic levels (Chiodini et al., 2004, 2020; Chiarabba et al., 2020a). Indeed, an increase  
440 in the concentration of mineralized endogenic fluids corresponds to seismic sequences (Barberio et  
441 al., 2017). The source of these fluids has been identified in rocks located at a depth of about  
442 10 km (**Figure 1**). The influx of deep CO<sub>2</sub> could favor their formation and ascent to the surface.  
443 According to Di Luccio et al. (2010), these deep fluids mainly migrate along the NW-SE striking  
444 faults and fractures of the Central Apennines. This process is captured by the high-absorption patterns  
445 (**Figure 4b**).

446 This is the first time that geophysical responses to deep fluid migrations are identified along the  
447 seismogenic fractured zones of the Central Apennines. Our results do not exclude that those fluids  
448 could move in the shallower portion of the crust, especially where the permeability is higher, as within  
449 carbonates and basin filling deposits. Regardless, the maximum recorded water level variation in the  
450 Apennines aquifers during the AVN (e.g., Gran Sasso aquifer) is only 1.8 m (Devoti et al., 2018).  
451 The absorption patterns evolve during the sequence as expected for high-absorption deep CO<sub>2</sub>-  
452 bearing fluids previously trapped in the fault systems (Miller et al., 2004). The development of a high-  
453 pressure front allows the propagation of fluids diffusing through the seismogenic zone and creating  
454 aftershocks. The absorption patterns show the evolution of this front from the location of the Amatrice  
455 earthquake towards the north and south when fluids diffuse across the fault planes (**Figure 4b**).  
456 Northern migration happened primarily during the Visso sequence, when the Monti Sibillini acted as  
457 a barrier (Improta et al., 2019). The Norcia sequence corresponds to the expansion of the  
458 overpressurized trapped fluids across the fractured region (Pastori et al., 2019), leading to the  
459 corresponding expanded absorption anomaly.

### 460 **5.3 Parameter map**

461 **Figure 5a,b** summarizes the combined spatial variation of scattering losses and absorption at 1.5 Hz.  
 462 High-scattering and high-absorption patterns (red) correspond to the areas north of the 1997 Colfiorito  
 463 earthquake and south of the 2009 L'Aquila earthquake before the sequence. This pattern is visible  
 464 also at higher frequencies (12 Hz – **Figure 6a**). During the AVN, HS-HA concentrate on the southern  
 465 and western portions of the seismogenic faults (red squares in **Figure 5a,b**). In the northern part of  
 466 the epicentral area, high absorption (orange in **Figure 5a,b**) replaces the pre-sequence low scattering  
 467 and low absorption patterns (green). This variation in time and space is consistent with the permeation  
 468 of fluids across the northern portion of the seismogenic fault zones. However, the absence of  
 469 scattering losses contrasts with the presence of wide fracture networks near the Visso epicenter and  
 470 north of it. These networks are confined near, and specifically south and west of the other two  
 471 mainshocks (**Figure 5b**, red). The structural models confirm that fluid pathways follow the direction  
 472 of the maximum horizontal stress (Sibson, 2000), which in the Central Apennines is NW-SE-oriented  
 473 and parallel to the strike of the active normal faults (Di Luccio et al., 2010). At higher frequencies  
 474 (12 Hz), these pathways are not visible (**Figure 6**). High frequencies are more sensitive to small-scale  
 475 features, and they cannot map variations of attenuation over wide tectonic structures. The  
 476 consequence is that large-scale tectonic structures confine the inferred deep fluid flow and fracturing.  
 477 **Figure 5b** details how fluids pervade the southern fault planes during the Amatrice sequence  
 478 following the NW-SE preferred orientation of the faults and the elongation of Apennine belt. Yet,  
 479 fracturing does not expand toward Visso, with the red patterns stopping around Norcia by the end of  
 480 the AVN. The high-scattering and high-absorption pattern thus point to northern migrations of fluids  
 481 along tectonic structures, associated with fracturing up to the Norcia epicenter.

## 482 6. Conclusions

483 The main results of this study are that:

- 484 1) Peak delay analysis delineates and characterizes the structural (e.g., Monti Sibillini thrust)
- 485 and lithological (e.g., fractured carbonate rocks) domains of the Central Apennines over all

the studied frequency bands. High-scattering patterns highlight fracturing occurring during the AVN, with high-scattering anomalies focusing south and west of the seismogenic zone.

2) Coda-Q mapping marks the concentration of fluids across the seismogenic zone during the sequence. It detects a progression in time associated with fluid expansion from the Amatrice epicenter, mapping the migrations of deep CO<sub>2</sub>-rich fluids across the fractures and the fault networks of the Central Apennines.

3) Low-frequency parameter-space maps show the development of the fluid-filled fracture network, suggesting that large-scale tectonic structures constrain the deep fluids flow. Fluids permeate the northern fault region after the Visso earthquake. Still, wider fracturing was stopped by the Monti Sibillini structural boundary, so that fluids primarily expanded across the southern Norcia network in the last phase of the AVN.

These results point to a common feature for earthquake sequences occurring across the Central Apennines: the deep migration and expansion of CO<sub>2</sub>-bearing fluids along the NW-SE elongated seismogenic zone. The front and area of expansion of these processes are visible mapping attenuation mechanisms in time and space. Knowing their variations has a profound impact on assessing seismic hazard from earthquake ground motion in order to mitigate risk. Mapping scattering and absorption in the 3D space through seismic sequences could provide us with unprecedented sensitivity on structures and processes that lead to mainshocks and aftershocks in fault networks and their effect on earthquake ground motion amplitudes.

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paper can be found at: <http://www.isprambiente.gov.it/it/progetti/suolo-e-territorio-1/ithaca-catalogo-delle-faglie-capaci>.

Murat2D is an open-access MATLAB<sup>®</sup> code available at <https://doi.org/10.5281/zenodo.5121429>.

Many of the plots were generated using the Generic Mapping Tools, version 4.2.1 ([www.soest.hawaii.edu/gmt](http://www.soest.hawaii.edu/gmt), last accessed December 2008; Wessel and Smith, 1998) and using the Scientific Colour Maps (Crameri 2018; <http://doi.org/10.5281/zenodo.1243862>).

## CRediT authorship contribution statement

**Simona Gabrielli:** Conceptualization, Methodology, Software, Writing- Original draft preparation, review, and editing. **Aybige Akinci:** Conceptualization, Data curation, Writing- Original draft preparation, review, and editing. **Guido Ventura:** Writing-Reviewing. **Ferdinando Napolitano:** Methodology, Writing. **Edoardo Del Pezzo:** Methodology, Validation. **Luca De Siena:** Conceptualization, Writing-Reviewing, Software.

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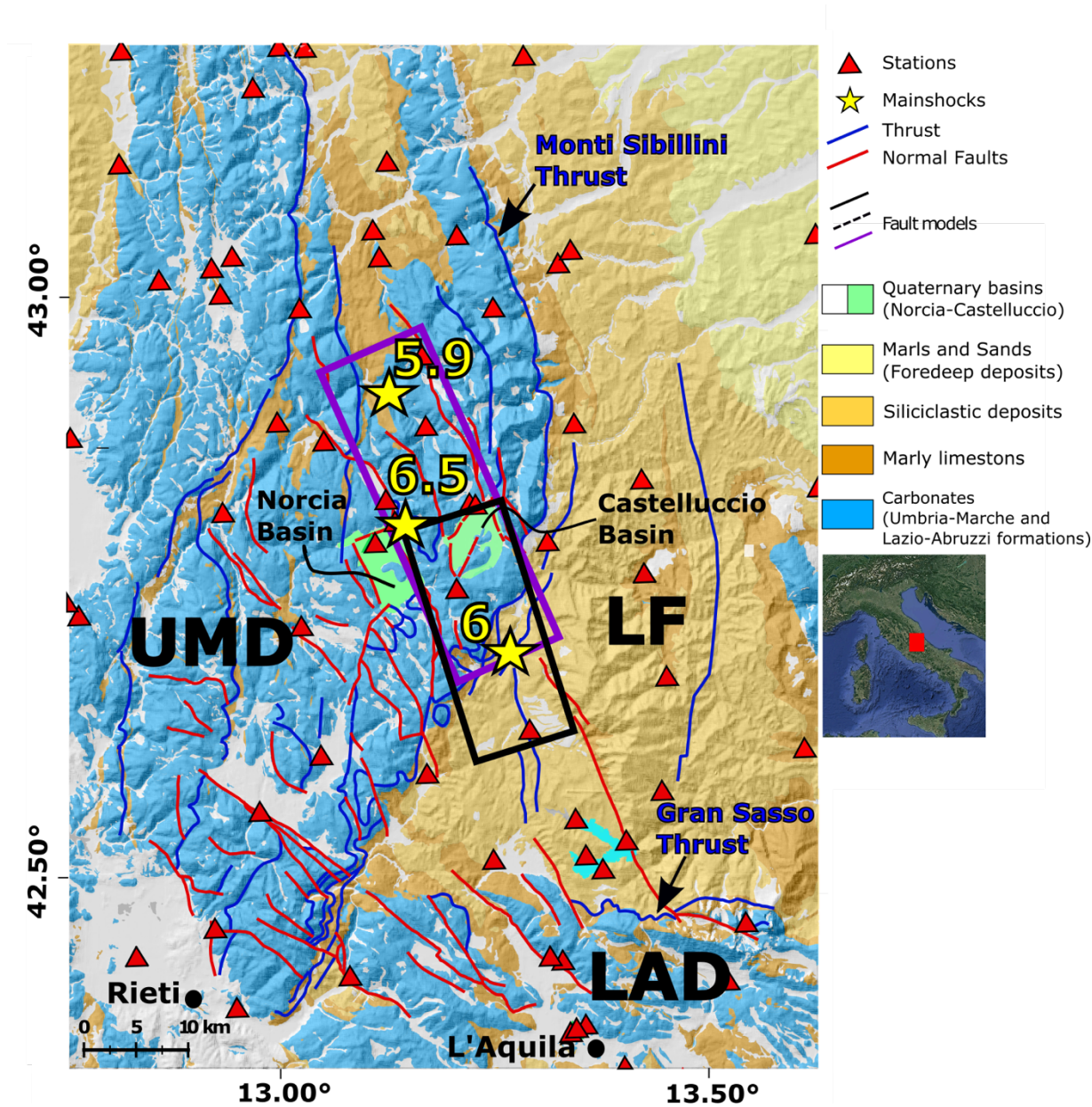
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**Table 1.**  $Q_c^{-1}$  for the two main dataset, with their associated standard deviation  $\sigma$ , obtained from the linear regression (**Figure S4**) at each frequency band. \* and # are the dependence of  $Q_c^{-1}$  vs. frequency for the Pre-Sequence and 2016-2017 Sequence, respectively.

$f$ (Hz)	Pre-Sequence (*) $Q_c^{-1} \pm \sigma$	2016-2017 Sequence (#) $Q_c^{-1} \pm \sigma$
1.5	$0.006 \pm 0.003$	$0.006 \pm 0.003$
3	$0.003 \pm 0.001$	$0.003 \pm 0.001$
6	$0.0020 \pm 0.0006$	$0.0020 \pm 0.0005$
12	$0.0011 \pm 0.0005$	$0.0011 \pm 0.0004$

(\*)  $Q_c^{-1} = (0.0075 \pm 0.0007)f^{(-0.74 \pm 0.10)}$ ; (#)  $Q_c^{-1} = (0.0076 \pm 0.0005)f^{(-0.76 \pm 0.07)}$

722 **Figures**



723

724 *Figure 1 Simplified geological map of Central Italy (after Di Bucci et al. 2021). In blue, the*  
 725 *carbonates of the Umbria-Marche (UMD) and Lazio-Abruzzi (LAD) domains; in yellow, the foredeep*  
 726 *domain (LF - Laga formation). The seismic network used for the sequence period is represented with*  
 727 *red triangles. Yellow stars correspond to the Amatrice ( $M_w6$ ), Visso ( $M_w5.9$ ) and Norcia ( $M_w6.5$ )*  
 728 *mainshocks. The black and purple boxes are the Amatrice and Norcia fault planes respectively. Study*  
 729 *area within the Italian Peninsula framework is shown in the inset on the right panel.*

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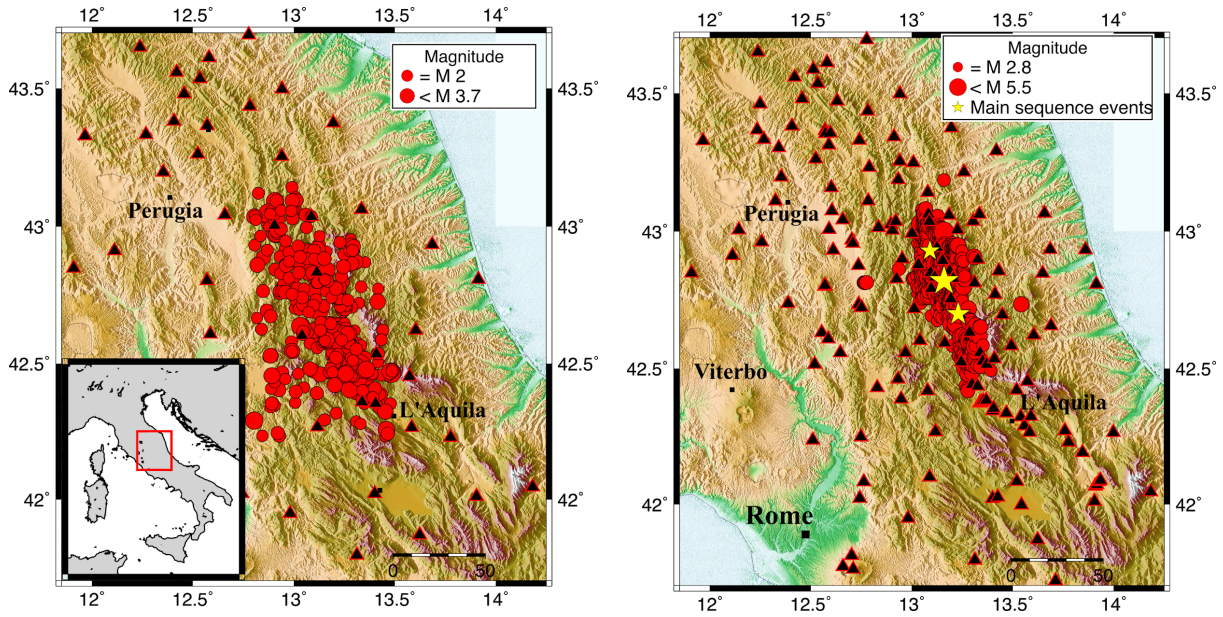
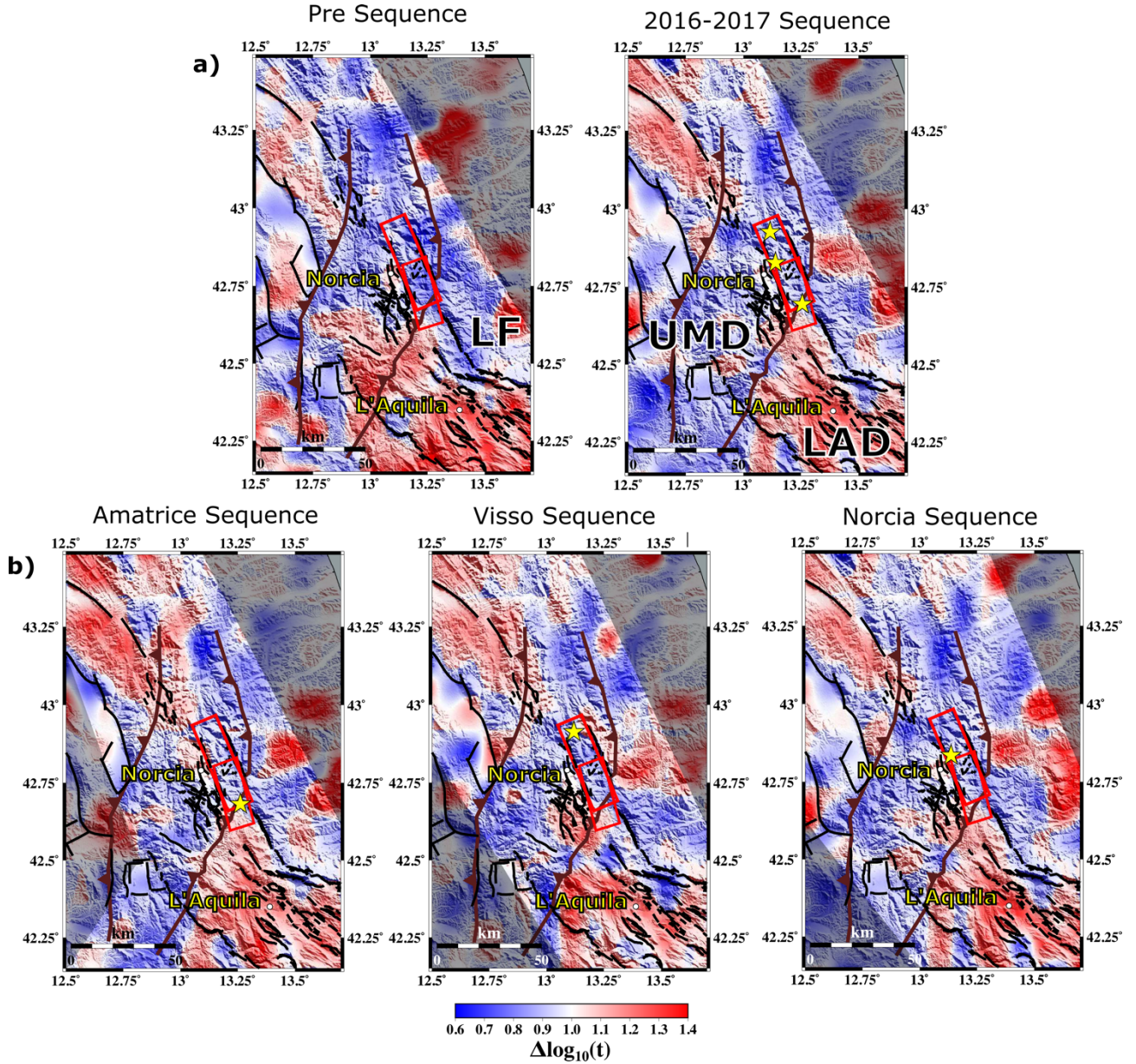


Figure 2 Dataset used for the analysis and the seismic network for the pre-sequence (left), and the Amatrice - Visso - Norcia sequence (right). Black triangles represent the stations; red circles the seismic events; stars indicate the main events (Amatrice - Visso - Norcia) of the 2016 - 2017 seismic sequence. Study area in the lower-left panel in the Italian Peninsula framework.



736  
 737 *Figure 3 Spatial and temporal variation of Peak Delay at  $f_c = 1.5$  Hz over the a) Pre-sequence, the*  
 738 *2016-2017 sequence and b) three individual sequences time frames. Red boxes are the fault plane for*  
 739 *the Amatrice and the Norcia earthquakes and black lines the faults from ITHACA catalogue. Brown*  
 740 *lines are the main thrust of the area. The stars indicate the main shocks of each 2016-2017 sequence.*  
 741 *The maps have been restricted to the area of interest. The main geological domains are highlighted:*  
 742 *LF - Laga Formation; UMD - Umbria-Marche Domain; LAD - Lazio-Abruzzi Domain.*



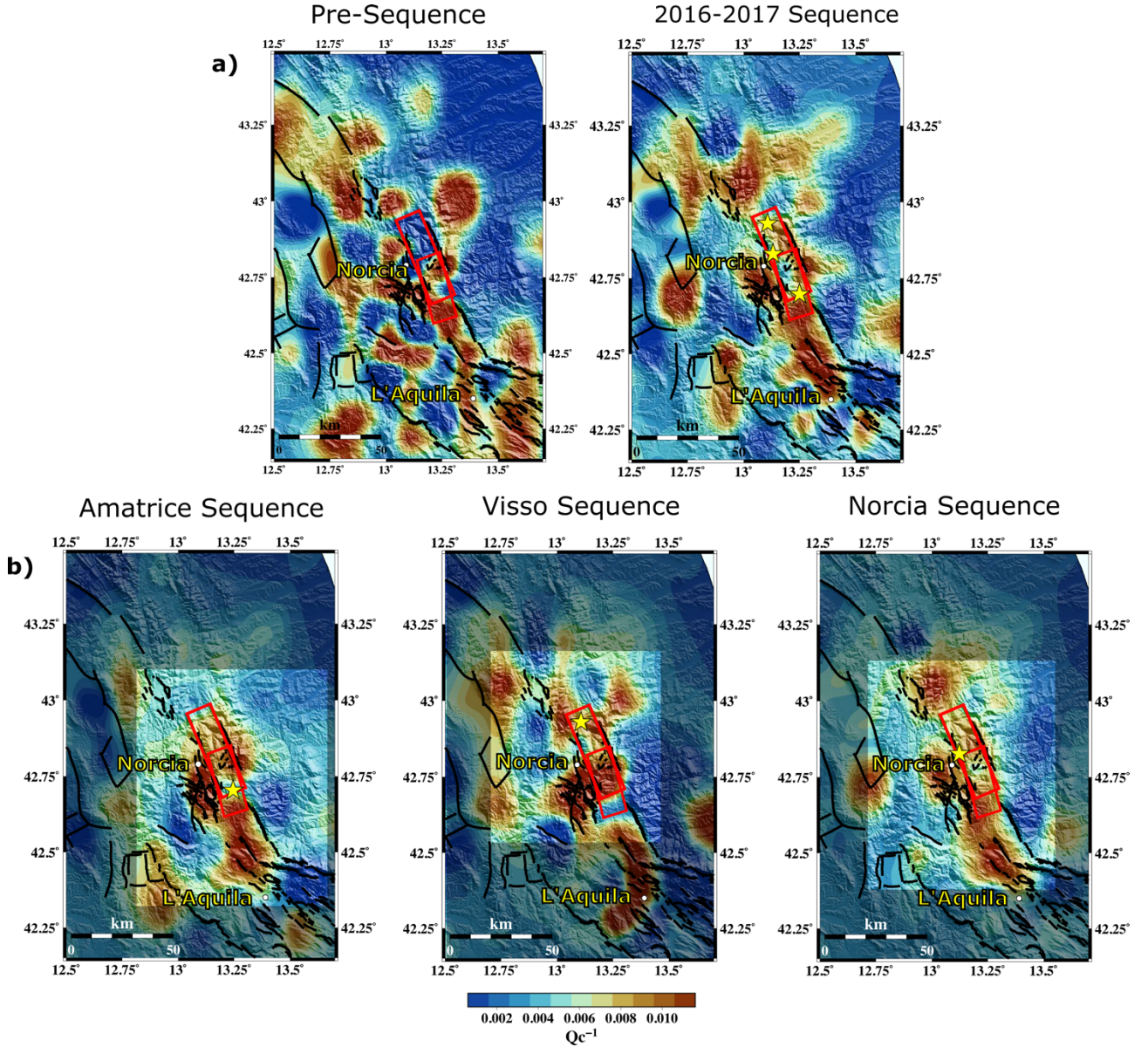


Figure 4 Spatial variation of  $Q_c^{-1}$  at  $f_c = 1.5$  Hz for the a) Pre-sequence and the 2016-2017 sequence and b) three individual sequences time frames. Red boxes are the fault plane activated during the AVN sequence and the black lines are the fault lines from the ITHACA catalogue. The stars indicate the main shocks of each 2016-2017 sequence. The maps have been restricted to the area of interest and the gray masks are covering the areas unresolved by the checkerboard tests at each sequence.

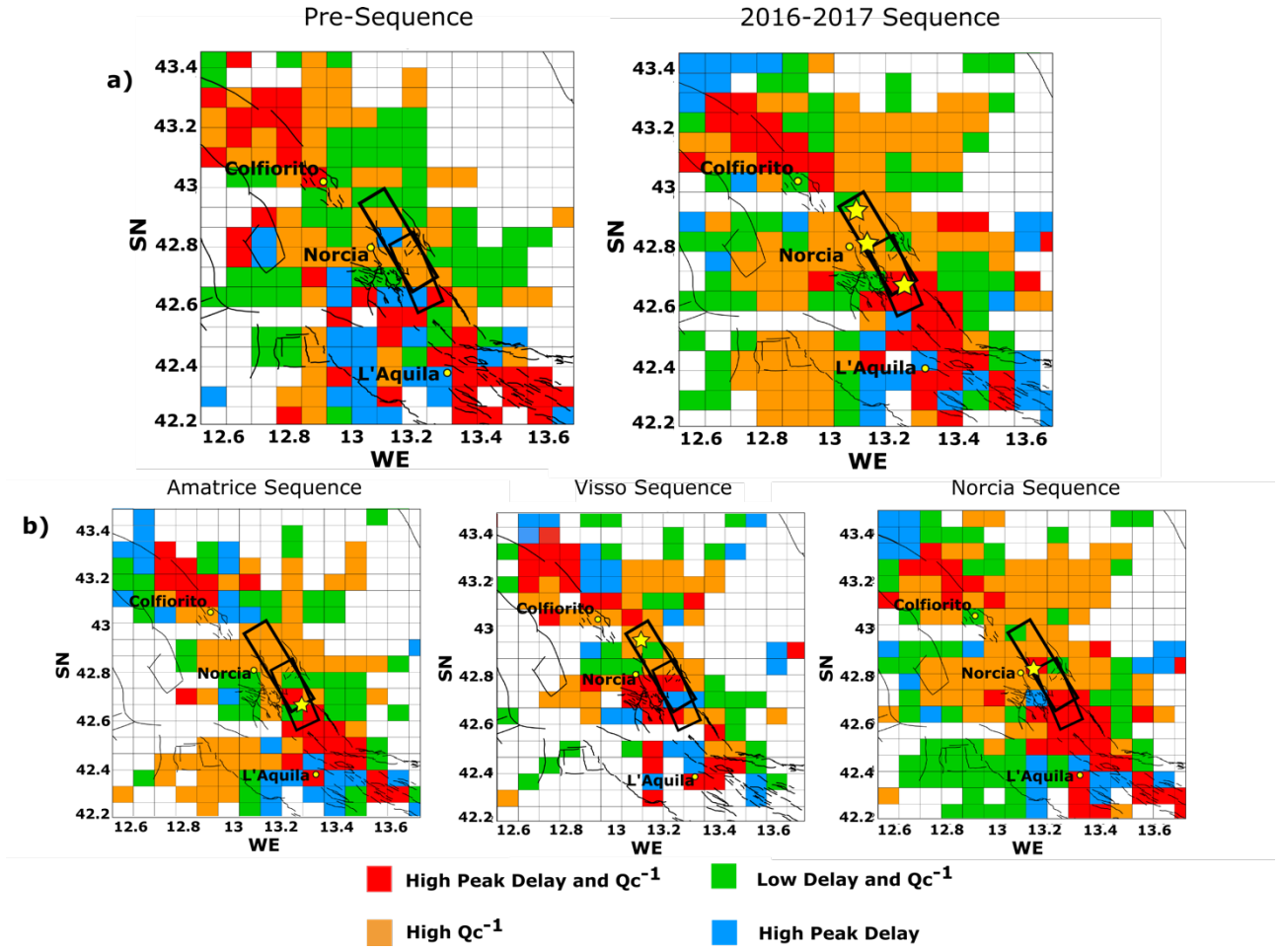


Figure 5 Parameter separation map at  $f_c = 1.5$  Hz of the a) Pre-sequence and the 2016-2017 sequence and b) three individual sequences time frames. The red color for high scattering and high absorption (HS-HA), orange for low scattering and increased absorption (LS-HA), light blue for high scattering and low absorption (HS-LA), green for low scattering and low absorption (LS-LA), and white for the areas with a level of discrimination less than 1% of the maximum variations.

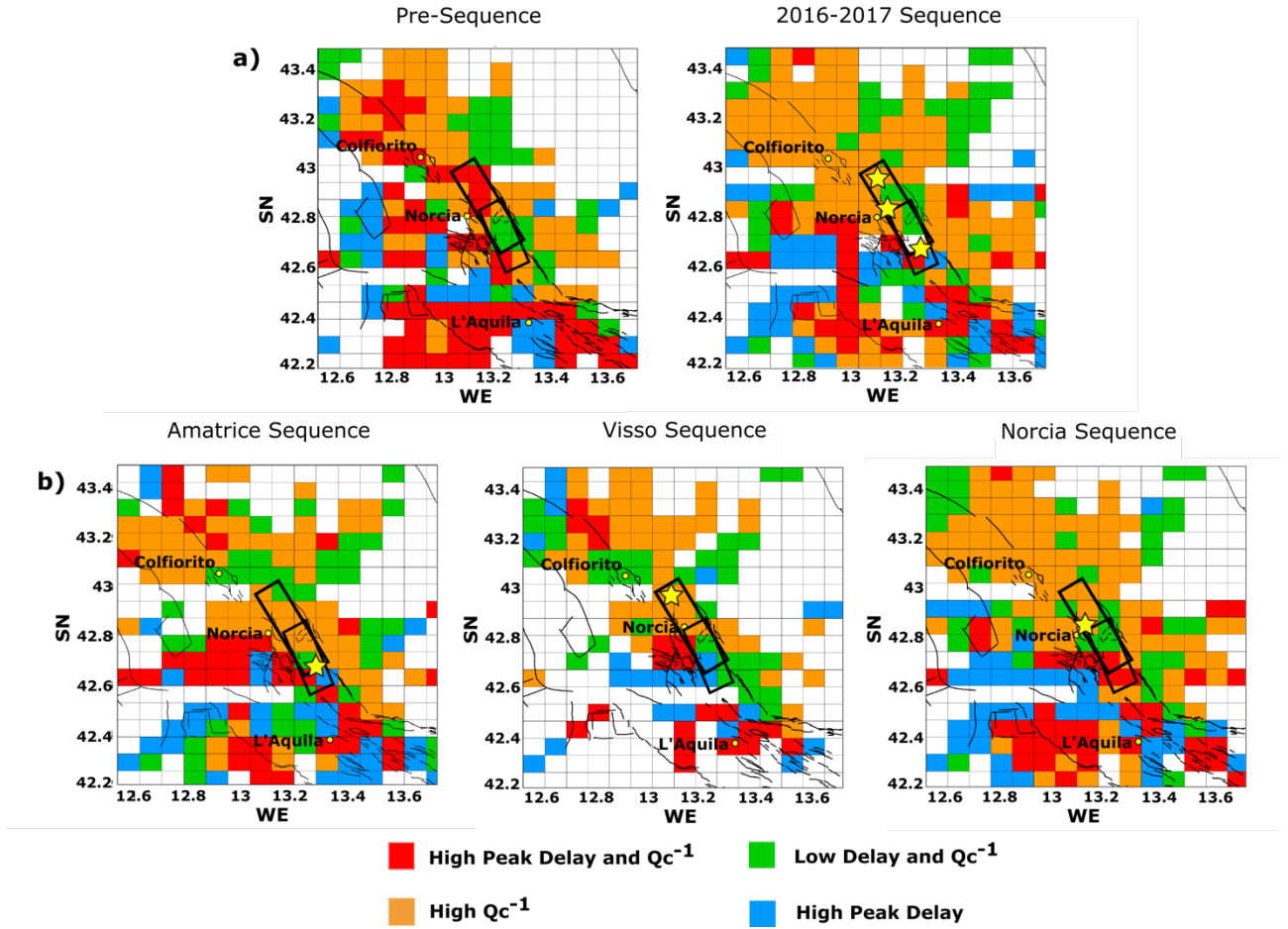


Figure 6 Parameter separation map at  $f_c = 12$  Hz of the a) Pre-sequence and the 2016-2017 sequence and b) three individual sequences time frames. The red color for high scattering and high absorption (HS-HA), orange for low scattering and increased absorption (LS-HA), light blue for high scattering and low absorption (HS-LA), green for low scattering and low absorption (LS-LA), and white for the areas with a level of discrimination less than 1% of the maximum variations.