

Temporal Variation of the Spectral Decay Parameter Kappa Detected before and after the 2016 Main Earthquakes of Central Italy

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ABSTRACT

We investigated the temporal variation of the spectral decay parameter κ before and after two main earthquakes that occurred in the central Italy region, namely the Amatrice (M_w 6.0) of 24 August 2016 and the Norcia (M_w 6.5) of 30 October 2016 earthquakes. For this analysis, we used seismograms from the central Italy dense seismic array stations, and earthquakes located at hypocenter distances $r < 80$ km, having magnitudes M_w 3.4–6.5. The dataset consists of 393 events recorded at 92 stations. We estimated, for both earthquake sequences, average functions $\tilde{\kappa}(r)$ that describe the distance dependence of κ along the S-wave source-station paths using acceleration spectra from foreshocks, main-shock, and aftershocks. We observed that there was a regional attenuation drop within approximately two months after the Amatrice earthquake. Then, $\tilde{\kappa}(r)$ tends to return toward the attenuation values observed before the occurrence of the main event, namely to the values of $\tilde{\kappa}(r)$ obtained from the foreshocks, when the earthquake cycle is probably completed. We also estimated the near-source kappa (κ_s) using aftershocks from 24 August 2016 to 3 September 2016. The results show that the values of κ_s are lower than those from aftershocks located to the north near the epicenter of the Amatrice earthquake, suggesting that the tectonic stress was probably high near the rupture zone, and that there may be a likely fluid flow of crustal fluids. $\tilde{\kappa}(r)$ obtained from the foreshocks of the Norcia earthquake is like that calculated with the records of the Amatrice aftershocks. Then, $\tilde{\kappa}(r)$ drops to lower attenuation values during the Norcia main event and tends to increase again during the aftershocks. From the analysis of these two earthquake sequences that occurred in a short-time interval in central Italy, we conclude that the temporal variation of $\tilde{\kappa}(r)$ could be a valuable indicator to monitor the earthquake cycle.

KEY POINTS

- Temporal variation of the decay parameter κ before and after the 2016 earthquakes in central Italy.
- The variation of the average $\tilde{\kappa}(r)$ along the path can be related to fluid flow in the seismogenic zone.
- The temporal variation of $\tilde{\kappa}(r)$ may be a good indicator to monitor the earthquake cycle.

INTRODUCTION

Several geophysical investigations have shown that the temporal and spatial distribution of aftershocks seem to correlate with physical mechanisms that are time dependent, such as state friction (Dieterich, 1972), after slip (Bürgmann *et al.*, 2002), poroelastic rebound (Jónsson *et al.*, 2003), and static stress drop estimates (Kemna *et al.*, 2021). The recent studies have suggested that changes in pore pressure can induce crustal

stresses a few months after a strong earthquake (Albano *et al.*, 2019; Convertito *et al.*, 2020). These changes in pore pressure can explain the spatial and temporal distributions of aftershocks (Nur and Booker, 1972; Bosl and Nur, 2002; Albano *et al.*, 2017; among others). Moreover, to explain the decay of the number of aftershocks with time, usually observed during

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earthquake sequences, Nur and Booker (1972) proposed that the presence of a viscous element is necessary, and they show that the flow of pore fluid provides this viscous component. Because the presence of fluids in the crust can increase S-wave attenuation, a spatial and temporal variability of the spectral decay parameter κ is expected. Q-tomography studies in the central Italy region (Chiarabba *et al.*, 2009; Amoroso *et al.*, 2017) show attenuation and velocity heterogeneities that may be related to fluid-pressure migration in the fault system of this region. The previous studies of seismic attenuation (Castro *et al.*, 2000) in the Umbria–Marche region of central Italy show significant variability of the parameter κ that could be related also to the presence of fluids in the crust.

In this article, we study the temporal variation of the spectral decay parameter κ in central Italy using earthquakes from the Amatrice–Norcia 2016 seismic sequence. The Amatrice (M_w 6.0) earthquake (42°42' N, 13°13.8' E) occurred on 24 August 2016 and caused severe damage and casualties in the village of Amatrice (Chiaraluce *et al.*, 2017; Fiorentino *et al.*, 2018). Many aftershocks were reported to occur for several days, which gradually migrated to the north from the epicentral area of the initial rupture, suggesting that a diffusive transit process was taking place, perhaps related to the flow of pore fluids (Tung and Masterlark, 2018; Albano *et al.*, 2019). After the Amatrice mainshock, it is likely that the flow of fluids reduced the stability of the fault system and triggered the sequence (Gabielli *et al.*, 2022), including the M_w 5.9 earthquake of 26 October 2016, which occurred near the village of Visso (42°54.6' N, 13°7.8' E), and on 30 October a larger event (M_w 6.5) that occurred on the town of Norcia (42°49.8' N, 13° 6.6' E) causing further damage. The red stars in Figure 1a are the epicentral locations of these earthquakes.

There are several factors that may impact the estimates of the attenuation parameter κ , particularly to the near-surface component κ_0 . Ktenidou *et al.* (2013) investigated the variability of κ in a vertical array that recorded earthquakes at a down-hole, and found a significant variability of κ_0 at the surface and at the rock sites. Perron *et al.* (2017) used a semiautomatic procedure to measure κ and show that the associated uncertainty of the estimates of κ depend on the bandwidth used to determine κ . They also found that site amplification has an important impact in the estimate of κ_0 . Hollender *et al.* (2020) found that soil–structure interaction may cause high-frequency amplifications that can affect the estimation of κ . However, this effect can be considered part of the κ_0 component of κ . Parolai and Bindi (2004) show that site effects may not affect the determination of κ when the site resonances are below the frequency band used to calculate κ .

We focus on this article in the average regional source–station path contribution of κ ($\bar{\kappa}(r)$) and minimize the uncertainties of the κ estimates by making a careful selection of the data used. Most of the records analyzed come from sites having frequency resonances outside of the frequency band used to

calculate κ ($f = 8$ –38 Hz), and the selected earthquakes ($M_w > 3.4$) have corner frequencies considerably lower than 8 Hz. In addition, we used an inversion technique that separates source, path, and site effects from the estimates of κ (e.g., Van Houtte *et al.*, 2011).

DATA

We analyzed accelerograms and velocity records from the central Italy dense seismic array stations that recorded the 2016 Amatrice (M_w 6.0) and the Norcia (M_w 6.5) earthquake sequences. The dataset consists of 393 earthquakes located at hypocenter distances $r < 80$ km, having magnitudes $3.4 < M_w < 6.5$, recorded by 92 stations (Fig. 1b) from the Italian National Seismic Network, which is managed by the Istituto Nazionale di Geofisica e Vulcanologia, and the National Accelerometric Network, which is managed by the Civil Protection Department. Most stations are on class B sites ($V_{S30} = 360$ –800 m/s), using EC8 site classification, and the natural frequency of resonance is between 3 and 6.7 Hz, outside the frequency band (8–38 Hz) used to calculate κ . The magnitude–distance distribution of the recordings is displayed in Figure 2. Most of the events have a magnitude $M_w < 4.9$ and have epicentral distances of less than 140 km.

We selected earthquakes having records with signal-to-noise ratio (SNR) greater than three and that were recorded for more than 50 stations to assure that the earthquake locations are reliable. Moreover, the earthquakes selected ($M_w > 3.4$) have corner frequencies lower than the frequency band (8–38 Hz) used to estimate κ . It is expected that the corner frequency (f_c) is considerably lower than 8 Hz for earthquakes with $M_w > 3.4$ (Aki, 1987). For instance, the rupture length of an M_w 3.5 event is approximately 0.26 km (Wells and Coppersmith, 1994), and that gives an $f_c = 4.35$ Hz, using Brune (1970) source model; larger earthquakes have smaller f_c .

The time series are generally sampled at 100 samples per second and are baseline corrected by subtracting the average of all points following the same method as Pacor *et al.* (2016). The S-wave spectral amplitudes were calculated with time windows selected using a distance-dependent energy criterion. A 4 s minimum length was used for close hypocenter distance range, to be able to resolve above 1 Hz. The windows start 0.1 s before the direct S-wave arrival and end when the accumulated energy reaches 90% of the total recording for $r < 25$ km, 80% for 25–50 km, and 70% for $r > 50$ km. These windows contain primarily S waves and avoid surface-wave contamination. Finally, the selected windows are tapered with a Hanning window, and the spectral amplitudes are smoothed using $b = 40$ with the Konno and Ohmachi (1998) technique. We combine the north–south (N–S) and the east–west (E–W) components ($A(f) = \sqrt{A(f)_{N-S}^2 + A(f)_{E-W}^2}$) to estimate κ .

METHOD

We computed κ using a similar method introduced by Anderson and Hough (1984), in which the logarithm of the

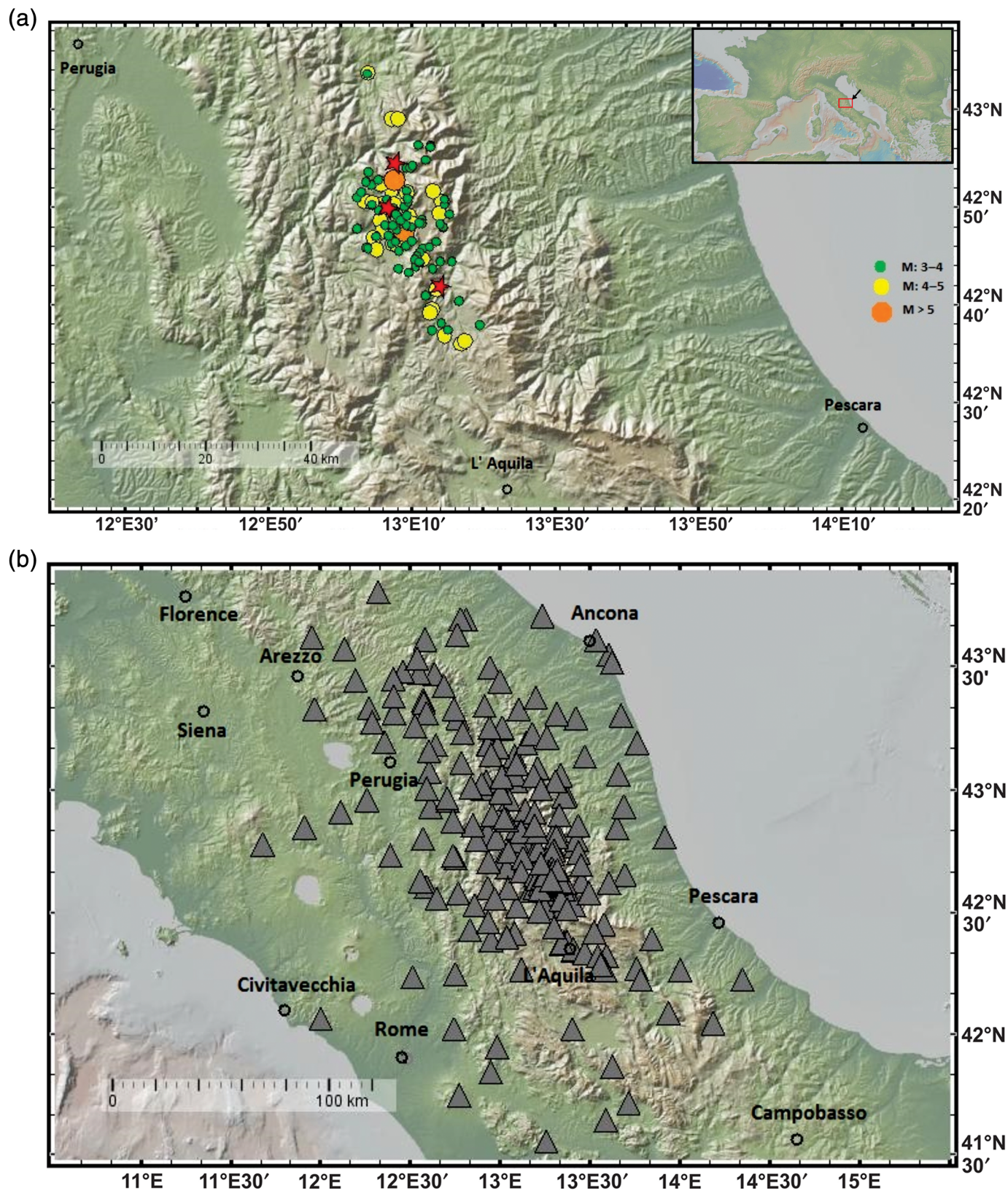


Figure 1. (a) Maps of the distribution of earthquakes analyzed with magnitudes ranging between 3.4 and 6.5. The red stars correspond to the epicenters of the M_w 6.0 Amatrice (42°42' N, 13°13.8' E), the M_w 5.9 Visso (42°54.6' N, 13°7.8' E), and the M_w 6.5 Norcia (42°49.8' N, 13°

6.6' E) earthquakes. The top right inset shows a regional map of the location in central Italy (shown with the red rectangle). (b) Map with recording stations. The color version of this figure is available only in the electronic edition.

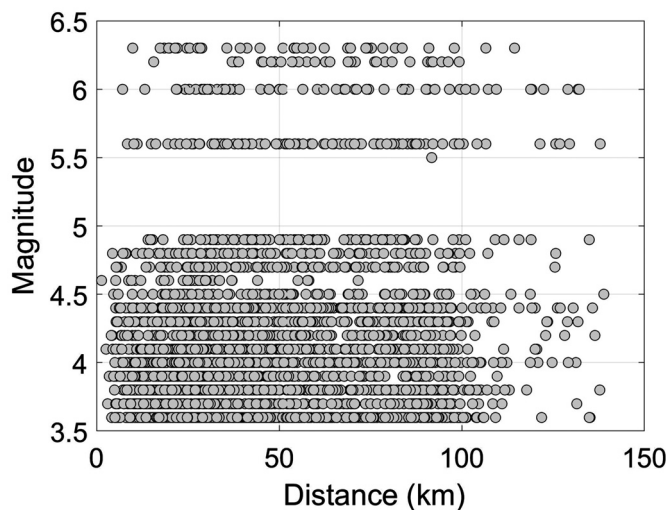


Figure 2. Magnitude–distance distribution of the recordings of the dataset used.

high-frequency *S*-wave spectral amplitude acceleration is least-squares fitted, and κ is estimated from the slope of the linear fit that equals $-\pi \text{Log}(e)\kappa$. We estimated the median κ and the corresponding standard deviation with a semiautomatic technique that precomputes the slopes over 11 frequency bands with length varying between 8 and 38 Hz (Lanzano *et al.*, 2022). The parameter κ is calculated via the least-squares fit if at least 65% of the spectral ordinates exceeds an SNR threshold of three, and if the lowest frequency of the band is larger than the corner frequency of the theoretical Brune's spectrum of the event, computed considering a typical stress drop value of 3 MPa for central Italy (Bindi *et al.*, 2004) and $V_s = 3.0$ km/s, the average crustal velocity value based on the standard model of central Italy (De Luca *et al.*, 2009). The median value of κ is discarded if it was precomputed with less than 6 of the 11 frequency bands considered and if the associated standard deviation is larger than 0.015 s (the observed variability of κ at a given distance). The variability of κ is estimated by selecting κ from records having the same hypocenter distance and calculating the standard deviation.

The resulting values of κ were modeled following Anderson (1991), Ktenidou *et al.* (2014), and Castro *et al.* (2022) as

$$\kappa(\kappa_s, r, \kappa_0) = \kappa_s + \tilde{\kappa}(r) + \kappa_0, \quad (1)$$

in which κ_s is the attenuation near the source, $\tilde{\kappa}(r)$ is the average attenuation along the *S*-wave source-station distance *r*, and κ_0 is the attenuation near the site. A similar inversion scheme was previously introduced by Van Houtte *et al.* (2011) to separate source, site, and path contributions to κ .

We determined first $\tilde{\kappa}(r)$ with the nonparametric technique proposed by Anderson (1991), which defines a function that describes the variation of κ with distance without assuming

an a priori functional form. For that purpose, equation (1) can be rewritten as (Castro *et al.*, 2022):

$$\kappa(r) = \kappa_1 + \tilde{\kappa}(r), \quad (2)$$

in which κ_1 includes both the attenuation near the source and near the site. To solve equation (2), it is assumed that $\tilde{\kappa}(r)$ is a smooth function of *r*, that κ varies slowly with distance, that $\tilde{\kappa}(0) = 0$, and that the shape remains the same for all the earthquakes and that undulations in the observed κ are related to κ_1 . The function $\tilde{\kappa}(r)$ is shifted downward or upward, depending on the value of κ_1 . This empirical model provides curves that are unbiased by a priori assumptions about the nature of the distance dependence of $\tilde{\kappa}(r)$ (e.g., Anderson, 1991).

We estimate κ_1 in a second iteration by correcting the observed values of κ with the function $\tilde{\kappa}(r)$ obtained solving equation (2). Then, we solved the following system of equations as in Castro *et al.* (2022):

$$\kappa_{1ij} = \kappa_{0i} + \kappa_{sj}, \quad (3)$$

in which κ_{1ij} is the corrected value, by the average path attenuation ($\tilde{\kappa}(r)$), of the observed κ from site *i* and source *j*; κ_{0i} is the near-site attenuation parameter at station *i*; and κ_{sj} is the near-source attenuation from earthquake *j*. To resolve the degree of freedom between κ_{0i} and κ_{sj} , we constrained equation (3) to satisfy the condition:

$$\sum_{i=1}^N \kappa_{0i} = 0, \quad (4)$$

in which *N* is the number of reference sites used for that constraint. This constraint is irrelevant for the analysis of $\tilde{\kappa}(r)$, which is our primary interest. The values of κ_{0i} of the reference sites vary between 0.0049 and 0.0183.

RESULTS AND DISCUSSION

The Amatrice (M_w 6.0) of 24 August 2016 and the Visso (M_w 5.9) of 26 October earthquakes

Figure 3a shows the average attenuation along the *S*-wave path $\tilde{\kappa}(r)$ obtained using estimates of κ from stations that recorded the Amatrice main event (solid line). These values of κ are like those obtained by Castro *et al.* (2000) using earthquakes from the Umbria–Marche, central Italy region, namely, 0.026–0.057 s between 20 and 83 km. These values of κ are also consistent with the mean value of 0.005 s obtained by Bindi *et al.* (2004) in the same region. We also computed $\tilde{\kappa}(r)$ using records from one foreshock recorded on 18 January 2016, about seven months before the main event (asterisks), and from aftershocks that occurred for 15 days (circles), 30 days (triangles), 2 months (diamonds), and 3 months (crosses) after the main earthquake. The estimates of $\tilde{\kappa}(r)$ using aftershocks from 15–30 days and 3 months, as well as those from the Norcia aftershocks are within

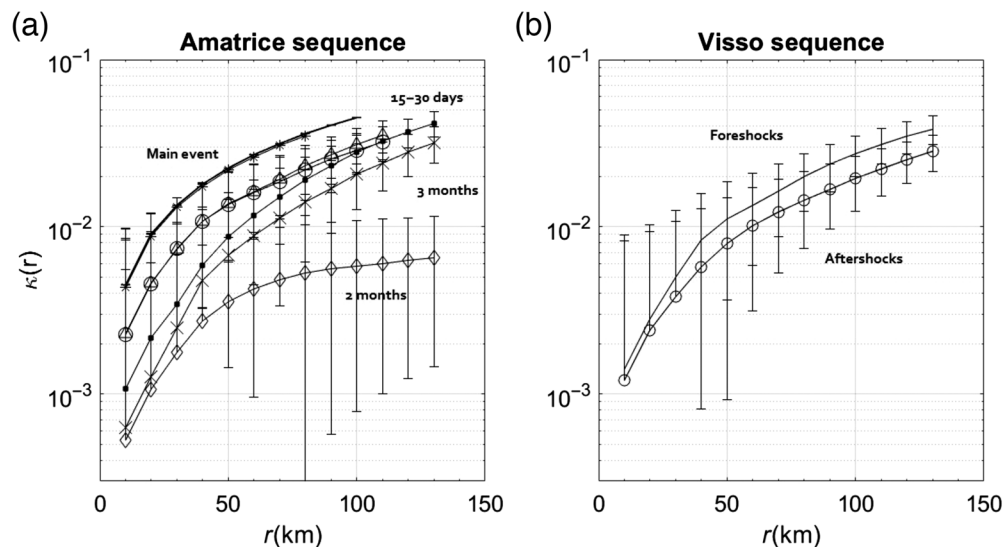


Figure 3. (a) Average source-station S-wave path kappa $\tilde{\kappa}(r)$ calculated from the records of the Amatrice earthquake (M_w 6.0) of 24 August 2016 (solid line), from foreshock (asterisk), from 15 days of aftershocks (circles), from 30 days of aftershocks (triangles), from 3 months of aftershocks (crosses), and from 2 months of aftershocks (diamonds). The $\tilde{\kappa}(r)$ is calculated using foreshocks of the Norcia earthquake is represented with filled squares. (b) $\tilde{\kappa}(r)$ is calculated from foreshocks (continuous line) and aftershocks (circles) of the Visso earthquake (M_w 5.9) of 26 October 2016.

the error bars of the corresponding estimates. For the Visso sequence, the error bars overlap between foreshocks and aftershocks (Fig. 3).

Based on these results, it seems that the attenuation in the epicentral area remain approximately unchanged (3% increased) for at least seven months before the main earthquake. During the Amatrice sequence, Gabrielli *et al.* (2022) observed high scattering, which is consistent with the high values of $\tilde{\kappa}(r)$ showing in Figure 3a before and during the mainshock. An increase in attenuation is expected during main earthquakes due to rock damage generated by the fault rupture that increases rock permeability (Ben-Zion and Ampuero, 2009; Castro and Ben-Zion, 2013; Kelly *et al.*, 2013; Malagnini and Parsons, 2020) allowing fluid flow. When rocks are water saturated the friction coefficient decreases facilitating sliding and thus decreasing the quality factor Q of the S waves significantly and increasing the overall attenuation at the same time (Johnston *et al.*, 1979). Then, $\tilde{\kappa}(r)$ gradually decreased by 39% after the first 30 days of the main earthquake, and then the attenuation dropped considerably (85%) after two months. It is possible that, after the main event fluids flowed outside of the epicentral area, and the stress drop produced by the mainshock reduced the permeability of the rocks with a consequent reduction of attenuation. Malagnini *et al.* (2022) observed a notable decrease of $Q_s^{-1}(f, t)$ after normal faulting earthquakes of central Italy. After this period, $\tilde{\kappa}(r)$ starts increasing for the next month, probably due to fluids redistribution. Two months after the Amatrice main event the aftershocks migrated 20 km north (Chiaraluce *et al.*, 2017; Tung

and Masterlark, 2018) and triggered the Visso (M_w 5.9) mainshock. Figure 3b shows that $\tilde{\kappa}(r)$ had approximately the same attenuation level before the Visso main event as the three-month aftershocks of the Amatrice earthquake, and $\tilde{\kappa}(r)$ also decreased during the Visso aftershocks as shown in Figure 3b.

A possible explanation of the temporal variation of $\tilde{\kappa}(r)$ can be related to stress variations and changes in the elastic properties of the medium, as part of a postevent phase. These changes of $\tilde{\kappa}(r)$ could also be related to the migration of pressurized fluids in the epicentral area (e.g., Lucente *et al.*, 2010). Several authors (Chiodini *et al.*, 2004; Miller *et al.*, 2004; Di Luccio *et al.*,

2010; Malagnini *et al.*, 2012) have proposed that carbon dioxide (CO_2)-rich fluids and gas releases modulate the seismicity in the central Italy region. Changes in permeability of the rocks during seismic sequences can produce attenuation variations and create fluid-flow pathways that can contribute to the triggering of mainshock sequences (Malagnini *et al.*, 2022).

We also computed the near-source kappa (κ_s) using aftershocks from 24 August 2016 to 3 September 2016 and the two-step inversion described earlier. These events are azimuthally well recorded to assure that the estimates of κ_s are not affected by possible anisotropy of $\tilde{\kappa}(r)$. Figure 4 shows the values of κ_s plotted chronologically. The errors of the κ_s estimates range between 0.0005 and 0.0024, less than 13% of the estimated values of κ_s .

The spatial variability of κ_s after the Amatrice earthquake is shown in Figure 5, in which the blue star represents the epicenter of the main event and the circles the location of the aftershocks. Near the epicenter of the main event, the values of κ_s are lower than those from aftershocks located north from the main event. This suggests that the tectonic stress was probably high near the rupture zone. Experimental data show that attenuation decreases with increasing pressure (Johnston *et al.*, 1979). Figure 6a shows that κ_s tends to increase when the focal depth of the aftershocks decreases, probably because crustal permeability decreases with depth, favoring the presence of fluid-saturated rocks in the upper crust (Tung and Masterlark, 2018). The errors of the focal depth (H) vary between 0.2 and 0.7 km, less than 10% of H . The line is the best-fitting linear regression, which has a negative correlation coefficient of -0.38 , indicating a weak correlation between κ_s and H . Figure 6b displays the

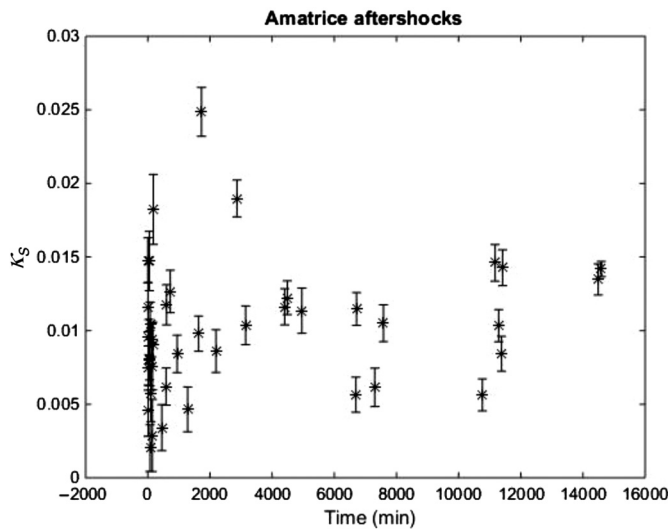


Figure 4. Kappa near the source (κ_s) computed from aftershocks that occurred during 15 days after the Amatrice earthquake (M_w 6.0) of 24 August 2016.

distribution of κ_s with earthquake magnitude and shows that earthquakes in the magnitude range of 3.5–4.0 have wide variability of attenuation near the source. However, κ_s seems to increase from 0.0046 for M_w 4.0 to 0.0147 for M_w 6.3 for larger magnitude ($M_w > 4$) events, although the apparent increasing trend is not clear. It is possible that larger magnitude events may generate a bigger rock-damage area, increasing the rock permeability and facilitating the presence of fluids.

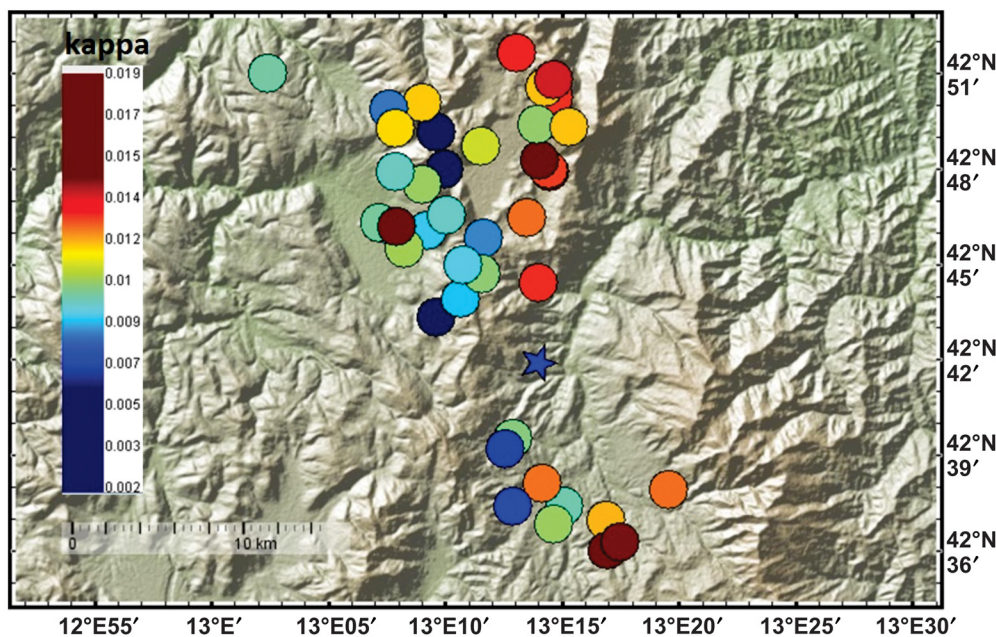


Figure 5. Spatial distribution of near-source attenuation (κ_s) of the aftershocks occurred during the 15 days after the Amatrice earthquake (M_w 6.0) of 24 August 2016 (blue star). The color version of this figure is available only in the electronic edition.

The Norcia earthquake (M_w 6.5) of 30 October 2016

For this earthquake sequence, we analyzed foreshocks that occurred from 8 October 2016 to 29 October 2016, one day before the main event, and aftershocks that occurred from 30 October at 06:40 hr, eight minutes after the main event, to 16 November 2016.

Figure 7 shows the resulting $\tilde{\kappa}(r)$ functions obtained from the foreshocks (continuous line), the main event (triangles), and the aftershocks (stars). The error bars of the estimates of $\tilde{\kappa}(r)$ vary between 0.00096 and 0.00397 s. The values of $\tilde{\kappa}(r)$ from the foreshocks is within the values of the $\tilde{\kappa}(r)$ functions obtained from the Amatrice aftershocks (filled squares in Fig. 3b), suggesting that the state of stress and the elastic properties of the media tend to return to the prevailing conditions after the Amatrice earthquake. The Norcia main event generated a significant attenuation drop, possibly related with an increase in tectonic stress and migration of fluids outside of the epicentral zone. Gabrielli *et al.* (2022) observed low scattering during the Norcia sequence, which traduces into low attenuation and low $\tilde{\kappa}(r)$. The values of $\tilde{\kappa}(r)$ from the aftershocks show that the attenuation increased probably during the recuperation phase of the elastic properties of the media after the main event and after completing the earthquake cycle.

CONCLUSIONS

From the analysis of two earthquake sequences that occurred in a short-time interval in central Italy, we estimated average functions $\tilde{\kappa}(r)$ that describe the distance dependence of the spectral decay parameter κ along the S-wave source-station paths. We observed a regional drop of the attenuation parameter κ within approximately two months after the Amatrice earthquake (M_w 6.0) of 24 August 2016. Then, $\tilde{\kappa}(r)$ tends to return toward the attenuation values observed before the occurrence of the main event, namely to the values of $\tilde{\kappa}(r)$ obtained from the foreshocks, when the earthquake cycle is likely completed. Because $\tilde{\kappa}(r)$ obtained from the foreshocks of the Norcia earthquake (M_w 6.5) of 30 October 2016 is comparable to that calculated with records from the Amatrice aftershocks, it is likely that at that point the tectonic stress is returned to its

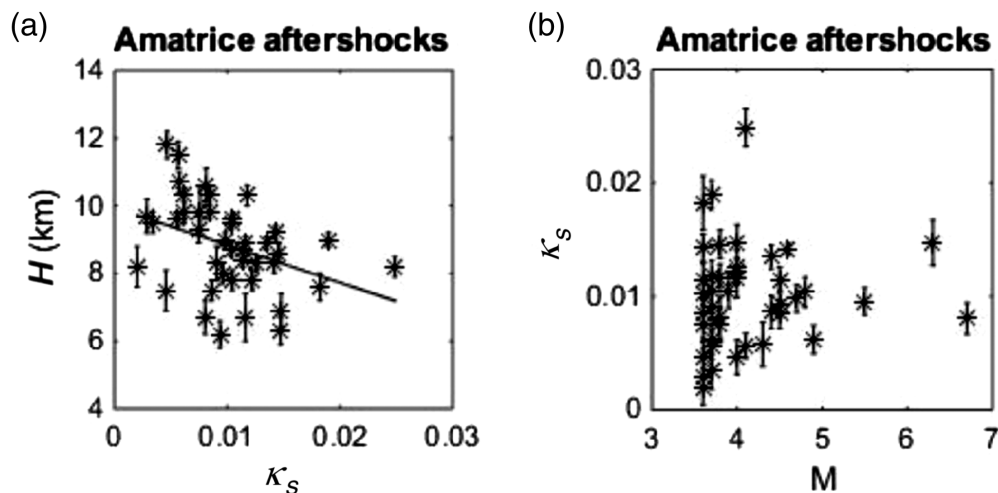


Figure 6. (a) Focal depth and (b) magnitude versus kappa near the source (κ_s) from the aftershocks occurred during the 15 days after the Amatrice earthquake (M_w 6.0) of 24 August 2016. The continuous line in panel (a) is the linear regression least-squares fit using all data points.

original state. Then, $\tilde{\kappa}(r)$ drops during the Norcia main event and tends to increase again during the aftershock sequence. A possible explanation of this temporal variability of the regional $\tilde{\kappa}(r)$ is that during the Amatrice earthquake sequence the rock damage generated by the foreshocks increased the rock permeability permitting the crustal fluids to flow, decreasing the friction coefficient and facilitating sliding (Fig. 3a). After the main event the fluids migrated toward the Visso epicentral area saturating the rocks, making the quality factor Q of S waves significantly lower and increasing the attenuation (Fig. 3b). In the meantime, the tectonic stress was transferred

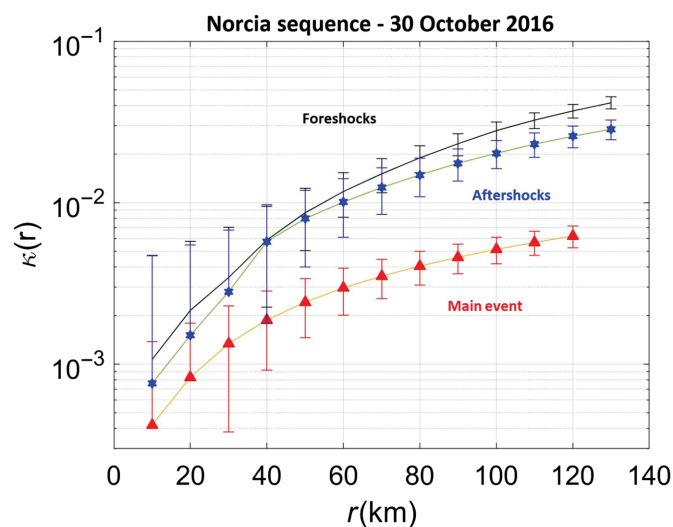


Figure 7. Average source-station S -wave path kappa $\tilde{\kappa}(r)$ calculated from the records of the Norcia earthquake (M_w 6.5) of 30 October 2016 (triangles) from foreshocks (black continuous line) and aftershocks (stars). The color version of this figure is available only in the electronic edition.

to the Norcia region generating the foreshocks and eventually the main event. The Norcia mainshock increased the fracturing and allowed crustal fluids to flow, facilitating the triggering of the aftershocks and increasing the attenuation (Fig. 7).

The near source κ_s is low near the epicenter of the Amatrice earthquake, increasing toward the north and south of the epicenter (Fig. 5). This, together with the observed temporal variations of $\tilde{\kappa}(r)$, indicates that fluid flow must be an important factor controlling the rupture process. For instance, Gabrielli *et al.* (2022) observed that the evolution of

seismic sequences across the Apennines is consistent with the role of fluids with high CO_2 content, as reported by other authors (Chiodini *et al.*, 2004; Miller *et al.*, 2004; Di Luccio *et al.*, 2010; Malagnini *et al.*, 2012).

We conclude that the temporal variation of $\tilde{\kappa}(r)$ could be a good indicator to monitor the earthquake cycle in central Italy.

DATA AND RESOURCES

The data used come from permanent networks operated by the Istituto Nazionale di Geofisica e Vulcanologia (INGV): the National Seismic Network (RSN) and the Mediterranean Network (Mednet); the Rapid Response Networks that are operated together with the University of Genova and the Réseau Seismologique et Géodésique Français (RESIF). Other permanent stations belong to the National Accelerometric Network (RAN) operated by the Department of Civil Protection. The acceleration records can be obtained from the Italian Accelerometric Archive (<http://itaca.mi.ingv.it>) and the velocity records from the European Integrated Data Archive (EIDA; <http://eida.rm.ingv.it>). Some plots were made using Generic Mapping Tools (<http://www.soest.hawaii.edu/gmt/>; Wessel and Smith, 1998) and with GeoMapApp (<http://www.geomapp.org>). All websites were last accessed in May 2021.

DECLARATION OF COMPETING INTERESTS

The authors acknowledge that there are no conflicts of interest recorded.

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