Text DR1. Data and network

For tomographic analysis we build on from previous catalog of foreshock of Chiaraluce et al., (2011), who identified and analyzed a catalog of 561 foreshock recorded during the three months preceding the 6 April 2009 mainshock. Three-component seismograms were recorded at the digital broad-band stations of the permanent Seismic National Networks managed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) of Rome.

Notwithstanding the catalog of Chiaraluce et al., (2011) in which the P and S foreshock arrival times were automatically picked, here we refined the quality of the P and S phase timing by manually re-pick all the foreshock waveforms. Furthermore, we take advantage of the seismic stations located close to the foreshocks epicentral area and belonging to the Abruzzi regional permanent dense seismic network managed by the INGV personnel based in L’Aquila (Fig. DR1).

All these waveforms have been handpicked for the first time, yet. The use of data from regional network have two main advantages; 1) the national seismic network has very few stations in the area affected by the foreshock activity, so the local network recordings allow to significantly increase the number of phases and the accuracy of both earthquake detection and hypocentral location; 2) a large number of events was too small-sized to be recorded by the remote stations of the national seismic network, so the actual number of retrieved foreshocks has increased as well.

The P- and S-wave arrival times were weighted following a scheme in which weights 0, 1, 2 and 3 have uncertainties less than 0.05, 0.1, 0.2, and 0.3 s, respectively.

The refined high quality P- and S-wave arrival times from both the national and regional network were therefore merged into a single dataset. The final catalogue consisted of more than 1500 events manually reviewed and located at depths down to 15 km.
Figure DR1. Map of the stations used in this study: green triangles are the INGV permanent national stations; white triangles are the permanent regional station managed by the INGV personnel in L’Aquila. Red solid circle are the foreshocks occurred from 2009/01/01 to 2009/04/07 23:59 UTC and used in this study for 3D tomographic analysis.

Text DR2.a 3D tomographic Inversion

We are interested to track the $V_p$ and $V_p/V_s$ variations in the crustal volume surrounding the mainshock during the progressive occuring of the foreshock. We therefore perform a time-lapse seismic tomography (Foulger et al, 2003) applying a standard tomographic approach (Haslinger, 1998) and inverting travel time data recorded in different but not overlapping temporal frames (epochs P1, P2 and P3). The comparison of velocity variations over the same crustal volume in different time period highlights how and where the elastic properties of the medium change through time while the events occurs. However, spurious time change of velocity can be ascribed to the comparison of tomographic models characterized by a different resolution and ray coverage. To minimize such artefacts we have followed the approach proposed by Foulger et al., (2003). In this approach, a first tomographic model is obtained using all the available events data for the study area. This model, which will be time-independent, has been used as the starting model. In this study, we have adopted the tomographic model of Di Stefano et al. (2011,) as the starting model, since it is obtained by using aftershocks recorded during the 3 months following the occurrence of the Mw 6.1, 6 April 2009 mainshock and, thus, cover the fault system almost uniformly.

Temporal variations are second order effects and its detection requires tomographic inversion performed using dataset that span restricted time intervals (Foulger et al., 2003). Time-lapse tomography has been therefore carried out using three different subset of events corresponding at three different epochs suggested by the temporal evolution of seismicity: epoch P1 (from 1 January 2019 to March 30, 2019, before the occurrence of the Mw 4.1 foreshock), epoch P2 (Mw 4.1, 30
March 13:38 UTC to 6 April 2009 01:32 UTC, before the occurrence of the Mw 6.1 mainshock),
epoch P3 (from Mw 6.1, 6 April 01:32 UTC to 7 April 2009 23:59 UTC).
We first performed a preliminary 1D location by using the Hypoellipse code (Lahr, 1989) and a
reference 1D velocity model (Valoroso et al., 2013). We then selected events with
hypocentral solutions that satisfied the following criteria: (1) a minimum number of 6 P- and 1 S-
phases, (2) minimum distance of 10 km from the hypocenter to the closest station, (3) location
errors < 1 km, and (4) azimuthal gap less than 200°. The events that met the above selection criteria
are 777 and provide a total of number of 13.372 P waves and of 8.869 S-P arrival times difference.

Seismic tomography is performed using the Simulps14q code, based on the linearized, iterative,
damped least square inversion method (Thurber, 1983), which inverts simultaneously for three-
dimensional hypocentral locations and, after parameters separation, for $V_p$ and $V_p/V_s$ at nodes of
3D grid minimizing the residual between the observed and computed travel times. The chosen
parameterization of the 3D model is based on the 3D grid nodes parameterization of Di Stefano et
al., (2011), with 5 km spacing (19 nodes) in the horizontal plane (x and y directions) and 2 km
spacing (11 nodes) in depth (from 0 km to 100 km). We have also assigned a uniform $V_p/V_s$ of
1.88, computed through the modified Wadati method (Chatelain, 1978). The outer nodes were kept
fixed during in the inversion. Damping is applied to stabilize the inversion process and this
parameter has been selected empirically by running a series of single-iteration inversions with
different damping values (Eberhart-Phillips, 1998). A damping of 150 has been selected after
plotting the trade-off curves of data variance vs. model variance for the different iteration. The
selected damping allowed us to greatly reduce data variance with moderate increases in model
variance (Eberhart-Phillips, 1998). For each epoch, a final root-mean-square of 0.18 s was reached
after 2 iterations steps, with a variance improvement of 31%, 37% and 18% for period P1, P2 and
P3, respectively.

**Text DR2.b Resolution Analysis**

To assess the reliability of the tomographic model, we have performed the ray sampling and the full
resolution matrix. For a well-resolved node, the diagonal elements should be close to 1 and the off-
diagonal elements should be close to 0. The resolution of a well-resolved node should be peaked
without meaningful contribution from nodes not adjacent (Eberhart-Phillips, 1998). The distribution
of the diagonal elements of the resolution matrix was therefore compared with the off-diagonal
elements and the derived Spread Function SF (that is how strong and peaked the resolution is at
each node) has been selected (Michelini and McEvilley, 1991). A well resolved parameter has small
volume over which the velocity is averaged (compact averaging vectors) and consequently a low SP
values. Following the method of Toomey and Foulger (1989), for all our models we select SF=3 as
a reliable threshold for well-resolved parameters, below which nodes are characterized by a
satisfactory ray sampling and compact averaging vector.

We also computed the Derivative Weight Sum (DWS) to quantify the ray density around each node
(Fig. DR4, and DR5) (Toomey and Foulger (1989)). Large DWS values indicate high ray density.
Figures DR4 and DR5 clearly show the increasing ray density using the data recorded at the
Abruzzi regional permanent seismic stations.

To test the resolution power of the data we performed the restore resolution test (Zhao et al., 1992)
where results of the tomography in P2 are used as the target model and to compute the synthetic
taveltimes for each epoch (P1, P2 and P3). We prefer the use of such restoring test because it
directly shows how the most significant anomalies is observed (i.e., the high $V_p/V_s$ in P2) could be
similarly recoverable in the 3 epochs, giving more information that classic checkerboard test. For
each epoch P1, P2 and P3 we calculate the synthetic arrival times within the synthetic model using
the source-receiver distribution of the real datasets. To simulate the real datasets, gaussian white-
noise with standard deviation of 0.10 s e 0.15 s for P and S wave data, respectively, has been added
to synthetic traveltimes. The new traveltimes are re-weighted according to the new noise level. We
then inverted the final dataset using the same starting model (Di Stefano et al., 2011) and the same inversion parameters.
The results of the test are shown in Figure DR6 for the layer at 8 km depth (the layer close to the nucleation depth of both the mainshock and the largest foreshock). We display the final models computing the percent deviation (%) from the starting model. Synthetic test show that, inside the well resolved part of the models (SF<3), the deviation of the final models from the input model are within 5% for both $V_p$ and $V_p/V_s$. Thus, results of synthetic test and the analysis of the resolution matrix indicate that $V_p$ and $V_p/V_s$ models are reliable within the volume with SF $\leq 3.0$. 

Figure DR2. Down-dip sections of $V_p$ (left) and $V_p/V_s$ (right) models shown for the three different epochs: P1 (top panels), P2 (middle panels), and P3 (bottom panels). Red star: $M_w$ 6.1, 6 April 2009 mainshock. Yellow star: $M_w$ 4.1, 30 March 2009 foreshock. The green contour lines show the coseismic slip ($m$) of the mainshock from Cirella et al., (2009). The purple contour line represents the volume comprising the nodes with spread function $SP \leq 3$ and enclosing the well resolved volume.
Figure DR3 $V_p$ (left) and $V_p/V_s$ (right) models shown for the layer at 8 km for the periods P1 (top panels), P2 (middle panels) and P3 (bottom panels). Red star: $M_w$ 6.1, 6 April 2009 mainshock. See Figure DR2 for the meaning of purple line.
Figure DR4. Derivative Weight Sum (DWS) relative to the $V_p$ 3D inversion at 8 km depth for the three different epochs: P1, P2 and P3 (See Figure DR2 for details on P1, P2 and P3). a), b), c) DWS computed without considering the Abruzzi permanent regional stations; d), e), f) DWS computed considering the Abruzzi permanent regional stations. The simplified trace of the L’Aquila fault is also shown (red line). Blue dashed box is the surface projection of the 2009 mainshock causative fault (Cirella et al., 2012). Red star: $M_w$ 6.1, 6 April 2009 mainshock. See Figure DR2 for the meaning of the purple line.
Figure DR5. Derivative Weight Sum (DWS) relative to the $V_p/V_s$ 3D inversion at 8 km depth for the three different epochs. See Figure S4 for details. See Figure DR2 for the meaning of purple line.
Figure DR6. Results of the restoring resolution test for $V_p$ (left panels) and $V_p/V_s$ (right panels) for the three different epochs: P1, P2 and P3. The purple line contours the volume with SF $\leq 3.0$. 
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Text DR3. Spatio-temporal analysis of foreshocks and fluid migration

In the spatio-temporal analysis of foreshocks, we assume that the migration of hypocentres is related to a pulse in pore pressure caused by water fluids that propagate into the deep dolomitic reservoir. The radius $r$ of the trigger front, in an isotropic medium, is related to the solution of the Darcy’s formula (Shapiro et al., 2003) by the following relation:

$$ r = \sqrt{4\pi Dt} $$

where $D$ is the hydraulic diffusivity (in m$^2$/s) and $t$ is the time (in seconds). In our case, the radius $r$ is a 3D Euclidean distance evaluated from the hypocentre of the first foreshock.

Due to the complexity of the system, we analyzed the spatio-temporal evolution of the foreshocks using our new 3D tomographic locations within eight different time-windows containing the most prominent clusters of events with the largest foreshocks production. As one can see from the distance-time plot, foreshocks delineate different pulses of forward and backward migration (Fig. DR7). We calculate the mean centroid of foreshocks for each window and the associated $r$ corresponding to the 2-standard deviation of the hypocentral coordinates. This provides a spatially averaged picture of the foreshocks migration through time (Fig. DR8) and the related hydraulic diffusivity value (Fig. DR9).

![Figure DR7. Plot of the distance of foreshocks from the first event of the sequence vs. time (in days). We discarded distances larger than 6 km.](image)
Figure DR8. Plot of the foreshock centroids as a function of the Julian day (blue circles, the numbers refer to the Julian day corresponding to each of the eight time-windows and the small arrow point to the foreshock migration direction). The green and red stars represent the epicentres of the Mw 4.1, 30 March foreshock and of the Mw 6.1, 6 April 2009 mainshock, respectively.

Figure DR9. Plot of the foreshocks migration distance as a function of time (Julian day), together with the corresponding isotropic hydraulic diffusivity.
In order to convert diffusivity into permeability $K$ (in $m^2$), we adopt the following equation:

$$D = K / \varepsilon \nu C_w$$

where $\varepsilon$ and $\nu$ are the rock porosity and the fluid viscosity, respectively, by using $\nu = 10^{-3}$ Pa$\times$s; $\varepsilon = 0.05$. $C_w$ is the coefficient of the isothermal compressibility of water, which strongly depends on pressure, temperature and salt content. From the thermal logs of the Varoni1 well (available at http://www.videpi.com/videpi/pozzi/dettaglio.asp?cod=6789; location in Fig. 1a) we know that a very low geothermal gradient characterizes this area (borehole bottom temperature $T=62^\circ C$ at 5777 m depth), in accordance with regional estimates published by Della Vedova et al., (2001) for the Apennines. We consider the simplest case of water with a small amount of salt (<1% weight). The formulas (from Danesh, 1998) are the following:

$$C_w = 10^{-6} \times (C_0 + C_1 T + C_2 T^2)$$

Where $C_w$ is in $psi^{-1}$ (pounds per square inch) at temperature $T$ (Fahrenheit) and the coefficients depend on pressure $P$ (in $psia$)

$$C_0 = 3.5846 - 0.000134P$$
$$C_1 = -0.01052 + 4.77 \times 10^{-7} P$$
$$C_2 = 3.9267 \times 10^{-5} - 8.8 \times 10^{-10} P$$

The coefficient of correction for salt content ($W_s$) is

$$W_s = 1 + (-0.052 + 2.7 \times 10^{-4}T - 1.14 \times 10^{-6}T^2 + 1.121 \times 10^{-9}T^3) W_s$$

For our calculation, taking into account the average hypocentral depths of foreshocks, we consider a reference depth of 7 km, a temperature $T=100^\circ C$ and salt content of 1%, providing $C_w = 2 \times 10^{-10}$ Pa$^{-1}$. According to our results, the permeability values of the deep dolomitic reservoir affected by the largest foreshocks production range between $K = 1.0 \times 10^{-15}$ $m^2$ and $K = 6.0 \times 10^{-15}$ $m^2$.

Text DR4. Animation files

In order to better capture the 3D structure of the tomographic models discussed in this paper and the spatial pattern of foreshocks with respect to the L’Aquila Fault and the surrounding velocity medium, we provide some animations. The compressed movies have been prepared using the Paraview software v 5.5.2 (http://www.paraview.org/) and can be opened using any application supporting .avi files.

Movies DR1-DR7 are provided in the following zipped folder. Please click to download.

2020011_Movies DR1-DR7.zip

MovieDR1-Movie_Foreshocks_01.avi

3-D perspective of the L’Aquila Fault (slip model of the 6 April 2009 earthquake from Cirella et al., 2009) with hypocentral locations of the foreshocks analysed in this paper (orange points: P1; green points: P2; yellow points P3) and aftershocks (small white points; from Valoroso et al., 2013).
MovieDR2-P1_Vp_slice.avi
3-D perspective view (looking to the North) of sequential vertical slices through the Vp tomographic model for period P1. The L'Aquila fault is shown as coloured wireframe. Orange points are foreshocks of period 1. The big violet sphere is the 6 April mainshock hypocentre, the smaller green sphere is the 30 March foreshock hypocentre.

MovieDR3-P1_VpVs_slice.avi
3-D perspective view (looking to the North) of sequential vertical slices through the Vp/Vs tomographic model for period P1. The L'Aquila fault is shown as coloured wireframe. Orange points are foreshocks of period 1. The big violet sphere is the 6 April mainshock hypocentre, the smaller green sphere is the 30 March foreshock hypocentre.

MovieDR4-P2_Vp_slice.avi
3-D perspective view (looking to the North) of sequential vertical slices through the Vp tomographic model for period P2. The L'Aquila fault is shown as coloured wireframe. Orange points are foreshocks of period 1, green points foreshocks of period P2. The big violet sphere is the 6 April mainshock hypocentre, the smaller green sphere is the 30 March foreshock hypocentre.

MovieDR5-P2_VpVs_slice.avi
3-D perspective view (looking to the North) of sequential vertical slices through the Vp/Vs tomographic model for period P2. The L'Aquila fault is shown as coloured wireframe. Orange points are foreshocks of period 1, green points foreshocks of period P2. The big violet sphere is the 6 April mainshock hypocentre, the smaller green sphere is the 30 March foreshock hypocentre.

MovieDR6-P3_Vp_slice.avi
3-D perspective view (looking to the North) of sequential vertical slices through the Vp tomographic model for period P3. The L'Aquila fault is shown as coloured wireframe. Orange points are foreshocks of period 1, green points foreshocks of period P2, yellow points foreshocks of period P3, small white points are aftershocks (by Valoroso et al., 2013). The big violet sphere is the 6 April mainshock hypocentre, the smaller green sphere is the 30 March foreshock hypocentre.

MovieDR7-P3_VpVs_slice.avi
3-D perspective view (looking to the North) of sequential vertical slices through the Vp/Vs tomographic model for period P3. The L'Aquila fault is shown as coloured wireframe. Orange points are foreshocks of period 1, green points foreshocks of period P2, yellow points foreshocks of period P3, small white points are aftershocks (by Valoroso et al., 2013). The big violet sphere is the 6 April mainshock hypocentre, the smaller green sphere is the 30 March foreshock hypocentre.

References


