Rupture history of the 2009 L'Aquila (Italy) earthquake from non-linear joint inversion of strong motion and GPS data

Antonella Cirella[1], Alessio Piatanesi[1], Massimo Cocco[1], Elisa Tinti[1], Laura Scognamiglio[1], Alberto Michelini[1] and Anthony Lomax[2]

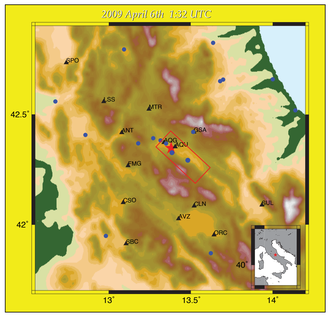
cirella@ingv.it

(1) Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Rome, Italy

(2) ALomax Scientific, Mouans-Sartoux, France.

Abstract

The 2009 L'Aquila earthquake (Mw 6.3) occurred in the Central Apennines (Italy) on April 6th at the 01:32 UTC and caused nearly 300 casualties and heavy damages in the L'Aquila town and in several villages nearby. The main shock ruptured a normal fault striking along the Apennine axis and dipping at nearly 50° to the SW. Most of the aftershocks are also associated with normal faulting, which is consistent with the present-day tectonic setting of this sector of the Apennines. The identification of the fault geometry of the L'Aquila main shock relies on the aftershock pattern, the SAR interferometric data, the GPS displacements as well as the induced surface breakages. The earthquake allowed for the collection of an excellent data set for normal faulting events. In this study, we have imaged the rupture history of the L'Aquila earthquake using a nonlinear joint inversion of strong motion and GPS data. Our results show that slip distribution on the fault is quite heterogeneous and characterized by a small shallow slip patch located up-dip the hypocenter and a large and deeper patch located southeastward. The rupture velocity is larger in the up-dip than in the along-strike direction. This difference can be partially accounted by the local crustal structure, which is characterized by a high velocity layer above the hypocenter (9.46 km) and a lower velocity below. The latter velocity seems to have affected the along strike propagation since the largest slip patch is located at depths between 9 and 14 km. The imaged slip distribution correlates well with the on-fault aftershock pattern as well as with mapped surface breakages. The rupture history is also consistent with the large PGA values recorded at L'Aquila that is located right above the hypocenter.



1. Inversion Methodology

We use a two-stage nonlinear technique [Piatanesi et al., 2007], which involves the joint inversion of strong motion records and geodetic data.

To account for rupture complexity, the model is described by four spatially variable fault parameters - peak slip velocity, slip direction, rupture time and rise time. The final slip distribution is derived by the inverted parameters. The finite fault is divided into subfaults with model parameters assigned at the corners, whereas the parameters within each subfault are allowed to vary through bilinear interpolation of the nodal values. We adopt a single window approach. Although the procedure allows for the choice of different analytical forms of the source time function.

During the first stage of the inversion, a "heat-bath" simulated-annealing algorithm explores the model space to generate an ensemble of models that efficiently sample the good data-fitting regions. In the second stage (appraisal), the algorithm performs a statistical analysis of the model ensemble and computes an average model and its standard deviation, by weighting all models of the ensemble by the inverse of their cost function values.

Figure 1. Map of the fault geometry of the 2009 L'Aquila earthquake. The red box represents the surface projection of the fault plane adopted in this study. Black triangles represent the selected strong motions stations. Blue dots represent the GPS sites. The red star indicates the epicenter.

2. Rupture Process of the 2009 L'Aquila Earthquake

The 2009 L'Aquila earthquake provided an unprecedented data set of seismograms and geodetic data for a normal faulting event. The hypocenter has been located at 42.35°N, 13.38°E at a depth of 9.5 km [Chiarabba et al., 2009].

In this study, we have selected 14 accelerograms from the RAN and the MedNet station AQU, and 17 GPS displacements obtained by the INGV network [Anzidei et al., 2009]. The epicentral distances of the recording sites are less than 70 km (Figure 1). The azimuthal coverage is good and several seismic and GPS stations lie on the hanging wall of the causative fault. The recorded accelerograms are integrated to obtain ground velocity time histories and then band-pass filtered between 0.02 and 0.5 Hz with a two-pole, two-pass Butterworth filter. We use a specific crustal model retrieved from receiver functions [I.Bianchi, personal communication,2009]for computing synthetic seismograms at AQU and AQG; while for all the other receivers we use a model based on the Bagh [Bagh et al., 2007] 1-D structure, except for the shallowest layer (0-1.5 Km) for which we adopt the wave velocities obtained from the surface group velocity dispersion analysis (RF and Herm_Bagh in Figure 2). The adopted fault is striking N133°E, and dipping 54° to the SW; it is 28 km long and 17.5 km wide, with the shallow top border at 0.5 km depth. We invert simultaneously for all the parameters at nodal points equally spaced (3.5 km) along strike and dip. During the inversion, bounds of 0 to 2.5 m/s at 0.25 m/s interval were allowed for the peak slip velocity; the rise time varies between 1 and 2 sec at 0.25 sec interval and the rake angle from 250° to 290° in steps of 10°. The rupture time at each grid node is constrained by the arrival time of a rupture front having a speed comprised between 1.8 and 2.8 km/s.

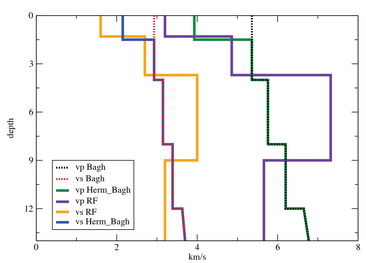
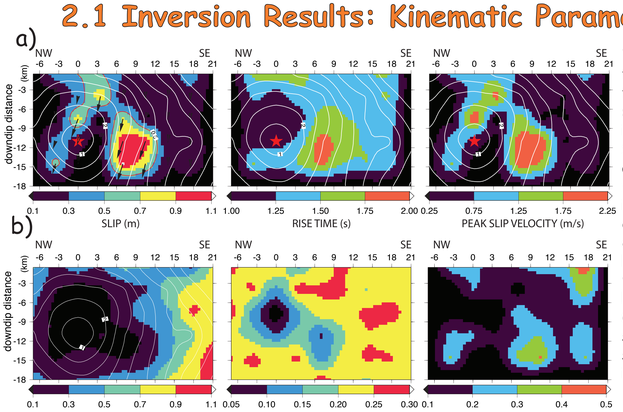


Figure 2. S- and P- velocity profiles adopted to compute the Green Function

2.1 Inversion Results: Kinematic Parameters



The inverted average source model is shown in Figure 3 together with the distribution on the fault plane of the square root of variance. It has been obtained after averaging those rupture models (nearly 30.000) having a cost function not exceeding the 5% of the minimum cost function value (i.e., the best fitting model). Two patches of slip characterize the imaged rupture history. The largest slip concentration is located at nearly 8 km SE from the nucleation and a second smaller slip patch is located above the hypocenter at shallower depths (i.e., nearly 3 km in the up-dip direction). The inferred rise time ranges between 1.5 and 2.0 s in correspondence of the main slip patch. The larger asperity features a peak slip velocity of about 2.25 m/s, which corresponds to a maximum slip of about 1.1 m; the maximum slip in the shallow patch is nearly 0.7 m. The rake angle in correspondence of the maximum slip is -102°, in agreement with a mechanism of prevalent normal faulting with a minor right-lateral component of slip. The rupture front propagation is faster along the up-dip direction (rupture speed ranges between 2.2-2.8 km/s) than along-strike direction (≈ 2 km/s). The total duration of the rupture is about 6.5 s. Although we adopted a large fault plane to image the model parameters, significant slip occurs only on a segment of about 18 km which agrees well with relocated aftershocks distribution. The seismic moment of the average model is Mo=3.5 × 10^{18} Nm, which is consistent with the Regional Centroid Moment Tensor solution.

Figure 3. a) Inverted rupture model (average model from ensemble inference) of the 2009 L'Aquila earthquake. Left, middle and right panels show total slip, rise time and peak slip velocity distributions, respectively. The rupture time is shown by contour lines (in seconds); the black arrows displayed in left panel represent the slip vector. b) Square root of variance of rupture time, rise time and peak slip velocity for the average rupture model computed through ensemble inference.

2.2 Inversion Results: Data-Fit

Figure 4 shows the comparison between recorded and synthetic data and it reveals a more than satisfactory agreement. The synthetic ground velocities match fairly well the recorded seismograms at most of the stations (Figure 4-a). Discrepancies at some sites result most likely from inadequate modeling of the complex wave propagation and from the inadequate accounting of the site effects (both not included in our simulations). In contrast, the fit of the GPS displacements is very good and Figure 4b illustrates the match between observed and calculated coseismic horizontal and vertical displacements (upper and bottom panel, respectively).

2.3 Rupture Velocity & Crustal Structure

Despite its moderate magnitude, the 2009 L'Aquila shows evidence of rupture directivity.

The analysis of our inverted models suggests that the rupture velocity along the up-dip direction is larger (≈ 2.8 km/s) than along-strike (≈ 2 km/s). We note that the high velocities of the crustal structure near the nucleation area can explain the difference in rupture speed between up-dip and along-strike propagation. Indeed, the 1-D velocity model below the AQU station shows a high velocity layer between 3 and 9 km depth, thus affecting the up-dip rupture propagation (see Figure 5).

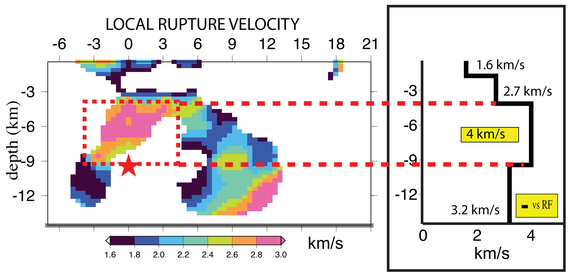


Figure 5. Local rupture velocity distribution, (left panel, white color is associated to slip values lower than 0.3 m) and S- velocity profile adopted to compute the Green function at AQU and AQG sites.

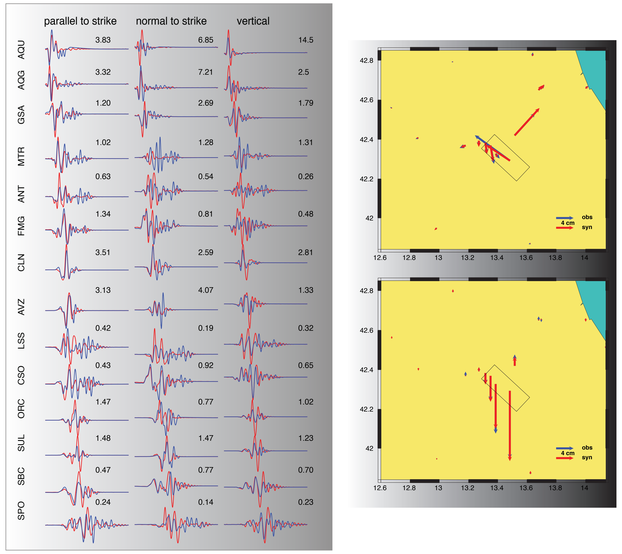


Figure 4. a) Comparison of recorded strong motions (blue lines) with synthetic waveforms computed from the inverted rupture model (red lines). Numbers with each trace are peak amplitude of the observed waveforms in cm/s. b) Comparison of measured (blue arrows) with synthetic (red arrows) horizontal (upper panel) and vertical (bottom panel) coseismic displacements.

3. Slip History & Seismicity Pattern

The heterogeneous slip distribution imaged for the 2009 L'Aquila earthquake correlates well with the on-fault aftershock pattern and agrees with the observed surface breakages (Figure 6). Surface breakages (≤ 10 cm, EMERGEO WG, 2009) are located just above the shallowest slip patch on the fault plane. Of much interest is to note also that the aftershocks cluster around the high slip patches and several moderate-magnitude aftershocks are clustered near the nucleation, consistently with the slip pattern.

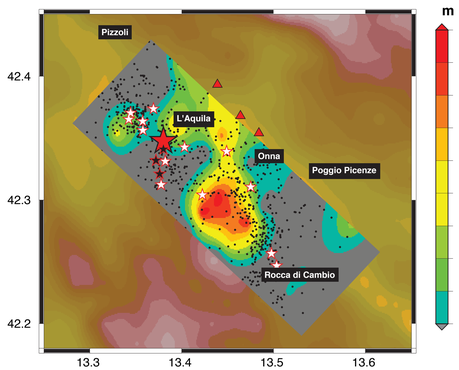


Figure 6. Inverted rupture model projected on the Earth surface. Colors on the fault plane indicate the slip distribution, white contours represent the position of the propagating rupture at 1 s interval. The red star shows the location of the mainshock, black and white stars show the location of the strongest foreshocks and of the largest magnitude aftershocks (ML > 4.0), respectively, black dots the other aftershocks and the red triangles show the location of the observed surface breakages.

Conclusive Remarks

- We image the rupture history of the 2009 L'Aquila (Central Italy) earthquake using a nonlinear joint inversion of strong motion and GPS data.

- The inferred slip distribution is heterogeneous and characterized by a small, shallow slip patch located up-dip from the hypocenter (9.5 km depth) and a large, deeper patch located southeastward.

- The rupture velocity is larger in the up-dip than in the along-strike direction. This difference can be partially accounted by the crustal structure, which is characterized by a high velocity layer above the hypocenter and a lower velocity below.

- The imaged slip distribution correlates well with the on-fault aftershock pattern as well as with mapped surface breakages.

- The proposed source model for the 2009 L'Aquila earthquake is consistent with the observed peak ground morion pattern.

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