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Key Points:
- Investigation of the ground deformation and source geometry of the 2016 Amatrice earthquake (Central Italy)
- Coseismic displacements modeling through a 3-D finite elements approach jointly exploiting DInSAR measurements and a 3-D fault model
- Evidence of a bilateral rupture propagating along two en echelon normal faults conjoined at the hypocenter

Supporting Information:
- Supporting Information S1

Correspondence to:
P. Tizzani,
tizzani.p@irea.cnr.it

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Ground deformation and source geometry of the 24 August 2016 Amatrice earthquake (Central Italy) investigated through analytical and numerical modeling of DInSAR measurements and structural-geological data

G. Lavecchia[1], R. Castaldo[2], R. de Nardis[1], V. De Novellis[2], F. Ferrarini[1], S. Pepe[2], F. Brozzetti[1], G. Solaro[2], D. Cirillo[1], M. Bonano[2], P. Boncio[1], F. Casu[2], C. De Luca[2], R. Lanari[2], M. Manunta[2], M. Manzo[2], A. Pepe[2], I. Zinno[2], and P. Tizzani[2]

[1]CRUST-DiSPUTer-Università di Chieti-Pescara "G. d'Annunzio", Chieti Scalo, Italy, [2]Istituto per il Rilevamento Elettromagnetico dell'Ambiente-Consiglio Nazionale delle Ricerche, Naples, Italy

Abstract We investigate the ground deformation and source geometry of the 2016 Amatrice earthquake (Central Italy) by exploiting ALOS2 and Sentinel-1 coseismic differential interferometric synthetic aperture radar (DInSAR) measurements. They reveal two NNW-SSE striking surface deformation lobes, which could be the effect of two distinct faults or the rupture propagation of a single fault. We examine both cases through a single and a double dislocation planar source. Subsequently, we extend our analysis by applying a 3-D finite elements approach jointly exploiting DInSAR measurements and an independent, structurally constrained, 3-D fault model. This model is based on a double fault system including the two northern Gorzano and Redentore-Vettoretto faults (NGF and RVF) which merge into a single WSW dipping fault surface at the hypocentral depth (8 km). The retrieved best fit coseismic surface deformation pattern well supports the exploited structural model. The maximum displacements occur at 5–7 km depth, reaching 90 cm on the RVF footwall and 80 cm on the NGF hanging wall. The von Mises stress field confirms the retrieved seismogenic scenario.

1. Introduction

On 24 August 2016 (01:36 UTC) the intra-Apennine extensional fault system of Central Italy released a M_w 6.0 destructive earthquake [*Tinti et al.*, 2016] between the towns of Norcia and Amatrice (Figure 1a). The main shock produced widespread damages and fatalities, devastating several localities and killing about 300 people. The main event was followed by a significant aftershock (M_w 5.4), located 15 km to the NW.

After 1 week, the epicentral area reached a length of about 40 km, in the NNW-SSE direction, largely developing at the hanging wall of the WSW dipping active extensional Vettore and Gorzano faults (VF and GF, respectively, see Figure 1b). The main event was located at a depth of about 8 km; the fault plane solution was almost purely extensional with NNW-SSE striking focal planes (Figure 1c).

After 2 months, on 26 October (19:18 UTC), another major earthquake (M_w 5.9) occurred 25 km to the NW, and few days later, on 30 October (06:40 UTC), a third major earthquake (M_w 6.5) nucleated in between the first two. The overall 2016 Central Italy sequence extends for a length of ~60 km in the NNW-SSE direction, largely developing at the hanging wall of the WSW dipping active Vettore and northern Gorzano faults.

In this paper, we focus on the ground deformation and source geometry of the 24 August event, referred hereafter to as Amatrice earthquake (AEQ), which was the only event that occurred at the time of this paper submission.

The AEQ epicentral area has been imaged by several spaceborne synthetic aperture radar (SAR) sensors which allowed, through the differential interferometric SAR (DInSAR) technique [*Franceschetti and Lanari*, 1999], retrieval of the coseismic displacements. In particular, after 1 week following the main event several DInSAR deformation maps (interferograms) were generated, using images acquired from ascending and descending orbits and from radar sensors operating at different frequencies: Advanced Land Observing

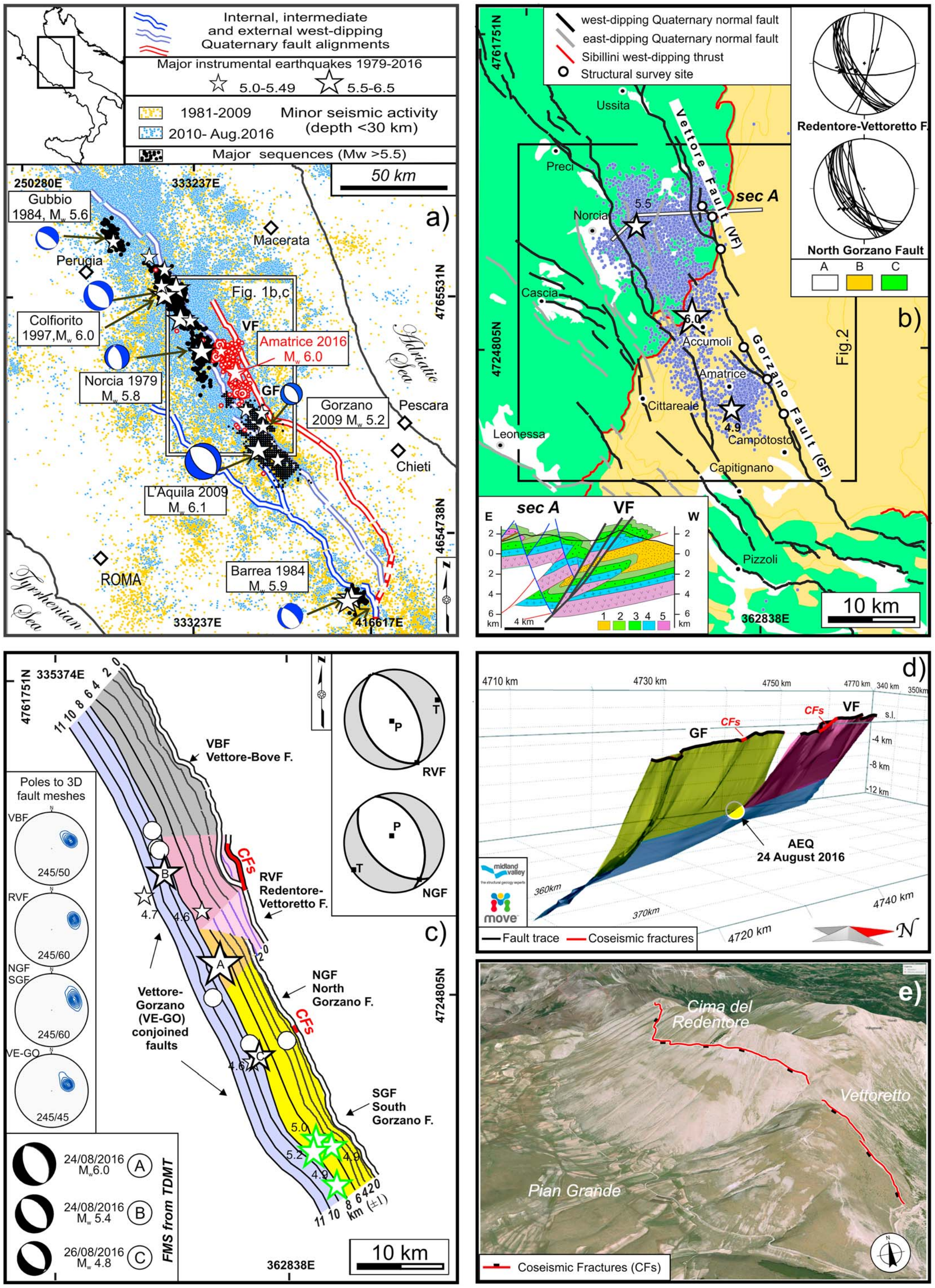

Figure 1. Seismotectonic framework. (a) Background seismicity since 1981, with major instrumental sequences and active fault alignments [*Lavecchia et al*., 2012]. (b) Amatrice earthquake epicentral area (24 to 31 August 2016), with active normal faults and preexisting compressional structures (A: Quaternary continental deposits, B: Meso-Cenozoic marly carbonate multilayer; C: late Miocene siliciclastic sediments); the stereonets report newly fault slip data; the geologic section is from *Brozzetti and Lavecchia* [1994] (1: siliciclastic deposits; 2, 3, and 4: carbonate multilayer; 5: Triassic evaporites). (c) Depth contour lines of the Vettore-Gorzano fault alignment, with main hypocenters of the Amatrice 2016 sequence (white dots and stars) and of the northernmost L'Aquila 2009 sequence (green stars); the stereonets on the upper right corner report average Amatrice fault plane solutions for events with $M_W > 3.5$, TDMT focal mechanisms available at http://cnt.rm.ingv.it/tdmt.html; the stereonets on the left represent density contour of poles to Gorzano and Vettore surfaces as built in Figure 1d. (d) Computed 3-D fault model; the traces of the cross sections used for the reconstruction are given in Figure S1a. (e) Google Earth image of the Mount Vettore with, highlighted in red, the trace of the coseismic fractures (CFs) surveyed along the RVF; CFs location is in Figure 1c.

Satellite-2 (ALOS2), at L-band; Sentinel-1 (S1), at C-band; and COSMO-SkyMed (CSK), at X-band. Note also that the time intervals of the exploited ascending and descending interferograms typically do not allow us to discriminate the surface displacement effects of the main event from those of the major aftershocks. However, because of the rather low magnitude of the aftershocks ($\leq M_w$ 5.4), they can only marginally contribute to the overall surface deformation pattern.

In this paper, we investigate the earthquake source and its main characteristics, benefiting from the large availability of DInSAR measurements. To do this, we invert the available DInSAR deformation maps to retrieve the parameters characterizing the finite dislocation sources that we initially use to model the fault ruptures. Subsequently, we extend our modeling analysis through a 3-D finite element (FE) numerical optimization, jointly exploiting the DInSAR measurements and a 3-D model of the VF and GF, generated by integrating the available structural-geological and seismological information. This allows us to highlight the key role played by the configuration of the Gorzano-Vettore system, characterized by distinct faults at surface but interconnected at depth.

2. Exploited Data

2.1. Structural Data and Fault Model Generation

The Quaternary extensional system of Central Italy consists of well-exposed west dipping, high-angle, normal faults, crosscutting a preexisting, late Miocene in age, fold-and-thrust belt [*Lavecchia et al*., 1994]. Geological, geodetic, and seismological data coherently highlight an active SW-NE tensional stress field [*Ferrarini et al*., 2015].

At the surface, the west dipping faults consist of individual fault segments, extending 20 to 35 km along strike [*Boncio et al*., 2004], arranged in major alignments which may reach lengths of some hundreds of kilometers (Figure 1a). Since instrumental times, the alignment from Gubbio to L'Aquila has released three main normal-faulting earthquakes (Norcia 1979, M_w 5.9; Colfiorito 1997, M_w 6.0; and L'Aquila 2009, M_w 6.1) [*Lavecchia et al*., 2011]; conversely, the most external alignment, after a long period of inactivity, was first marginally activated by some of the major aftershocks of the 2009 L'Aquila sequence [*Lavecchia et al*., 2016] and, 7 years later, by AEQ and the following 2016 Central Italy seismic sequence. AEQ was located within the southern sector of the overall sequence; it nucleated at a depth of about 8 km, beneath the relay zone between the overlapping southern VF (Redentore-Vettoretto fault in Figure 1c) and northern GF en echelon segments (Figure 1b). The fault plane solutions of AEQ and of the major events occurred in the following week are almost purely extensional, with WSW dipping preferential focal planes (Figure 1c). Their attitude closely recalls in strike, dip, and rake the active outcropping faults (Figures 1b and 1c).

Relevant coseismic fractures (CFs in Figure 1c) were generated for a continuous length of 5.8 km along the bedrock fault scarp of the southern end of the VF (the Redentore-Vettoretto fault) (Figure 1e). These CFs were characterized by average throw of 10–13 cm, with maximum values of 20–25 cm. More isolated CFs, with a downthrow of 1–2 cm, were also recognized along the GF (site d in Figure S1 in the supporting information).

2.2. Three-Dimensional Geometric Fault Model

The GF and VF 3-D fault model has been generated by integrating, detailed fault traces (scale 1:25,000), fault slip data, geological cross sections, focal mechanisms, and available hypocentral data sets (Figures 1 and S1).

In particular, to retrieve the GF surface, we integrated the structural-geological data with high-quality hypocentral locations of the northern half of L'Aquila 2009 aftershock sequence [*Valoroso et al*., 2013]. Depth contour lines of the southern GF already available in the literature were also considered [*Lavecchia et al*., 2012]. The GF surface extends for ~35 km along strike, dipping to WSW with an average dip of ~60° at depths $<$8 km and of ~45° at depths between 8 and 11 km (Figures 1c and 1d).

To retrieve the VF surface, we integrated the structural-geological information with the presently available seismological information [*Gruppo di Lavoro INGV sul terremoto di Amatrice*, 2016] (TDMT in http://cnt.rm.ingv.it/tdmt.html).

The VF is articulated in two left-stepping sections (pink and grey areas in Figure 1c), with an overall length of 35 km and WSW dip angles of 50° to 60°. At a depth of about 8 km, the GF and VF converge into a continuous surface, which extends in the N°155 direction, with an average dip of 45°, for a length of about 65 km. The stereo projections of Figures 1b and 1c highlight the good fit in attitude among the outcropping faults, the surfaces reconstructed at depths, and the preferential seismic planes from focal mechanisms.

Downdip, the GF and VF surfaces were traced to reach an approximate depth of about 11 km coinciding with the calculated base of the local seismogenic layer, intended as the depth above which the 90% of seismicity occurs (D90) (Figure S2).

2.3. DInSAR Measurements

In our study, four interferograms have been exploited for the DInSAR analysis of the 2016 Amatrice earthquake. They are relevant to SAR image pairs acquired both from ascending and descending orbits and exhibiting good spatial coverage and interferometric coherence characteristics. In particular, two coseismic ALOS2 and S1 interferograms, whose main information are reported in Table S1, were investigated. The analysis of these coseismic DInSAR measurements revealed a spoon-like shape geometry of the detected surface deformation pattern (Figures 2a, 2b, 2c and 2d) characterized by two NNW-SSE striking main distinctive lobes. The ascending and descending DInSAR maps were also properly combined to retrieve the vertical and the east-west displacement components, which are reported in Figures 2e and 2f. Moreover, in order to mitigate the noise effects and achieve a significant improvement of the signal/noise ratio, we have applied a filtering step [*Wiggin*, 2001] to the retrieved surface deformation patterns. In particular, the contour map of the filtered vertical coseismic displacements is reported in Figure 2g. We also observe that despite the different shape of the lobes, they have nearly the same maximum vertical deformation (about 20 cm) and overall areal extent (about 13 km^2). Finally, in terms of faulting mechanism, the hanging wall block is affected by maximum subsidence that is located to the west of Gorzano-Vettore faults alignment (Figure 2e). This tendency is also supported by the E-W ground deformation component, which is consistent with a normal slip faulting mechanism (Figure 2f).

3. Source Investigation

3.1. Analytical Modeling

In order to retrieve the seismogenic fault parameters responsible of the coseismic displacements, we jointly inverted the selected ALOS2 and S1 DInSAR maps. Our modeling strategy follows a rather well-established two-step approach [*Solaro et al.*, 2016]: a nonlinear inversion to estimate the fault planes parameters, followed by a linear inversion to retrieve the slip distribution on the fault planes. We first investigated a set of two finite dislocation planar sources in an elastic and homogeneous half-space [*Okada*, 1985], for which all source parameters for both sources were set free during the inversion. The choice of using two planar sources in the optimization procedure is conditioned by the presence of two main distinctive lobes in the detected surface deformation patterns (Figure 2). In Figure 3a the best fit parameters for the investigated two planar sources (referred to as Fault 1 and Fault 2) are summarized (see also Figure S3). Moreover, in order to have a more accurate estimate of the slip along the fault planes, a distributed slip was computed by partitioning the two planes into 20×10 patches. Also, in this case we jointly inverted the selected ALOS2 and S1 DInSAR interferograms. To this aim, a linear inversion procedure has been performed by fixing the parameters of the nonlinear inversion and searching for the differential slip on each patch, by inverting the following system of equations expressed in matrix form [*Atzori et al.*, 2009]:

$$\begin{bmatrix} \mathbf{d}_{\mathbf{DInSAR}} \\ 0 \end{bmatrix} = \begin{bmatrix} \mathbf{G} \\ k\nabla^2 \end{bmatrix} \cdot \mathbf{m}$$

where $\mathbf{d}_{\mathbf{DInSAR}}$ is the DInSAR data vector, $\mathbf{m}$ is the vector of unknown slip values, $\mathbf{G}$ is the Green's matrix with the point source functions, and ∇^2 is a smoothing Laplacian operator weighted by an empirical coefficient k. The system solution is obtained by means of the singular value decomposition method. In this case, we found that the two causative faults are characterized by two main regions with a maximum slip of about 1.2 m at depth of 5–7 km along the two faults, located beneath the two main detected lobes (Figures 3b and 3c). The RMSE estimates of the residual displacements (i.e., the difference between measured and modeled displacements) were 3, 2.1, 2, and 2.9 cm for the ALOS2 descending, ALOS2 ascending, S1 descending, and S1 ascending DInSAR maps, respectively.

Since the spatial orientations of the two planar solutions are very similar, we also investigated the possibility that a single but more extended planar fault might be capable of simulating the observed two lobes

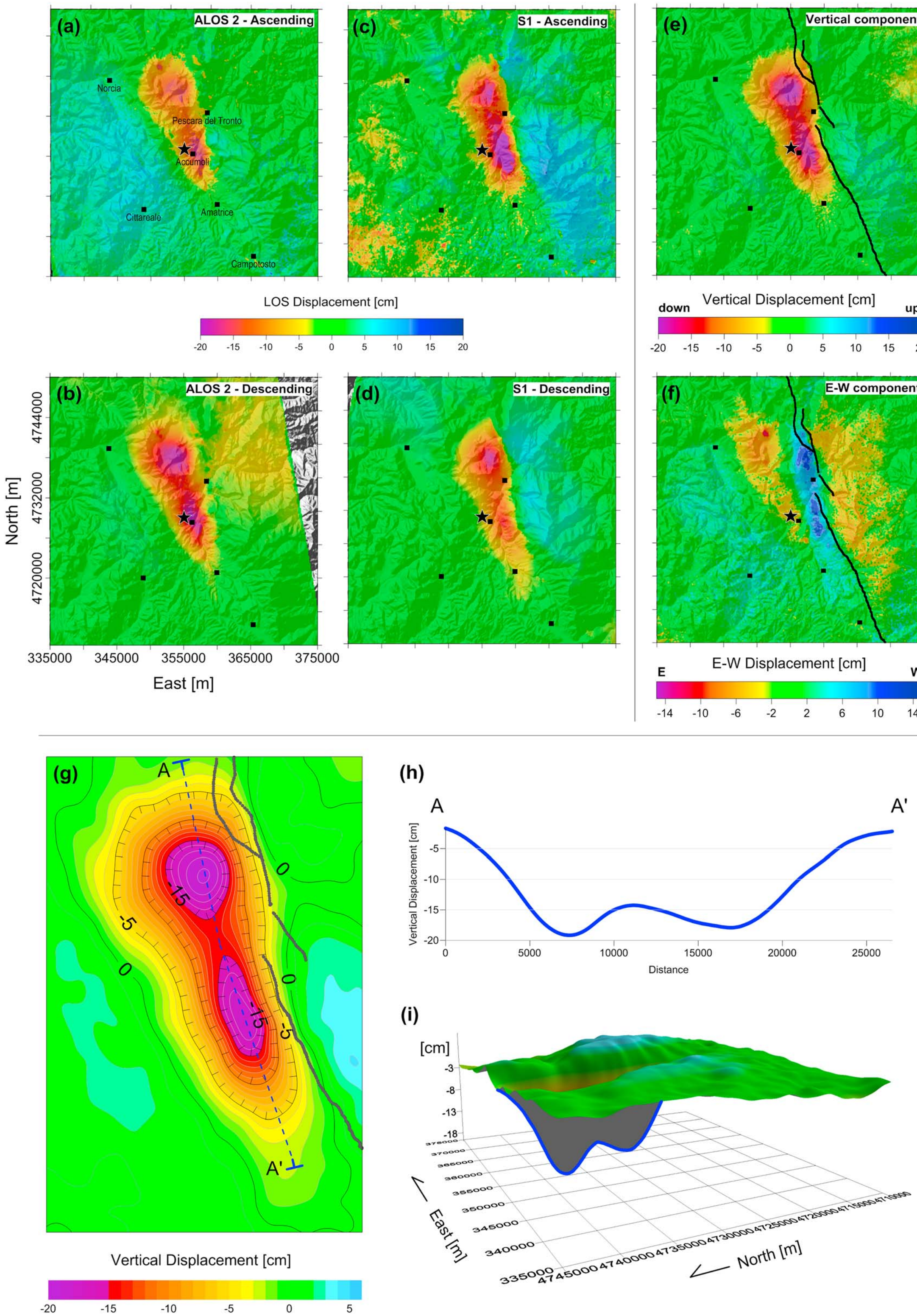

Figure 2. DInSAR measurements. (a, b) DInSAR (LOS) maps computed by using ALOS2 data acquired from ascending orbits on 9 September 2015 and 24 August 2016 (Figure 2a) and from descending orbits on 25 May 2016 and 31 August 2016 (Figure 2b). (c, d) DInSAR (LOS) maps computed by using S1 data acquired from ascending orbits on 15–27 August 2016 (Figure 2c) and from descending orbits on 21–27 August 2016 (Figure 2d). (e, f) Surface deformation components computed from both ascending (Figures 2a and 2c) and descending (Figures 2b and 2d) DInSAR maps: vertical component (Figure 2e) and east-west component (Figure 2f). The black star indicates the main shock location. (g) Contour map obtained following a spatial filtering step. (h) Plot along the A-A′ section encompassing the region of maximum ground deformation lobes. (i) A 3-D view of the vertical deformation pattern.

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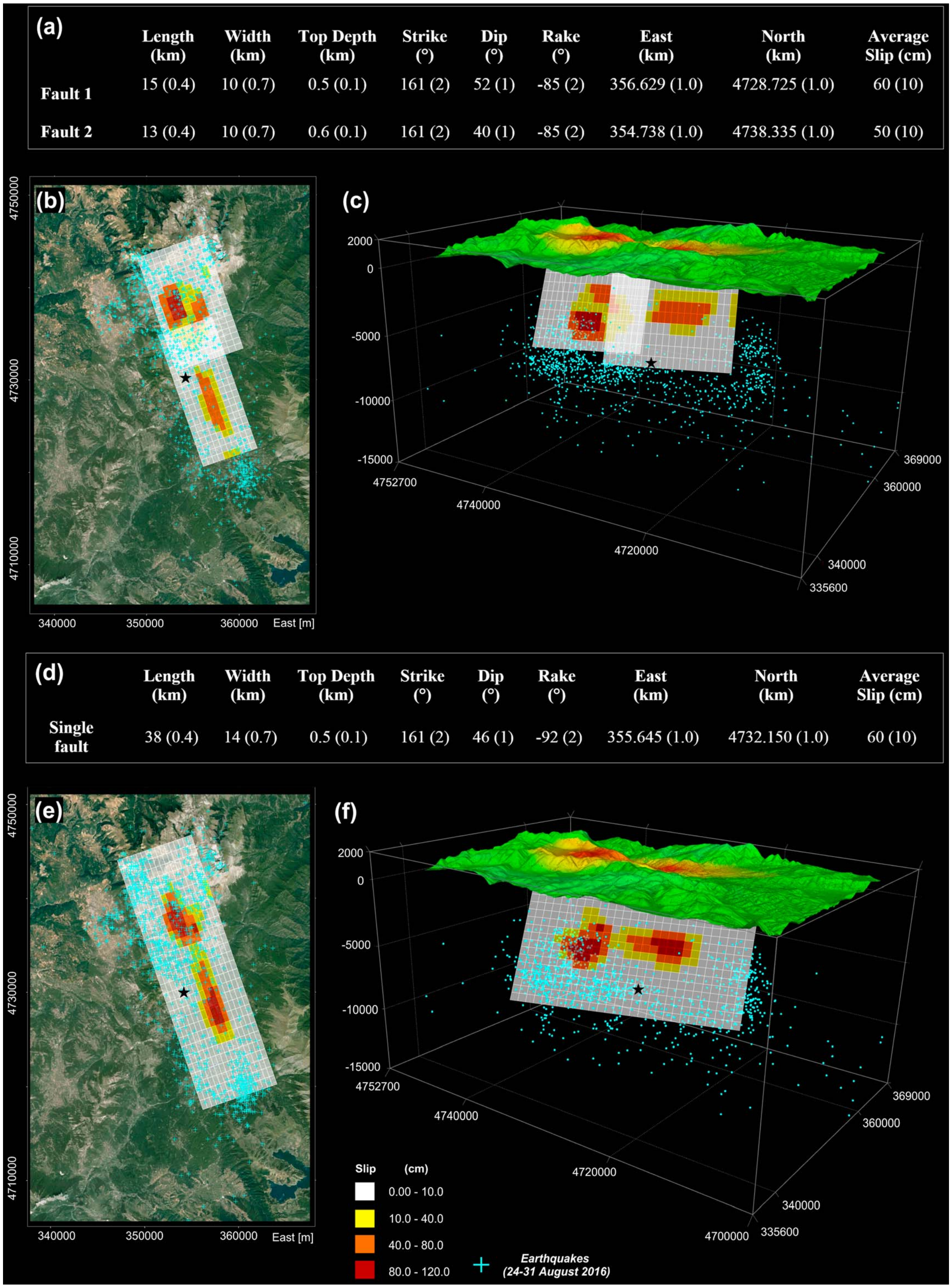


(a)

	Length (km)	Width (km)	Top Depth (km)	Strike (°)	Dip (°)	Rake (°)	East (km)	North (km)	Average Slip (cm)
Fault 1	15 (0.4)	10 (0.7)	0.5 (0.1)	161 (2)	52 (1)	-85 (2)	356.629 (1.0)	4728.725 (1.0)	60 (10)
Fault 2	13 (0.4)	10 (0.7)	0.6 (0.1)	161 (2)	40 (1)	-85 (2)	354.738 (1.0)	4738.335 (1.0)	50 (10)

(d)

	Length (km)	Width (km)	Top Depth (km)	Strike (°)	Dip (°)	Rake (°)	East (km)	North (km)	Average Slip (cm)
Single fault	38 (0.4)	14 (0.7)	0.5 (0.1)	161 (2)	46 (1)	-92 (2)	355.645 (1.0)	4732.150 (1.0)	60 (10)

Figure 3. Coseismic slip distribution retrieved through the Okada inversion. (a) Fault parameters retrieved from the two fault inversion; (b, c) distributed slip (over 20×10 patches, each of these extending for about $0.8 \times 1.0\ km^2$) displayed in map view (Figure 3b) and 3-D view (Figure 3c). (d) Fault parameters retrieved from the single fault inversion, (e, f) distributed slip (over 28×16 patches, each of these extending for about $1.6 \times 0.8\ km^2$) displayed in map view (Figure 3e) and 3-D view (Figure 3f). The aftershock distribution, with $M_L > 2$, spanning from 24 to 31 August (corresponding to the last day of the satellite SAR data temporal coverage) are depicted with cyan crosses; the black star indicates the main shock location.

displacement pattern. The retrieved fault parameters are reported in Figure 3d (single fault) (see also Figure S4); in this case, the RMSE estimates were 3.1, 2.3, 2.1, and 3 cm for the ALOS2 descending, ALOS2 ascending, S1 descending, and S1 ascending DInSAR maps, respectively, rather consistent with those obtained for the two-fault model. Moreover, the single fault modeling shows that the maximum slip is concentrated into two main patches at depths of 5–7 km (Figures 3e and 3f), very similar to the distributed slip pattern retrieved in the two-fault case. Therefore, our modeling results and DInSAR measurements suggest that it is not possible to uniquely discriminate which is the best configuration capable to simulate the surface displacement pattern between two faults or a single one. Accordingly, we have further extended our analysis by applying a numerical optimization procedure which allows us to take into account, in addition to the DInSAR measurements, the available structural-geological data.

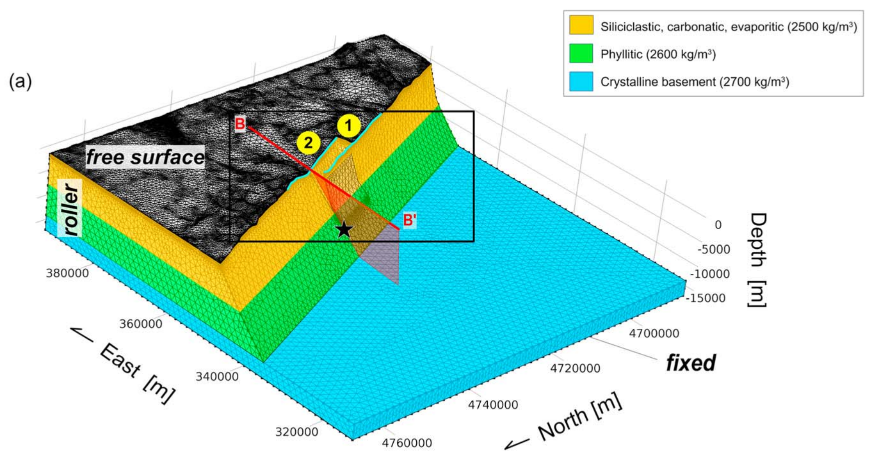
3.2. Finite Element Modeling

We implemented a 3-D numerical model based on a FE method which jointly exploits the DInSAR measurements and the here built 3-D fault model. In particular, we analyzed the seismic event in a structural-mechanical context under the linear elastic mode to solve for the retrieved displacements. We considered an area extending for $80 \times 80\ \text{km}^2$ (east and north directions, respectively) and with a depth of 15 km; such a large zone, with respect to the coseismic epicentral region, allows us to assume the edge effects as negligible (Figure 4a). Within the developed heterogeneous model, we also assumed that the single geological units were isotropic and characterized by homogeneous mechanical properties. The entire numerical domain is discretized by considering 164,800 tetrahedral elements, with the elements size ranging from 250 m to 2.5 km. To reduce the computational effort, the mesh becomes coarser as the distance increases from the seismogenic fault. Boundary conditions were applied as follows: the upper boundary, representing the Earth's surface, was not constrained; the bottom boundary was fixed at a depth of 15 km, while rollers are applied at the four sides of the considered numerical domain. In addition, we assume specific internal boundary settings for the Gorzano-Vettore fault pattern in order to simulate the tectonic contacts among the achieved structural domains.

Concerning the model setup, it follows the approach presented in *Tizzani et al*. [2013]. In addition, we remark that the unlocked sectors of the Gorzano-Vettore fault pattern were modeled as contacts without frictional forces, the locked portions as identity pairs, and the bottom of the seismogenic layer surface as roller constraints. Our model evolves through two stages [*Castaldo et al*., 2016]: a gravitational stage is first applied, during which the initial state of stress is evaluated; subsequently, we model the coseismic displacement field through the application of a couple of forces along the fault. This procedure is performed by assuming the geometry of the complex fault planes, constrained by the 3-D structural information, and searching for the applied forces relevant to the hanging wall and the footwall seismogenic patches. In particular, the best fit solution is selected by searching for the minimum of the RMSE of the residuals (between the DInSAR and the modeled displacements). Specifically, as optimization tool we use the search grid method [*Sen and Stoffa*, 2013]. Details about the modeled fault parameters are provided in Figure 4b.

Our modeling approach allowed us to quantify the displacments relevant to the contacts of the hanging wall and footwall areas along both the VF and the GF, showing two well distinct zones of coseismic displacements at a depth of about 5–7 km (Figures 4c and 4d). In particular, in the hanging wall area the maximum displacement reaches a value of about 80 cm on the Northern Gorzano fault (NGF) and of 60 cm on the Redentore-Vettoretto fault (RVF) (Figure 4c). In the footwall area, we obtain a maximum total displacement of about 75 cm on the NGF and of 90 cm on the RVF (Figure 4d). Note also that the retrieved displacements in the footwall area of RVF significantly extend up to the surface, in rather good agreement with the in situ surveyed ruptures which are particularly evident in this zone (see Figure S1).

Our solution, accounting also for the topography of the considered area, shows a very good fit with the observed ground deformations, both in terms of shape and amplitude of the residual signal. This is evident when comparing the best fit solution for the ALOS2 (Figures S5a and S5b) and the S1 (Figures S5c and S5d) measurements, with the corresponding radar LOS-projected results of the FE model, respectively. In particular, the performed misfit analysis revealed rather small RMSE values for the achieved residuals, especially for the ALOS2 ascending (RMSE = 1.1 cm) and S1 ascending (RMSE = 1.3 cm); moreover, we found values of 2.4 cm and 3.1 cm for the ALOS2 and S1 descending, respectively.



(b)

Rupture patch	Length (km)	Width (km)	Top depth (km)	Bottom Depth (km)	Strike (°)	Dip (°)	Rake (°)	Total max displ. HW (cm)	Total max displ. FW (cm)
1	11.8	7.8	-1.5	-8	155	60	-85	80	75
2	9	10.6	0.0	-8	155	50	-85	60	90

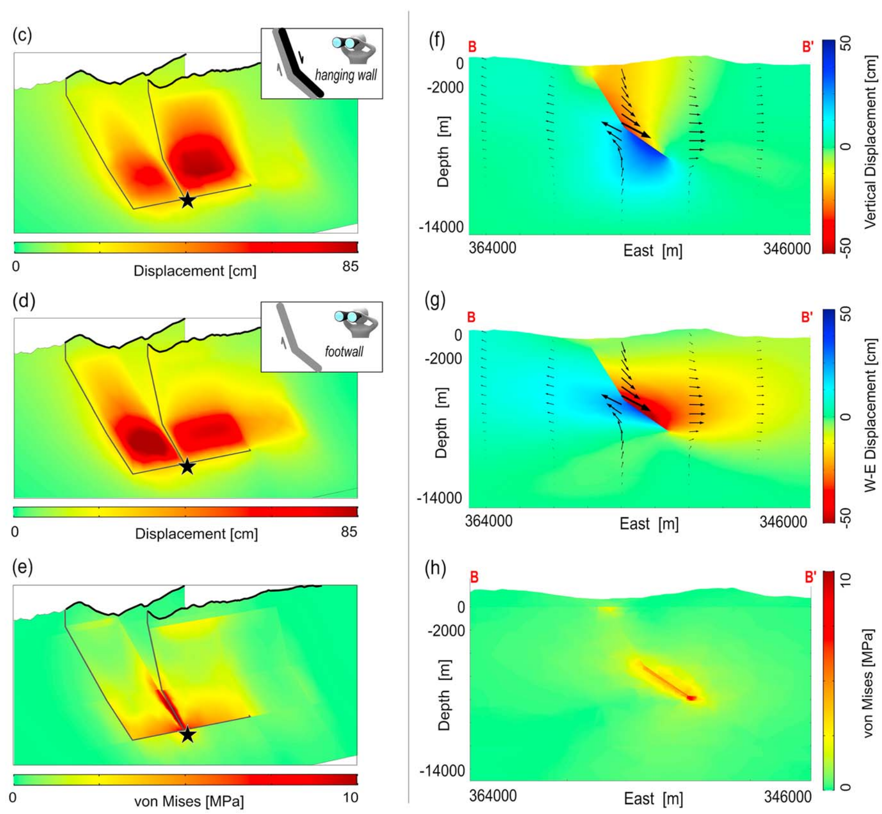


Figure 4. Three-dimensional FE modeling results. (a) Setup of the performed FE model showing the numerical domain discretization with the locations of the NGF (labeled as 1) and RVF (labeled as 2). The boundary conditions and subdomains setting are also reported. (b) Estimated fault parameters. (c) Amplitude of the retrieved displacements (relevant to the black rectangle area in Figure 4a) shown in 3-D view to emphasize the dislocation effect on the hanging wall of RVF and NGF. (d) Same as Figure 4c but relevant to the footwall side. (e) von Mises stress distribution shown in 3-D view. All views represent the coseismic effects recorded on the hanging wall side. (f–h) Results relevant to the selected 2-D cross section ($N = 4{,}733{,}000$) identified in Figure 4a by the red segment B-B′. In particular, we show the vertical (f) and E-W (g) components of the retrieved displacements and the von Mises stress field (h); the black arrows indicate the modeled displacement vectors. The black star indicates the main shock location.

In order to further investigate the validity of our model, we have analyzed the coseismic stress field distribution along the GF and VF segments, through the von Mises failure criteria [*Negredo et al.*, 1999]. The von Mises stress field distribution (Figure 4e) showed that the highest stress magnitudes are located just in proximity of the intersection between the en echelon GF and VF, which at a depth of about 8 km converge in a unified surface.

Finally, we have reported in 2-D cross section the vertical and E-W components of the optimized displacement respectively (Figures 4f and 4g), and the associated von Mises stress field (Figure 4h). Note that the displacement vectors distribution further emphasizes the asymmetrical motion of the hanging and footwall blocks. The maximum value of von Mises stress is reached at a depth of about 8 km, in the hypocenter region.

4. Discussion and Conclusion

We have extensively exploited multisensor/multiorbit DInSAR measurements relevant to the 24 August 2016 Amatrice earthquake (AEQ), to investigate the seismogenic source through analytical and numerical modeling techniques.

The starting point of our study has been the analysis of a set of ALOS2 and S1 coseismic DInSAR maps which revealed a spoon-like shape geometry of the detected surface deformation pattern with two NNW-SSE striking main distinctive lobes, each of these characterized by nearly the same maximum vertical deformation (about 20 cm) and areal extent (about 13 km^2) (Figure 2). These patterns could be considered as the effect induced by two distinct faults or due to the propagation of the rupture of a single fault. Accordingly, we have investigated both cases by considering a single and a double dislocation planar source in an elastic and homogeneous half-space. For both sources we retrieved two main regions with a maximum slip of about 1.2 m at depth of 5–7 km, beneath the two deformation lobes (Figure 3).

Nevertheless, the assessment of the spatial distribution of the residuals, based on RMSE analysis, did not allow us to uniquely discriminate which was the best fit scenario between these two cases.

Accordingly, we have further extended our inversion of the DInSAR measurements by applying a numerical optimization procedure, in a 3-D FE structural-mechanical environment. As a priori information, we introduce the independently generated geometric model of the Vettore and Gorzano faults (Figure 1d). This model shows a double fault system at depth shallower than 7–8 km and a single fault system at greater depths. The performed 3-D FE modeling (Figure 4) is controlled by such an input geometry, but it offers a more realistic solution in light of the available geological and geophysical information. Furthermore, it allowed us to somehow conciliating the findings obtained from the single and double dislocation planar source inversion.

We found that the retrieved best fit coseismic surface deformation pattern well supports the exploited structural model (Figure S5). Our 3-D FE modeling results confirm that the maximum displacement occurred at a depth of about 5–7 km, affecting both the hanging wall and the footwall areas of the NGF and RVF. In particular, the displacement reached maximum values of 90 cm on the RVF footwall and of 80 cm on the NGF hanging wall.

Starting from the modeled displacement values and rupture area (about 180 km^2), we have computed a total seismic moment of about 2.5×10^{25} dyne cm. This value indicates a moment magnitude of about M_w 6.2, which is slightly greater than that derived from TDMT (M_w 6.0) [*Tinti et al.*, 2016].

The retrieved von Mises stress field (Figures 4e and 4h) provides a good representation of the retrieved seismogenic scenario characterized by a bilateral rupture propagating on two distinct planes conjoined at the base; this rupture resulted in a stress change of 5–6 MPa, with respect to the lithostatic loading.

Our results may be relevant for a better comprehension of the use of active master fault segmentation pattern in defining the seismogenic potential of a zone and its seismic hazard. In fact, according to our hypothesis, the Amatrice earthquake did not nucleate within one of the intra-Apennine individual seismogenic sources [*Boncio et al.*, 2004; *Basili et al.*, 2008], but rather within the interlink zone at depth between two of them. This was just a preferential locus for concentrating shear traction and favoring earthquake nucleation.

To conclude, our analysis shows that the hypothesis of a bilateral rupture propagating along two en echelon faults connected at the hypocenter is well supported. A bilateral rupture was previously highlighted by inversion of both strong motion and GPS data [*Gruppo di Lavoro INGV sul terremoto di Amatrice*, 2016], but no conclusive information on the geometric configuration and earthquake-fault association are yet available. It is interesting to underline the peculiarity of the bilateral symmetric propagation characterizing this normal fault earthquake. In such, AEQ is different from a larger percentage of Italian earthquakes [*Tinti et al*., 2014; *Calderoni et al*., 2015], which prevalently shows a unilateral propagation path.

This study provides insights on the seismogenic source of the 2016 Amatrice earthquake and, more generally, confirms the capability of our 3-D FE approach to investigate complex earthquakes [*Tizzani et al*., 2013; *Castaldo et al*., 2016; *Solaro et al*., 2016], providing in this case a simple way to differentiate between approximately bilateral and predominantly unilateral ruptures. Future use of this approach can be relevant to both natural risks assessment and natural resources management/exploitation fields.

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