New insights into the 2012 Emilia (Italy) seismic sequence through advanced numerical modeling of ground deformation

InSAR measurements

P. Tizzani, R. Castaldo, G. Solaro, S. Pepe, M. Bonano, F. Casu, M. Manunta, M. Manzo, A. Pepe, S. Samsonov, R. Lanari, and E. Sansosti

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[1] We provide new insights into the two main seismic events that occurred in 2012 in the Emilia region, Italy. We extend the results from previous studies based on analytical inversion modeling of GPS and RADARSAT-1 InSAR measurements by exploiting RADARSAT-2 data. Moreover, we benefit from the available large amount of geological and geophysical information through finite element method (FEM) modeling implemented in a structural-mechanical context to investigate the impact of known buried structures on the modulation of the ground deformation field. We find that the displacement pattern associated with the 20 May event is consistent with the activation of a single fault segment of the inner Ferrara thrust, in good agreement with the analytical solution. In contrast, the interpretation of the 29 May episode requires the activation of three different fault segments and a block rotation of the Mirandola anticline. The proposed FEM-based methodology is applicable to other seismic areas where the complexity of buried structures is known and plays a fundamental role in the modeling of the associated surface deformation pattern.


1. Introduction

[2] On 20 May 2012, at 02:03 UTC, an $M_l = 5.9$ earthquake occurred in the central alluvial Po Plain near the town of Finale Emilia, Italy. The seismic sequence evolved with some decreasing local magnitude aftershock events ($M_l \leq 5.1$) until 29 May at 7:00 UTC, when an $M_l = 5.8$ seismic event occurred around the Mirandola village, ~10 km SW of the 20 May main shock epicenter (Figure 1a). These seismic events resulted in major industrial and residential building damages as well as 27 fatalities and the evacuation of about 20,000 residents. The focal solutions for these two main shocks show WNW-ESE-oriented and E-W-oriented nodal planes, respectively, and approximately N-S compressional kinematics (www.globalcmt.org).

[3] The region struck by the 2012 Emilia seismic sequence represents the northern segments of the Apennines accretionary prism-foredeep system, for which, in the last decade, several analyses aimed at detecting the active geodynamic processes affecting this area have been performed [Carminati and Vadacca, 2010, and references therein]. The key outcomes resulting from these studies are (i) the identification in the upper crust of the occurrence of the stress field along-depth variations, with normal faulting above and thrusting below, and (ii) the interference of local tensional stresses with regional compression in the Mirandola anticline region. In this context, the 2012 seismic sequence represents a great opportunity to analyze the interaction processes between the regional and local stresses that are released during seismic events.

[4] The large amount of data available for the considered area, acquired through InSAR analyses and geophysical and deep borehole geological investigations, allows for the extensive study of the relationship between the ground deformation fields and the activated fault segments associated with the $M_l 5.9$ and $M_l 5.8$ main shocks. To this aim, we first perform classic analytical modeling [Okada, 1985] by investigating a RADARSAT-2 (RSAT-2) interferogram that, encompassing the two main earthquakes, allows for quickly identifying the upper crust regions affected by the faulting processes. Then, we analyze the role of the buried geological structures of the inner Ferrara thrust (IFT) and the Mirandola fault–related anticline (MFA) in the modulation of the observed ground deformation by developing a numerical model based on a finite element method (FEM) implemented in a structural-mechanical context [Fagan, 1992]. We show that the rock failure phenomena that occurred were strongly conditioned by the geological complexity of the investigated area and propose an interpretation of the two main shock deformation processes.

2. Geological and Structural Outlines

[5] The North Apennines fold and thrust belt has grown during the Neogene and Quaternary times along an eastward retreating westward directed subduction zone [Doglioni et al., 1999]. The radial advance of the subduction process induced the progressive eastward migration of thrust fronts, foredeep basins, and extensional back-arc tectonics [Carminati and Vadacca, 2010]. The subsurface geometry of the northern Apennines frontal thrust system, detected by seismic reflection profiles [Pieri, 1983], shows several arcuate structures [Carminati et al., 2010]. Among them, we focus on the Ferrara arc region (Figure 1a) where the two investigated main shock
episodes occurred. The main active structures of this region are the IFT front and the MFA (Figure 1a). The IFT front represents a sublinear E-W low-angle thrust front arc characterized by deeper active structures faulting the arenaceous and carbonate units as well as the Lower Pre-Pliocene and Post-Pliocene successions (Figure 1b). The MFA is a seismogenic source buried below the Po Plain sediments, located at the western edge of the Ferrara arc [Scrocca et al., 2007]. The overall effect of these deep structures is a shortening along the Apennines front, as confirmed by GPS data, showing an average rate of shortening of about 1–2 mm/yr [Devoti et al., 2011]. This is also supported by borehole breakouts, historical seismicity, seismic reflection profiles, and geomorphologic studies [Carminati et al., 2010, and references therein].

3. SAR Data Analysis

[SAR data acquired on 30 April and 17 June 2012 over descending orbits (side-looking angle of about 30°) by the RSAT-2 sensor were used to generate a differential SAR interferogram encompassing the two main seismic events that occurred on 20 and 29 May 2012. Note that for the interferogram generation, precise satellite orbital information and the 3 arcsec Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) of the study area were used for removing the topographic phase contribution. The related deformation map (Figure 2a), obtained by performing a complex multi-look operation resulting in a pixel size of about 90 m x 90 m, reveals a maximum...
displacement along the radar line of sight (LOS) of about 17 cm (corresponding to a sensor-target range decrease); such a map is exploited in the following to perform the InSAR data modeling analysis.

4. Analytical Modeling

In order to retrieve the earthquake source locations and their geometrical characteristics, the RSAT-2 displacement map was modeled by finite dislocation faults in an elastic and homogeneous half-space [Okada, 1985]. In particular, we searched for all the parameters free for each fault by using a nonlinear inversion based on the Levenberg-Marquardt least-squares approach [Marquardt, 1963]; the InSAR data were subsampled through a QuadTree algorithm [Jónsson et al., 2002] over a mesh of about 4600 points.

The best fit solution, hereinafter referred to as Model 1, consists of two distinct reverse fault planes corresponding to the south dipping IFT and MFA for the 20 and 29 May events, respectively (see Figure 1b), whose parameters are
reported in Table 1. The model results (see Figure 2b) show a good fit with the measured InSAR data, as clearly highlighted by the residual map in Figure 2c, where values smaller than 2 cm are generally found. However, small areas with higher residuals are also noted; they appear at the locations corresponding to the few aftershocks with $M_l \geq 5.0$ not considered in the inversion procedure and that occurred in the same time period covered by the RSAT-2 interferogram.

The results of uncertainty analysis (standard deviations and trade-offs) for the nonlinear inversion of the IFT and MFA model parameters are also presented in Figures 2d and 2e, respectively. The trade-off analysis shows that the geometry and slip values cannot be unambiguously resolved, since a strong correlation between slip and width exists.

In addition, we compare the retrieved fault parameters with those computed by Bignami et al. [2012] and Serpelloni et al. [2012], who inverted an RSAT-1 interferogram and GPS data, respectively. The corresponding parameters reported in Table 1 provided the two best fit solutions, hereinafter named Model 2 and Model 3, respectively. By considering the modeling results summarized in Table 1, we remark the good consistency among the three inversion results for the IFT structure, particularly for what concerns InSAR Models 1 and 2. Differently, more significant discrepancies are present for the results relevant to MFA. Note, in particular, the rather different values of the dip angles as well as width and slip parameters for the three models in spite of the limited presence of residuals for Models 1 and 2 (supporting information) that implies a good fit for both analytical models.

It is worth noting that a second interferogram also develops a numerical model based on an FEM, which allowed us to account for all geological and geophysical information available for the considered area.

5. FEM Model

To further extend the investigation of the ground deformation pattern caused by the 2012 Emilia seismic sequence and retrieved through the InSAR analysis, we developed a numerical model based on an FEM, which allowed us to account for all geological and geophysical information available for the considered area.

![Table 1. Fault Parameters for the 20 May (IFT) and 29 May (MFA) Earthquakes](image)

<table>
<thead>
<tr>
<th></th>
<th>IFT</th>
<th>MFA</th>
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<tbody>
<tr>
<td></td>
<td>Model 1 (this work)</td>
<td>Model 2 [Bignami et al., 2012]</td>
</tr>
<tr>
<td></td>
<td>Model 1 (this work)</td>
<td>Model 2 [Bignami et al., 2012]</td>
</tr>
<tr>
<td>Length (km)</td>
<td>14.8</td>
<td>19</td>
</tr>
<tr>
<td>Width (km)</td>
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<td>4</td>
</tr>
<tr>
<td>Top depth (km)</td>
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<td>4</td>
</tr>
<tr>
<td>Dip (deg)</td>
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<td>115</td>
</tr>
<tr>
<td>Strike (deg)</td>
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<td>43</td>
</tr>
<tr>
<td>East (km)</td>
<td>681.6</td>
<td>683.3</td>
</tr>
<tr>
<td>North (km)</td>
<td>4969.9</td>
<td>4968.9</td>
</tr>
<tr>
<td>Slip (cm)</td>
<td>80</td>
<td>90</td>
</tr>
<tr>
<td>Geodetic</td>
<td>$1.12 \times 10^{18}$</td>
<td>$1.82 \times 10^{18}$</td>
</tr>
<tr>
<td>Moment (Nm)</td>
<td>$1.24 \times 10^{18}$</td>
<td>$9.79 \times 10^{17}$</td>
</tr>
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11 The RMS of the residuals between RSAT-2 and Model 1 is 1.29 cm; the seismic moments are $1.16 \times 10^{18}$ Nm and $0.76 \times 10^{18}$ Nm for the 20 and 29 May events, respectively (www.globalcmt.org).

12 In particular, we analyzed the seismic events in a structural-mechanical context under the plane strain approximation mode to solve for the retrieved displacements [Fagan, 1992]. We defined the subdomain setting of the FEM model using available geologic and structural information derived from the oil and geothermal well logging (Figure 1a) and the interpretation of the seismic line indicated as AA’ in Figure 1(http://unmig.sviluppoeconomico.gov.it/ videpi/). These data are distributed along a NNE-SSW alignment that crosses the area where the ground deformation associated with the two seismic events was measured (Figure 2a). From this information, we derived the 2D structural geometric domains of the region at depth along the AA’ line and extended such a structure for the 50 km covering the area from Modena to Ferrara (NW-ESE direction) (see Figure 1). This geometric extrusion is reliable thanks to (i) the essentially E-W linear extension of the buried geological structures (Figure 1) and (ii) the condition of nearly no displacement variation along the extrusion direction. The latter statement, supported by the two nearly constant fault rake values detected through seismological analyses (www.globalcmt.org) and analytical modeling (see Table 1), allowed us to apply the plane strain approximation mode to solve for the measured displacements [Fagan, 1992].

13 In this context, from the RSAT-2 InSAR displacement map, we performed 2D optimization by focusing on the two BB’ and CC’ profiles, shown in Figure 2a, which cross the areas of maximum deformation associated with the $M_l 5.9$ and $M_l 5.8$ seismic events, respectively.

14 According to Carminati and Vadacca [2010], we assumed stationarity and linear elasticity of the involved materials by considering a solution of classic equilibrium mechanical equations [Fagan, 1992]. Within the developed heterogeneous model, we also assumed that the single geological units were isotropic and characterized by homogeneous mechanical properties. We evolved our model through two stages: during the first stage (pre-seismic), the model compacted under the weight of the rock successions (gravity loading) until it reached a stable equilibrium. At this level, we considered only the retrieved tensional field while maintaining the total displacements equal to zero. At the second stage (co-seismic), where the stresses were released through a nonuniform slip along the faults, we used an iterative optimization procedure based on a trial-and-error approach.
approach [Tarantola, 2005], allowing to follow the evolution of the faulting processes within the best fit solution retrieval. Therefore, we achieved (i) the active seismogenic structures responsible for the observed ground deformation, (ii) the effects of the different mechanical constraints on the ground deformation pattern, and (iii) the spatial distribution of the local stress field.

[15] Boundary conditions (Figures 3a and 3b) were applied as follows: the upper boundary, representing the Earth’s surface, was not constrained; the bottom boundary was a fixed...
constraint; and finally a symmetry condition was assumed for the SSW and NNE areas to make the edge effects negligible. Moreover, three different boundary settings were considered in order to represent the sedimentary and tectonic contacts between the different rock successions (Figures 3a and 3b): (i) free mechanical constraints where the faults are kept locked; (ii) roller constraints (active mechanical discontinuities), which allow the faults to freely slip under the applied stress field; and (iii) boundary loads along which the forces are concentrated and transferred to the boundary subdomains. Note that the latter two boundary settings were derived through the above-mentioned trial-and-error optimization approach. In particular, to evaluate the boundary setting best fit configuration (see Figures 3a and 3b) responsible for the observed ground deformation, we generated several forward structural-mechanical models for the $M_5$ 5.9 and the $M_5$ 5.8 seismic events (250 and 300, respectively). They were obtained through the activation of different structural segments whose geometries were set via the borehole and the seismic line information. For each step of the iterative process, we generated a forward model and compared the predicted and measured ground deformation fields in order to select the minimum RMS solution (see Figures 3c and 3d).

In Figures 3c and 3d we compare the best fit solutions for the RSAT-2 data with the analytical (we consider Model 1 of Table 1 and Figure 2) and heterogeneous FEM models along the BB’ and CC’ lines, respectively. It is evident that the FEM models developed along these profiles show a better fit to the observed ground deformation pattern, in terms of shape and amplitude of the signal, for both seismic events. We observe that the use of a linear inversion to retrieve the slip distribution on the fault planes may improve the RSAT-2 best fit solution obtained through the analytical modeling. However, the small values of the computed residual map of Figure 2c indicate that our solution can be considered suitable to characterize the two causative faults.

Moreover, the FEM solution associated with the 20 May event provides a section of the displacement distribution (see arrows in Figure 3e) that is consistent with the activation of a single segment (red line in Figure 3g) of IFT. Note that the retrieved analytical modeling solution, whose projection along the BB’ profile is depicted by the green segment in Figure 3g, represents a good approximation of the activated structure in correspondence to IFT. We also remark that the displacement map shown in Figure 3e emphasizes that the co-seismic deformation field was strongly constrained by the active mechanical discontinuities (see the blue lines in Figure 3a) located SSW and NNE of the detected maximum deforming area.

Conversely, the FEM modeling relevant to the 29 May event encompassed a displacement pattern (Figure 3f) that highlighted the existence of a counterclockwise roto-translation of the Mirandola block along the N-S direction (see arrows in Figure 3f). This implies that the deformed crustal areas are, in this case, strongly influenced by the geometric complexity of the buried structures (Figure 3b). This result justifies both the fault thrust process, as expected from the available focal mechanism solutions (www.globalcmt.org), and the subsidence phenomena found in the region SSW of the maximum uplift area (Figure 3f). Moreover, the evolution of the failure mechanism involved three different segments of the Mirandola anticline (red lines in Figure 3h), thus explaining the discrepancies in the previously presented analytical modeling solutions, which are discussed in section 4 (see also Table 1).

Finally, Figure 3f shows a section of the displacement spatial distribution at SSW of the detected maximum deforming area; this is a consequence of the unconstrained structural condition at SSW (see Figure 3b). Indeed, the geological evidence indicates that the active tectonic structures SSW of MFA are located ~20 km from the maximum deformation area; accordingly, their effects on the corresponding local stress field are negligible.

6. Conclusions

We extensively investigated the retrieved InSAR deformation patterns associated with the main shock episodes that occurred on 20 May ($M_5$ 5.9) and 29 May ($M_5$ 5.8) by exploiting classic analytical modeling and structural-mechanical FEM modeling; the latter approach accounts for all available geological and structural information for the analyzed area in an FEM context and allows us to better characterize the tectonic scenario.

The exploitation of these different modeling approaches improves understanding of the several aspects concerning the type and evolution of the failure mechanisms responsible for the two main shock episodes. In particular, the performed analysis permitted (i) to detect the active seismogenic structures responsible for the observed ground deformation, (ii) to evaluate the impact of the regional tectonic constraints on the modulation of the retrieved deformation field, and (iii) to provide a detailed characterization of the rock failure mechanisms.

The achieved results suggest a reactivation process of preexisting faults (Figures 3a and 3b) that have accumulated energy over the last 500 years (http://emidius.mi.ingv.it/CPTI11/) by absorbing the compressional tectonic regime between the Apennines and Adriatic plates [Doglioni et al., 1999]. Moreover, the analysis along the active structures of the Mirandola anticline reveals the occurrence of oblique direction displacements along the active seismogenic faults.

In this context, the Emilia earthquake sequence occurred in the region characterized by a seismic gap of several hundred years (http://emidius.mi.ingv.it/CPTI11/) and confirmed that the tectonic structures, buried under the Plio-Quaternary deposits of the Po Plain, are active. More specifically, the shape of the detected ground deformation is a consequence of the nearly E-W alignment of the buried structures of the Ferrara Front. The 2012 Emilia seismic sequence could be interpreted as an effect of the long-term regional tectonic compression, which was responsible for the northward bending of the Po River course, the deviation of the Panaro River trace, and the growth of the Mirandola anticline located at shallow depths under the Po Plain [Burrato et al., 2003]. Moreover, the active thrusting processes of the Ferrara Front revealed by our results, see Figures 3e–3f, are fully consistent with a shortening accommodation at a rate smaller than ~2 mm/yr, which was recently proposed by Devoti et al. [2011] and based on the pre-seismic GPS measurements.

We point out that the proposed modeling approach is general and can be applied to other tectonic contexts to better understand the impact of geological complexity on the resulting rock failure phenomena.

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References


