AN INTRIGUING PERSPECTIVE ON THE SOURCE GEOMETRY AND SLIP DISTRIBUTION OF THE 2016 AMATRICE MW 6.2 EARTHQUAKE (CENTRAL ITALY) FROM GEOLOGICAL AND SATELLITE DATA

P. Tizzani¹, M. Bonano¹, P. Boncio², F. Brozzetti², R. Castaldo¹, F. Casu¹, D. Cirillo², C., De Luca¹, R. de Nardis², V. De Novellis¹, F. Ferrarini², R. Lanari¹, G. Lavecchia², M. Manunta¹, M. Manzo¹, A. Pepe¹, S. Pepe¹, G. Solaro¹, I. Zinno¹

¹ IREA-CNR, Napoli, Italy
² DISPUTE-R, Università G. D’Annunzio, Chieti, Italy
³ Dipartimento della Protezione Civile, Roma, Italy

Abstract. On August 24, 2016, at 01:36 UTC, the intra-Apennine extensional fault system of central Italy released a destructive earthquake (Amatrice 2016, Mw 6.0 TDMT, Mw 6.2, QRCMT). It produced widespread damage and fatalities, killing about 300 people and severely destroying the town of Amatrice and other small localities. The event dramatically recalls the April 6, 2009 normal fault earthquake (Mw 6.3), which nucleated about 40 km southward of the Accumoli earthquake, causing about 300 casualties and destroying the town of L’Aquila.

After few hours, the Accumoli earthquake was followed by a significant aftershock (Mw 5.5, QRCMT), which nucleated ~15 km NW-ward. In the following days, five events having Mw between 4.5 and 5.0 were released and the sequence mainly grew northward.

At today (October 4, 2016), the epicentral area extends in the NNW-SSE direction, for a length of about 25-30 km. It is located at the hanging-wall of the WSW-dipping Vettore-Gorzano active extensional fault system. Relevant co-seismic deformations were highlighted soon after the main shock. This was located at a depth of about 8 km; its epicenters are located within the relay zone between the two en-echelon fault segments. The epicentral area well coincides with the pattern revealed by DInsAR measurements, which is characterized by a double-eyed co-seismic shape. In particular, we generated several interferograms by using ALOS and Sentinel 1-A and B constellation data acquired on both ascending and descending orbits to show that most displacement is characterized by two main subsiding lobes of about 20 cm on the fault hanging-wall; this is consistent with the calculated focal mechanism.

By inverting the generated interferograms, following a classical Okada analytical approach, the modelling results account for two sources related to main shock and more energetic aftershock. The time interval between the ascending and descending (August 31, 2016) does not discriminate the effects derived from the main 24 August event and by its aftershock, but the low magnitude of the second event can only very marginally contribute to the overall deformation pattern.

The reconstructed 3D fault model consists in two major interconnected fault segments, Vettore and Gorzano, which are individual at depth shallower than about 7-8 km and converge into a unified surface at higher depths. The Vettore-Gorzano unified surface has a length of 65 km, dips WSW-ward with an angle of about 45-50° and reaches a depth of 11 km, where, according to the proposed reconstruction, detaches on an east-dipping basal detachment. The stereo-projection highlights the almost perfect fit in attitude among the outcropping faults, the surfaces reconstructed at depths, the preferential seismic planes from focal mechanisms, as well as the attitude of primary co-seismic facture.

Through Finite Element numerical modelling that jointly exploits DINSAR deformation measurements and structural-geological data, we reconstruct the 3D source of the Accumoli 2016 normal fault earthquake which well fit a Mw 6.2, event. We evolved the 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 non uniform slip along the faults, we used an iterative optimization procedure based on a trial-and-error approach,
allowing to simulate the evolution of the faulting processes within the best fit solution retrieval. Accordingly, we achieved (i) the active seismogenic structures responsible for the observed ground deformation, (ii) the spatial distribution of the local stress field in term of volumetric stress and strain.

The inversion shows that the co-seismic displacement area was partitioned on two distinct en echelon fault planes, which at the main event hypocentral depth (8 km) merge in one single WSW-dipping surface. Slip peaks were higher along the southern half of the Vettore fault, lower along the northern half of Gorzano fault and null in the relay zone between the two faults; field evidence of co-seismic surface rupture are coherent with the reconstructed scenario.

Coseismic Deformation Field and Source Modelling for the Amatrice Event of August 24, 2016 by Means of InSAR and CGPS Data

C. Tolomei, G. Pezzo, C. Bignami, S. Atzori, E. Trasatti, A. Antonioli, S. Stramondo, S. Salvi
Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy

Introduction. On August 24, 2016 at 1:36 UTC, a Mw 6.0 magnitude earthquake struck a wide area in the central Apennines of Italy between the towns of Norcia and Amatrice, with the epicenter located close the village of Accumoli. The mainshock was followed by an Mw 5.4 earthquake, about one hour after the main event, and by thousands of further aftershocks along a NW-SE strip extended for about 30 km between Amatrice and Norcia.

Immediately after the main event, the INGV personnel involved in the production of InSAR data for the emergency support was activated in order to measure the coseismic crustal deformation and generate a model of the seismic source to support the emergency management. The first preliminary source model was generated within 20 hours of the mainshock.

We present the InSAR co-seismic deformation measurements and the seismic source model obtained by the inversion of InSAR and GPS data.

In the framework of the activities carried out to provide scientific support to the national Civil Protection Department during the Amatrice earthquake, INGV was activated to generate geodetic measurements of the co-seismic deformation and models of the seismic source. A similar function is carried out by CNR/IREA, and the two institutes worked closely together to cross-validate their InSAR results. Here we present the initial results obtained by the INGV InSAR working group within 30 hours from the mainshock.

SAR data. During the first week after the mainshock, several SAR images from various sensors and different frequency bands became available; from them seven interferometric pairs were processed to investigate the co-seismic displacement field. In particular, the satellite interferometric analysis exploited the Japanese satellite ALOS-2 (JAXA), operating in the L-band (wavelength of 23.6 cm), the Sentinel-1 constellation (C-band, wavelength 5.6 cm) from the European Space Agency (ESA), and the Italian COSMO-SkyMed (CSK) constellation (X-band, wavelength of 3.1 cm) developed by the Italian Space Agency (ASI). The first image pair was acquired from ALOS-2, available about 20 hours after the earthquake.

Tab. 1 shows the interferometric SAR pairs used for the analysis of surface displacement along the respective radar Lines of Sight (LoS).
Tab. 1 – Details of the coseismic interferometric pairs (those marked with * were used in the data inversion).

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Acquisition mode</th>
<th>Interferometric pair [ddmmyyy]</th>
<th>Wavelength [cm]</th>
<th>Perpendicular Baseline [m]</th>
<th>Orbit</th>
<th>Track</th>
<th>Incidence angle [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALOS-2*</td>
<td>StripMap</td>
<td>09092015, 24082016</td>
<td>23.6</td>
<td>-198</td>
<td>Ascending</td>
<td>197</td>
<td>36.6</td>
</tr>
<tr>
<td>Sentinel 1</td>
<td>IWS</td>
<td>20082016, 26082016</td>
<td>5.56</td>
<td>105</td>
<td>Descending</td>
<td>95</td>
<td>39</td>
</tr>
<tr>
<td>Sentinel1*</td>
<td>IWS</td>
<td>21082016, 27082016</td>
<td>5.56</td>
<td>79</td>
<td>Descending</td>
<td>22</td>
<td>39</td>
</tr>
<tr>
<td>Sentinel1*</td>
<td>IWS</td>
<td>15082016, 27082016</td>
<td>5.56</td>
<td>32</td>
<td>Ascending</td>
<td>117</td>
<td>39</td>
</tr>
<tr>
<td>CSK*</td>
<td>StripMap</td>
<td>20082016, 28082016</td>
<td>3.1</td>
<td>101</td>
<td>Descending</td>
<td>N/A</td>
<td>30.6</td>
</tr>
<tr>
<td>Sentinel 1</td>
<td>IWS</td>
<td>22082016, 28082016</td>
<td>5.56</td>
<td>-29</td>
<td>Ascending</td>
<td>44</td>
<td>39</td>
</tr>
<tr>
<td>ALOS-2*</td>
<td>StripMap</td>
<td>25052016, 31082016</td>
<td>23.6</td>
<td>88</td>
<td>Descending</td>
<td>92</td>
<td>32.9</td>
</tr>
</tbody>
</table>

Fig. 1 – Co-seismic interferograms retrieved from ALOS-2, Sentinel-1 and COSMO-SkyMed data acquired between the August 24 event: A) ascending ALOS-2; B) descending ALOS-2; C) ascending Sentinel-1; D) descending CSK. See Tab. 1 for further details.
In Fig. 1 are reported some examples of the interferograms produced during the sequence. Each fringe corresponds to a ground displacement equal to half of the sensor radar wavelength (shown in Tab.1).

The LoS ground displacement was obtained from the unwrapping of the interferometric fringes. The confirm the surface subsidence observed in past normal fault earthquakes in the Apennine (e.g., the Mw 6.3 L’Aquila earthquake, 2009), extending for about 25 km along the N-NE direction. The maximum displacement value was about -20 cm in correspondence of the area of Accumoli.

The analysis of the LoS displacement maps, allowed to detect some local surface phenomena, probably related to slope instability; they were especially well depicted in the co-seismic deformation map from CSK data, which provide higher spatial resolution and accuracy.

Thanks to special support from ESA, it was possible to fully exploit the Sentinel-1 constellation capacities. ESA provided data from Sentinel-1B satellite even though it is still in the commissioning phase and therefore not fully operational. It was thus possible to generate “cross-sensor” interferograms with a 6-day temporal baseline (instead of the ordinary 12 days) consequently doubling the observation temporal sampling.

**Source modelling.** The InSAR data used in the inversion procedure were about 19500 measurements obtained by sub-sampling 5 unwrapped interferograms (those marked with * in Tab. 1) and 107 CGPS site displacement measurements obtained by the INGV-CNT Working Group “GPS Geodesy” (2016).

The following modelling procedure was adopted: the geocoded displacement maps were sampled over a double resolution grid, with a point every 500 m in the area with significant deformation and every 2000 m outside. Then, the datasets were modeled through an analytical elastic dislocation model (Okada, 1985), with the fault plane geometry and rake estimated using a non-linear inversion algorithm (without any external constraint) and the slip distribution obtained through a damped linear least square inversion, with a positivity constrain.

A single and double source were tested. In Tab. 2 we summarize the inversion results for both hypotheses.

### Tab. 2 – Parameters of the modelled seismic sources. Note: The above values of length, width and depth of each fault are related to the area with larger slip value.

<table>
<thead>
<tr>
<th>Model</th>
<th>Observed Mw</th>
<th>Geodetic Magnitude</th>
<th>Length</th>
<th>Width</th>
<th>Depth</th>
<th>Strike</th>
<th>Dip</th>
<th>Rake</th>
<th>Max Slip</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single fault</td>
<td>6.0 (+ 5.3)</td>
<td>6.2</td>
<td>–21 km</td>
<td>–9 km</td>
<td>–1500 m</td>
<td>164°</td>
<td>46°</td>
<td>–73°</td>
<td>120 cm</td>
<td>1.4 cm</td>
</tr>
<tr>
<td>Double fault–North</td>
<td>6.0 (+ 5.3)</td>
<td>6.2</td>
<td>–8 km</td>
<td>–8 km</td>
<td>–3000 m</td>
<td>175°</td>
<td>39°</td>
<td>–65°</td>
<td>140 cm</td>
<td>1.4 cm</td>
</tr>
<tr>
<td>Double fault–South</td>
<td>–12 km</td>
<td>–5 km</td>
<td>–2500 m</td>
<td>165°</td>
<td>51°</td>
<td>–70°</td>
<td>130 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Conclusions.** The single and double fault models show very similar slip distributions (Fig. 2) and the fit with the data is similar (Tab. 2). Though the majority of fault slip appears to be located below a depth of about 4 km and there is limited slip towards the surface, if the fault plane is geometrically extended to intersect the surface, its trace runs parallel and very close (within ± 800 m) to the trace of the Gorzano-Laga-Vettore fault system (Fig. 2), suggesting that this is the fault responsible for the mainshock. For the two faults model the same pattern can be observed for the South fault, while the trace of the north fault turns toward NE and should emerge about 3 km to the east of Mt. Vettore.

The models are also coherent with the aftershock distribution, especially for the northern segment, although the relocated seismicity seems to highlight geometrical complexities not fully recovered by the geodetic models. Both models show that, moving southward from the
The two larger slip concentrations are located at depths of –6 km in the northern area (for both models), and of –4 km underneath Accumoli. Depending on the model, the slip values are approximately equal to zero at depths shallower than 1.5-3 km (to the north) or 700 m (to the south). Slip values of few cm for the most superficial patches of the faults are modelled in an uneven way.

The Amatrice event has once more demonstrated the maturity of InSAR data monitoring in providing scientific support for operational crisis management. Only 20 hours after the mainshock the first source model based only on the ALOS 2 interferogram, was generated. This model, and its successive updates integrating more InSAR interferograms and eventually also GPS data, were crucial for the source identification, and supported the National Civil Protection authorities in their analysis of the situational awareness. The timely results were also possible thanks to the availability of multiple SAR instruments, which presently allows to reduce the post-event revisit time with any sensor, to 1-2 days on average. The remaining issue to maintain a high monitoring capacity for these applications at the global scale is the need of a continuous, long term background mission over the seismically active areas, which is presently in place only for Sentinel-1 and ALOS 2.

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References