Rupture History of the 2016 Norcia Earthquake from Strong Motion and Gps Data

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Tectonic setting

The evolution of this sector of the chain has been characterized by multi-phased contractional and extensional deformation resulting in a long term fault segmentation.

MAJOR REGIONAL TECTONIC STRUCTURES

Vettore-Bove Fault System (VBFS)

Mt. Sibillini Fault System (MST)

Laga Mt. Fault System (LMFS)

...help us to constrain the geometry of the faults in the source inversion.

30th October Mw 6.5
strike 151° dip 47° rake -89°
strike 330° dip 43° rake -91°

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Constraining fault geometry

Complexity of source geometry from DInSAR data

The far-field coseismic crustal deformation detected by Alos2 after the M_w 6.5 event shows a pattern of the fringes distribution characterized by:

1. a maximum gradient along the VBFS;
2. an abrupt deformation gradient to South;
3. an uplift lobe near Norcia.

suggest the activation of a multi-fault structure

Permanent deformation caused by the October 26th and 30th main shocks

DInSAR data from Cheloni et al. GRL 2017

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Constraining fault geometry

VBFS

SEISMICITY from: Chiaraluce et al., SRL 2017

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Suggested us to test a source geometry with 2 faults oriented as the VBFS and the MST strikes.

- presence of NNE-SSW striking structures possibly inherited from past tectonics;
- deformation pattern inferred from satellite observations;
- geometry of the activated fault systems highlighted by the aftershocks distribution.

Combining:

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Retrieving the source model

**INPUT:**
✓ Joint inversion **36 SM stations & 114 GPS stations**
✓ velocity structure: 1D CIA model (Herrmann et al., 2011) for SM and GPS
✓ Frequency band 0.02 – 0.5 Hz
✓ 2 faults with geometry (2km x 2km patches):
  ☛ main fault 34 km x 16 km, strike 155 and dip 47;
  ☛ secondary fault 10 km x 16 km, strike 210, dip 36.

FAULTS GEOMETRIES AND POSITIONS ARE CHOSEN FOLLOWING THE GEOLOGICAL, GEODETIC AND SEISMOLOGICAL KNOWLEDGE OF THE AREA.
Retrieving the source model

The kinematic parameters of the fault planes have been selected by performing more than 20K+ inversions with different values of kinematic parameters and quantitatively measuring the goodness of fit based on variance reduction.

**EXPLORED KINEMATIC PARAMETERS RANGE**
✓ rise time: 0.5-1.5 s  
**Main Fault:**
✓ rupture velocity: 2.5-3.0 km/s  
✓ rake: 45° -125°  
**Secondary Fault**
✓ rupture velocity: 2.5-3.0 km/s  
✓ rake: 10° -100°  
✓ rupture starting point: 0-6  
✓ delay time (of rupture starting point): 0-2.0 s  

We have verified that the resulting **best model** is not an extreme model in the ensemble by comparing it with the mean model and its standard deviation.
Imaged slip models

Results:
- $V_r1 = 2.8 \text{ km/s}; V_r2 = 2.7 \text{ km/s}$
- Rise time 1.2s both faults
- Similar Max slip ~ 3m
- Delay 1s
- Rupture reaching the surface
- $M_w = 6.56$ [$M_{w1} 6.45$ $M_{w2} 6.25$]

Variance reduction
- $VR_{SM} = 75.9\%$
- $VR_{GPS} = 99.6\%$
- $\text{TOTAL VR} = 76.05\%$

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Seismicity form Chiaraluce et al., SRL 2017
Imaged slip models

Variance reduction
VR_SM=75.9%
VR_GPS=99.6%
TOTAL VR=76.05%
Fitting ground velocity time histories

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Fitting GPS coseismic displacement

Horizontal components

Vertical components

Variance reduction VR_GPS=99.6%

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Imaged slip models: THE MOVIE

- The second fault starts rupturing 0.8 s after the nucleation.
- Peak slip value is reached at the same time on both faults (~4 s).
- The rupture also propagates southward on the main fault.

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Comparison between slip distributions

Norcia coseismic surface ruptures

Ametrice ruptures

Norcia

Ametrice

Ametrice slip from Tinti et al., GRL 2016

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Why 2 faults instead of one?

...and why do we choose the N210 fault?
Why two faults...
The chosen faults fit better than others?
Results...

The rupture history of the October 30\textsuperscript{th} ($M_w$ 6.5) main shock displays:

- a **non-planar geometry**; rupture nucleated on the VBFS normal faults and propagated on a deep portion of the MST, suggesting a kinematic inversion of the thrust;

- the coseismic rupture of **the same slip patch** that broke during the first main shock of August 24\textsuperscript{th} (Amatrice) and of **the area between** the two slip patches that ruptured during the Amatrice event.

- the heterogeneous **slip distribution reflects on the surface slip**: the surface rupture tips match the outline of the seismogenic fault area that experienced $>0.6$-m slip in the uppermost 2 km (Villani et al., 2018)
Three distinct fault systems were activated during the seismic sequence, and they participated to the rupture history of the Norcia (Mw 6.5) main shock: the VBFS, the MST and the northern tip of the LMFS.

The presence of these inherited faults, separating different geological domains, appears to modulate evolution of the sequence interfering with coseismic slip distribution and fault segments interaction.

The obtained rupture history indicates that, in this sector of the Apennines, compressional structures inherited from past tectonics can be reactivated and inverted dissecting the hangingwall of the NW-SE oriented Quaternary normal faults and can break co-seismically contributing to generate moderate-to-large magnitude earthquakes.

The retrieved rupture histories raise serious concerns on our understanding of fault segmentation and have important implications on seismic hazard assessment of the area.
Grazie!
Is the solution stable for additional data?

...working with A. Avallone and G. Pezzo
Is the solution stable for additional data?

We are verifying the stability of the resulting **best model** with the addition of HRGPS and DinSAR data.

![Map](image)

**11 HRGPS stations**

**Variance reduction:**
- \(\text{VR}_{\text{SM- HRGPS}} = 77.90\%\)
- \(\text{VR}_{\text{GPS}} = 99.51\%\)
- \(\text{TOTAL VR} = 77.98\%\) \(\text{Mw} = 6.61\)

**BEST 20K+ models**

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HRGPS fit

Variance reduction VR_SM-HRGPS=77.9%
Is the solution stable for additional data?

We are verifying the stability of the resulting best model with the addition of HRGPS and DinSAR data.

Variance reduction: VR_SM-HRGPS=75.87%  VR_GPS=99.35%  VR_SAR=88.94%
TOTAL VR=76.56% Mw= 6.59
Is the solution stable for additional data?

Afterslip?

~5/10 cm preliminary
DInSAR fit

Alos2 ASC

Alos2 DES
31/08/2016 – 9/11/2016

Observed
Modeled
Residuals
The rupture history of the October 30$^{th}$ ($M_w$ 6.5) main shock displays:

- a **non-planar geometry**; rupture nucleated on the VBFS normal faults and propagated on a deep portion of the MSTS, suggesting a kinematic inversion of the thrust;

- the coseismic rupture of **the same slip patch** that broke during the first main shock of August 24$^{th}$ (Amatrice) and of **the area between** the two slip patches that ruptured during the Amatrice event.

- the heterogeneous **slip distribution reflects on the surface slip**: the surface rupture tips match the outline of the seismogenic fault area that experienced $>0.6$-m slip in the uppermost 2 km (Villani et al., 2018)
The proposed source geometry seems to be:

➢ capable to reproduce the HRGSP data when jointly inverted with the GPS and SM data-set;

➢ capable to reproduce the main shape and the extension of the DInSar coseismic displacement (when inverted), as well as the abrupt deformation gradient to the south, and the shape and amplitude of the deformation lobe of Norcia.

The observed residuals are likely due to along-strike geometrical complexities of the segments not included in our fault model, as well as to the effect of topography (not included in our simulations).

For these reasons, we are now working on including topography and 3D velocity models in our Green’s functions.
Residual values

Alos2_asc

Alos2_des

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Residual values

The residuals between synthetic and observed deformation patterns show that the discrepancies are located near the fault surface expression, which are likely due to along-strike geometrical complexities of the segments not included in our fault model, as well as to the effect of topography (not included in our simulations).

Moreover, the residuals might also be related to the large temporal span between the two passages of the satellite, which includes several days and, in particular, the 26 October main shock.
**Alos2_asc**

![Histogram for Alos2_asc](chart1.png)

- 5539/6668
- 83% res <= 5 cm

**Alos2_des**

![Histogram for Alos2_des](chart2.png)

- 6518/7015
- 93% res <= 10 cm
- 4933/7015
- 70% res <= 5 cm
We are working on...

- A further detailed study assuming a more complex fault geometry is ongoing to improve the fit and include other data (e.g. SAR and GPS)

- Topography and 3D velocity models allow us to better combine source effects with propagation effects

- Further dynamic studies on the spatio-temporal relation of these main events are necessary for the future
Is the best model representative of the ensemble?

We have verified that the resulting best model is **not** an extreme model in the ensemble by comparing it with the mean model and its standard deviation.

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2016 August 24 barrier
VS
2016 October 30th secondary fault

2016 October 30th secondary fault (Scognamiglio et al., 2018)
2016 August 24th fault (Cirella et al., 2018)
2016 August 24th barrier (Cirella et al., 2018)

East-Along dip view

South-west view
South view
South-east view
Why two faults instead of one?

![Graph showing variance reduction for two fault scenarios: ONE fault only SM and Presented model.](image-url)
Why two faults instead of one?

Presented model

ONE fault only SM

ONE fault only SM + GPS

Presented model
NORCIA $M_w$ 6.5: constraining fault geometry

TDMT focal mechanisms for $M_w \geq 3.0$

NE-SW trending focal mechanisms in the VBFS hanging-wall

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Is the solution stable for additional data?

We are verifying the stability of the resulting **best model** with the addition of HRGPS and DinSAR data.
In order to check the consistency of the complex seismic source model obtained with the surface geological setting, we construct 2 cross-sections about 15 km-long each and oriented running nearly orthogonal to the two inverted faults.
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Goals

➢ present the obtained multi-fault rupture model of the October 30th 2016 M6.5 Norcia earthquake and interpret it in the framework of this complex sequence of moderate to strong magnitude earthquakes.
& conclusions

Three distinct fault systems were activated during the seismic sequence, and they participated to the rupture history of the Norcia (Mw 6.5) main shock: the VBFS, the MSTS and the northern tip of the LMFS.

- The presence of these inherited faults, separating different geological domains, appears to modulate evolution of the sequence interfering with coseismic slip distribution and fault segments interaction.

- The obtained rupture history indicates that, in this sector of the Apennines, compressional structures inherited from past tectonics can both segment the Quaternary normal faults NW-SE oriented and break co-seismically contributing to generate moderate-to-large magnitude earthquakes.

- The retrieved rupture histories raise serious concerns on our understanding of fault segmentation and have important implications on seismic hazard assessment of the area.