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A Crustal model of the region interested by the 2016 Central Italy Seismic Sequence, by integrating Local Earthquake Tomography and Bouguer Gravity Anomalies data

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OVERVIEW

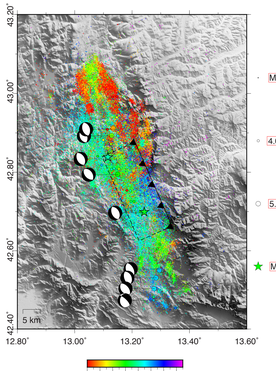

Figure 1 August 24/16 - June 2017 relocated seismicity with focal mechanisms of the the Mw > 5.0 earthquakes from TDMT solutions (http://cnt.rm.ingv.it/tdmt). Hypocenters are shallower in the northern portion of the fault system.

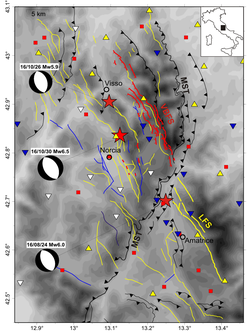

Figure 2 The Central-Northern Apennines with indicated the NNW-SSE active normal fault systems of Miocene-Pliocene Sibillini Mts thrust (MST) and of NNE-SSW Laga Mts (LFS). The red stars identify the epicenters of the three main shocks of the 2016 seismic sequence

The junction zone between the Central and Southern Apennines is a complex geological area.
During the 2016-2017 Central Italy seismic sequence this region experienced a cascade of nine earthquakes larger than Mw > 5.0, including three M6+ normal faulting earthquakes that ruptured a complex array of fault segments (Fig.1 and 2).
The two largest mainshocks, the August 24th Mw=6.1 Amatrice and the October 30th Mw=6.5 Norcia, ruptured adjacent normal faults with ancillary structures and with overlapping slip on shallow faults surfacing on the western slope of the Vettore mountain range.

The great quantity of geologic, geodetic and seismological data that came from this seismic sequence provided a unique opportunity to better understand this complex geological area characterized by the occurrence of of multiphased contractional (Mio-Pliocene) and extensional (Quaternary) deformation.
However, although the region was the target of recent intense geophysical investigation, large uncertainties still remain about the deep architecture of the thrust-and fold belt. 3D Vp and Vp/Vs models determined by Local Earthquake Tomography (LET) surveys (Carannante et al., 2013, Chiarabba et al., 2018) suffer from limited lateral resolution (5 x 5 km) restricted to the epicentral area and limited vertical penetration (12km) (Fig. 4). Besides, deep seismic reflection profile totally lack in the area, while hydrocarbon exploration is concentrated only in the southern region between the zones interested by the 2016 Amatrice and 2009 L'Aquila seismic sequence.

In order to obtain crustal images of the epicentral region with improved spatial resolution and exploration depth we propose the joint inversion of passive seismic and gravity data

INTEGRATE SEISMOLOGICAL AND GRAVITY DATA

For the **first step** of our integrated approach we transform the most recent 1D regional velocity model (Di Stefano et al., 2011; Fig. 3 a)) into the starting density model (Fig. 3 c)) with a scaling relationship (Fig. 3 b)) derived from Nafe and Drake experimental measurements (Nafe and Drake, 1957) for the sediments (vp < 3.5 km/s) and Brocher (2008) for higher velocities.

For the **second step**, earthquake arrival times recorded by 50 permanent and temporary seismic stations, deployed after the occurrence of the first, August 24, 2016 mainshock are analysed and selected for epicentral solution that have 1) a minimum of 10 P and 5 S phases; 2) a minimum distance of 10 km from the hypocenter to the closest station; 3) location error less than 1 km and 4) azimuthal gap less than 180° (Chiarabba et al., 2018).
A total of 44,177 earthquakes with 748,197 P-wave and 656,484 S-P arrival times were inverted with the iterative damped least square algorithm (Haslinger, 1998).
After 5 iteration steps, the tomographic model, discretized by a 3D grid with lateral resolution lenght of 5 km x 5 km and layers of 3 km depth up to 25 km reached a final rms error of 22 s, corresponding to a variance improvement of 32% (Fig. 4).

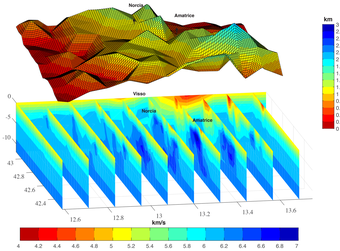

Figure 4 YZ slices through the 3D tomographic Vp model. The surface topography is superimposed to the model.

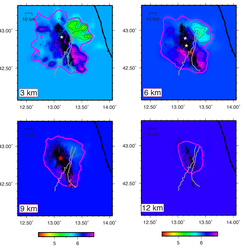

Figure 5 Vp depth layers at 3, 6, 9, 12 km with superimposed the limit of the well resolved volume (Spread Function <=3)

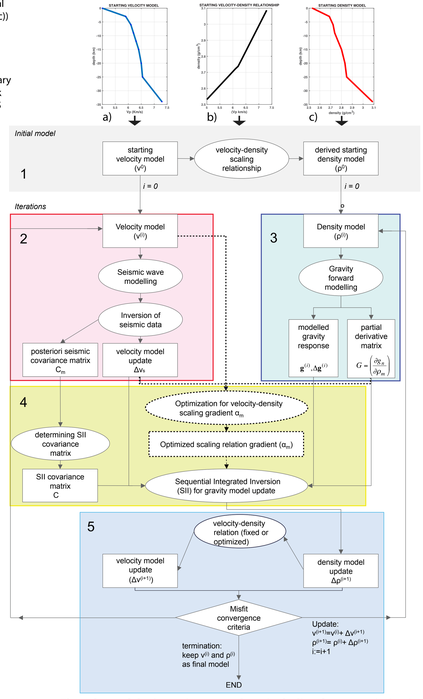

Figure 3 Flow chart of the inversion procedure, including future optimization of density and velocity scaling gradients (indicated by black lines). Different colors separate the relevant steps of the procedure

With the transformed 3-D grid of density values we define 6084 polyhedral bodies of 12° x 4° and variable height. The expression derived by Pohanka (1988) for a polyhedral body with density linearly dependent on some coordinates is used for the computation of the three components of the gravity field (Tondi and de Franco, 2006) and the partial derivative matrix (see **step 3**).

For all the gravity data (Barzaghi et al., 2002) the a-priori error (the square root of the diagonal elements of Cgg) is set equal to 1.0 mGal, the update to the velocity model resulting from the tomographic model ((Δv_k), Chiarabba et al., 2018) is used as constraint for the density update and we proceed to **step 4** of the flow chart with the optimization of the density-Vp scaling relationships:

$$\alpha_m = \frac{\left[\left(G^T C_{gg}^{-1} G\right)^{-1}\left(G^T C_{gg}^{-1} g\right)\right]_m}{v_m^0 + \Delta v_m}$$

and of the density values with SII method (Tondi et al., 2012):

$$\Delta\rho = \left(G^T C_{gg}^{-1} G + C_{mm}^{-1}\right)^{-1}\left(G^T C_{gg}^{-1}\Delta g + \alpha C_{mm}^{-1}\Delta v\right)$$

The evaluation of data misfit and of data quality of the solution (**step 5,** Figs. 5, 7) allows us to identify and keep the final model (Fig. 6).

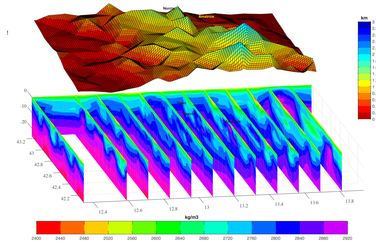

Figure 6 XY slices through the final 3D density model. The surface topography is superimposed to the model.

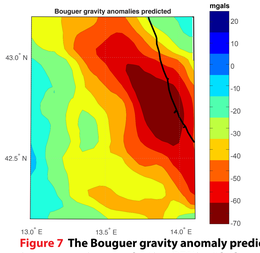

Figure 7 The Bouguer gravity anomaly predicted (average variance reduction 97%) with the optimized density model.

RESULTS AND DISCUSSION

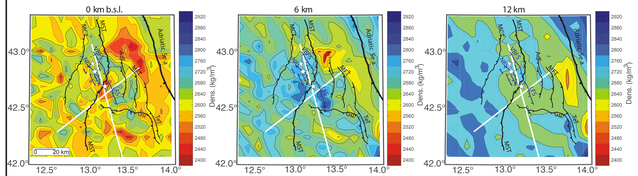

Figure 8 Horizontal density slices at 0, 6, 12 km depth. White stars are the epicenters of the Amatrice, Norcia and Visso earthquakes. The blue lines are active normal faults (VBFS - Vettore-Bove Fault System, LFS - Laga Fault System, NFS - Norcia Fault System). Black lines are Neogene thrust faults (MST - Mts Sibillini Thrust, MCT - Mt Cavallo Thrust, AqT - Acquasanta Thrust, MFT - Montagna dei Fiori Thrust, TeT - Teramo Thrust, GsT - Gran Sasso Thrust). The white lines are the traces of the two density sections showed in Fig. 9.

The 3-D density model is characterized by significant lateral density variations. The upper crust is characterized by pronounced hig-density bodies (2650-2750 kg/m^3) in the axial zone of the range and by a broad low-density wedge (2400-2550 kg/m^3) in the external zone. The former relates to the Mesozoic carbonate rocks of the Umbria-Marche sequence, the latter to the stack of Plio-Quaternary terrigenous deposits of the external thrust-and-fold-belt.

Main lateral density variations and high-density bodies correlate to the trajectories of the main Pliocene thrust faults and to the associated ramp-anticlines, respectively (Fig. 8). In particular, the Mts Sibillini Thrust (MST) has a clear signature in the density model. Its lateral ramp separates two high-density bodies, the western one correlates to the upthrown side of the Umbria-Marche Mesozoic succession, the eastern one to the Acquasanta anticline (Figs 8 and 9). Conversely, the causative normal faults (VBFS, LFS in Fig. 8) have a subtle signature.

The longitudinal cross-section (Fig. 9) shows that a relatively low-density layer (2600 kg/m^3) is sandwiched between two high-density regions (> 2760 kg/m^3). The low-density body can be related to the phyllitic sequence (Phy) located in between the evaporitic sequence of the Umbria-Marche multilayer (Ev) and the crystalline basement (Bas). The three mainshocks, which have hypocentral depths between 5 and 7 km, therefore nucleated within high-density (high velocity) carbonates of the Umbria-Marche succession.

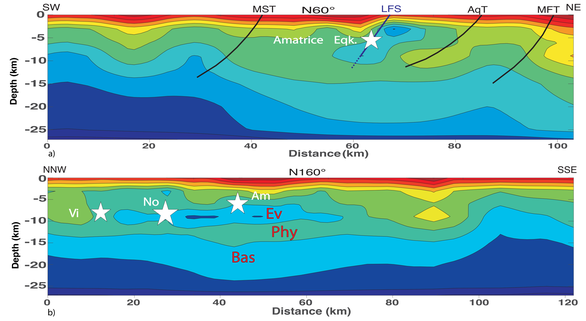

Figure 9 SW-NE (a) and NNW-SSE (b) density sections across the epicentral region. Thick lines denote schematically main faults inferred from surface data and lateral density variations. Ev - high density Triassic evaporites; Phy - low density phyllitic basement (Permo-Trias); Bas - high density crystalline basement

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