New insights into the rheology of a normal fault: the Mw6.1 2009 L'Aquila case study

Rossella Fonzetti *[1,2], Luisa Valososo[1], Pasquale De Gori[1] and Claudio Chiarabba[1]

1: Istituto Nazionale di Geofisica e Vulcanologia (Rome,Italy)

2: Università degli Studi Roma Tre (Rome, Italy)

* rossella.fonzetti@uniroma3.it

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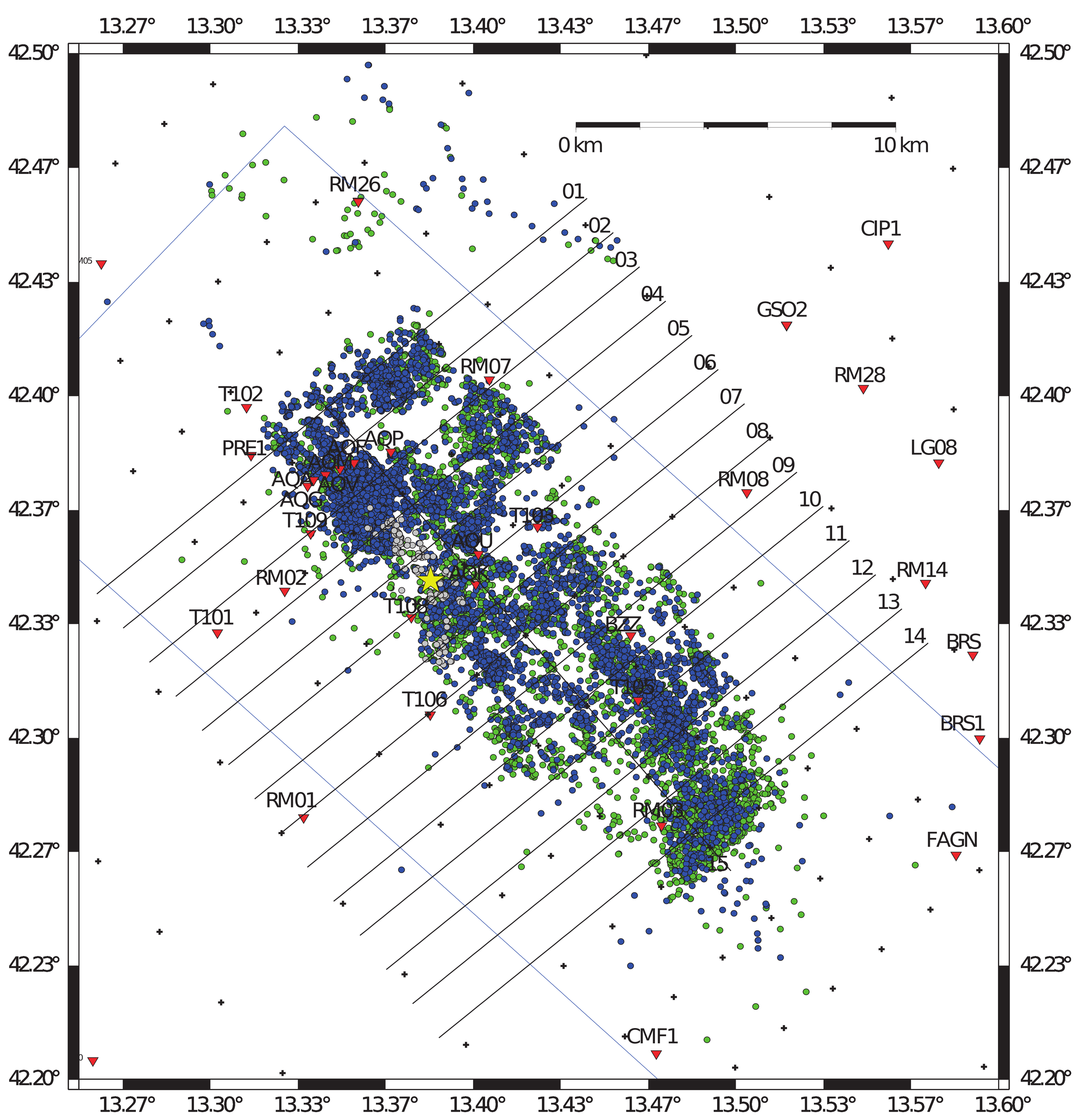
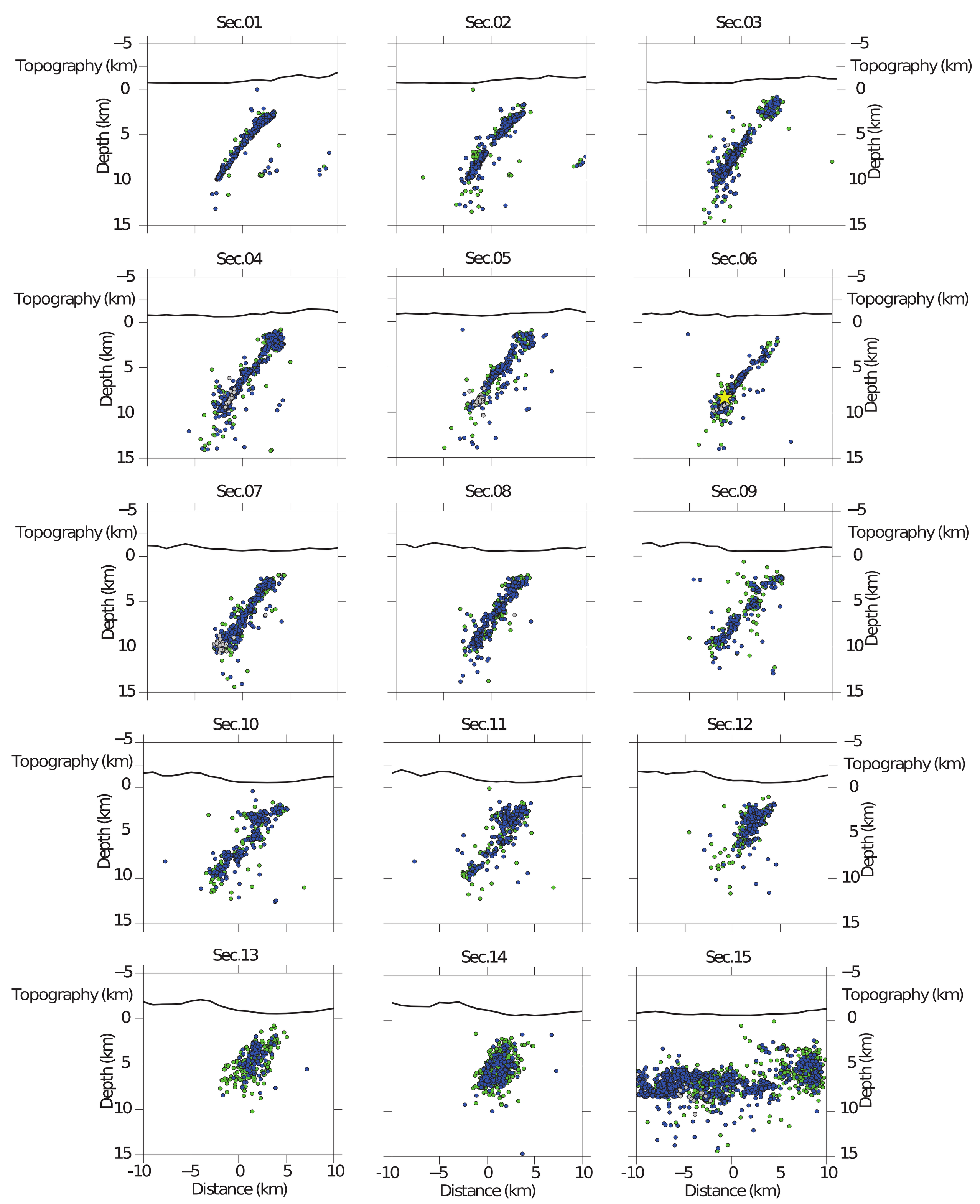


Fig. 1: Relocated seismic events from 7th January to 10th December 2009, obtained by means of TomoDD inversions. The blue box is the projection of the Paganica fault at the surface. The black crosses are the grid nodes for the TomoDD inversion. The red triangles are the seismic stations. The black straight lines are the traces of vertical sections shown in Fig. 2: sections 1–14 striking N50°E, section 15 is striking N140°E.

Fig. 2: Vertical cross sections that show the depth distribution of aftershocks occurring within ±0.8 distance.



ABSTRACT

How seismogenic faults accommodate the slip accumulated during the interseismic period is one big challenge in seismology. Seismic imaging of fault zones can highlight their rheology helping in the understanding of the origin, propagation, and arrest of seismic ruptures and triggering processes. Here, we show that 3D high resolution tomography, constrained by a high-precision and large earthquake seismic catalog, reveal the presence of rheological barrier on the normal fault ruptured during the 2009 L'Aquila earthquake. The earthquake originated on a reactivated and inverted thrust, with a rigid body which acts as a structural barrier at the intersection between the overlying thrusts and the normal fault below.

INTRODUCTION

In this study, we compute a high resolution image of the fault responsible for the 2009 L'Aquila earthquake obtained by a 3D Double-Difference (DD) local earthquake tomography (Zhang and C. H. Thurber 2003) and the high-precision, large earthquake catalog by Valoroso et al., (2013-2014). We combines cross-correlation and phase readings to compute Vp and Vp/Vs models along the fault plane with a resolution of 2 km.

The 6th April (01:32 UTC) 2009 Mw 6.1 normal faultinng earthquake developed along the Paganica fault, after a Mw 4.1 foreshock and a swarm that started on March 30th (Chiaraluce et al. 2011). The Paganica fault is part of an about 20 km long array of Quaternary normal faults systems (Chiarabba et al. 2009).

DATA AND METHOD

We use the 1D seismic catalog of Valoroso et al. 2013 to compute high-resolution 3D earthquakes relocations (Fig.1) and to obtain Vp and the Vp/Vs velocity models.These seismic events were recorded by 132 seismic stations (red triangles in Fig.1), managed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) and by the French LGIT network (Margheriti et al. 2010). We combined these travel time differences (delay times) with delay times measured via cross-correlation (CC) waveform coming from correlated earthquakes, selecting only the seismic events on the Paganica fault.

We use the Double-Difference seismic tomography TomoDD code (Zhang and C. H. Thurber 2003) and a total of 13,604 seismic events. To optimize the sampling on the fault, we used a 40° rotated grid, perpendicular to the strike of the Paganica fault (Fig. 1) and a 3D grid with different spacing, reducing the distance of nodes near the fault to increase the sampling and the number of rays inside this area.

We use a strategy to optimize the Vp/Vs computation, computing first the 3D Vp model, using all the phase readings; and then the 3D Vp/Vs models, using only the stations with both P- and S-wave readings, with a similar sampling of Vp and Vs models.

SEISMICITY DISTRIBUTION

The high-resolution DD relocations highlight how complex is the geometry of the Paganica fault. Seismicity developed over an area of about 100^2km Fig. 1) and between about 2-15 km depth (Figure 2). The Paganica fault seems activated at different times during the sequence. In particular, the foreshocks that occurred in the period of January-March 2009 are located near the mainshock of the L'Aquila seismic sequence and along the fault to the north (sections 04-07 in Fig. 2). The Paganica fault has a dip of about 45° and it is characterized by a complex structure. We observe:

1) an area with ***lack in seismicity*** located at a depth of about 3-6 km, visible in sections 02, 03, 06, 09 and 10.

2) a ***dispersion in the aftershock distribution*** in the shallow crust (at depths less than 5 km, sections 09, 10, 11). This interesting aspect could be explained by hypothesizing the existence of small splays, secondary to the main plane.

Fig. 5: Zoom on the vertical sections of Vp and Vp/Vs models on main portions of the fault. The yellow star is the 6th April mainshock. The black dots are the aftershocks with a ML ≤ 4.0. The red lines indicate the fault system highlighted by velocity anomalies and the relocated aftershocks.

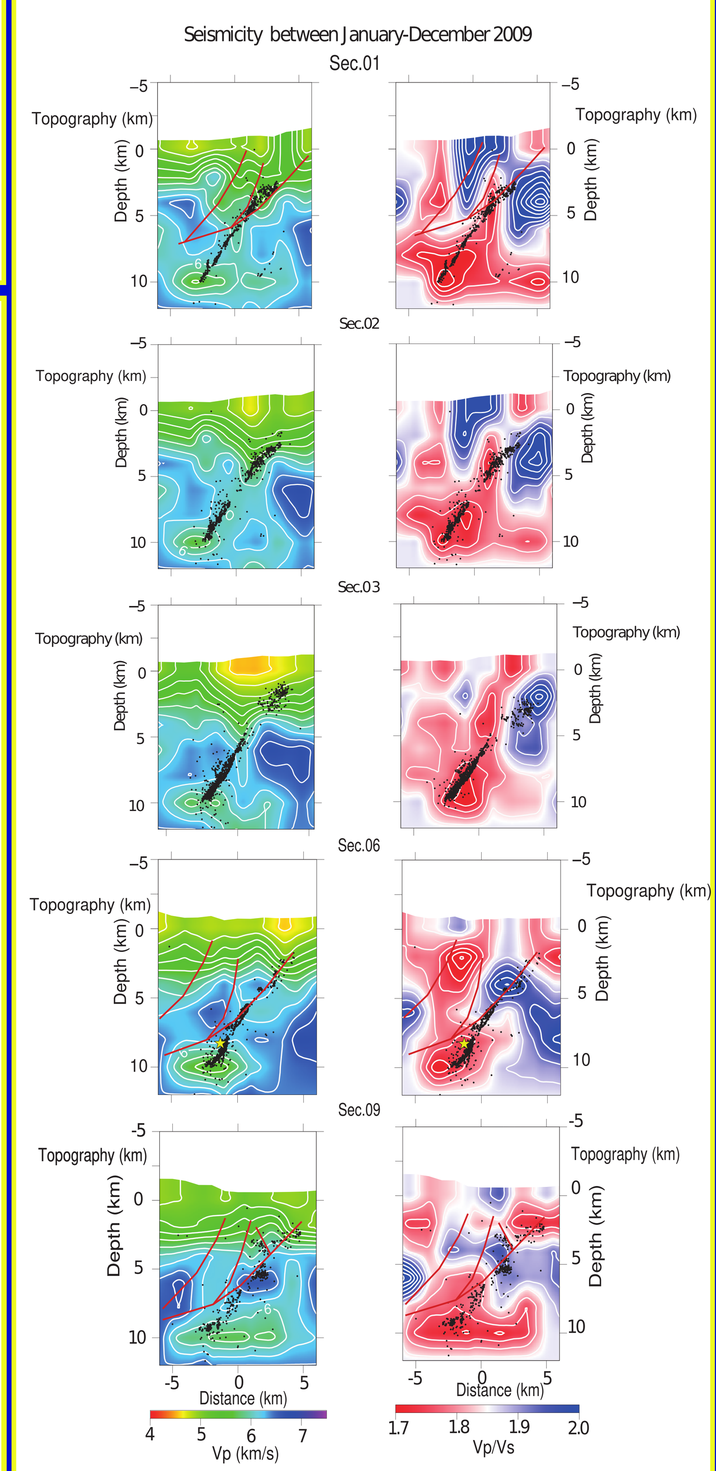
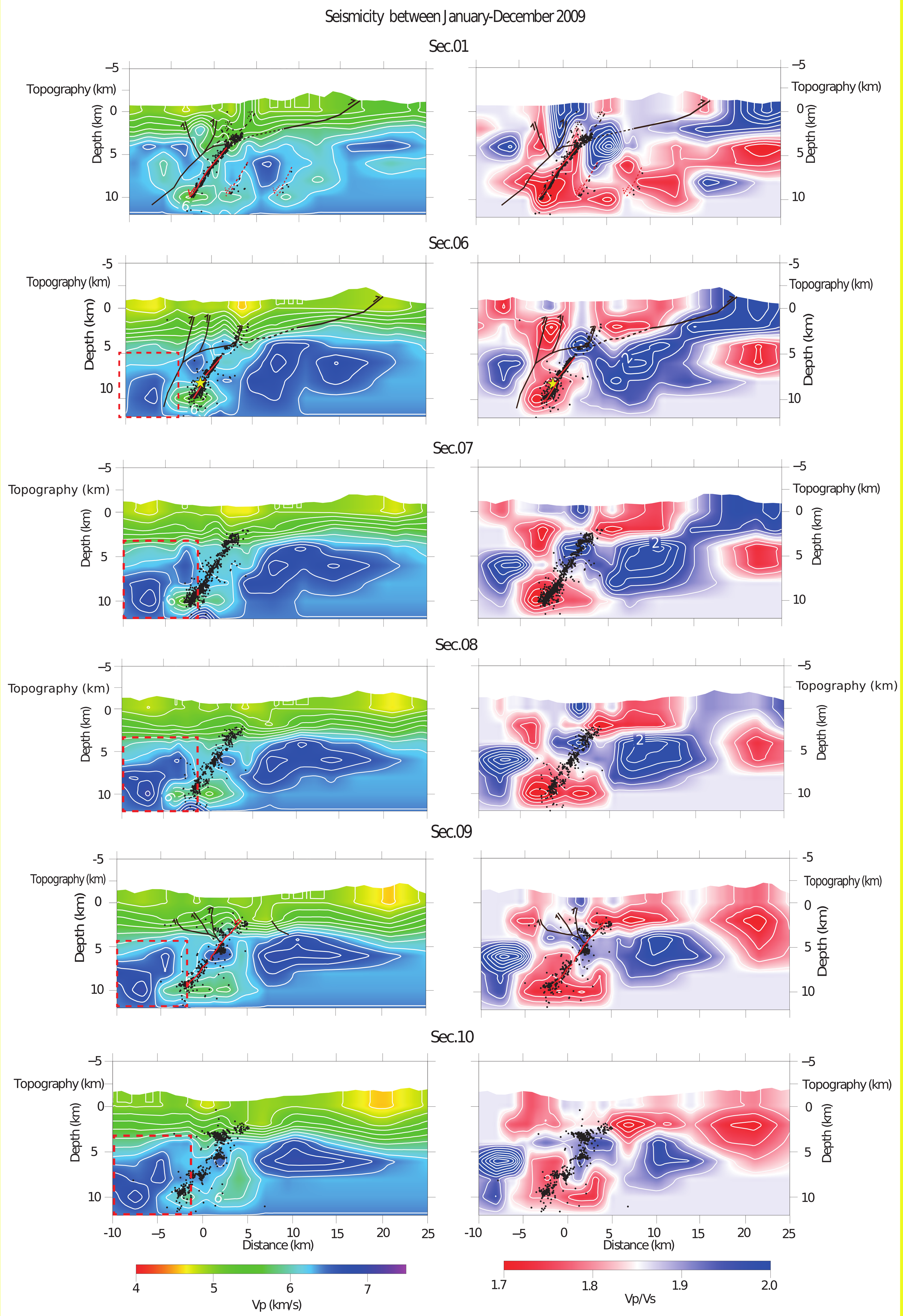


Fig. 4: Vertical sections of Vp and Vp/Vs models for the regional structure. The brown lines in sections 01, 06 and 09 indicate the thrust system, emphasized by the velocity anomalies. The red lines in the same sections represent the normal fault system drown by relocated aftershocks and the dashed lines indicate the presumed fault planes. The red boxes in sections 06-10 emphasize the hight Vp area, showing the asperity portion of the fault system. The yellow star is the 6th April mainshock. The black dots indicate the aftershocks with ML ≤ 4.0.



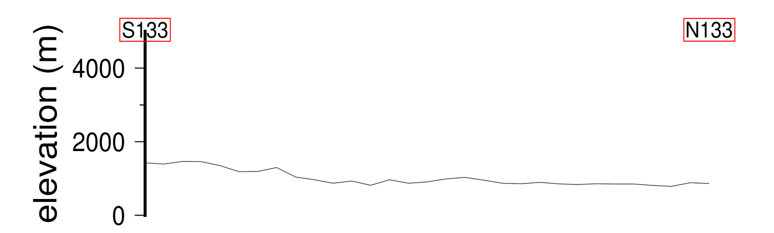
MODEL RELIABILITY

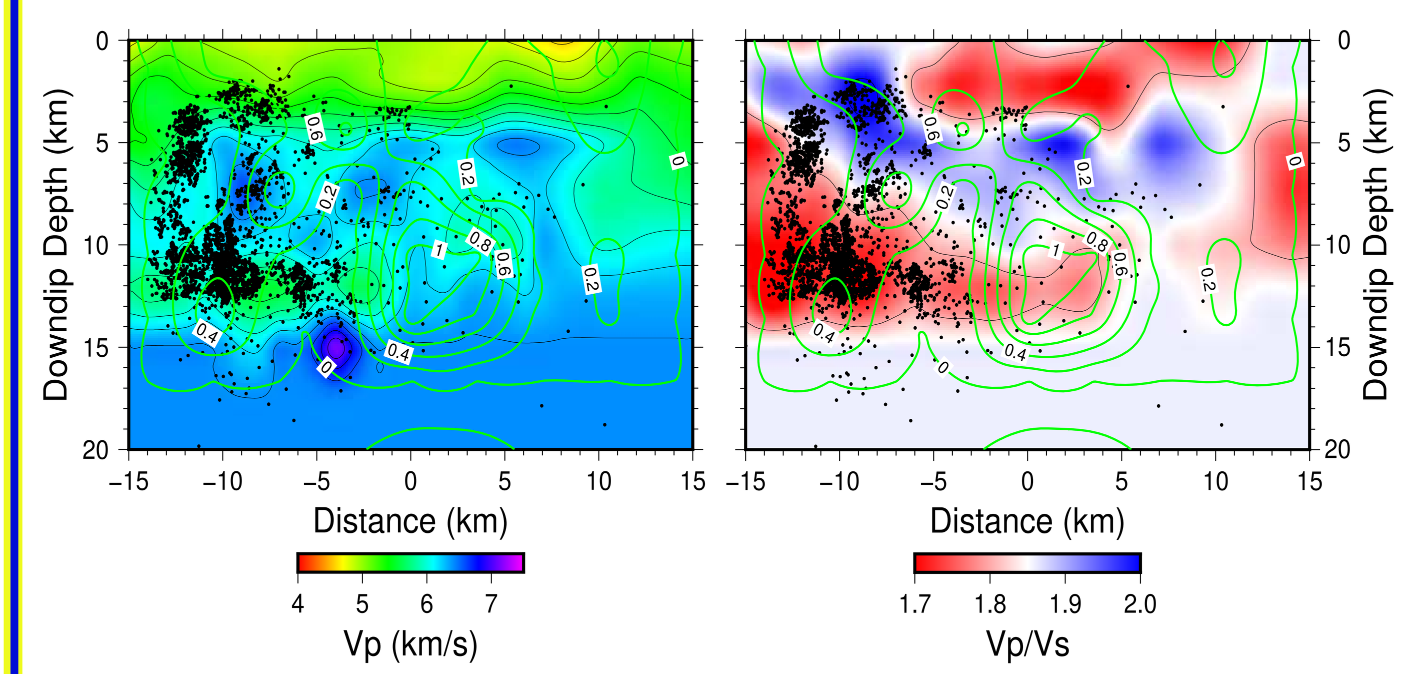
To evaluate the model resolution, we carried out synthetic tests, assessing the capability to reproduce the synthetic 3D input models. We created a checkerboard model, alternating variation of +/- 5% at each node of the layers and modified in this way both the Vp and Vp/Vs models. We observe a decrease in resolution with depth, while the layers from 4 to 10 km depth are well resolved.

Fig.3: Resolution tests (checkerboard test) perturbing for layers of the Vp and Vp/Vs models. These models are obtained by inverting the entire dataset. The black crosses represent the grid nodes used for TomoDD inversions. For each black box, the upper panel denotes the final model obtained by inverting synthetic data; and the lower panel denotes the synthetic model perturbed.

Seismicity between January-December 2009
Sec. Downdip

Fig. 6: Down-dip section of Vp and Vp/Vs models along the fault. The black dots indicate the aftershock with ML ≤ 4.0. The green lines are the coseismic slip from Cirella et al. 2009.





TOMODD VELOCITY MODELS AND DISCUSSION

The new high resolution velocity models show:

1) The complexity of the Paganica fault, where the normal fault seems reactivating a system of a main thrust at about 5 km depth from which 3 minor back-thrusts splays (sections 01 and 06 in Fig.4). This complex geometry reseamble a flower strucure to the south (section 09 in Fig.4). We infer that the Paganica fault is a reactivated positively inverted thrust.

2) The lack of seismicity observed at 6-7 km and at 9 km, close to the mainshock (sections 02,03, and 06 in Fig. 5) corresponds to a high Vp and low Vp/Vs volume, suggesting the presence of a structural barrier due to the interaction of two different fault system (Fig. 4 and 5). In addition, a dispersion in seismicity between 3 and 5 km depth (Fig. 4, section 09), is ascribable to the presence of the back-thrusts.

3) A migration of seismicity toward the northwest.

Aftershocks are located in the areas of low coseismic slip (Fig. 6), in the northernmost sections (sec 01-05 in Fig. 1). This suggests how after the Mw 6.1 mainshock the seismicity migrated northwards.

CONCLUSION

In this study, we obtained high-resolution tomograms of the Paganica fault involved during the L'Aquila 2009 seismic sequence by means of DD local seismic tomography (Fig. 4-6). The relocation of the seismic events allowed us to obtain more detailed information about the geometry of the Paganica fault. This is composed of ancient three-thrusts and back-thrusts systems, located between 2 to 5 km depth, reactiveted as normal fault. The combination of these faults systems caused the development of a structural barrier (high Vp and low Vp/Vs, as a dense and ahnydrous geological body) which could rupture in the future earthquakes.

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