Three dimensional seismic imaging and earthquake locations in a complex, normal faulting region of southern Apennines (Italy)

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Motivations

- The Campania-Lucania portion of Southern Apennines is a high seismic hazard area: a composite systems of active normal faults coexist, which are causative of large and damaging earthquakes in the past centuries.

- An intense, continuous micro-seismic activity is currently recorded, that appears connected and delineates the primary fault structures generating moderate to large earthquakes.

- High-quality data are nowadays available from a dense network of seismometers (short-period and broad-band) and accelerometers (AMRA, INGV, DPC)

Can the background micro-seismicity be used to infer high-resolution images of the active fault zones and of the embedding crustal medium?
High resolution imaging of fault structures

- Joint interpretation of P- and S-wave velocity structure
- Relocated seismicity

High quality catalogue:

- S-wave identification by polarization filtering
- P- and S-phase refined re-picking based on cross-correlation

Tomographic inversion strategy:

- Joint inversion of hypocentral and velocity parameters
- Multi-scale approach
Outline

- Seismicity and geological setting
- Data and processing techniques
- Tomographic method
- Inversion strategy
- Observed data inversion
- Conclusion
A complex architecture of the southern Apennines is originated by the deformation of:

- the **Western Carbonate platform**
- **Apulia Carbonate platform**
- the **Lagonegro basin**

The southern Apennines chain is a NE-directed fold and thrust belt, with the Apulian promontory representing the orogenic foreland.
Earthquakes M 5.5+ occur along a system of NW-SE striking normal faults along the Apenninic chain and an approximately EW oriented strike-slip fault transversely cutting the belt.

Background micro-seismicity is likely generated along the major fault segments activated during the most recent earthquakes.
Earthquake waveform data-set

**Network**
- Covered area 100x70 km$^2$
- 42 stations, average dist 10-20 km

**Data Collection**
- 1311 events from 09/2005 to 04/2011
- Moment magnitude: 0.9-3.1
- Initial P- and S-phase manual pick

**Selection**
- Re-location in 1D reference model
- Gap <200°, 5 P 2 S, RMS<0.5s
- 634 events, 6425 P 3214 S
Data processing
S-wave detection by polarization filtering and waveform coherence analysis

S characteristic function (CF)

CF common receiver sections

3C processing
- Rotation from the observation system (ZNE) to ray coordinate system (LQT)
- Polarization filtering
  - Energy ratio H
  - Rectilinearity P
  - Directivity D
- Construction of characteristic function

Lateral coherence of the waves as a function of the hypocentral distance

The first arrival coincides with the first arrival of the S-waves

Amoroso et al 2012, BSSA
Data processing
P and S refined re-picking by waveform cross-correlation

Traces aligned on P manual picks
Traces aligned on P adjusted picks

SCL3
Hypo dist (km)
NSC3
Hypo dist (km)
VDS3
Hypo dist (km)

Time (s)

Traces aligned on S manual picks
Traces aligned on S adjusted picks

COL3
Hypo dist (km)
NSC3
Hypo dist (km)
RDM3
Hypo dist (km)

Time (s)

Manual pick
Refined pick
Manual pick
Refined pick
Tomographic method

TOMOTV*: Iterative, linearized, tomographic approach for the joint inversion of P and S arrival times to infer the earthquakes location and 3D velocity models

**Initial Model**
Velocity model $v_0$
Eqks location $x_0$, $y_0$, $z_0$, $T_0$

- Trilinear interpolation of the velocity model in a finer grid
- Calculation of theoretical travel-times (Podvin and Lecomte, 1991)
- Back-ray tracing
- Accurate calculation of the travel time by integrating the slowness along the ray path

**New Model**
Velocity model $v_0 + dv_0$
Eqks location $x_0 + dx_0$, $y_0 + dy_0$, $z_0 + dz_0$, $T_0 + dT_0$

$\Delta t = t_{\text{obs}} - t_{\text{cal}}$

- Preconditioning and smoothing of the matrix
- Inversion of the matricial system $\Delta t = Gm$
  LSQR (Paige and Saunders, 1982)

**Results**

- RMS > threshold
  - New Model became the Final Model
- RMS < threshold

*Tomographic method* was proposed by Latorre et al., 2004.
The reference 1D, P- and S-velocity models

- The **P-wave Minimum 1D velocity model** is computed by a joint inversion of layered velocity model, station corrections and hypocenter locations (VELEST, Kissling et al, 1995)

- An initial Vp/Vs value of 1.85 is estimated by minimizing the RMS of S-wave arrival times

- P-wave average station delays indicate a wide-scale, lateral variation of seismic velocities in the SW-NE direction, consistent with the transition between the carbonatic platform outcrops at South-West and the Miocene sedimentary basins at North-East

*Matrullo et al., 2013*
Inversion strategy
Parametrization

Multi-scale approach

A series of inversion progressively decreasing the grid spacing are performed. The starting model for each inversion being in the final model of the previous one (Chiao and Kuo, 2001).

**Synthetic pattern**

**Recovered pattern**

Dx, Dy, Dz= 12x12x4 km³

Dx, Dy, Dz= 6x6x2 km³

Dx, Dy, Dz= 3x3x1 km³
Assessment of solution reliability

Checkerboard tests

Resolvability of checkerboards

The semblance between exact and recovered checkerboard anomalies provides a quantitative resolution estimate (Zelt, 1998)
1D profiles from 3D velocity models

- Good agreement with sonic logs but smoother velocity variations
- Vp/Vs ratio sharply increases at 2-6 km depth along the fault zone.
- At approximately the same depth we observe a peak in earthquake distribution.
3D P- and S-velocity models: plan view

P-wave

- Sharp velocity variation in the SW-NE direction down to 8 km depth
- At South-West the outcrops of the Campanian Platform and the uplift of the Apulian Platform are detected by the high P-velocity anomaly (6.0-6.8 km/s)

S-wave

- At North-East the low P-velocities are related to the sequence of Quaternary basins and the thickening of the Lagonegro units
- The S-model reproduce features similar to the P-model but with a smoother resolution
**Seismic image of ‘an earthquake reservoir’**

- The P-wave model follows the main lithological discontinuities.
- The microseismicity tends to cluster at the top of the basement and at the top of the Apulian Platform carbonates, and it is confined within a 15 km wide block bounded by the SW and NE Boundary Faults and including the Central Fault, along which the main shock of the MS 6.9, 1980 earthquake nucleated.
- The VP/VS ratio shows a sharp increase from near-surface values of 1.7-1.8 to 2.0-2.2 between 5 and 10 km depth. A diffused high VP/VS ratio occurs within the Apulian Platform carbonates located between the SW and NE Boundary Faults.
- The VP×VS product defines a volume characterized by relatively low values.
Conclusions

- A comprehensive picture of the upper crustal structure of the Irpinia active fault system has been obtained.

- The 3D P- and S-wave velocity models well delineating the main lithological discontinuities.

- Background seismicity is concentrated within the multiple-faulted block, which embeddes the graben-like system.

- The microearthquake activity confined within the highest Vp/Vs volume and the combined interpretation of Vp/Vs ratio, and Vp x Vs product suggest that, fault lubrication processes may occur.

- These processes control the concentration of background seismicity within an active fault-bounded block, and the nucleation of large earthquakes such as the Ms 6.9, 1980 Irpinia earthquake through pore-pressure increase on fluid-filled cracks located within the damage zone volume surrounding the major active faults.