SCHATZALP Induced Seismicity Workshop
Session - Injection Plays

A Detailed Analysis of Initial Seismicity Induced by Wastewater Injection in the Val d'Agri Oil Field (Italy)

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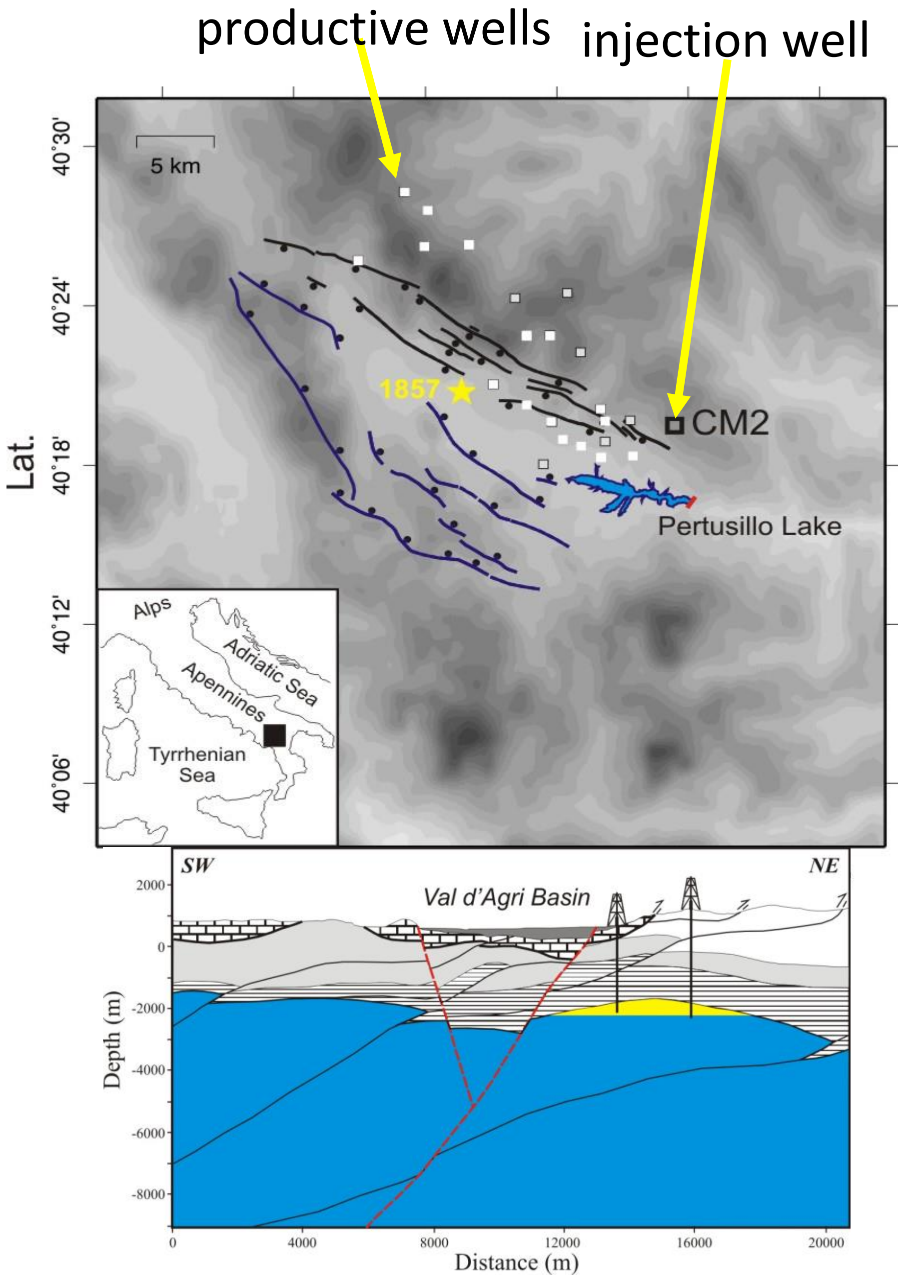
The Val d'Agri Basin

- ❑ Southern Apennines extensional belt.
- ❑ Quaternary basin (NE-SW extension).
- ❑ NW-SE trending basin-bounding normal faults capable of generating large earthquakes (1857, M7).

- ❑ Largest oil field in onshore Europe (~90.000 barrels/day).
- ❑ High productivity reservoirs (fractured, low-porosity, Cretaceous carbonates).
- ❑ Oil extracted from anticlines related to NW-SE trending Pliocene thrusts.
- ❑ Wastewater re-injected since June 2006 in the high-rate CM2 well (~2500 m^3/day, well-head pressure up to 14 MPa, interval: 2890-3096 m b.s.l.).

- ❑ Water impoundment with severe seasonal variations (Pertusillo Lake).

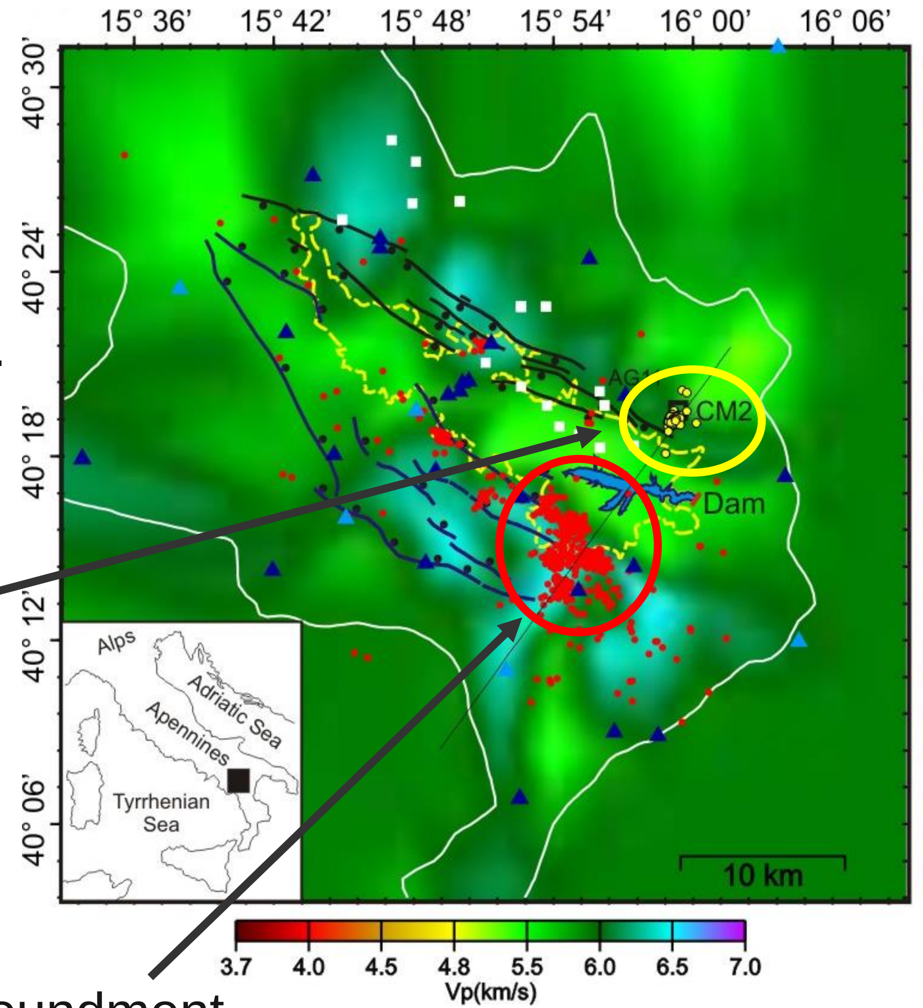


Induced Seismicity during the first stage of injection (June 2006 swarm)

The Val d'Agri Seismic Survey

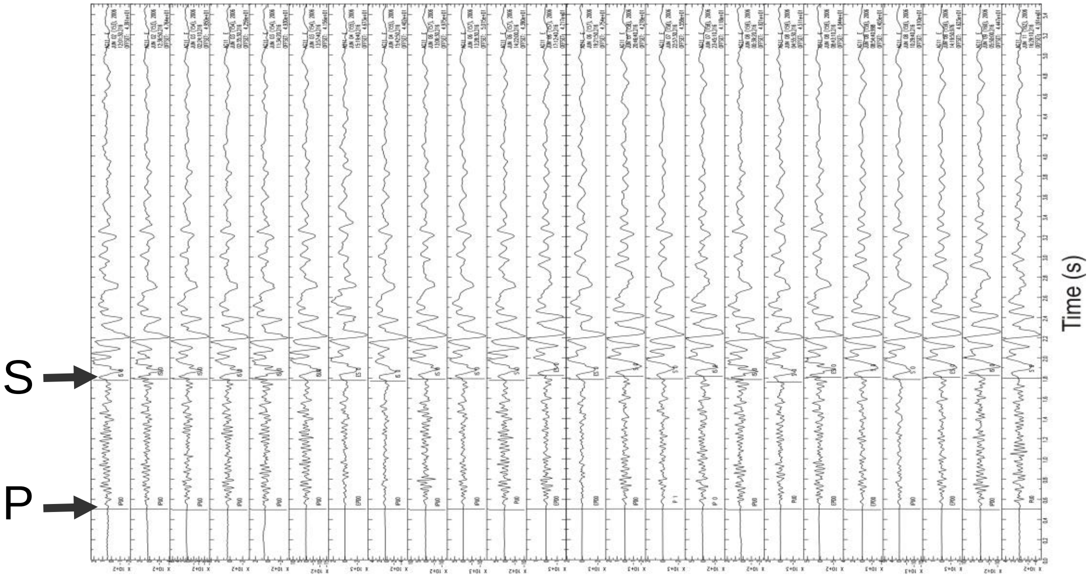
- May 2005 – June 2006.
- High-performance dense network of 23 temporary stations.
- Catalogue: 2000 earthquakes (M_L < 2.7).
- Magnitude completeness: Mc=0.4.

Swarm related to the injection well CM2 (yellow dots)

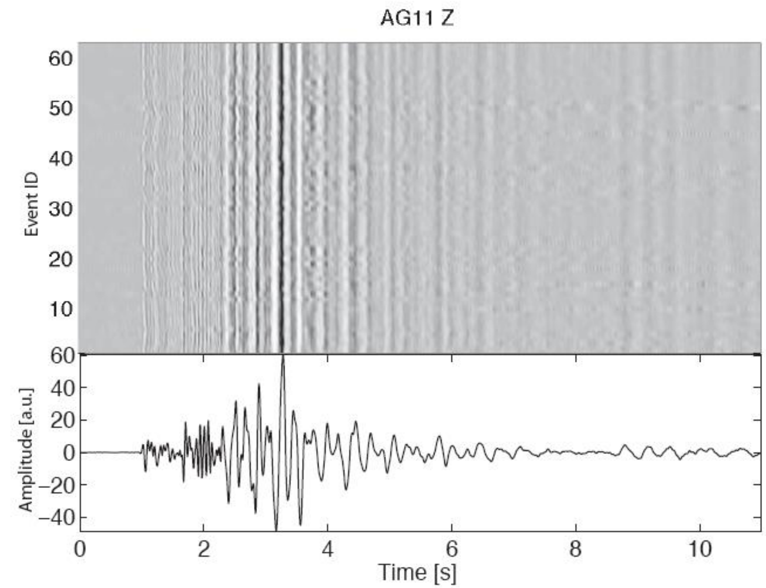


Seismicity induced by the water impoundment

The June 2006 swarm: data analysis



Waveforms of a cluster recorded at the closest station showing high coherence.



Stacked trace used for the cross-correlation matched filter technique.

Common receiver gathers show almost identical waveforms for most events

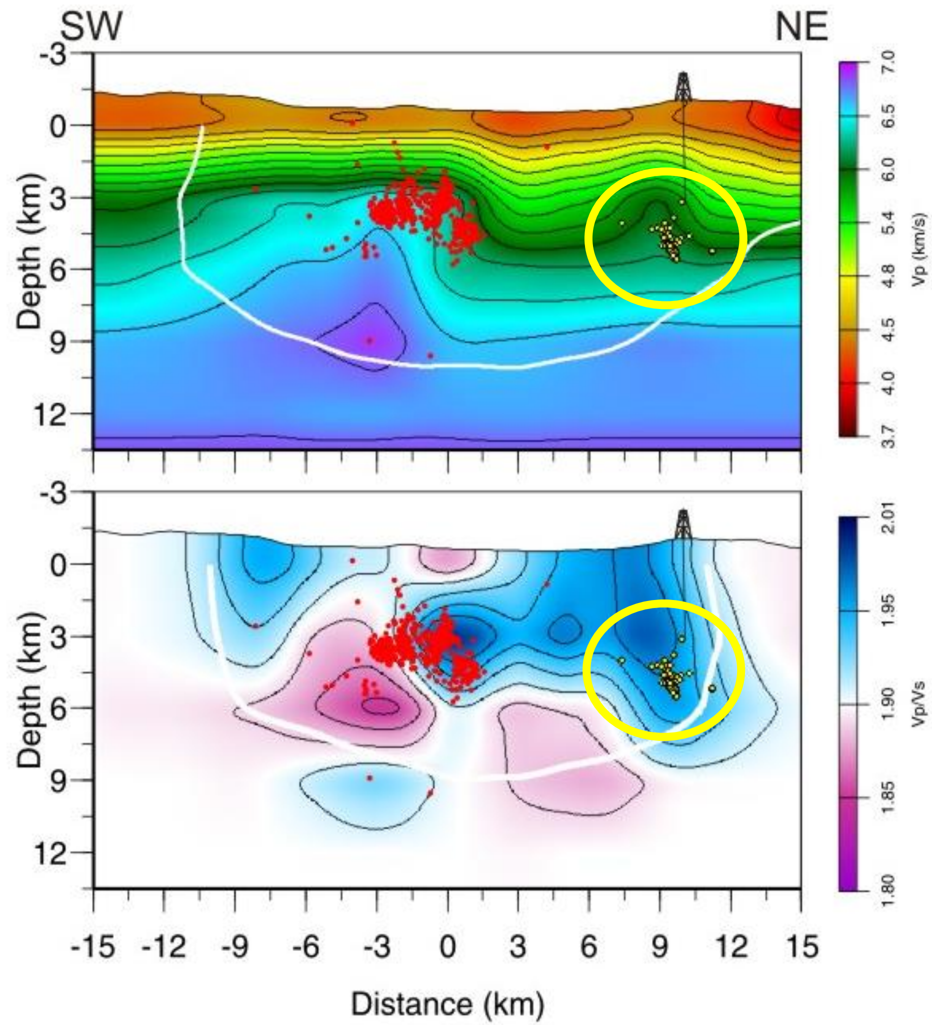
- Source locations and mechanisms are very similar (i.e. clustering).
- Earthquakes detected by cross-correlation matched filter technique.
- Very accurate manual picking of P- and S-phases by using coherence analysis.

The June 2006 swarm: 3D locations

- 2 – 12 June 2006.
- 111 small-magnitude events ($M_L \leq 1.8$).
- 69 events located by 3-D tomography:
(precision) vertical and horizontal formal errors < 200-250 m.
(accuracy) absolute depth errors < 400 m.

- First event recorded 3 hours after the beginning of injection.
- Closest event ~1 km distance from the well bottom.

The swarm occurs inside high-Vp,high-Vp/Vs limestones of the reservoir where fluids are injected (i.e. fractured, high pore pressure saturated limestone).



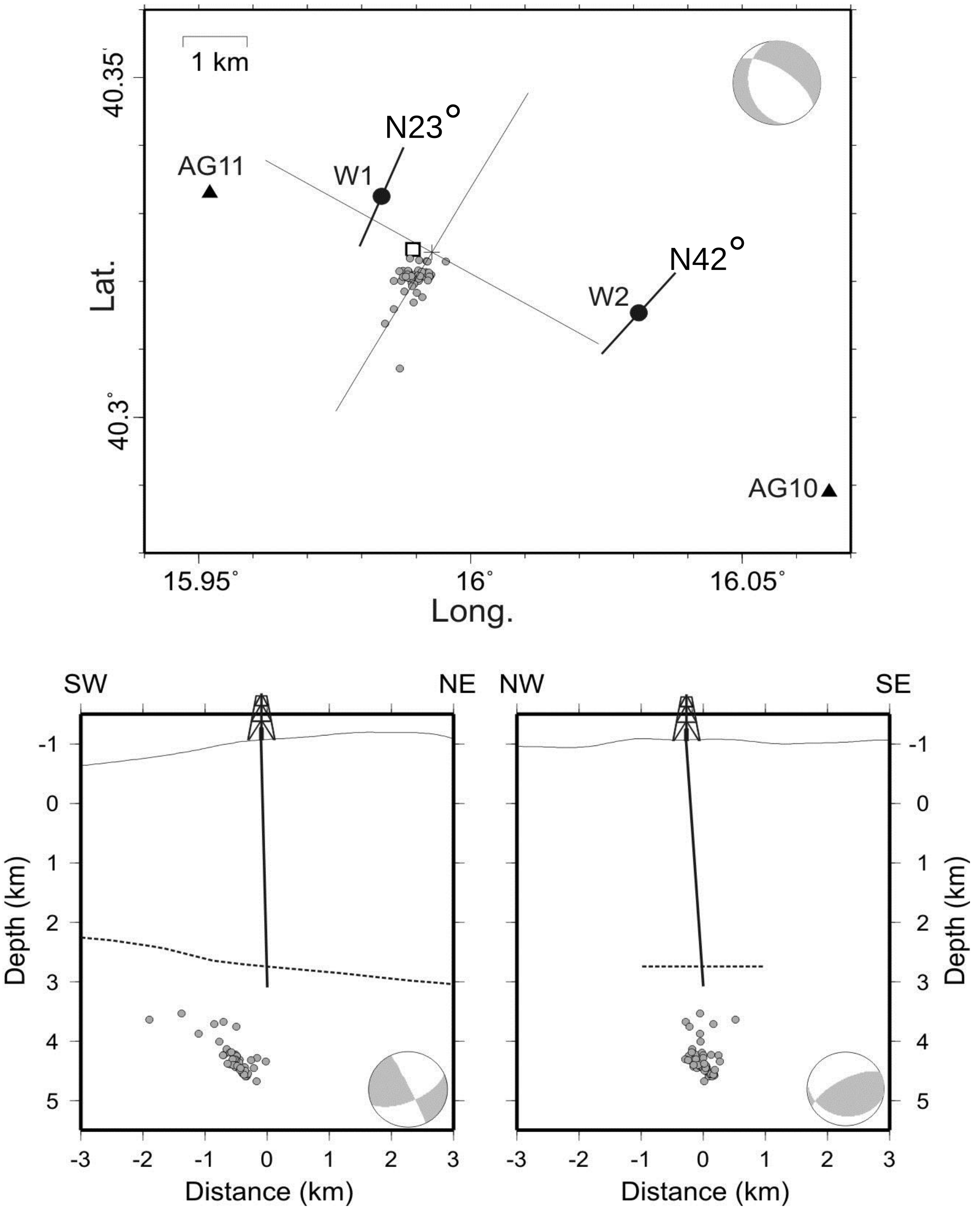
The June 2006 swarm: high-precision double-difference (DD) relative locations and focal mechanisms

❑ Hypocenters define a fault dipping ~50° to the NE.

❑ NW-SE and WNW-ESE trending normal focal mechanisms.

❑ One nodal plane of the composite focal solution is coherent with the dip of the fault.

❑ Focal mechanisms in agreement with the local extensional stress field defined by borehole breakouts (W1 and W2 define the min. horizontal stress S_{hmin}).



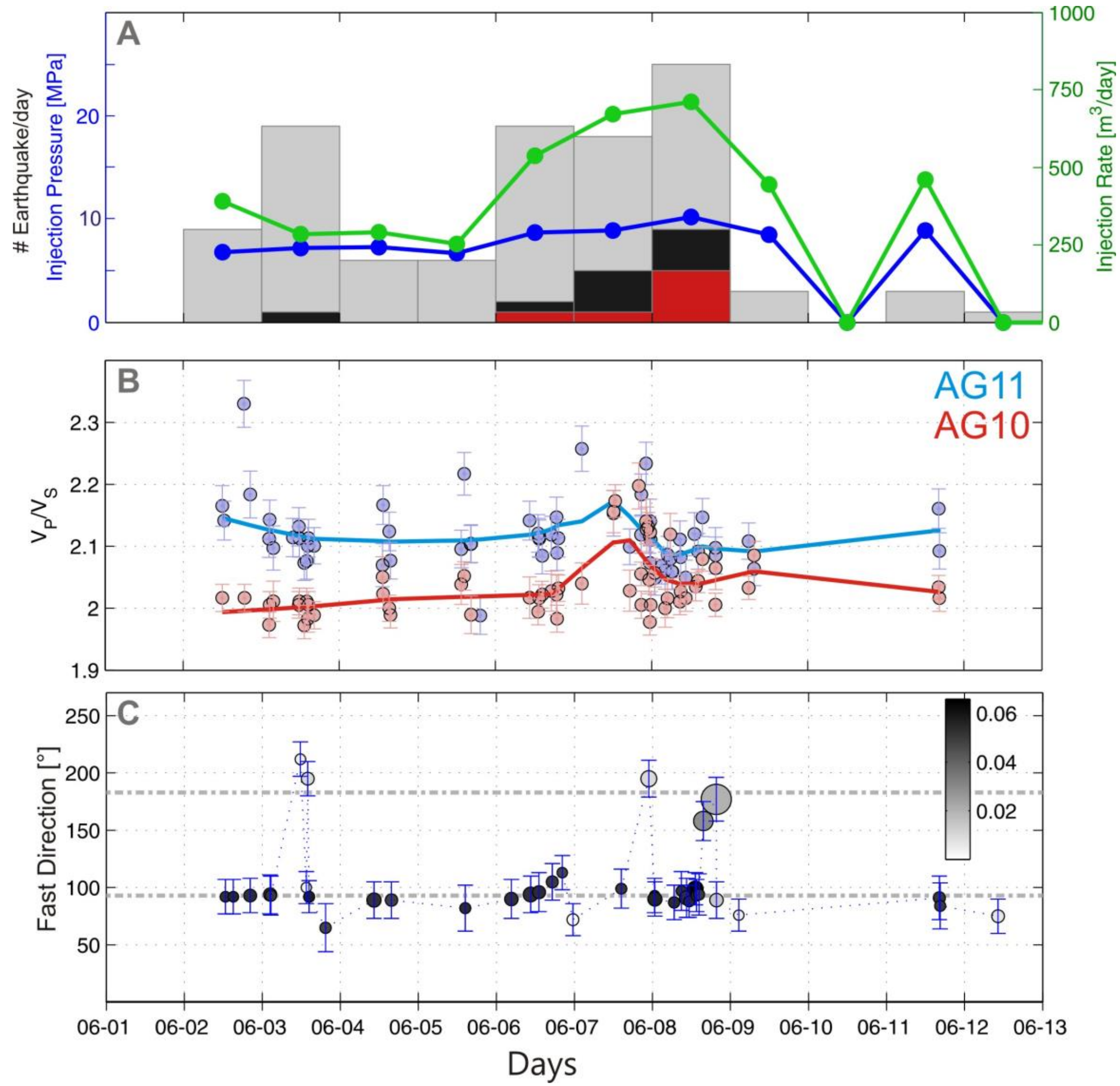
The June 2006 swarm

A – seismicity rate *vs* injection rate and well-head pressure.

- ❑ The number and magnitude of earthquakes correlate with injection activity.
- ❑ Rapid response of the system to the increase/decrease of injection parameters.

B – time series of the Vp/Vs ratio at the two stations closest to CM2 well.

- ❑ A Vp/Vs bump correlates with the increase of injection rate and pressure… build-up of pore-pressure in the saturated limestones?

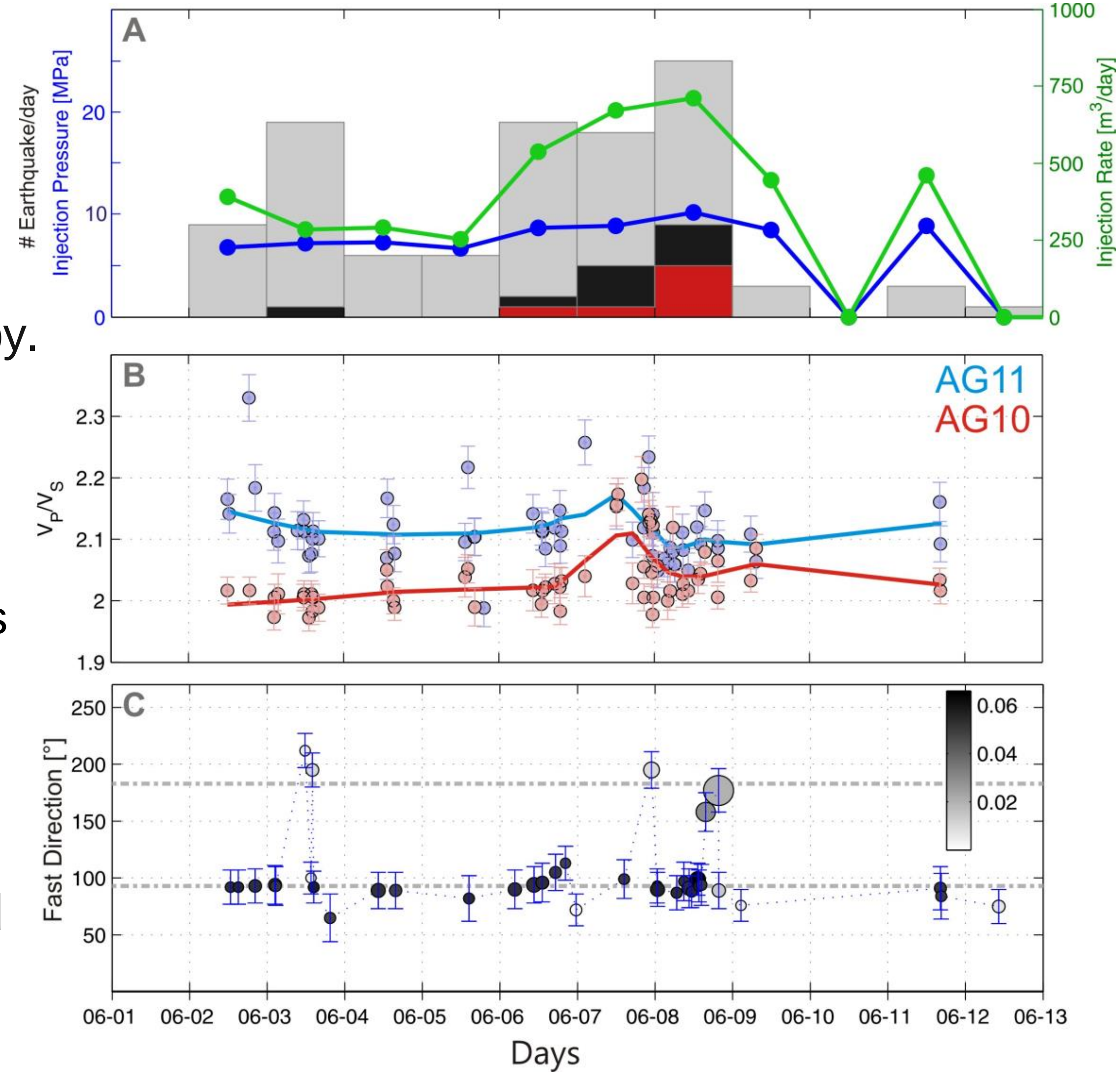


C – anisotropic parameters (polarization azimuth and delay time) by S-wave splitting analysis at the closest station.

❑ Evident S-wave crustal anisotropy.

❑ Average S-wave fast direction (N100°) almost orthogonal to the minimum horizontal stress (S_{hmin} = N23°) inferred by breakouts from the closest well.

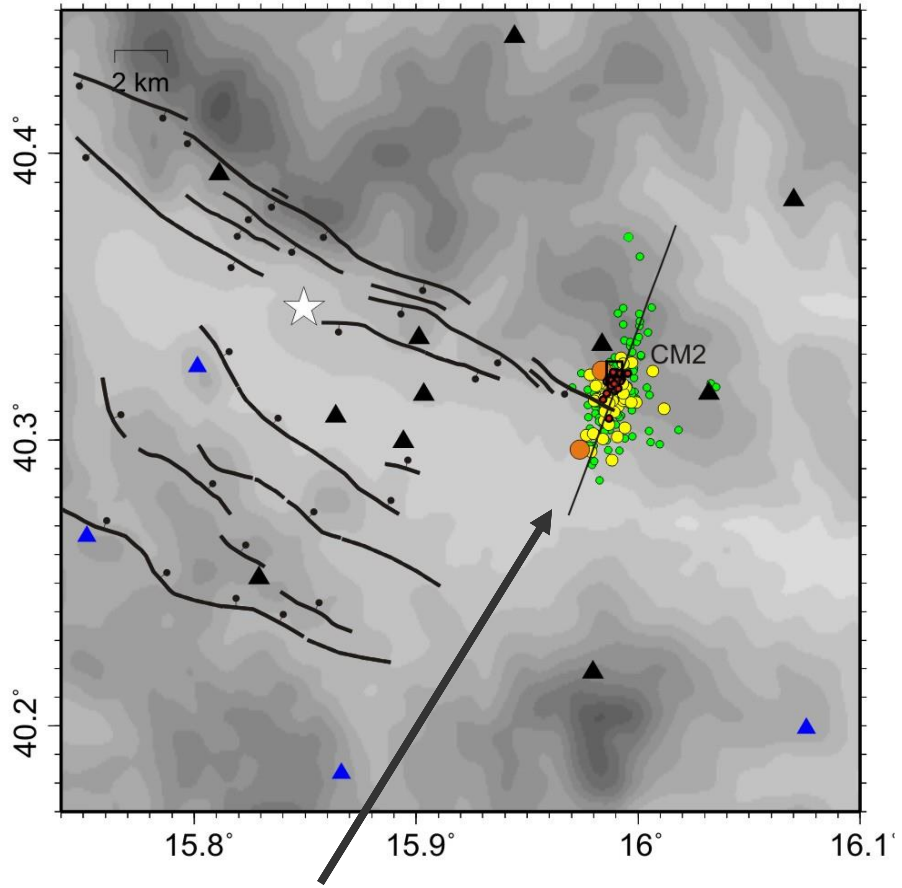
S-wave anisotropy suggests the presence of open and fluid-filled fractures striking WNW-ESE and aligned by the local extensional stress field.



Induced Seismicity related to the long-term injection activity (June 2006 – December 2013)

- ENI oil company monitoring network (**trigger mode**, 11 stations).
- INGV permanent stations (4 stations).
- Seismicity re-located in the 3-D tomographic model.
- vertical and horizontal formal errors: < 300-400 m.

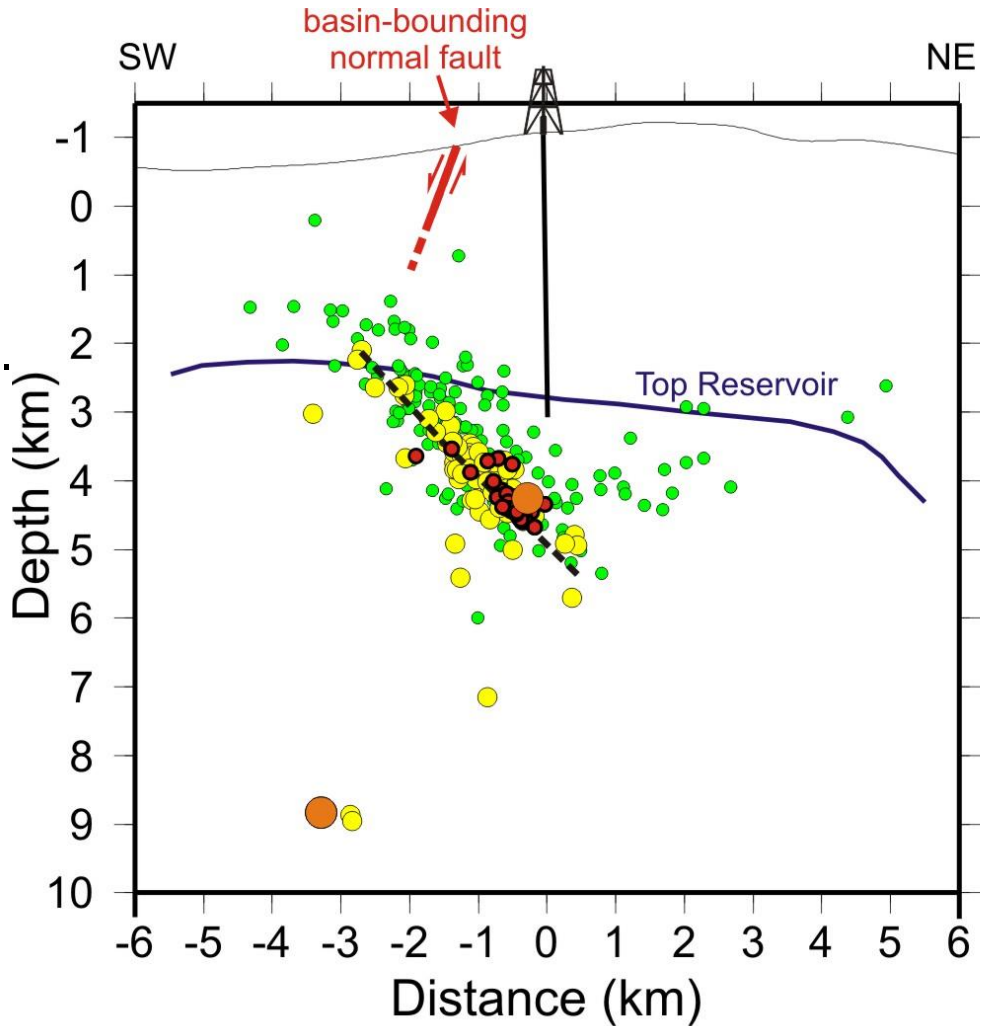
- 219 earthquakes ($M_L \leq 2.2$) within 5 km of the injection well.
- Magnitude completeness Mc ~ 1.2.



3-D re-located earthquakes recorded by ENI (black) and INGV (blue) stations (orange $M_L \geq 2$, yellow $1 \leq M_L < 2$, green $M_L < 1$).

Induced Seismicity related to the long-term injection activity (June 2006 – December 2013)

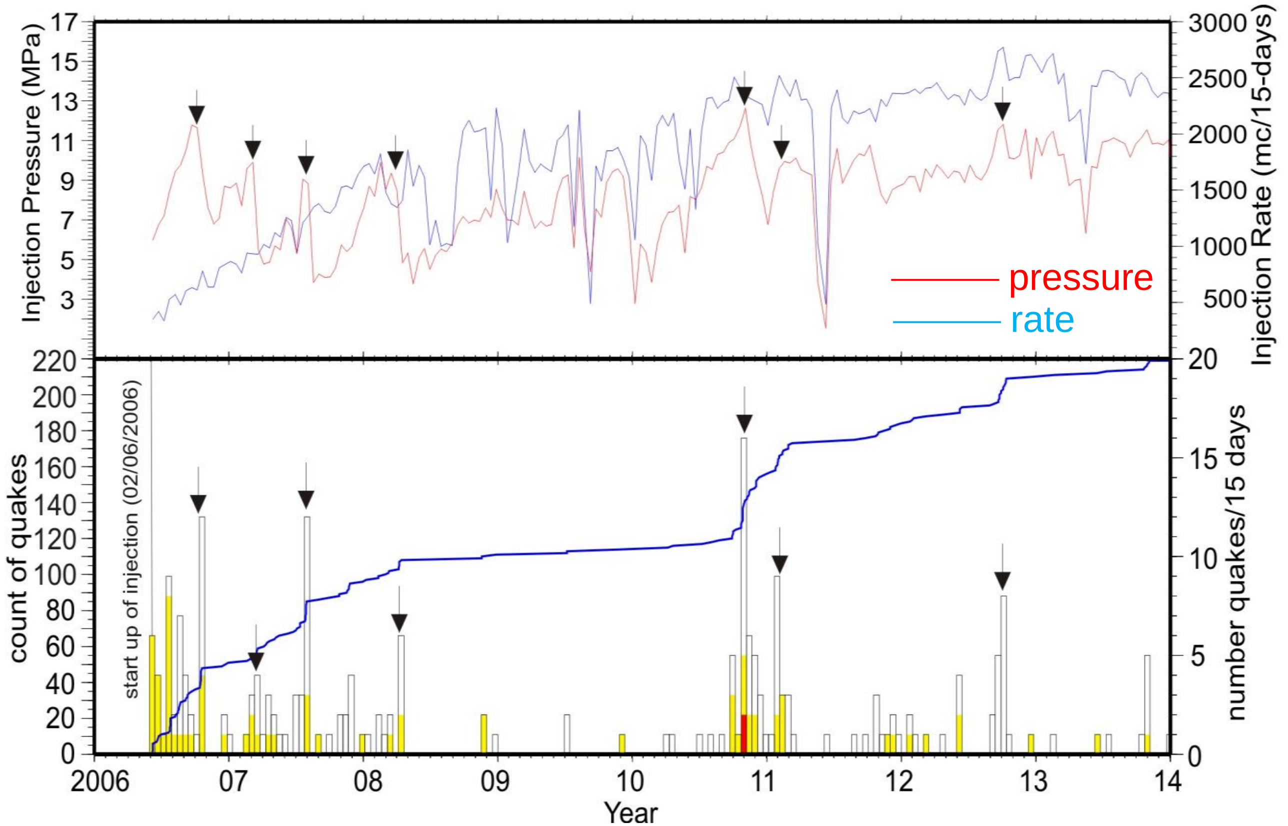
- The micro-seismicity defines a pre-existing fault dipping ~50° to the NE between 2.0-5.5 km depth.
- The June 2006 swarm concentrates along the lower part of the fault (red dots).
- The lower tip of the fault is located beneath the well bottom, 2 km deeper.
- The fault appears confined in the carbonate reservoir.
- No structural relationship with known Quaternary normal faults.



Induced Seismicity related to the long-term injection activity (June 2006 – December 2013)

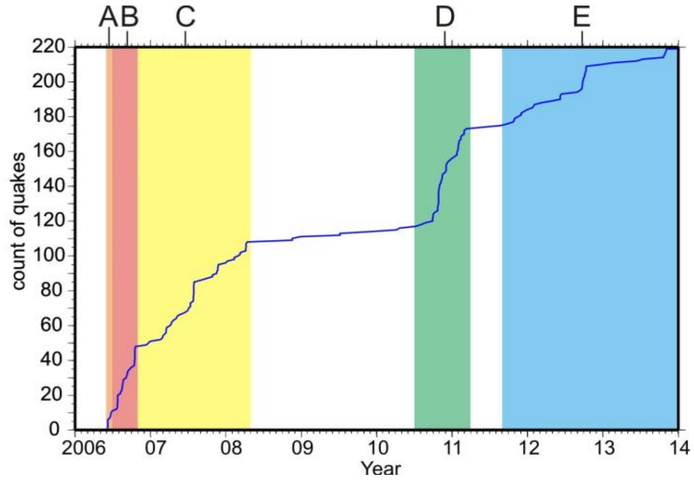
Seismicity Rate *vs* Injection Data

- Highly variable seismicity rate.
- Variable injection parameters.
- Swarms correlate to periods of high injection pressure.
- Two main swarms in 2006 and 2010 when the injection pressure was at its maximum (13-14 MPa).



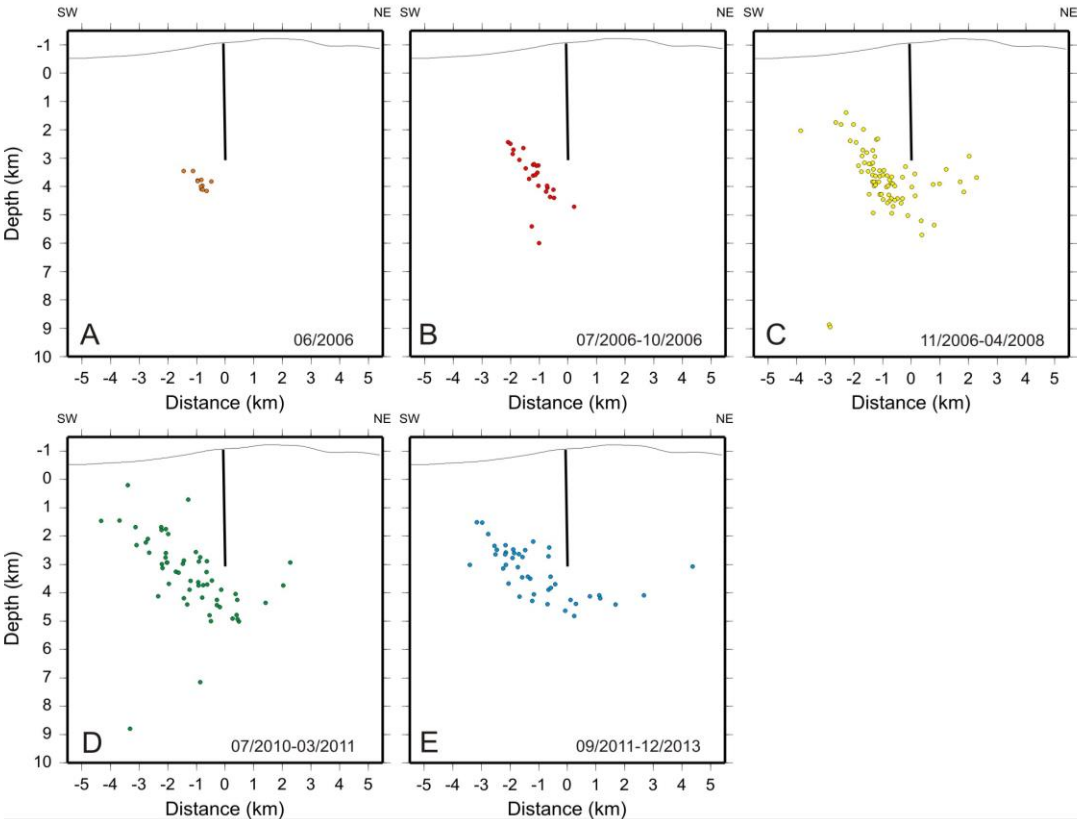
Top: injection rate (blue line) and well-head pressure (red line). Bottom: cumulative curve and number of events per 15 days (white = all events, red = $M_L \geq 2.0$, yellow $1 \leq M_L < 2.0$).

Induced Seismicity related to the long-term injection activity (June 2006 – December 2013)

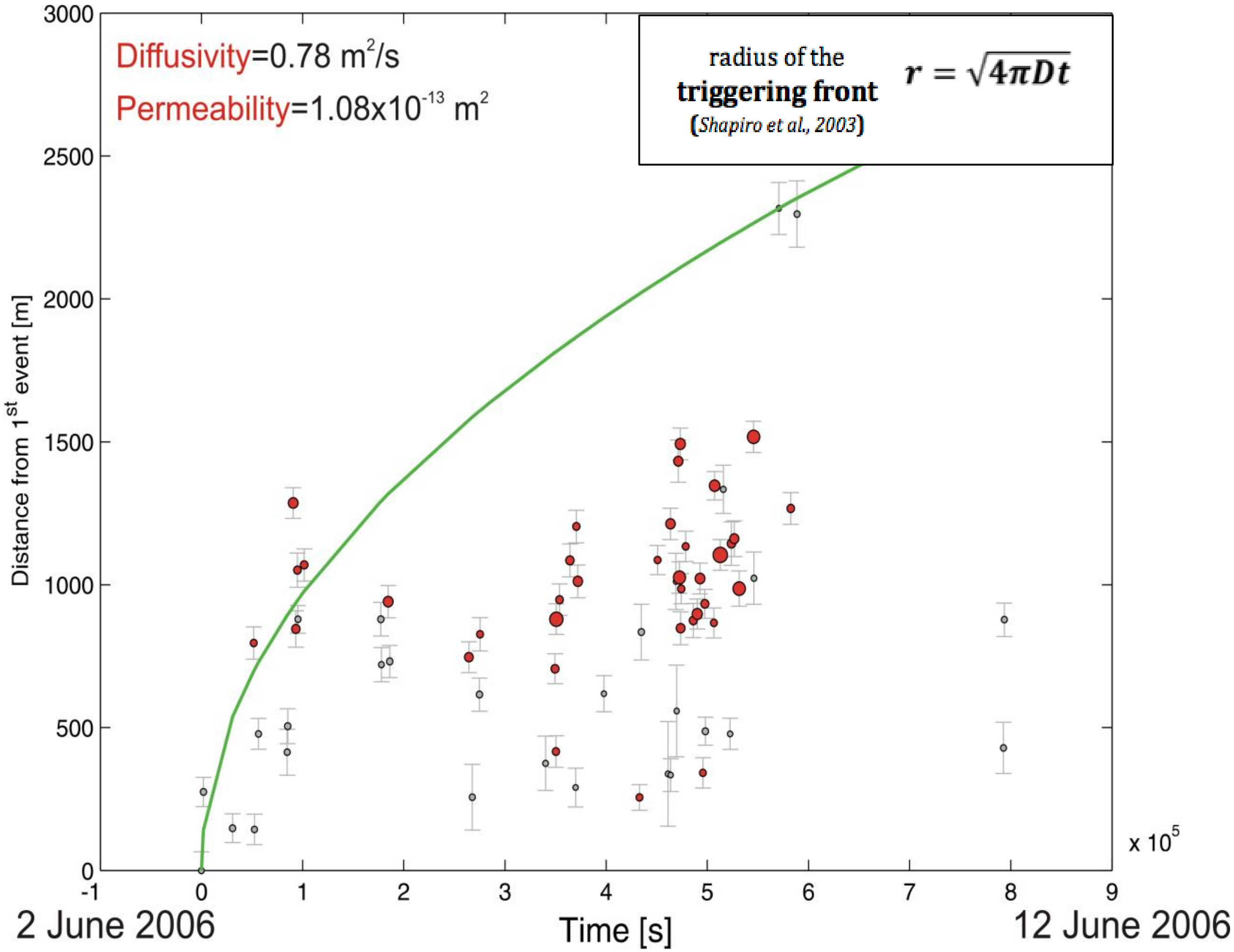


Spatiotemporal Evolution

- ❑ Migration of seismicity along the NE-dipping fault.
- ❑ The volume grew rapidly during June-October 2006 (up to 3 km).
- ❑ Seismicity continued to migrate southwestward and northeastward through 2007-2008 (up to 5.5 km).
- ❑ Seismicity "stabilized" since April 2008.



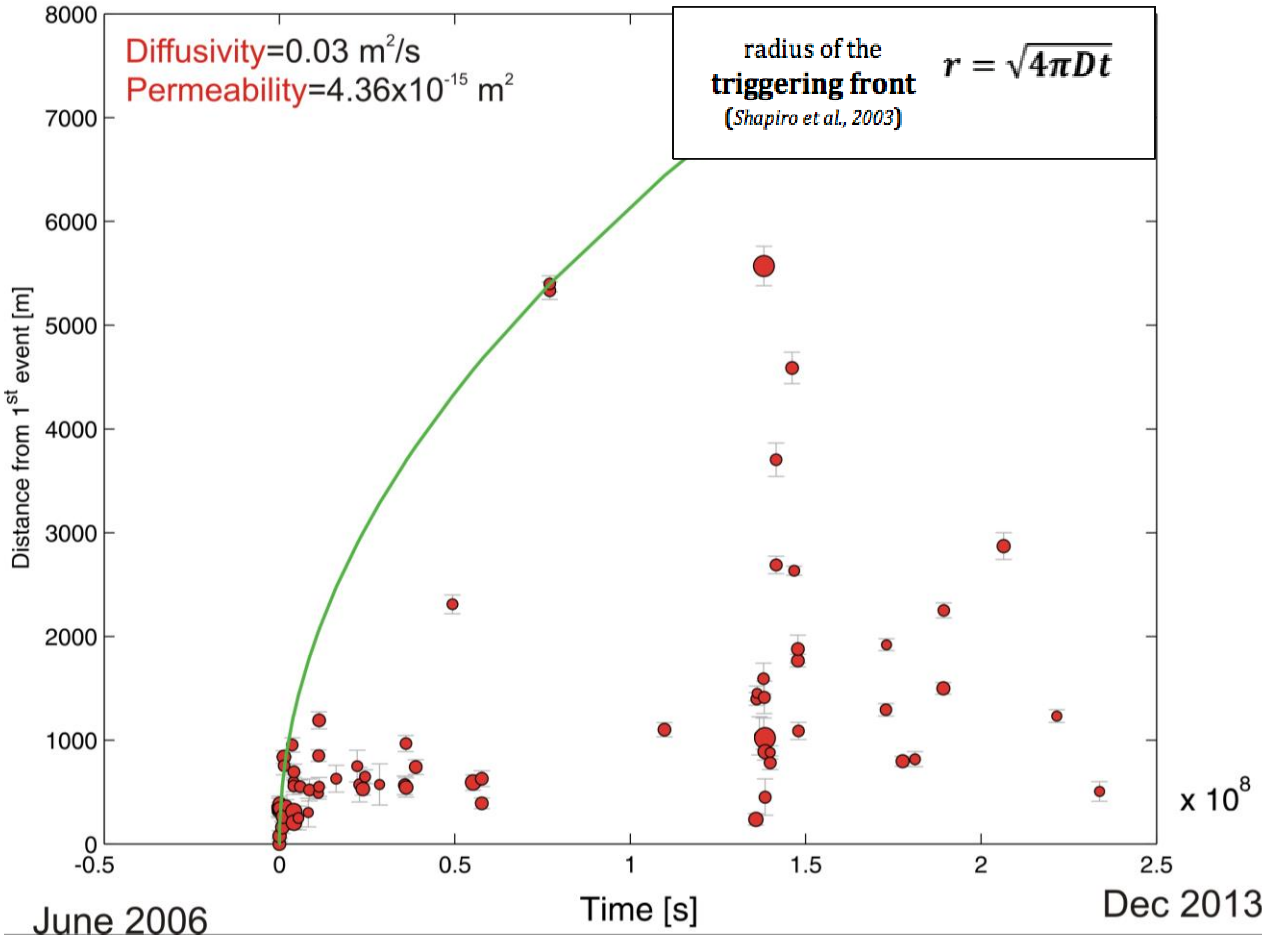
Hydraulic Diffusivity
June 2006 swarm



- Triggering front parabolic solution to fit the spatiotemporal distribution of seismicity.
- 90% of the seismicity agrees with an isotropic hydraulic diffusivity of 0.78 m^2/s.
- Equivalent permeability $k = 1.08\times10^{-13}\ m^2$.

Hydraulic Diffusivity 2006-2013 Data

- ❑ Hydraulic diffusivity $D = 0.03\ m^2/s$.
- ❑ Equivalent permeability $k = 4.36\times10^{-15}\ m^2$.



- ❑ Does the diffusivity decrease with time?
- ❑ Drawbacks:
  - injection parameters are highly variable with time.
  - the two catalogues have different magnitude completeness.

Conclusions

- The CM2 well induces micro-seismicity since the first day of injection.
- Rapid response of the system to changes in the injection parameters.
- Main swarms relate to peaks in the injection pressure.

- Normal-faulting events nucleate on fractures of a pre-existing fault-zone optimally oriented with respect to the local extensional stress field.

- The quick onset and migration of seismicity during the first stage of injection point to a rapid propagation of the pore pressure perturbations within an intensely fractured and saturated fault-zone.

- The high permeability ($k = 10^{-15}$ to 10^{-13} m^2) inferred by hydraulic diffusivity is coherent with the high productivity of the reservoir and with hydraulic well-tests.

- Future steps: hydrologic modelling.

Acknowledgements

This research was partially supported by the Project "Studi e rilevamenti in campo geofisico, sismologico e geochimico in Val d'Agri" under the agreement between ENI company and INGV.

We acknowledge the management of ENI E&P Division for providing fluid injection data and seismic data of the monitoring network, and ENI scientists for useful discussions on the monitoring of the oil field and on the reservoir characterization.