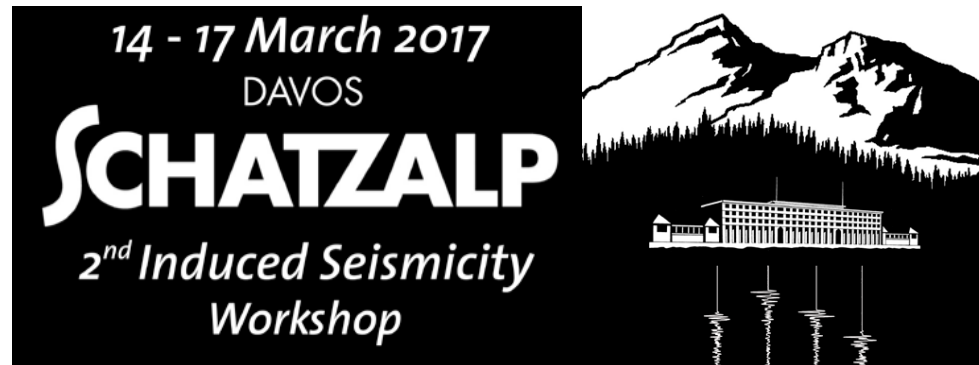
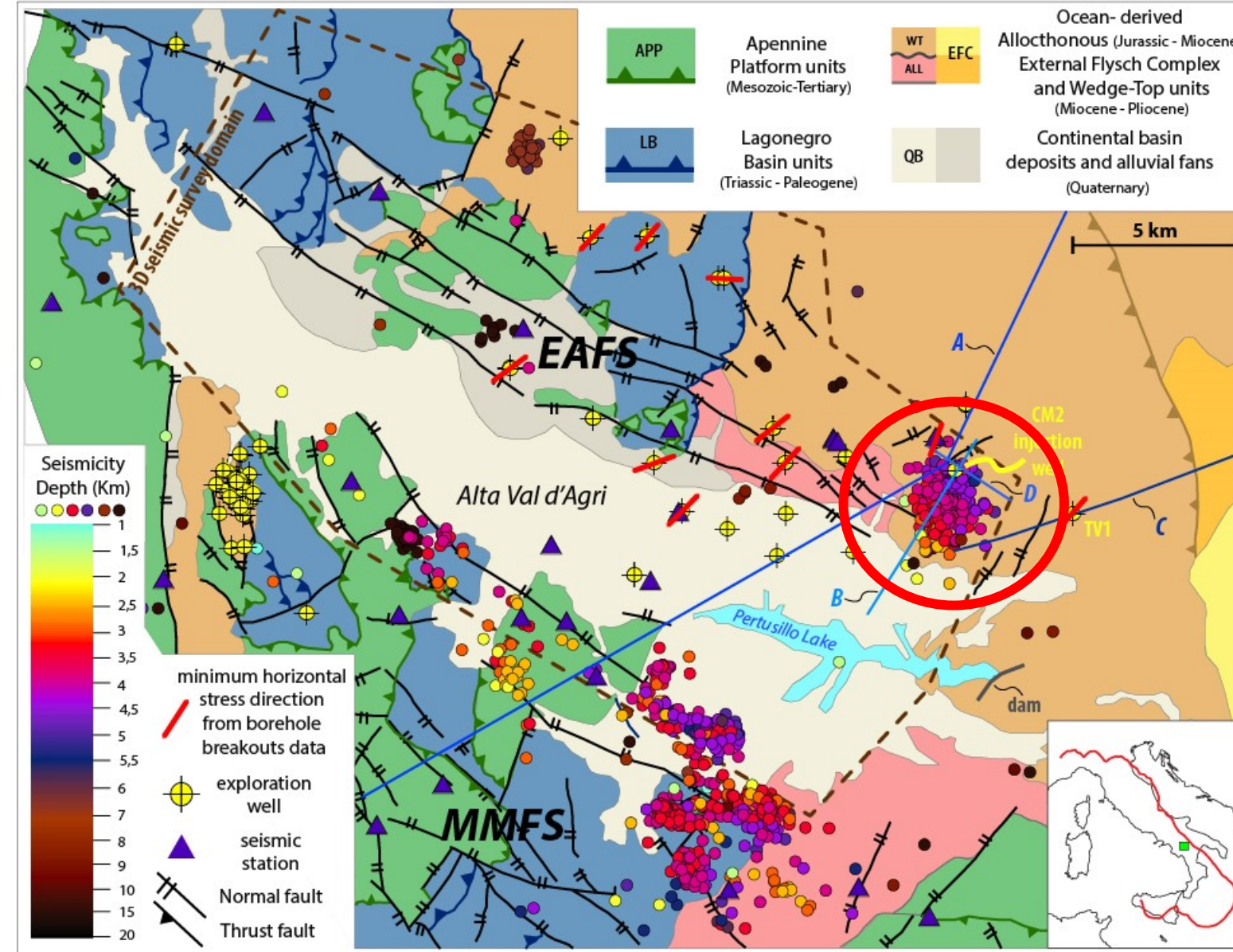


# Kinematic inversion of pre-existing faults by wastewater injection-related induced seismicity: the Val d'Agri oil field case study (Italy)

Buttinelli M., Improta L., Bagh S., Chiarabba C.



# The Val d'Agri (VdA) Oilfield



Southern Apennine - seismic area (Mw7 earthquake in 1857)

**The largest onland oilfield in Europe**

Oil from a fractured limestone reservoir (90,000 bbl/day with 3,000 m<sup>3</sup>/ day of formation waters)

Since June 2006, wastewaters are re-injected through the **Costa Molina 2 (CM2) high rate well, inducing microseismicity (MI < 2.2)**

SW seismicity was associated to the Pertusillo impoundment

Buttinelli et al., 2016

# The Val d'Agri geology

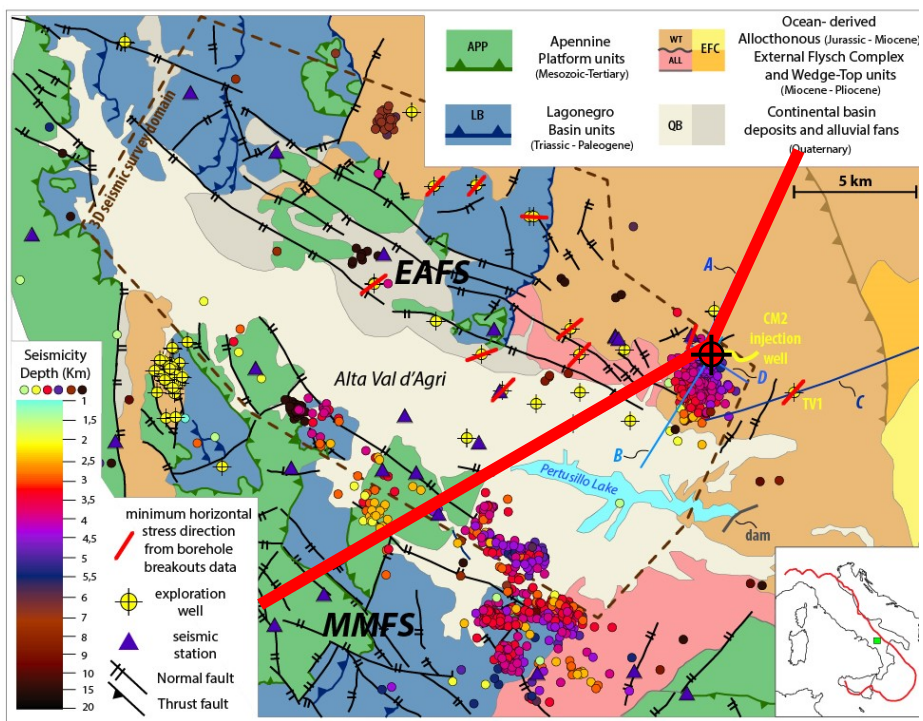


Very complex geologic structure due to a polyphasic tectonic evolution

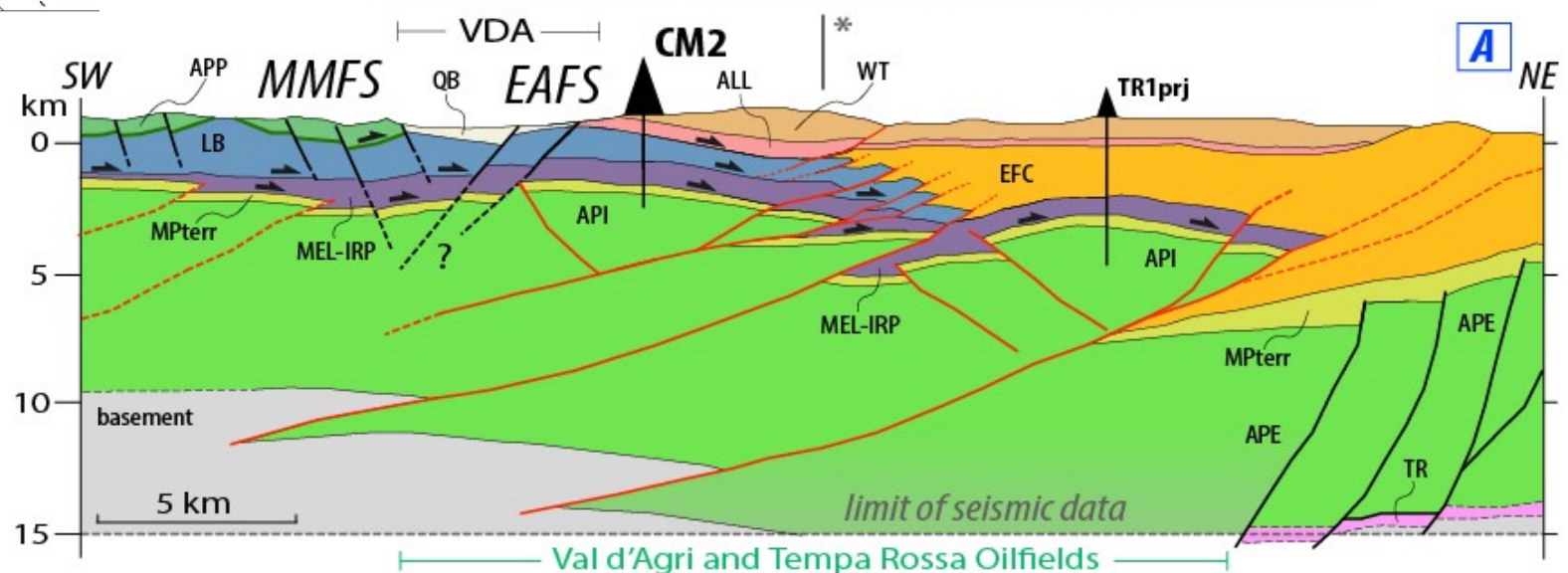
Deep structures: Mio-Pliocene **NE-verging thrust-related-fold systems (the oilfield structural traps)** sealed by a clayey **mélange layer (caprock)**

Quaternary extension → the VdA basin.

Shallow structures: NW-SE Quaternary **extensional fault systems (MMFS, EAFS)**



Buttinelli et al., 2016

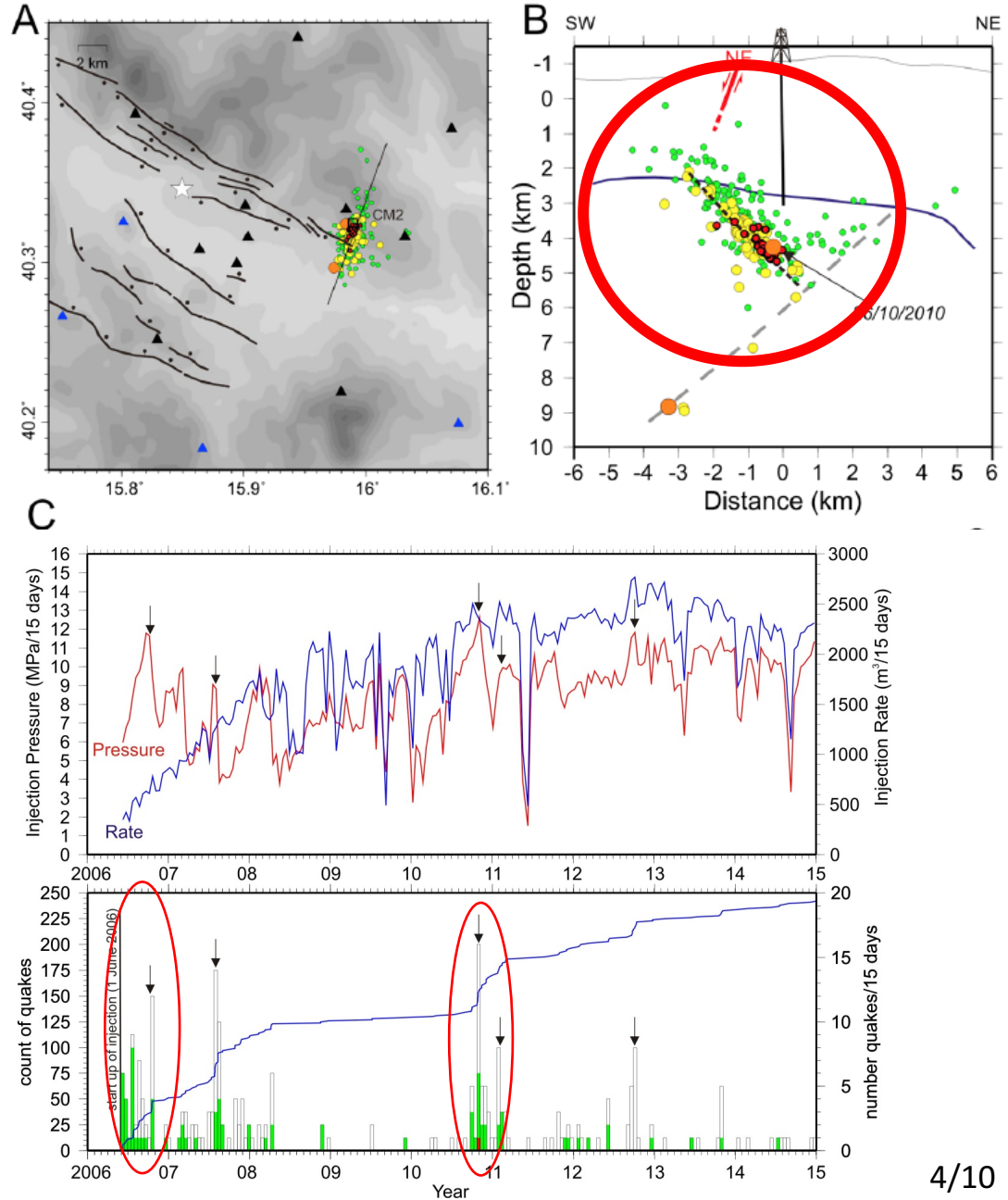


# 2006-2014 Induced MicroSeismicity

- ❑ **A first swarm** (69 events,  $M_L \leq 1.8$ ,  $M_c=0.4$ ) recorded by a temporary dense network operated by INGV **during the first injection tests** in June 2006
- ❑ **2006-2014 Swarm-seismicity** (248 events,  $M_L \leq 2.2$ ,  $M_c \sim 1.0$ ) recorded by the trigger-mode local network run by the oilfield operator (Eni S.p.A.)
- ❑ **Hypocenters delineate a a  $\sim 50^\circ$  NE-dipping plane.**
- ❑ Seismicity within 5 km of CM2 correlate with injection pressure.
- ❑ Seismicity rate strongly declined over the last 3 years (no events after 2015).

## WHAT IS THE RELATIONSHIP BETWEEN INDUCED EQKS AND THE GEOLOGICAL STRUCTURE?

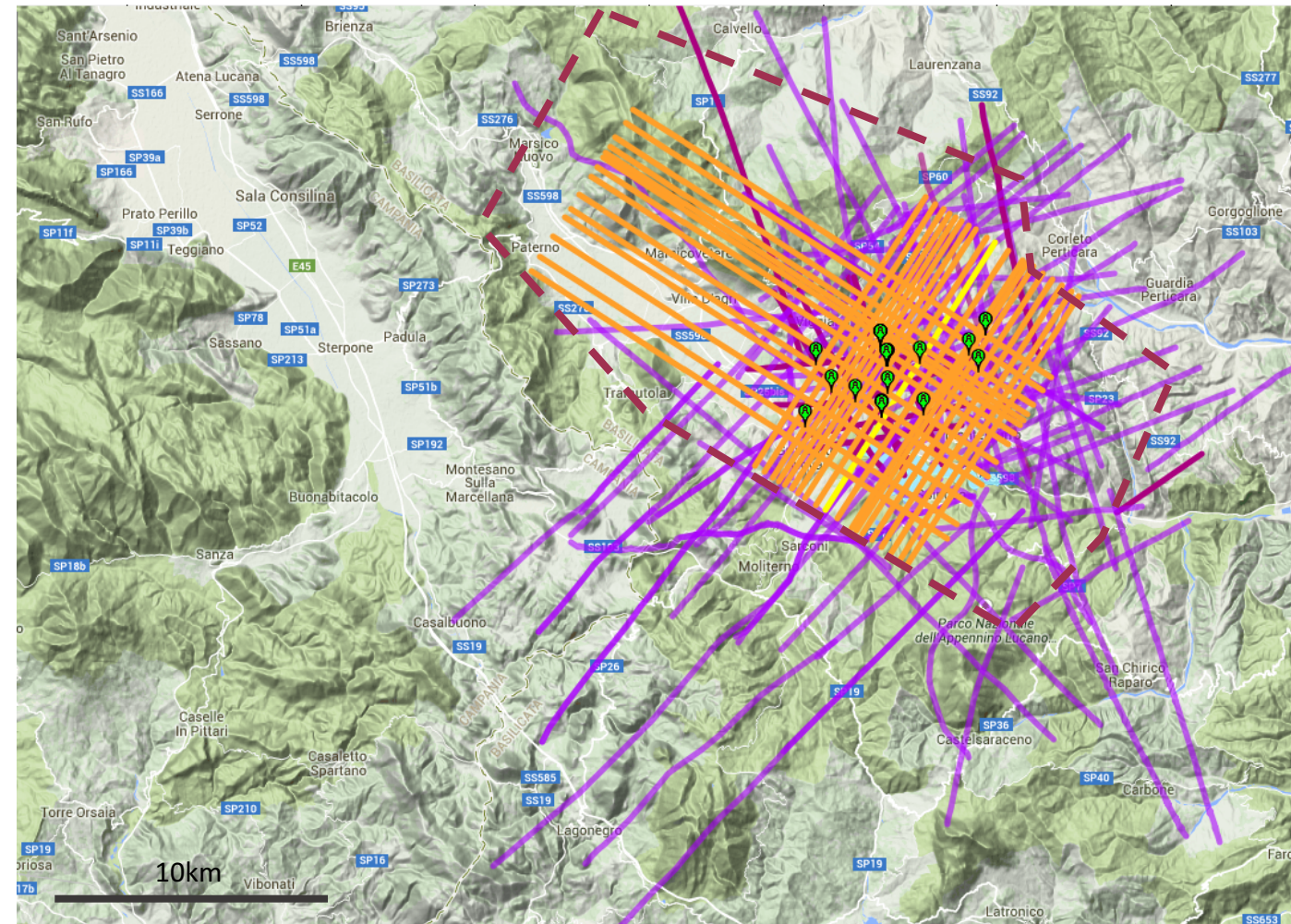
Improta et al., 2015

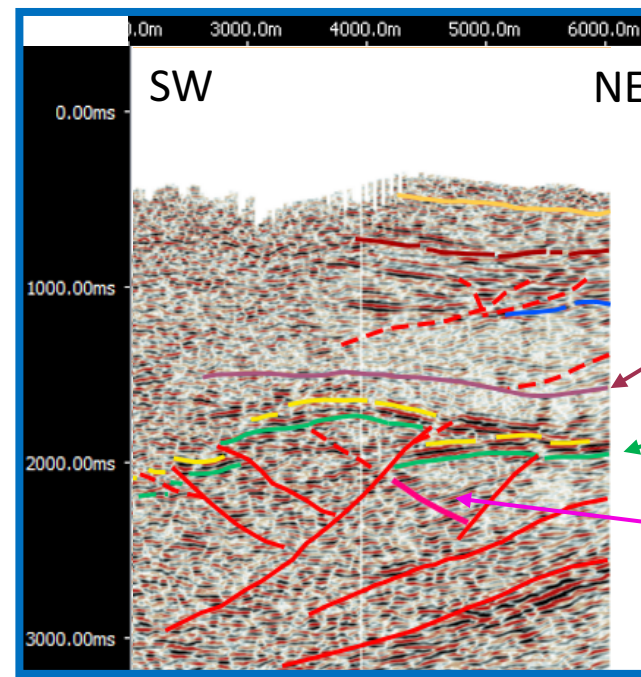
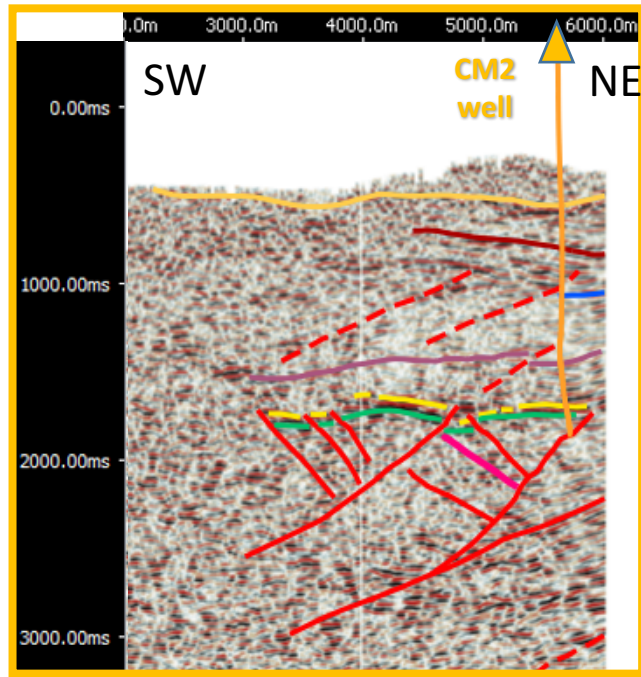
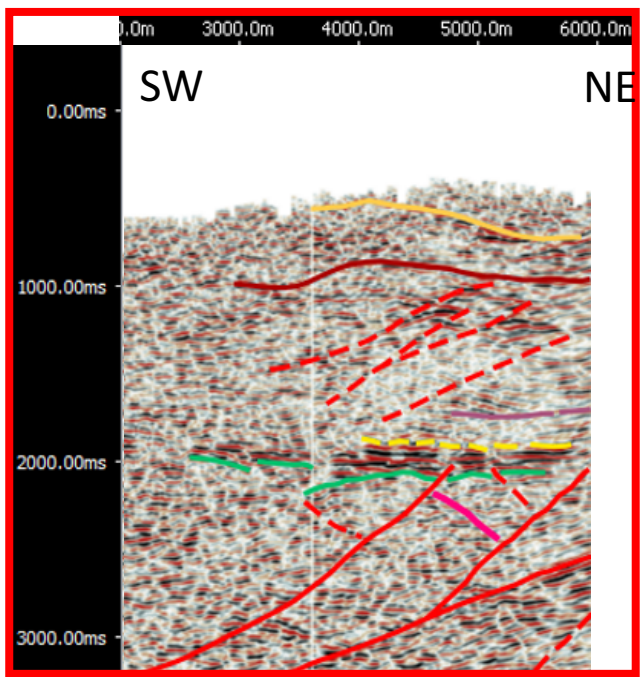




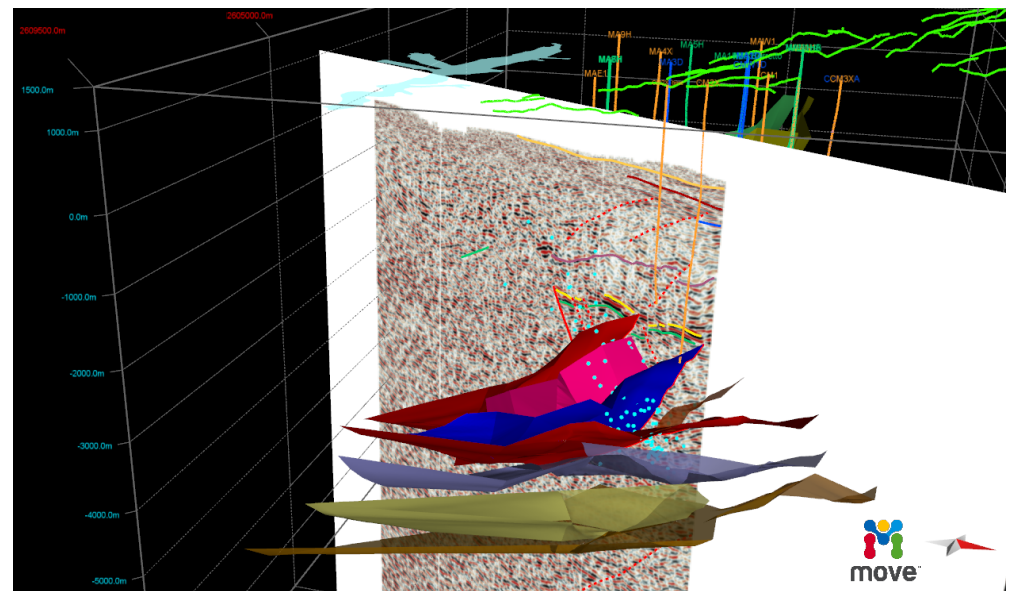
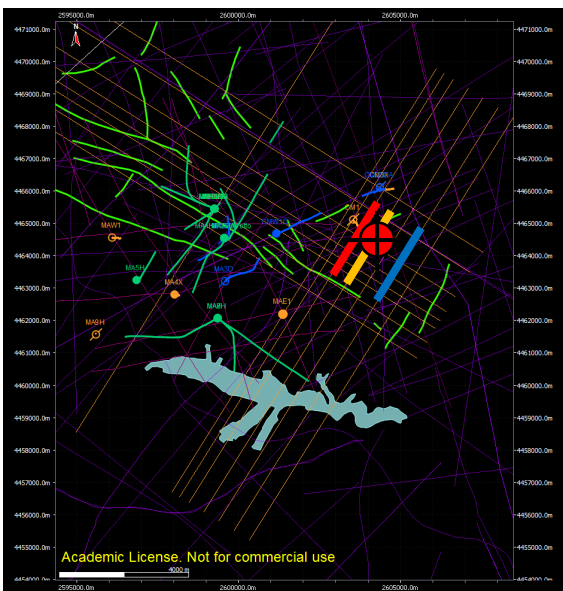
## 3-D structural model of the injection reservoir

- 595 km<sup>2</sup> 3D seismic survey (2D slices in orange)
- 153 2D seismic profiles
- 24 wells with geophysical logs (13 in the injection area)
  - ✓ stratigraphic constraints for horizons interpretations and seismostratigraphy, faults interpretation,
  - ✓ velocity models for the depth conversions,
  - ✓ borehole breakouts for stress direction analysis)





Top m $\grave{e}$ lange layer  
Top injection reservoir  
NE-dipping backthrust aligned with IS

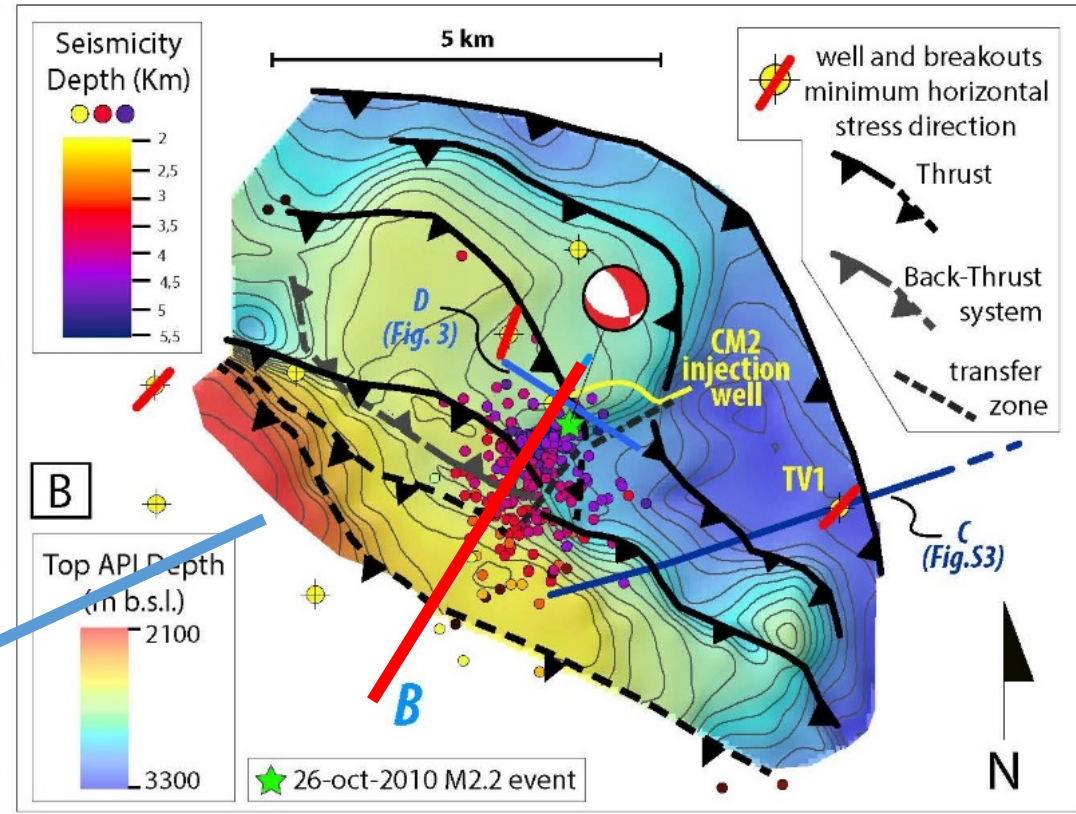
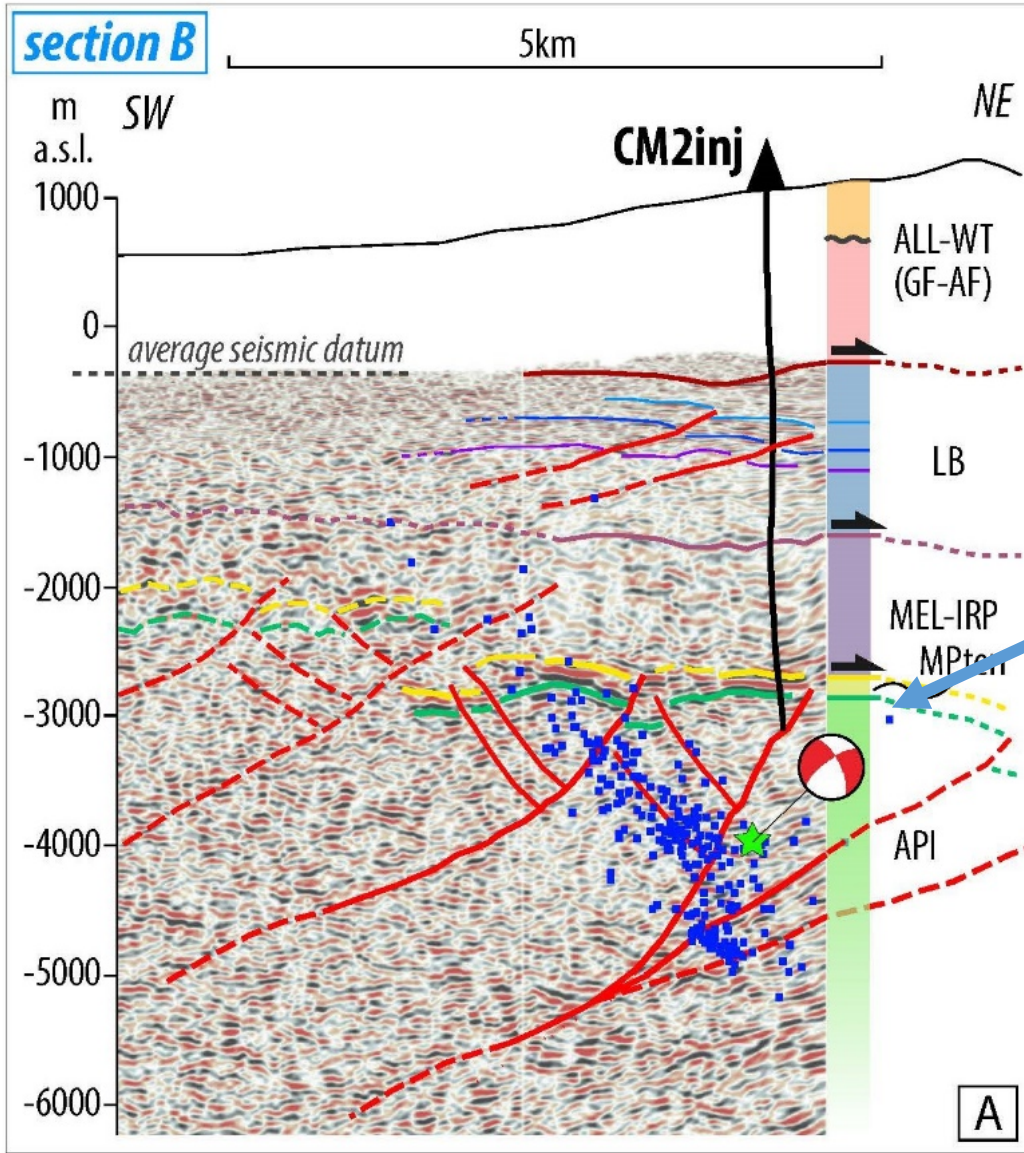


## THE INJECTION STRUCTURE

- 10 km-large blind thrusts and back-thrusts system ending into the m $\acute{e}$ lange layer
- **No evidence of large normal faults**
- Eqks correlate with a portion of a back thrust (pink line/surface laterally developed for 5 km)



# 3-D Crustal model vs. IS



TOP RESERVOIR  
STRUCTURAL  
MAP

**IS mostly within the reservoir** (few eqks within the sealing)

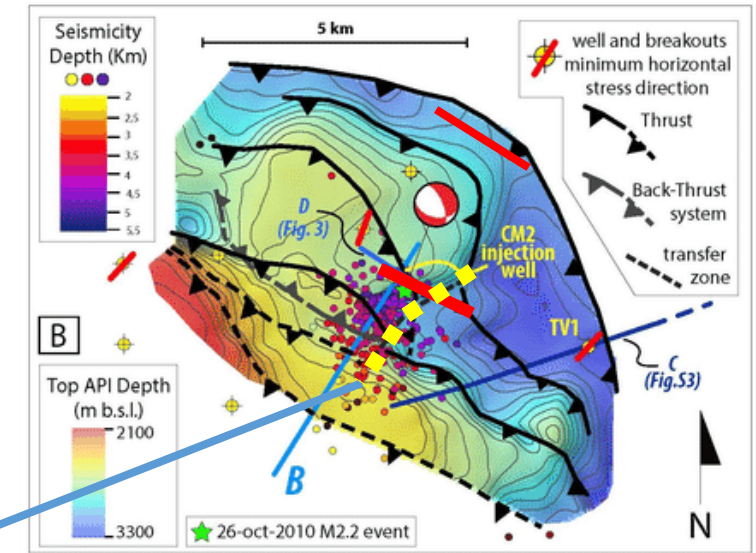
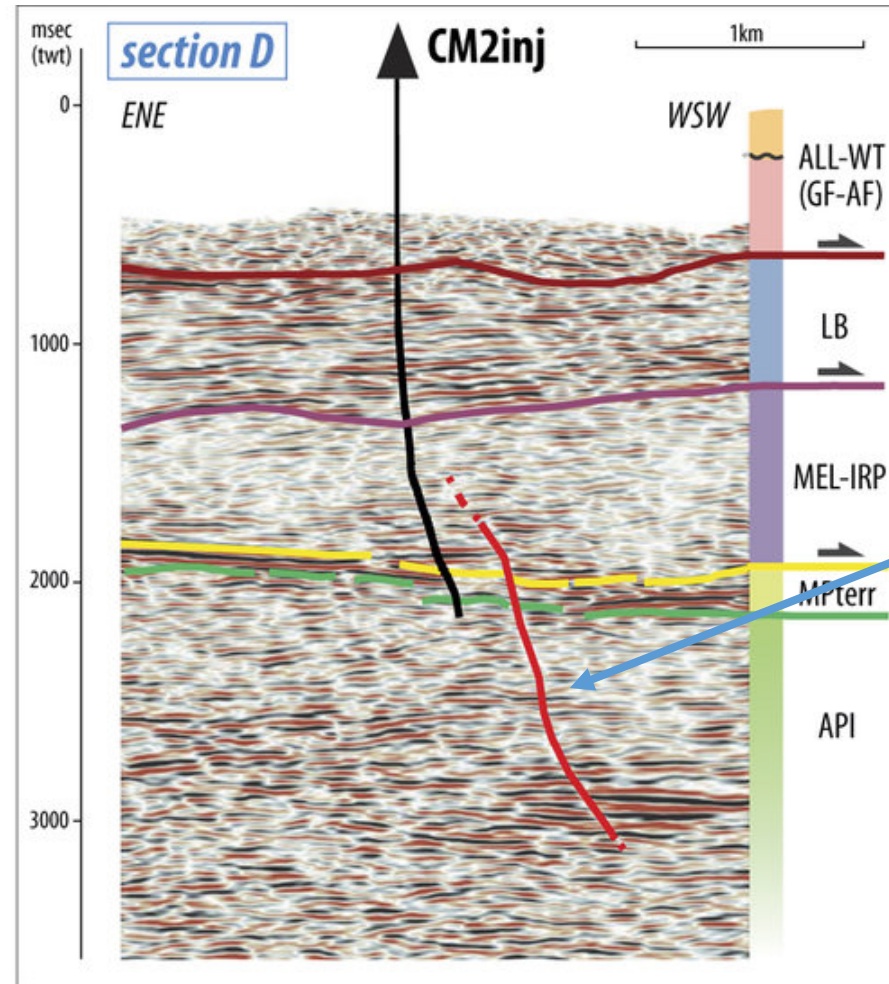
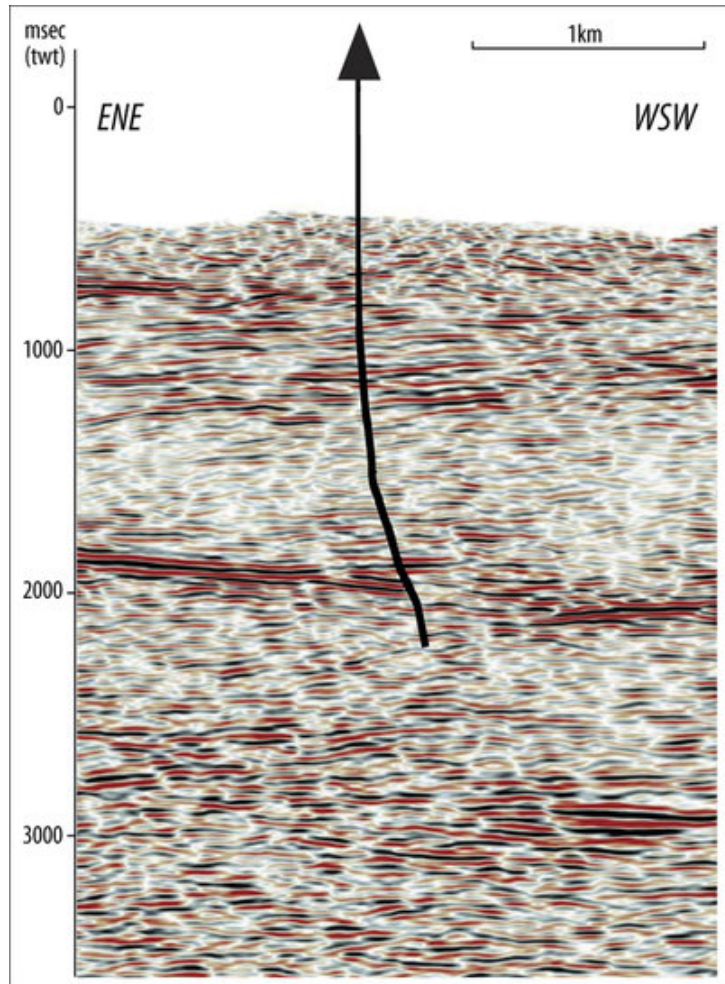
IS between 2-5 km compatible with an inherited back-thrust

Only a 2.5 km-large **portion of the back-thrust was reactivated in extensional domain** (kinematic invertson) because **favorably oriented within the present stress field** (minimum horizontal stress by borehole breakouts)

reservoir is shallower to the west (< 2500 m) and deeper to the east (> 3000 m)

→ **vertical structure / 2 compartments?**

# A possible vertical flow barrier



Sub-vertical transverse fault of the inherited thrust system

The fault ends up in the mélangé layer

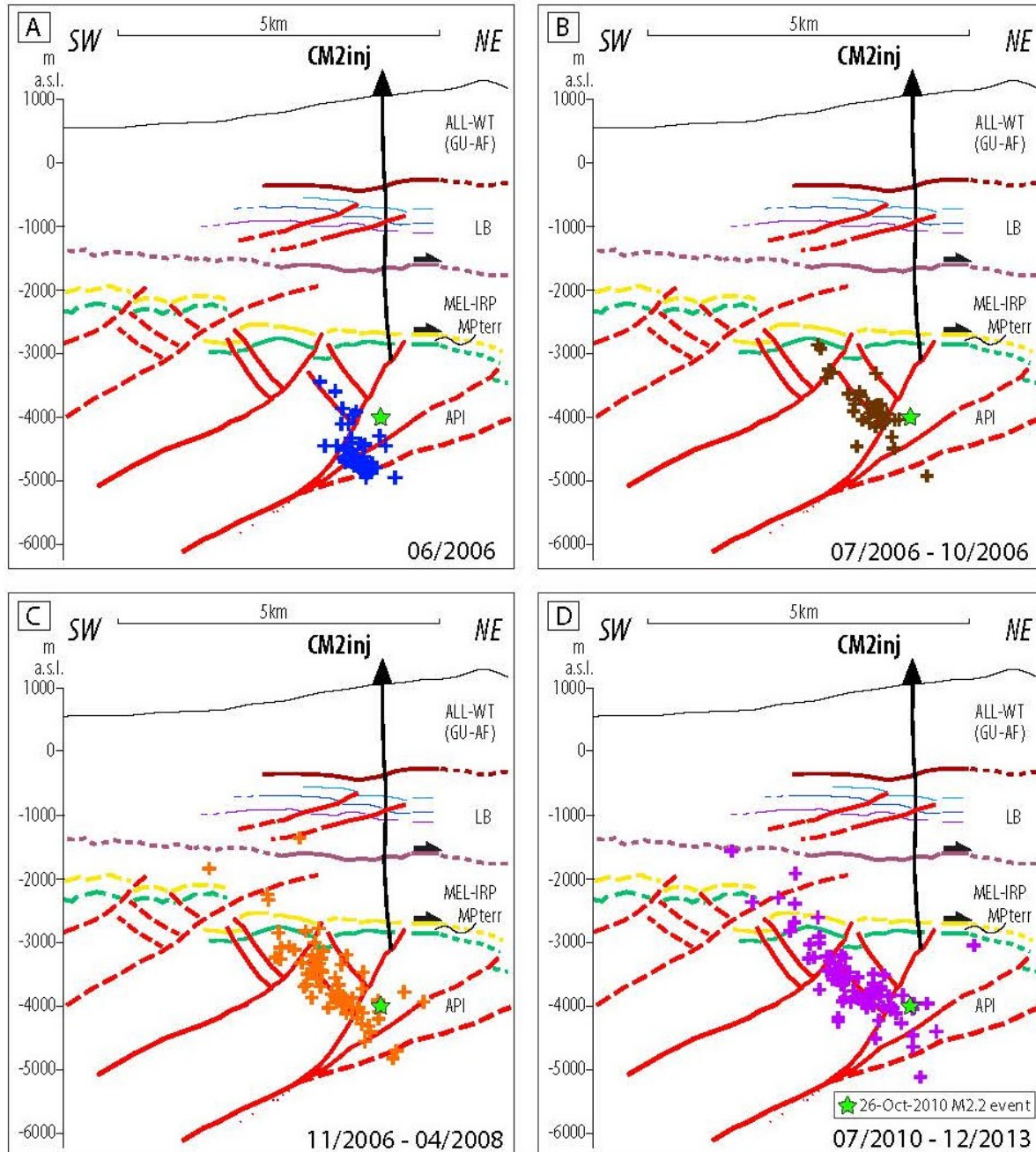
**Induced eqks due to pore pressure perturbations propagating through the back-thrust**

**The vertical fault possibly acted as a flow barrier favoring further pressurization**

Buttinelli et al., 2016



# Migration of induced eqks



- **IS migrated** upward rapidly from 5 km to 2.5 km depth along the back-thrust.
- **Event migration halted after 2008.**
- **Upward migration was hampered** by the low permeability mélange layer.
- **Downward migration was hindered** by the lowermost thrust or the lower units consisting of low permeable Triassic anhydrites ( $k=10^{-21}-10^{-18} \text{ m}^2$ )
- **The fracture permeability** of the fault-zone inferred by hydraulic diffusivity is **high, in the order of  $k=10^{-13} \text{ m}^2$ .**

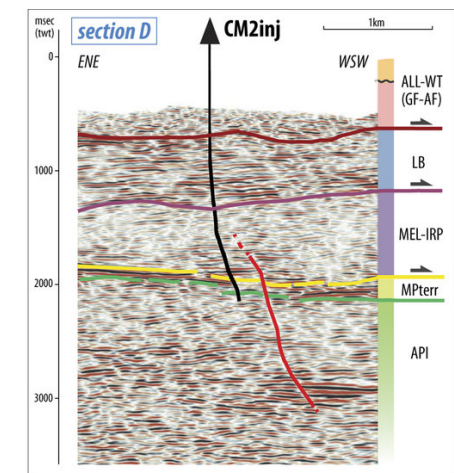
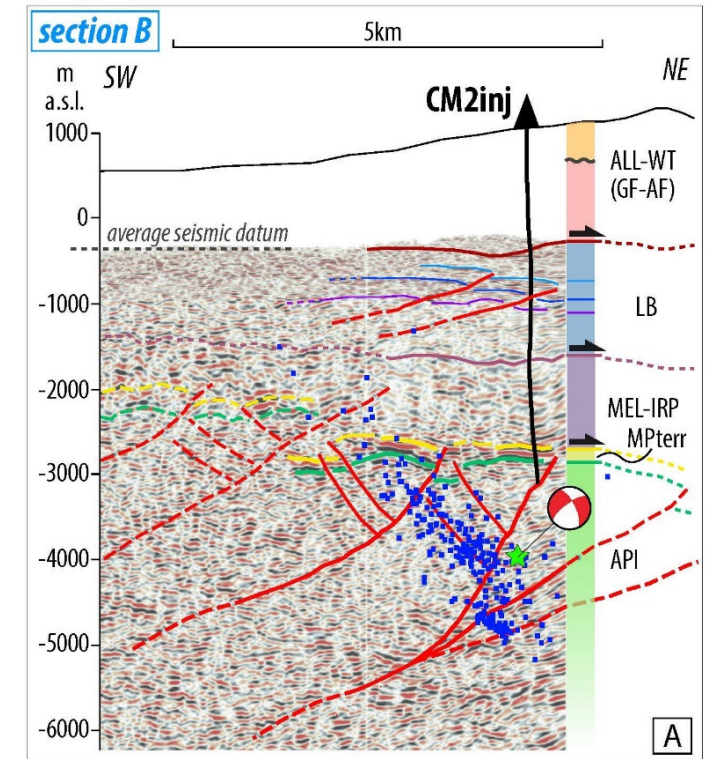
Buttinelli et al., 2016

# ...resuming

- ✓ Wastewaters re-injected by CM2 induced microseismicity ( $M_{i,max} < 2.2$ ) between 2006 and 2014. No IS after 2015
- ✓ We were able to understand the relationships between IS and geological structures reviewing a massive dataset of underground data
- ✓ IS inverted the kinematic of an inherited back-thrust, with no direct relationship with the large scale normal faults of VdA basin. Recent normal faults and older compressive faults have the same trend.
- ✓ IS repeatedly reactivate small portions (< 200 m) of the back-thrust optimally oriented within the present day stress field
- ✓ A transverse vertical fault to the SW of CM2 played a major role acting as a flow barriers, possibly causing a further and more rapid pressure increase in the injection volume.
- ✓ IS was hampered above and below the reservoir by low permeability formations
- ✓ The driving mechanism: 1) Propagation of pore-pressure pulses by an efficient network of conductive fractures in a water-saturated reservoir 2) channelling of pore-pressure perturbations through a high permeable fault zone acting as a fluid pathway

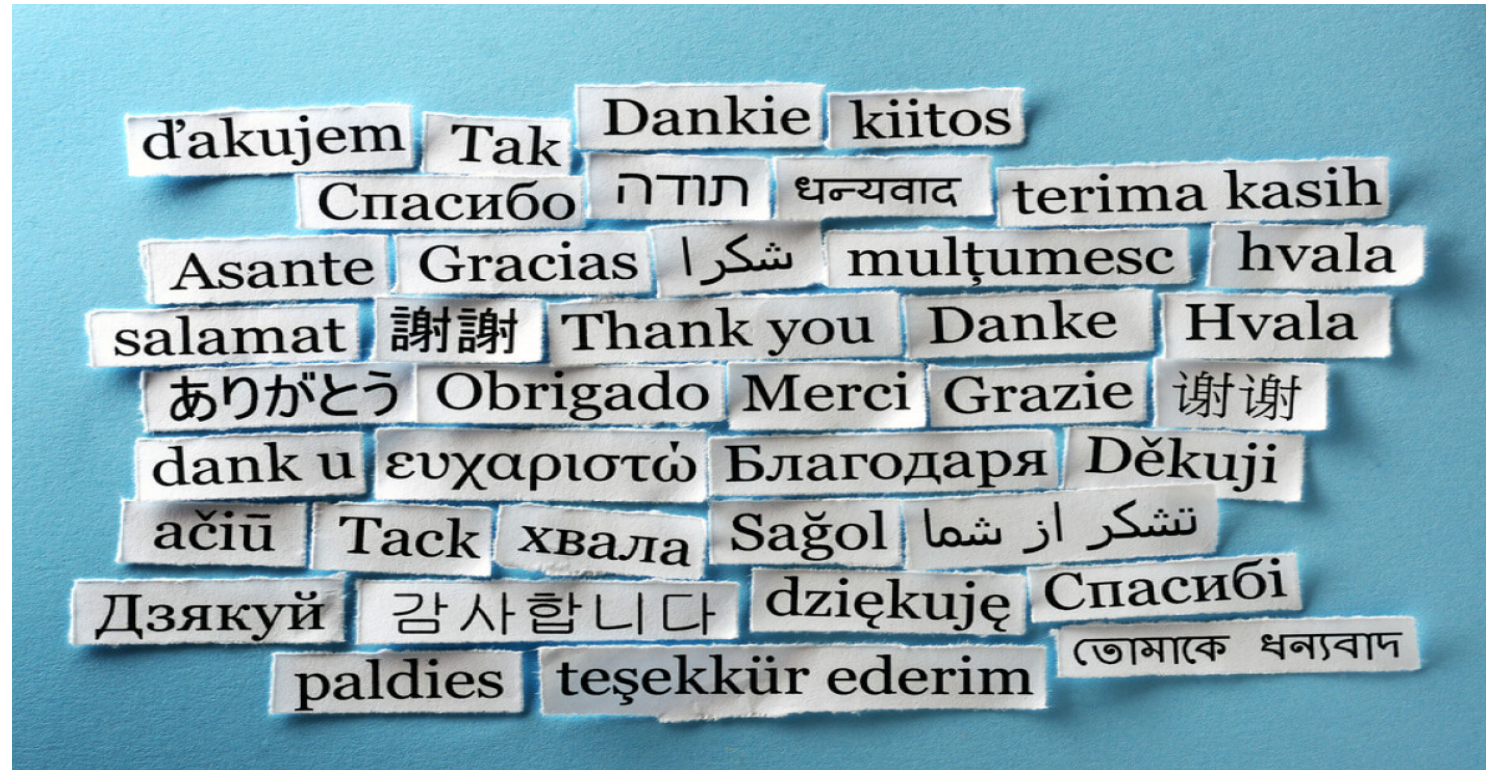
# ...TO CONCLUDE

**We emphasize the importance of an accurate 3D mapping all faults that might be reactivated by IS around the injection sites**





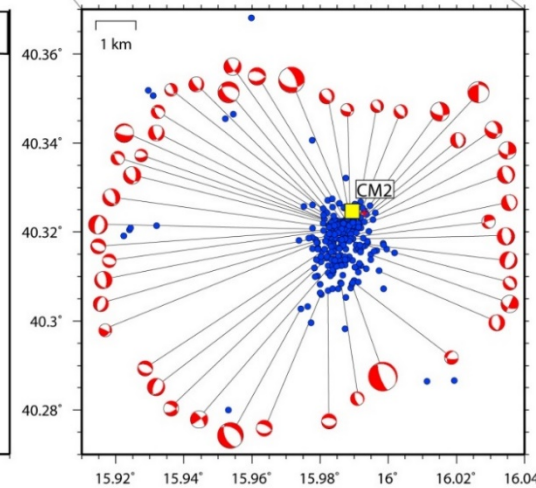
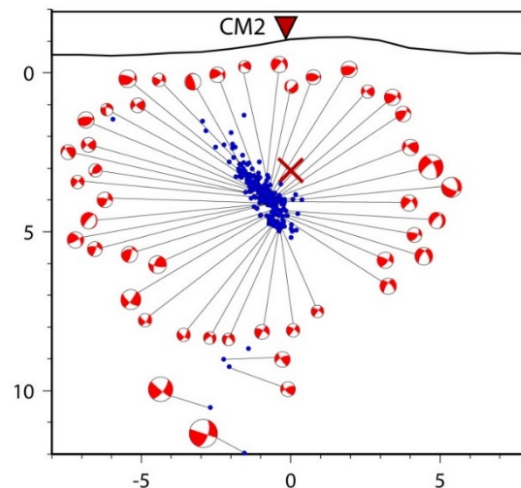
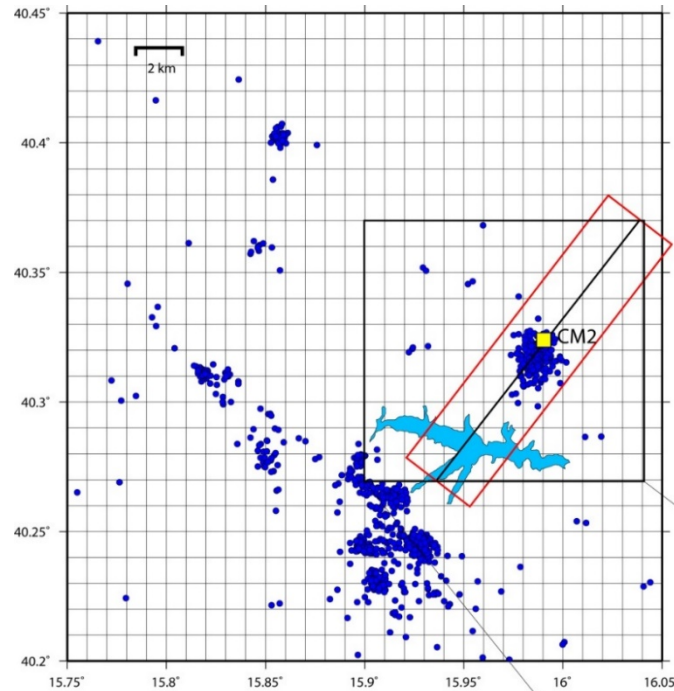
We acknowledge Eni S.p.A. for providing the underground dataset under a collaborative research agreement with INGV



See also Posters:

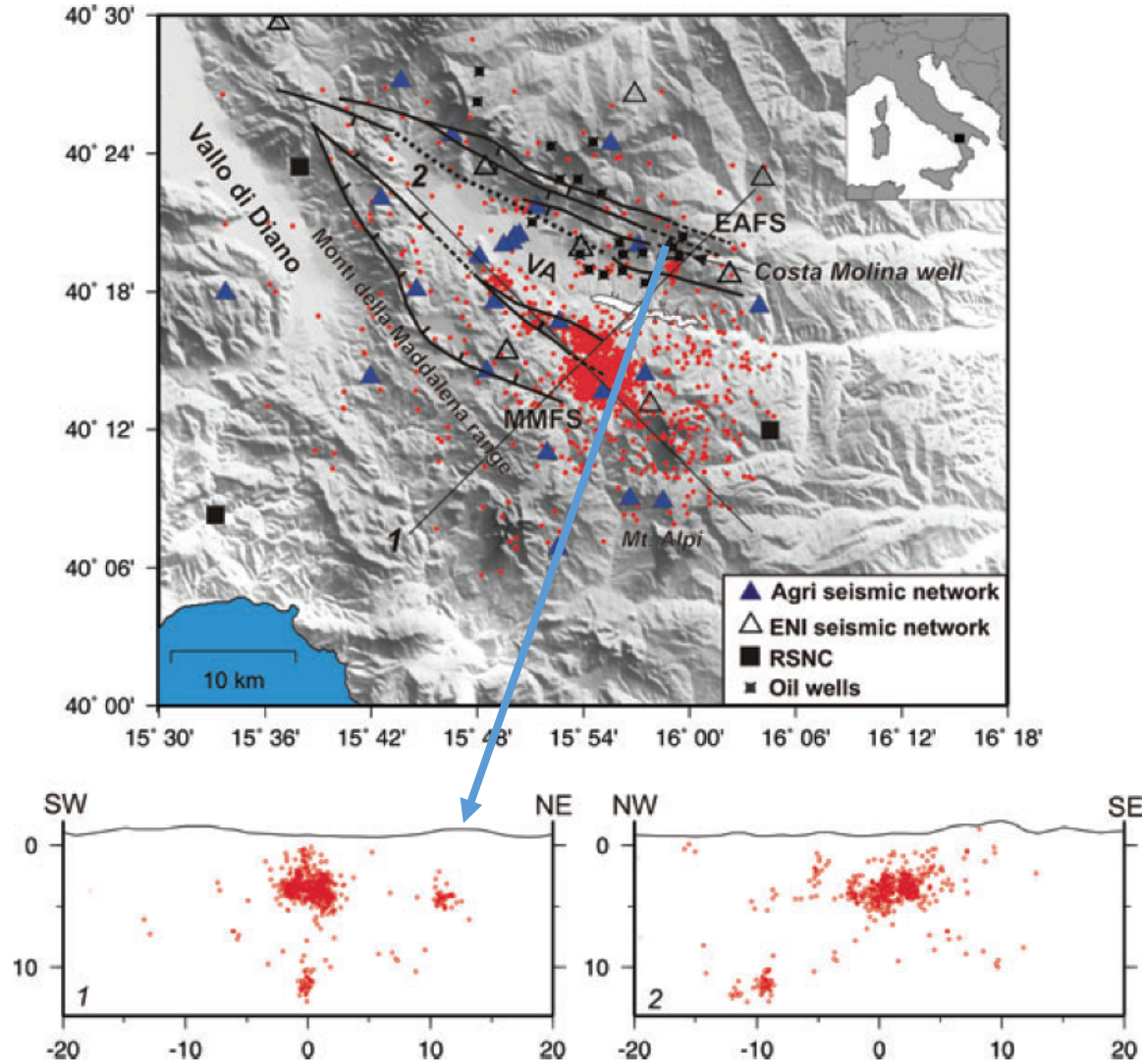
- P1-06 by L. Improta et al. Reservoir properties and wastewater induced seismicity at the Val d'Agri oilfield (Italy) shown by 3-D passive seismic tomography
- P2-15 by Antonio P. Rinaldi et al. *Seismicity induced by seasonal variation of reservoir level: the case of Pertusillo lake, Val D'Agri (Italy)*

# shallow crustal structure vs. IS@VdA

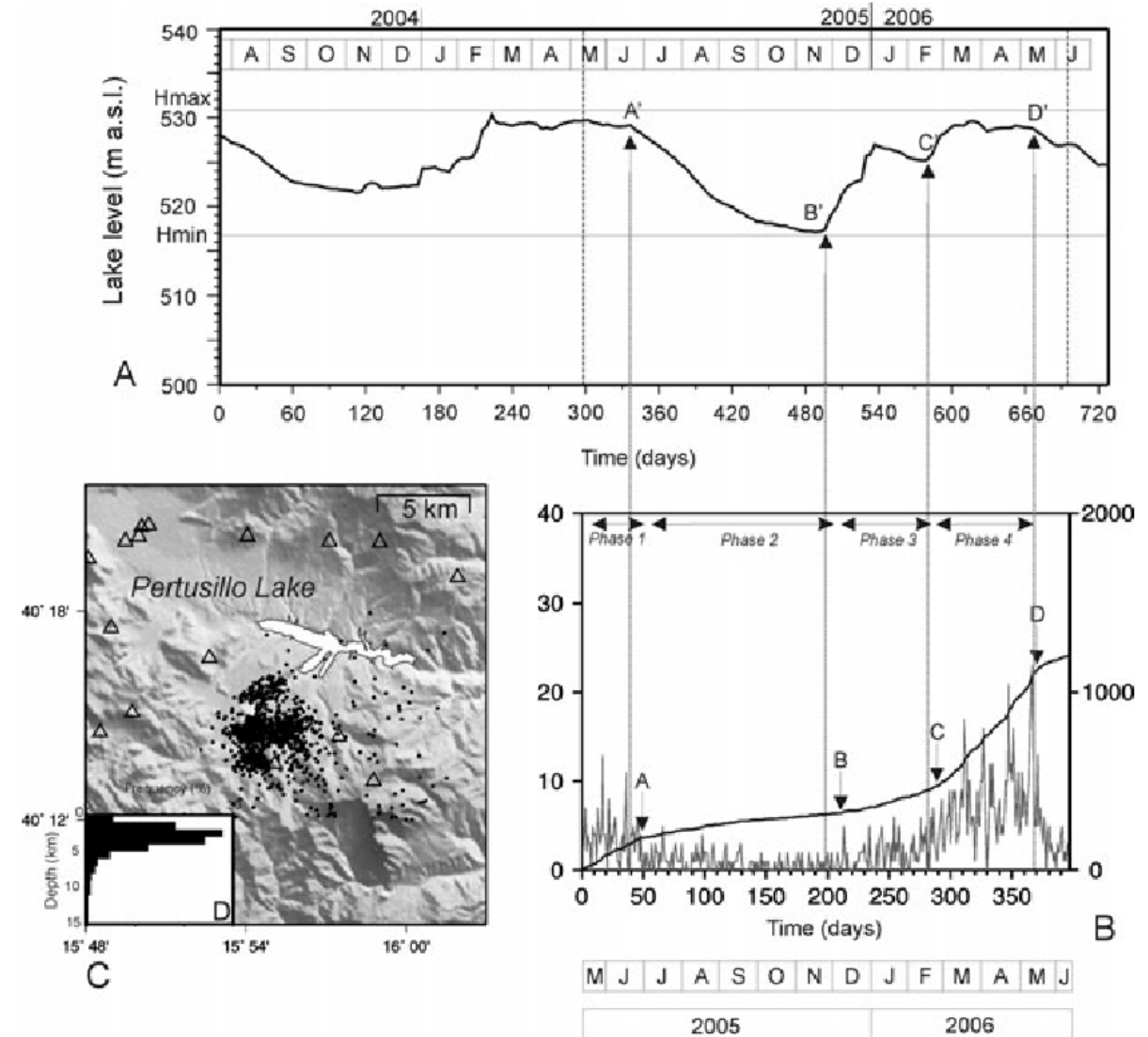


- Focal mechanisms show predominant normal faulting kinematic striking from WNW-ESE to NW-SE, with **the NE-dipping nodal plane coherent with the seismicity alignment onto one of the interpreted back-thrusts**
- Deeper events, including the  $M_L$  2.2 largest earthquake, possibly relate to the more external reverse faults,
- **Such focal mechanisms are also coherent with the current NE-trending extensional local stress field inferred by borehole breakouts**
- The SSW-NNE elongated earthquakes cloud matches the right lateral ramps of the arcuate thrusts and back-thrusts developed in the northwestern upheaved sector of the reservoir

# Induced seismicity in Val d'Agri



Valoroso et al., 2009



A case of RIS (Reservoir Induced Seismicity)