The architecture and mechanics of an active Low Angle Normal Fault: the Alto Tiberina Fault (northern Apennines, Italy)

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Geologia Strutturale e Geofisica

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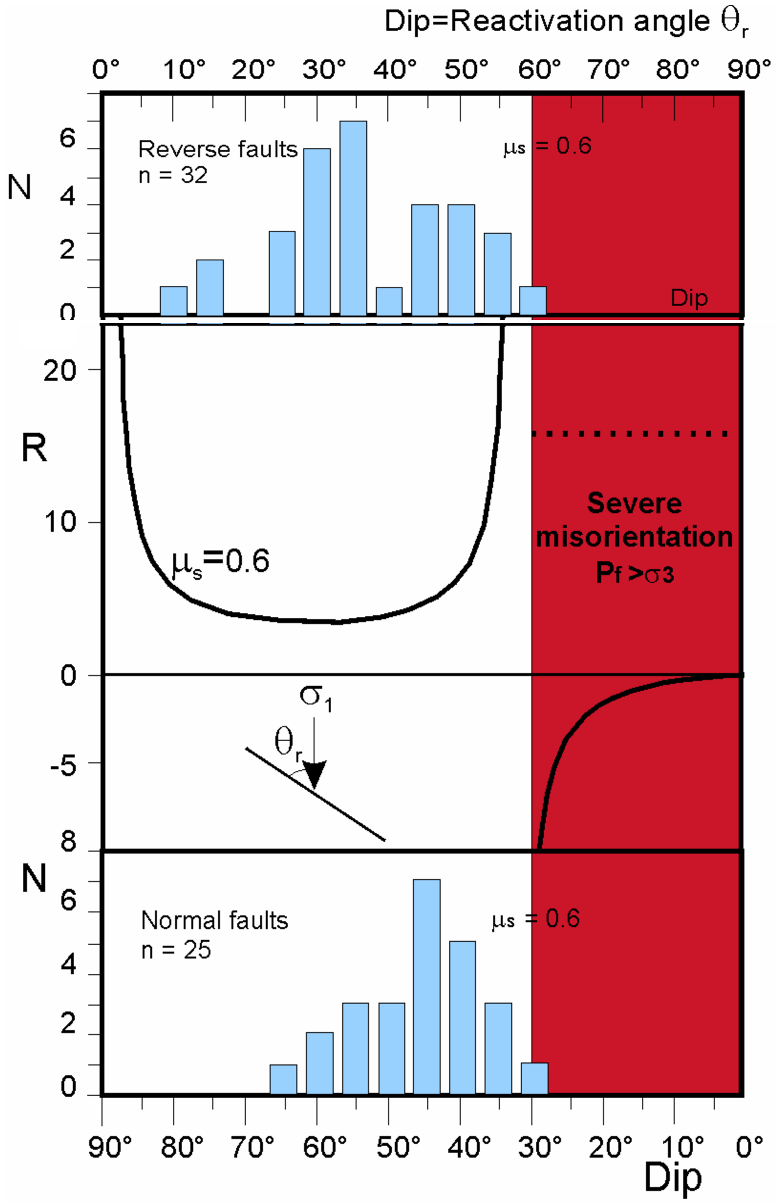
Euro-conference of Rock Physics and Geomechanics on Natural Hazards: thermo-hydro-mechanicl processes in rocks.

background: LANF paradox



$$R = \frac{\sigma_1 - P_f}{\sigma_3 - P_f} = \frac{1 + \mu_s \cot \theta_r}{1 - \mu_s \tan \theta_r}$$

Classical Anderson-Byerlee frictional fault mechanics (one principal stress is vertical and faults with $0.6<\mu s<0.85$) predicts no slip on normal faults dipping less than 30°.

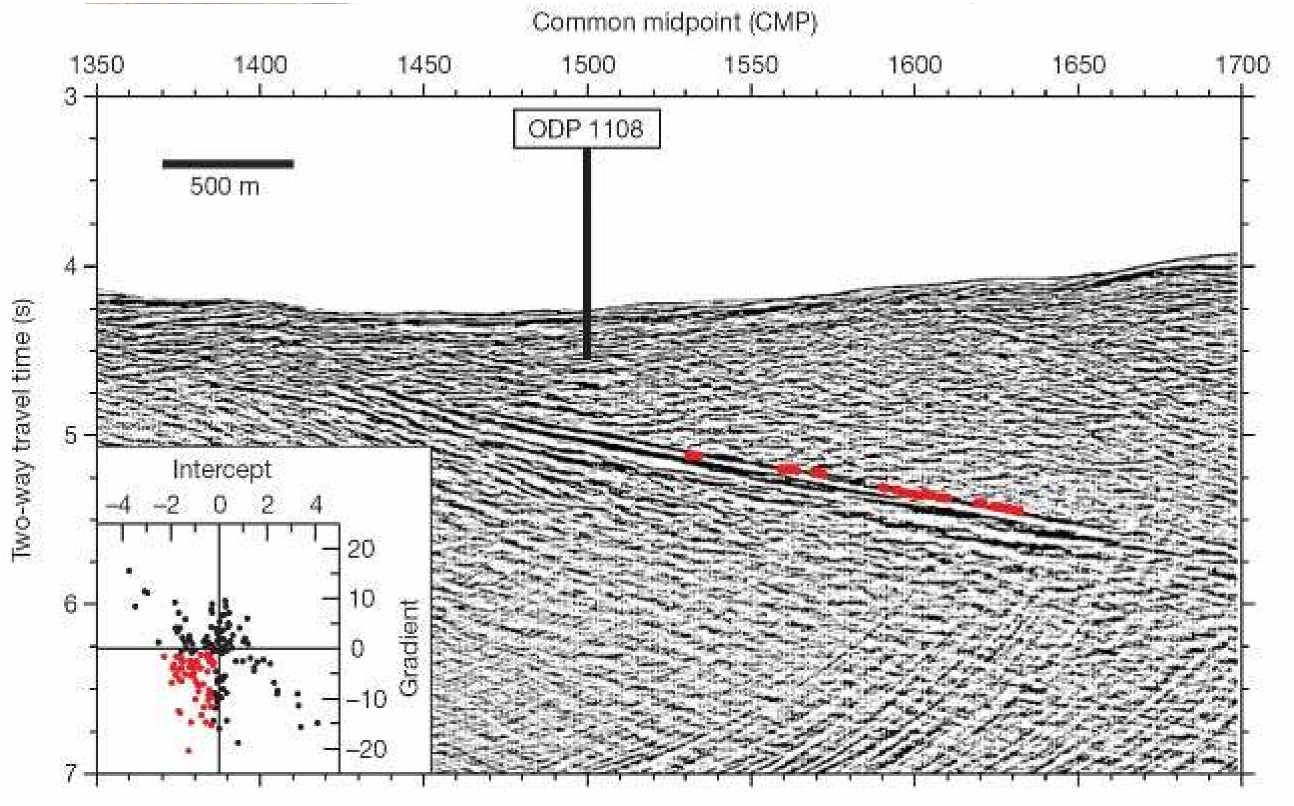
This is consistent with the observed dip-range of moderate and large dip-slip earthquakes (M>5.5) identified using positively discriminated focal mechanisms.

Jackson & White, JSG, 1989
Collettini & Sibson, Geology, 2001

geological/geophysical evidence

In stark contrast the geological evidence for active LANF appears to be overwhelming hanging been documented in many field based structural studies (e.g. Lister and Davies, 1999; Axen, 1999; Sorel, 2000; Hayman et al., 2003; *Collettini and Holdsworth, 2004*)…

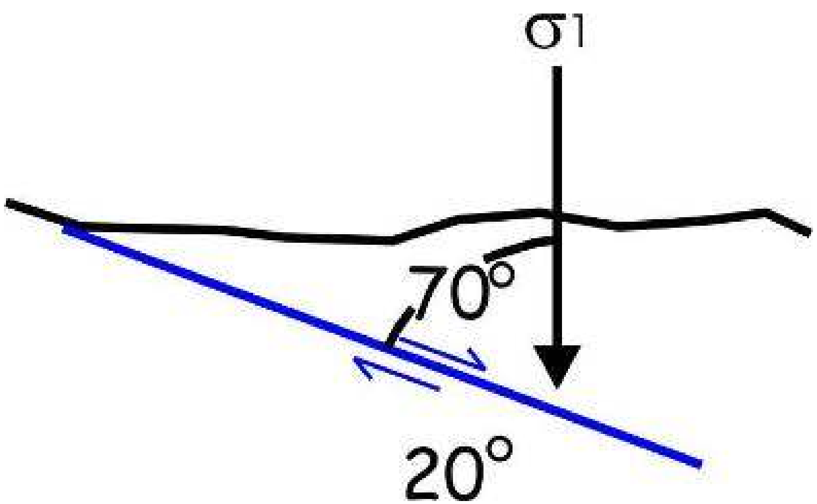
…and interpretation of seismic reflection profiles (Roy and Kenneth, 1992; Barchi et al., 1998; Laigle et al., 2000; *Floyd et al., 2001*)



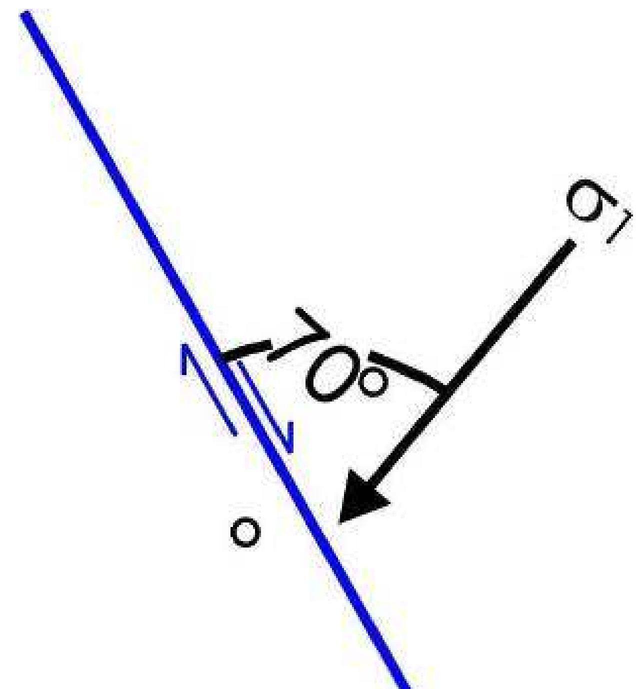
LANF enigma

Can eqks nucleate on LANF (dip<30°)?
Can LANF accomodate extension of continental crust?

Extensional environments, faults dipping less than 30°: the faults are severely misoriented for reactivation.

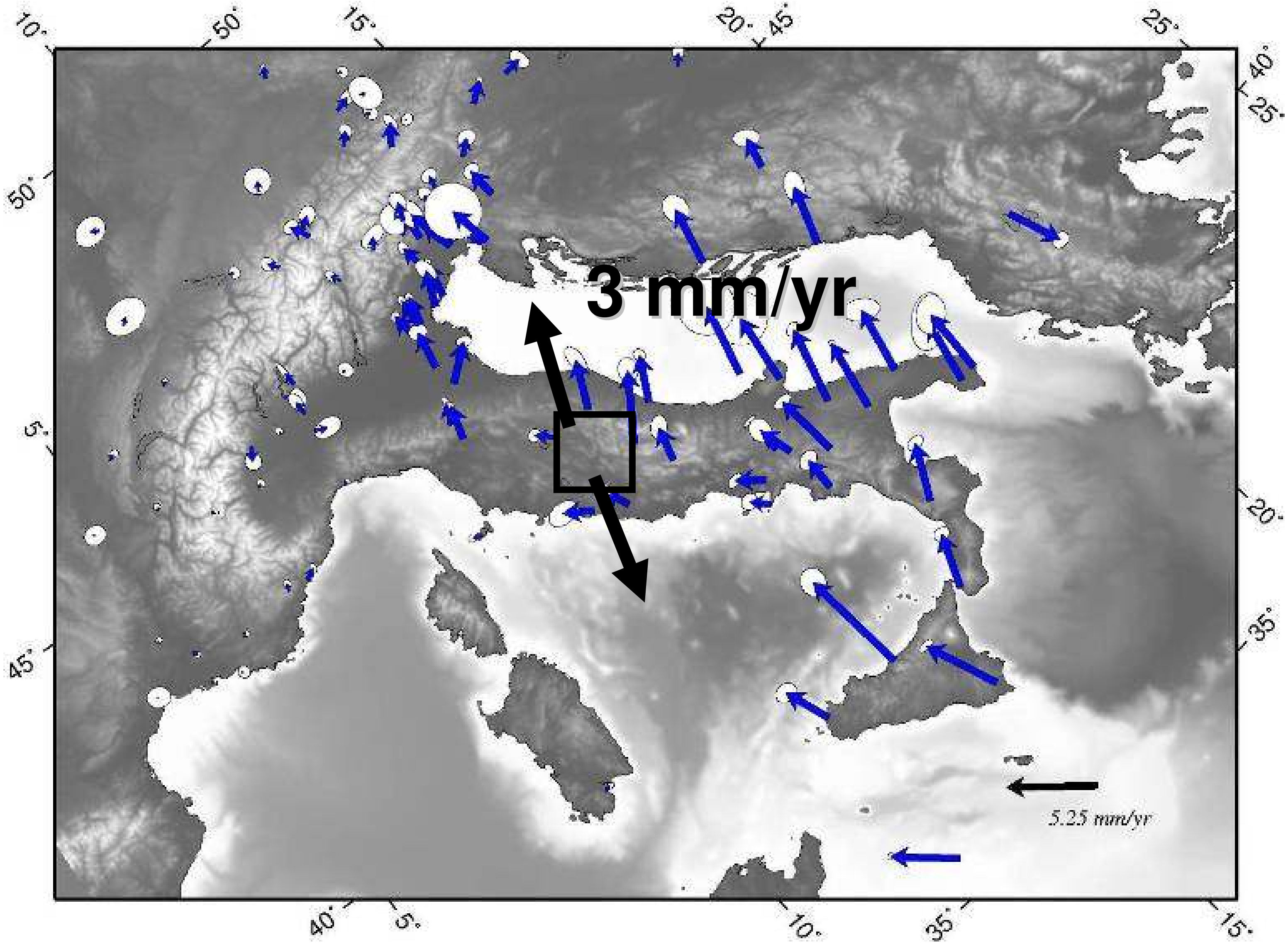


The San Andreas too is severely misoriented for fault reactivation (e.g. Townend & Zoback, GRL, 04)



study area

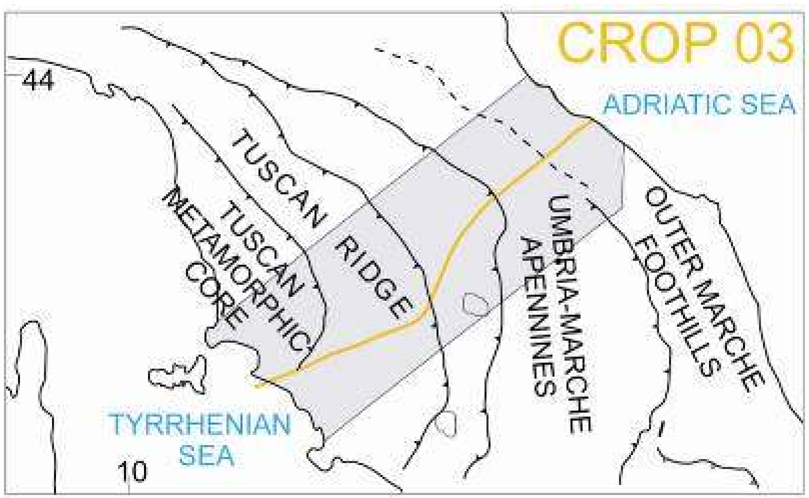
GPS velocity field keeping Eurasia fixed (*Dagostino and Selvaggi, 2004*)



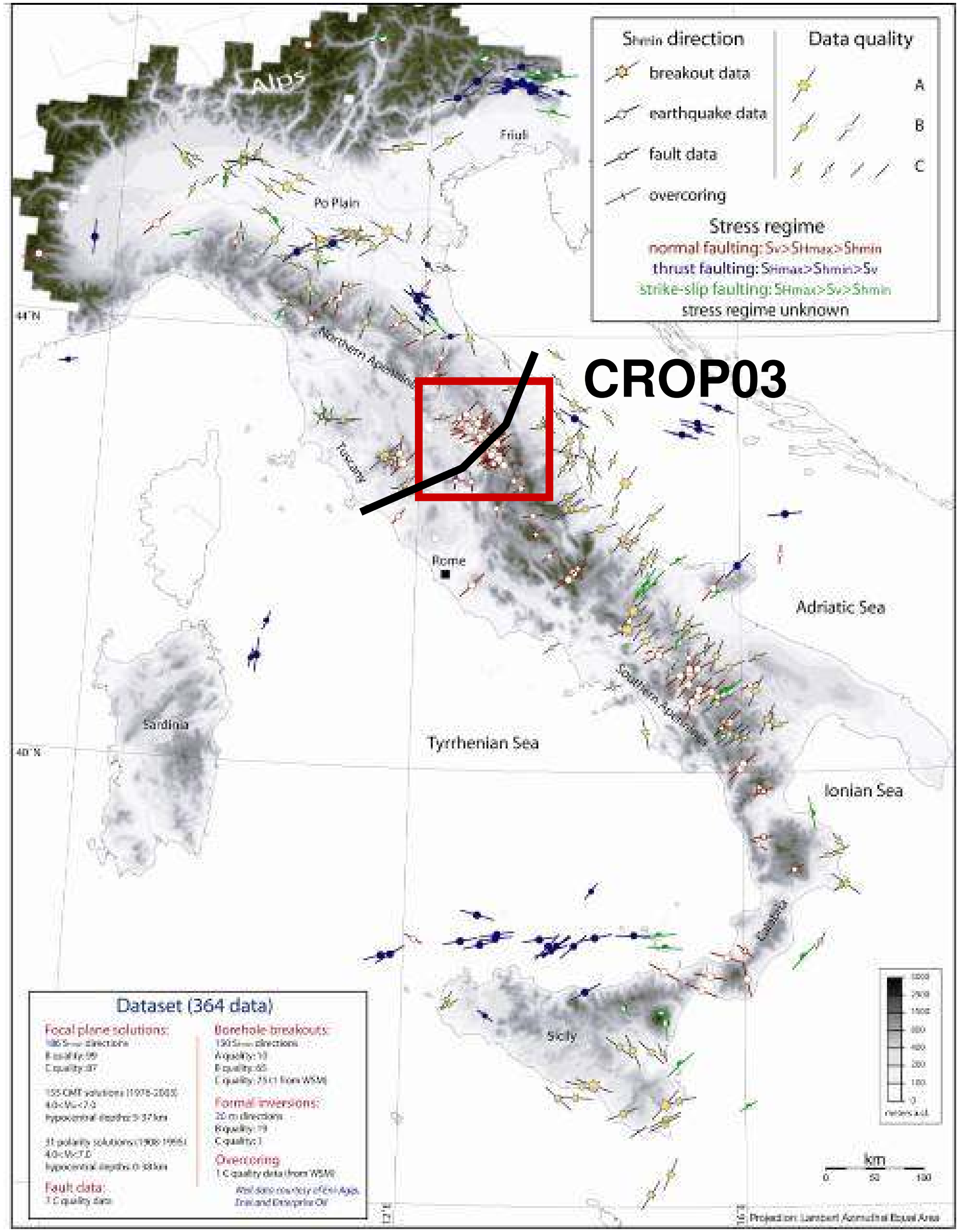
study area

The ENE trending direction of extension is confirmed by the directionof the Shmin derived from borehole breakout data

(Montone et al., 2004)

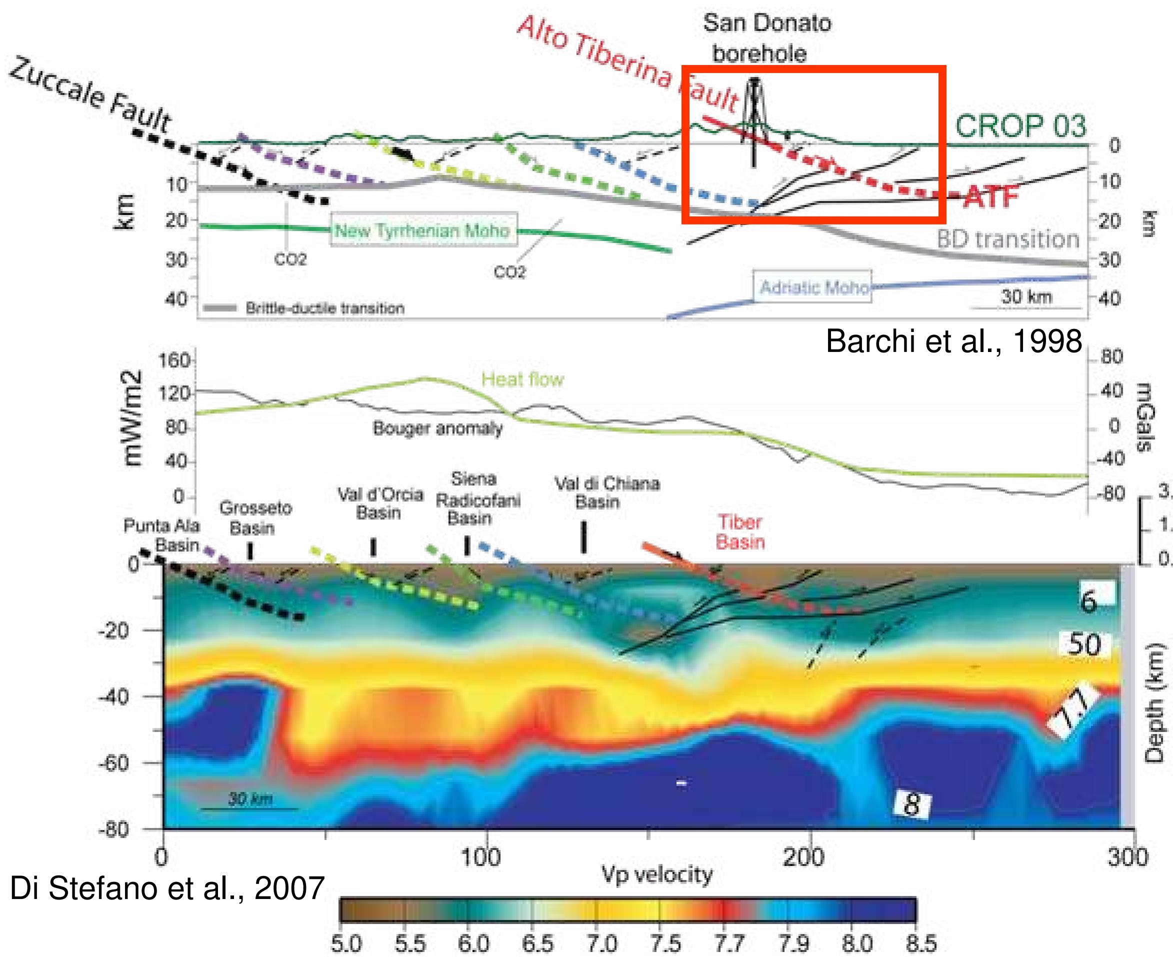


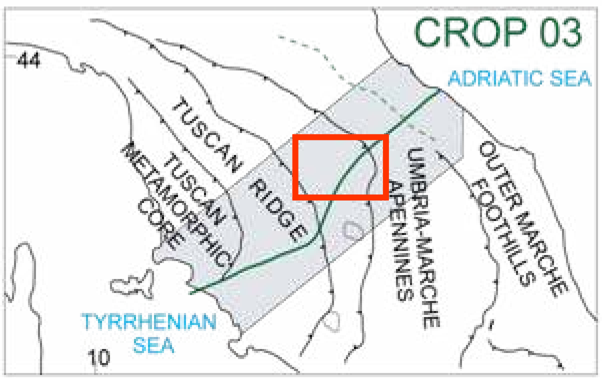
CROP03_ Deep crust
Barchi et al., 1998



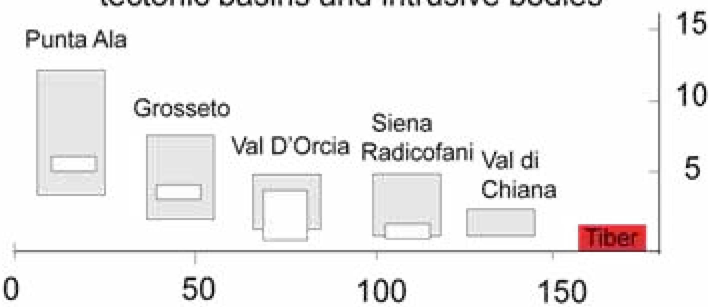
northern Apennines (CROP03)

active extension | active compression





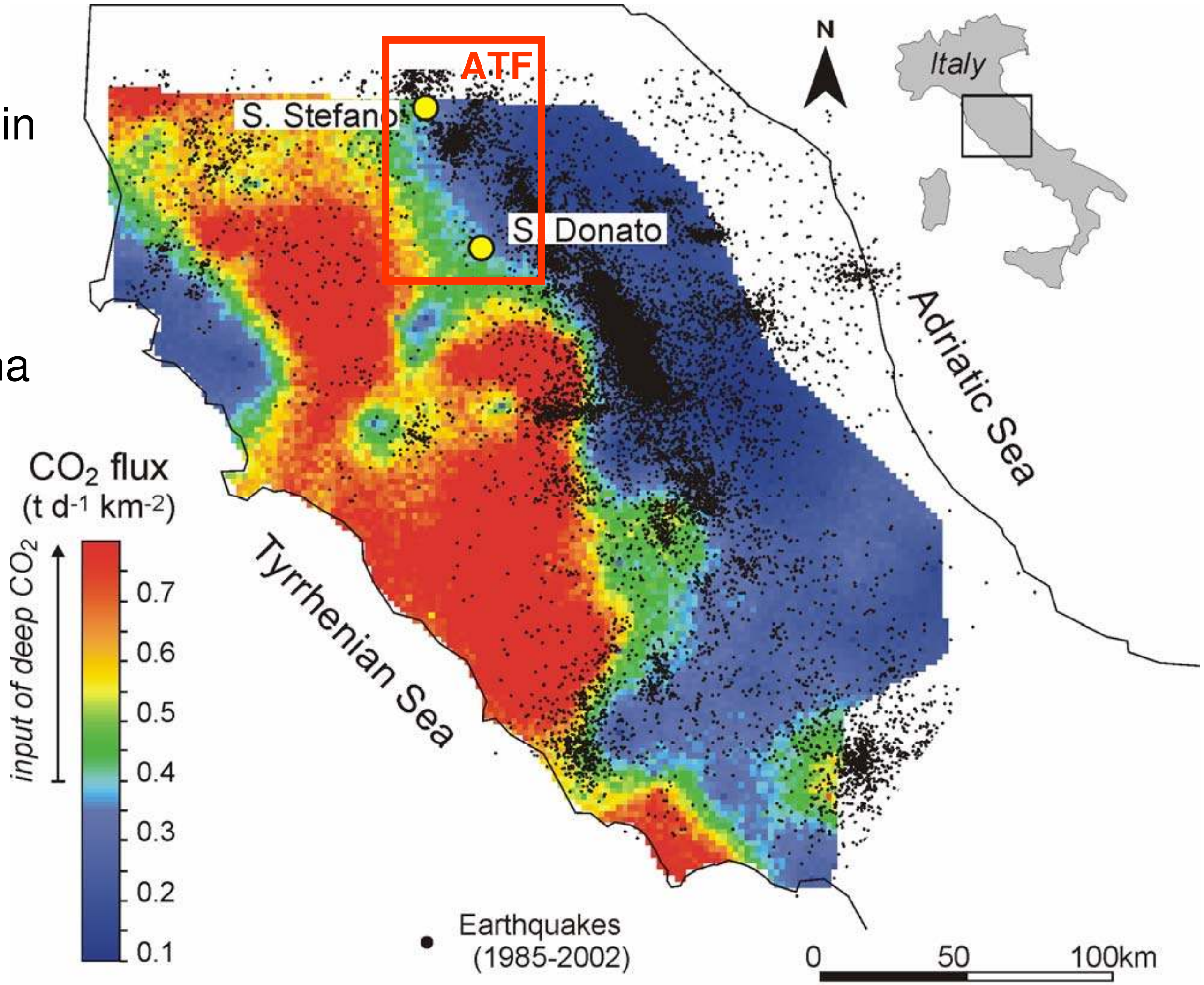
Space-time evolution of the syn-tectonic basins and intrusive bodies



deep seated CO2 degassing

~22,630 t d^{-1} produced in the extending area with ~12.160 t d^{-1} of deep seated CO_2.

For comparison the Etna volcano produces ~35.000 t d^{-1} CO_2.

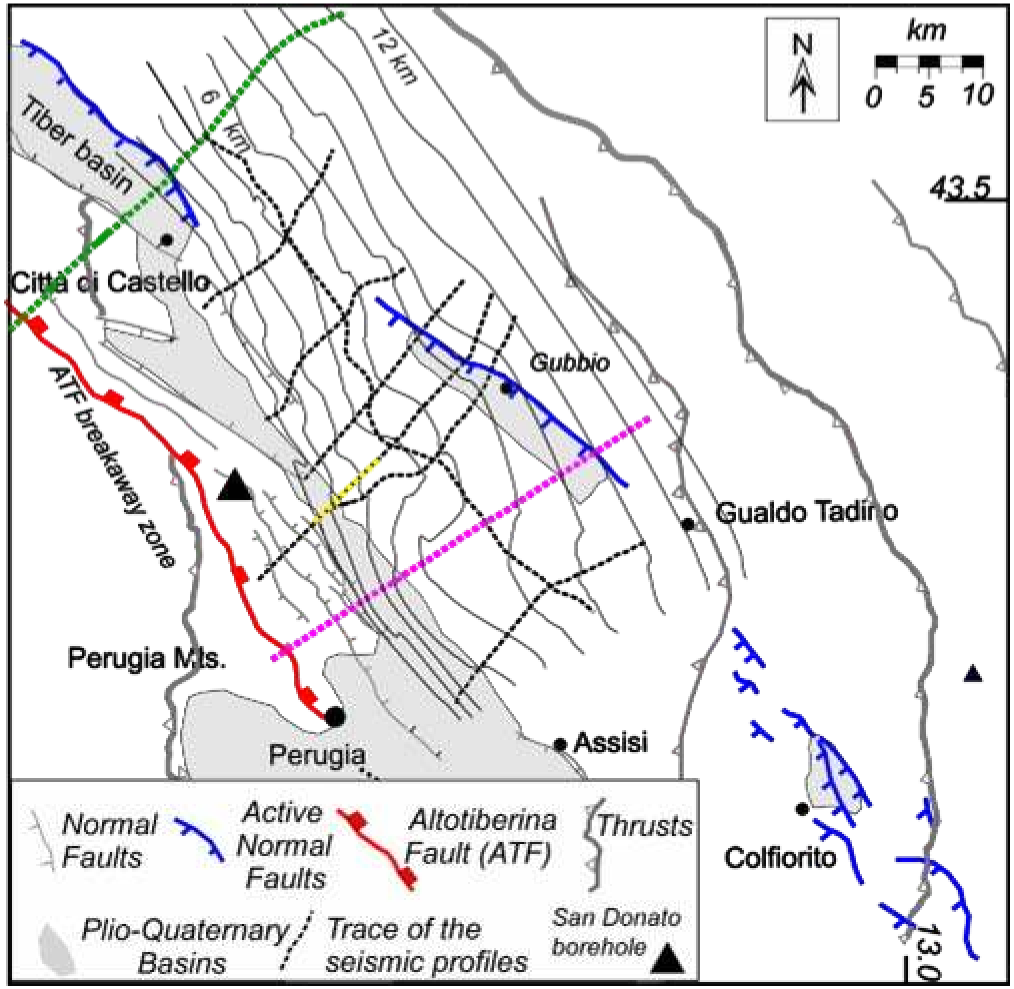


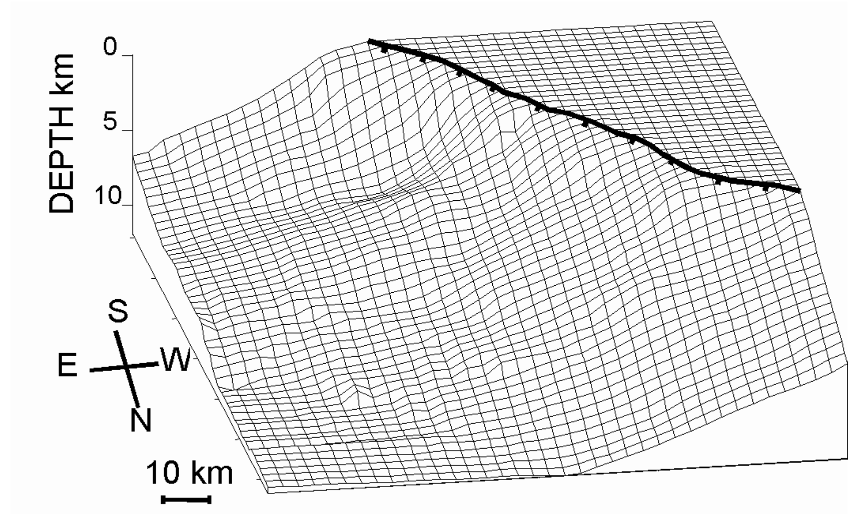
Chiodini et al., 2000
Chiodini et al., 2004

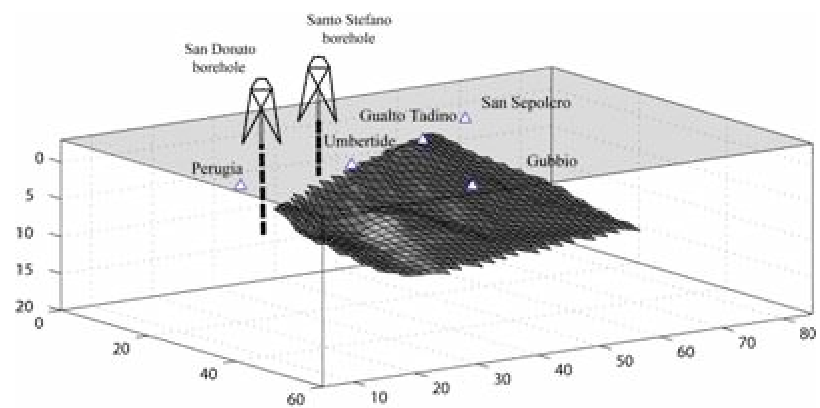
● boreholes that encountered fluid overpressure, within the Trassic Evaporites: CO2 at 85% of lithostatic load

3D image of the ATF

Depth convertion of the profiles performed using seismic interval velocities derived by boreholes



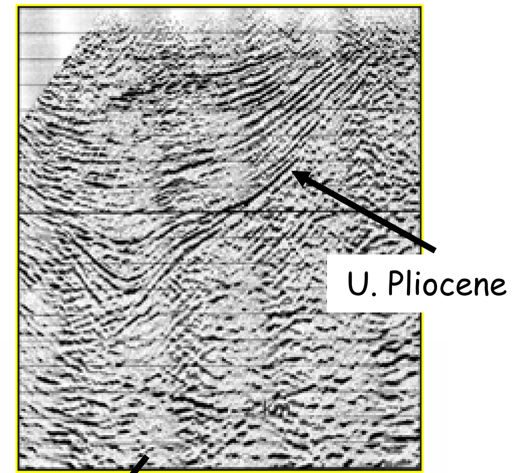


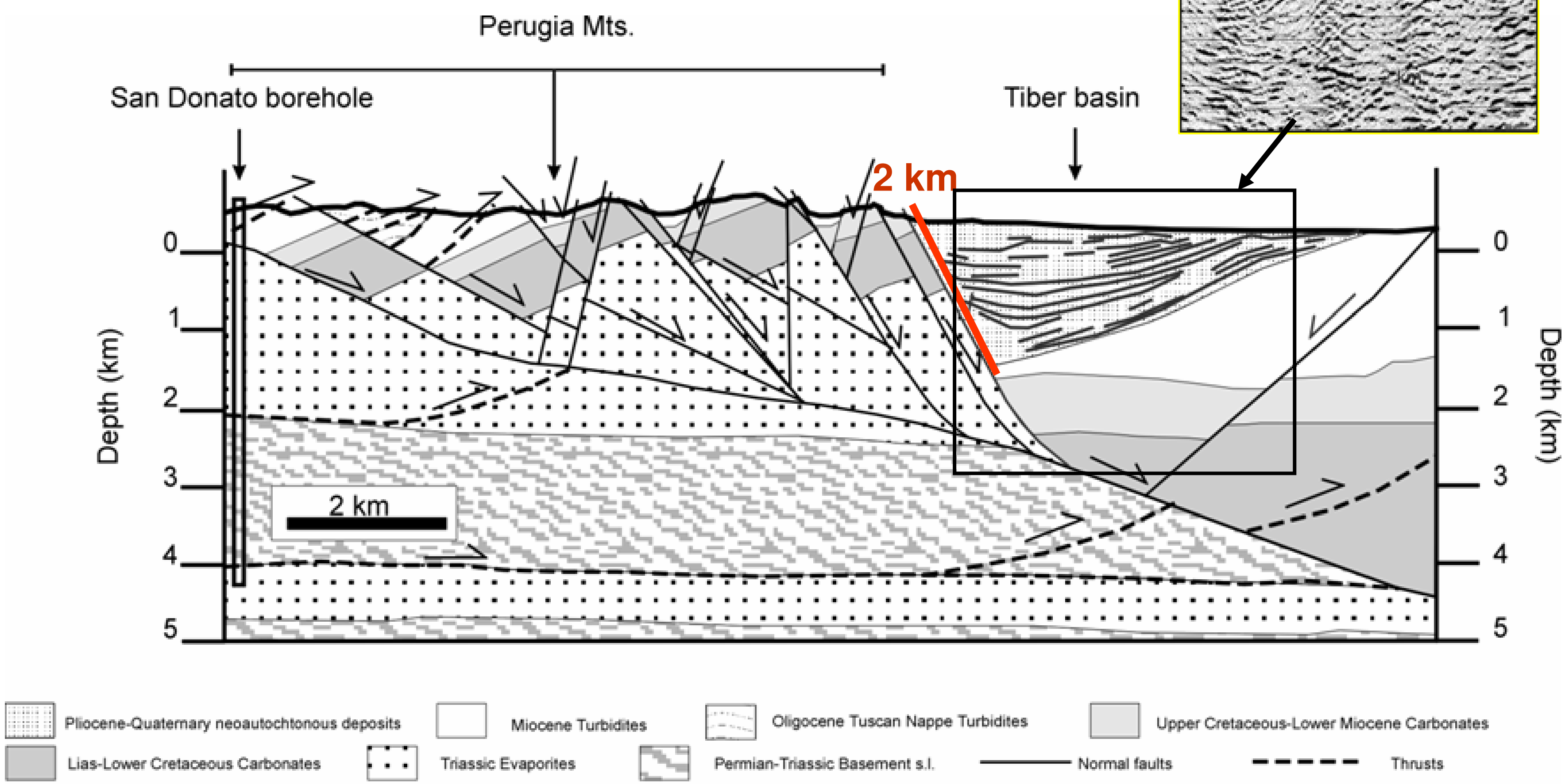


Location of the boreholes that encountered fluid overpressure, within the Trassic Evaporites

ATF long-term displacement

Age of syntectonic sediments of the basin and displacement of the basin-bounding fault, define a time-averaged long-term slip rate of ~***1 mm/yr*** in the last *2Ma* (*Upper Pliocene-Quaternary*)

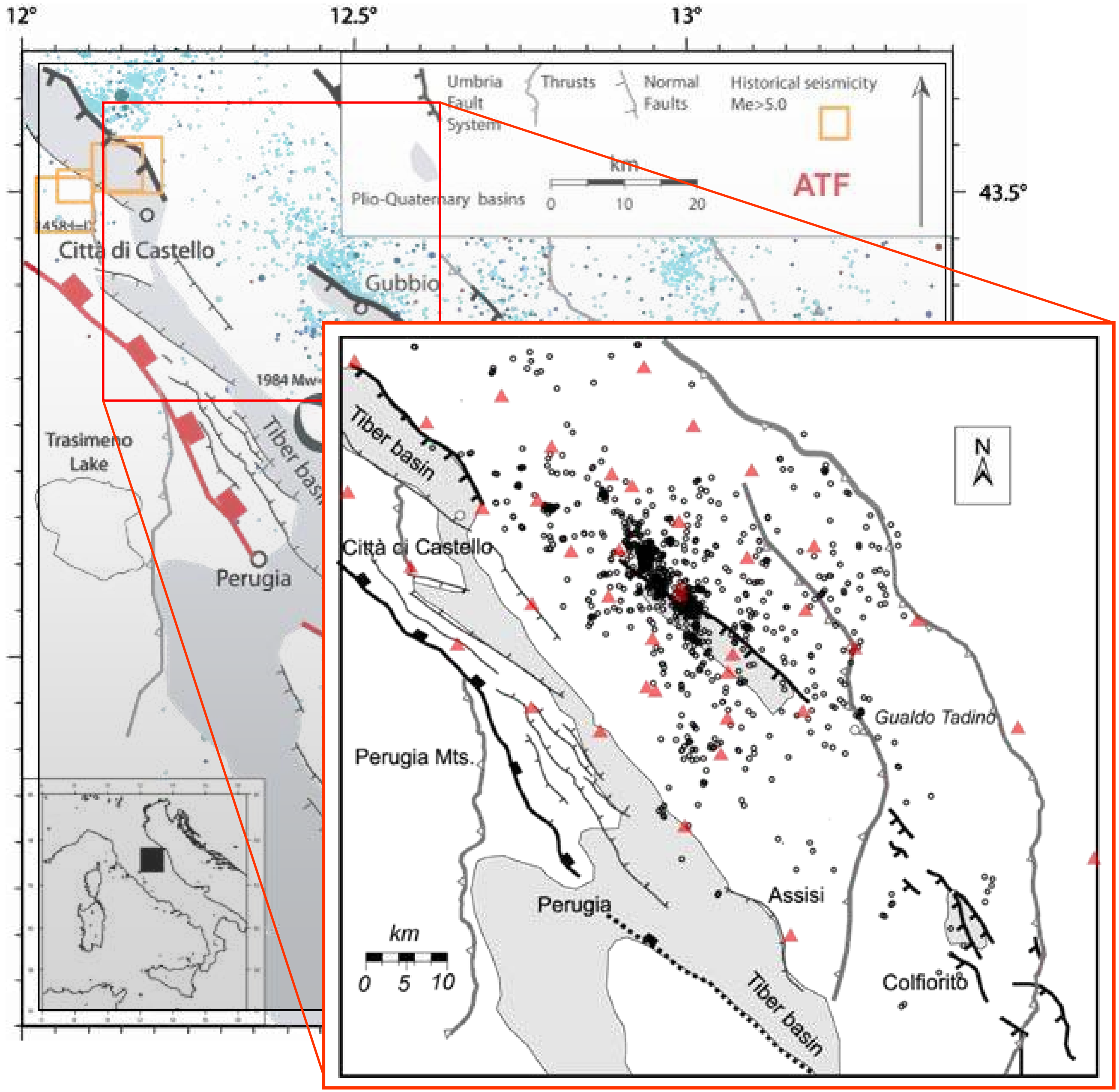




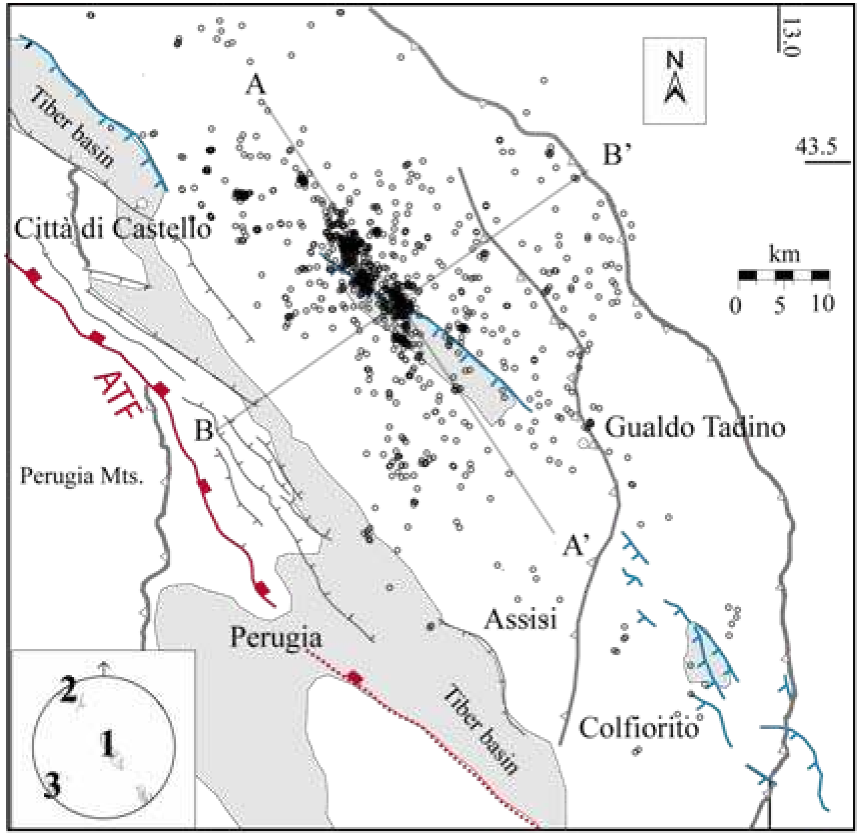
monitored area

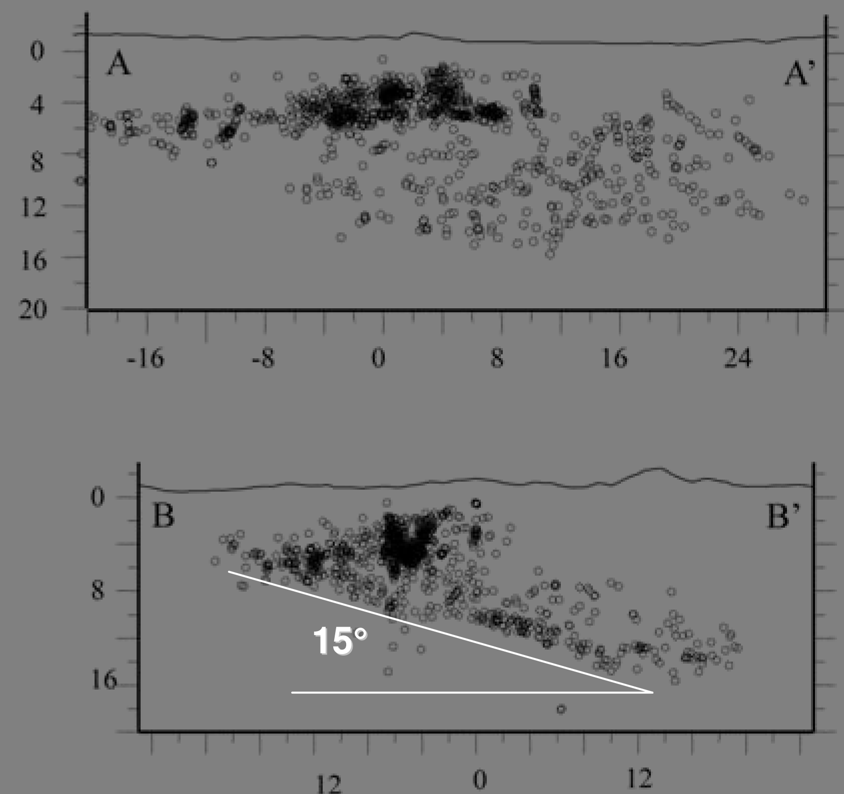
Instrumental seismicity is concentrated along the inner chain and the focal mechanism solution of the major events of the lat 20 years (5<Mw<6) confirm the ongoing ENE-trending extension

Hole of historical seismicity in the area where the active seismic profiles image the ATF

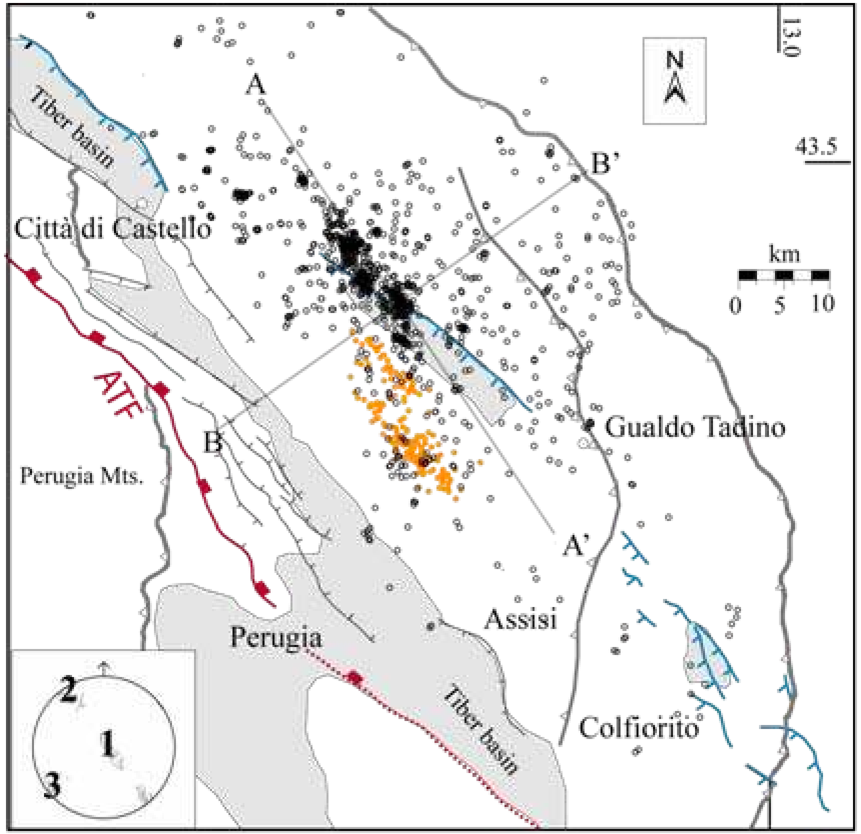


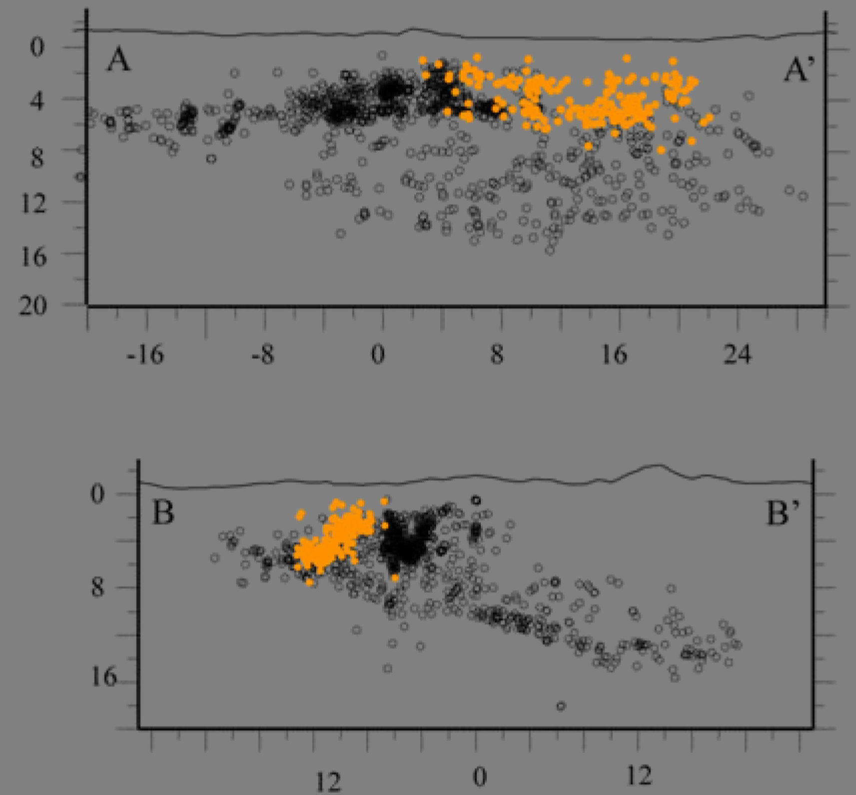
1416 relocated events with Ml < 3.1





Chiaraluce et al., JGR, in press

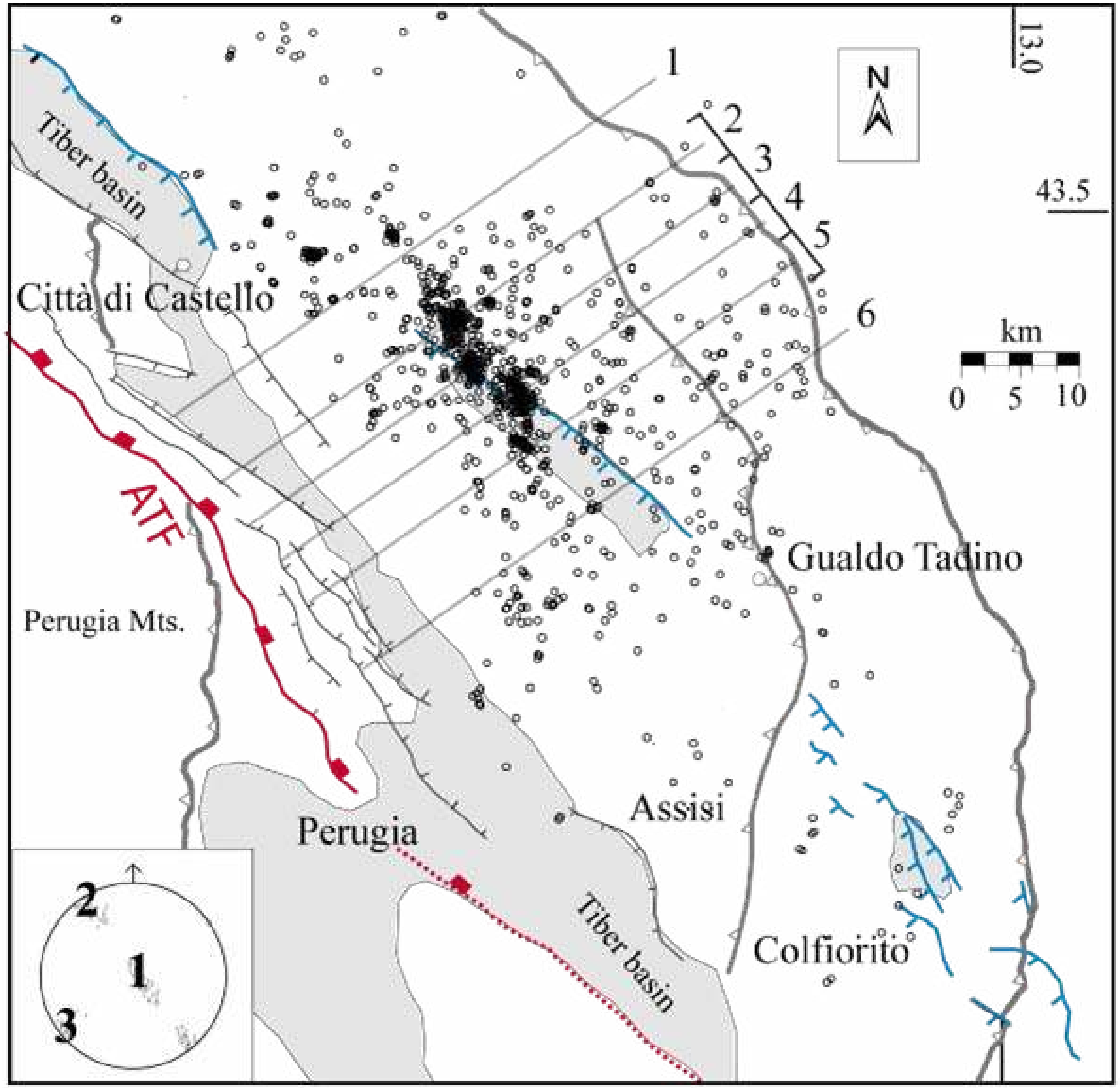




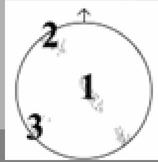
Gubbio 1984 (Mw 5.4)
seismic sequence

Chiaraluce et al., JGR, in press

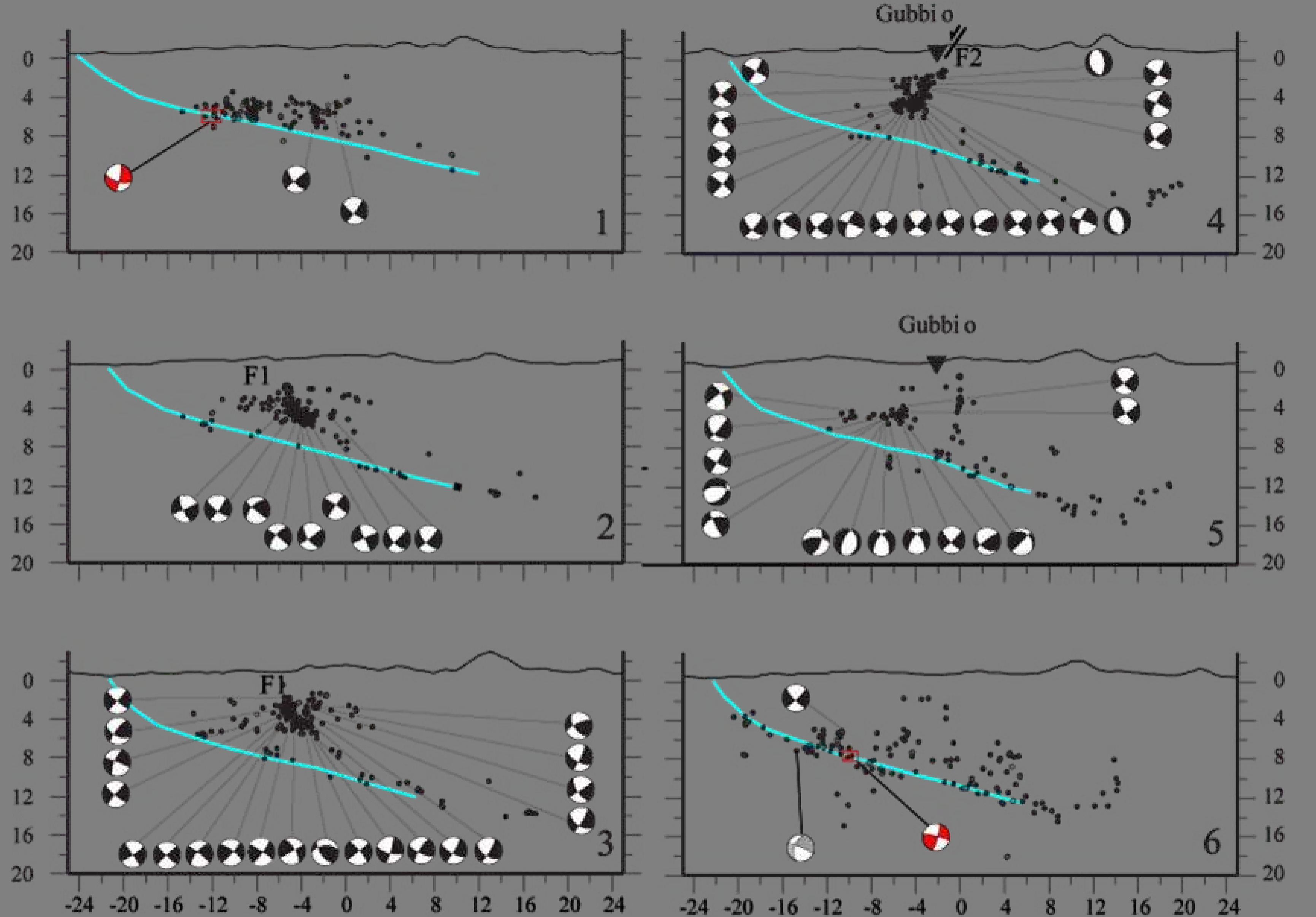
cross sections traces



details



2
1
3



Gubbi o
F2
F1
F1
1
2
3
4
5
6
0
4
8
12
16
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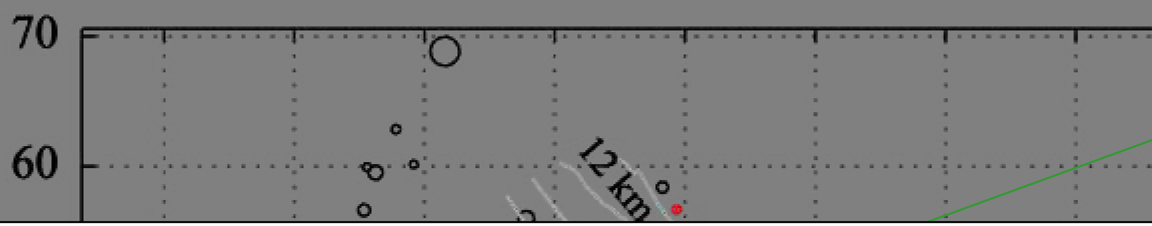
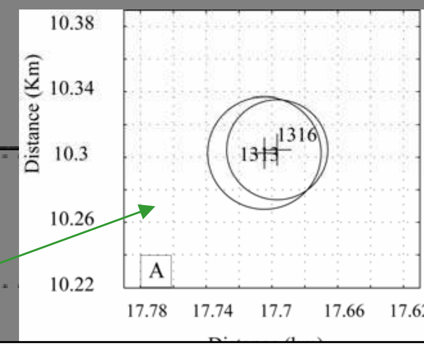
24

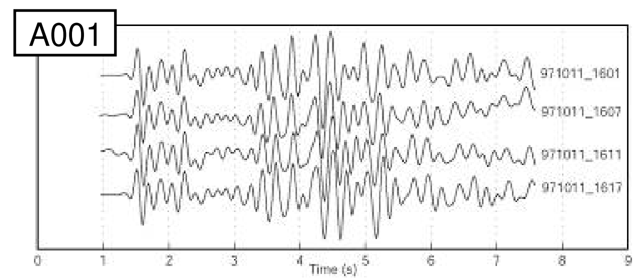
621 eqks on the ATF (ML<2.3)



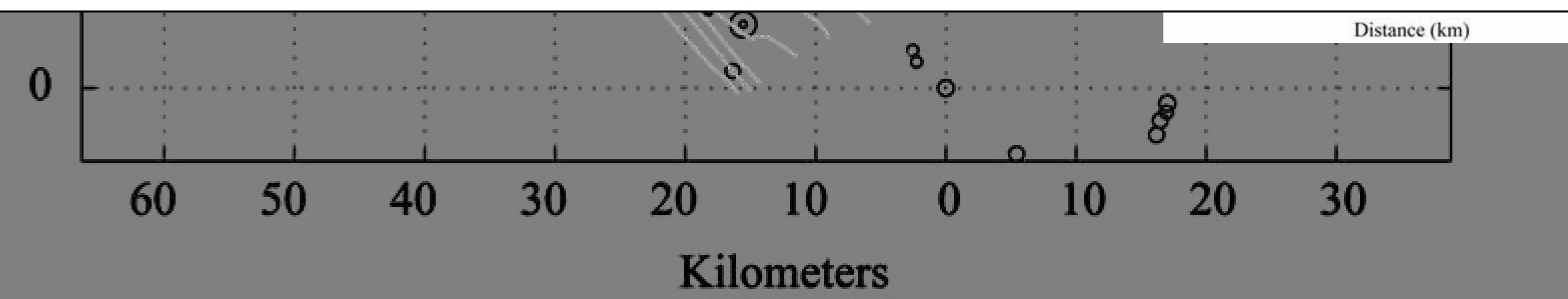


The events of the 28 clusters (3 groups of repeaters)…

- nucleate within 24 h from each other (60% within 1h)
- very similar magnitude
- very similar seismograms
- absence of obvious short term triggering
- no evidence for preferred migration direction (no streaks).



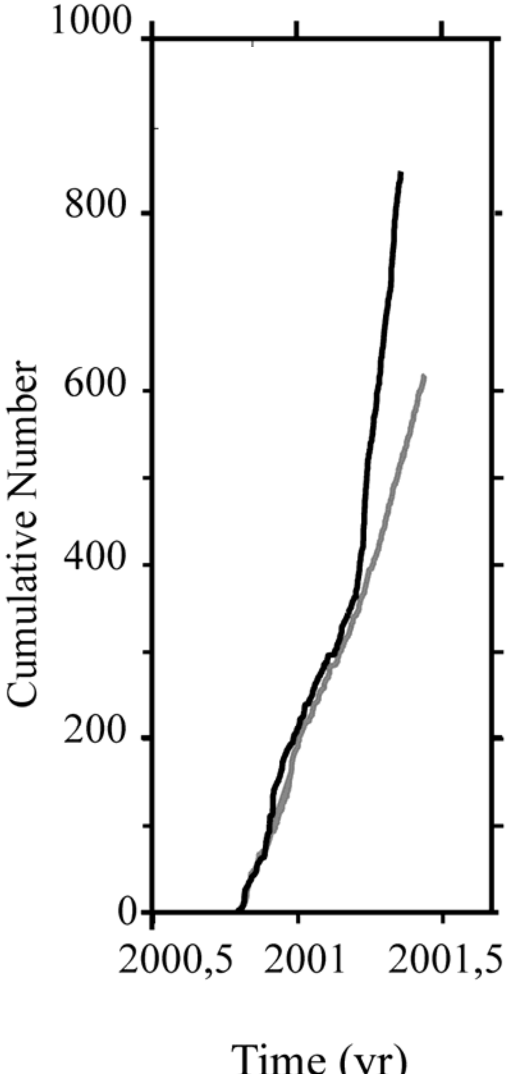
…suggesting a peculiar rheology of the ATF plane



rate of seismic release

Seismicity on the ATF hangingwall

Seismicity on the ATF plane



the ***rate*** of the seismic release

(3 events/day ML<2.3)

on the ATF fault plane is almost ***constant!!***

b-value

These values, while corroborating the hypothesis of different properties of the two fault zones (ATF vs HW)…

Are in contrast with the decreasing of b-value with depth observed in many tectonic areas (*Gerstenberger et al., 2001*).

Are in agreement with:

- lab. experiments showing higher values for deformation of ductile rocks and lower for brittle (*Scholz, 1968*).
- higher values were found in the *creeping* portion of the SAF in respect to the locked ones (*Amelung and King, 1997*)

…suggesting *creeping* evolution.

summary

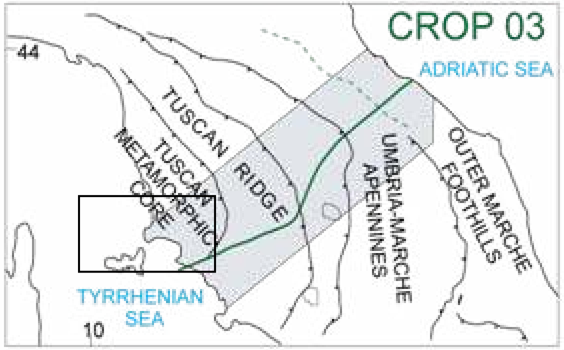
- extension accommodated by a LANF within a crustal volume characterized by vertical σ1 and fluid overpressure (CO2)

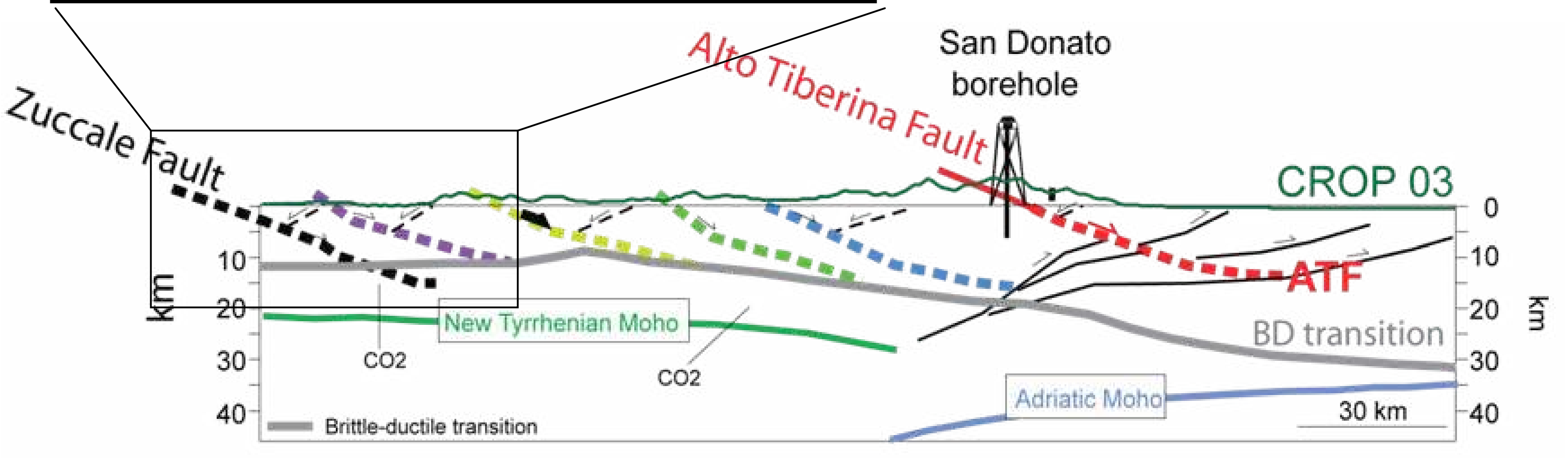
*All these seismological signatures suggest that such detachment is anomalously weak (μ**s<<0.6** or **Pf > σ3**) and accomodates deformation by aseismic creep plus microseismicity*

Do we have independent evidence to support this hypothesis?

- ATF related seismicity show an higher b values (1.06±0.07) than seismicity located in the hangingwall block (b = 0.85±0.03)

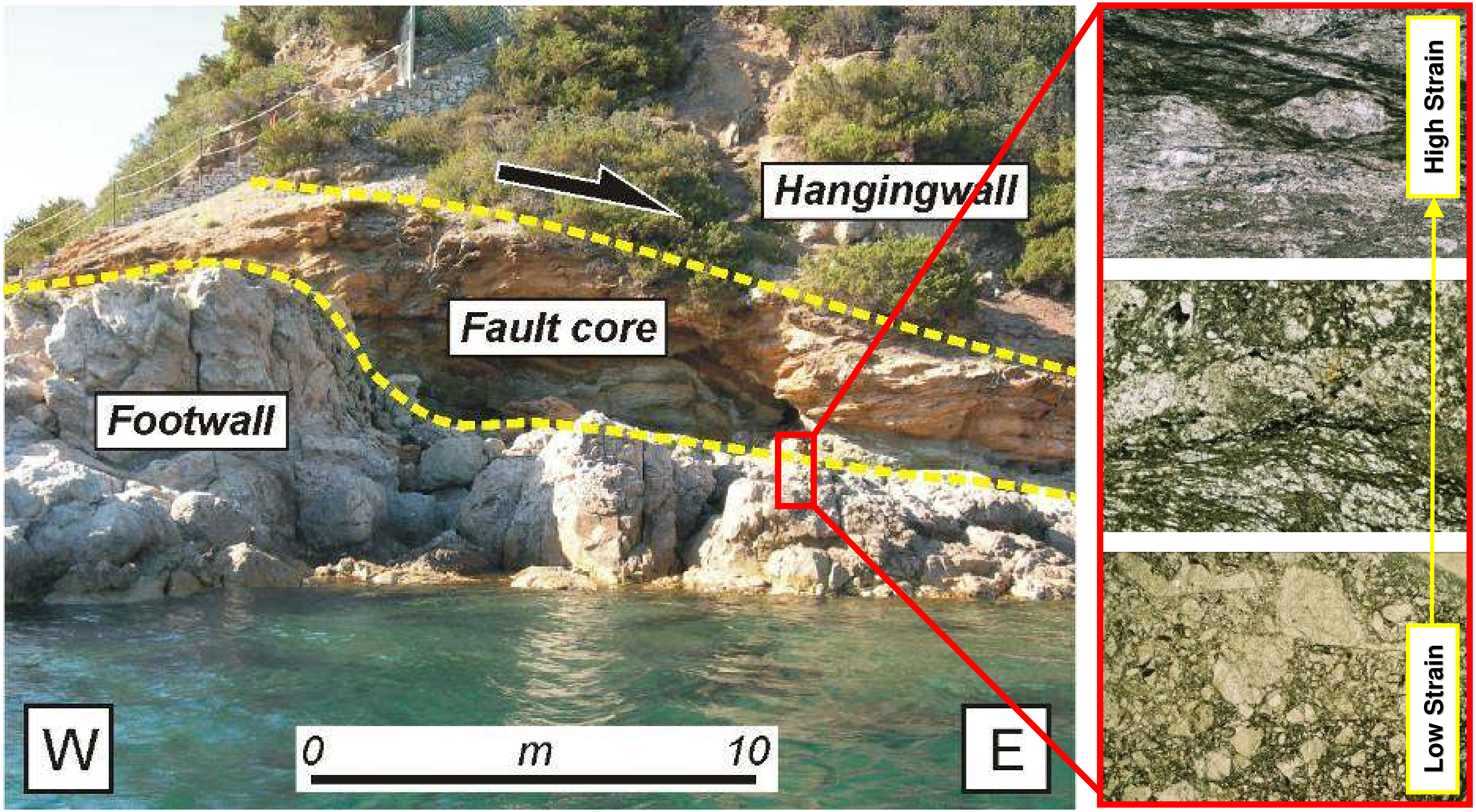
ATF analogue





Zuccale fault

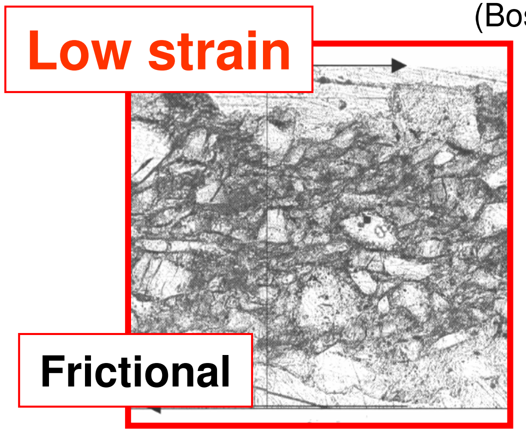
- Overprinting of cataclastic textures by foliated phyllosilicate-rich fabrics and associated weakening effects due to fluid-rock interaction
- Foliated fault rocks in fault core only, FW & HW deformation exclusively brittle
- With increasing strain switch from a cataclastic to pressure solution accommodated deformation along phyllosilicate-rich horizons

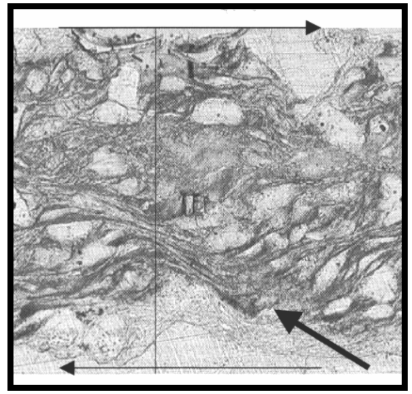


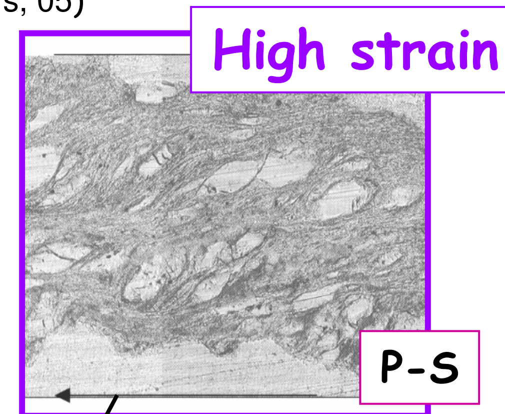
can experiments on simulated fault rocks explain weak rheology?

Exp. on rocks analogue of phyllosilicate show fault rock weakening accompained by the evolution from cataclastic texture to highly foliated microstructure.

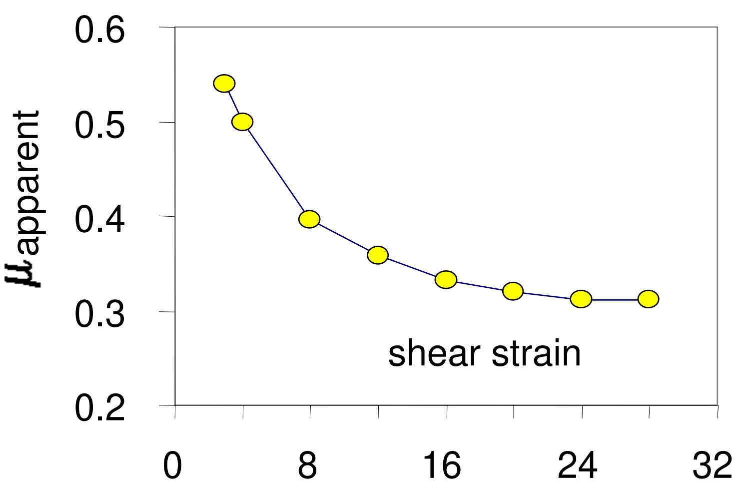
(Bos & Spiers JSG, 01; Bos et al., JGR, 02; Niemeijer & Spiers, 05)



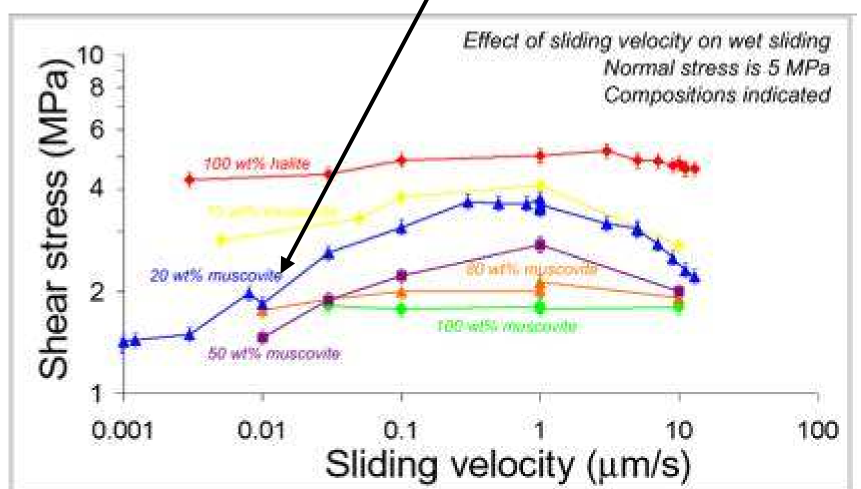




Decrease in friction moving from low to high strain



At low slip-rates the formation of foliated fault rock is a velocity-strengthening process pointing to aseismic creep)



LANF paradox?

If crustal extension is accommodated by a fault zone hundreds of meters thick

If the medium is governed by non Byerlee's friction ($\mu s<<0.6$)

If microseismicity is fluid driven and clustered in velocity weakening patches

If most of the fault is velocity strengthening and/or creeping

…the paradox does not exists!

thank you

good thoughts

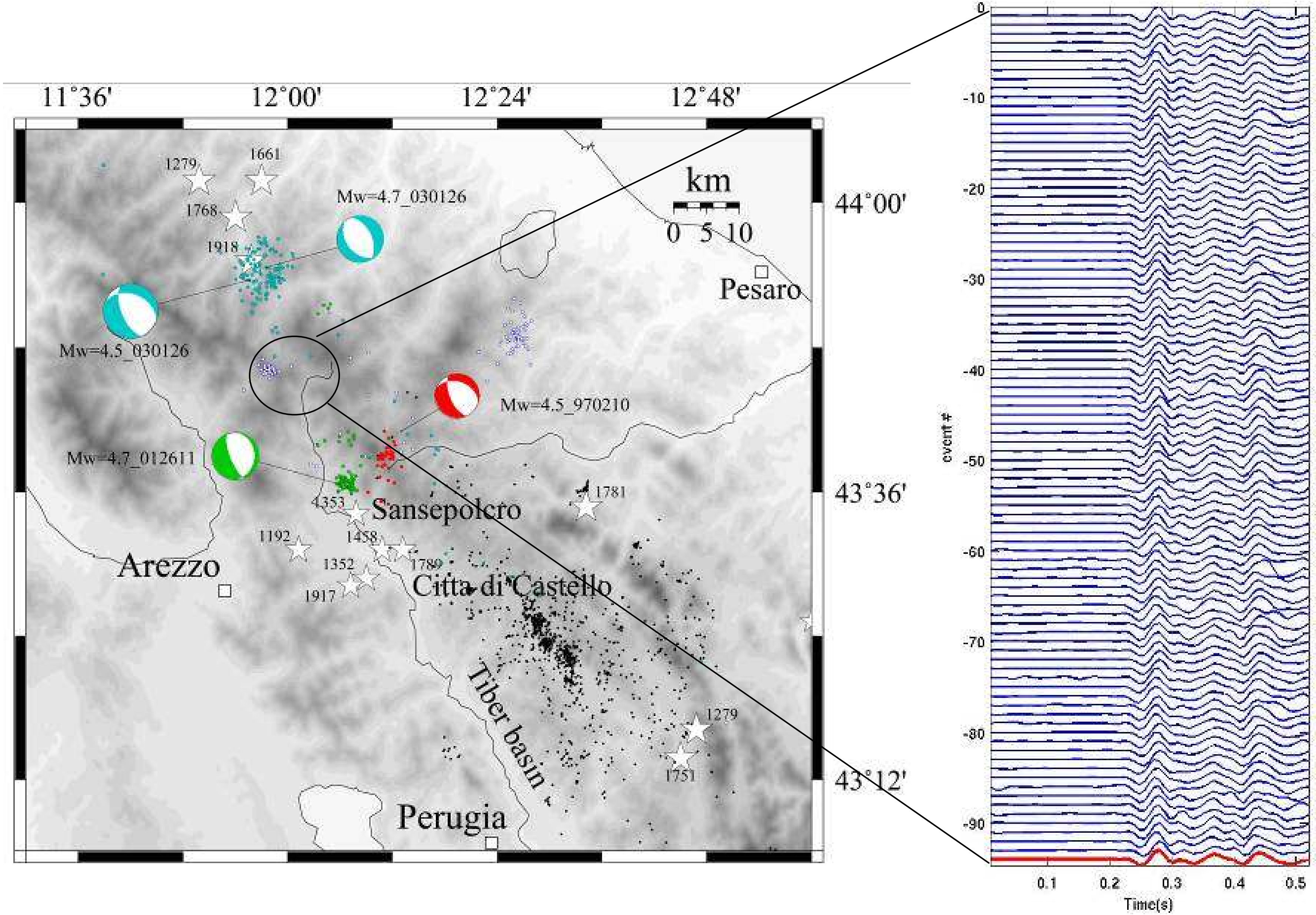
Seismologists: improve the resolution and enlarge the time window of the observation (ATF will be a test site for INGV, where we will install a permanent dense gps-seismic networks)

Geologists: find out the micro-earthquake signature on the fault outcrop

Lab: perform experiments on real samples and/or analogue materials

…all together: model the results!

NW


11°36'
12°00'
12°24'
12°48'
44°00'
43°36'
43°12'
km
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Pesaro
1279
1661
1768
1918
Mw=4.7_030126
Mw=4.5_030126
Mw=4.5_970210
Mw=4.7_012611
4353
Sansepolcro
1781
1192
1458
1789
1352
1917
Arezzo
Citta di Castello
Tiber basin
1279
1751
Perugia
event #
Time(s)

LANF paradox

If we consider that the strain is all concentrated on a planar fault (~0 m thickness)

If the medium is governed by Byerlee's friction ($0.6<\mu s<0.85$)

If the fault generate earthquakes (small-to-large magnitude)…

…**our observations are the first seismological evidence of LANF paradox.**

Paradox? No thanks!

If crustal extension is accommodated by a fault zone (hundreds of meters thick)

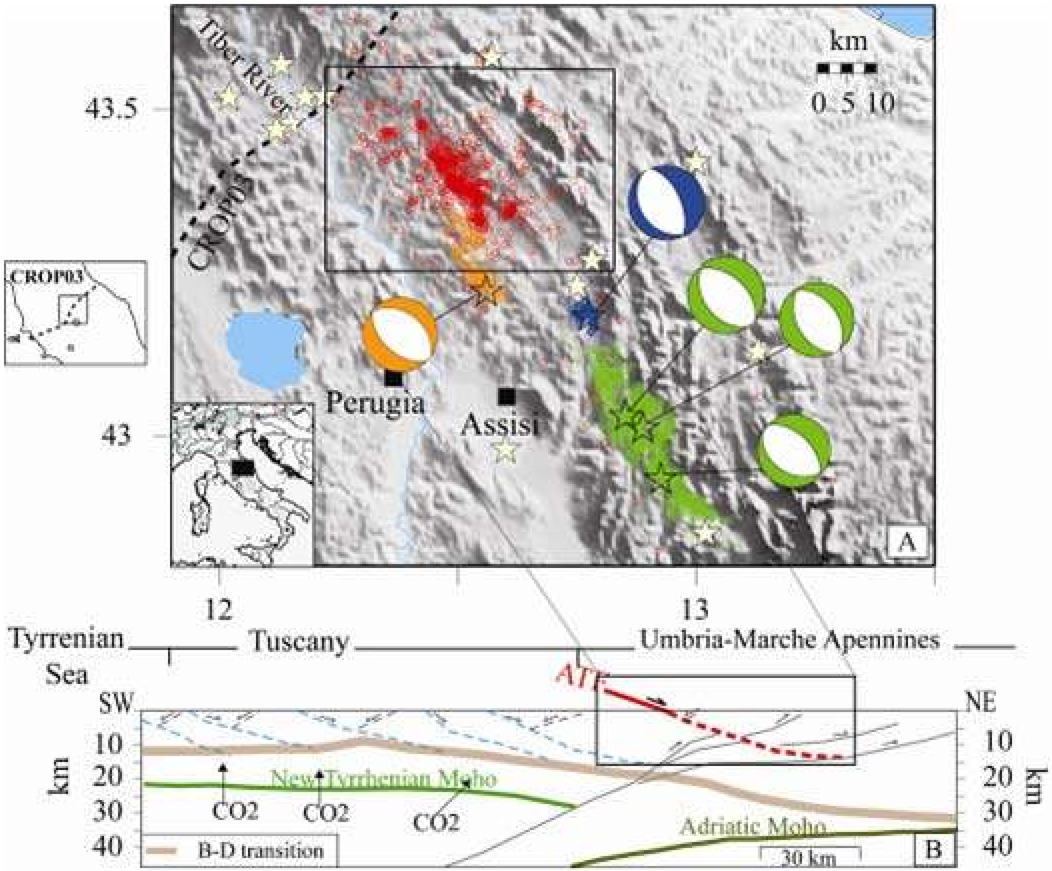
If the medium is governed by non Byerlee's friction ($\mu s<<0.6$)

If microseismicity is fluid driven and clustered in velocity weakening patches

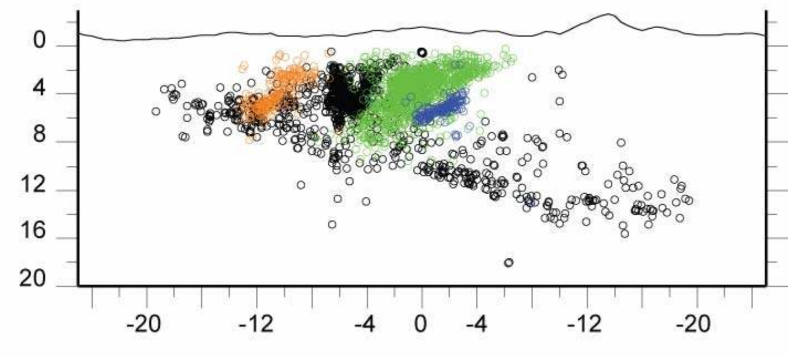
If most of the fault is velocity strengthening and/or creeping

…the paradox does not exists!

SW



Tiber River
CROP03
km
0 5 10
43.5
43
Perugia
Assisi
A
12
13
Tyrrenian Sea
Tuscany
Umbria-Marche Apennines
ATF
SW
NE
km
10
20
30
40
New Tyrrhenian Moho
CO2
CO2
CO2
Adriatic Moho
B-D transition
30 km
B



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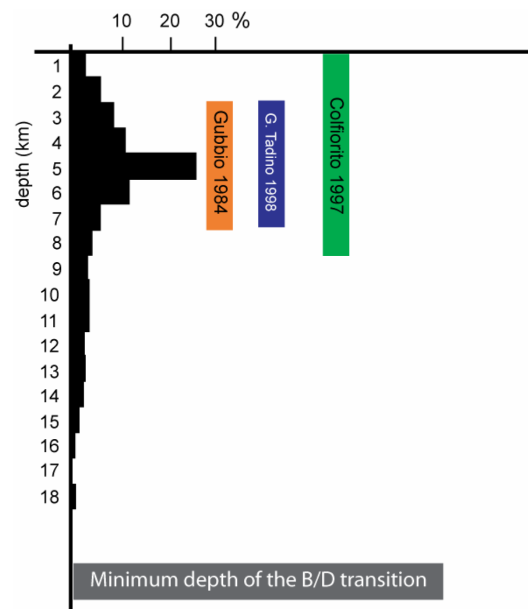

10 20 30 %
depth (km)
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2
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16
17
18
Gubbio 1984
G. Tadino 1998
Colfiorito 1997
Minimum depth of the B/D transition

...seismic activity on LANF

Moderate-to-large eqk

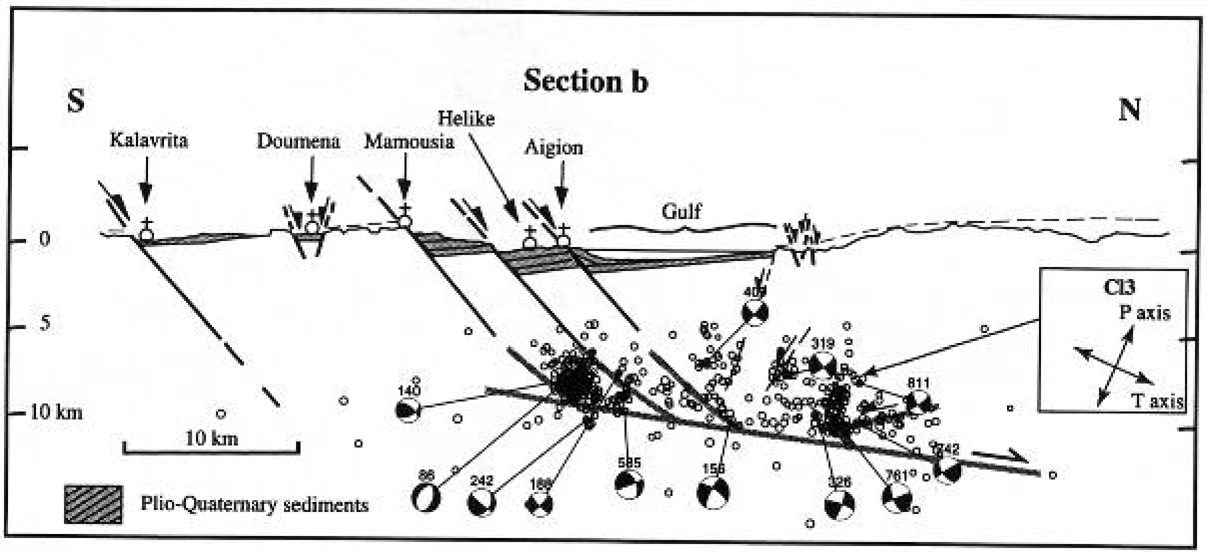
Three events (5.7<Mw<6.8) in Papa Nuova Guinea region (Abers, 1991; Wernicke, 1995) and Messina 1908 eqk (Pino et al., 2000)

Small-to-moderate triggered sub-events

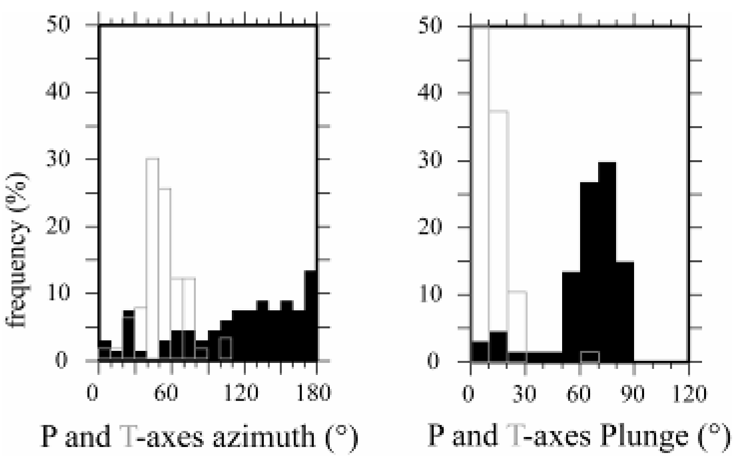
Dixie Valley, Nevada, 1954; Alasehir, Turkey, 1969; Gediz, Turkey, 1970; Irpinia, Italy, 1980

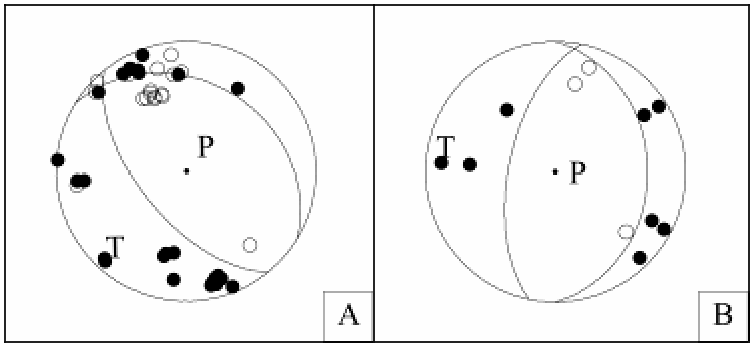
Microseismicity

Gulf of Corinth, Greece (Rigo et al., 1996)



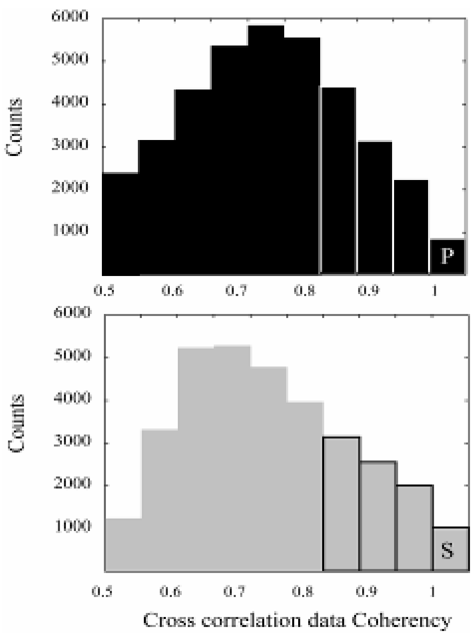
stress and strain

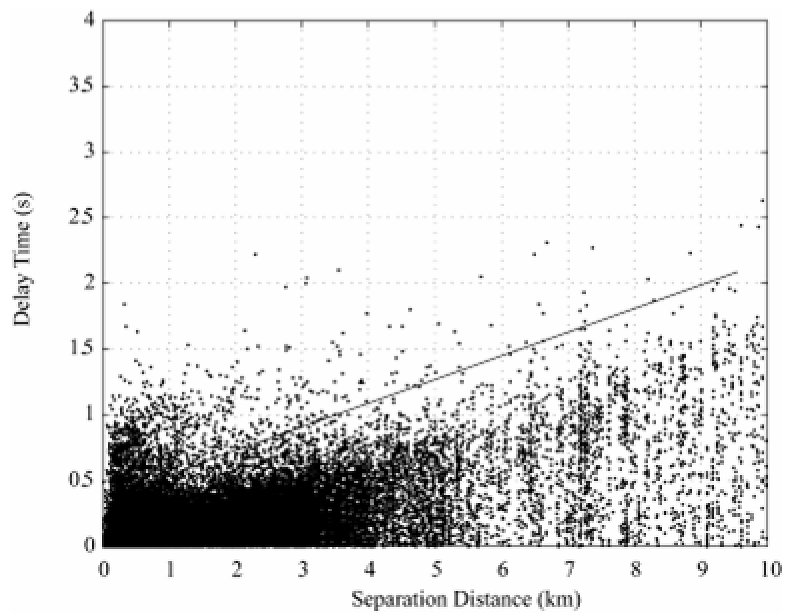




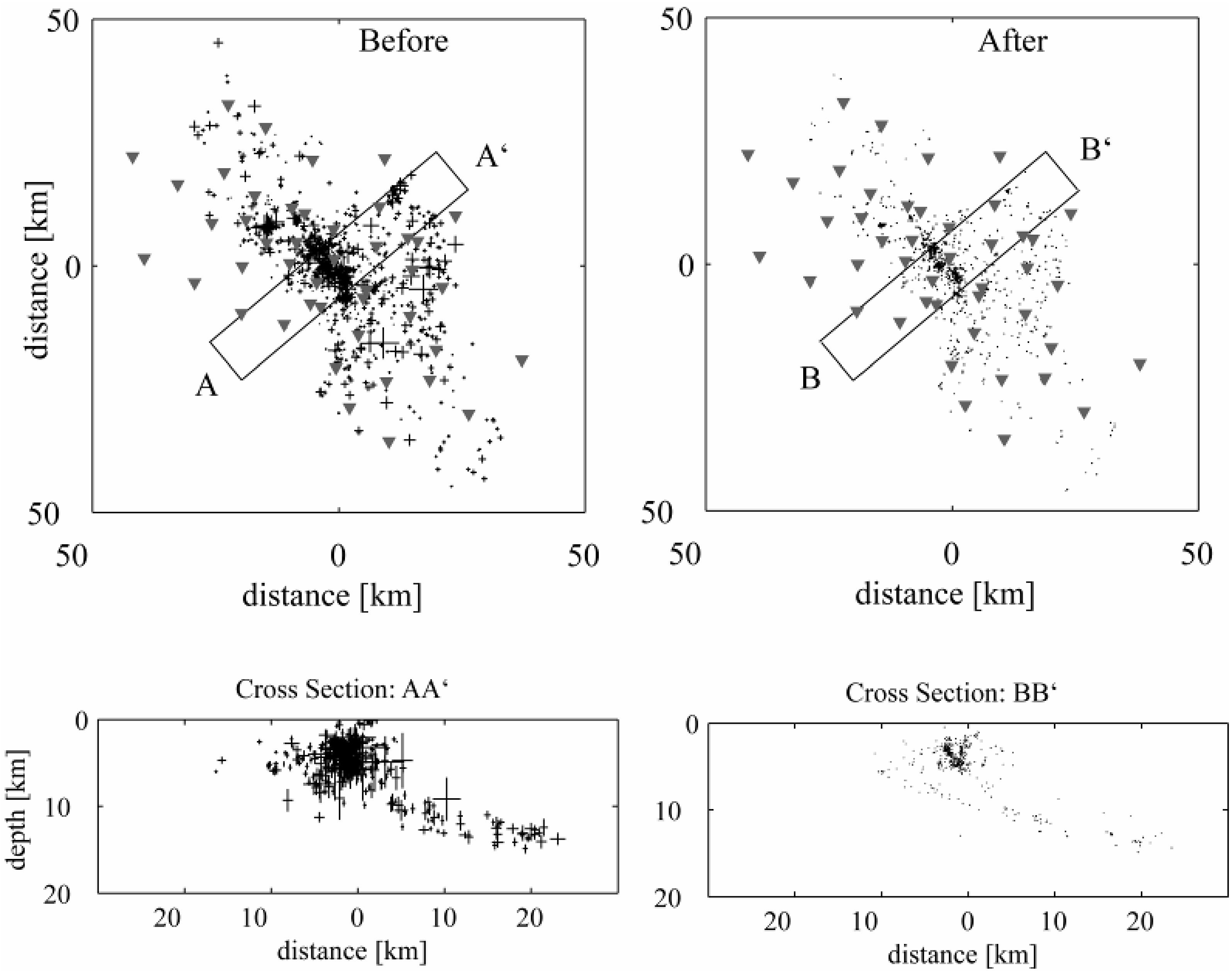
recolation method

Quality of the CC data. Histogram of the coherency values of P- and S-phases used to determine travel times differences between events at a common station.

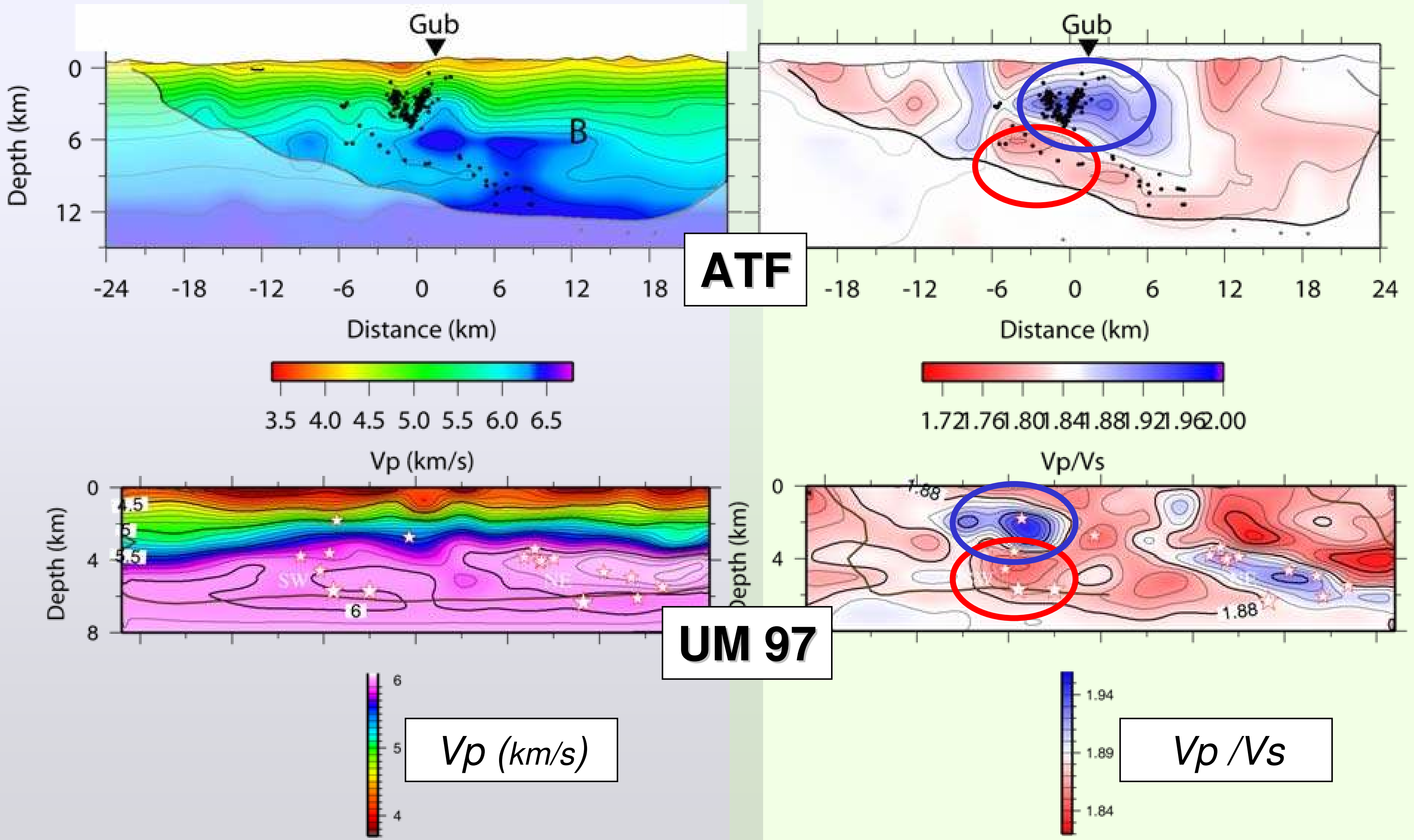




relocation results (1416 eqk)



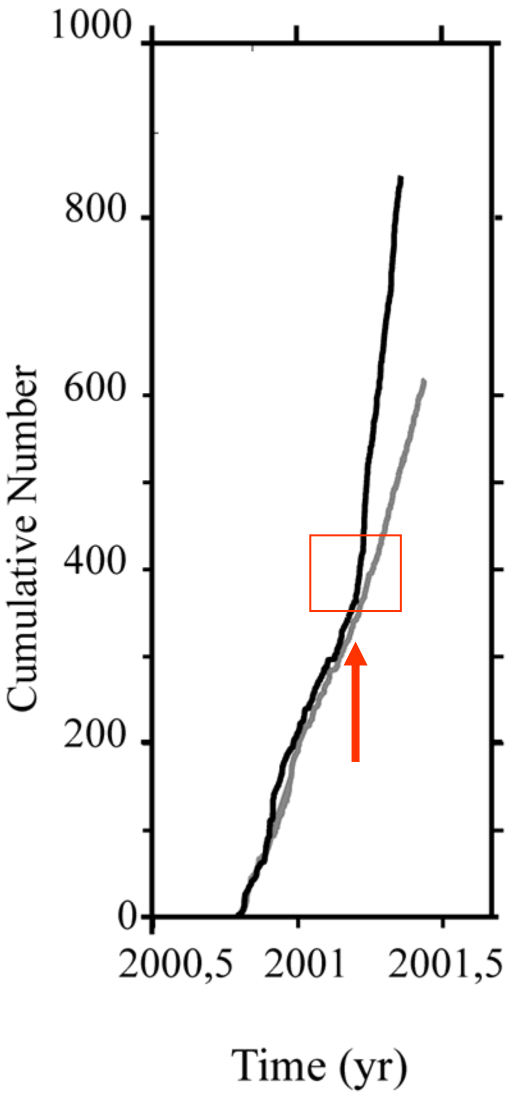
liquid vs vapour filled

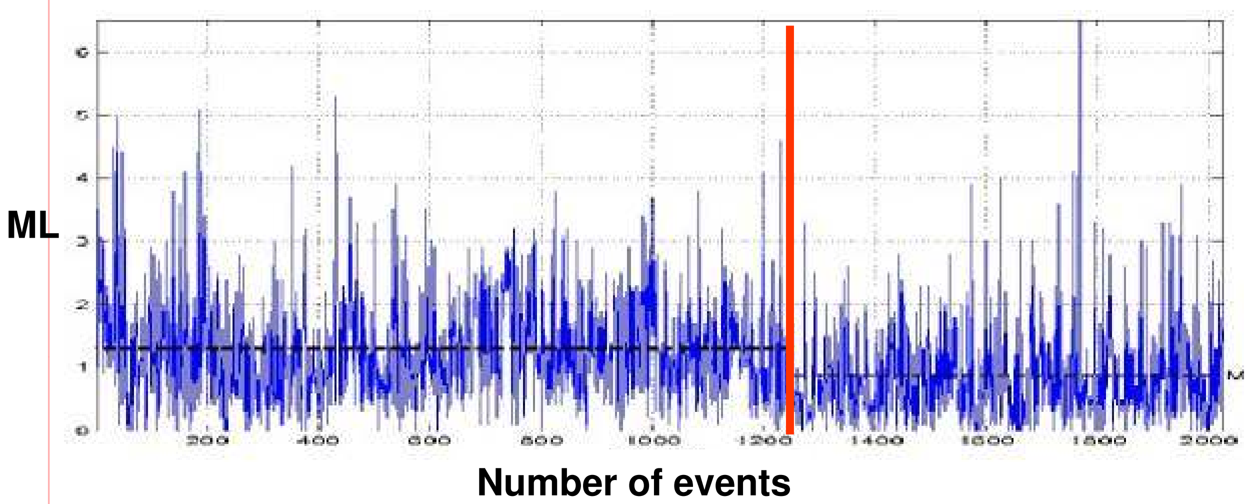


rate of seismic release

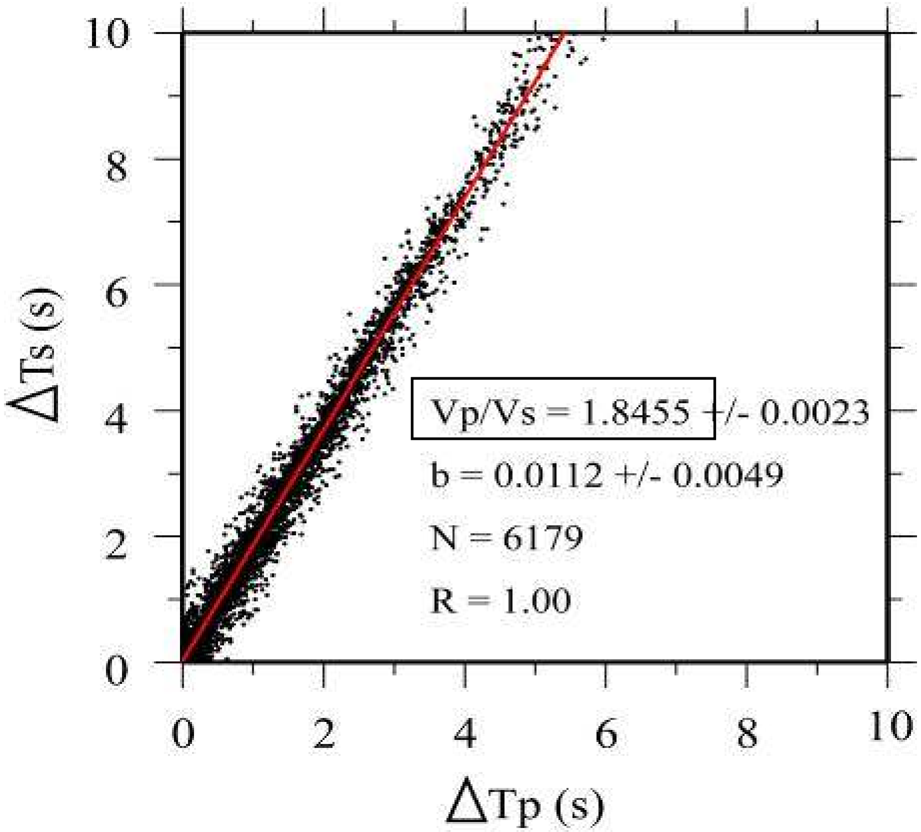
Seismicity on the ATF hangingwall

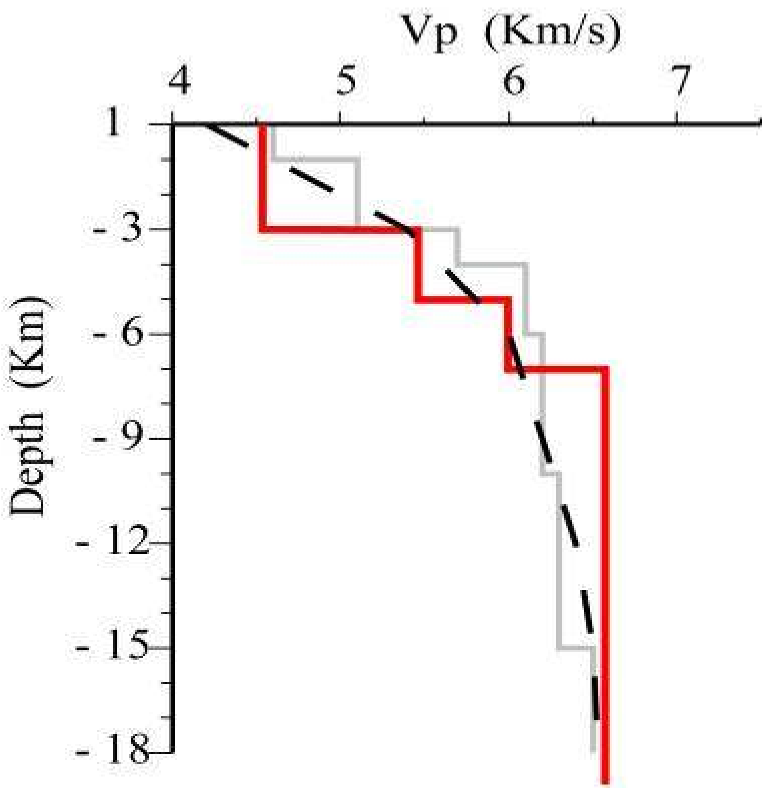
Seismicity on the ATF plane





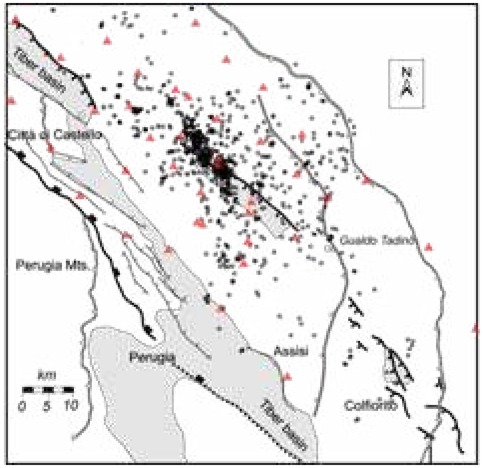
velocity model and Vp/Vs





relocation method

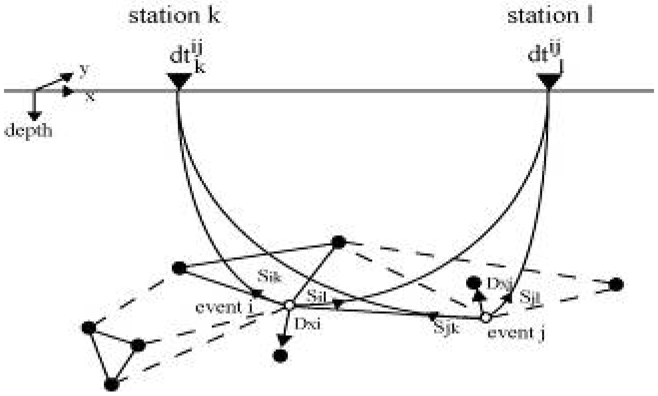
The seismological data set collected in 8 months deploying 33 seismic stations, is composed of 2000 events with M<3.1. Network geometry on the right (*Piccinini et al., 2001*)



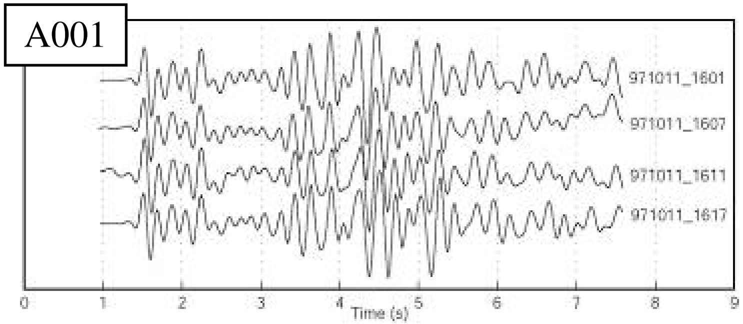
Double-Difference relocation algorithm (*Waldhauser and Ellsworth, 2000*)

$$\frac{\partial t_k^i}{\partial \mathbf{m}} \Delta \mathbf{m}^i - \frac{\partial t_k^j}{\partial \mathbf{m}} \Delta \mathbf{m}^j = dr_k^{ij},$$

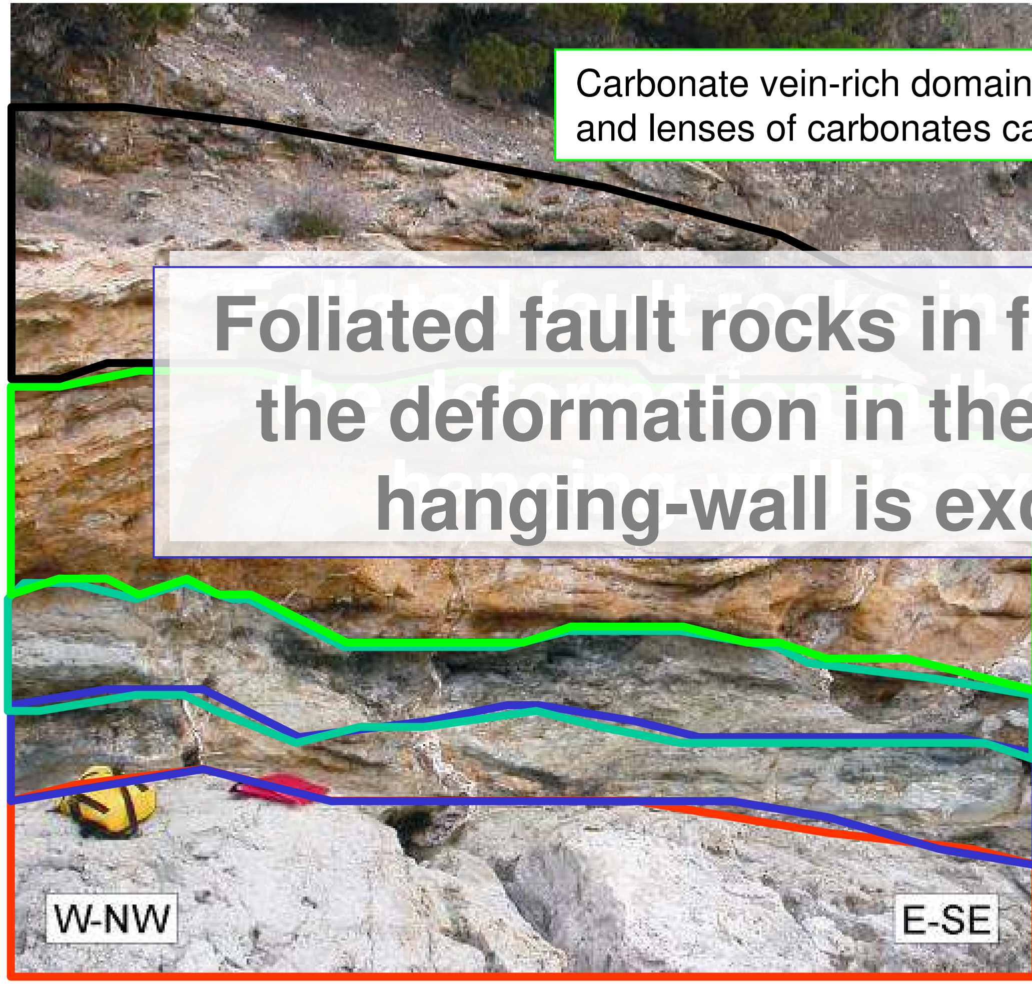
$$dr_k^{ij} = (t_k^i - t_k^j)^{obs} - (t_k^i - t_k^j)^{cal}$$



Waveforms cross-correlation (cc) method (*Schaff, 2002*). Example of multiplet recorded at station A001 containing P and S wave trains. The cc have been performed in the time domain within a tapered 2.56 s window (100 sps)



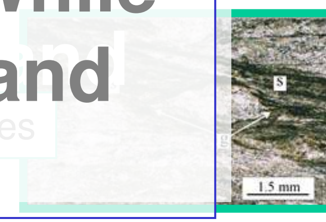
the Zuccale fault



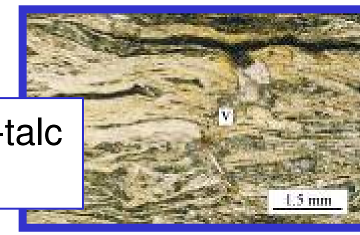
Foliated fault rocks in fault core only, while the deformation in the fault foot-wall and hanging-wall is exclusively brittle.

Fault gouge and fault breccia

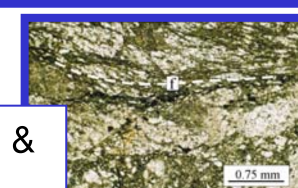
Carbonate vein-rich domain in cataclasite incorporating pods and lenses of carbonates calcshists and ultramafic material



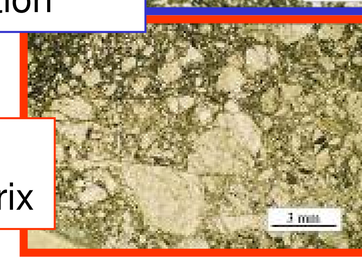
Heterogeneous unit of phyllonites



Higly foliated unit of tremolite-talc chlorite and reworked veins



Cataclastic textures overprinted & 'smeared out' into the foliation



Cataclasite set in a Carbonate-chlorite quartz matrix

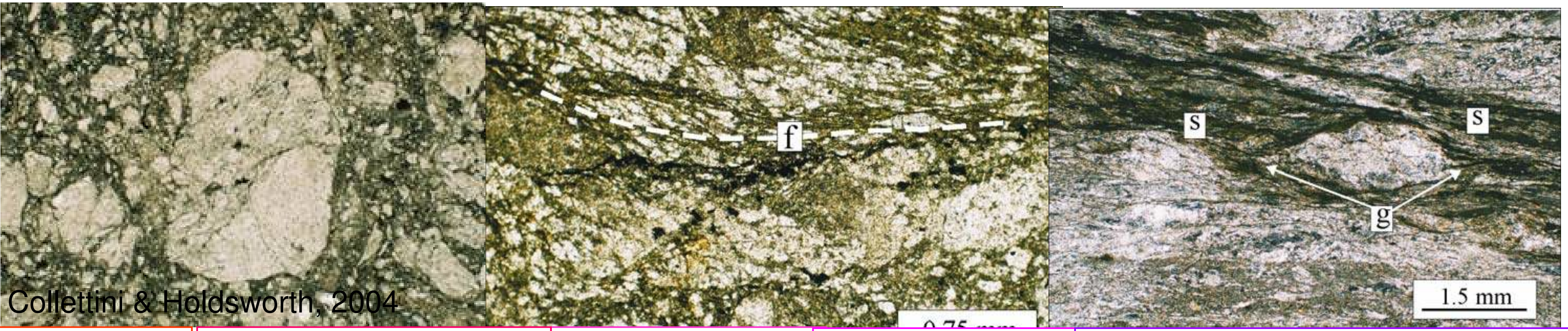
Collettini & Holdsworth, 2004

the Zuccale fault

The localization of strain into the foliated fault core suggests that these processes led to significant weakening of the fault zone

Low strain

High strain



Cataclasis	Brittle dilatancy & increase of permeability	Influx of hydrous fluids	Reaction with fine-grained cataclasites	Reaction softening & onset of fluid-assisted diss-ppt processes

621 eqks on the ATF (ML<2.3)