La fase di preparazione dei forti terremoti: appunti per una sismologia 2.0

Antonio Piersanti

INGV Roma

102° CONGRESSO NAZIONALE DELLA SOCIETÀ ITALIANA DI FISICA, Padova, 26-30 Settembre 2016

‘Within recent years scientists in several countries …have increased their efforts to understand the earthquake mechanism with the goals of earthquake prediction…At present the situation is very promising.’ (Alsop & Oliver, 1969 EOS)

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Recent technical advances have brought the goal of earthquake prediction within reach. With adequate funding several countries, including the U.S., could achieve reliable long-term and short-term forecasts in a decade.’ (Press, 1975 Scientific American)

The peaks of optimism were sessions at the Spring meeting of the American Geophysical Union (AGU) in 1973 (Lubkin 1973; Hammond 1973a) and 1974 (Hammond 1974). Prediction research was reviewed by Kisslinger (1974) in Physics Today. Prediction was covered extensively and in a generally optimistic light during the period 1972-1975

Hamilton (1974) said: 'The ability to predict the time, location and magnitude of seismic events presents earth scientists with an opportunity to help alleviate the ravages of earthquakes. The prediction capability is developing much more rapidly than all but a few scientists believed possible.'

Brace (1975) said: '...earthquake prediction is now a field with a great deal of scientific momentum, and those involved are optimistic about not only predicting but also controlling earthquakes.'

Geller: GJI 1997:

SUMMARY Earthquake prediction research has been conducted for over 100 years with no obvious successes... Theoretical work suggests that faulting is a non-linear process which is highly sensitive to unmeasurably fine details of the state of the Earth in a large volume, not just in the immediate vicinity of the hypocentre. Any small earthquake thus has some probability of cascading into a large event. Reliable issuing of alarms of imminent large earthquakes appears to be effectively impossible.

Geller: GJI 1997: (QUESTO ARTICOLO DOMINA LE RICERCHE PREDICTION-RELATED SU GOOGLE)

SUMMARY Earthquake prediction research has been conducted for over 100 years with no obvious successes… Theoretical work suggests that faulting is a non-linear process which is highly sensitive to unmeasurably fine details of the state of the Earth in a large volume, not just in the immediate vicinity of the hypocentre. Any small earthquake thus has some probability of cascading into a large event. Reliable issuing of alarms of imminent large earthquakes appears to be effectively impossible.

Brune, 1974

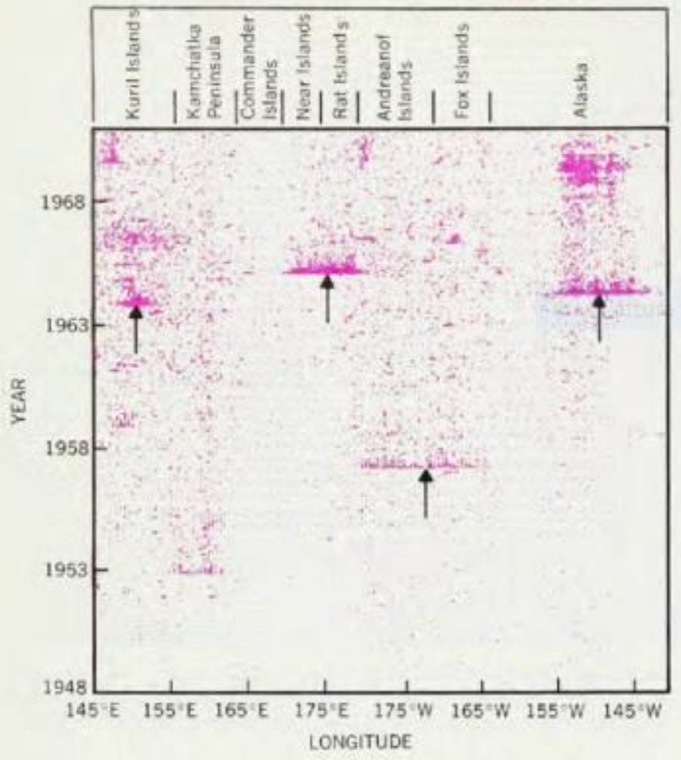
The general mechanical model for earthquake prediction is consistent with modern concepts. Unfortunately, it contains within it a possibly severe constraint on the accuracy of any prediction scheme: earthquakes represent a critical-limit phenomenon and might be triggered by a wide variety of effects such as atmospheric loading, tidal strains, nearby small and unpredictable earthquakes, unpredictable creep events in the mantle or shallow crust, or hopefully by the episodic and observable increase in tectonic strain.

One hope for earthquake prediction is based on finding reliable precursory phenomena. A systematic search for such phenomena associated with large earthquakes is just beginning

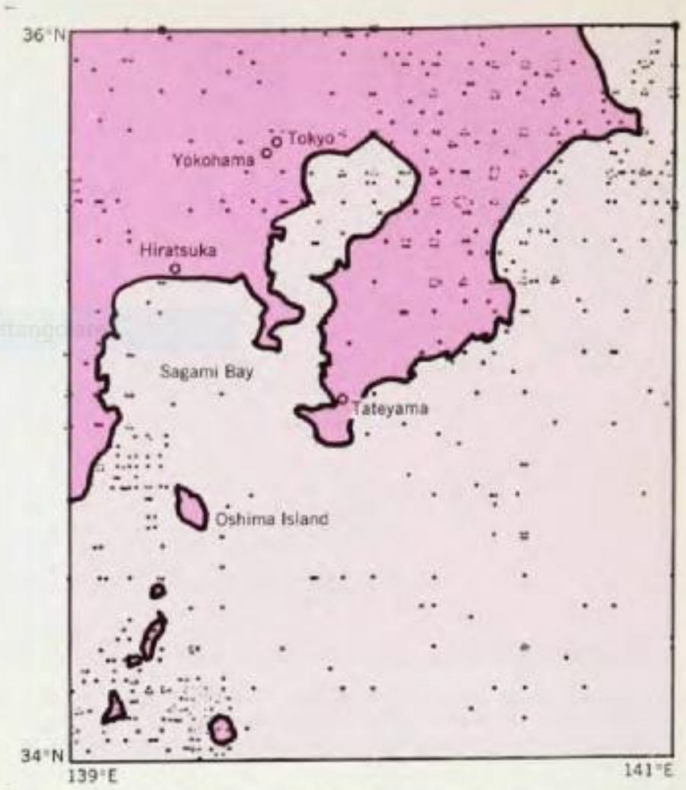
- https://en.wikipedia.org/wiki/Prediction_of_volcanic_activity

- https://en.wikipedia.org/wiki/Earthquake_prediction

Certo persiste il problema della maggiore difficolta' di osservazione del sistema sismogenetico rispetto al sistema vulcanico…ma e' tale maggiore difficolta' sufficiente a farci decretare il problema come certamente IMPOSSIBILE? Soprattuto alla luce dei recenti progressi nell'acquisizione e trattamento del dato?



Space-time plot of earthquakes in northwest basin of the Pacific shows major events and aftershocks (arrows) preceded by gaps in seismic activity. The greater number of points in recent years reflects the improved density and quality of recording instruments. (Unpublished data from E. R. Engdahl.) Figure 2



Inactive area in Sagami Bay, Japan, may be the site of the region's next major earthquake. The points are epicenters in the south Kanto region of Japan during 1926–67. This bay was the location of a great earthquake in 1923 and of others as far back as 818 AD. (From K. Shimazaki, reference 4.) Figure 3

Kisslinger (1974)

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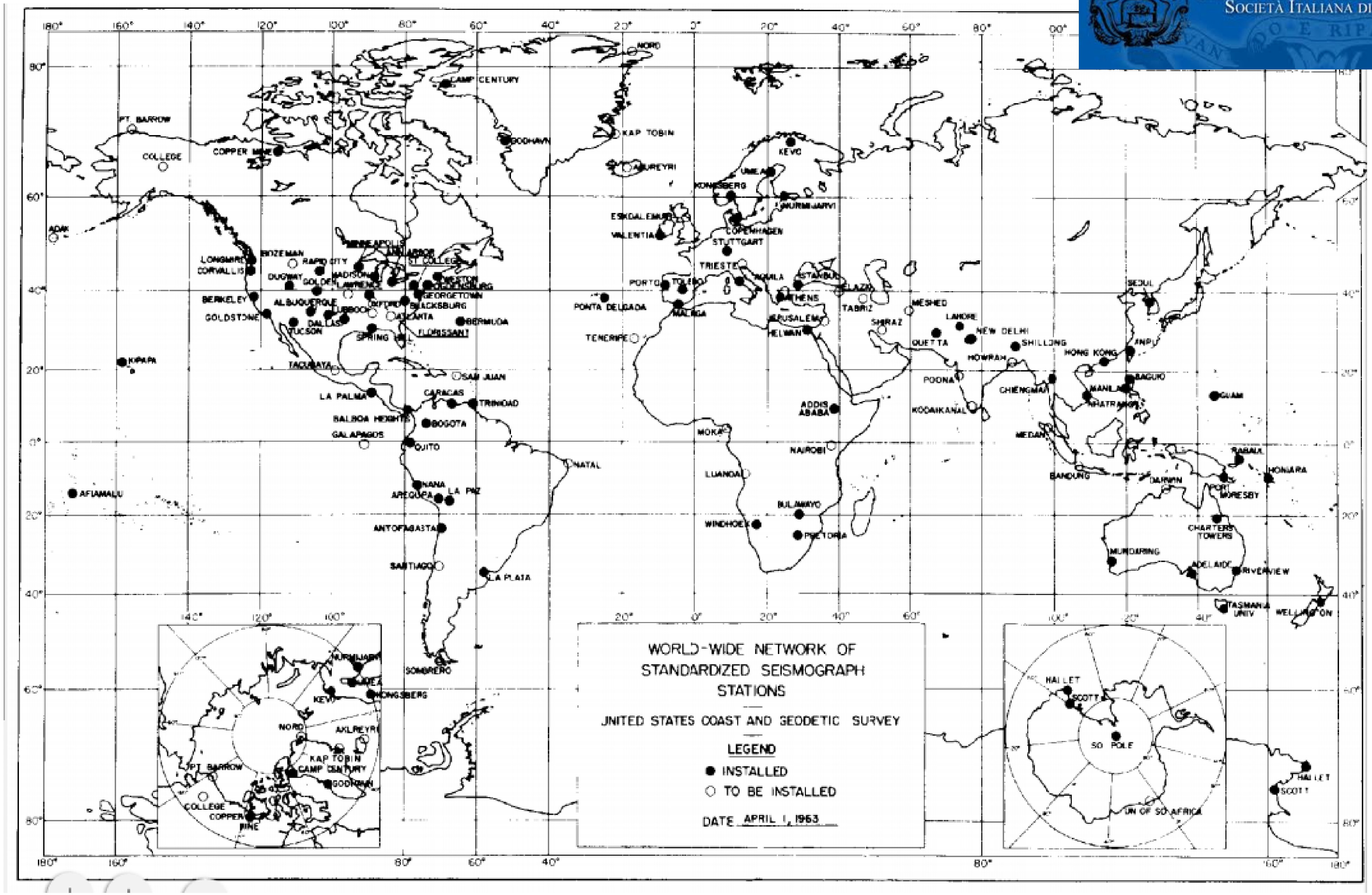

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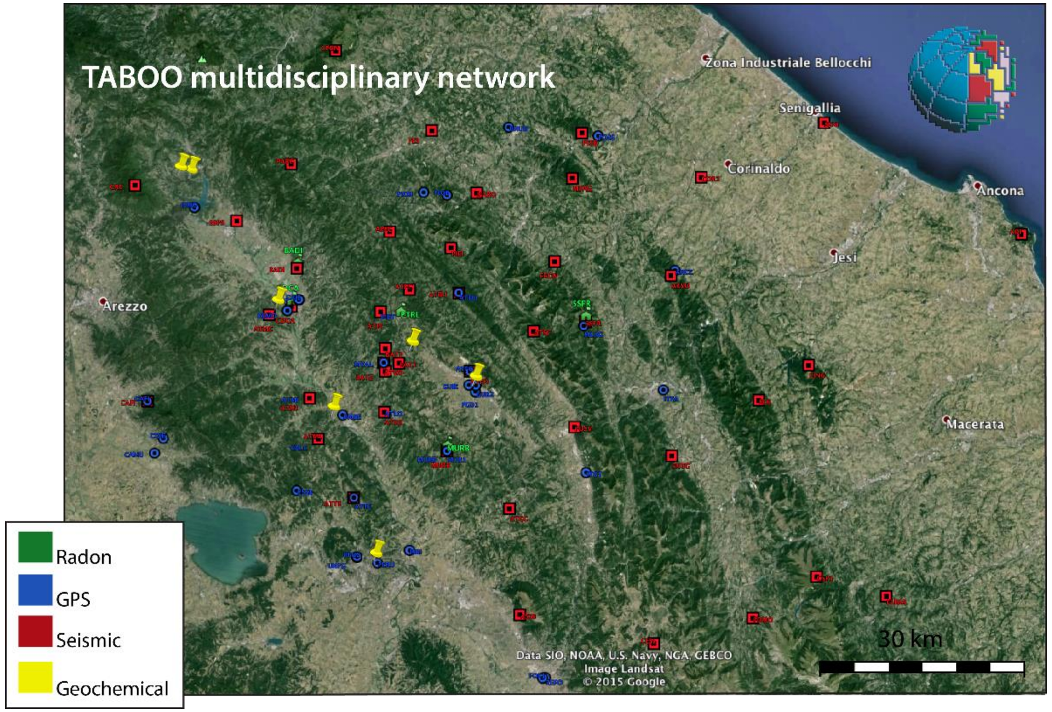
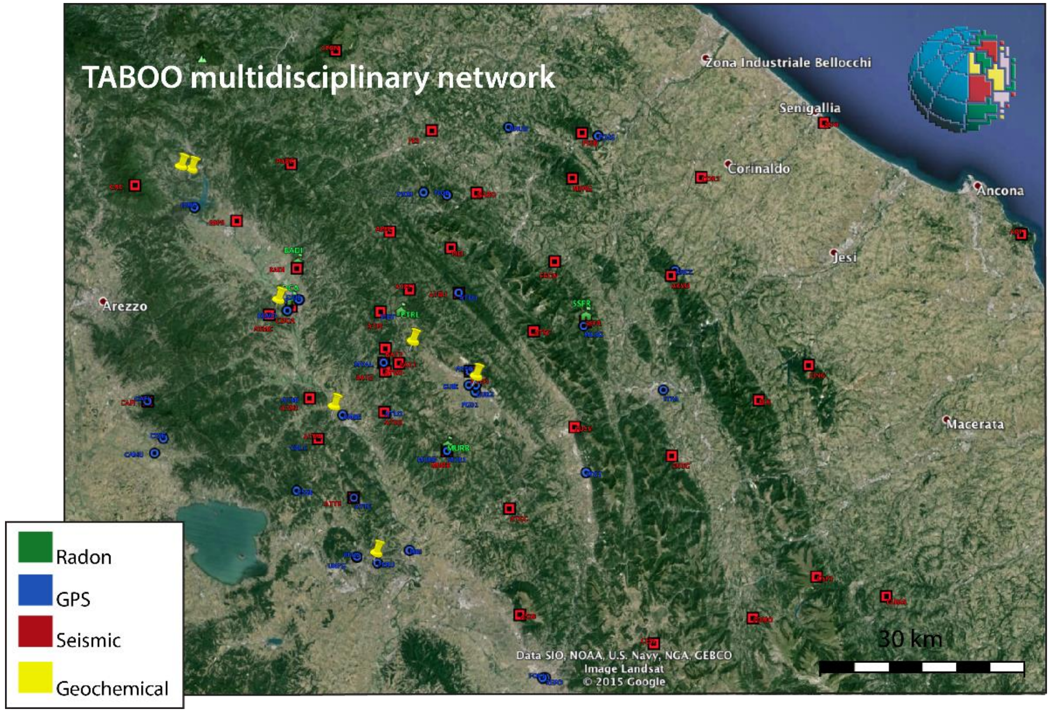

TABOO multidisciplinary network
Zona Industriale Bellocchi
Senigallia
Corinaldo
Ancona
Jesi
Arezzo
Macerata
30 km
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
© 2015 Google
Radon
GPS
Seismic
Geochemical

TABOO: Near Fault Observatory

The understanding of the multi-scale physical and chemical processes controlling faulting earthquake generation requires the availability of long time series of high-quality multidisciplinary data collected through high-resolution permanent observation systems.

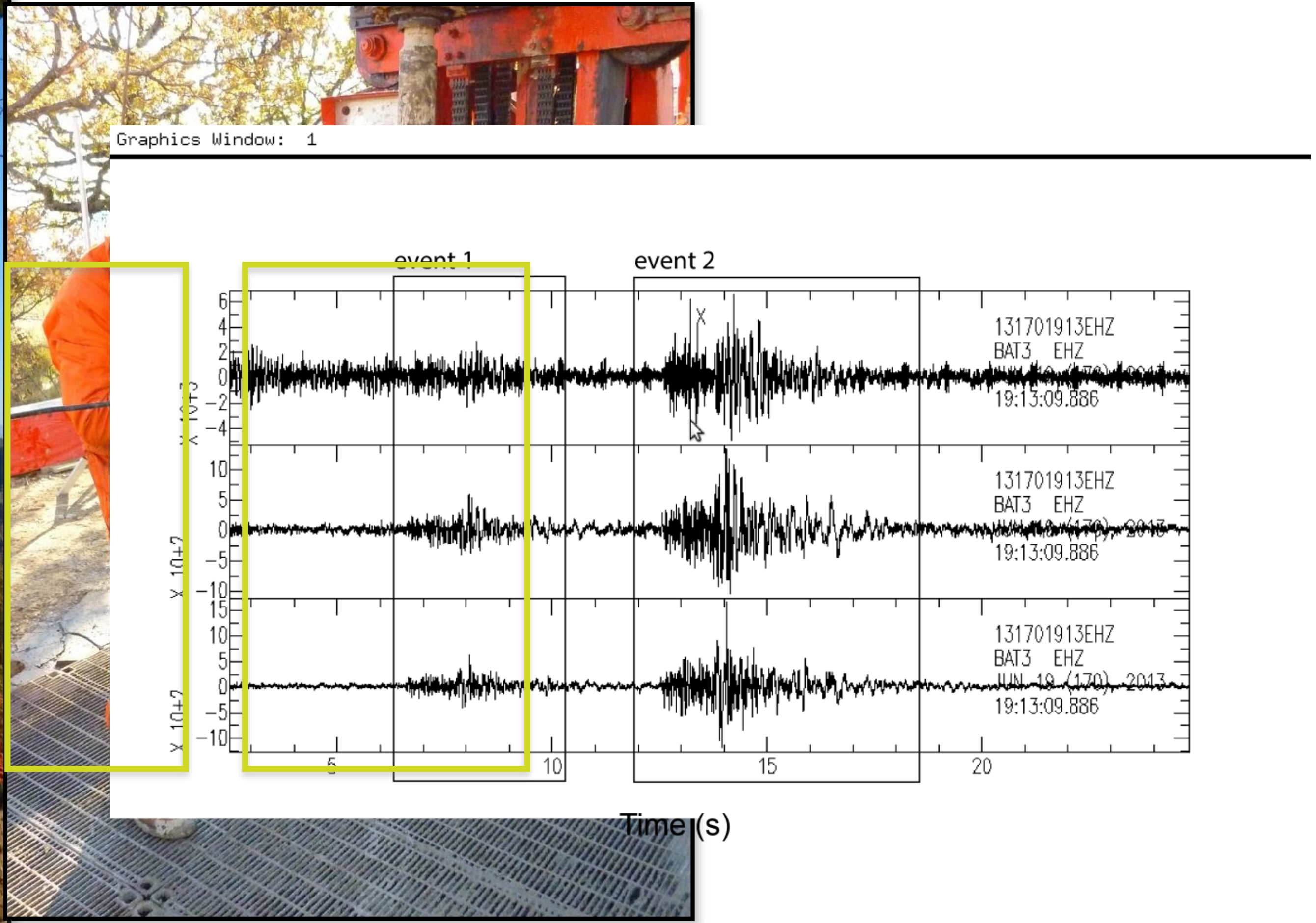
TABOO is devoted to the understanding of the short/long term deformation processes and related transient signals linked to the activity of a 60 km long normal fault system dominated by a large very low angle (15-20° ; LANF) normal fault [Alto Tiberina; ATF].



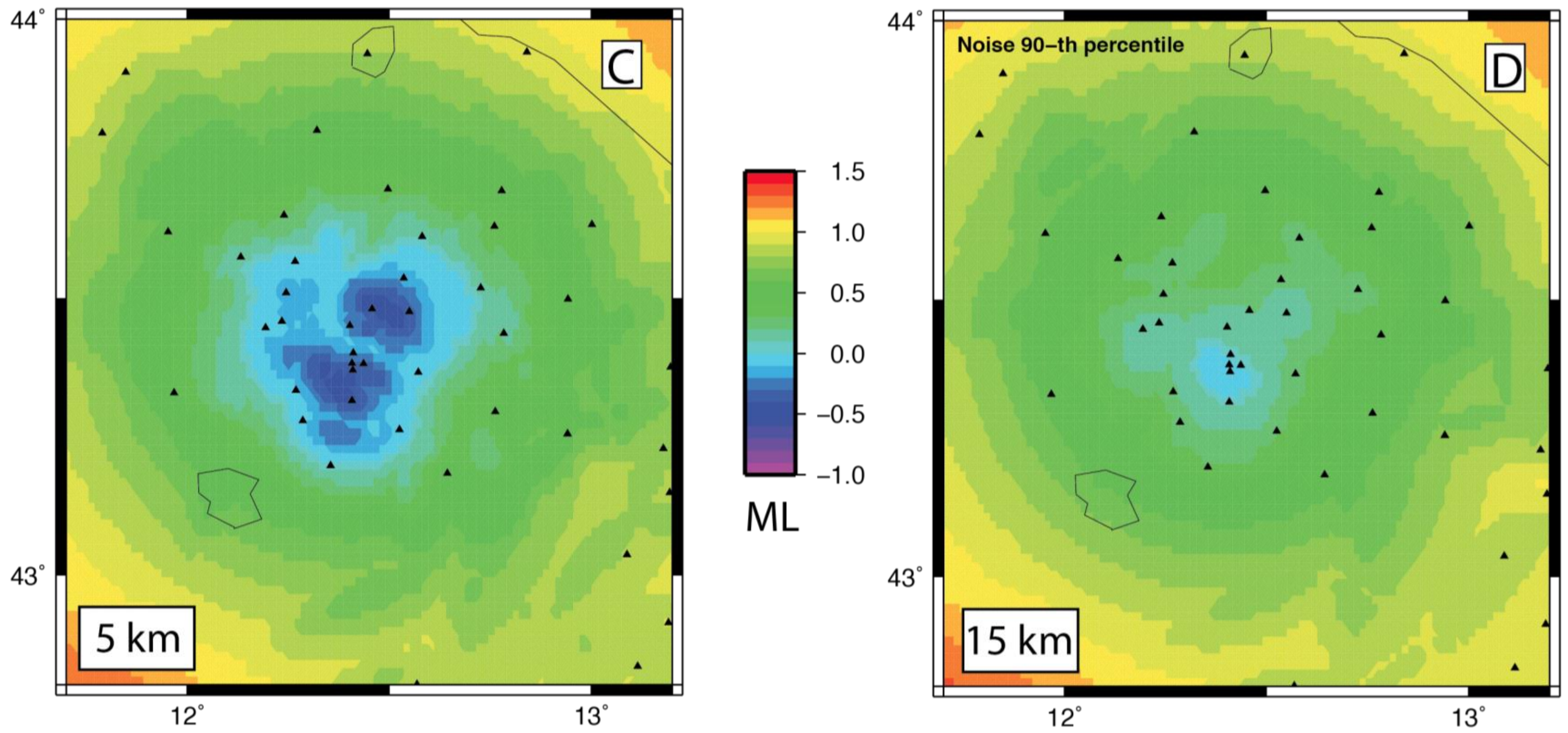
Shallow boreholes (250 m)

2 H_Z 3C passive sensors sampled at 0.5-1 kH_Z

Shallow boreholes

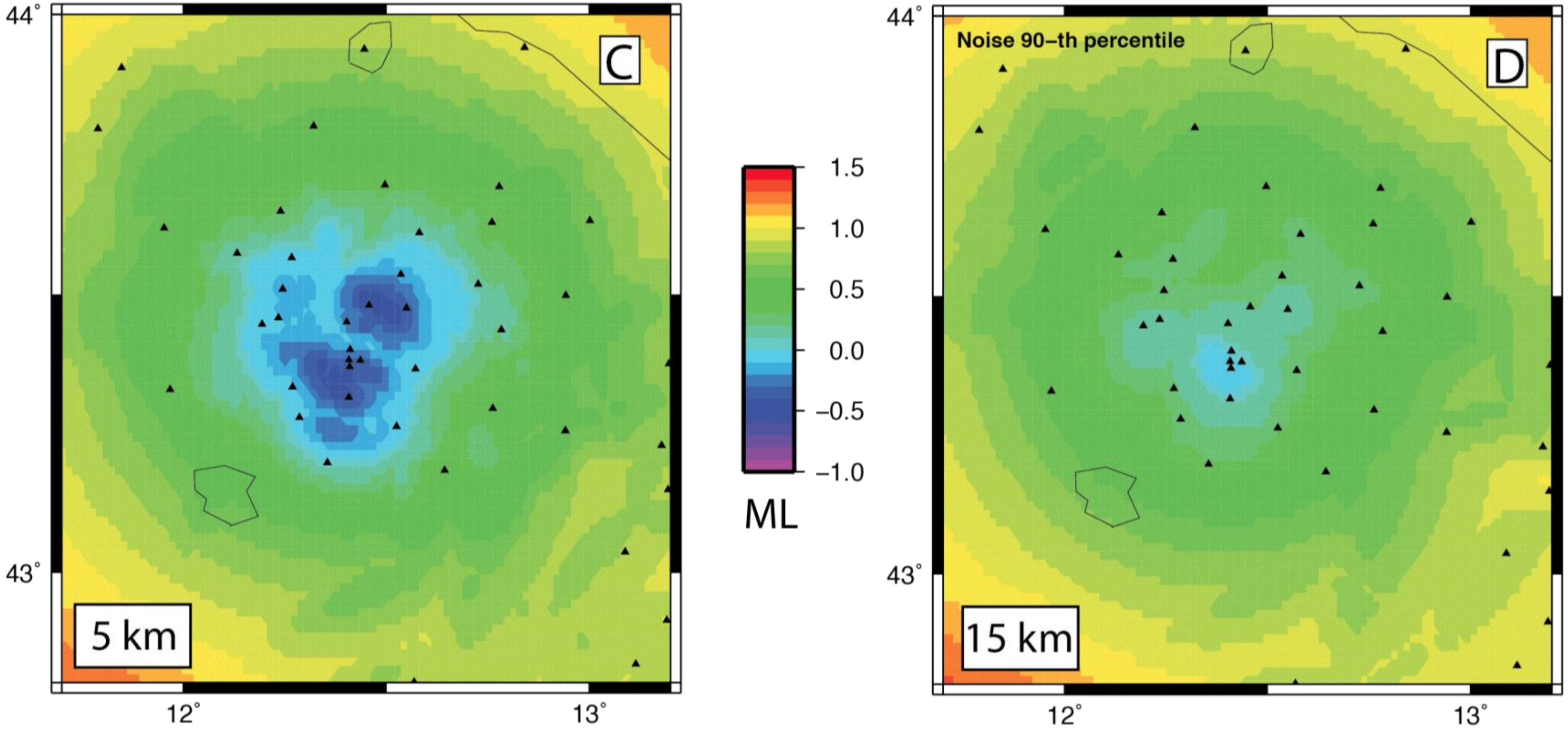


TABOO seismic network M_C



Chiaraluce et al., 2014

TABOO seismic network M_C



Chiaraluce et al., 2014

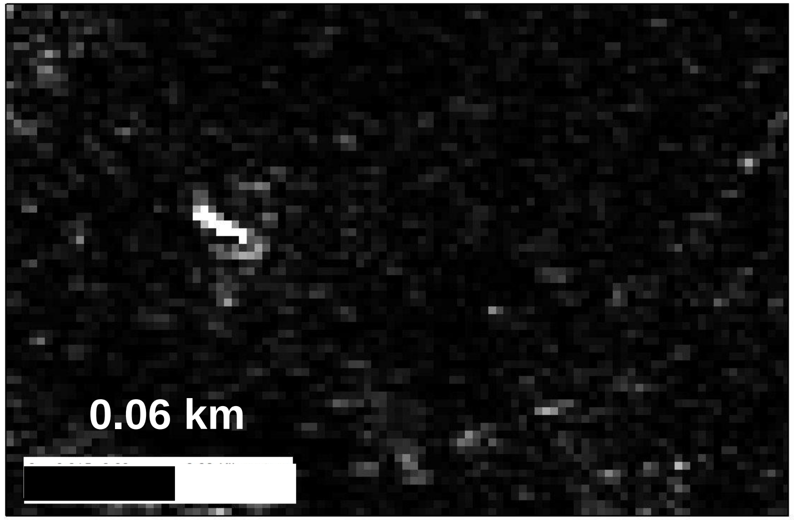
M=-1→ fratture millimetriche

New instruments

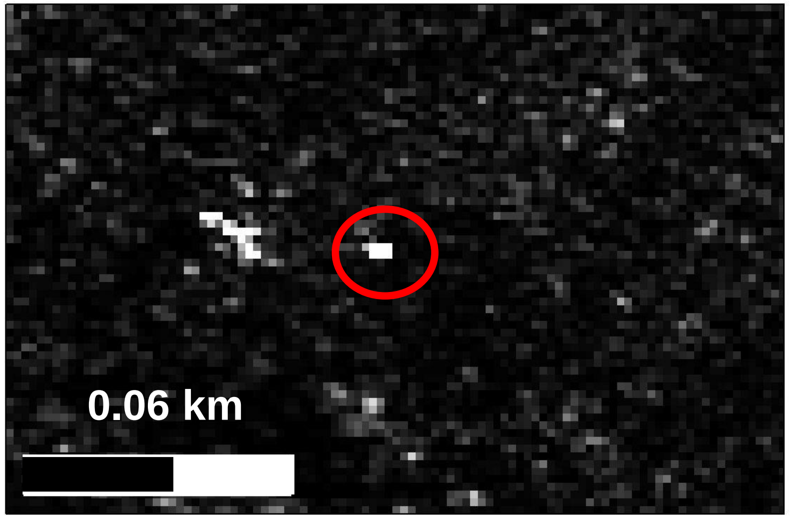
A network of SAR passive Corner Reflectors (CR) X-Band is under installation

Corner Reflectors

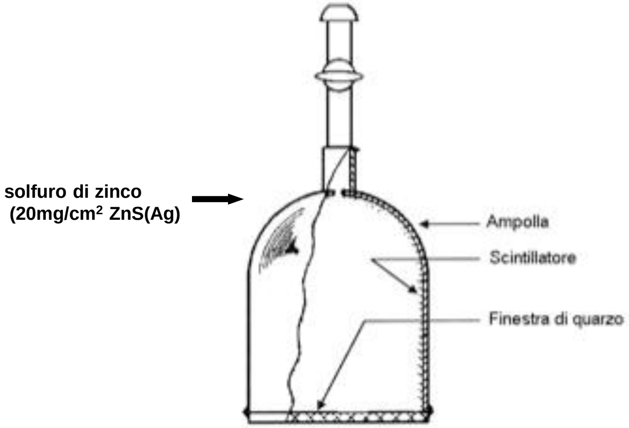
Thanks to the shape and size, the CRs allow obtaining a Radar Cross Section (RCS) resulting in an **high reflective point** in the SAR image



The development of a network of SAR passive Corner Reflectors (CRs) (first 7 sites have been already deployed in 2014) will be used to calibrate the results of the analysis with X-band COSMO-SkyMed SAR data and derive higher resolution velocity maps.



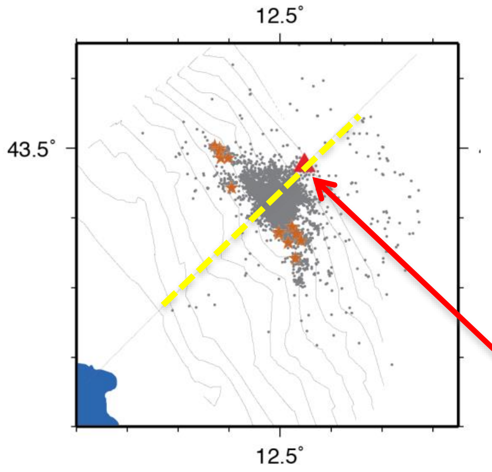
NEW INSTRUMENTS: Active measurement system for Rn



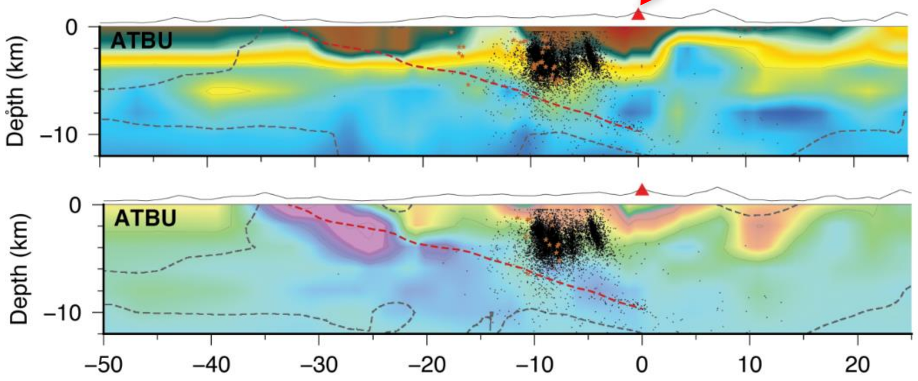
The detector is based on a Lucas cell powered by a 12V battery charged by a power supply connected to 220V or to a solar panel.

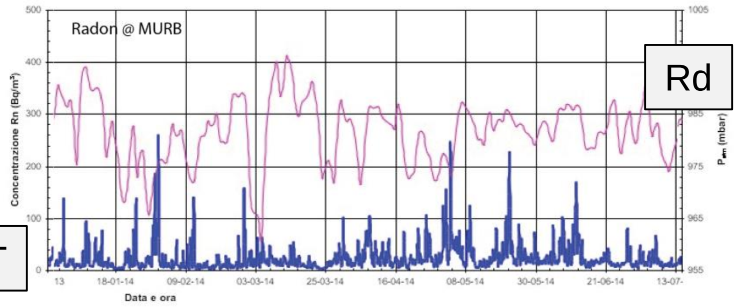
The majority of these instruments have been co-located with the seismometers.

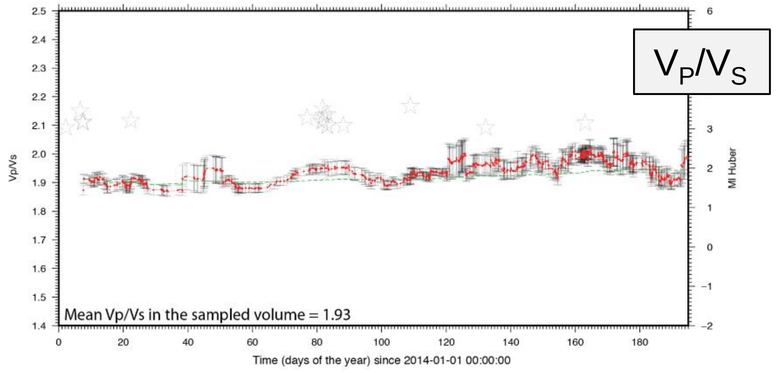
Combined queries to a common DB

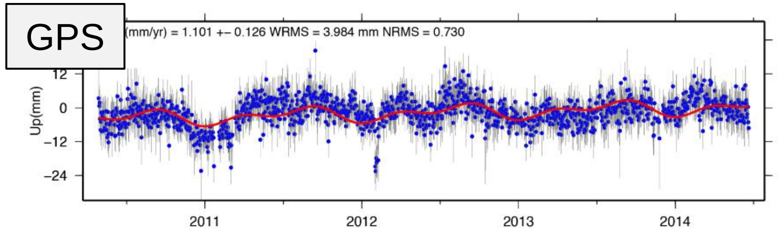


Requested station









… whatever

TABOO observing system

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- **Seismic network:**

  24-Short Period, 18-Broad Band, 12-StrainMeters

  boreholes array:

  9 SP stations (100-250 m)

- **HRcGPS network: 18**

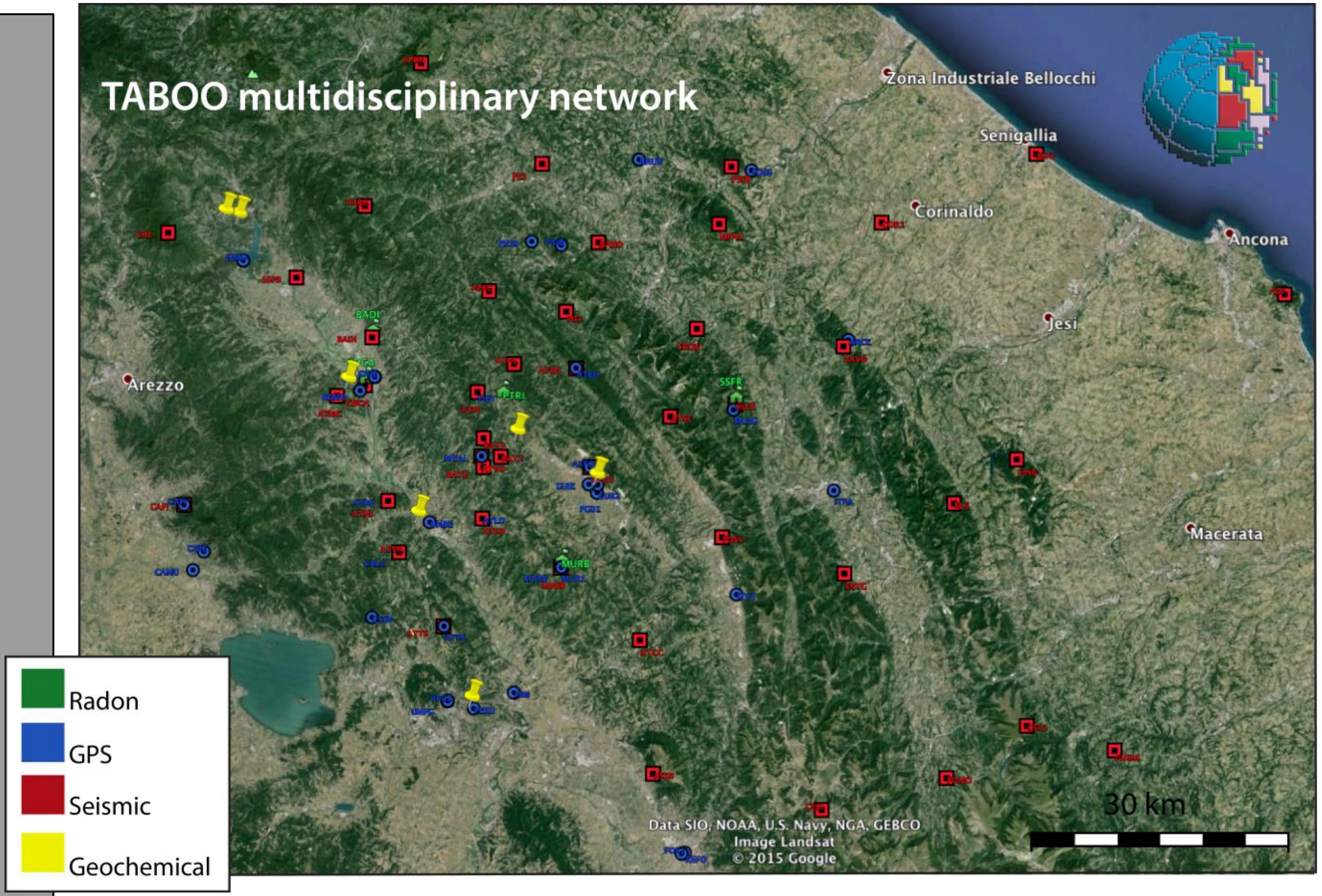
- **Radon stations: 5**

- **Electromagnetic stations:**

  2 (ELF and VLF)

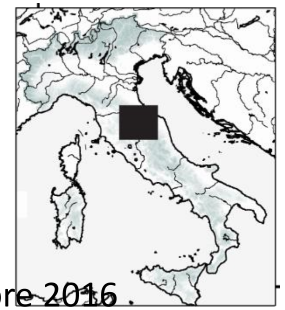
- **Corner Reflectors:**

  7 (passive antennas)



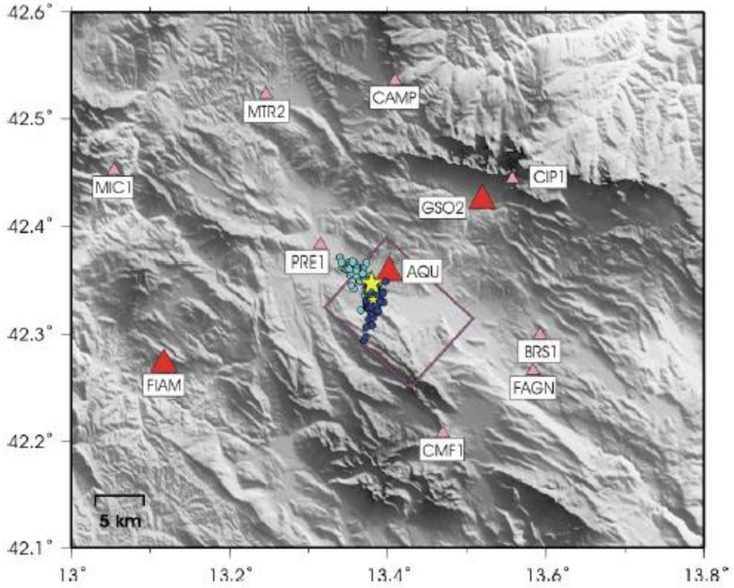
Future developments:

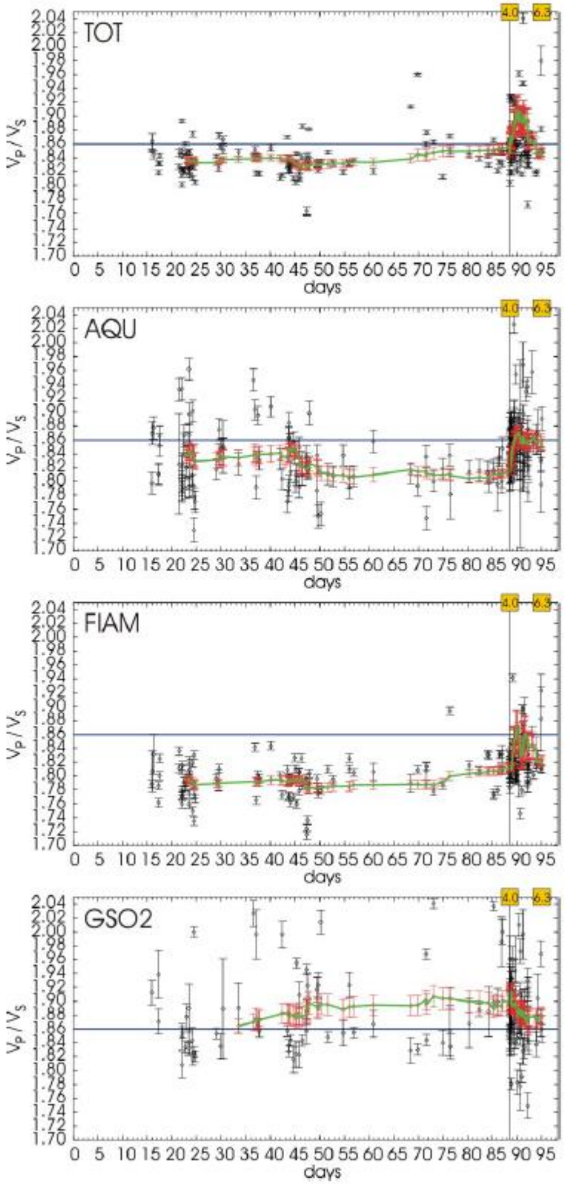
- **6 strain meters in boreholes**
- **9 strong motions**
- **6 geochemical stations**
- **3 CRs**



Elastic parameters transient variations:
2009 L'Aquila earthquake
(Lucente et al. 2010)

Observations on Foreshocks

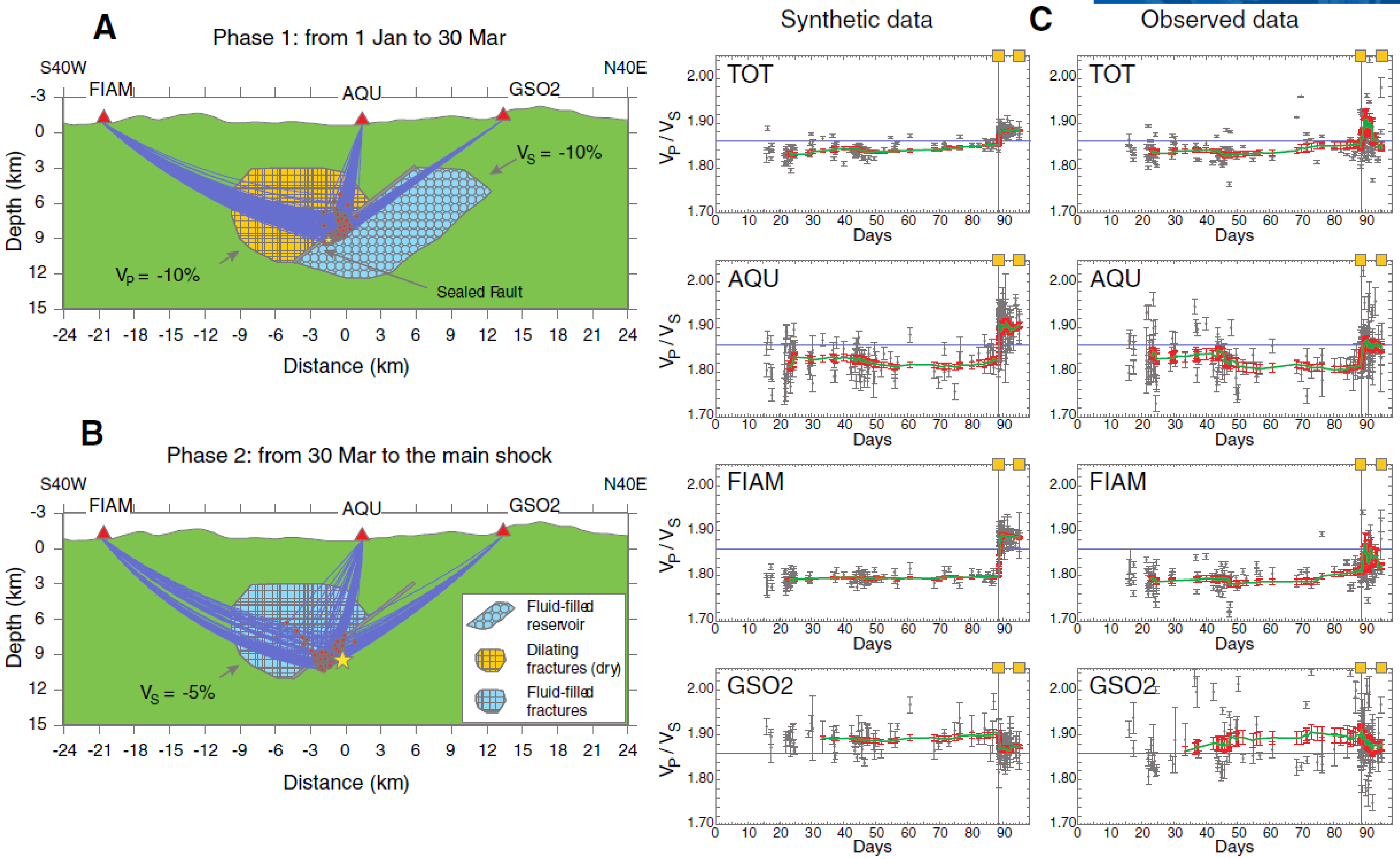




<u>Until March 30th:</u>
low values of V_P/V_S at AQU and FIAM (on the hanging wall) and high V_P/V_S values at GSO2 (on the foot wall)

<u>After March 30th:</u>
sharp increase of the V_P/V_S observed at AQU and FIAM, while the V_P/V_S drops at GSO2.

2009 L'Aquila earthquake(Lucente et al 2010)



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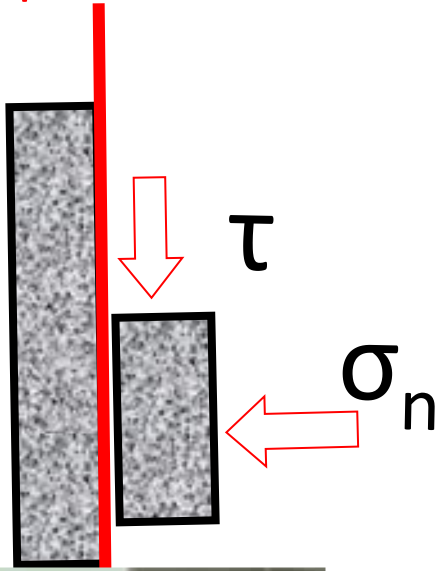
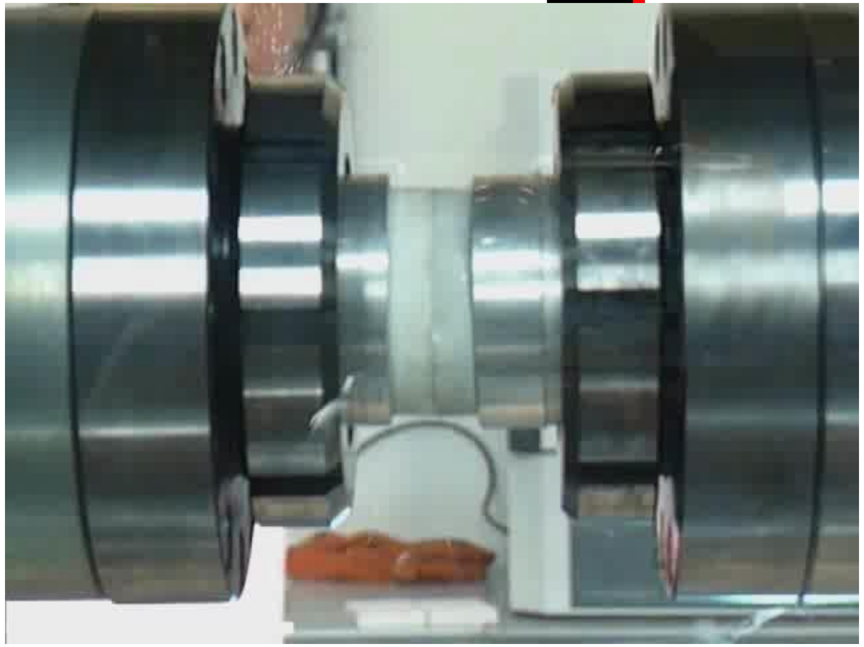
Rock samples and friction simulation





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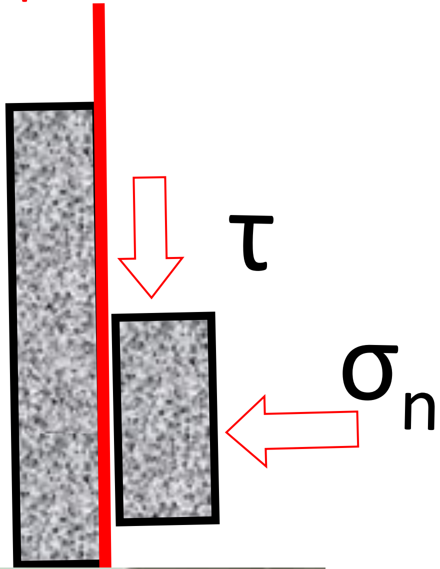

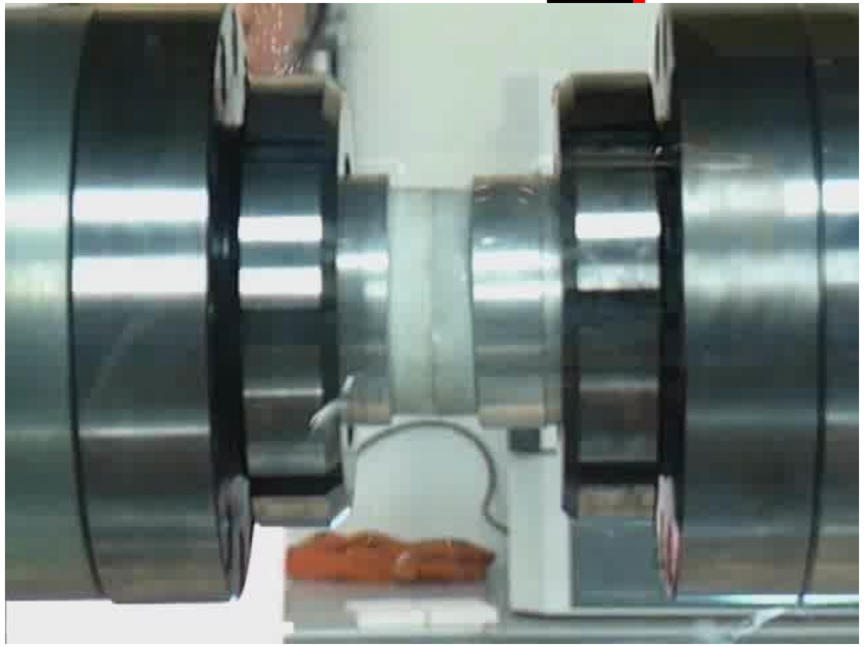

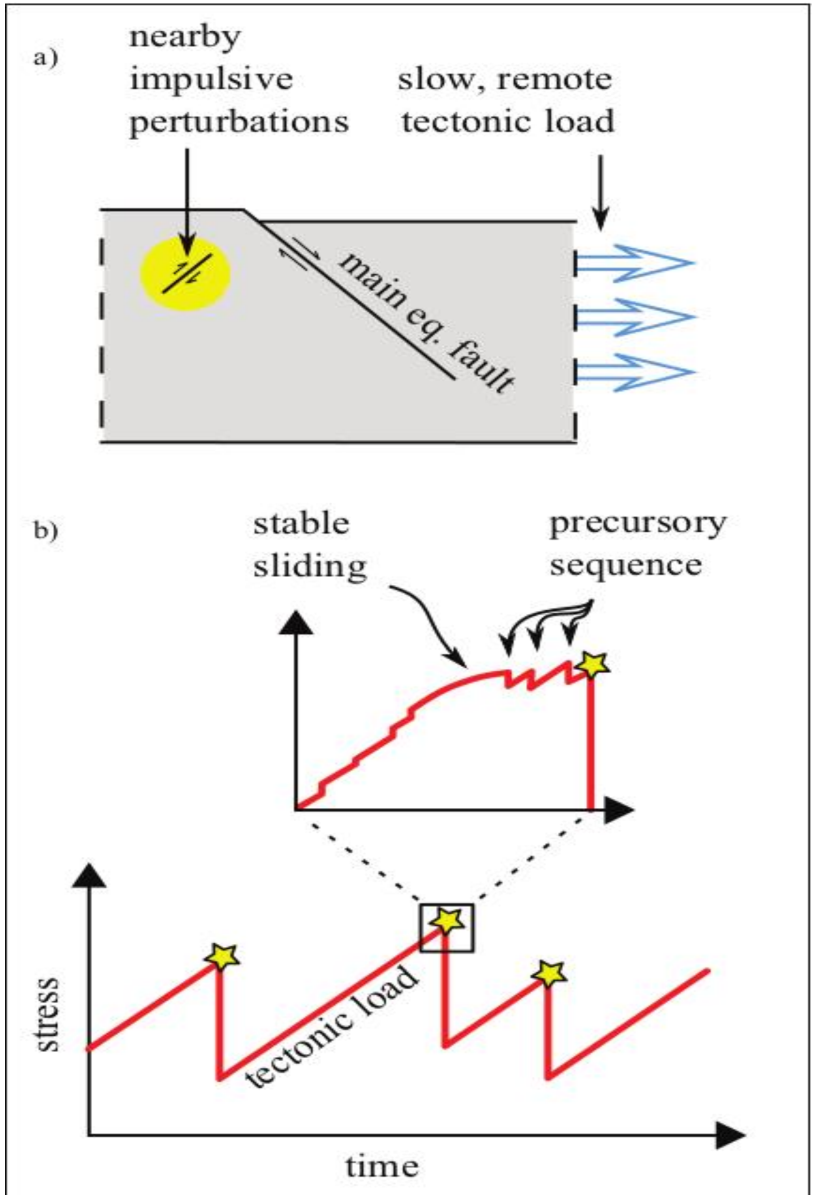

Studying The seismic cycle

Why it weakens
Why it re-strengthen
Any precursory signal?

Di Toro et al., 2012
Spagnuolo et al 2015
Spagnuolo et al GRL 2016

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NoFear (G. Di Toro)

New **O**utlook on seismic faults: **F**rom **EAR**thquake nucleation to arrest

B1. a1 NOFEAR: Ground-breaking nature and feasibility

NOFEAR aims at understanding the physics of earthquakes by integrating original field and newly conceived experimental studies with high-resolution numerical modelling. Modelling the earthquake source will (1) allow the up scaling of laboratory results to natural fault dimensions and ambient conditions, (2) produce synthetic seismograms and provide estimates of radiated energy to be compared with (high-resolution) natural ones. This approach ***will reveal a new view of earthquake physics, from rupture nucleation to arrest***.

NOFEARs' most ***relevant by-product will be the*** intense experimental investigation and ***physical comprehension of seismological, geophysical and geochemical phenomena associated with the initial stages of earthquake nucleation*** ("earthquake short-term precursors"). Some of these results will be also applied to landslide nucleation.

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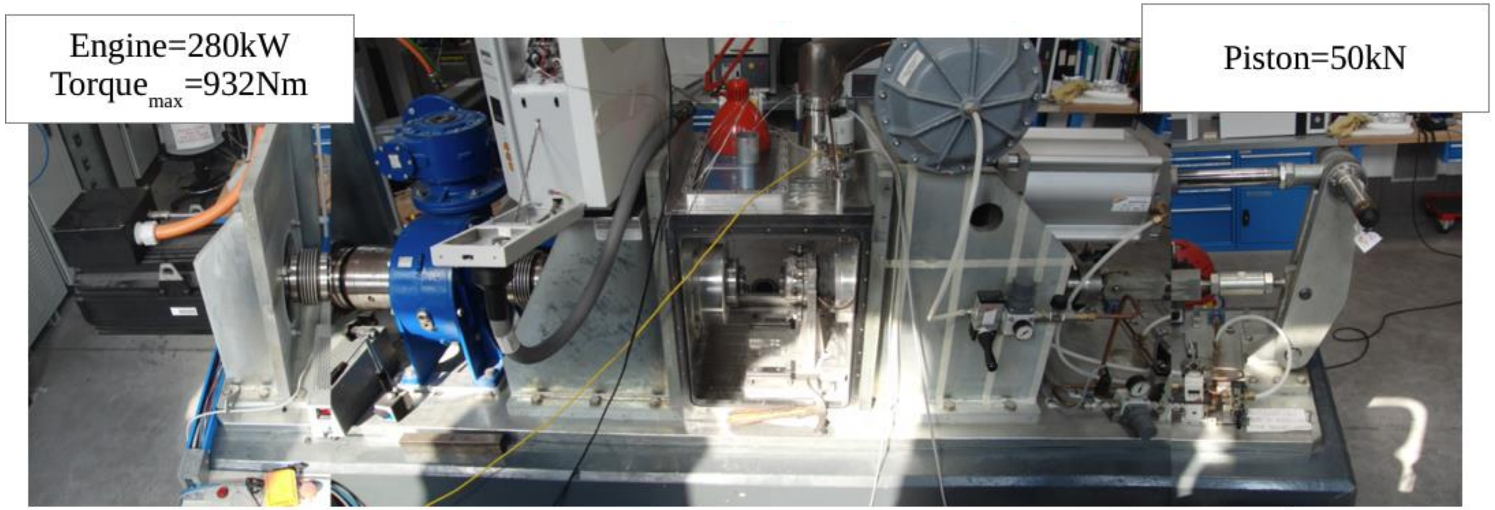
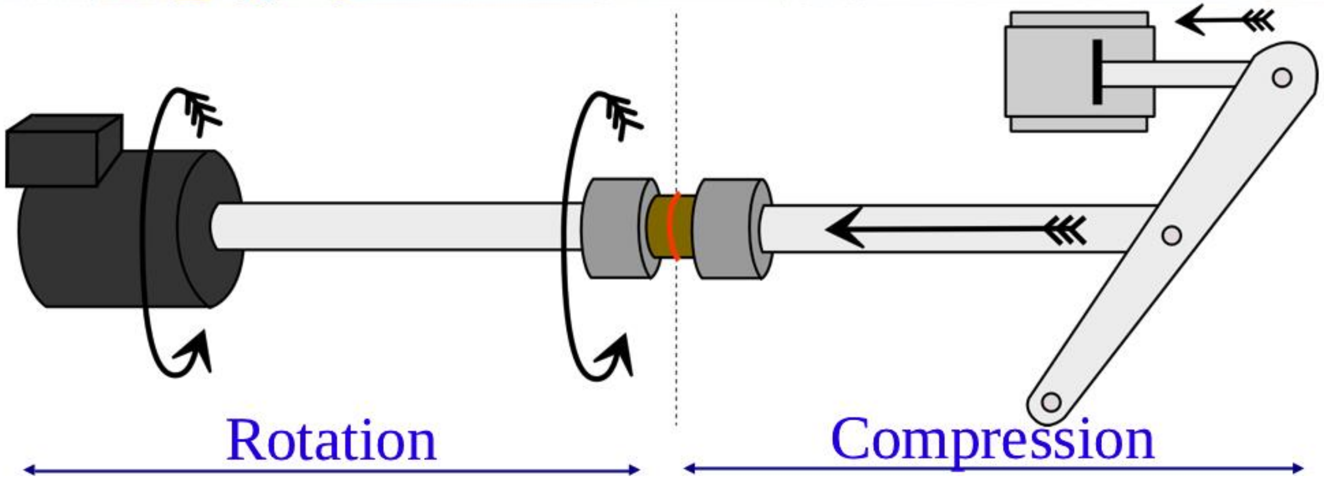
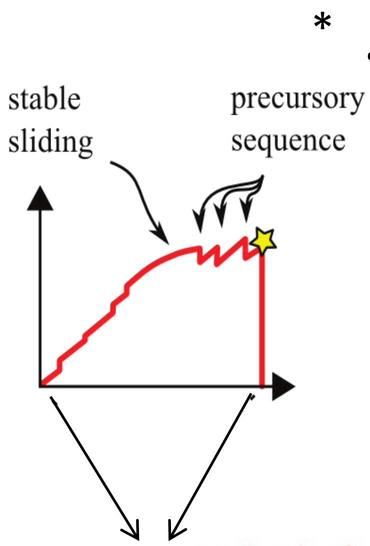
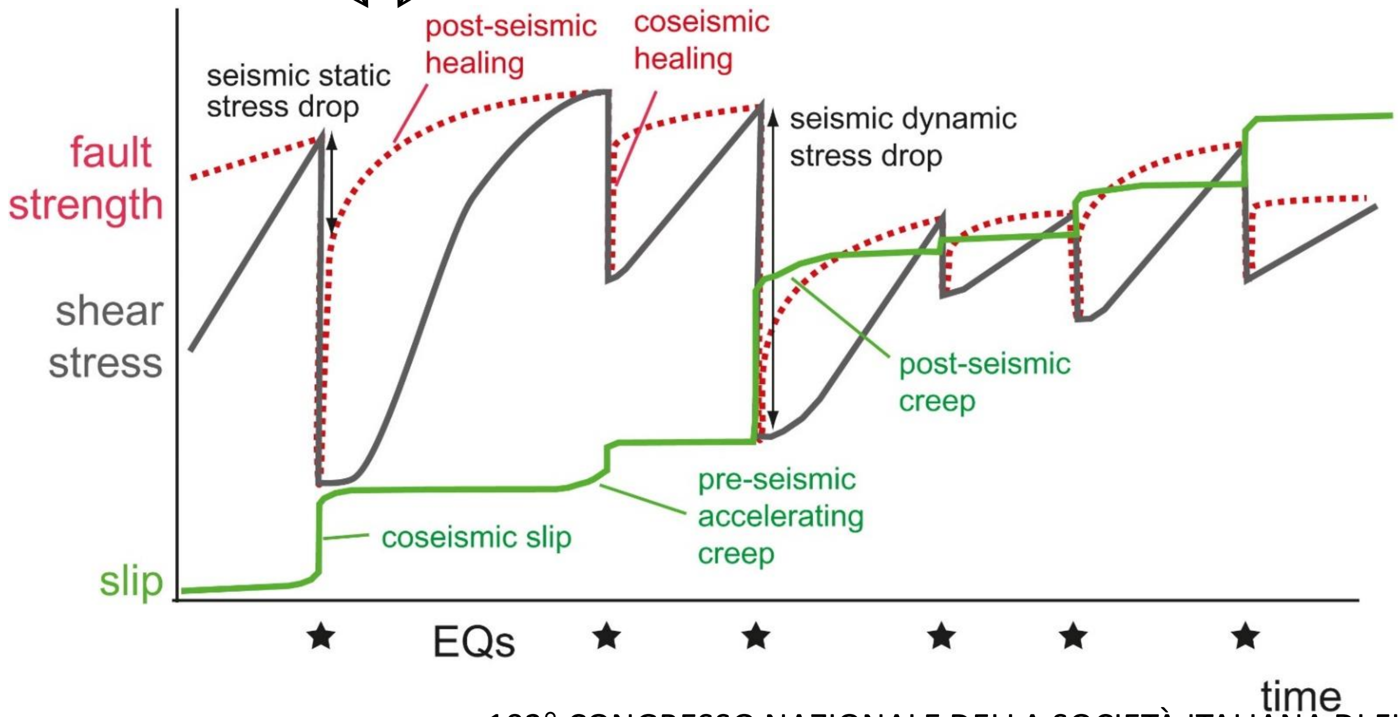
In order to study shear-strength reduction or friction we use:

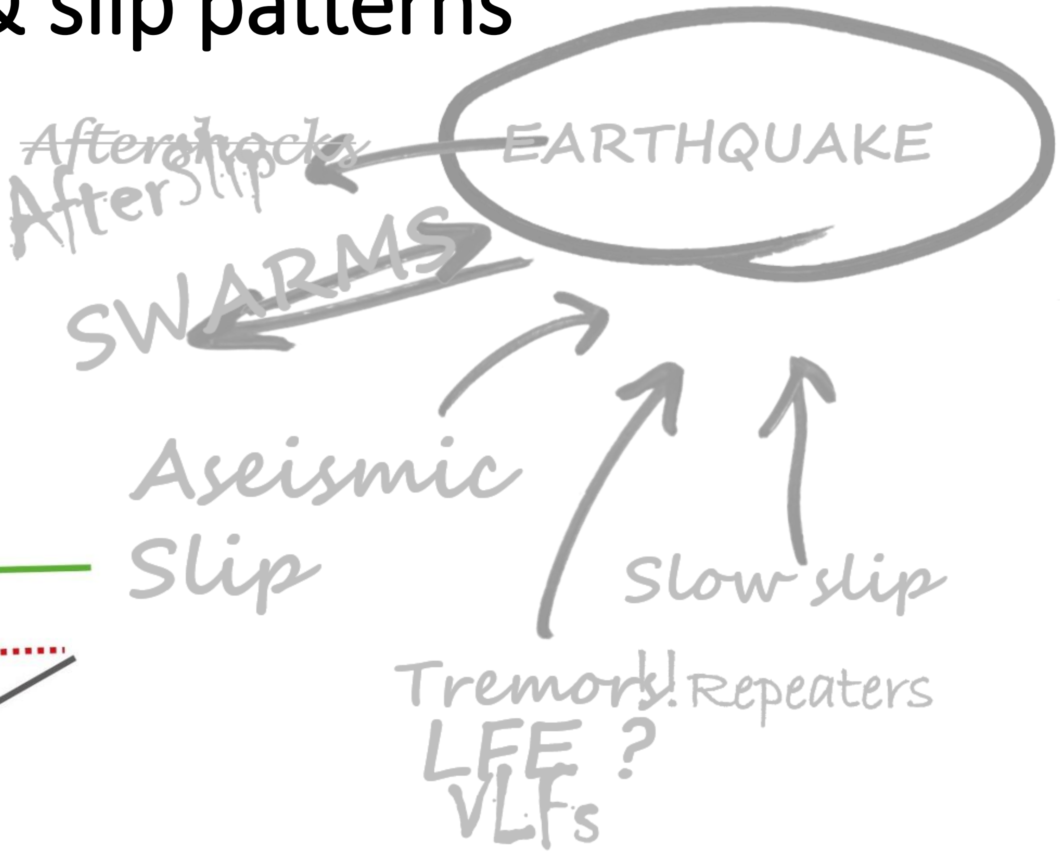




The seismic cycle & slip patterns



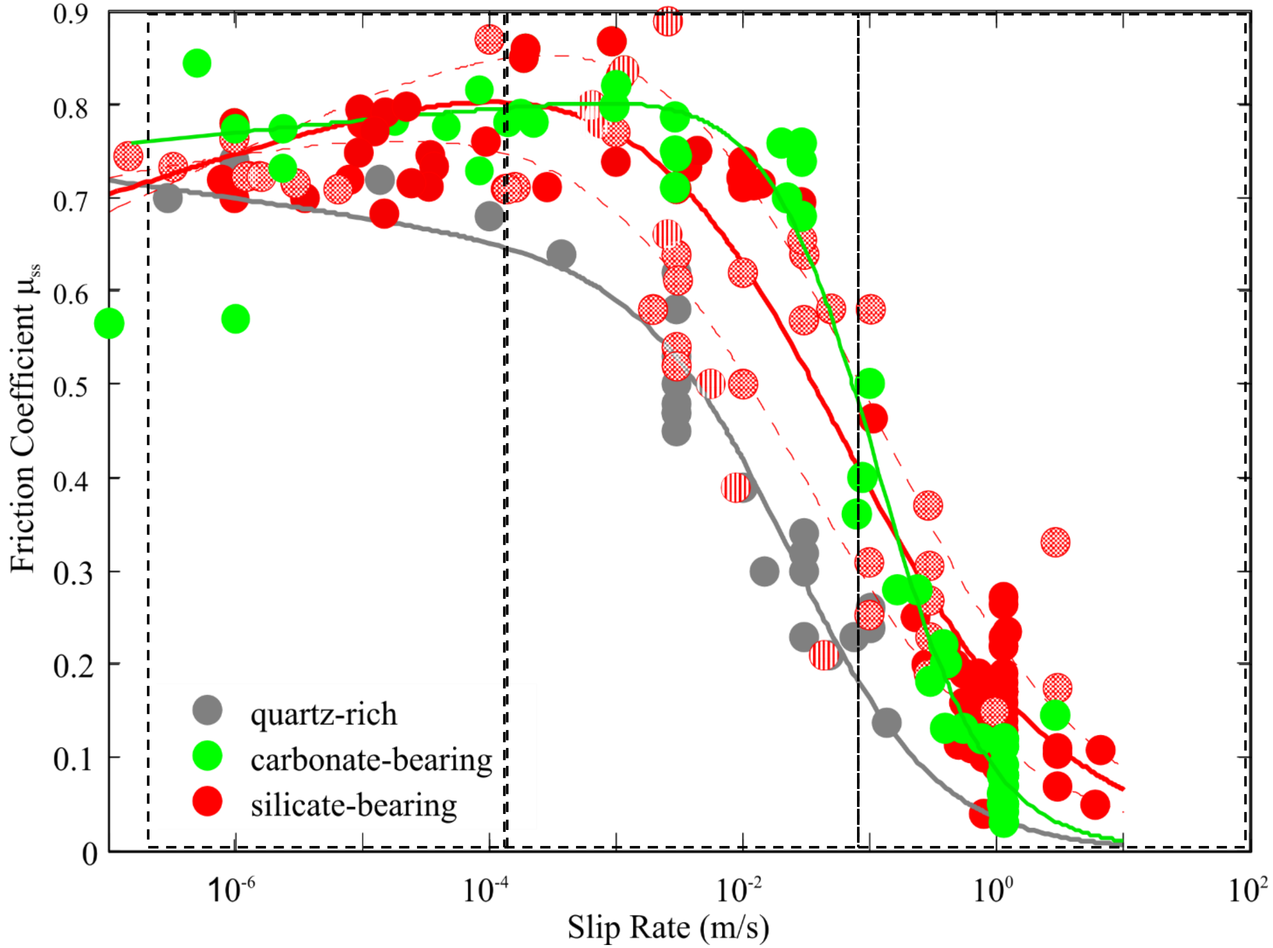




Di Toro et al., 2012
Spagnuolo et al 2015
Spagnuolo et al GRL 2016

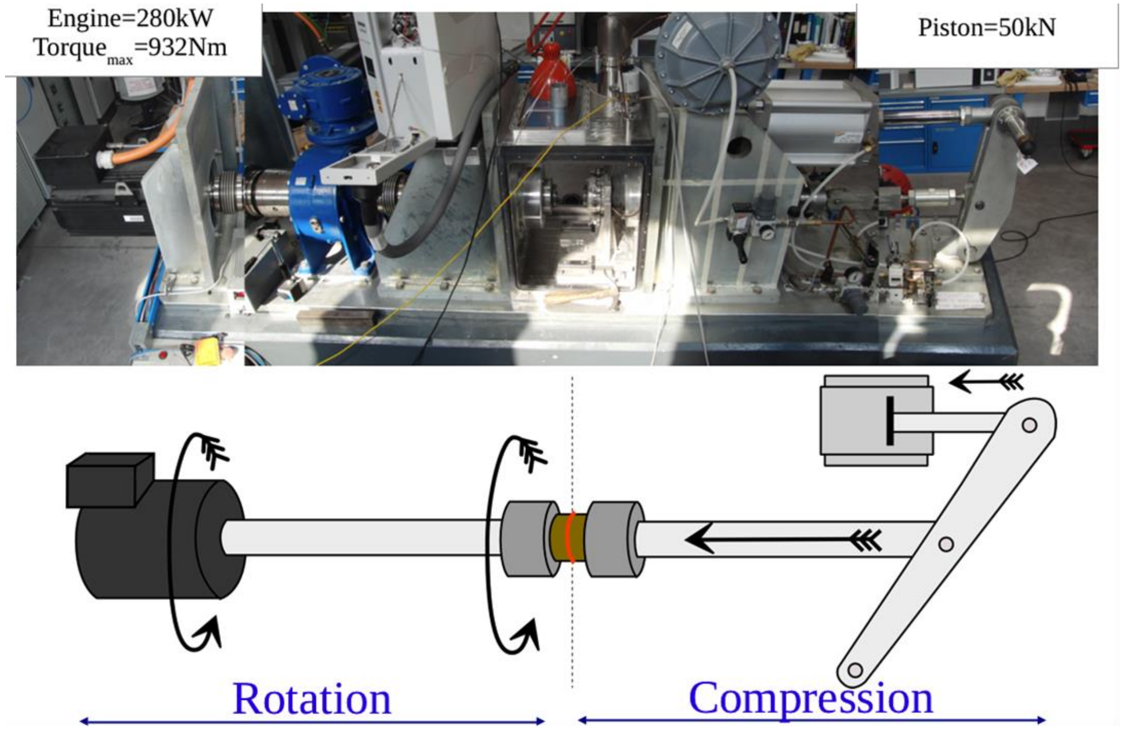
Experiments: frictional behaviours depend on V

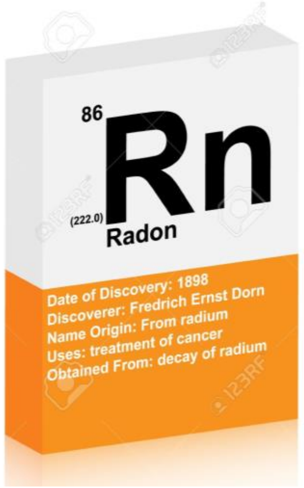
low velocities intermediate high velocities

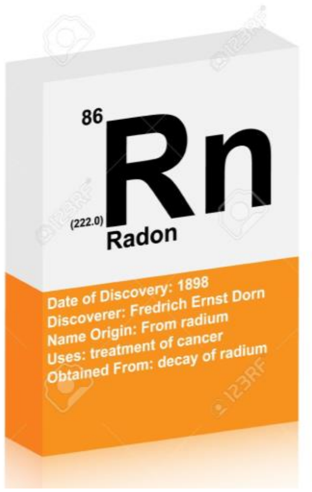


Spagnuolo et al. GRL 2016

Shiva si puo' usare anche per fare esperimenti sul radon







- Gas nobile radioattivo (decadimento α U e Th)
- ^{222}**Rn** isotopo principale: tempo dimezzamento 3,8 giorni
- inodore e incolore in condizioni standard
- Solubile in acqua
- **OMS** agente cancerogeno Gruppo 1, **US_EPA**
- Considerato 2° fattore di rischio (dopo il fumo) per i tumori polmonari

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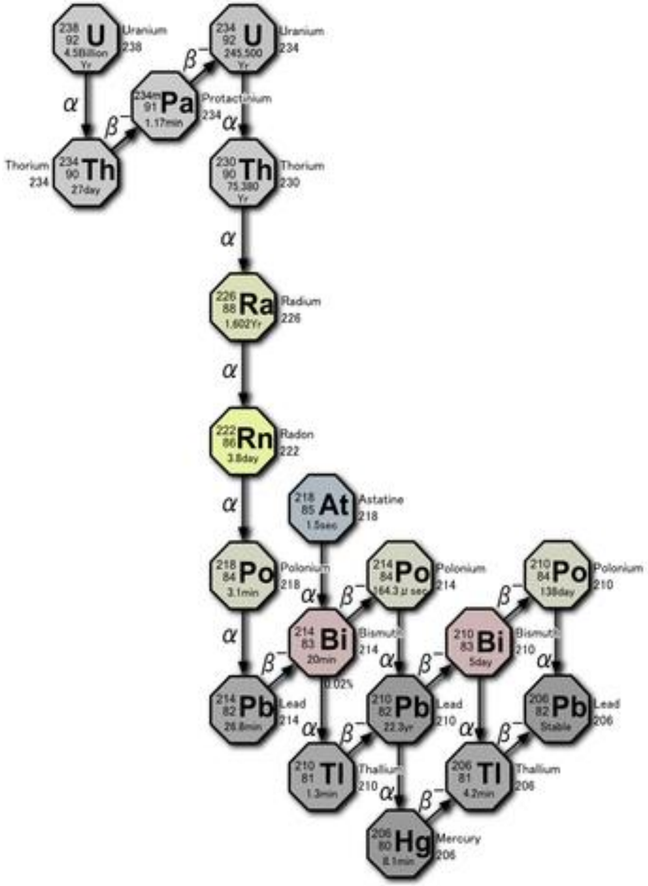
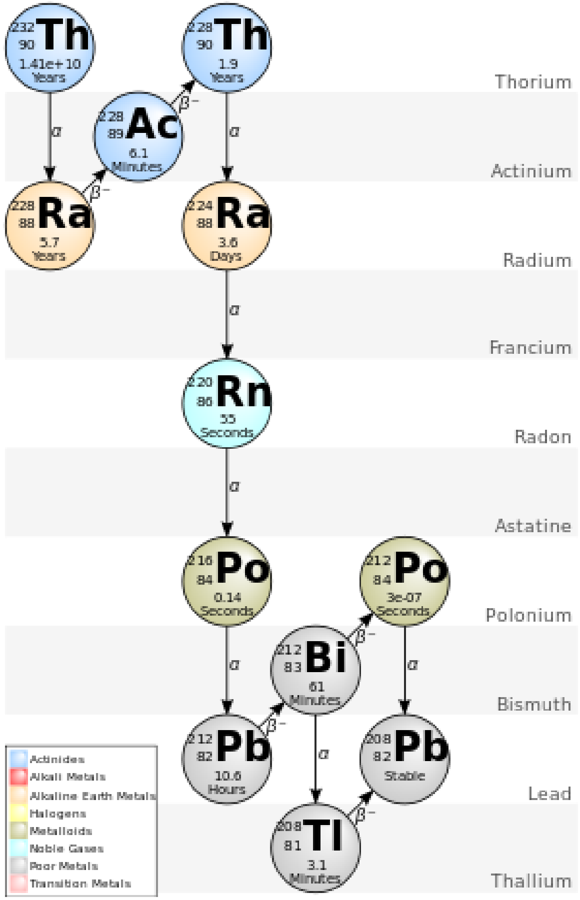
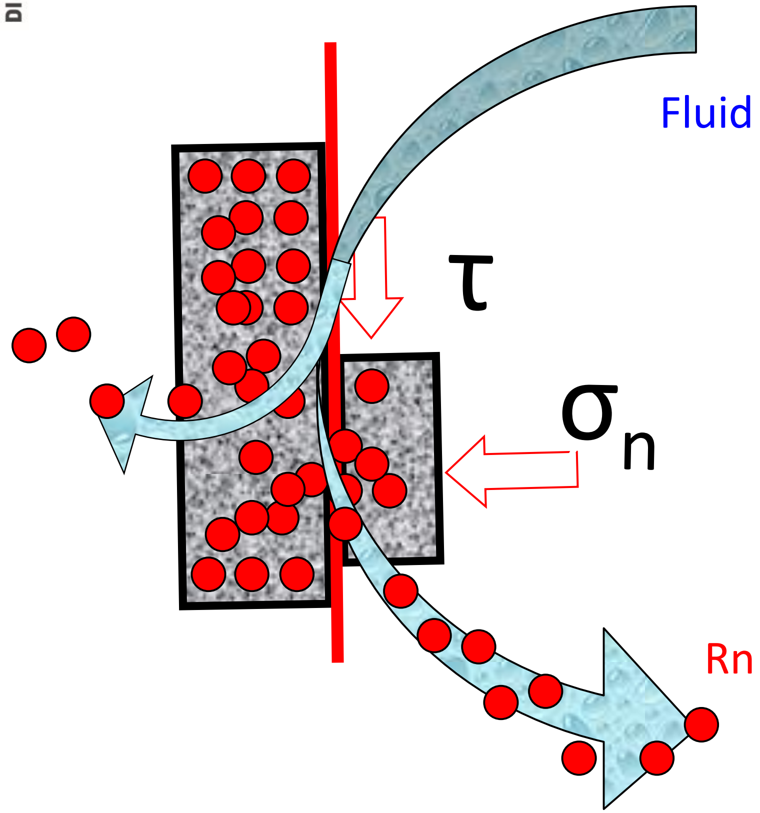


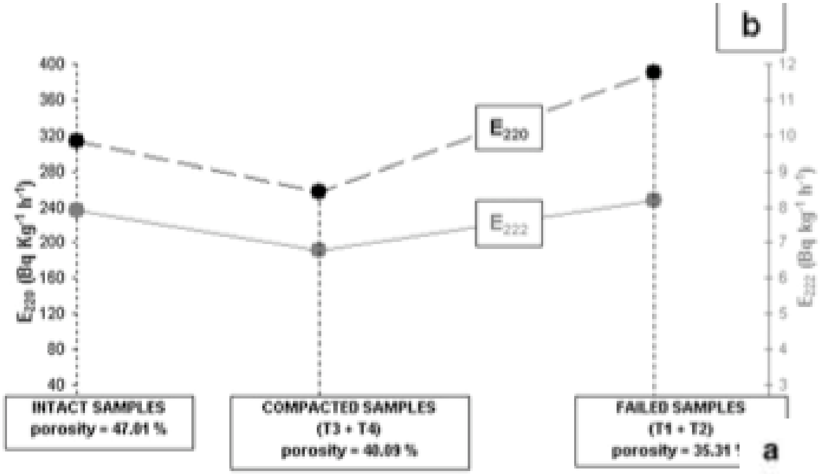
nuclide	historic name (short)	historic name (long)	decay mode	half-life (*a*=year)	energy released, MeV	product of decay
^{238}U	U_{I}	Uranium I	α	$4.468 \cdot 10^{9}$ a	4.270	^{234}Th
^{234}Th	UX_{1}	Uranium X_{1}	β^-	24.10 d	0.273	^{234m}Pa
^{234m}Pa	UX_{2}	Uranium X_{2}, Brevium	β^- 99.84% IT 0.16%	1.16 min	2.271 0.074	^{234}U ^{234}Pa
^{234}Pa	UZ	Uranium Z	β^-	6.70 h	2.197	^{234}U
^{234}U	U_{II}	Uranium II	α	245500 a	4.859	^{230}Th
^{230}Th	Io	Ionium	α	75380 a	4.770	^{226}Ra
^{226}Ra	Ra	Radium	α	1602 a	4.871	^{222}Rn
^{222}Rn	Rn	Radon, Radium Emanation	α	3.8235 d	5.590	^{218}Po
^{218}Po	RaA	Radium A	α 99.98% β^- 0.02%	3.10 min	6.115 0.265	^{214}Pb ^{218}At
^{218}At			α 99.90% β^- 0.10%	1.5 s	6.874 2.883	^{214}Bi ^{218}Rn
^{218}Rn			α	35 ms	7.263	^{214}Po
^{214}Pb	RaB	Radium B	β^-	26.8 min	1.024	^{214}Bi
^{214}Bi	RaC	Radium C	β^- 99.98% α 0.02%	19.9 min	3.272 5.617	^{214}Po ^{210}Tl
^{214}Po	RaC'	Radium C'	α	0.1643 ms	7.883	^{210}Pb
^{210}Tl	RaC"	Radium C"	β^-	1.30 min	5.484	^{210}Pb
^{210}Pb	RaD	Radium D	β^-	22.3 a	0.064	^{210}Bi
^{210}Bi	RaE	Radium E	β^- 99.99987% α 0.00013%	5.013 d	1.426 5.982	^{210}Po ^{206}Tl
^{210}Po	RaF	Radium F	α	138.376 d	5.407	^{206}Pb
^{206}Tl	RaE"	Radium E"	β^-	4.199 min	1.533	^{206}Pb
^{206}Pb	RaG	Radium G	-	stable	-	-



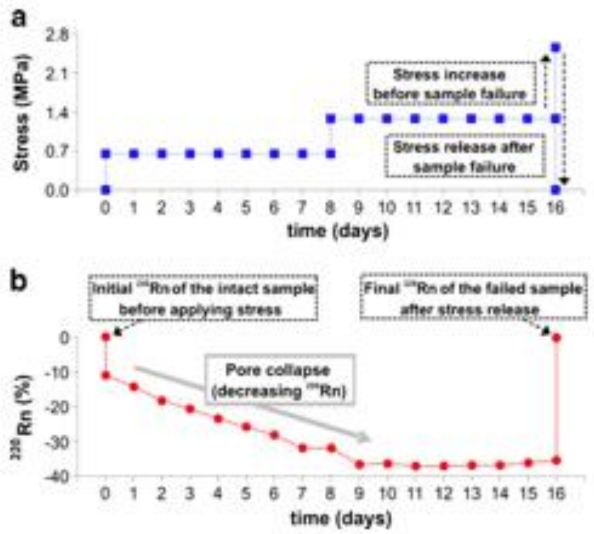
nuclide	historic name (short)	historic name (long)	decay mode	half-life (a=year)	energy released, MeV	product of decay
^{252}Cf			α	2.645 a	6.1181	^{248}Cm
^{248}Cm			α	3.4×10^5 a	5.162	^{244}Pu
^{244}Pu			α	8×10^7 a	4.589	^{240}U
^{240}U			β^-	14.1 h	.39	^{240}Np
^{240}Np			β^-	1.032 h	2.2	^{240}Pu
^{240}Pu			α	6561 a	5.1683	^{236}U
^{236}U			α	2.3×10^7 a	4.494	^{232}Th
^{232}Th	Th	Thorium	α	1.405×10^{10} a	4.081	^{228}Ra
^{228}Ra	$MsTh_1$	Mesothorium 1	β^-	5.75 a	0.046	^{228}Ac
^{228}Ac	$MsTh_2$	Mesothorium 2	β^-	6.25 h	2.124	^{228}Th
^{228}Th	RdTh	Radiothorium	α	1.9116 a	5.520	^{224}Ra
^{224}Ra	ThX	Thorium X	α	3.6319 d	5.789	^{220}Rn
^{220}Rn	Tn	Thoron, Thorium Emanation	α	55.6 s	6.404	^{216}Po
^{216}Po	ThA	Thorium A	α	0.145 s	6.906	^{212}Pb
^{212}Pb	ThB	Thorium B	β^-	10.64 h	0.570	^{212}Bi
^{212}Bi	ThC	Thorium C	β^- 64.06% α 35.94%	60.55 min	2.252 6.208	^{212}Po ^{208}Tl
^{212}Po	ThC′	Thorium C′	α	299 ns	8.955	^{208}Pb
^{208}Tl	ThC″	Thorium C″	β^-	3.053 min	4.999	^{208}Pb
^{208}Pb	ThD	Thorium D	stable	.	.	.

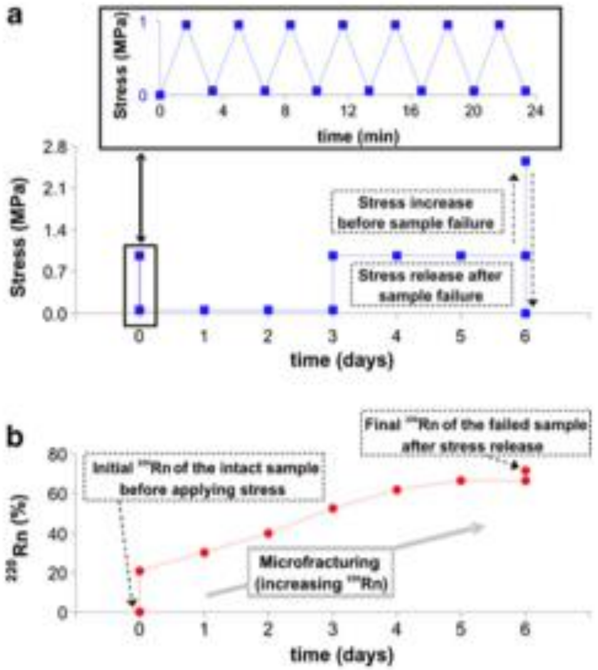

Fluid
τ
σ_n
Rn

REAL TIME RADON MONITORING IN LABORATORY



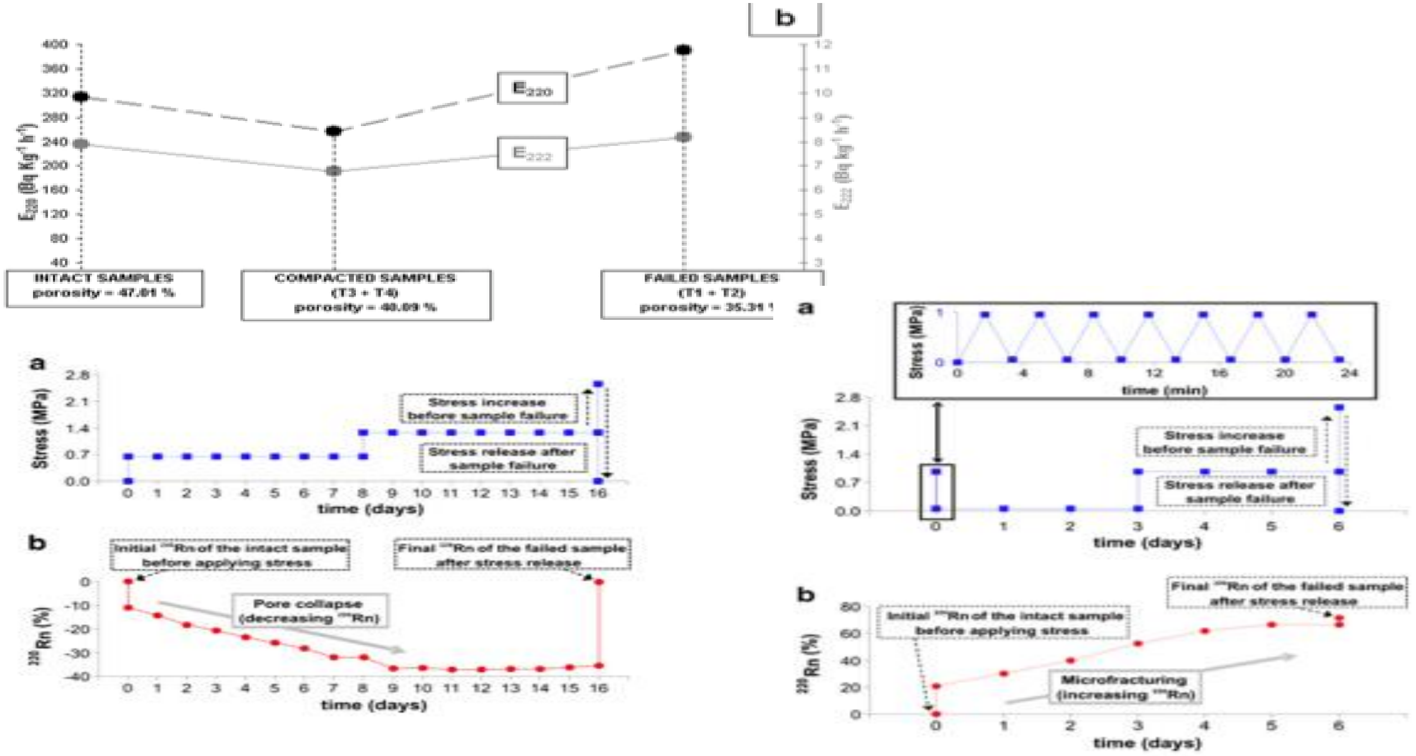
Tuccimei et al., GRL 2010: tufo caricato uniassialmente (normal load), snapshot in 3 diverse condizioni senza dipendenza temporale





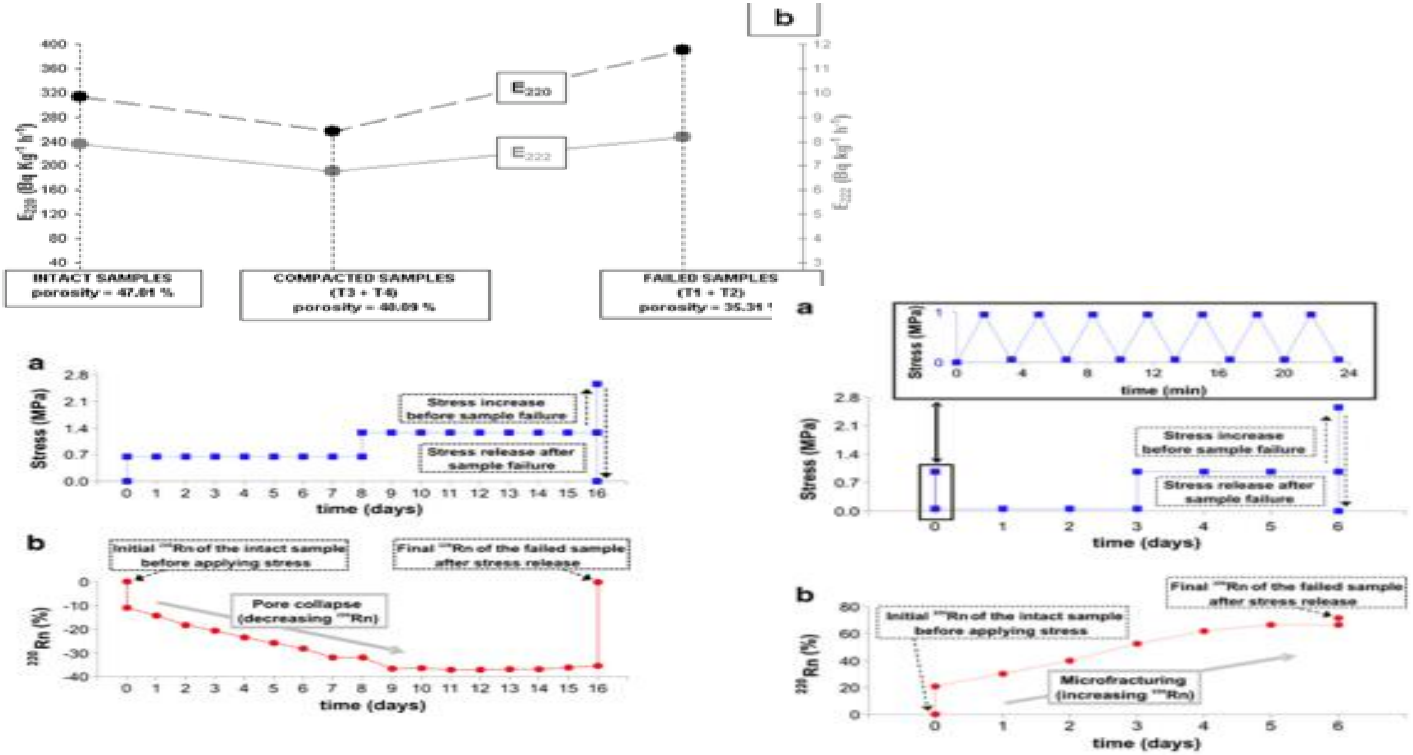
Scarlato et al., Boll Volc 2013: tufo caricato uniassialmente (normal load) 1 snapshot al giorno

Introdurre dipendenza temporale



Introdurre dipendenza temporale

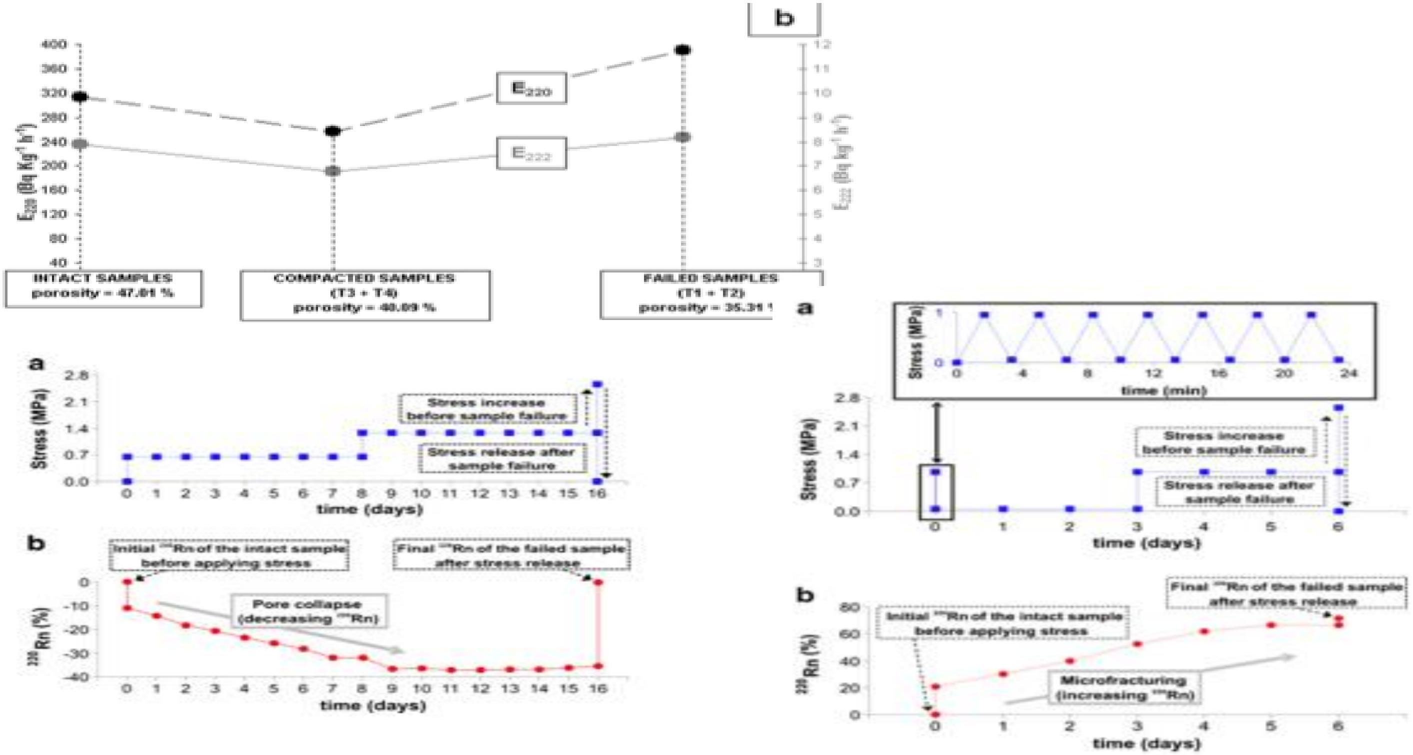
Introdurre shear stress



Introdurre dipendenza temporale

Introdurre shear stress

Misurare emissioni da rocce maggiormente caratterizzanti i sistemi sismogenetici

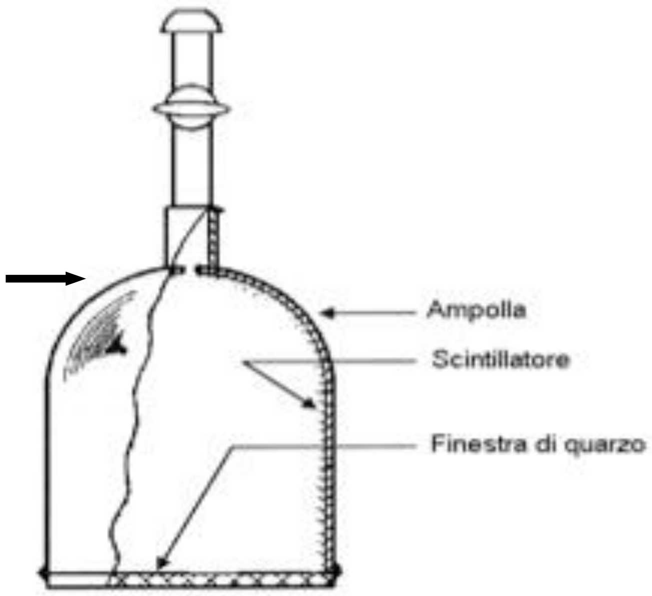


Introdurre dipendenza temporale

Introdurre shear stress

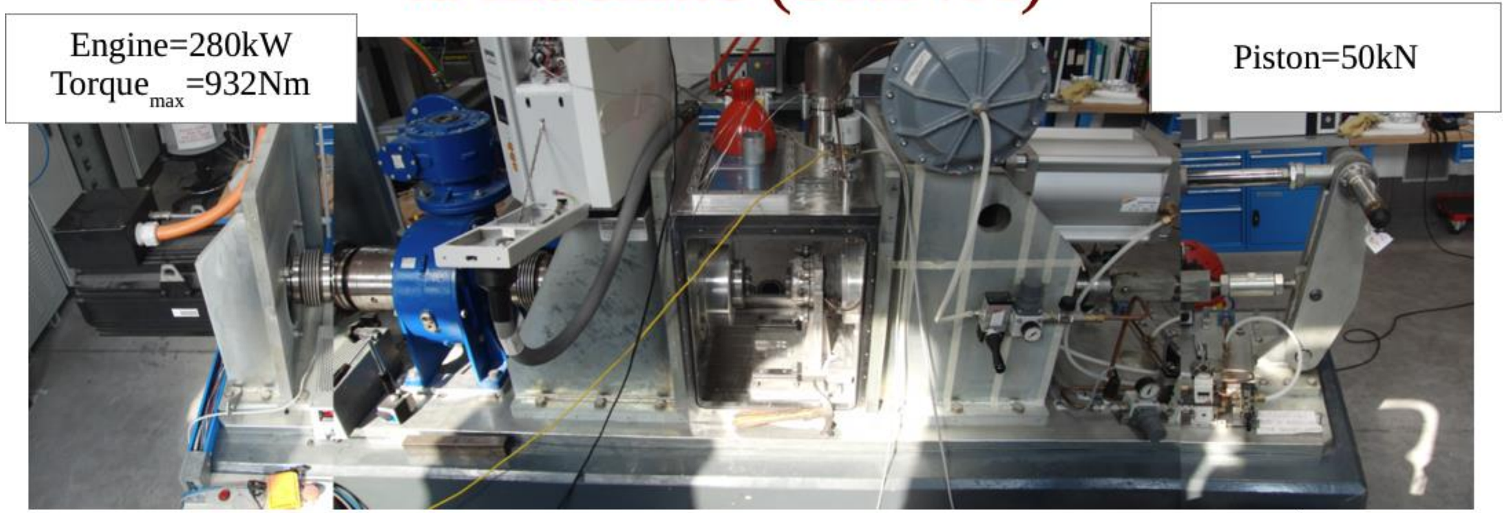
Misurare emissioni da rocce maggiormente caratterizzanti i sistemi sismogenetici

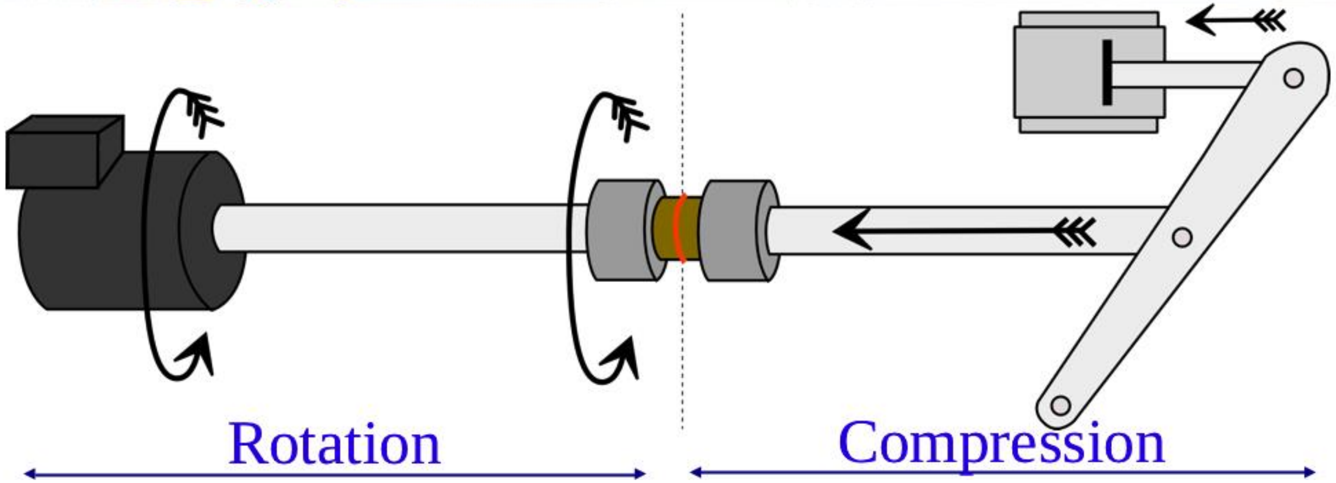
solfuro di zinco
(20mg/cm² ZnS(Ag)

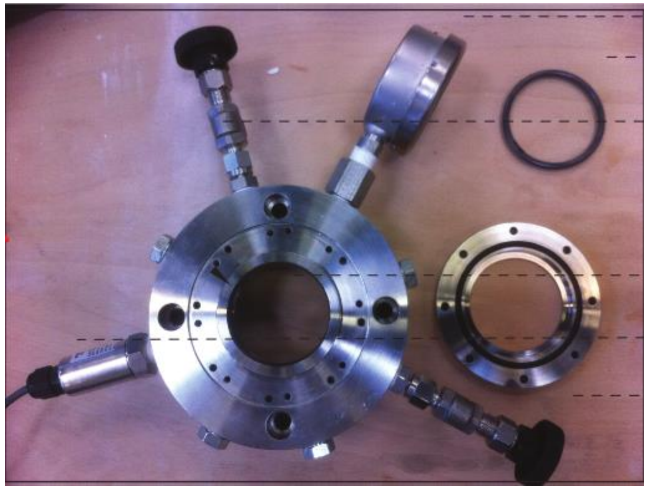


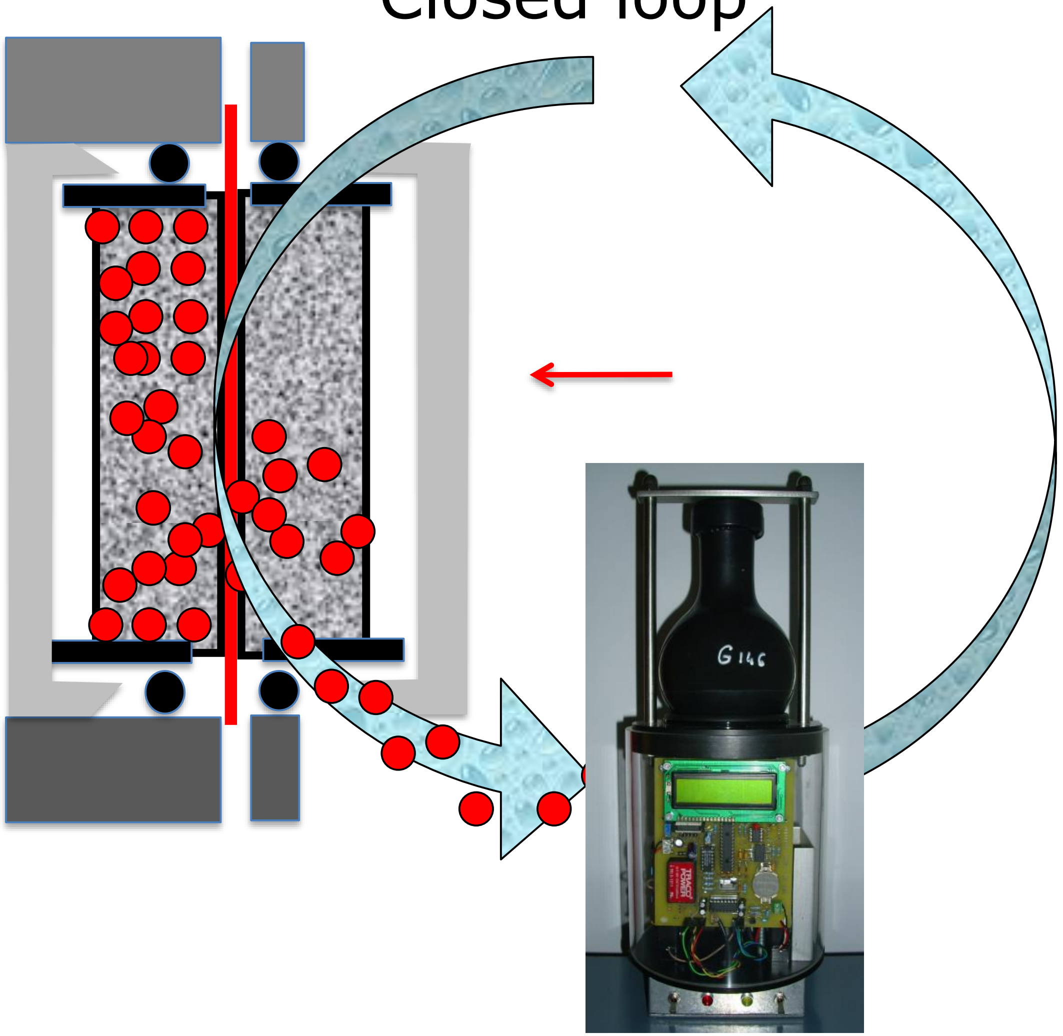
Per prima cosa ci serve un sistema di misura ad alta efficienza e sensibilita'

la machine (SHIVA)







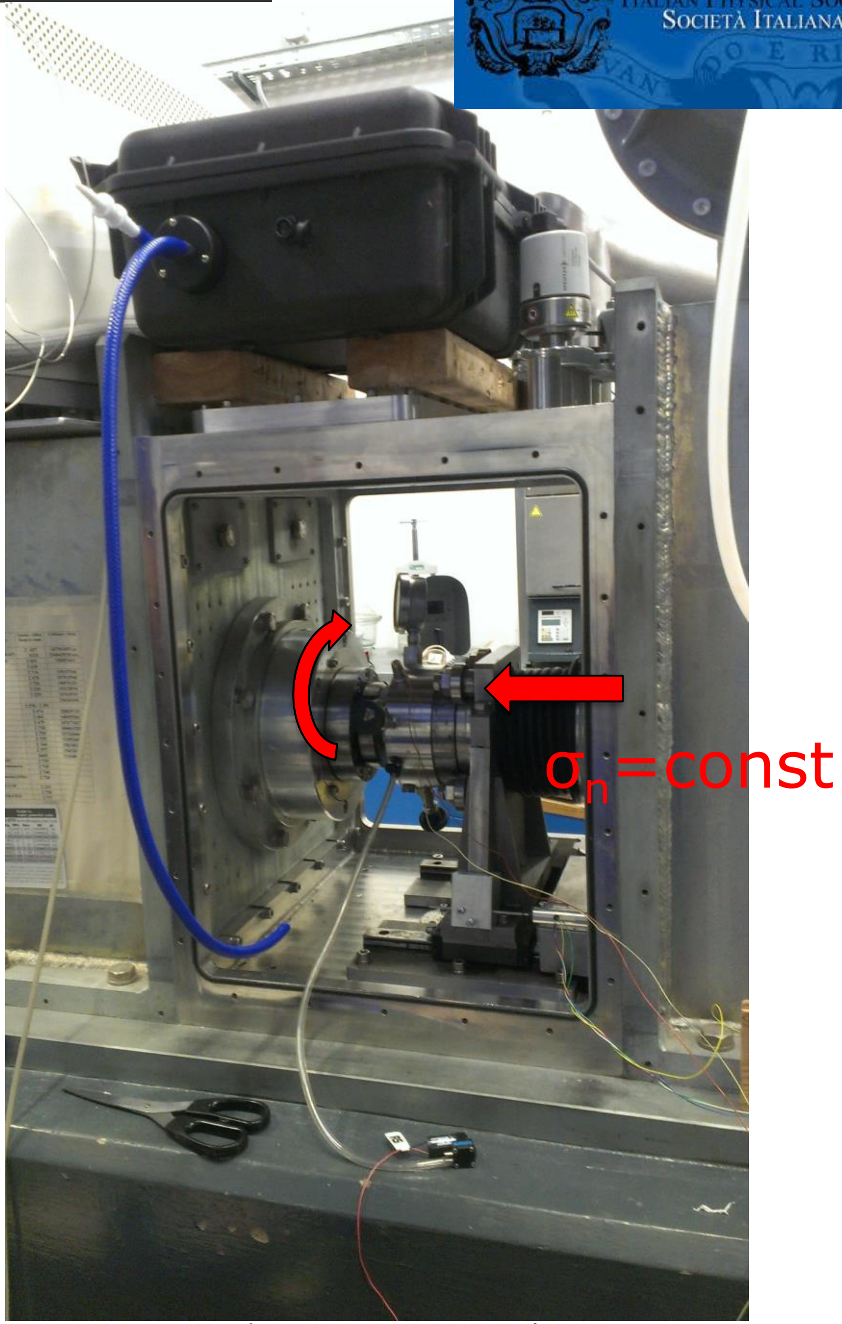

Closed loop

Introdurre dipendenza temporale

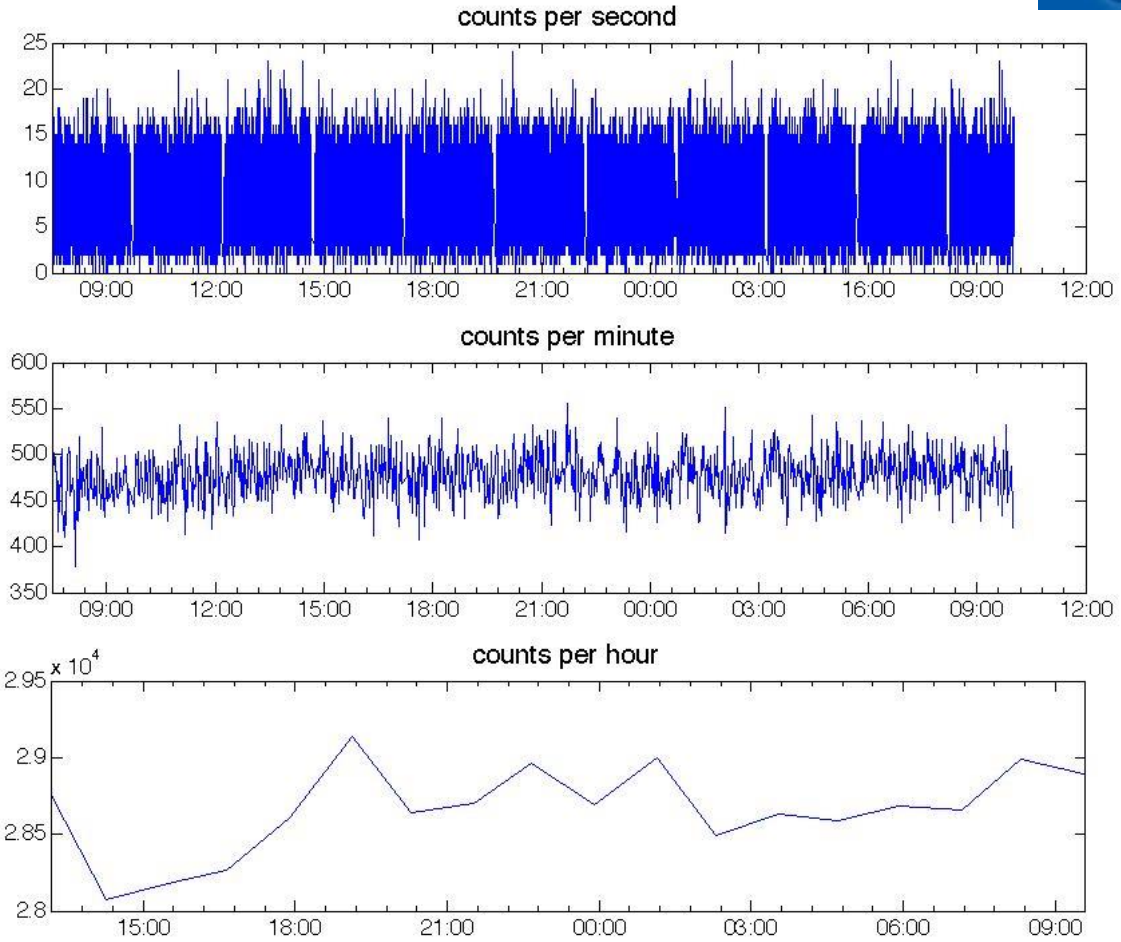
Introdurre shear stress

Misurare emissioni da rocce maggiormente caratterizzanti i sistemi sismogenetici

Realizziamo una configurazione efficace su SHIVA



Tufo



Misure significative per tempi di campionamento inferiori ai 10 s

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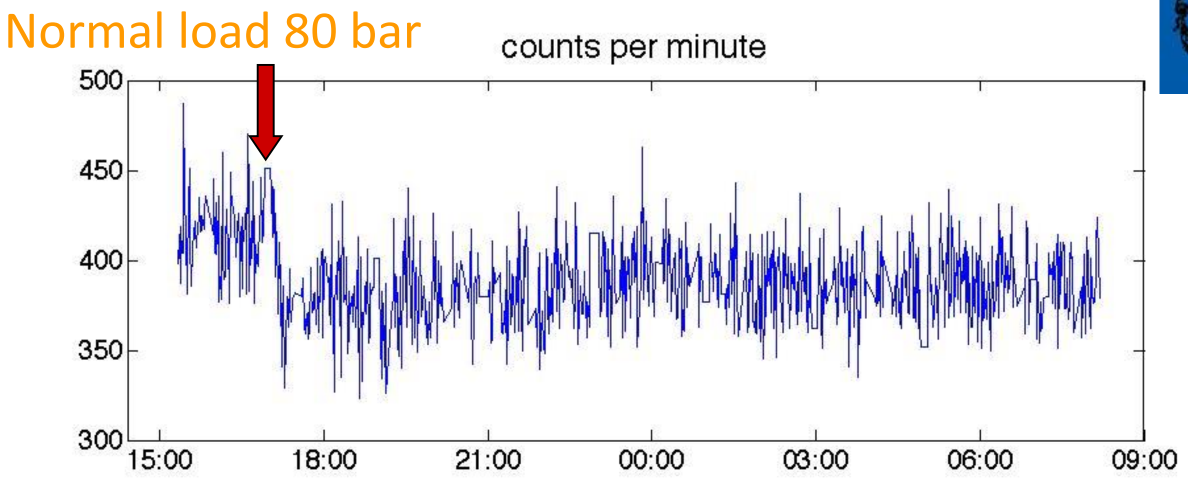
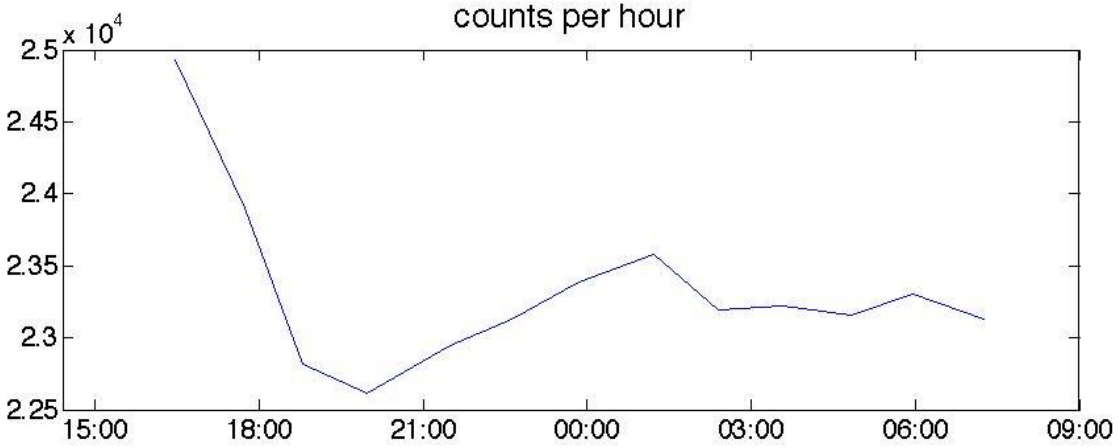
Tufo

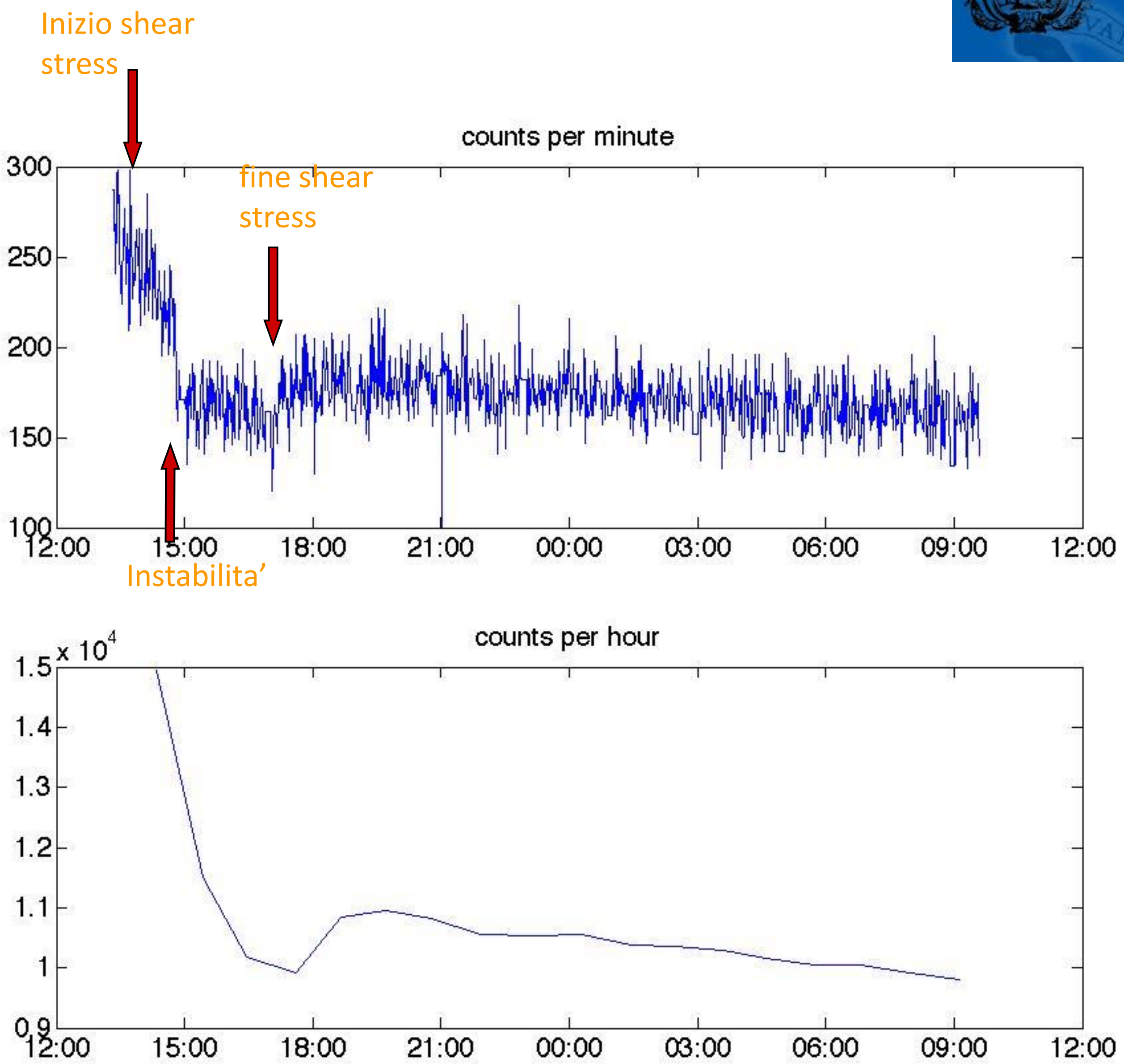




Variazione emissione radon contemporanea e all'applicazione del carico e molto steep (rilevabile grazie al tempo reale)

Il setup su SHIVA ci permette di aggiungere shear stress

Ancora una volta notare l'estrema velocita' di reazione



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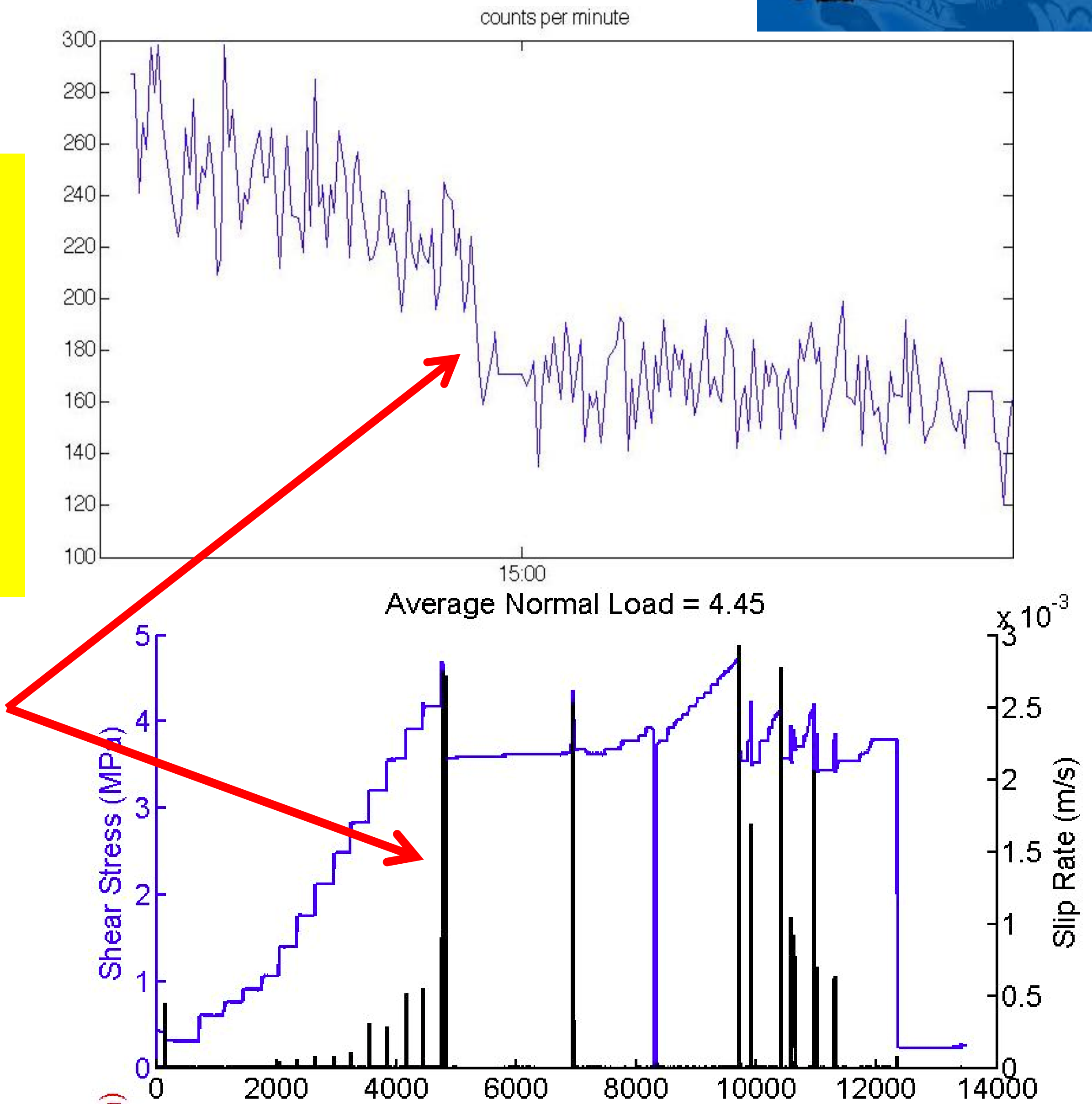
Tufo

L'instabilita' principale in termini di stress drop e slip rate coincide con massima variazione di radon emission

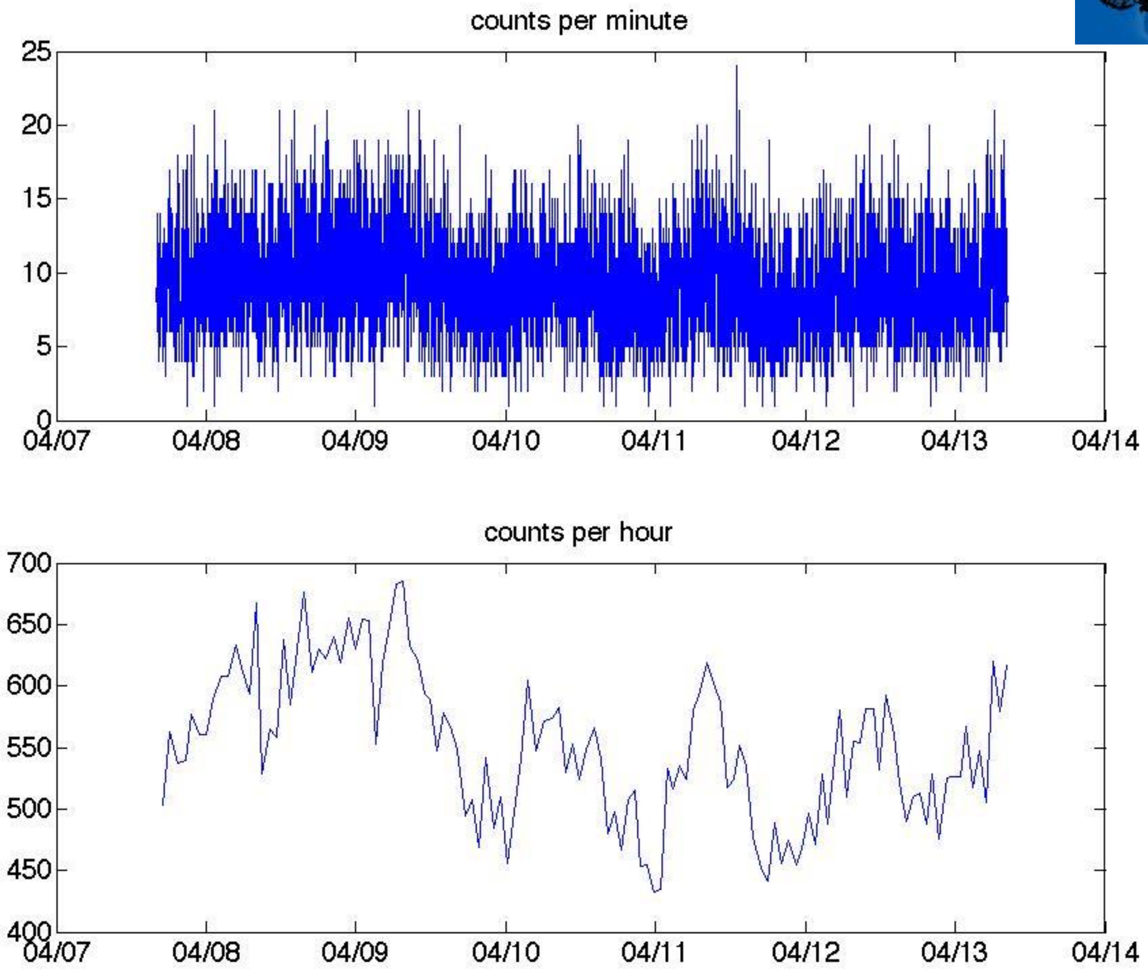
Instabilità principale



Riusciamo a fare misure significative su rocce maggiormente caratterizzanti un sistema sismogenetico (che contengono molto meno radon)?

Tonalite

Tonalite



La tonalite emana quasi 2 ordini di grandezza meno radon rispetto al tufo ma riusciamo a misurarla lo stesso in real time (misure significative sampling time ~5 min)

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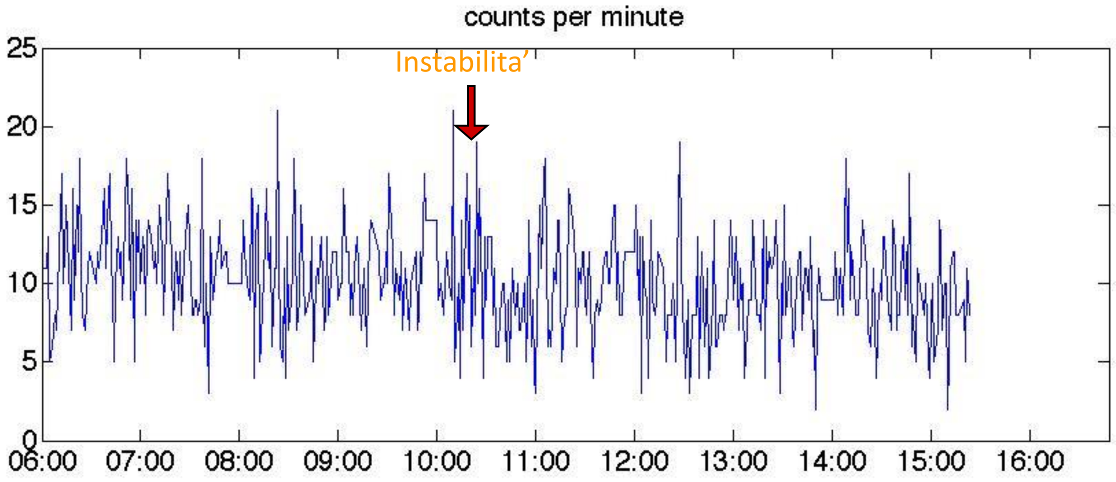
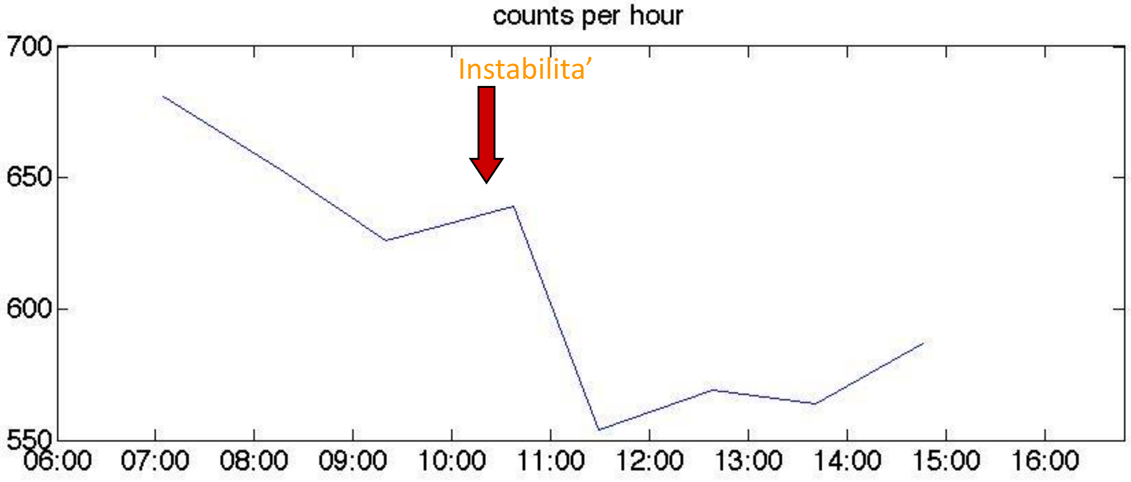
Tonalite





riusciamo anche a evidenziare le variazioni in coincidenza con le instabilita' "sismiche".

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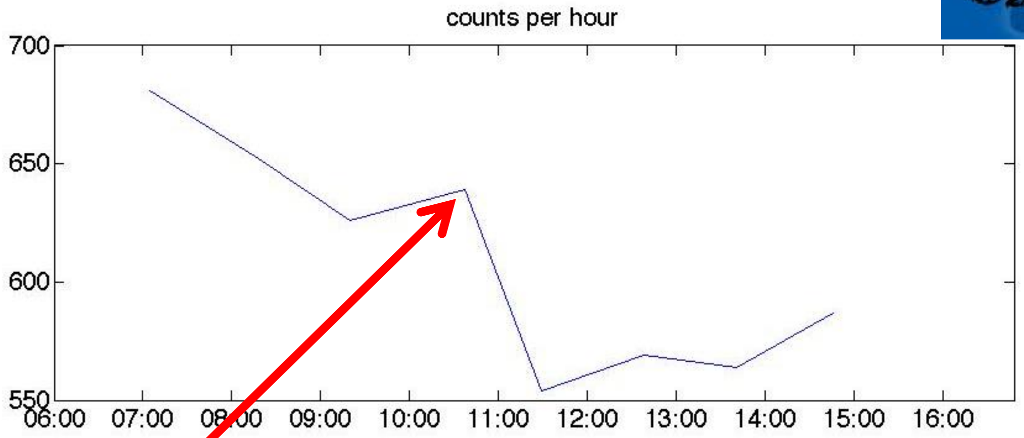
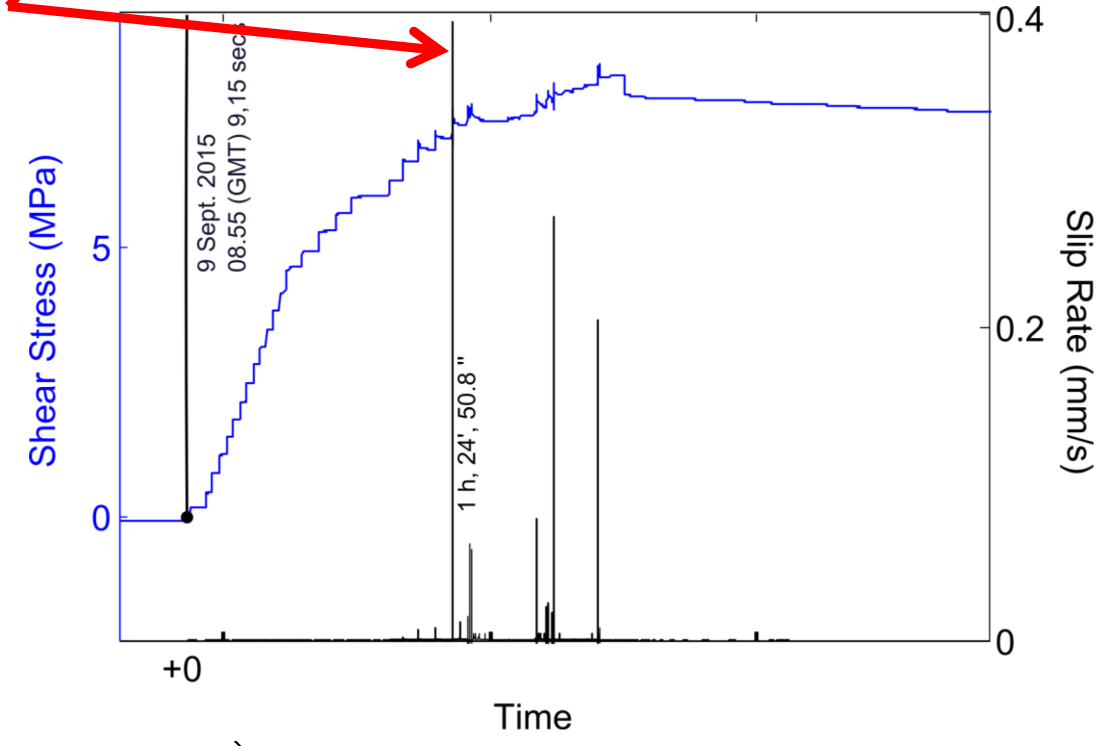


Tonalite

Instabilità principale



L'instabilità avviene dopo 1 h, 24', 50.8 ''
Dall'applicazione del carico tangenziale.

Cosa si fa sul campo rispetto al radon

Eulero vs Lagrange

In the *Eulerian specification* of the flow field, the flow quantities are depicted as a function of position **x** and time *t*. Specifically, the flow is described by a function

$$\mathbf{v}\left(\mathbf{x},t\right)$$

giving the flow velocity at position **x** at time *t*.

On the other hand, in the *Lagrangian specification*, individual fluid parcels are followed through time. The fluid parcels are labelled by some (time-independent) vector field **a**. (Often, **a** is chosen to be the center of mass of the parcels at some initial time t_0. It is chosen in this particular manner to account for the possible changes of the shape over time. Therefore the center of mass is a good parametrization of the velocity **v** of the parcel.)[1] In the Lagrangian description, the flow is described by a function

$$\mathbf{X}\left(\mathbf{a},t\right)$$

giving the position of the parcel labeled **a** at time *t*.

The two specification are related as follows:[2]

$$\mathbf{v}\left(\mathbf{X}(\mathbf{a},t),t\right)=\frac{\partial\mathbf{X}}{\partial t}\left(\mathbf{a},t\right)$$

because both sides describe the velocity of the parcel labeled **a** at time *t*.

Within a chosen coordinate system, **a** and **x** are referred to as the **Lagrangian coordinates** and **Eulerian coordinates** of the flow.

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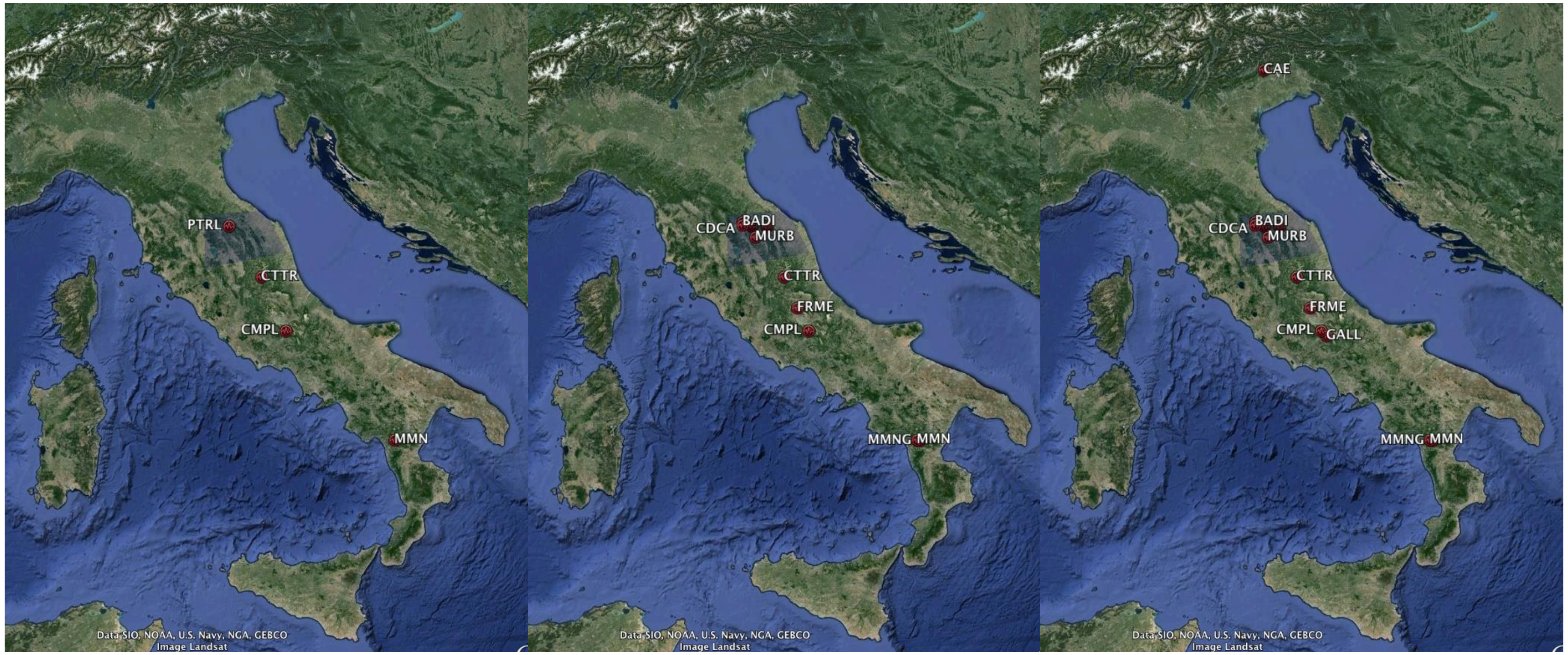


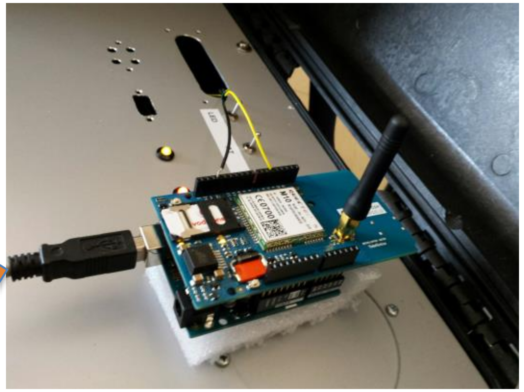
2009 → **2016**

15 stazioni permanenti

IRON


BADI
CDCA
PTRL
SSFR
MURB
NRCA
CTTR
FRME
CMPL
GALL
SPI
MCEL
Golfo di Terracina
Gulf of GaetaGolfo di Gaeta
Golfo di Pozzuoli
Naples
Bay of SalernoGolfo di Salerno
Bay of PaestumGulf of Salerno
Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth

Italian Radon mOnitoring Network



Arduino-Based DAQ Prototype

Sistema di misurazione attiva: Cella di Lucas

Italian Radon mOnitoring Network

CDCA

shelter

PTRL

indoor

MURB

pozzetto

Differenti tipologie di installazione

Italian Radon mOnitoring Network

BADI1

picchetto

(*Piersanti et al 2015*)

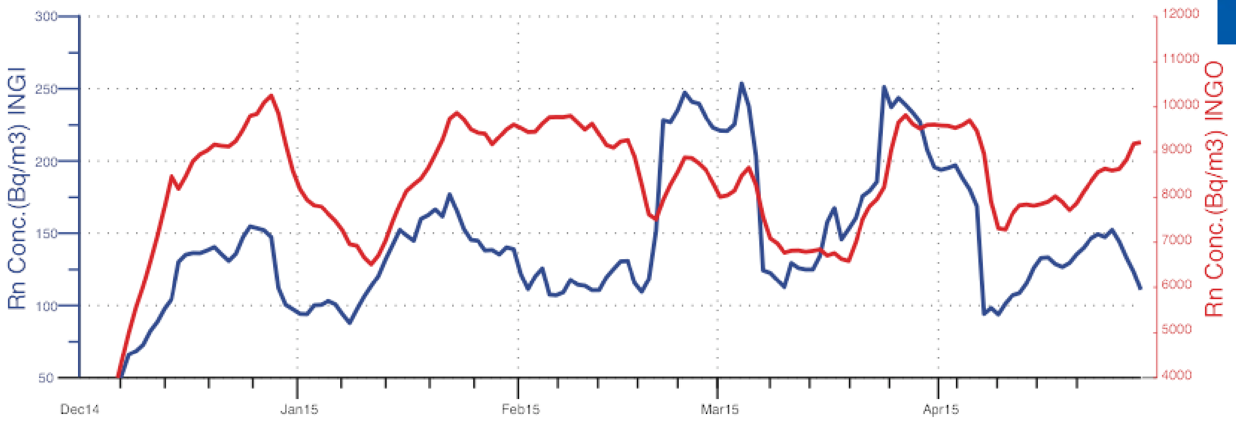


Fig. 11 14-days moving averaged time series of the radon concentration from INGI (blue line) and INGO (red line) stations during the period from January 2015 to April 2015.

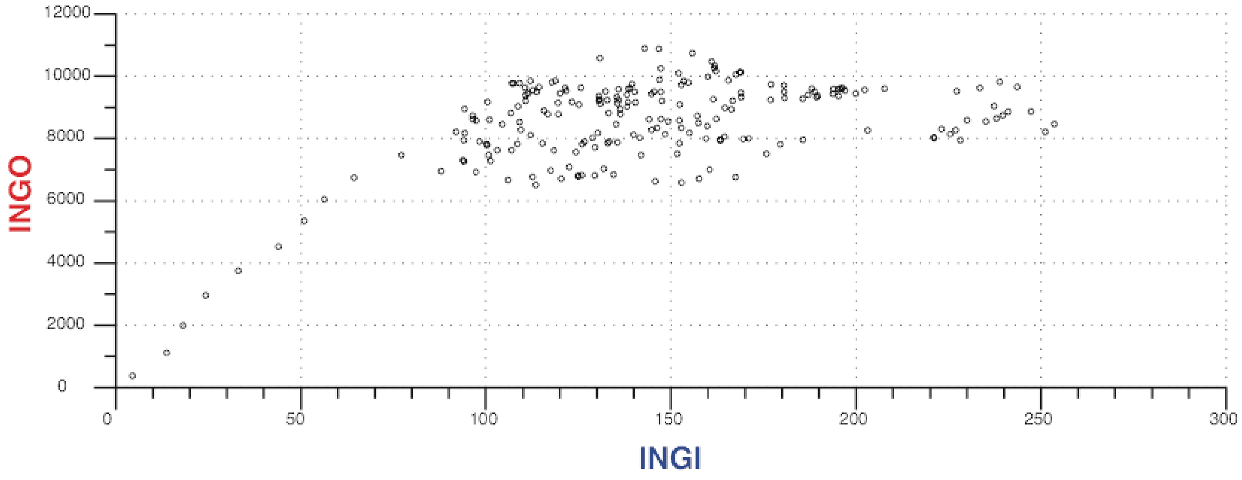
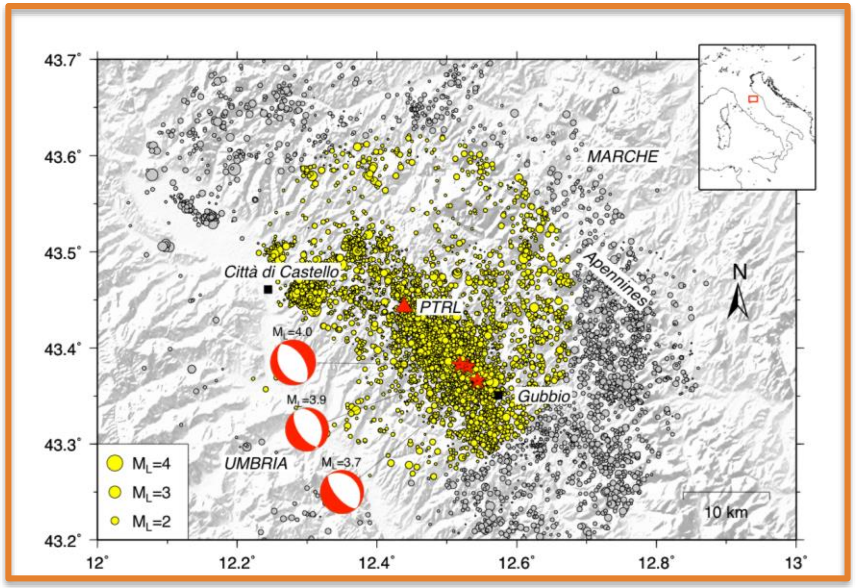
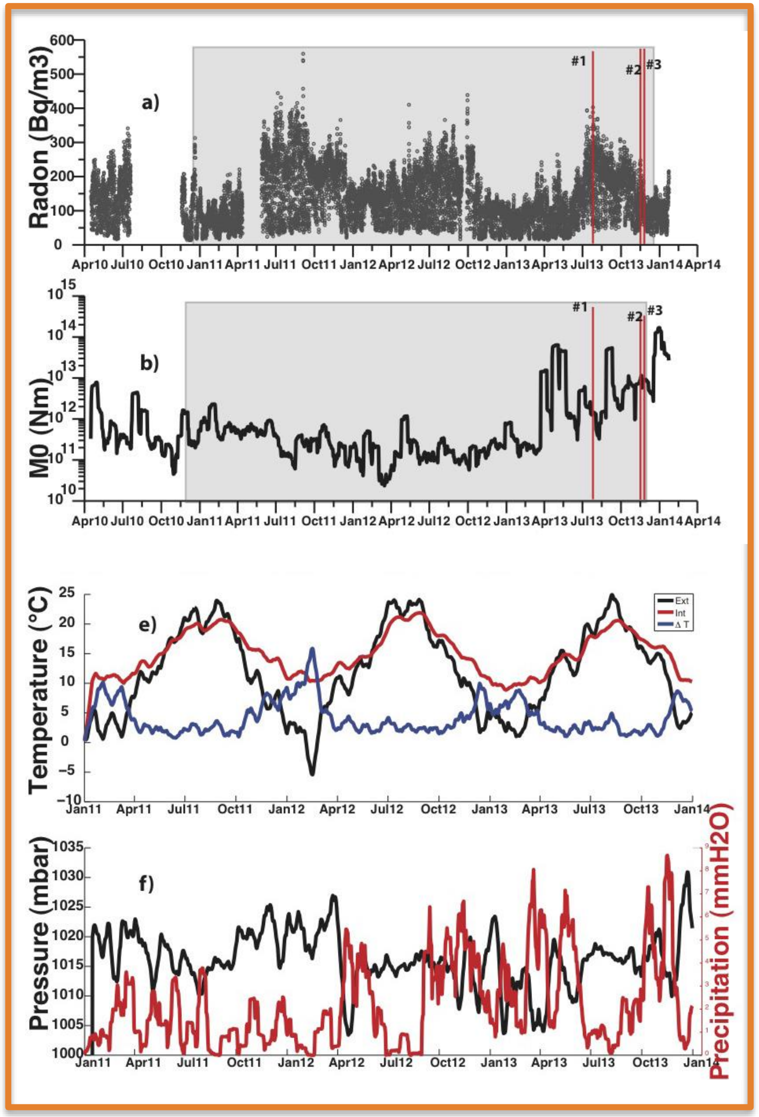


Fig. 12 INGO radon concentration versus INGI radon concentration during the period from January 2015 to April 2015.

PTRL: Dati, approccio di analisi,





Rn (Bq/m3)

M0 (Nm)

T (°C)

P,R (mbar mmH2O)

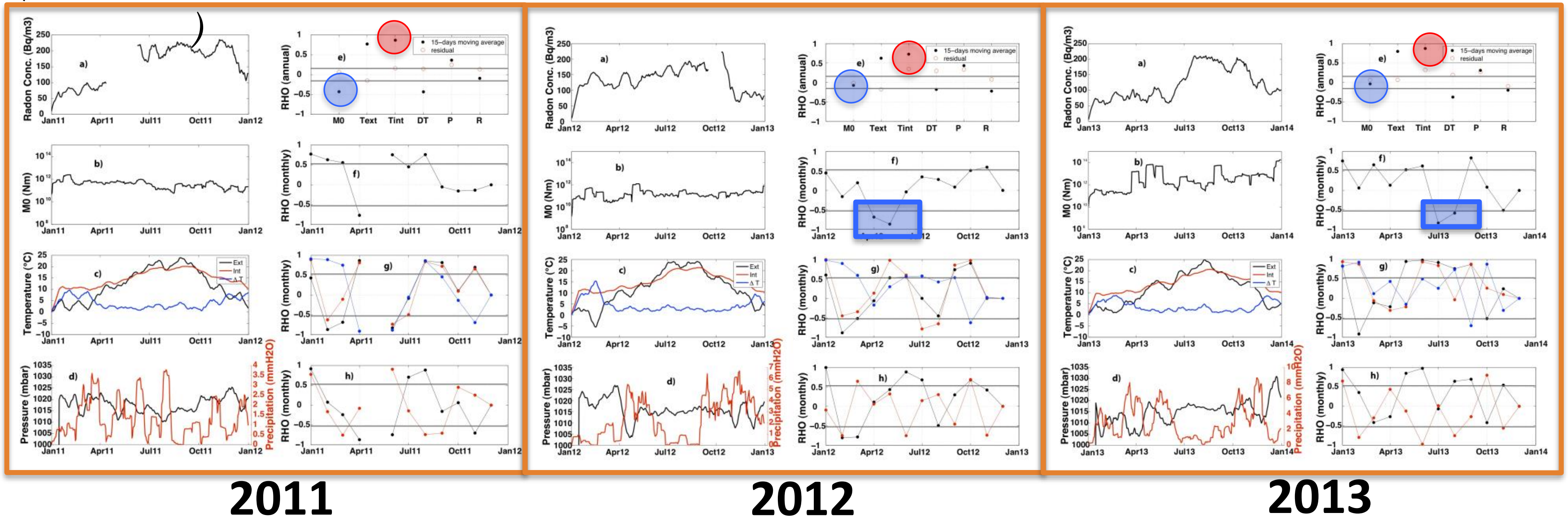
Gen2011 – Dic2013

(Piersanti et al 2015)

PTRL: Dati, approccio di analisi,

Pearson Corr: $RHO_{XY} = cov_{XY}/cov_X\, cov_Y$

(Piersanti et al 2015)



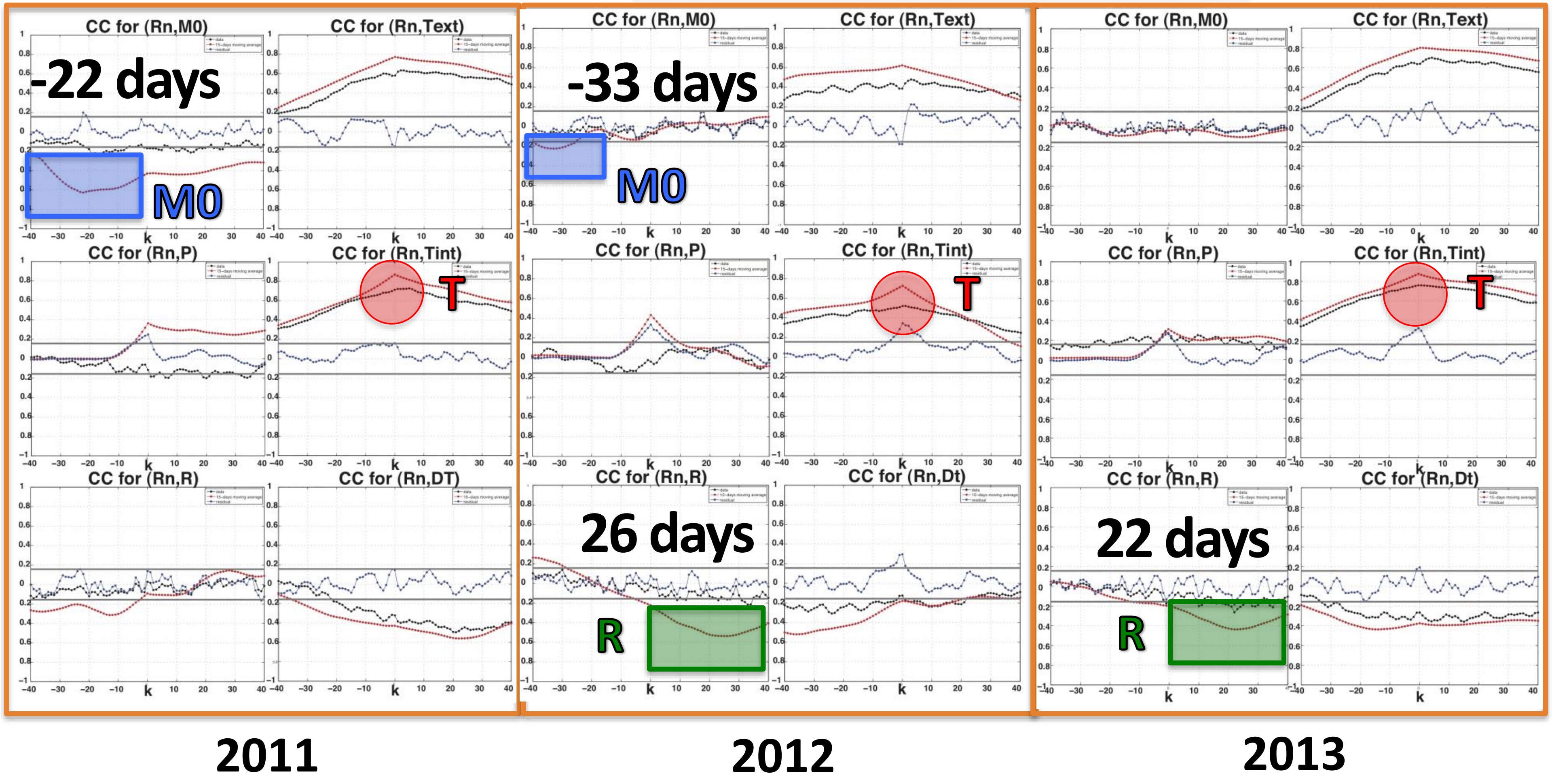
- RHO(Rn,T), RHO(Rn,R) sempre significativo (0,6÷0,9)
- RHO(Rn,P) < RHO(Rn,T) ma ancora significativo
- RHO(Rn,M0) non significativo su base annua globale, significativo nei mesi di riattivazione della sequenza

PTRL: Dati, approccio di analisi,

Lagged Corr:

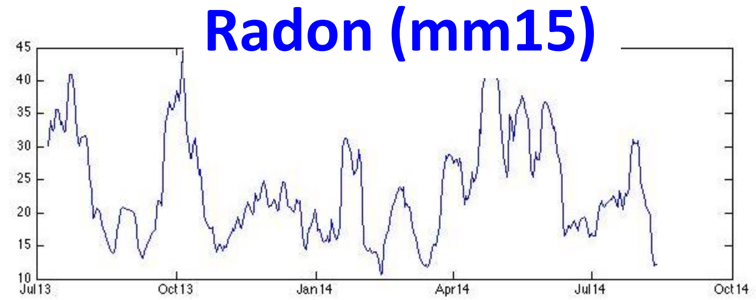
$$CC_{XY}(t) = \int_{-\infty}^{+\infty} X^*(\tau)\cdot Y(t+\tau)d\tau$$

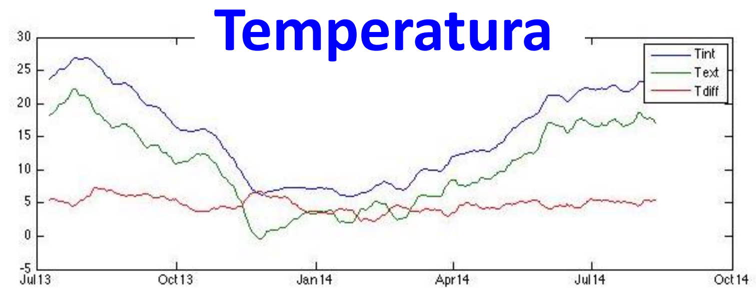
(Piersanti et al 2015)

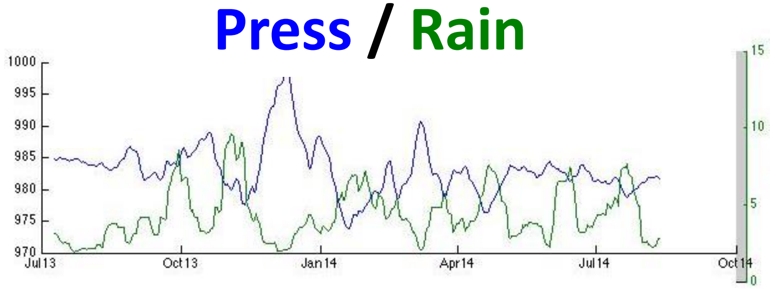


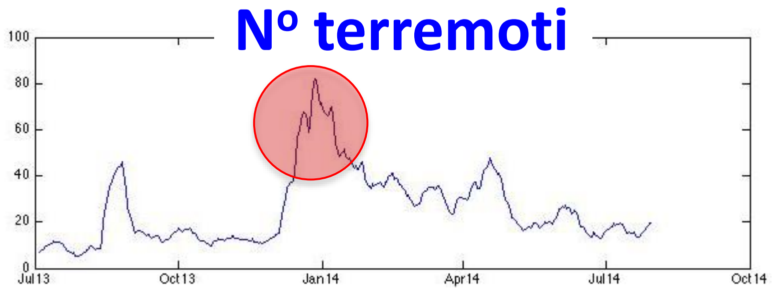
MURB: Dati, approccio di analisi

- Luglio2013 – Ottobre2014
- Radon raw > 150 Bq/m3
- Numero EQ ≈ 12,000
- 6 EQ 3.5 < M < 4









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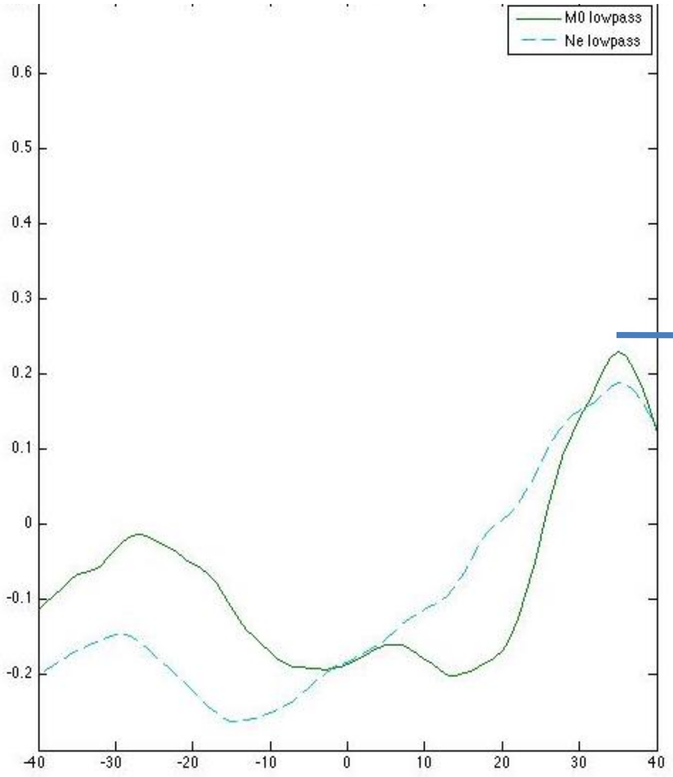
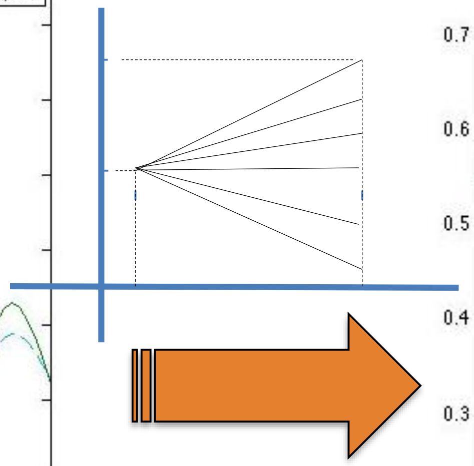
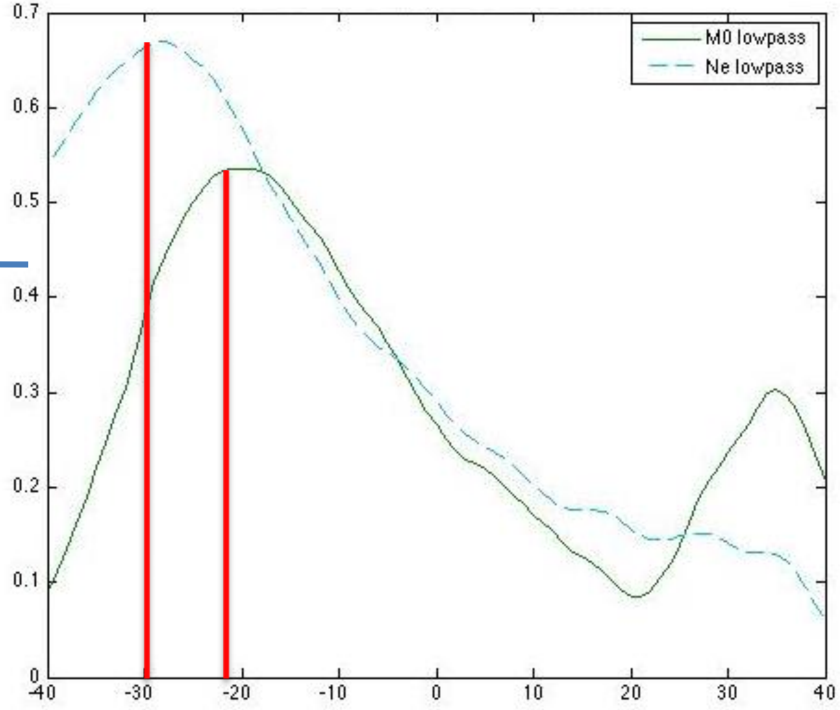
MURB: Dati, approccio di analisi

Radon and seismic activity correlation





Radon and seismic activity correlation



Effetto della "correzione" per i parametri meteo (T,P,R)

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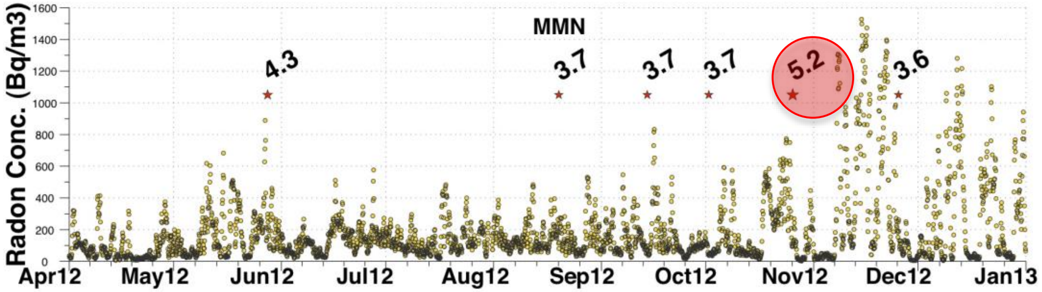
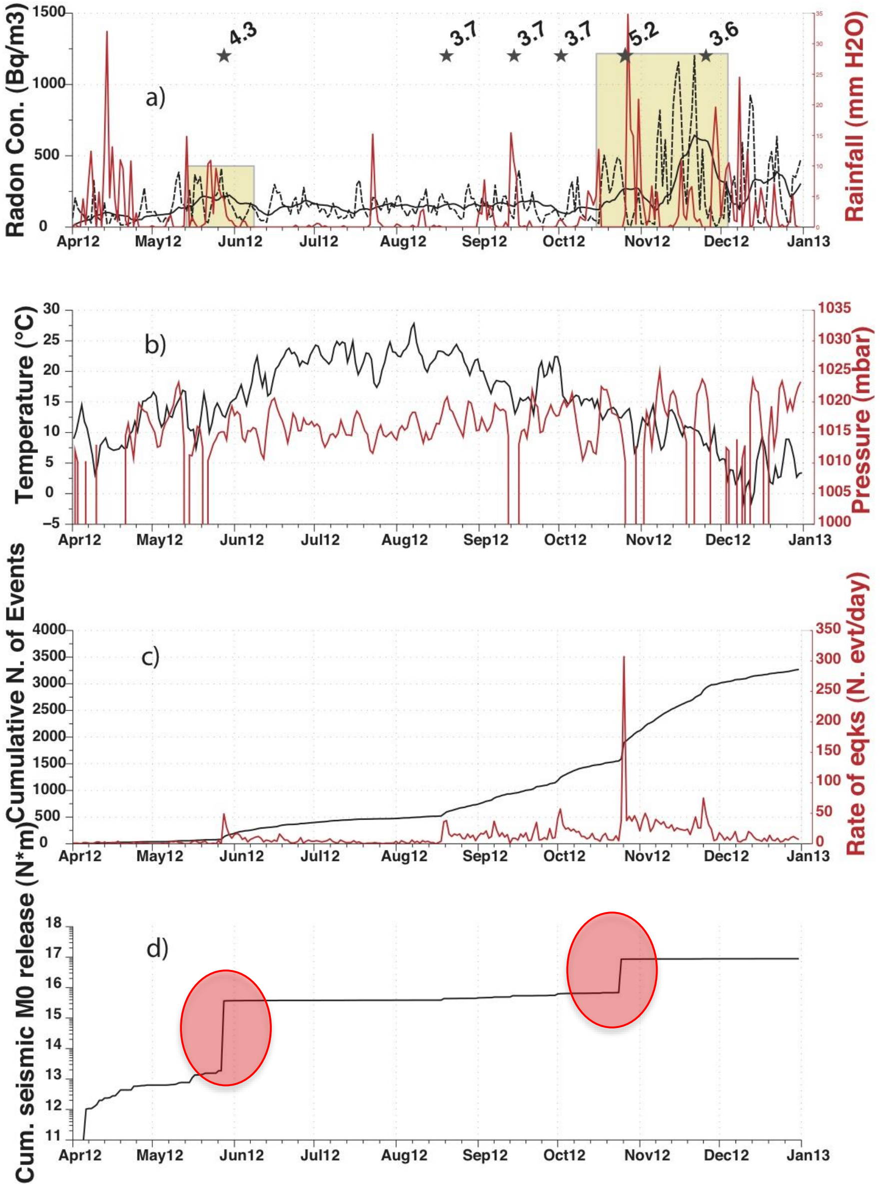
Mormanno: sequenza Pollino 2012

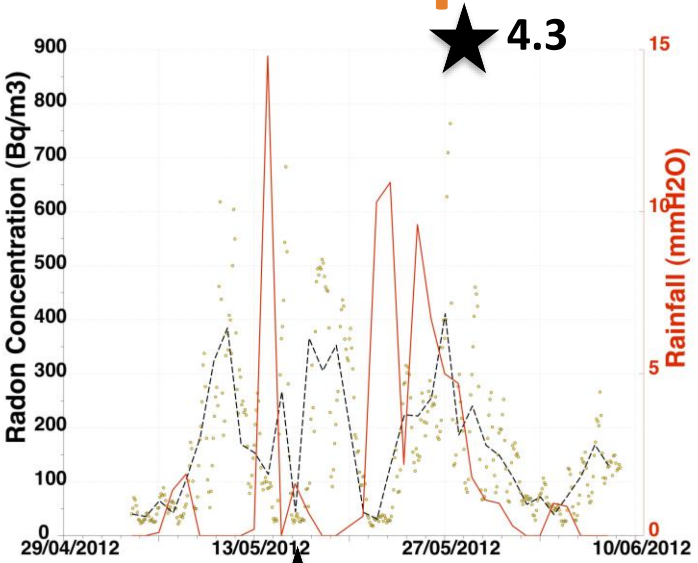


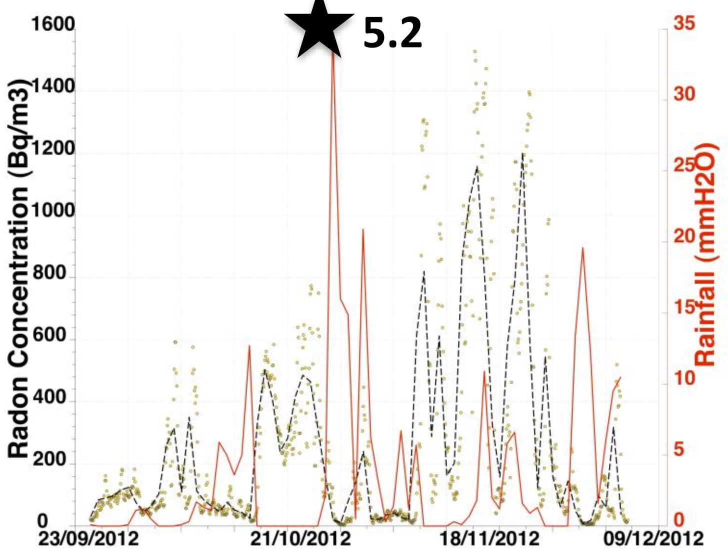


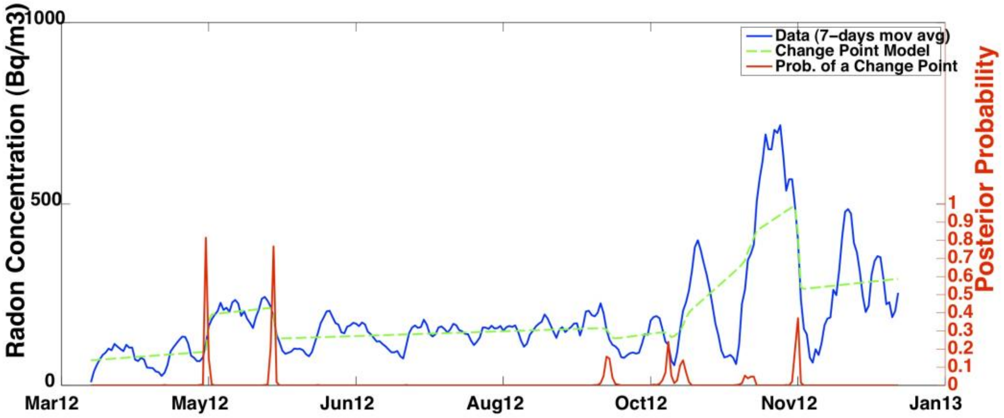
- **Dic2011 – Ott2014**
- **Radon raw > 1000 Bq/m3**
- **Numero EQ ≈ 5,000 (M<3)**

(Piersanti et al. 2016)

Mormanno: sequenza Pollino 2012





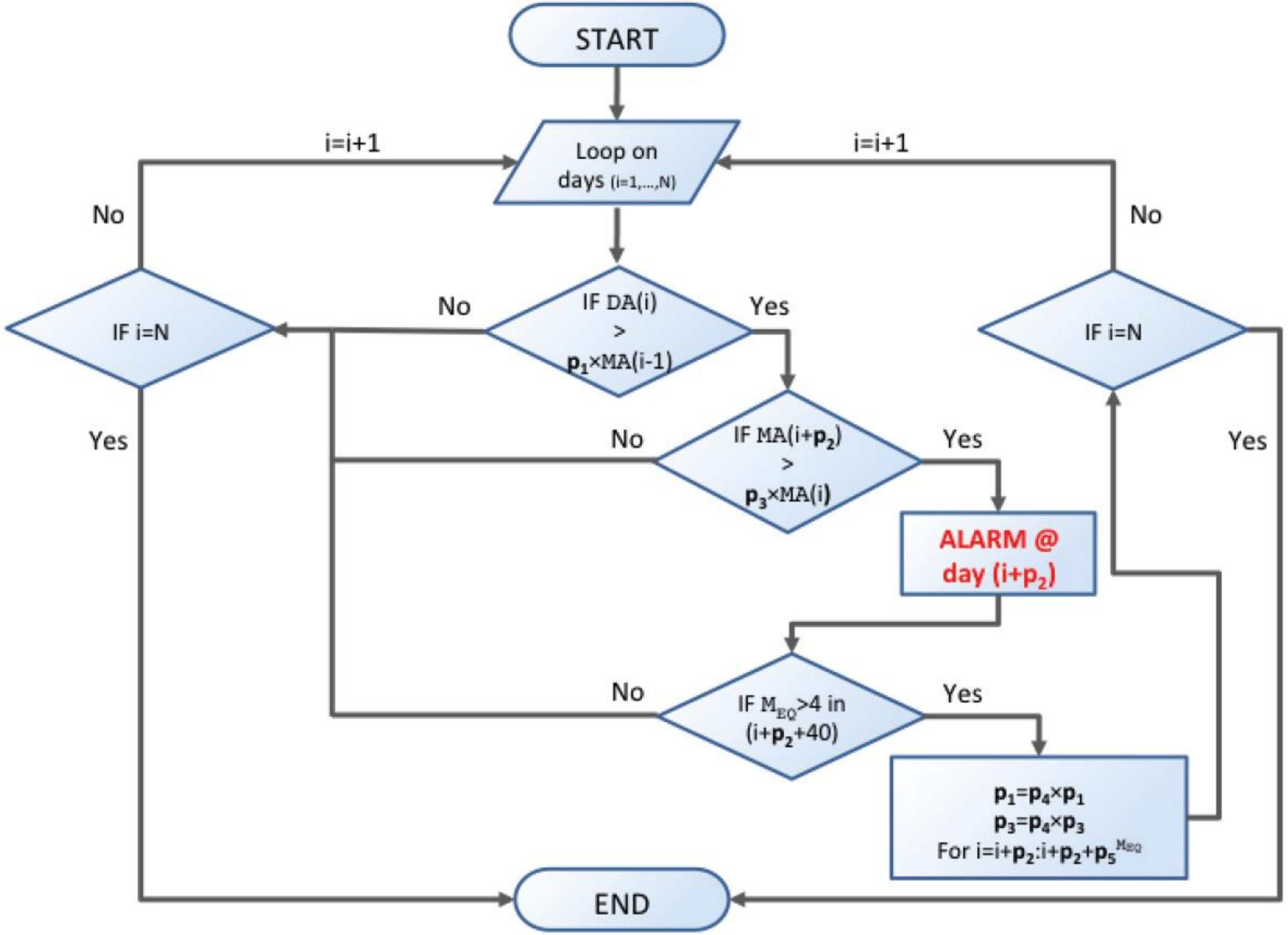


(*E. Ruggieri, International Journal of Climatology 2012*)

Change points significativi ≈ 20 giorni prima EQ4.3 (inizio sequenza) e EQ 5.2.

- **Approccio fenomenologico: su basi quantitative**
- **Approccio statistico: analisi change points**

Detection algorithm (Piersanti et al 2016)



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Detection algorithm (Piersanti et al 2016)

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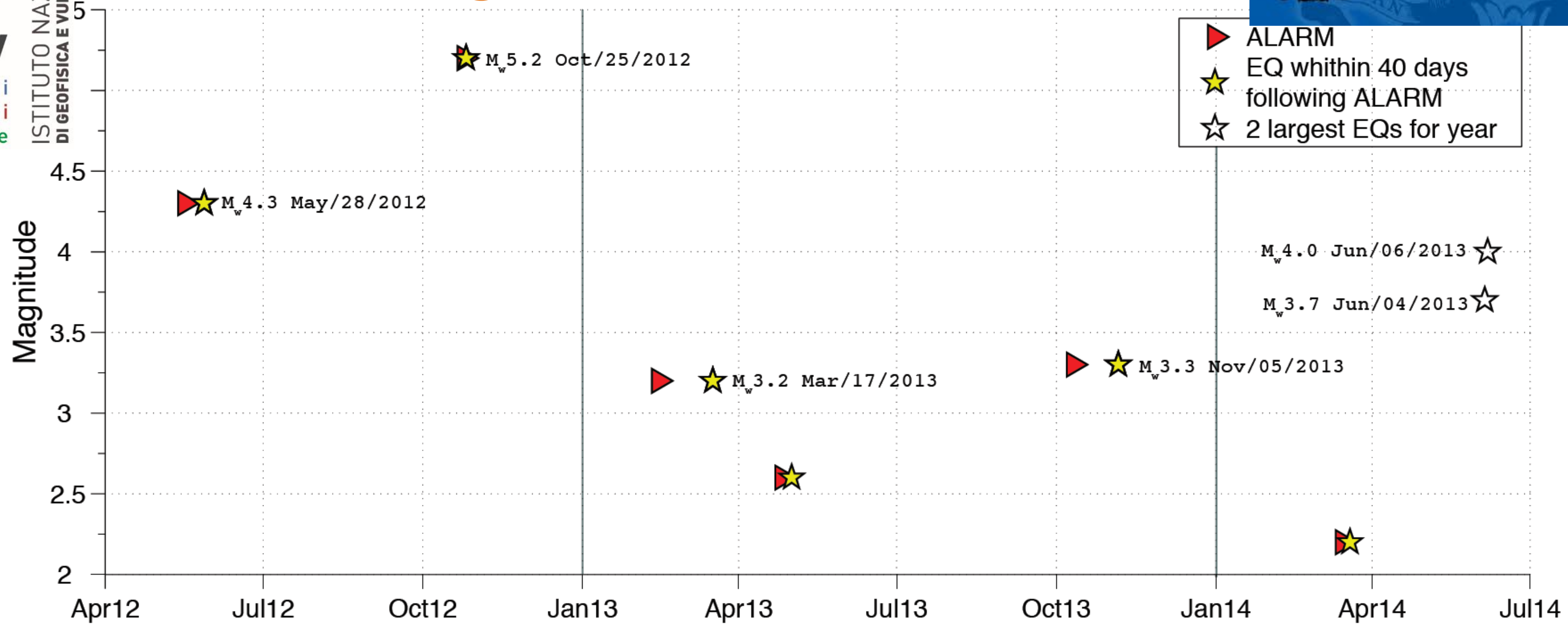

i) **DA** succeeds in forecasting the MW 5.2 mainshock of October 2012;
ii) **DA** succeeds in forecasting the two main events of the whole sequence (the MW 5.2 of October 2012 and the MW 4.3 of May 2012 that started the most active part of the sequence);

iii) **DA** succeeds in forecasting the major events for 2012 and 2013, while it fails for 2014;
iv) **DA** issues only one false alarm in three years.

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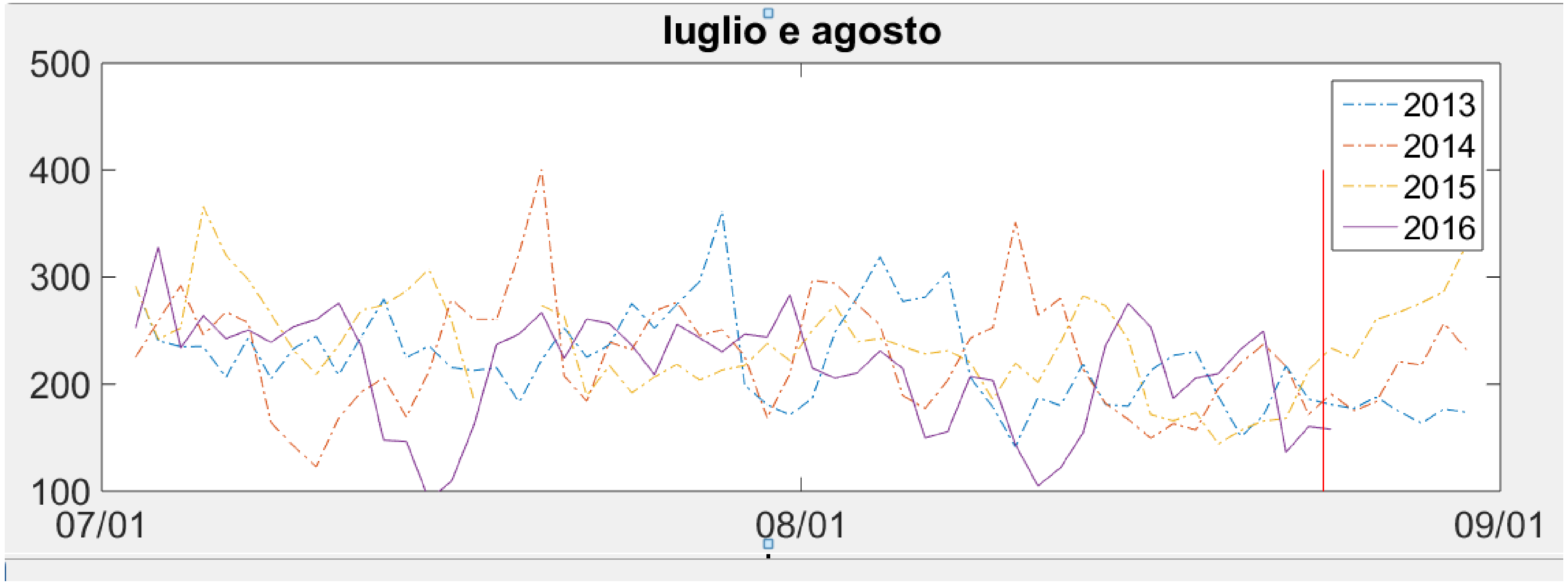
The M_L 6.0 Amatrice Earthquake of August 24th 2016

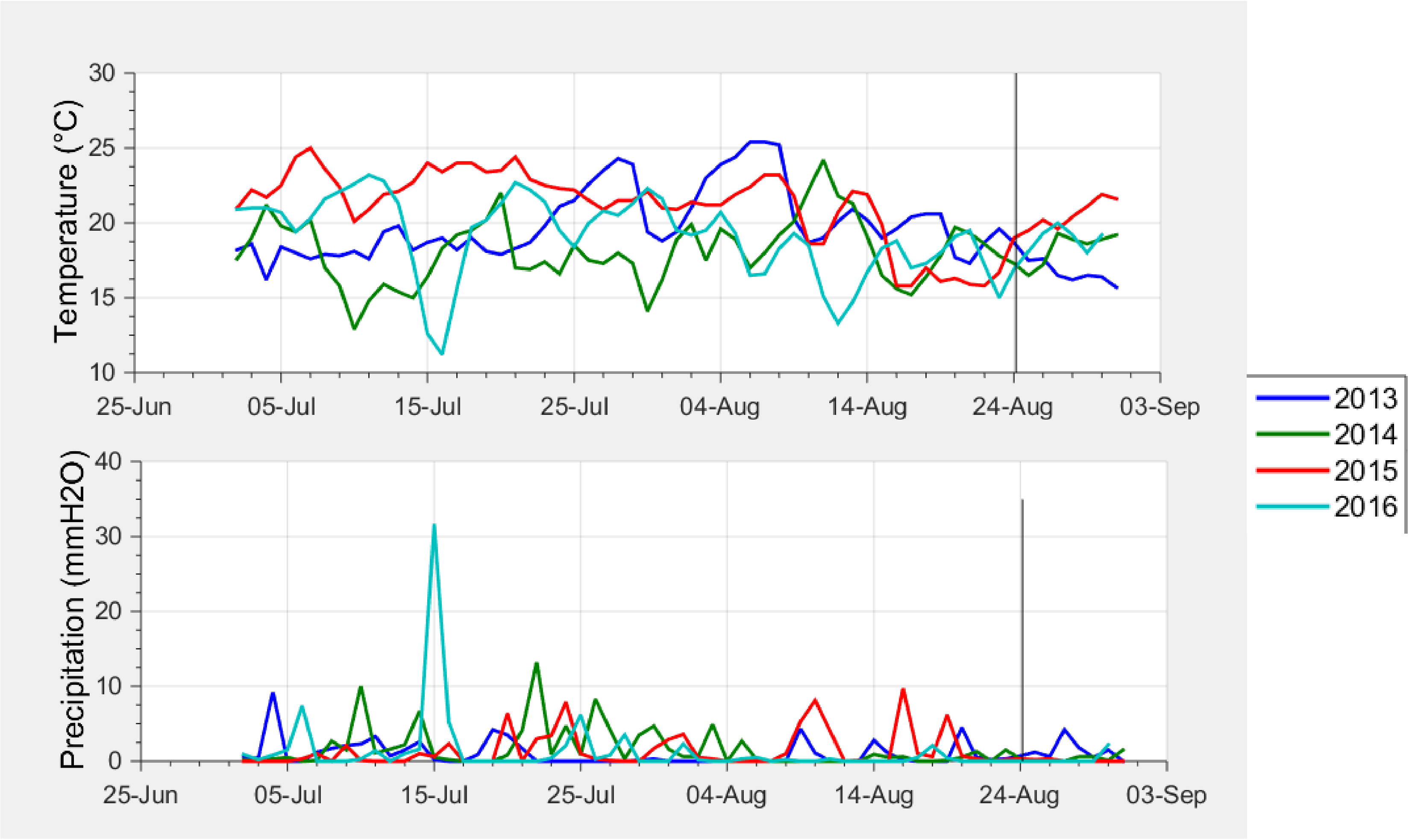
Terremoto Amatrice

Stazione radon Cittareale (CTTR)



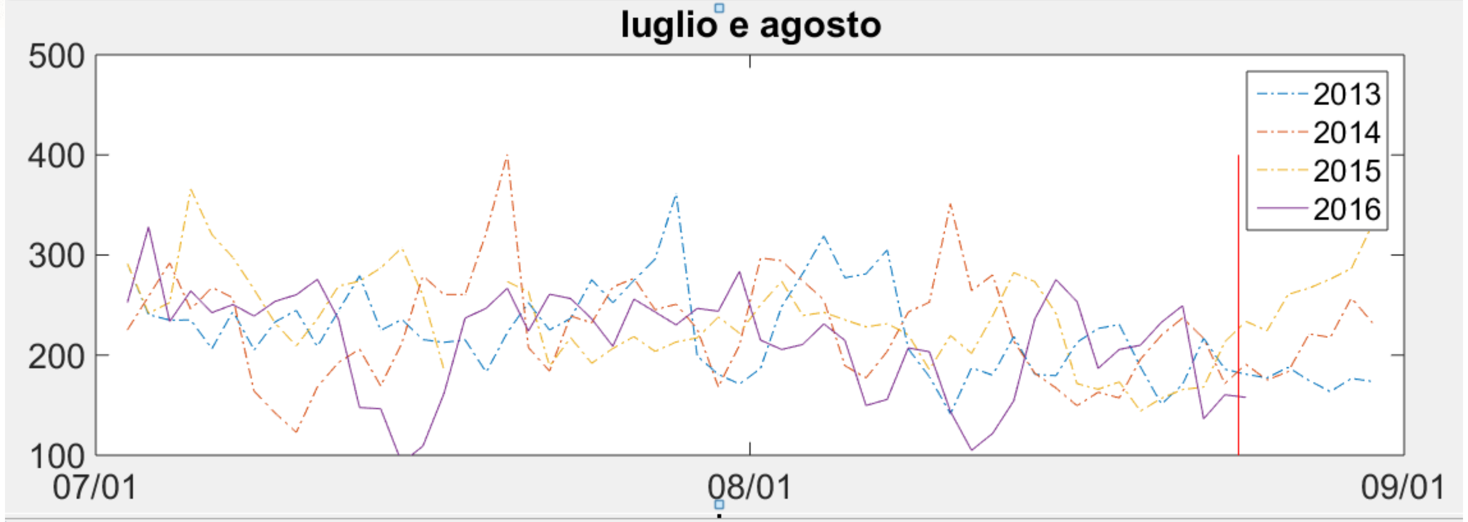
Terremoto Amatrice

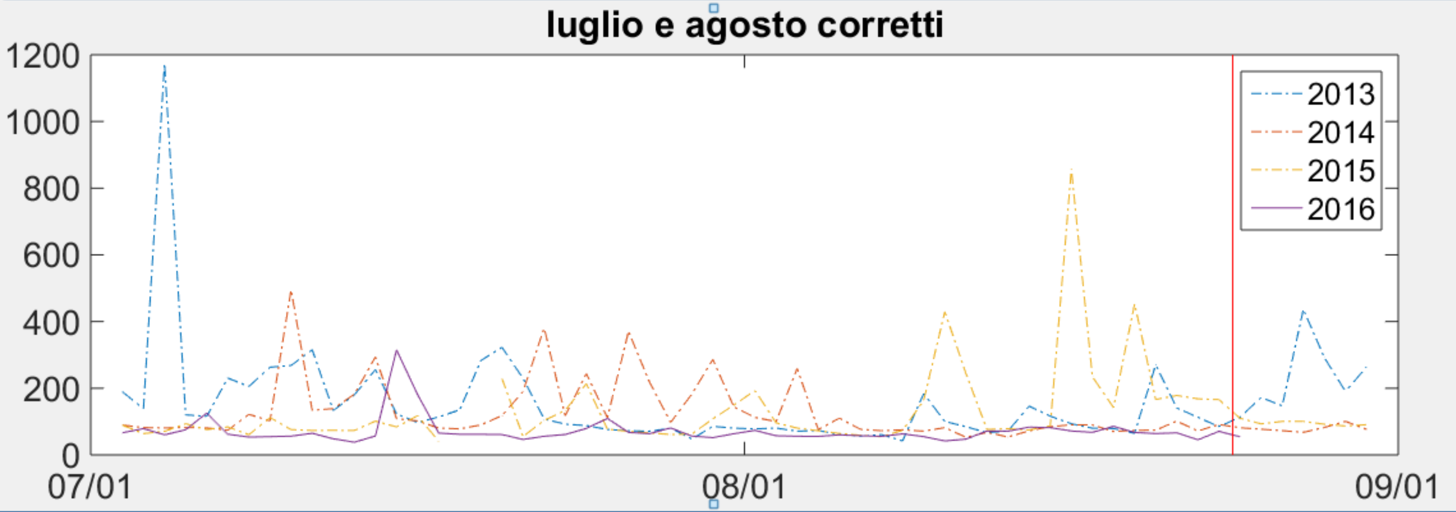
Stazione radon Cittareale (CTTR)



Terremoto Amatrice

Stazione radon Cittareale (CTTR)





Media a 4 settimane

	No corr	Corr
2016:	196 bq/m3	63 bq/m3
2015:	216 bq/m3	179 bq/m3
2014:	222 bq/m3	90 bq/m3
2013:	212 bq/m3	96 bq/m3

Media a 8 settimane

	No corr	Corr
2016	214 bq/m3	71 bq/m3
2015:	233 bq/m3	158 bq/m3
2014:	228 bq/m3	129 bq/m3
2013:	227 bq/m3	149 bq/m3

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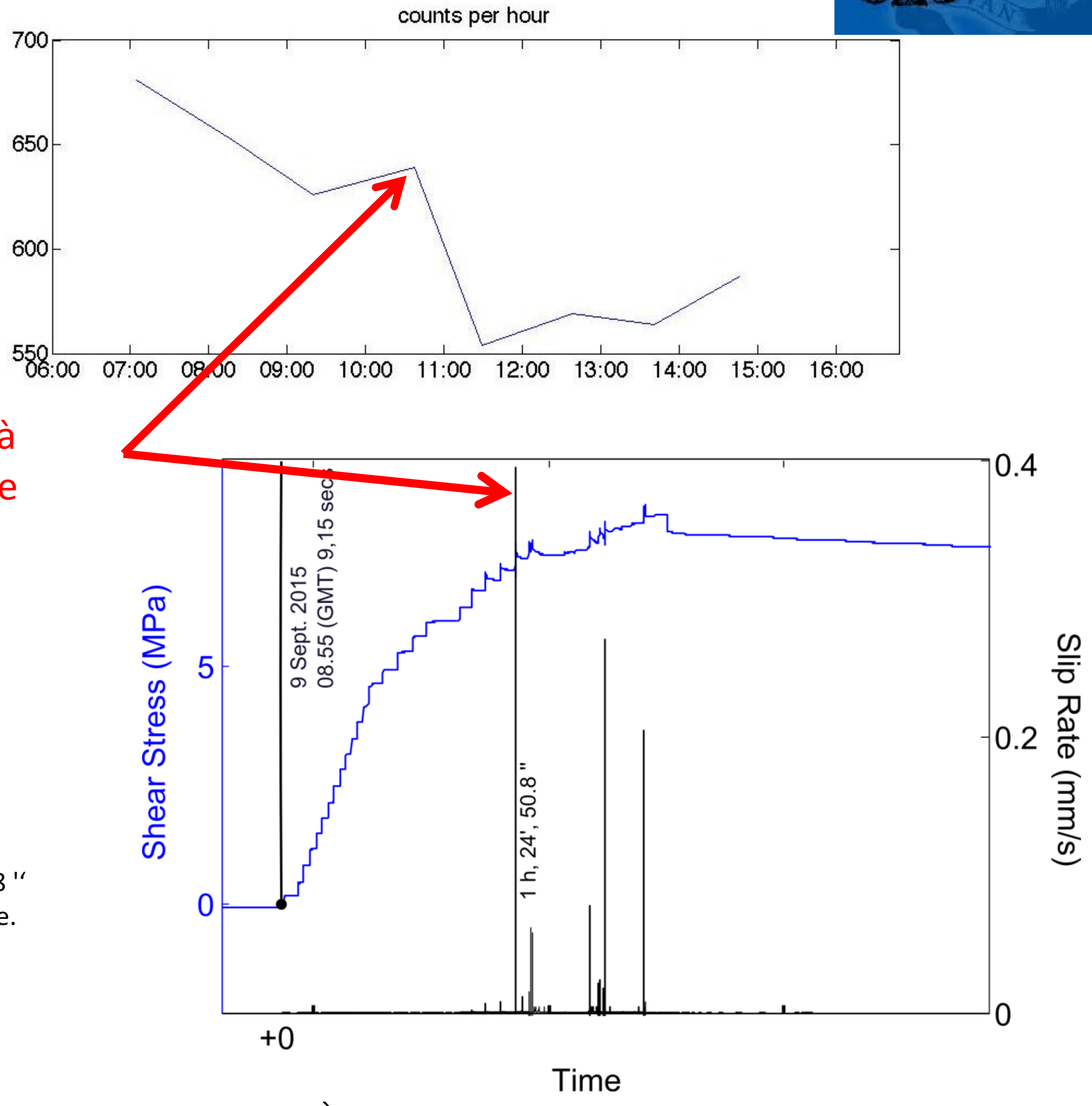
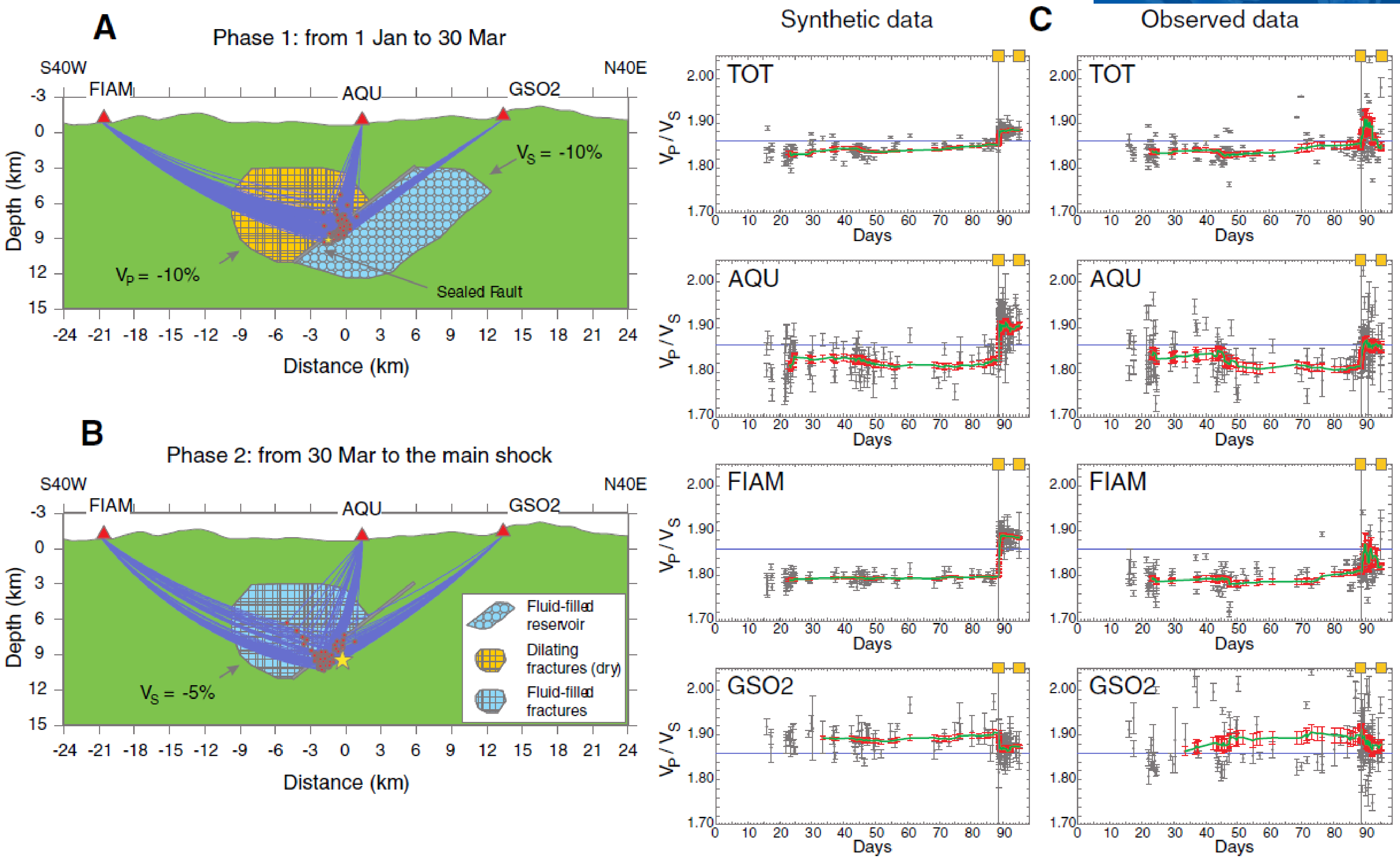
Instabilità principale



L'instabilità avviene dopo 1 h, 24', 50.8 ''
Dall'applicazione del carico tangenziale.

2009 L’Aquila earthquake(Lucente et al 2010)



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SI
PUO’
FARE!

SI

PUO’

FARE!

Ma non si fara da se’ !!