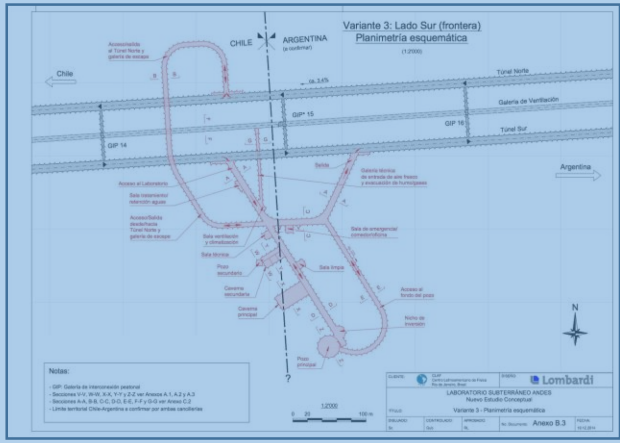
Fifth International Workshop for the Design of the ANDES Underground Laboratory

Buenos Aires, Argentina 29 - 30 June 2017



The ANDES Underground Laboratory, a Geophysical Research Opportunity

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SUMMARY

An underground laboratory located on one of the most active tectonic and seismic areas of the earth represents a superb opportunity for geophysics research projects planned for a better knowledge of the earth structure and dynamics, including the earthquakes generation process.

ANDES underground laboratories equipped with high sensitivity and broadband instruments will give the possibility to detect in a suitable conditions signals associated with parameter related to earth strain accumulation and release, including the earthquakes preparation and source dynamics.

Earthquakes are a potential problem for large-scale scientific experiments and are dangerous as well for the personnel inside of the facilities. The seismic signals detected in a low environmental noise site can provide high quality data, useful for improving the seismic early warning algorithms.

Underground laboratories equipped with instruments acquiring data related to the seismicity and to local strain accumulations, such as the Gran Sasso National Laboratory (LNGS-Italy) provide one of the bases for planning the future experiences of the geophysical research offered by ANDES.

THE ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA (INGV)

The INGV, founded in 1999, is the largest Italian body dealing with research in Geophysics and Volcanology.

The INGV operates in close coordination with the Italian Ministry of University and Research and with the Civil Protection authorities.

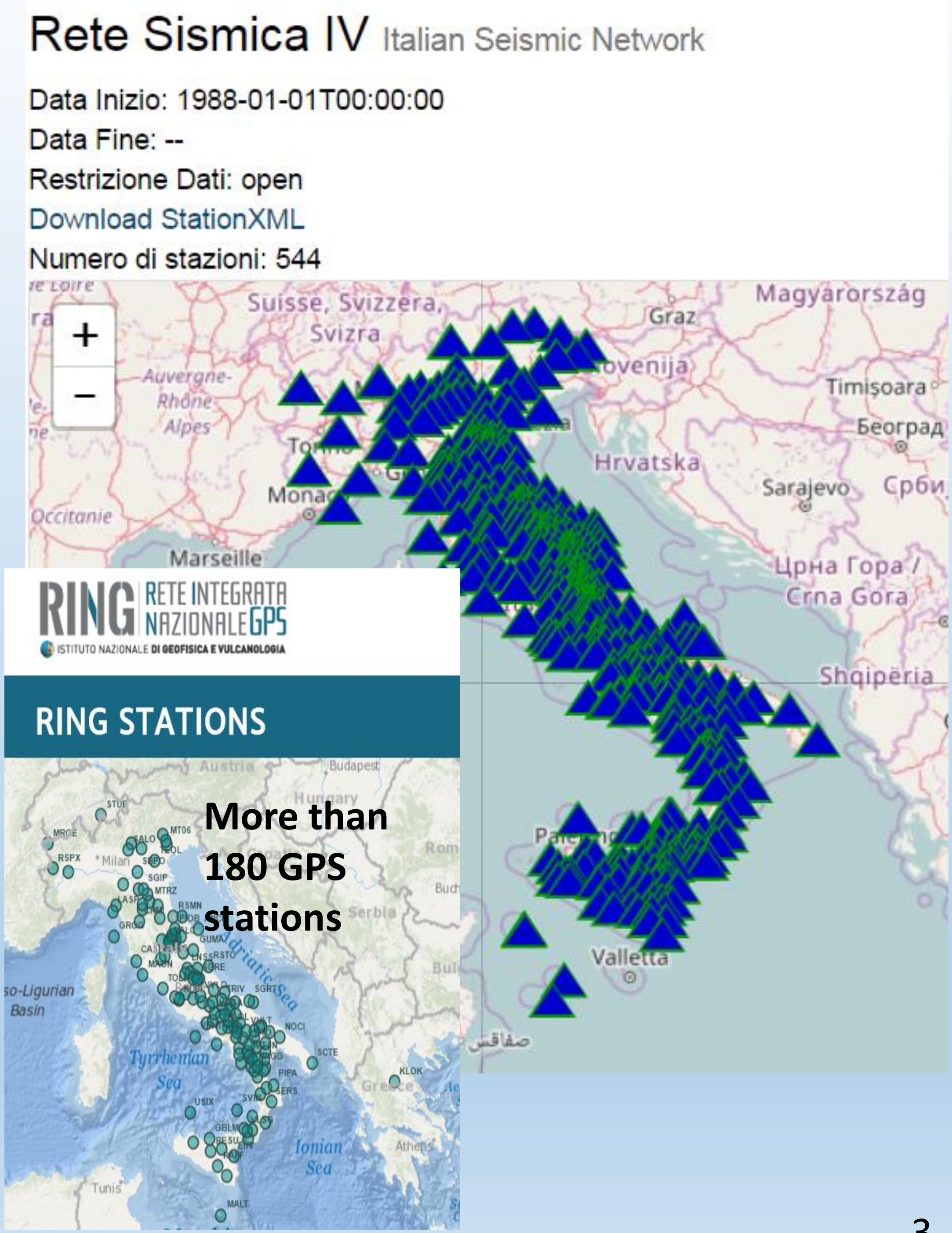
The INGV staff, about 900 units (researchers, technologists, technicians and administrators), is assigned to the INGV Departments in Milano, Bologna, Pisa, Rome (INGV Admin. + 3 Dept.), Napoli, Catania and Palermo.

INGV pays special attention to Education and Outreach through publications for schools, scientific exhibitions and dedicated Internet pages.

The Istituto Nazionale di Geofisica e Vulcanologia (INGV)

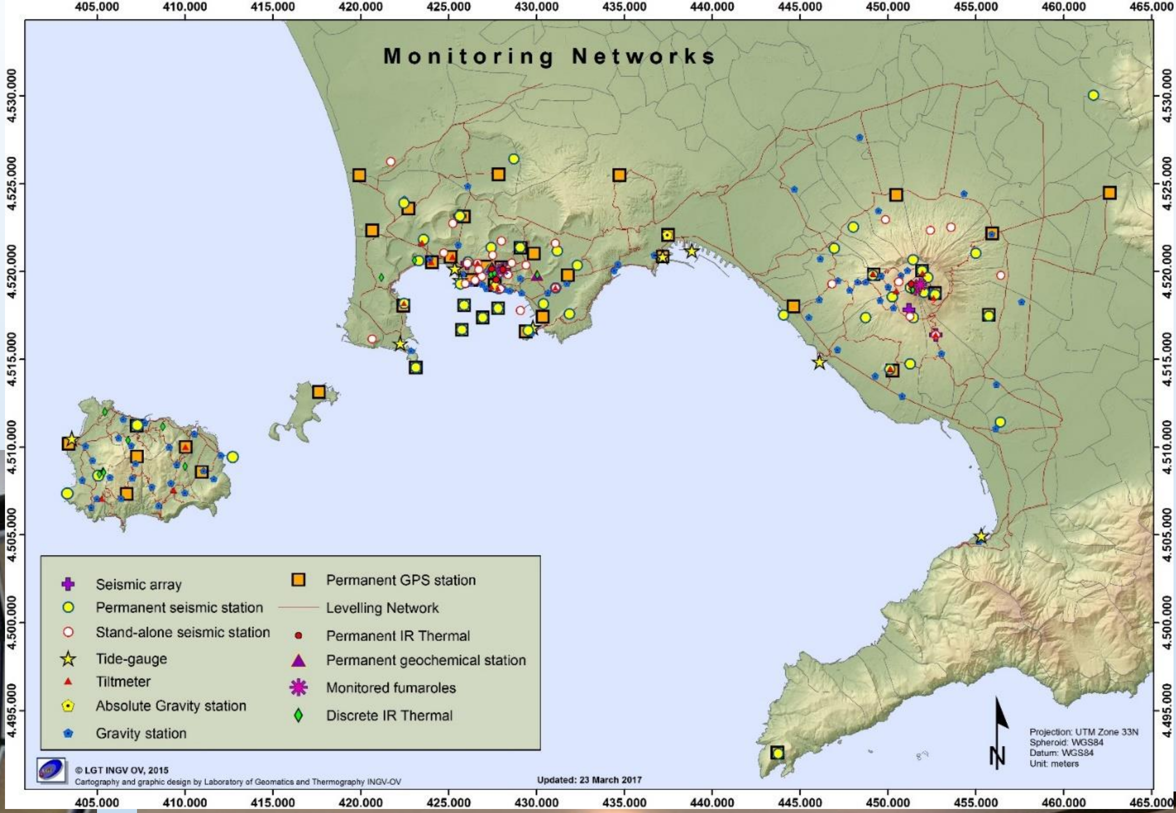
The INGV Monitoring Centers:

- the “**Centro Nazionale Terremoti**” (Rome), monitoring the seismicity of the italian territory



- H24 presence for monitoring the Italian seismicity.
- Data processing of the signals transmitted by about 550 seismic stations, integrated by 180 GPS stations (RING network)
- Direct communications with the Civil Protection Dept.

The Istituto Nazionale di Geofisica e Vulcanologia (INGV)



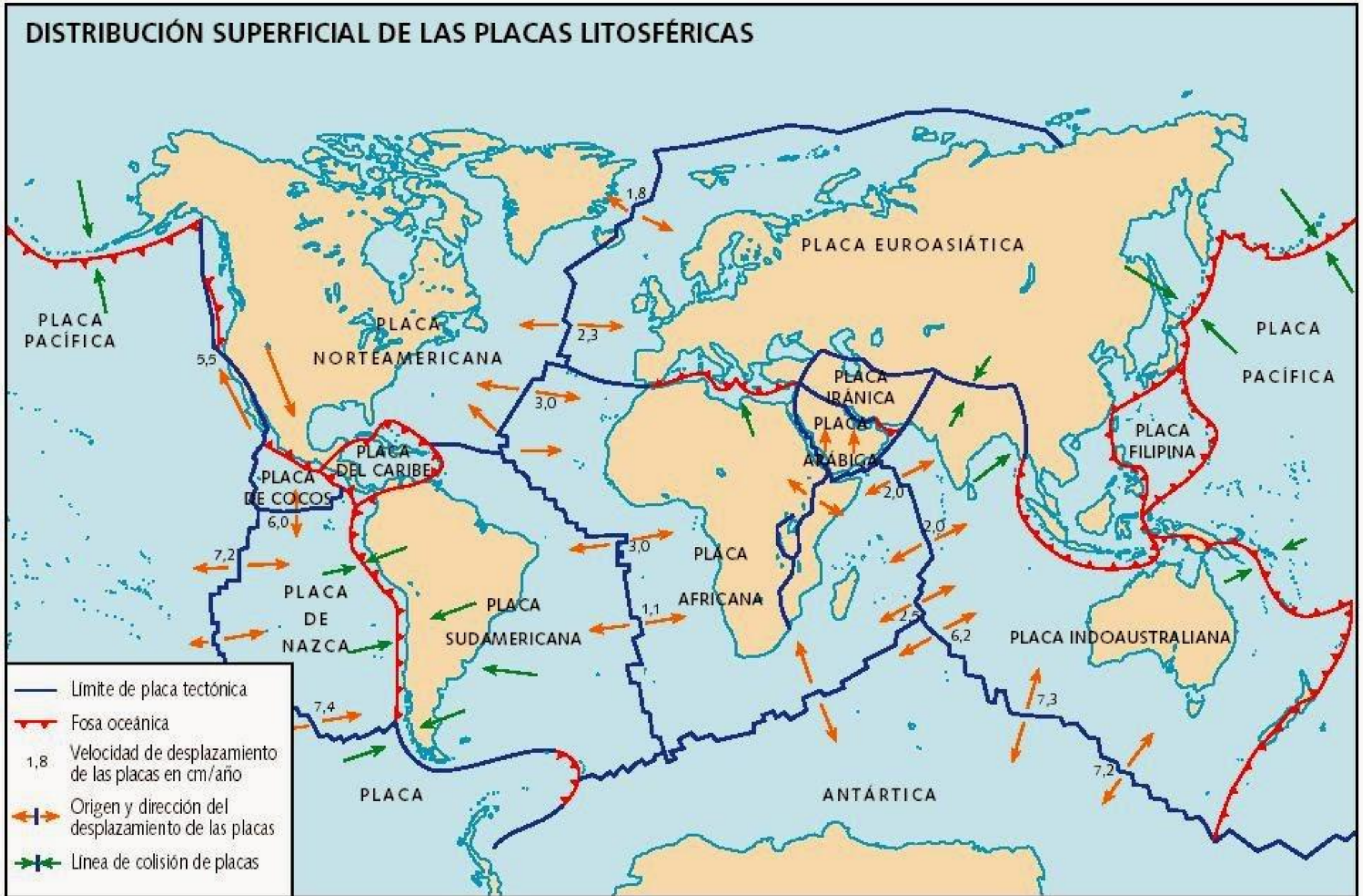
The INGV Monitoring Centers:

- the **Osservatorio Vesuviano** (Naples) and the **Osservatorio Etneo** (Catania) for monitoring and forecast the activities of the italian active volcanoes

- H24 presence for the moniroting the Campania and Sicily Region active volcanoes (Vesuvio, Campi Flegrei ed Ischia- Etna, Stromboli, Vulcano)
- Multiparametric data processing (seismic, geodetic, geochemical, thermal)
- Direct communications with the Civil Protection Dept.

One of the most active tectonic and seismic region of the Earth

The ANDES laboratory will be located at a distance of about 250 km from the trench where the plate dynamics is dominated by the subduction of the Nazca Plate beneath the South America Plate.



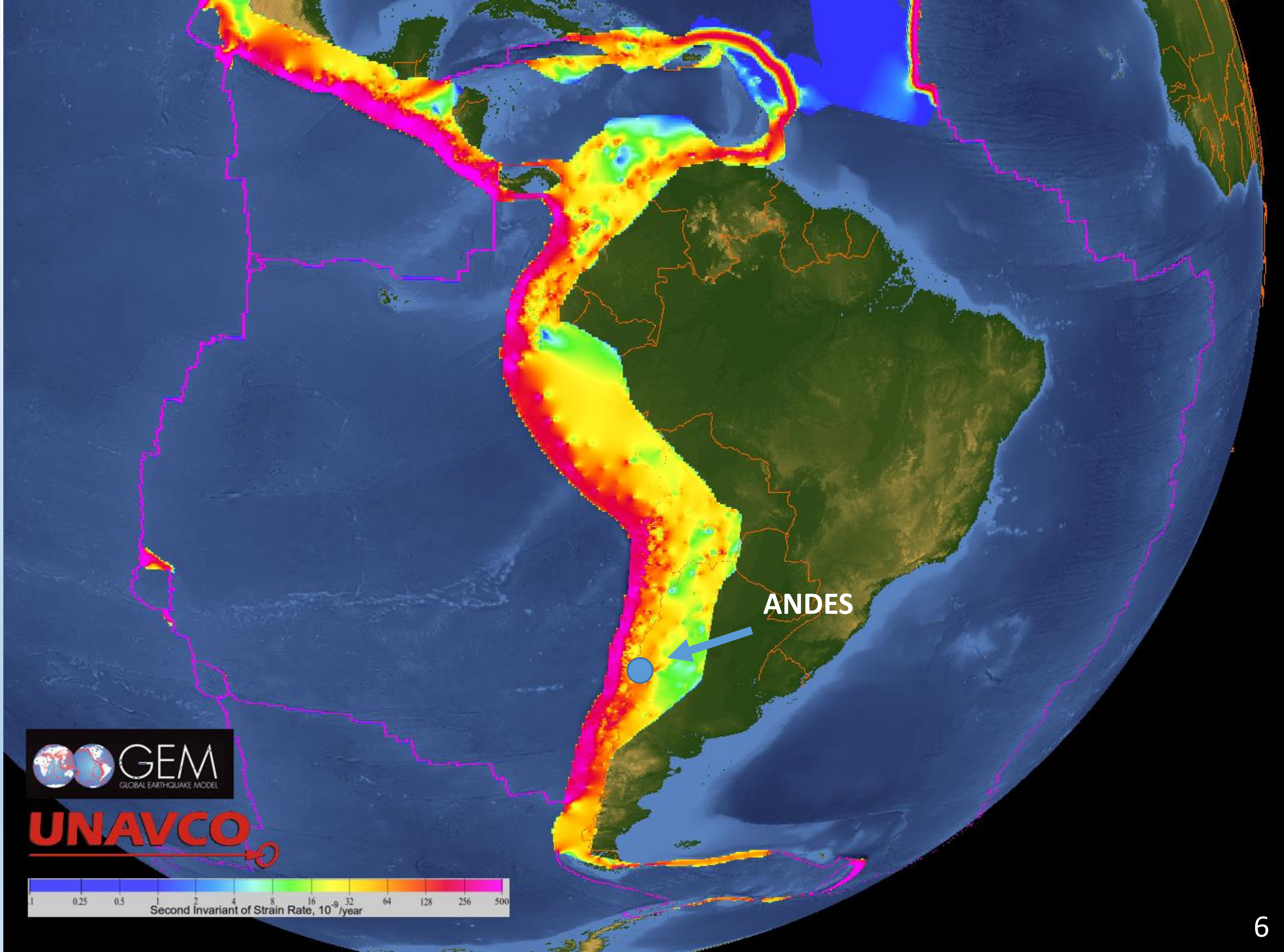
Map of world's major subduction zones (thick gray lines) and tectonic plate boundaries.

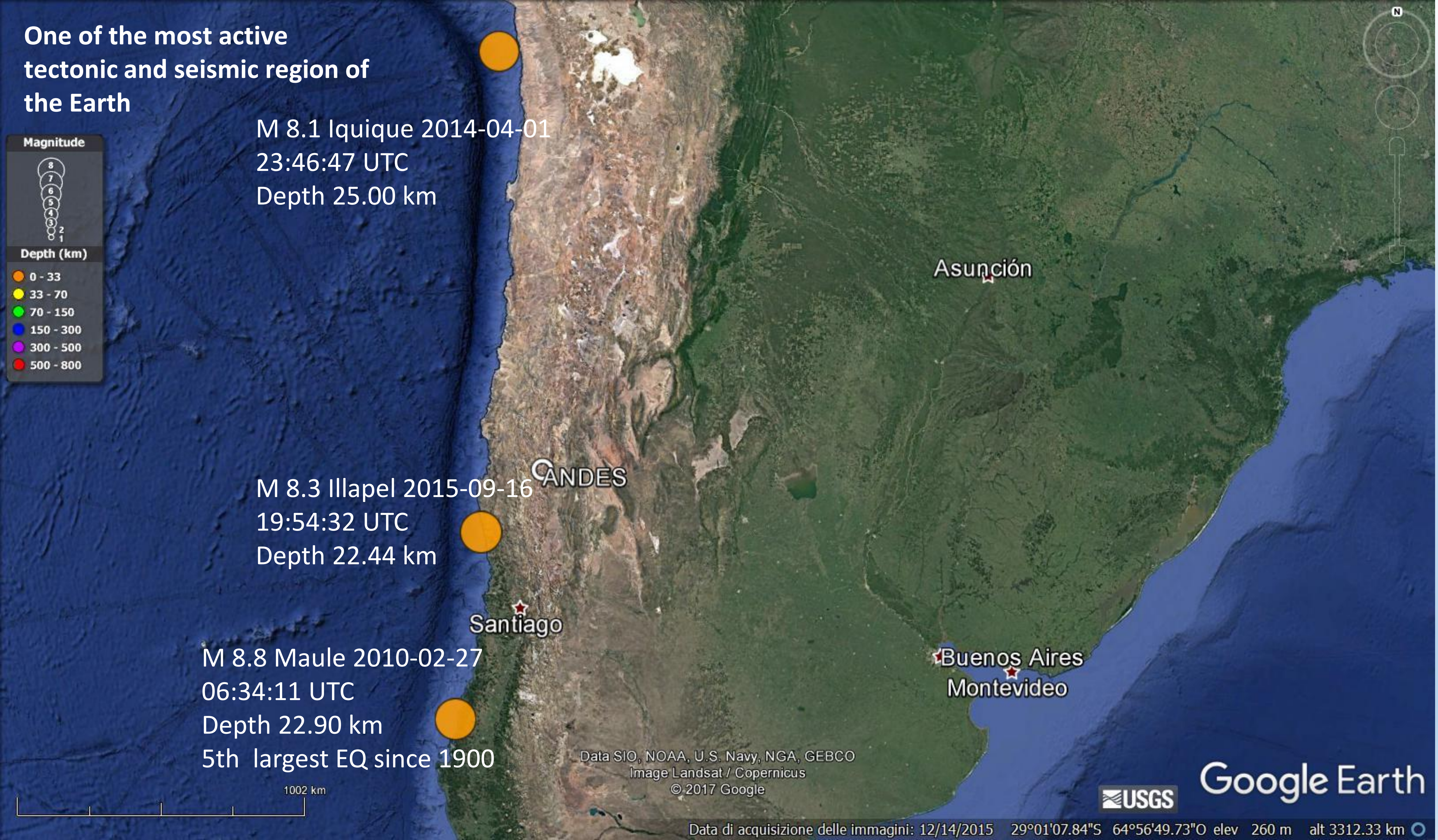
The relative convergence velocity between the Nazca Plate beneath the South America Plate is of about 65 mm/year (Kendrick et al., 2003).

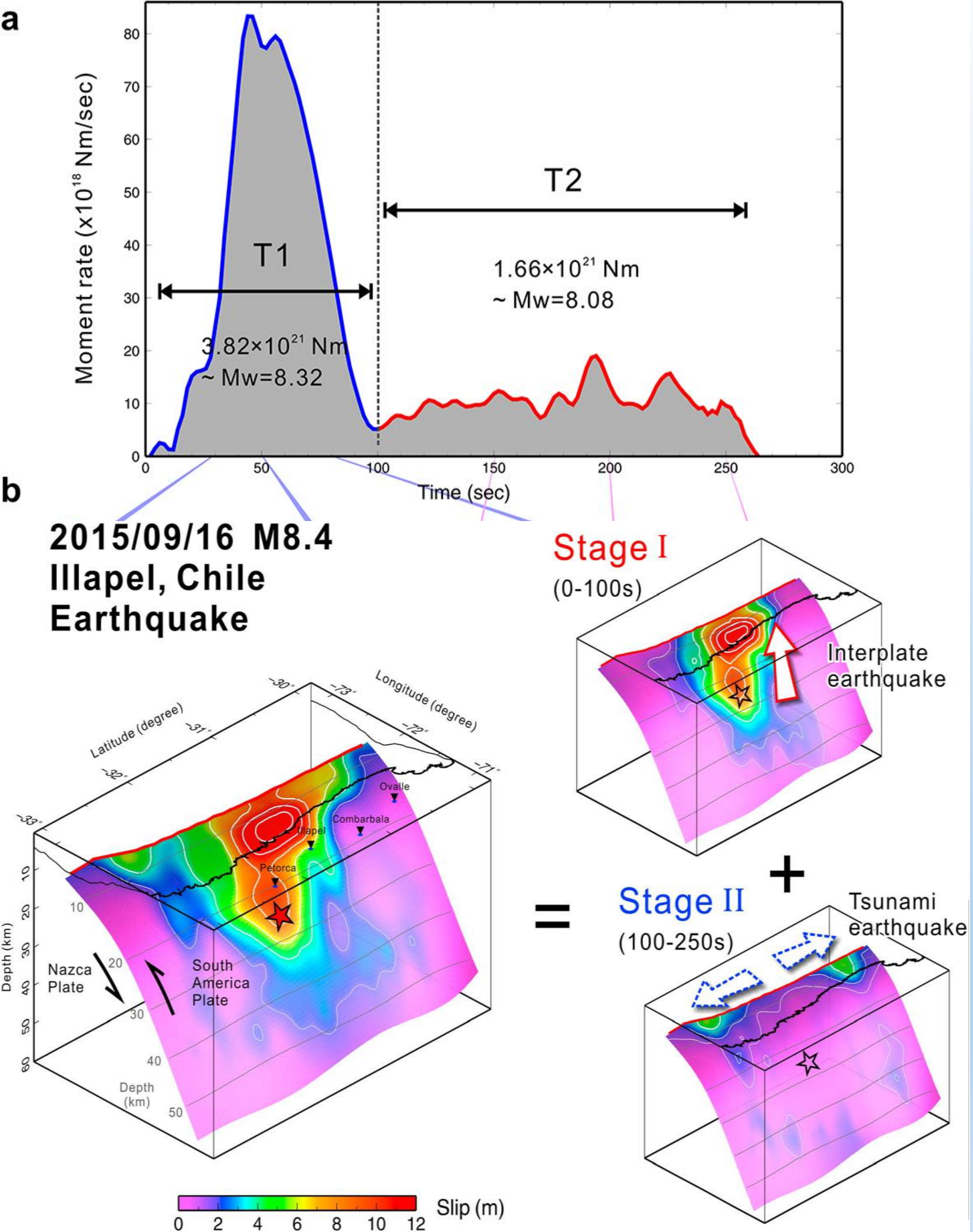
One of the most active tectonic and seismic region of the Earth

The ANDES localization

A train rate of 60-100 nε/year




One of the most active tectonic and seismic region of the Earth
Magnitude
Depth (km)
0 - 33
33 - 70
70 - 150
150 - 300
300 - 500
500 - 800
M 8.1 Iquique 2014-04-01
23:46:47 UTC
Depth 25.00 km
M 8.3 Illapel 2015-09-16
19:54:32 UTC
Depth 22.44 km
M 8.8 Maule 2010-02-27
06:34:11 UTC
Depth 22.90 km
5th largest EQ since 1900
ANDES
Santiago
Asunción
Buenos Aires
Montevideo
1002 km
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus
© 2017 Google
USGS
Google Earth
Data di acquisizione delle immagini: 12/14/2015 29°01'07.84"S 64°56'49.73"O elev 260 m alt 3312.33 km



Unlocking of the plate interface, plate convergence and loading rate

2015-09-16 Mw 8.3 Illapel EQ - A composite megathrust event

The largest global event in 2015, located in a seismic gap of the Peru-Chile subduction zone.

From the source model: two-stage rupture process distinct and temporally separated, with completely different slip characteristics:

- First stage with moment magnitude Mw 8.32, from the deeper locked zone and propagated in the updip direction toward the trench.

- Second stage with Mw 8.08, mainly in the shallow subduction zone with atypical repeating slip behavior.

The unique spatial-temporal rupture evolution presented in this source model is key to further in-depth studies of earthquake physics and source dynamics in subduction systems.

S.J. Lee et al., (2016),Two-stage composite megathrust rupture of the 2015 Mw8.4 Illapel,Chile, earthquake identified by spectral-element inversion of teleseismic waves, Geophys. Res. Lett., 43, 4979–4985,

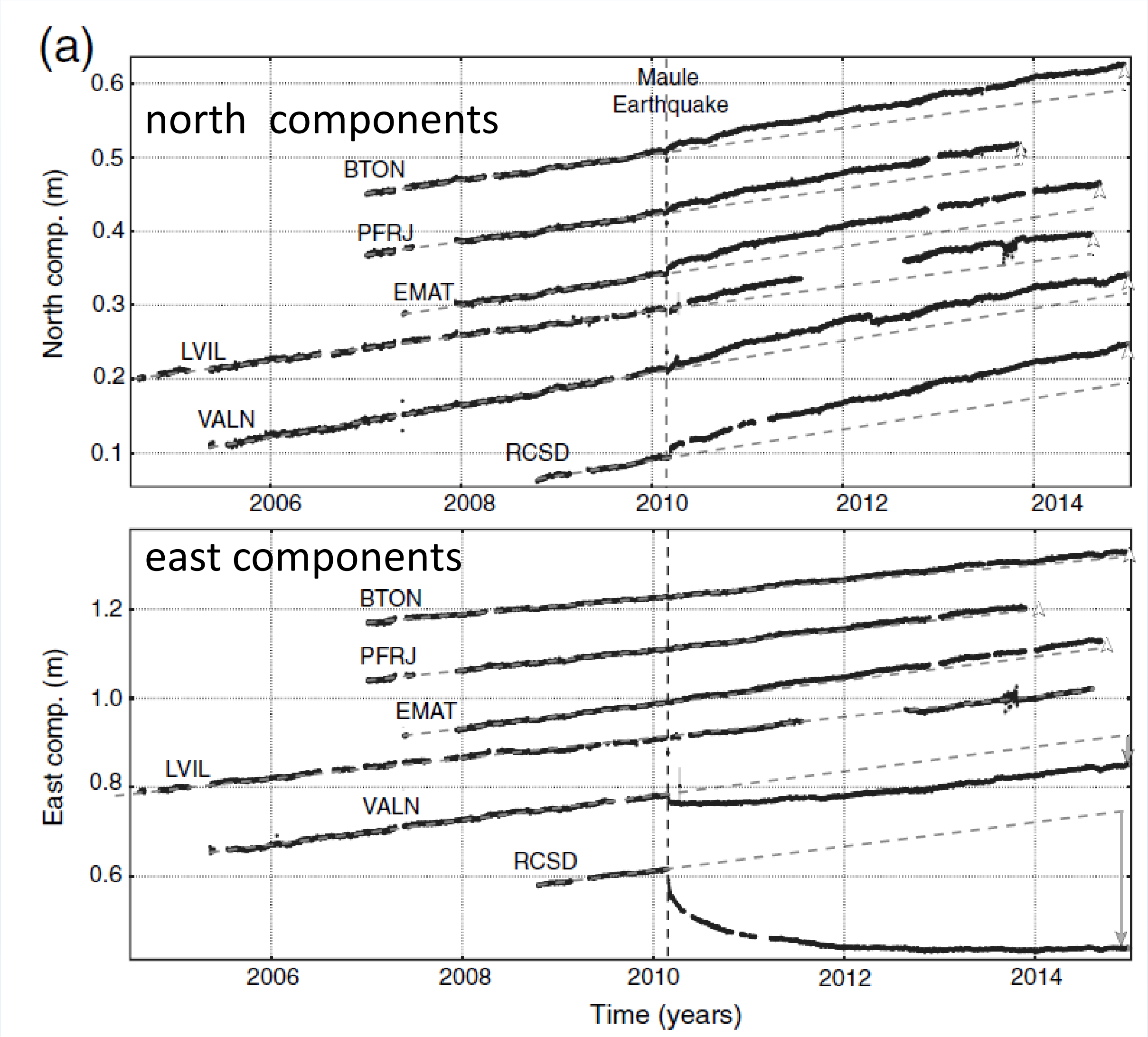
Unlocking of the plate interface, plate convergence and loading rate

2015-09-16 Mw 8.3 Illapel EQ – Strain rate increase

In the region of the 2015-09-16 Mw 8.3 Illapel EQ, after the 2010 Mw 8.8 Maule megathrust EQ, a large-scale postseismic deformation was observed, with a strain rate increase of about 15%.

Time series of coastal GPS permanent stations, ordered by increasing latitude

The dotted lines represent the preseismic trends estimated before the Maule earthquake, open arrows highlight the postseismic increase of the trend.



This behavior is in agreement with a viscous relaxation model

Sergio Ruiz et al., 2016 - "The Seismic Sequence of the 16 September 2015 Mw 8.3 Illapel, Chile, Earthquake", SRL (216), Vol.87, n.4

Unlocking of the plate interface, plate convergence and loading rate

“Deep non-volcanic tremors” and “Slow Sleep Events” .

Non-volcanic tremor is a very low amplitude seismic signal that may last from hours to months.

In some cases on the subduction interface (Shelly et al., 2007; La Rocca et al., 2009) it occurs with a surprising regularity and it is spatially and temporally coincident with slow slip events (SSE) or “slow earthquake”.

The SSE , lasting from days to weeks, have been observed in the **subduction zones** of Cascadia (Dragert et al., 2001), Japan (Obara and Hirose, 2006), Alaska, Mexico and New Zealand (Wallace et al., 2013).

The deep SSEs seems to occur where Qp and Vp/Vs data suggest an accumulation of fluid-rich underplated sediment at the interface, consistent with the idea that SSEs occur under high fluid pressure (L.M. Wallace, D. Eberhart-Phillips, GRL 2013).

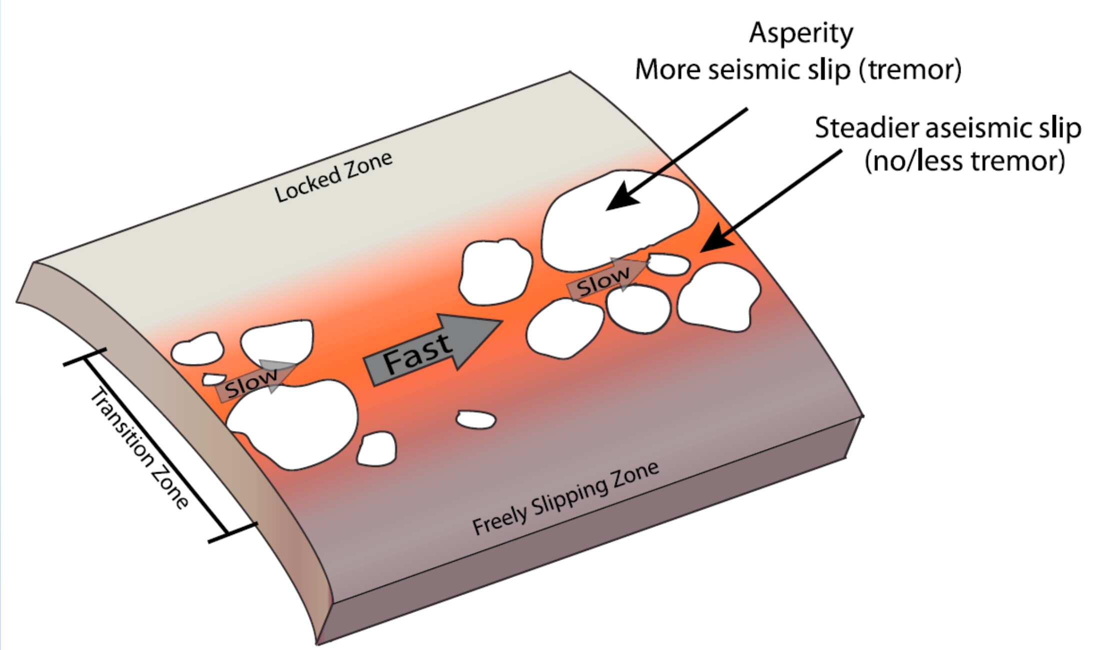
Alternatively, other evidences support the notion that tremor results from shear failure during slow slip.

Global observations of the location, spatial extent, magnitude, duration, slip rate, and periodicity of these aseismic slip transients indicate significant variation that may be exploited to better understand their generation.

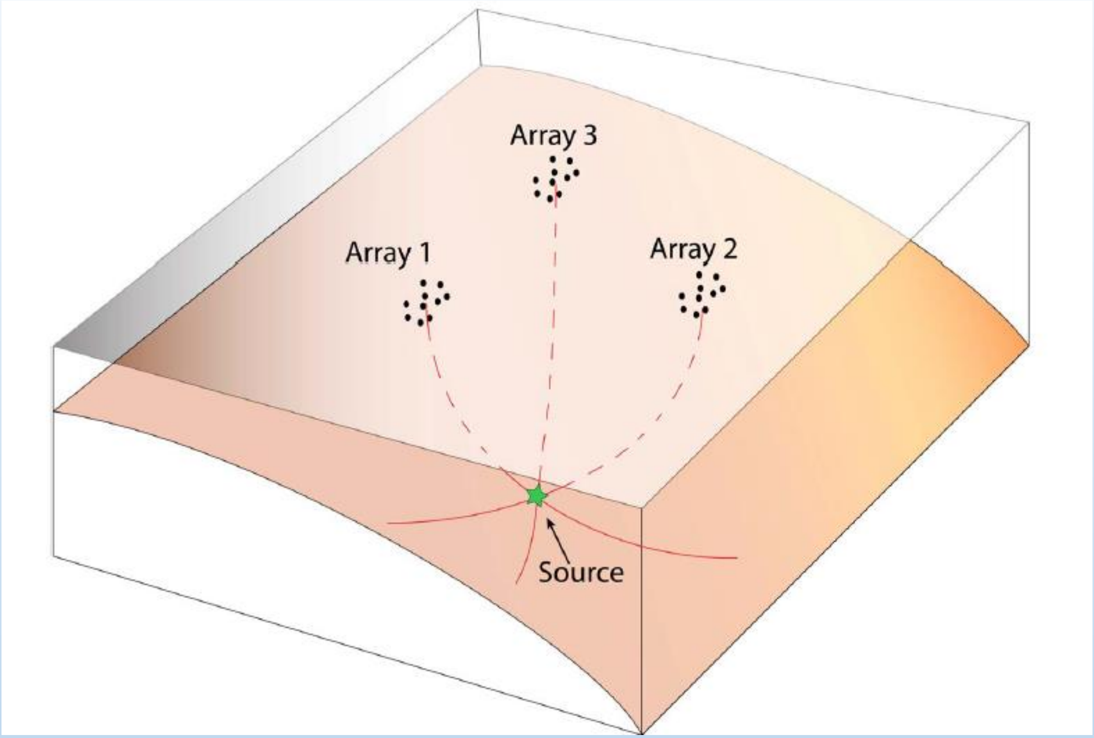
Unlocking of the plate interface, plate convergence and loading rate

“Deep non-volcanic tremors” and “Slow Sleep Events”.

The tremor asperities in the transition zone may control the evolution of slow earthquakes in space and time.
Data from multiple mini seismic arrays can provide detailed imaging of slow earthquakes



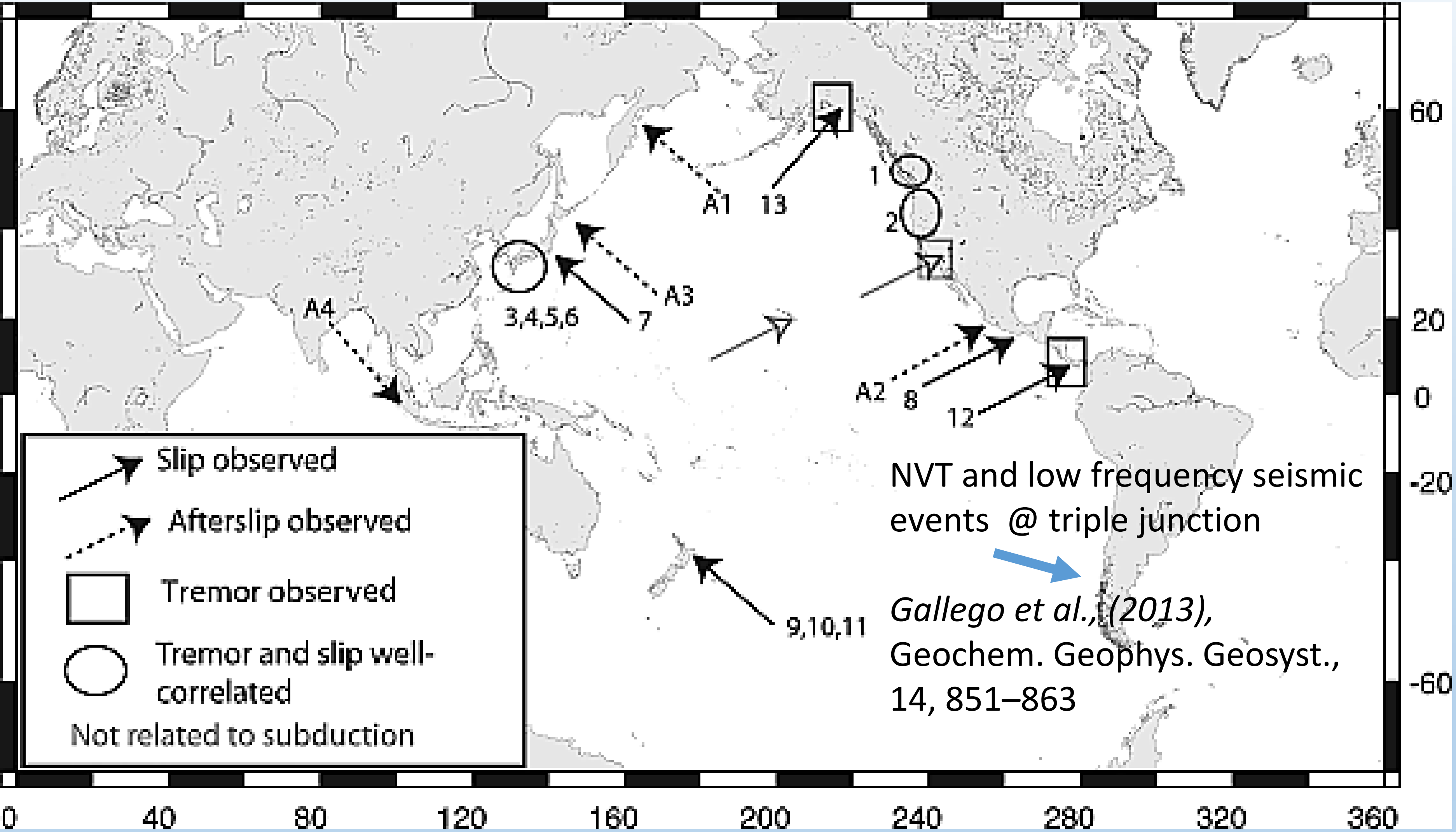
Schematic diagram showing a model of the transition zone.



Schematic diagram showing basic idea behind multibeam-backprojection (MBBP) algorithm

from A. Ghosh, et al. (2012) - Tremor asperities in the transition zone control evolution of slow earthquakes J. Geophys. Res., 117, B10301

Unlocking of the plate interface, plate convergence and loading rate
“Deep non-volcanic tremors” and “Slow Sleep Events”.



NVT and low frequency seismic events @ triple junction

Gallego et al., (2013), Geochem. Geophys. Geosyst., 14, 851–863

Arrows → Slow slip events (SSE)

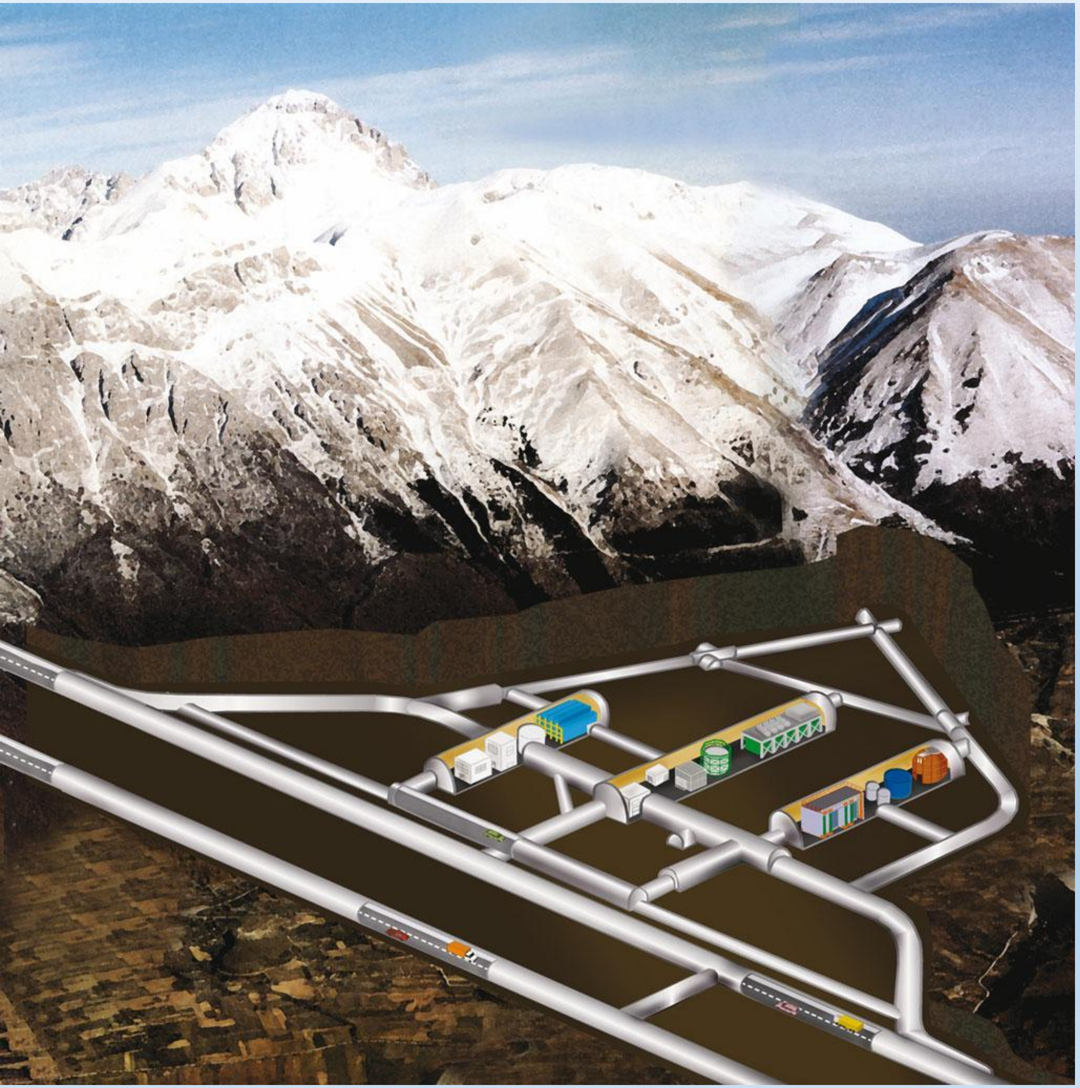
Circles → Non-volcanic seismic tremor (NVT) well correlated with SSE

Boxes → NVT not well correlated with SSE

from Schwartz, S. Y., and J. M. Rokosky (2007), Slow slip events and seismic tremor at circum-pacific subduction zones, Rev. Geophys., 45, RG3004,

Geopysical Research @ Underground Laboratory

High sensitivity and broadband instruments, able to monitor ground deformations, seismic signals, gravity changes and fluids migration, will give the possibility to detect in a suitable conditions signals associated with parameter related to earth strain accumulation and release, including the earthquakes preparation and source dynamics.



Seismic signals

- Broadband seismic stations and seismic arrays

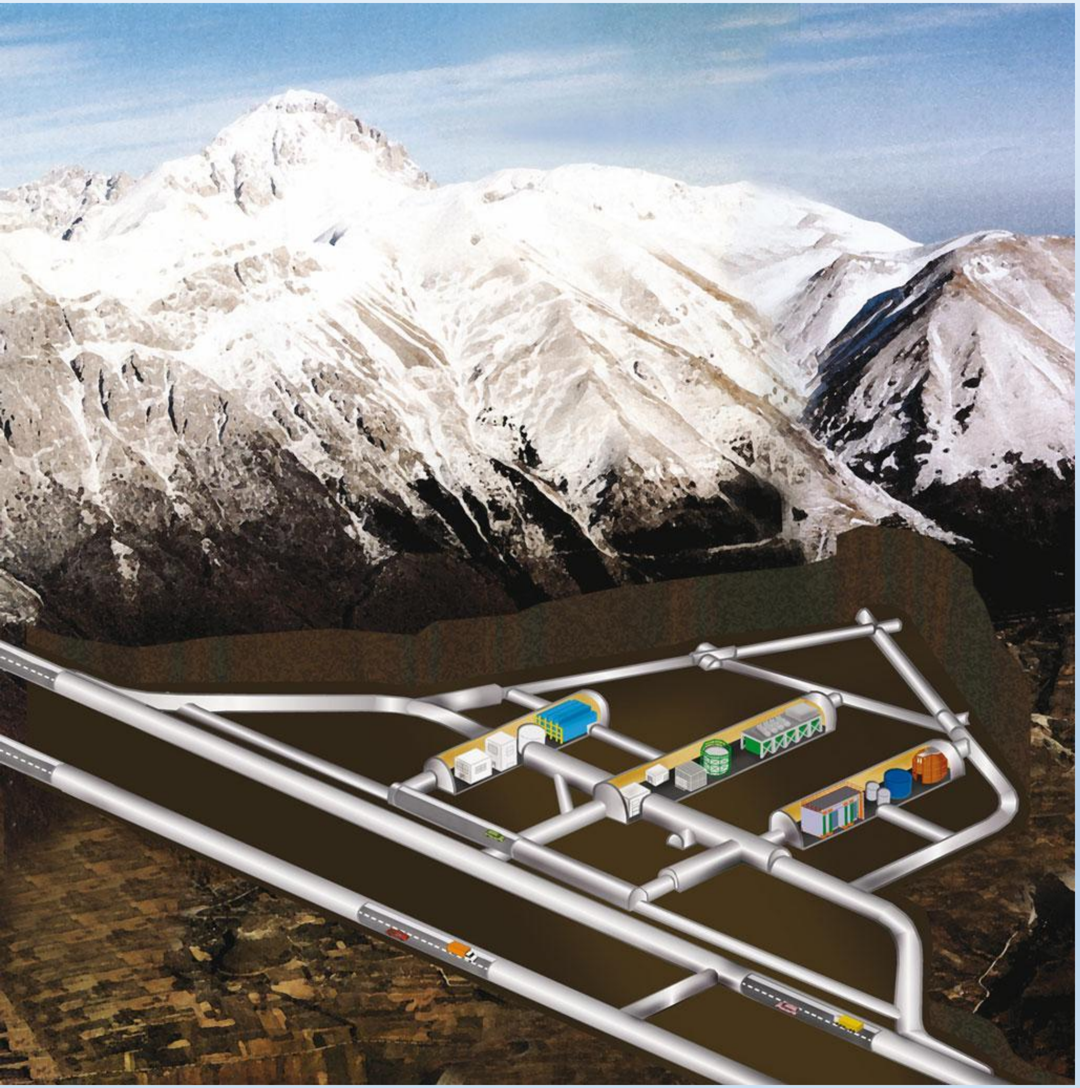
Ground deformation

- High sensitivity straimeters and tiltmeters

Strain-related phenomena

- Fluid pressure, acustic emission, radon emission etc.

Geopysical Research @ Underground Laboratory
Geodetic Strainmeter



Local phenomena:

- measurement of seismic phase velocities, from the comparison of straingrams and seismograms
- slow earthquakes (earthquake-like events that releases energy over a period much longer than usual earthquakes)
- hydrologically-induced deformation
- Earth and ocean loading tides (deformation caused by water pressure on the ocean floor)
- seasonal strain changes because of thermoelastic effects and seasonal charging and discharging of aquifers
- tectonic deformation

Global phenomena:

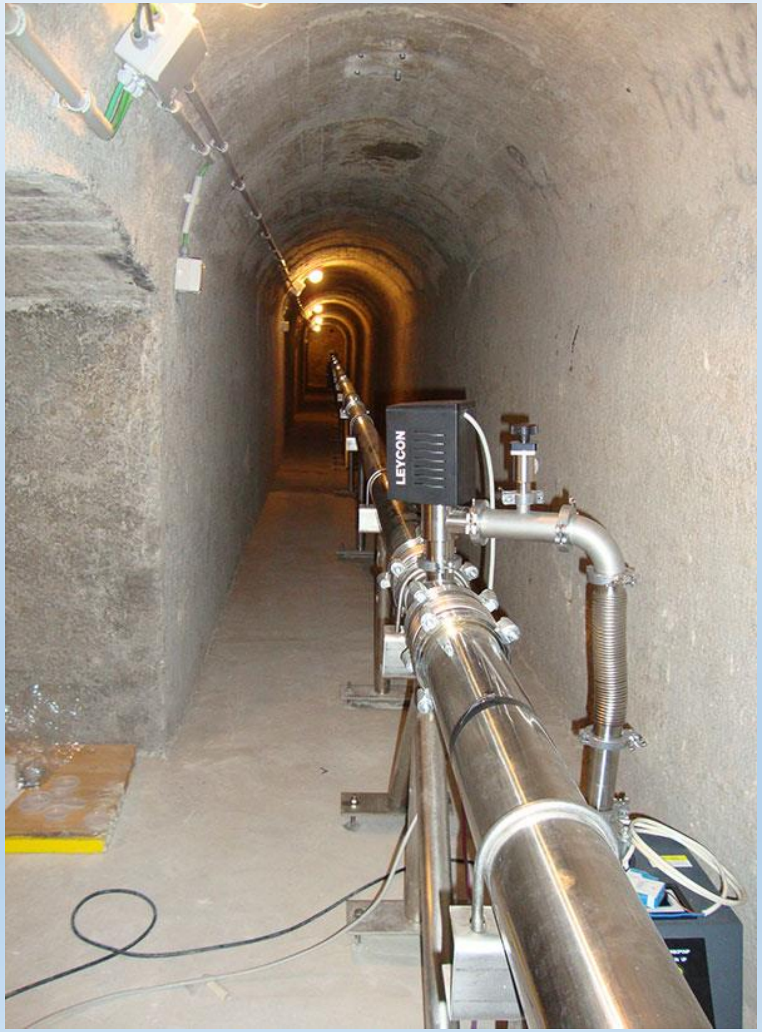
- free oscillations of the Earth triggered by large earthquakes
- background free oscillations, due to atmospheric motions and wind-driven ocean waves
- seismic core modes (spheroidal modes of the Earth's free oscillations whose energy is dominantly partitioned into the inner core as shear energy)
- Free Core Nutation, produced by the pressure coupling liquid_core-solid_mantle; it causes a resonance on the Earth response to tidal forcing in the diurnal tidal band period (also from VLBI observations)

Geopysical Research @ Underground Laboratory
Laser interferometer Installations

Laser strainmeters, based on the Michelson interferometer, with an path length of bout 70-100 m are installed in deep tunnels and underground labs

70 m long harm Strainmeters of the **GEODYN** facility at the Canfranc Underground Laboratory (Spanish Pyrenees)

(*Ref. A. Amoruso et al.,2017 Pure Appl. Geophys.)*



Laser straimenters (80 m long) installed at the south tunnel of the **Pizzi Deneri Observatory** (Etna volcano - Italy).
Part of the pipeline in the lower left.

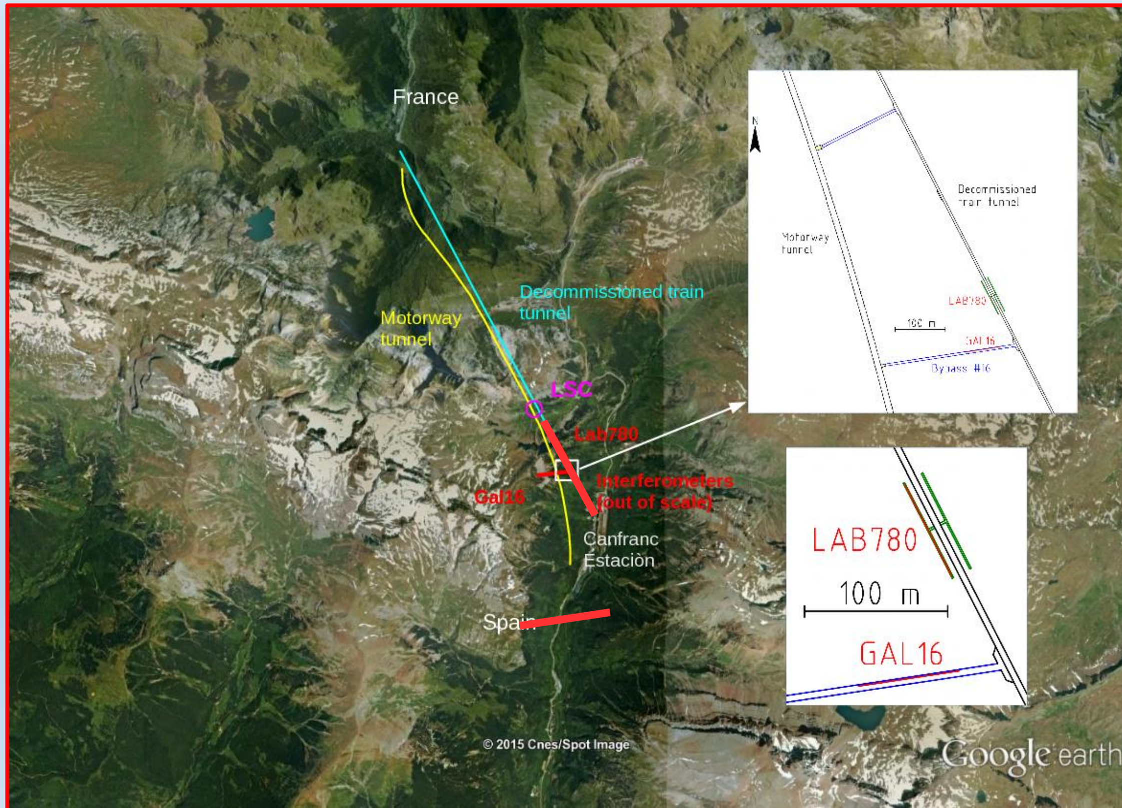
The rooms are mounted on concrete plinths, solid with the rock underneath and isolated from the tunnel floor (N & G order).

Gran Sasso interferometers
(LNGS, Italy, 1994-2013)

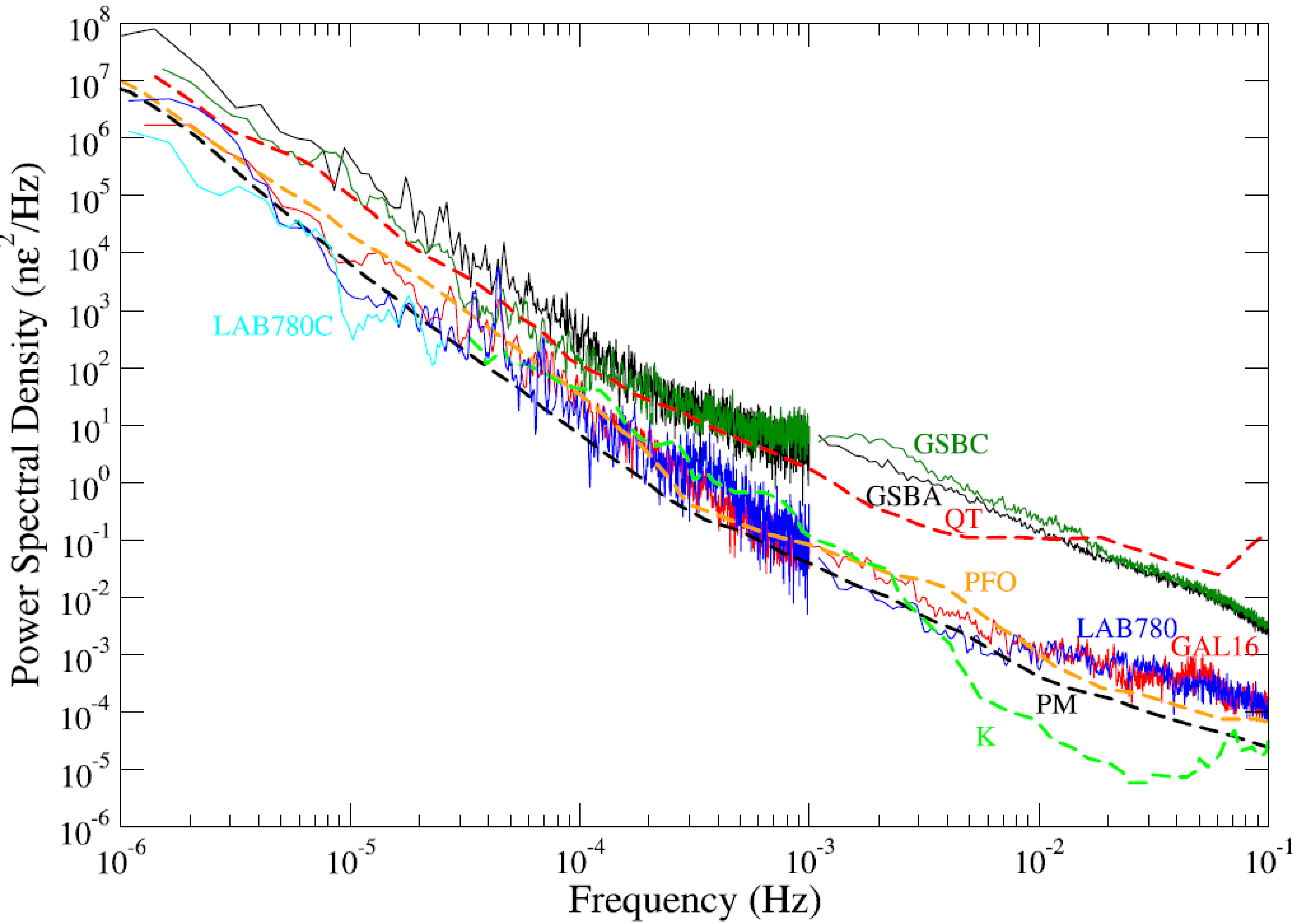
Baseline length: 90 m
Nominal resolution l/l < 10^{-12}
Maximum l/l nominally unlimited
Nominal bandwidth ≈ 200 Hz to 0 Hz
Maximum strain rate few 10^{-7} s^{-1}
1nε ⟷ l = 0.09μm

Canfranc interferometers
(LSC, Spain, 2011- present)

Baseline length: 70 m
Nominal resolution l/l < 10^{-12}
Maximum l/l nominally unlimited
Nominal bandwidth ≈ 200 Hz to 0 Hz
Maximum strain rate few 10^{-7} s^{-1}
1nε ⟷ l = 0.07μm



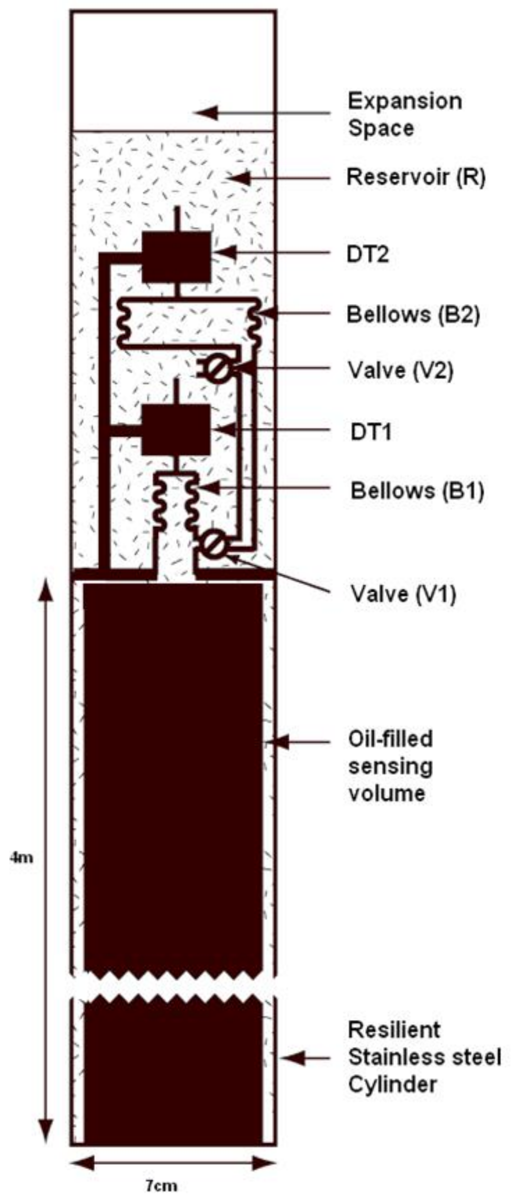
Power Spectral Density (PSD) of strain noise



- solid green and black lines (**GSBC** and **GSBA**), after removal of Earth tides – LNGS Gran Sasso, Italy (Amoruso et al., 2009);
- dashed red line (**QT**), Queensbury Tunnel, UK (Beavan and Goulty 1977);
- Dashed orange line (**PFO**), Pinon Flat Observatory, USA (Berger and Levine 1974);
- dashed black line (**PM**), Poorman Mine, USA (Berger and Levine 1974);
- dashed green line (**K**), Kamioka Observatory, Japan (Takemoto et al. 2004);
- solid red line (**GAL16**), solid blue line (**LAB780**) and solid cyan line (**LAB780C)** LAB780-data corrected for temperature, GEODYN at the Canfranc Underground Laboratory (Spain)

from A. Amoruso et al.,2017 Pure Appl. Geophys
DOI 10.1007/s00024-017-1553-7

Geopysical Research @ Underground Laboratory
The borehole Sacks-Evertson volumetric strainmeter



Constructed by Sacks et al. (1971) and widely deployed, consist of a stainless-steel cylinder cemented into a borehole, with a sensing volume filled with silicone oil.

Deformations of the surrounding rock force the oil in or out of the attached bellows.
The motion of the top surface of the bellows is translated into voltage by a differential transformer (DT).

The DT1 sensitivity is ~10^{-12} (1 pε) in strain with a maximum range of ~10^{-5} (10 $\mu\varepsilon$)
When V1 is closed, B2-DT2 is monitoring the volume of a fixed mass of oil decoupled from the Earth's strain field, but effected by a **temperature change, with a sensitivity of ~10^{-5}°C.**

When V1 is open the sensitivity is reduced by a factor of ~7.

Geopysical Research @ Underground Laboratory
The borehole Gladwin Tensor Strain Monitor (GTSM)

First installed in 1977, this borehole tensor strainmeter is built by GTSM Technologies in Queensland, Australia. The US Plate Boundary Observatory (EarthScope, UNAVCO) installed 74 GTSM during 2005-2008

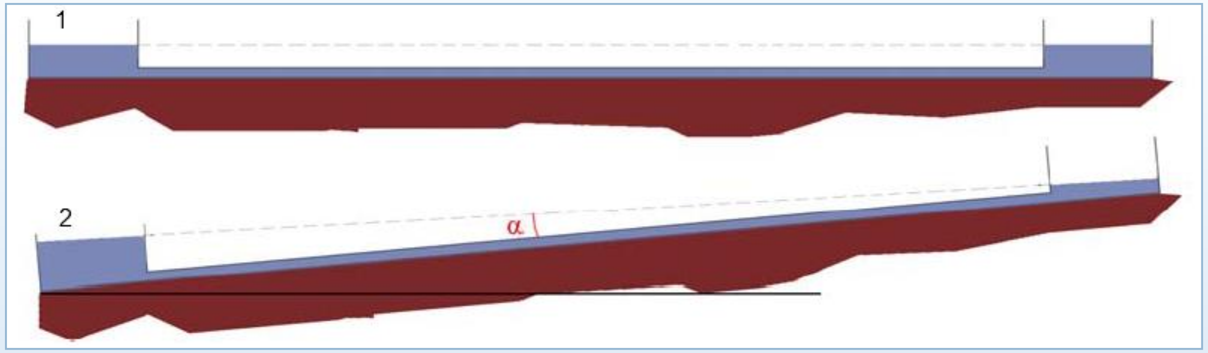
The GTSM is based on three sensors, each formed by three steel plates acting as capacitors, in three directions, at 120 degrees from each other.

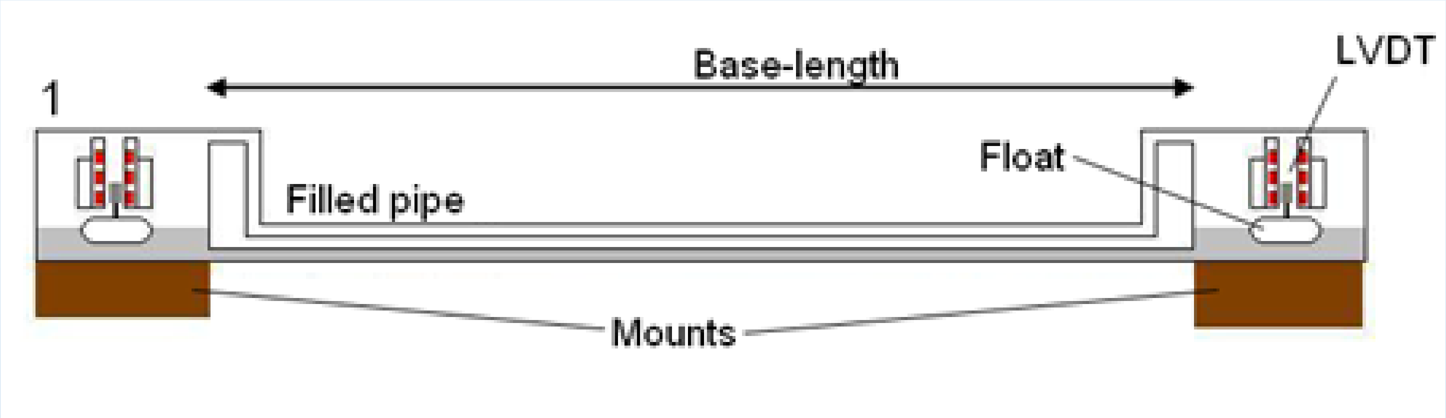
The ratio of the separation between each plate pair is calculated by the change in capacitance.

GTMS provides measurements of the strain with available range of amplitudes from ~1×10^{-10} (0.1 nε) to ~ 1×10^{-3} (1 mε)

Geopysical Research @ Underground Laboratory
Long baseline fluid tiltmeter

First by A. A. Michelson and H.G. Gale between 1914 and 1917- Misured interferometrically the liquid-level changes at the ends.

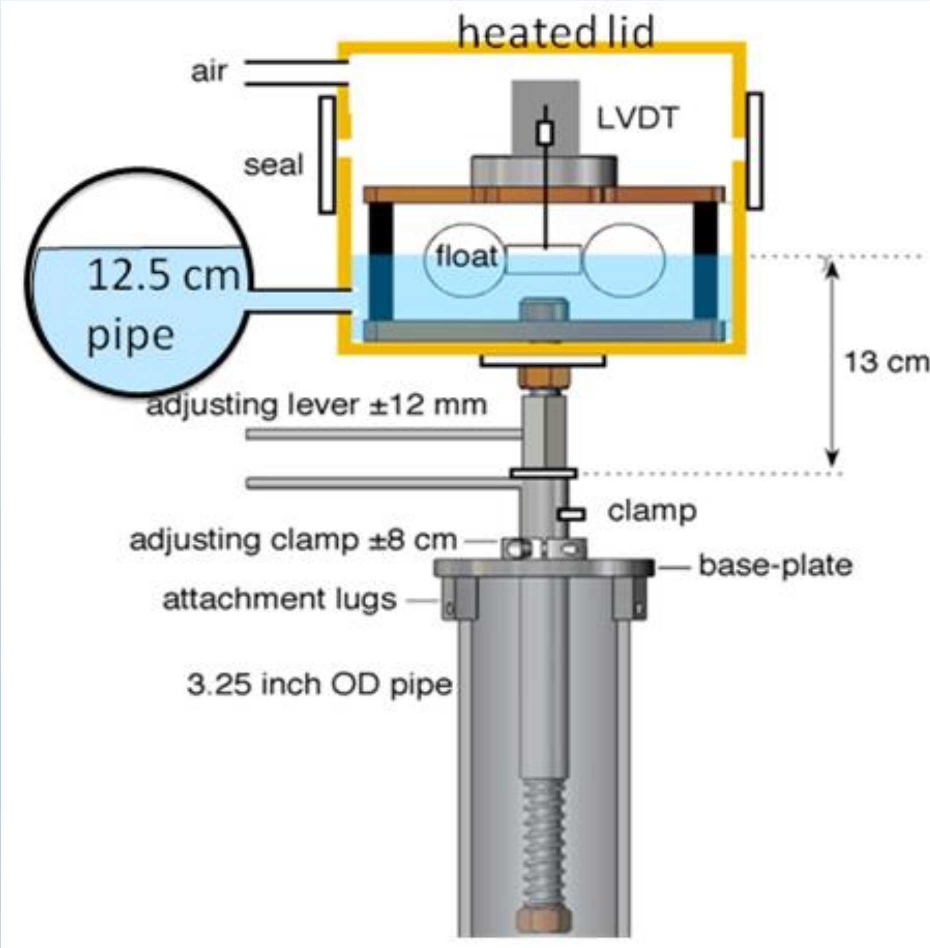




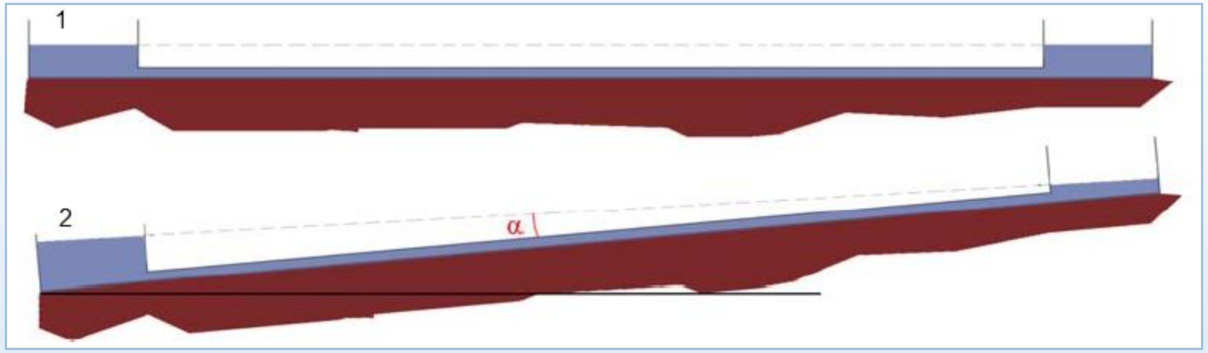
The current water tiltmeters design uses float sensors whose vertical positions are monitored by Linear Variable Differential Transformers (LVDT) with a range of ±6 mm and a nominal resolution of 0.1 µm.

Typical tilt sensitivities are of 1 nrad (0.001 µrad).

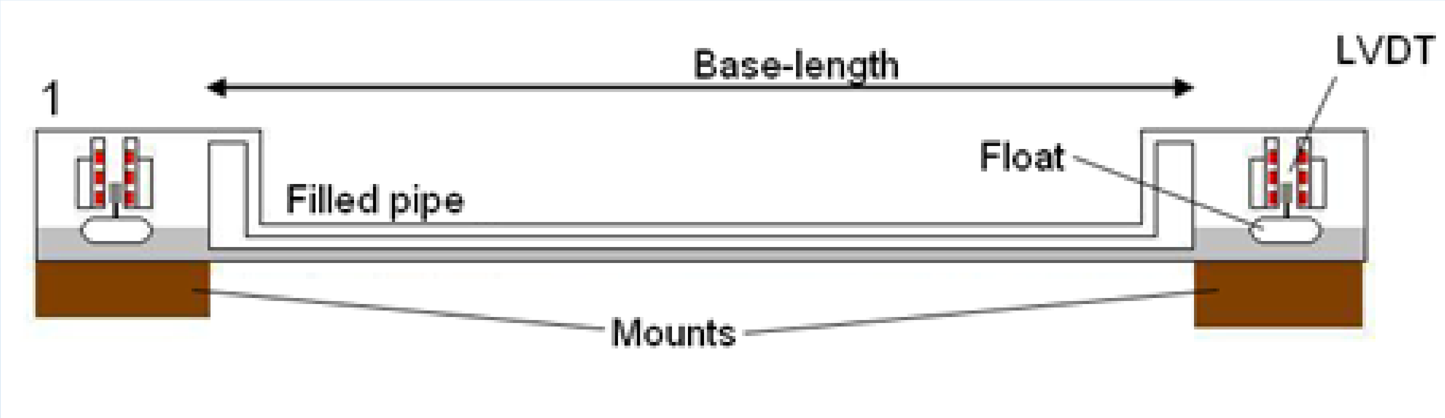
With careful installation,noise level for annual periods is less than 50 nrad, and for daily periods less than 5 nrad.

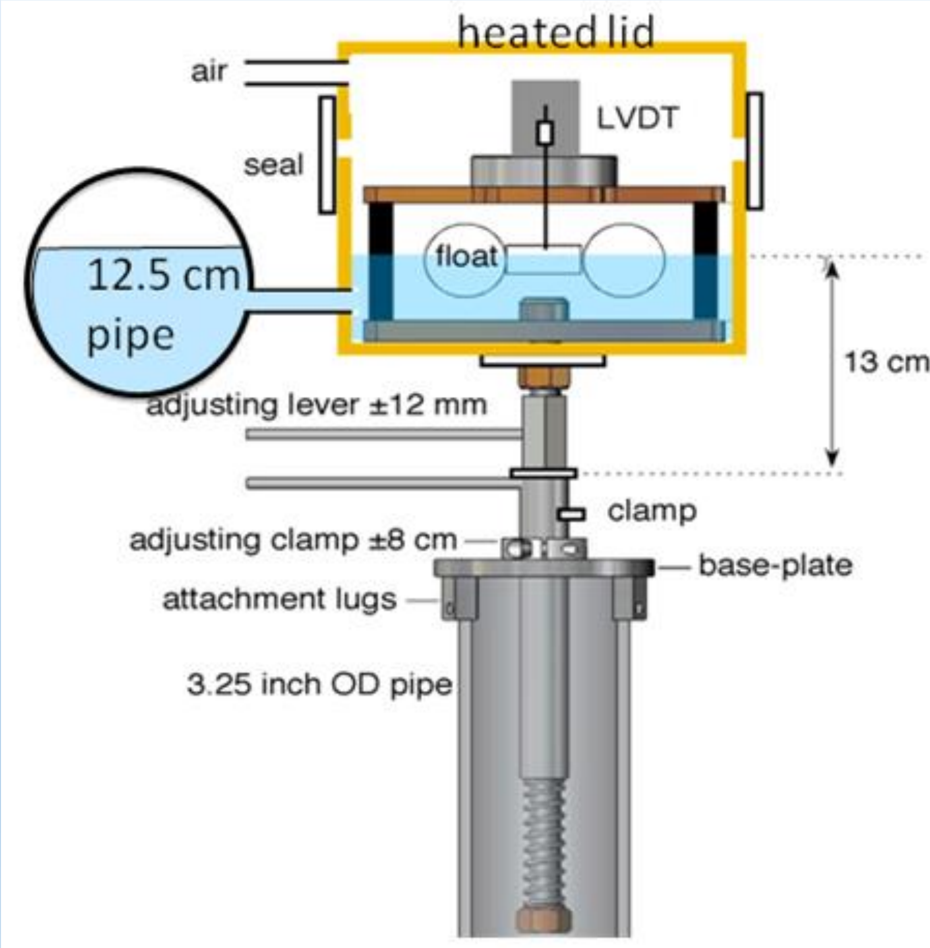


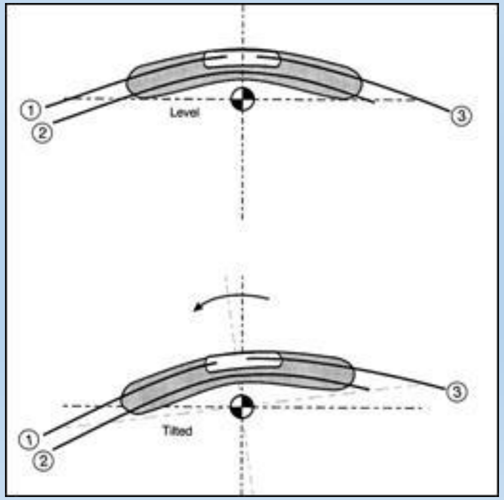
Geopysical Research @ Underground Laboratory
Long baseline fluid tiltmeter



First by A. A. Michelson and H.G. Gale between 1914 and 1917- Misured interferometrically the liquid-level changes at the ends.





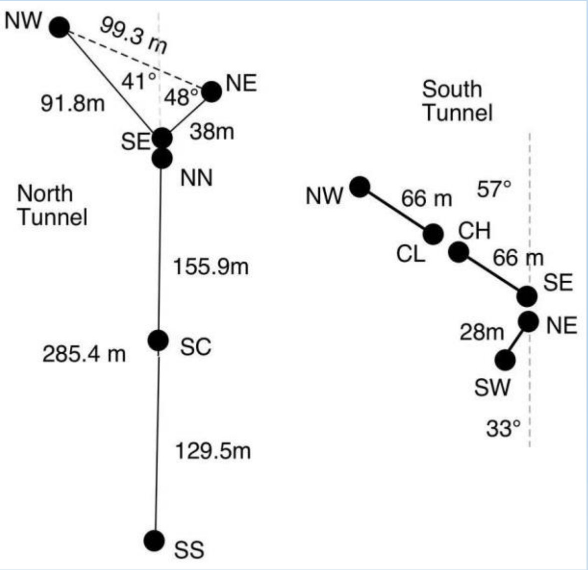


Other tiltmeters commercially available (platform and borehole) are based on a electrolytic bubble tilt, sensed electrically as a resistance bridge

Geopysical Research @ Underground Laboratory
Long baseline fluid tiltmeter

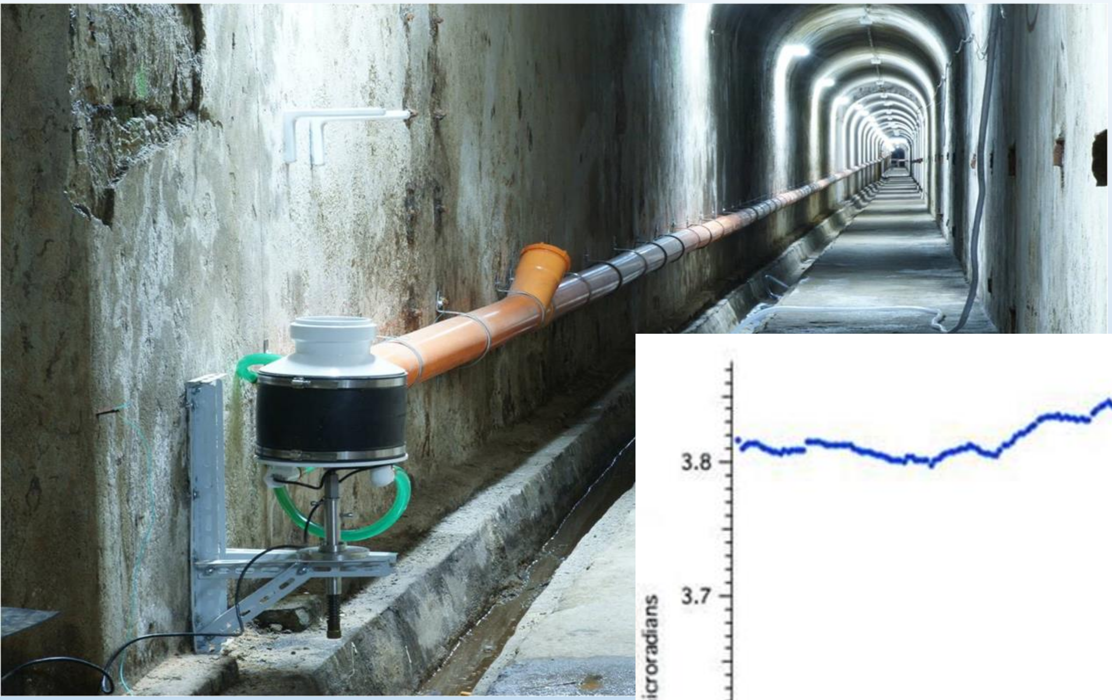
Water-pipe tiltmeters (28-278m lenghts) installed starting 2008 at the Campi Flegrei area (Naples-Italy).

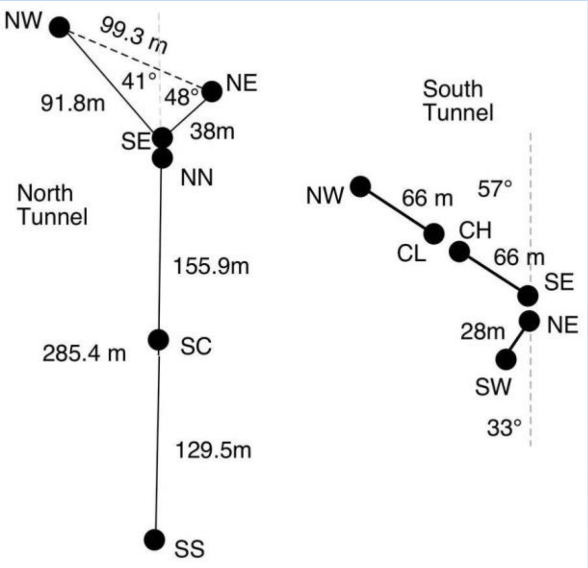
The installation tunnels are in the area of inflation and defilation related to the volcanic dynamic of Campi Flegrei caldera

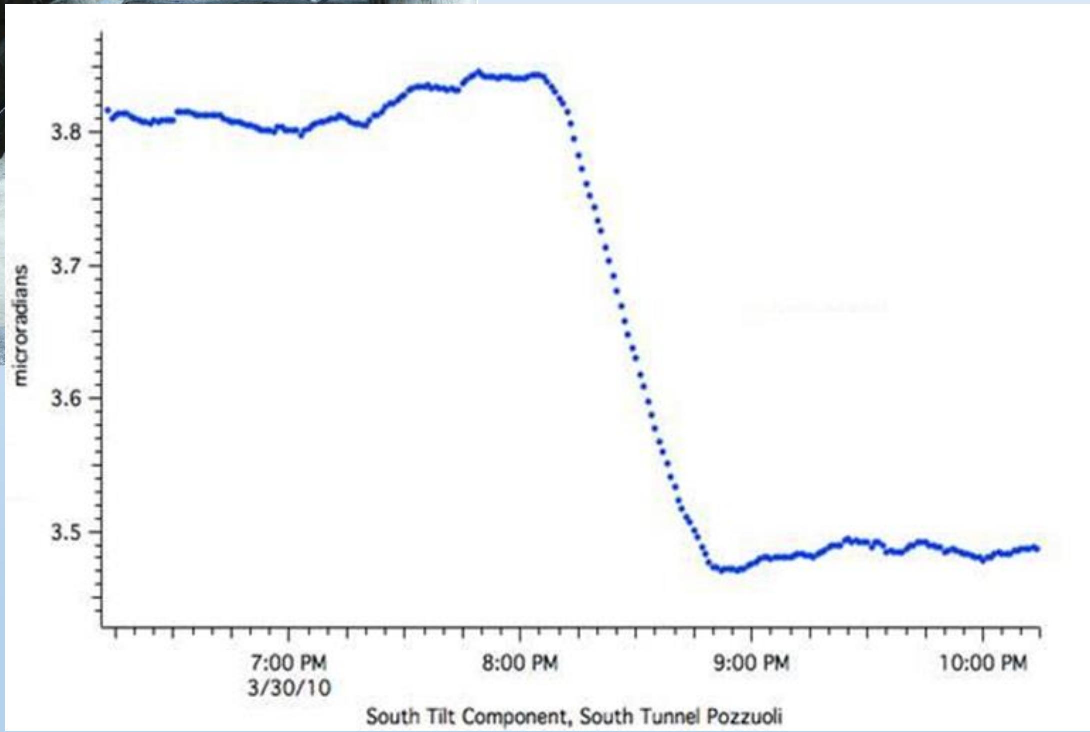


Amoruso, A, L Crescentini, R Scarpa, R Bilham, AT Linde and IS Sacks (2015), Abrupt magma chamber contraction and microseismicity at Campi Flegrei, Italy: Cause and effect determined from strainmeters and tiltmeters. J. Geophys. Res.-Solid Earth Version: 1 120 (8) 5467-5478

Geopysical Research @ Underground Laboratory
Long baseline fluid tiltmeter







On March 30, 2010 a subsidence event was recorded by the Southern Tunnel tiltmeter.

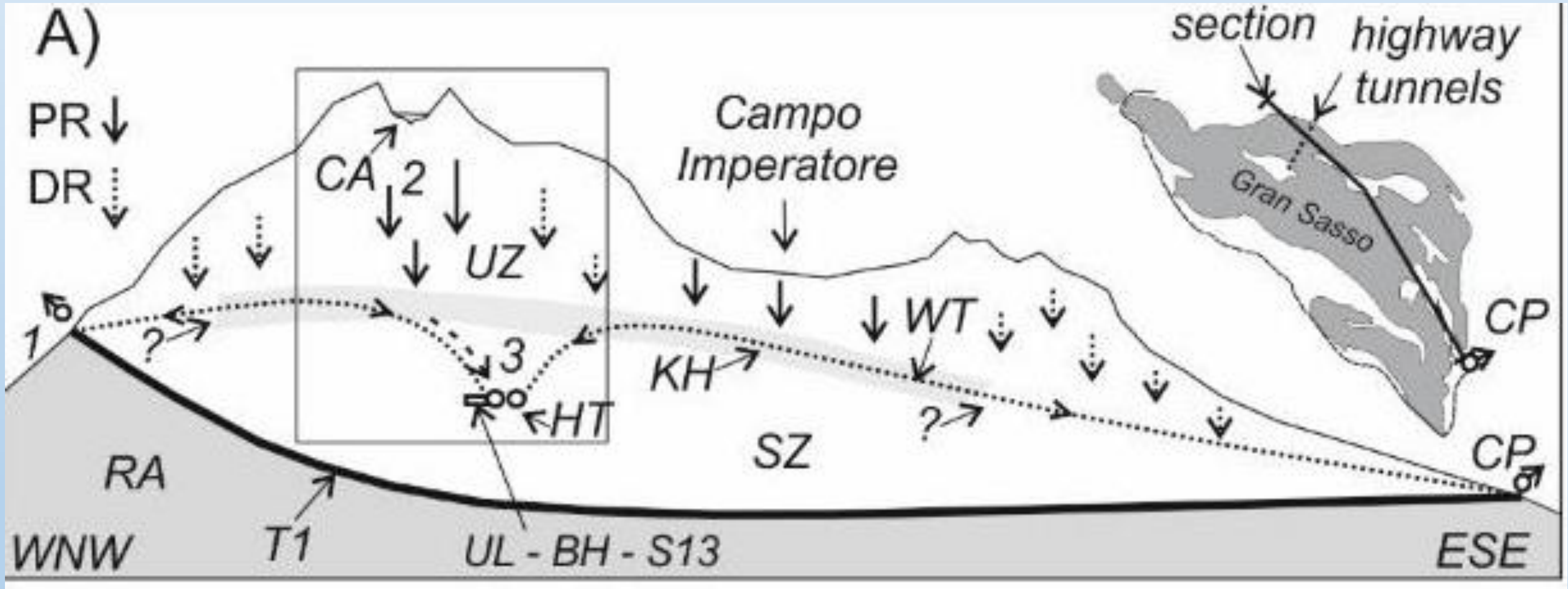
Total duration of the event was of about 40 minutes, with an amplitude of 341 nrad (removed tides), accompanied by microseismicity

(P. Romano, 2012 PhD Thesis)

Geopysical Research @ Underground Laboratory
Underground Hydraulic Pressure Monitoring

Water levels in wells are known to reflect stress changes in the ground, e.g. due to earth tides, loading tides, barometric loads, or seismic waves.
If the level of the water surface or water pressure at a constant depth are measured (e.g. Kümpel, 1992),
the water wells drilled into confined aquifers act as sensors for the strain tensor.

The Gran Sasso aquifer feeds spring groups, located at low altitude along the low permeability boundary, with a discharge of more than 18 m3/s [Adinolfi Falcone et al., 2008].



Gran Sasso aquifer, transversal to the highway tunnels (HT) and passing through the LNGS Underground lab (UL).

WT – water table; KH – karst horizon; T1 – permeability boundary (regional thrust);

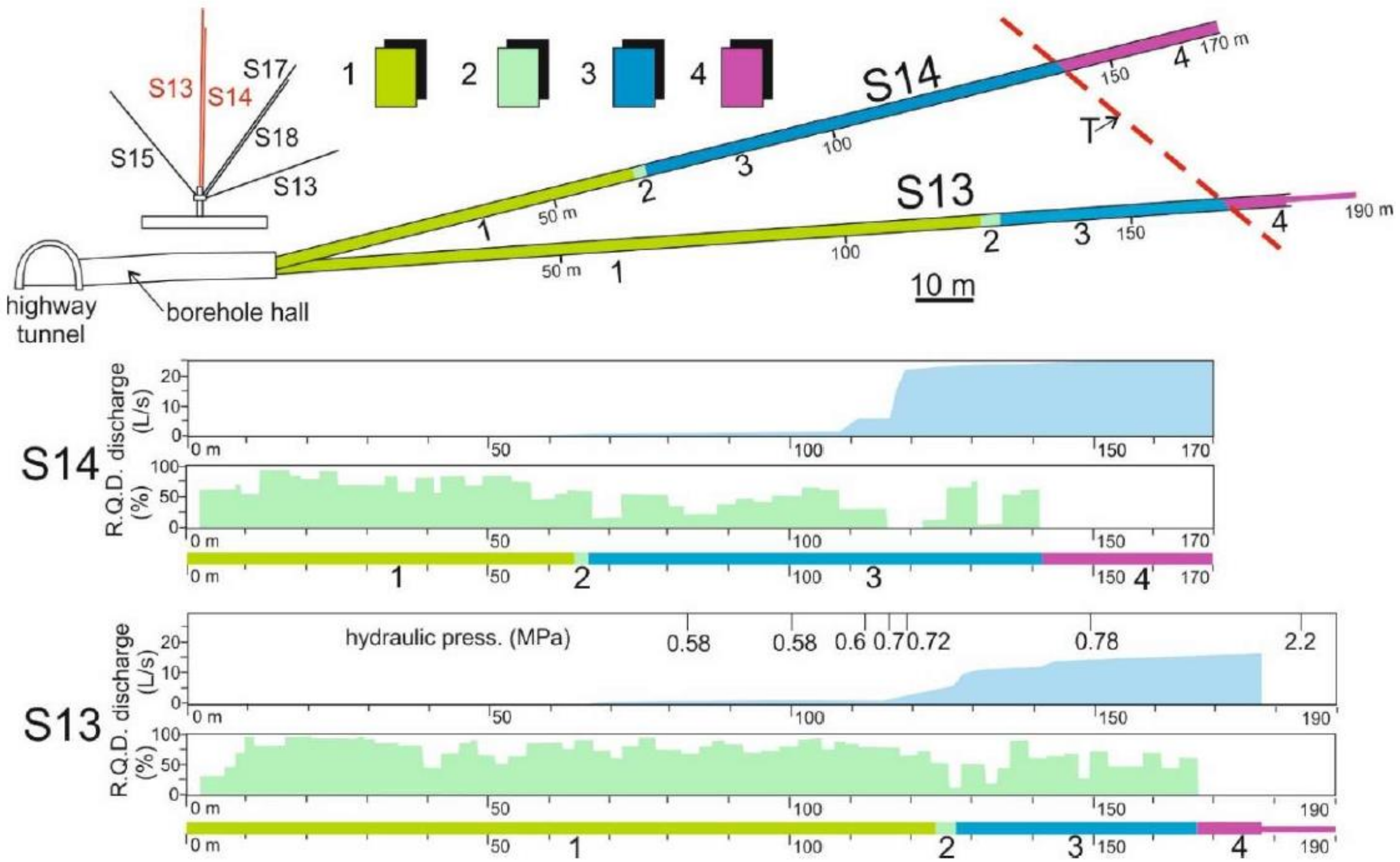
UZ – unsaturated zone; SZ – saturated zone; RA – regional aquiclude;

1 – overflow springs ; 2 – preferential groundwater flowpath; 3 – preferential groundwater flowing toward the UL;

Ref. G. De Luca et al., Hydraulic pressure variations of groundwater in the Gran Sasso under-ground laboratory during the Amatrice earthquake of August 24, 2016 - Annals of Geophysics, 59, Fast Track 5, 2016.

Geopysical Research @ Underground Laboratory
Underground Hydraulic Pressure Monitoring

The hydraulic pressure, temperature and electrical conductivity of ground water have been continuously monitored in the 200 m-long horizontal S13 borehole (hydrogeological logs) close to the LNGS laboratory (Gran Sasso)

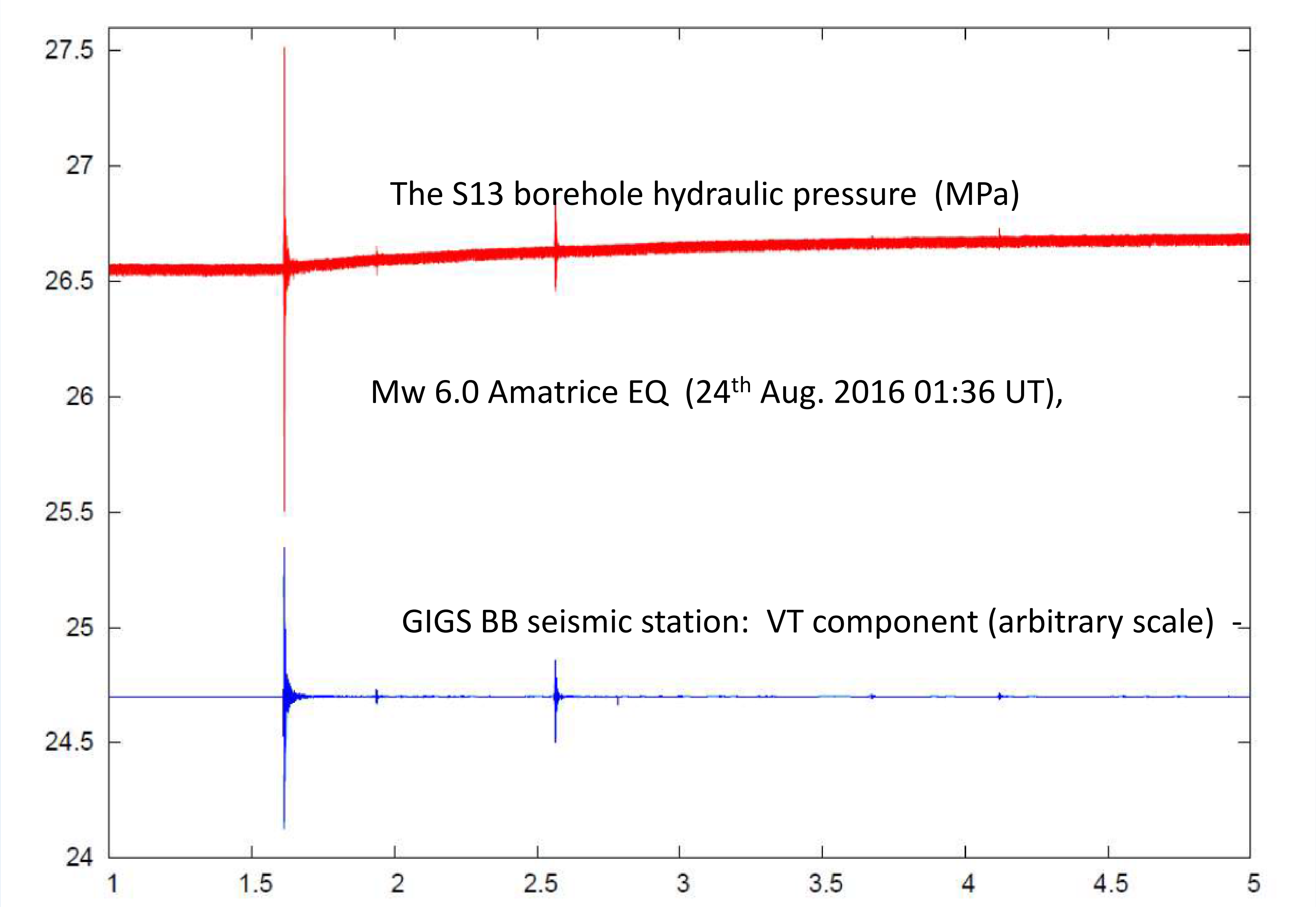


Ref. G. De Luca et al., Hydraulic pressure variations of groundwater in the Gran Sasso under-ground laboratory during the Amatrice earthquake of August 24, 2016
Annals of Geophysics, 59, Fast Track 5, 2016.

Geological and hydrogeological logs of S13 and S14 (R.Q.D.= Rock Quality Designation)

For S13 borehole is reported the hydraulic pressure and the discharge measured during the boring (*from Catalano and Salza, 2003*).

Geopysical Research @ Underground Laboratory
Underground Hydraulic Pressure Monitoring



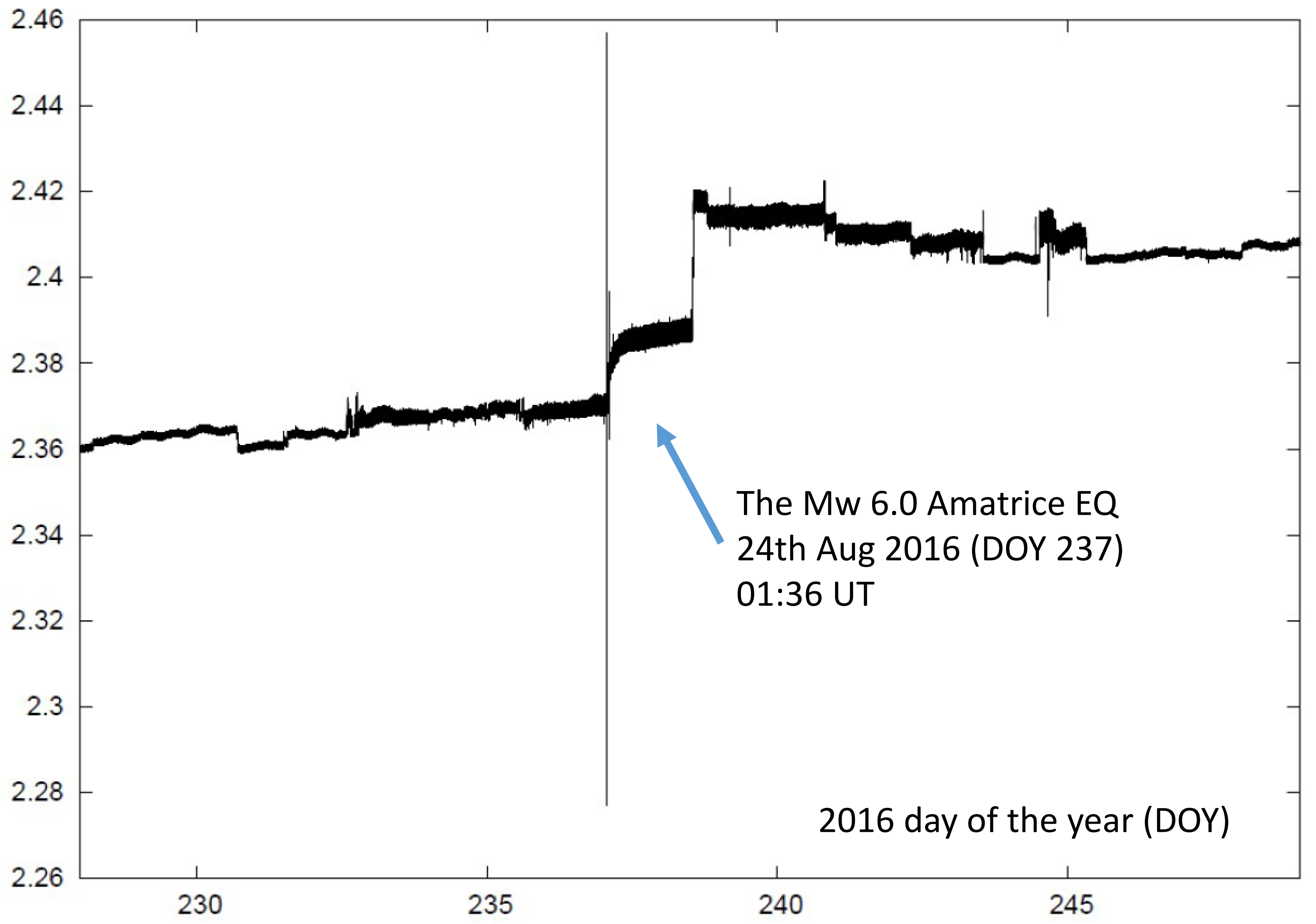
Time window: 24th Aug 2016 (01:00 – 05:00 UT).

Seismic signals at the S13 borehole hydraulic pressure continuously recording at 20 cps

The first event is the Mw 6.0 Amatrice EQ, followed by aftershocks. The major is the Mw 5.4 Norcia EQ at 02:33 UT)

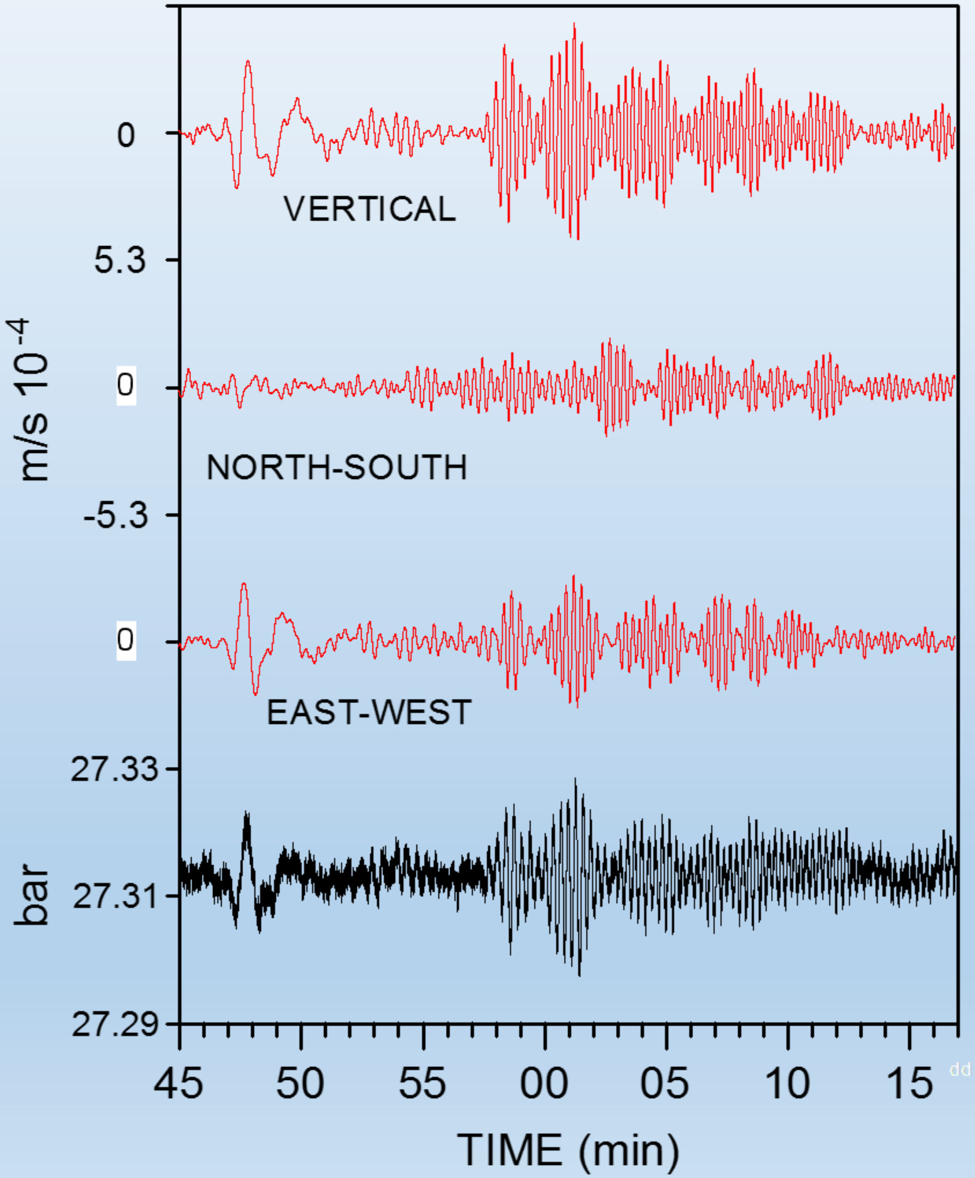
Ref. G. De Luca et al. (2016), Annals of Geophysics, 59, Fast Track 5, 2016.

Geopysical Research @ Underground Laboratory
Underground Hydraulic Pressure Monitoring



Plot of the relative changes of the hydraulic pressure (Mpa) before and after the Mw 6.0 Amatrice EQ - 24th Aug, 2016 01:36 UT

Ref. G. De Luca et al. (2016), Annals of Geophysics, 59, Fast Track 5, 2016.



Chile earthquake of Sep 16th, 2015 (offshore Coquimbo – Mw 8.3). The red traces are the vertical, north-south and east-west components of Trillium 240 s sensor (GIGS) and the black trace is the water pressure signal (the velocity scales for red traces have the same values). Time scale starts from 23:45 (UT).

Ref. G. De Luca et al. (2016), Annals of Geophysics, 59, Fast Track 5, 2016.

Early earthquake warning (EEW)

Earthquakes are a potental problem for large-scale scientific experiments and, of course, dangerous as well for the personnel inside of the facilities.

There are three potential consequences of seismic events to scientific facilities:

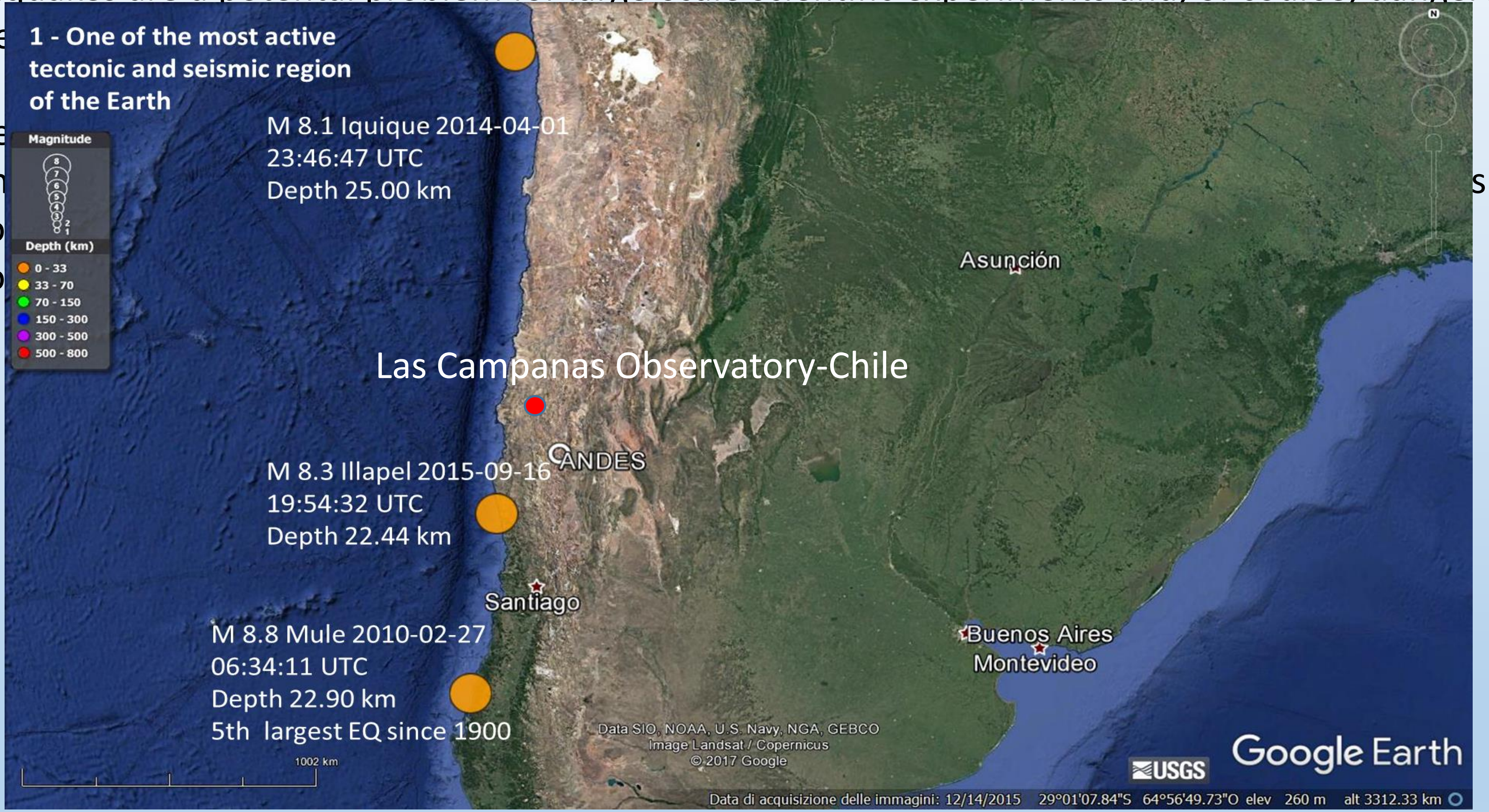
- Physical damage to components and systems (economic consequences for replacement parts & down time).
- Loss of operating time (not taking data & loss of efficiency).
- Loss of information (damaged data storage systems).

Early earthquake warning (EEW)

Earthquakes are a potental problem for large-scale scientific experiments and, of course, dangerous as well for the personnel inside

There

- Ph s & down time).
- Lo
- Lo

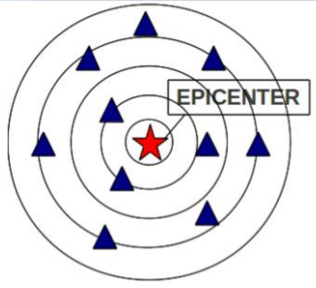


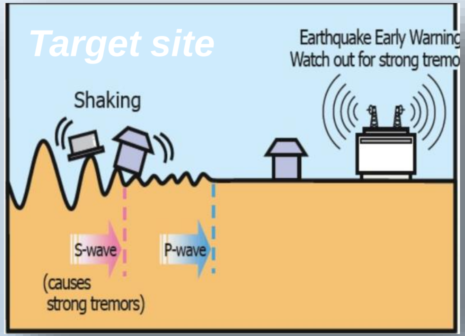
Astronomical observatories (meter-class telescopes and gravitational-wave interferometers) can be affected by earthquakes (*Coughlin et al, 2015 -Real-time earthquake warning for astronomical observatories, Experimental Astronomy 2015 , Volume 39, Issue 2*)

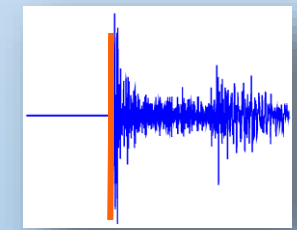
Output of an Early Warning System

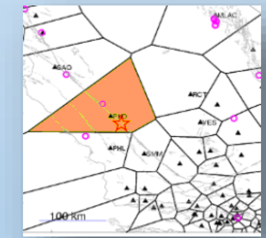
***Purpose**: To give a warning to the target area **before** the arrival of the strongest shaking*

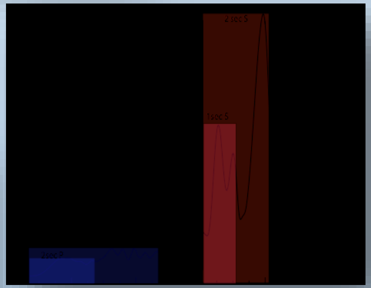
Seismic network

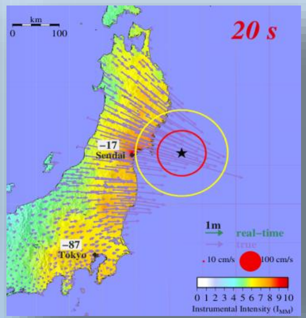












Origin Time

detection

location

Magnitude estimate

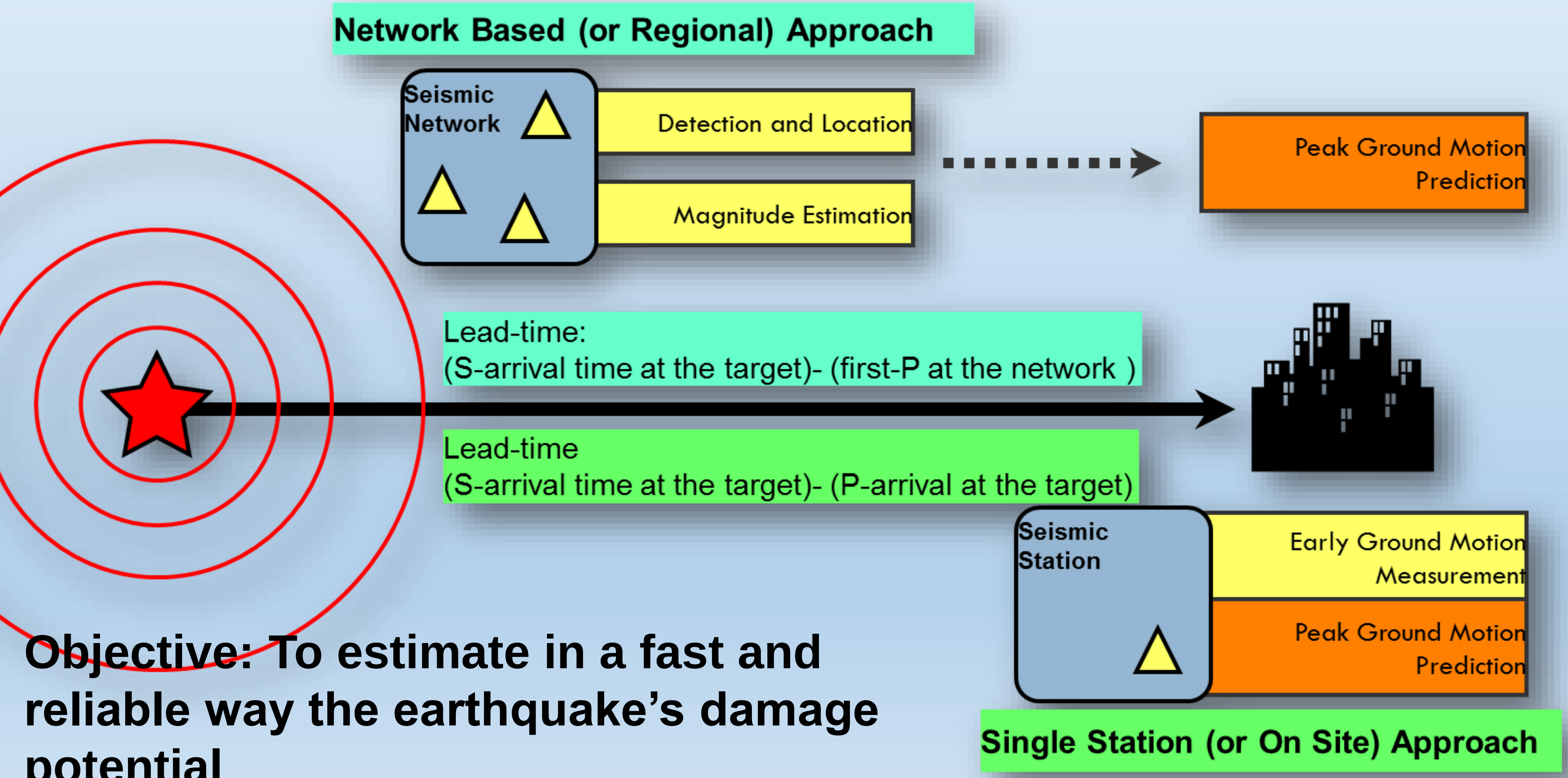
Alert warning

… … … ***Few seconds*** … … …

… … … tens of seconds or more

Satriano & Elia (2010). PRESTo, the earthquake early warning system for Southern Italy: Concepts, capabilities and future perspectives.
Soil Dyn Earthquake Eng
http://www.prestoews.org/

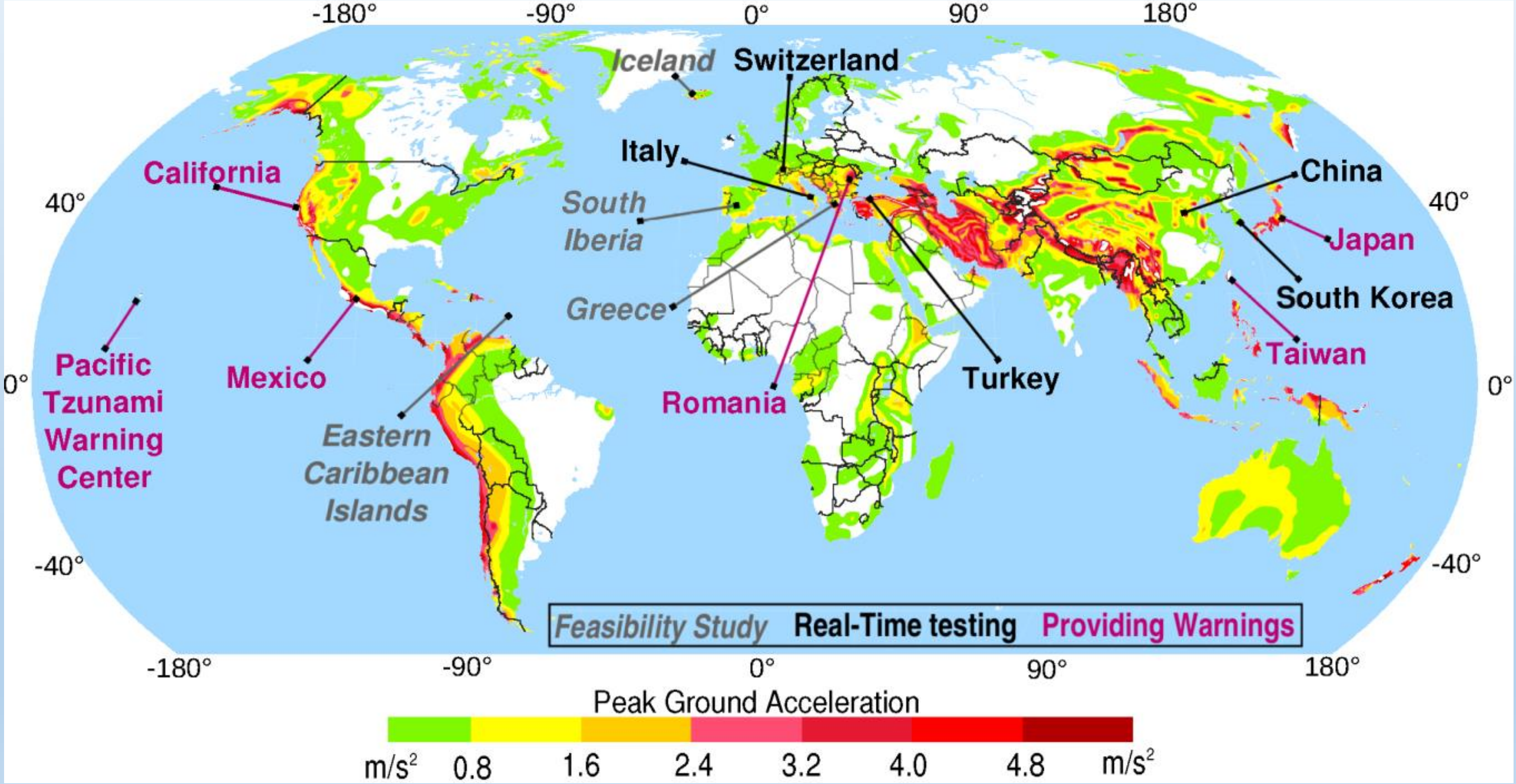
P-wave based Early Warning



Colombelli and Zollo, G.J.Int., 2015

Objective: To estimate in a fast and reliable way the earthquake's damage potential

Worldwide Early Warning Systems



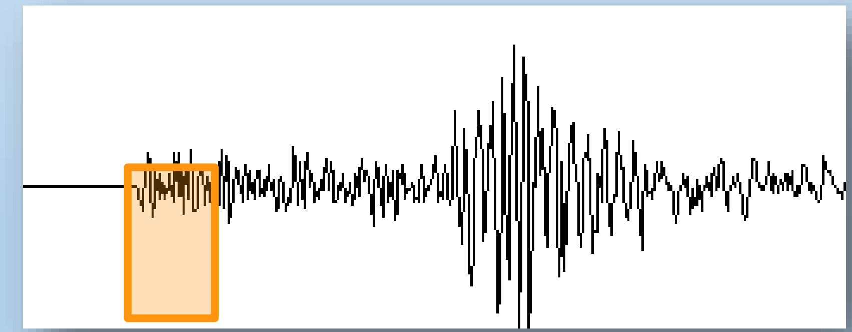
Big Earthquakes: The Problem of Magnitude Estimate

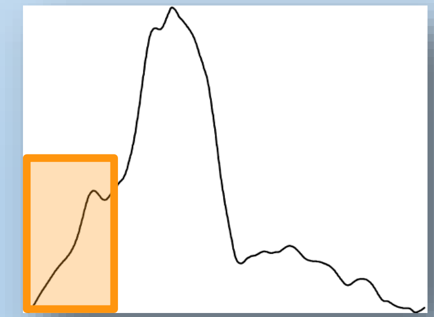
… is it possible to estimate the final magnitude of the event while the rupture is still ongoing and we don't know the way the rupture is propagating

?

Track and image the earthquake rupture while it is occurring

Integrate multi-disciplinary observations

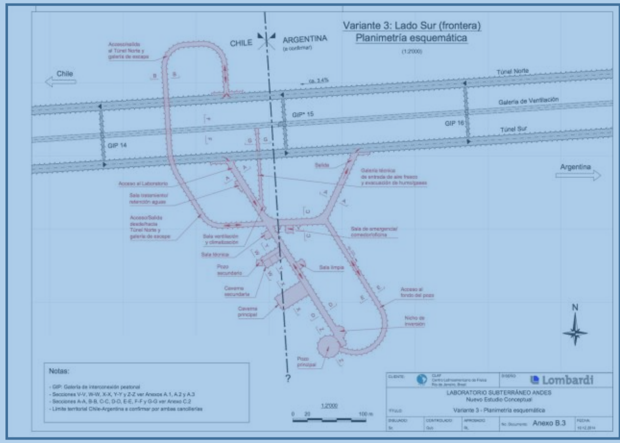




Moment Rate Function (MRF)

Fifth International Workshop for the Design of the ANDES Underground Laboratory

Buenos Aires, Argentina 29 - 30 June 2017



Gracias