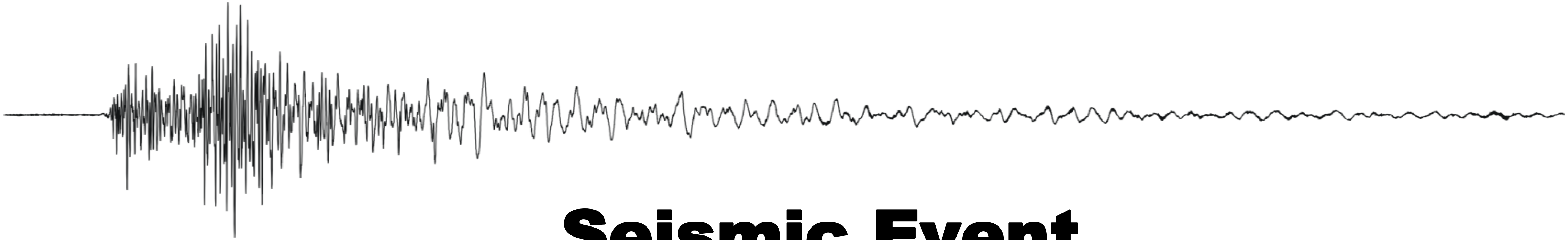

Seismic Event
M_L 3.7 Ricigliano (SA)
28/01/2024

Open File Report
The RISSC-Lab Team

F. Carotenuto, S. Colombelli, G. De Landro, L. Elia, G. Festa, A.G. Iaccarino, V. Longobardi, T. Muzellec, S. Nazeri, M. Palo, M. Picozzi, R. Rea, G. Russo, A. Scala, F. Scotto di Uccio, C. Strumia, S. Tarantino, M. Adil, A. Zollo

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RISSC-Lab: Laboratorio di RIcerca in Sismologia Sperimentale e Computazionale

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Irpinia Near-Fault Observatory

OUTLINE

- Seismotectonic setting
- Waveforms, location and mechanism
- Seismic Moment, Rupture radius and stress drop
- Strong Ground Shaking prediction – Shake Maps
- Earthquake Early Warning testing

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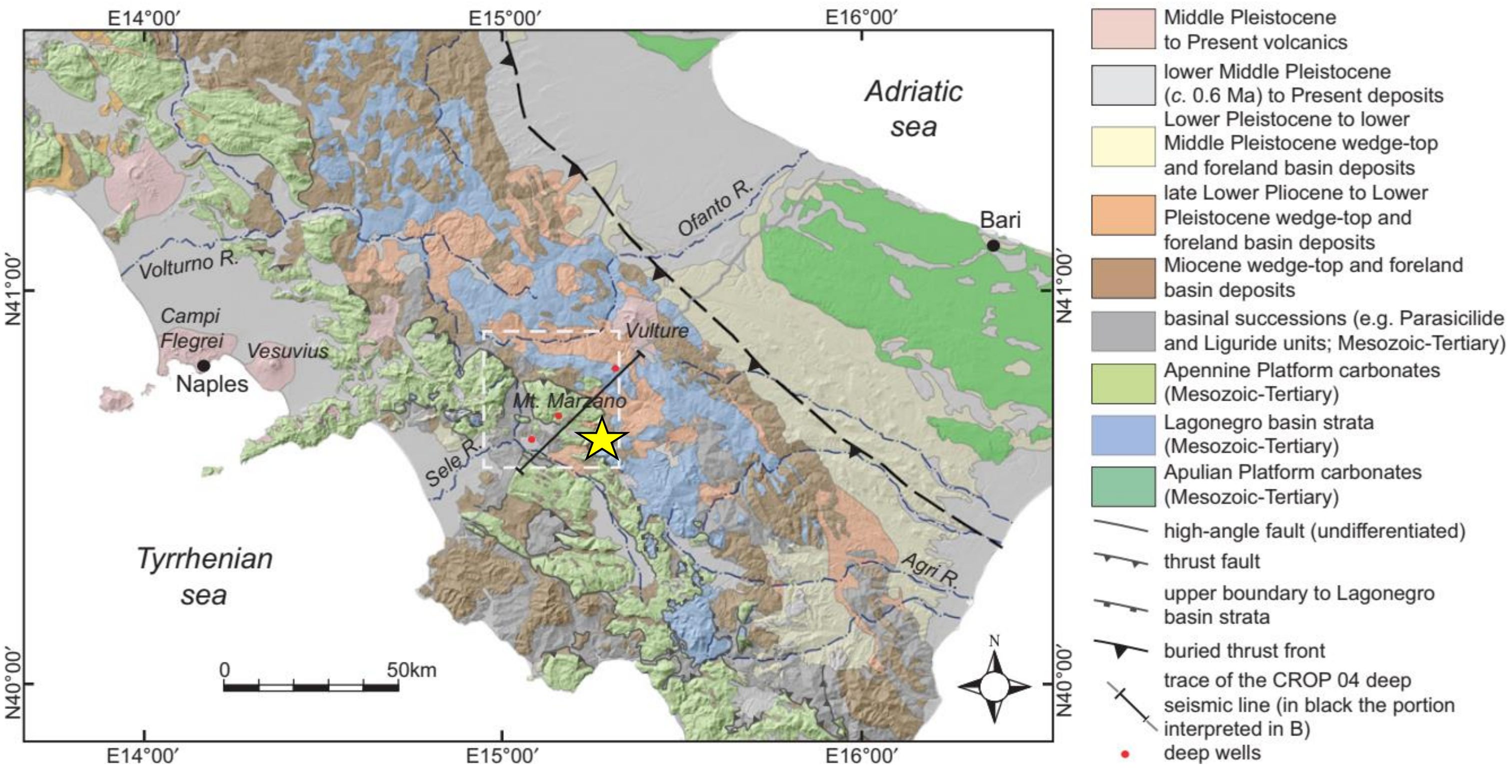
Seismotectonic Setting

Geological Setting



The ML 3.7 earthquake occurred along the Southern Apennines chain, a **fold and thrust belt** characterized by ENE-verging duplexes geometries and out-of-sequence thrusting due to orogenic contraction. It has been active since upper Eocene-Oligocene Miocene till late Pliocene. During the Quaternary the Southern Apennines thrust belt was dissected by NW-SE oriented normal faults that accommodated an **extensional tectonic phase**, according to a stress field with the axis of maximum extension coaxial to the axis of maximum compression of Apennines belt (*Doglioni 1995; Patacca et Scandone, 2007a, Ascione, 2013*). The figure shows the geological sketch map of Southern Apennines derived from Ascione *et al.* (*2013*).

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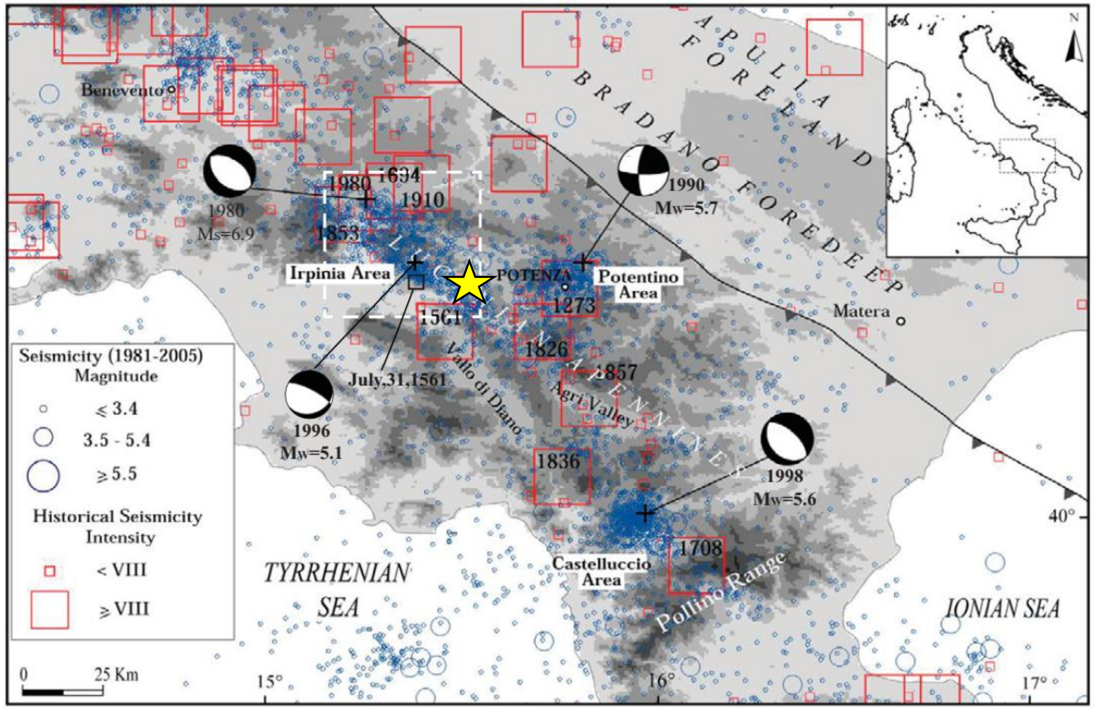
Historical and Instrumental Seismicity



Several historical earthquakes struck the Irpinia region with MCS intensity I ≥ X, occurred in A.D. 989, 1694, 1930, and 1962 (*CPTI Working Group, 2019; Ascione et al., 2013*). **The Ms 6.9, 1980 Irpinia earthquake** was the most destructive, instrumental earthquake of Southern Apennines **occurred along a system of NW-SE trending normal faults**. This event is described by a complex rupture process involving multiple fault segments according to (at least) three different nucleation episodes at 0 s, 20 s and 40 s times (e.g. *Bernard and Zollo, 1989*). In 1996 a seismic sequence with a mainshock of Mw 5.1 took place (*Cocco et al., 1999*) inside the epicentral area of 1980 earthquake.

In the figure the (historical and instrumental) seismicity and the focal mechanisms of the main last decade earthquakes are reported. The location of the January 28, 2024, ML 3.7 Ricigliano earthquake is indicated by the yellow star.

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Seismotectonic Context

Historical earthquakes up to X-XI MCS intensities and instrumental seismicity with moderate to large events depict the Southern Apennines as a region with one of the **highest seismic hazard** of the Mediterranean area, with segmented, seismogenic structures (lateral extent of few tens of kilometers) capable of **generating up to M 7 earthquakes** (*Chiarabba et al, 2005; Improta et al., 2014*). The **ML 3.7, 2024, Ricigliano Earthquake occurred near the southern tip** of the NE-dipping fault segment activated during **the Ms 6.9, 1980 Irpinia earthquake**. In the figure the sources of earthquakes larger than ML 5.5 in Southern Apennines are reported (*DISS Working Group, 2018*). The location of the Ricigliano earthquake is indicated by a yellow star.

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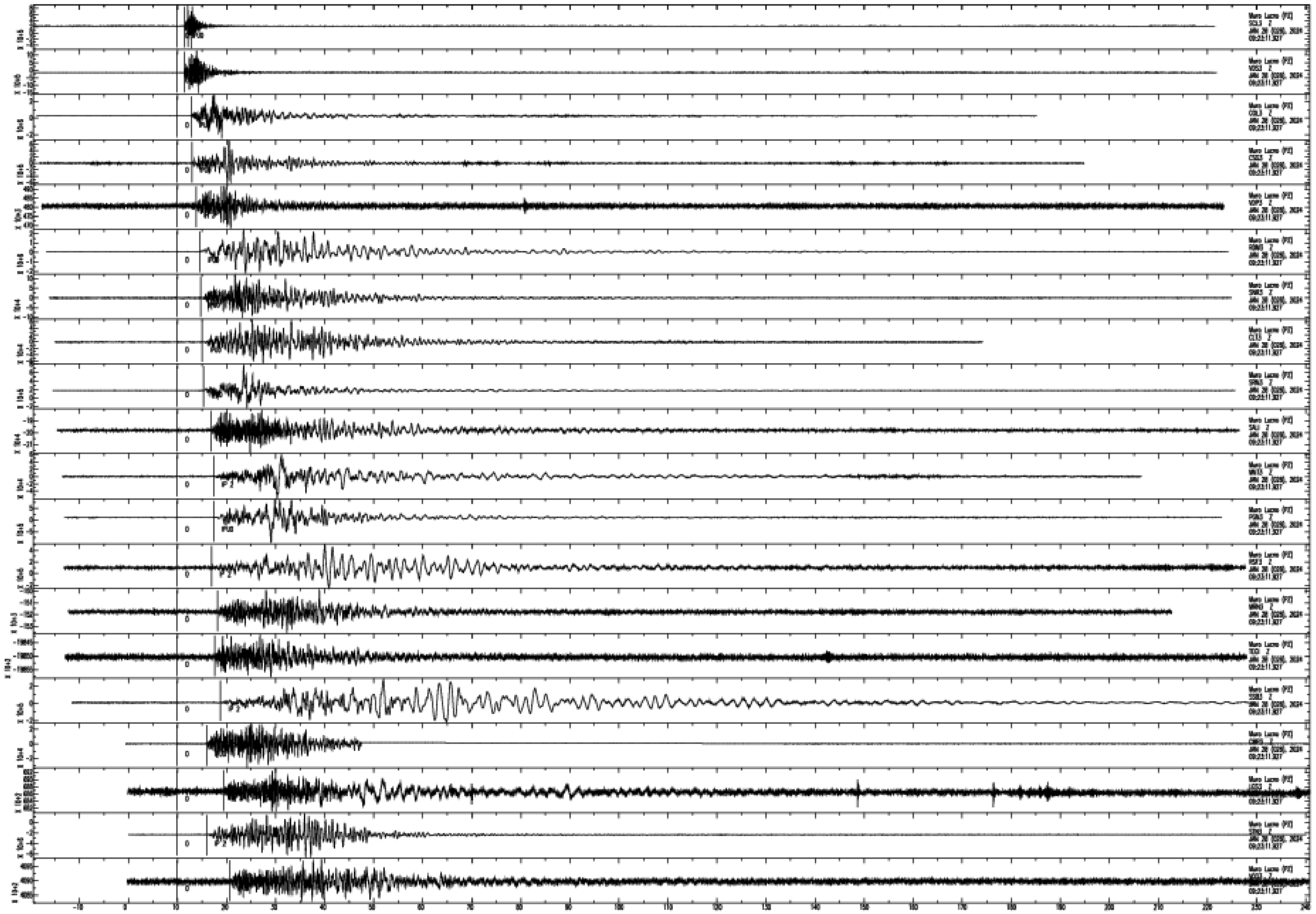
Seismic waveforms, Earthquake location & mechanism

Seismic records @ ISNet



Example of **seismic waveforms (vertical component)** recorded at the stations of ISNet, for the ML 3.7 event (28/01/2024 09:23:21 UTC) in the epicentral distance **range 5- 57 km.**

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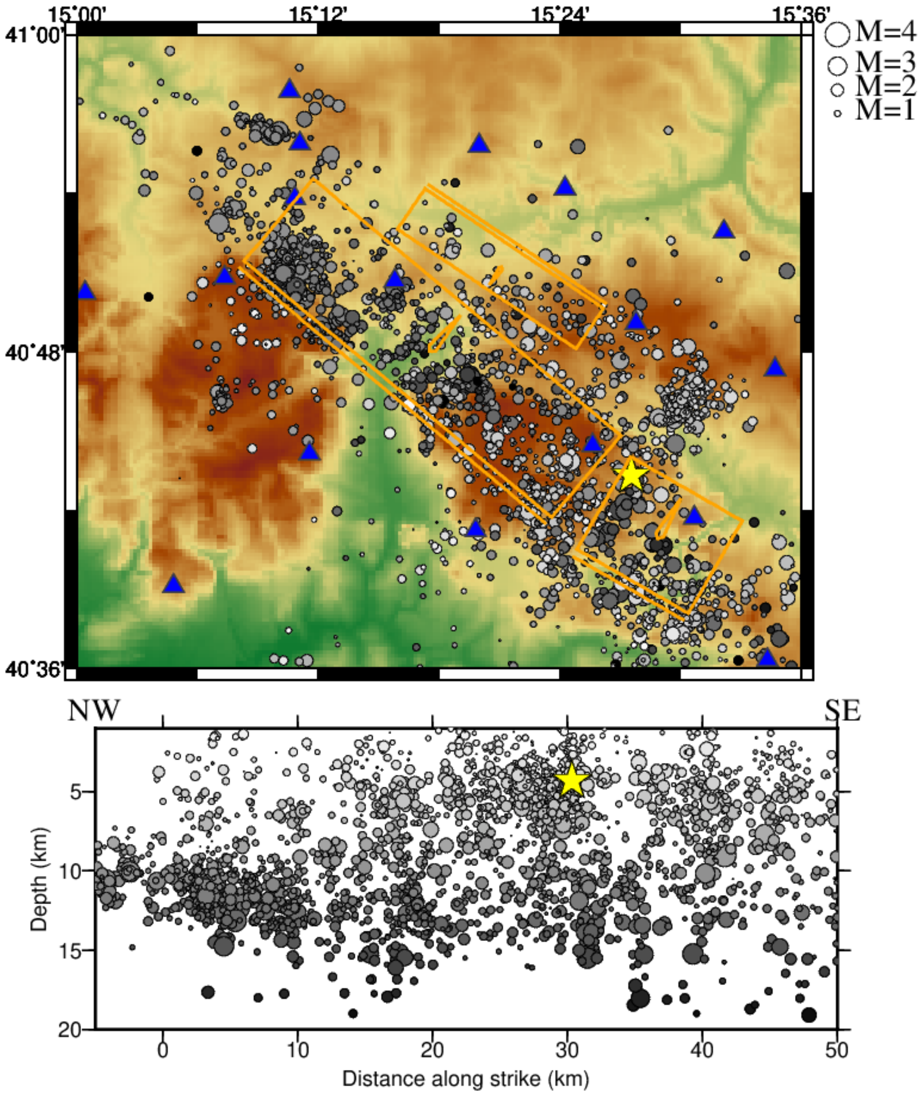
3D Absolute location



DATE & TIME: 2024/01/28 09:23:21.57
LAT: 40.7219 LON: 15.4595 Depth 4.3 km

We performed the absolute location of Ricigliano event with NLLoc (Lomax, 2009) and the 3D P- and S-wave models optimized for the area (De Landro et al. 2022). The yellow star represents the event location. The location is well constrained with 31 arrival times (17 P and 14 S), GAP 99°, RMS 0.2 s and horizontal and vertical location errors of 500 m.

The grey dots represent the events occurred from 2008 within ISNet (-0.4<ML<3.7), coloured by depth. The orange boxes represent the 80 Irpinia eqk fault segments (DISS, 2023). The bottom panel shows the distribution of seismicity along strike (NW-SE) versus depth.

The event occurred in the volume within the two fault segments involved in the 1980 Irpinia eqrthquake, which is interested by shallow seismicity between 2 and 6 km of depth.

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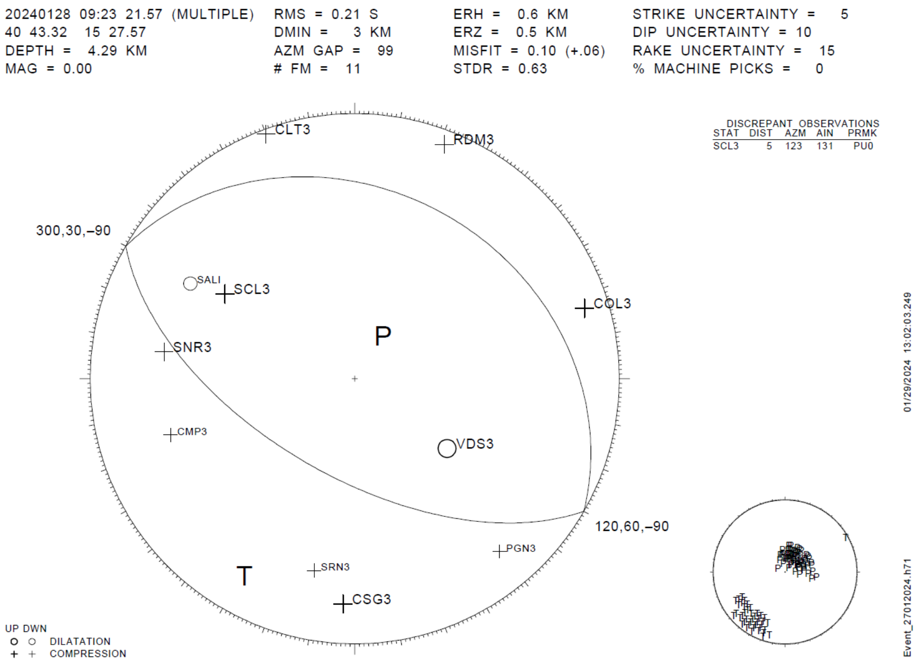
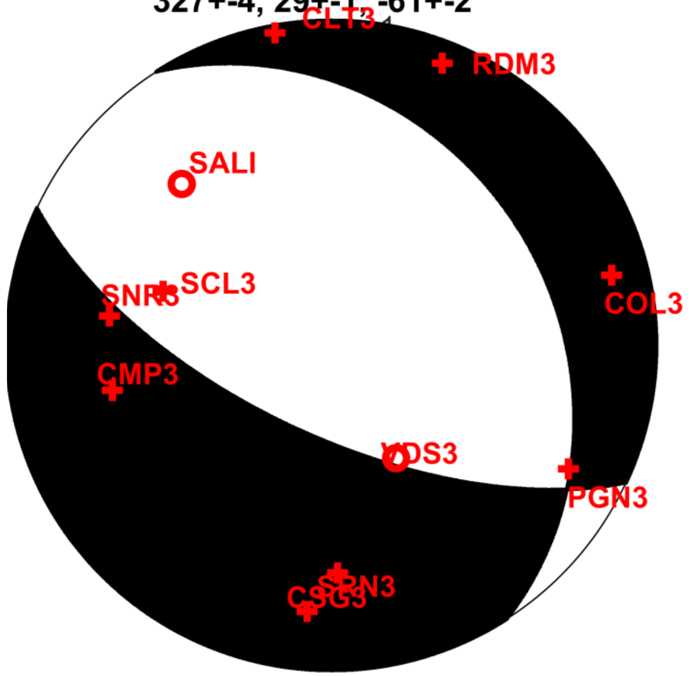
Focal Mechanism

(a)

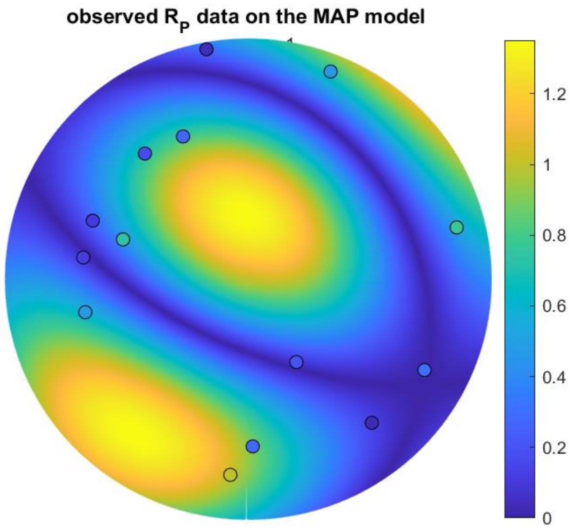


(b)

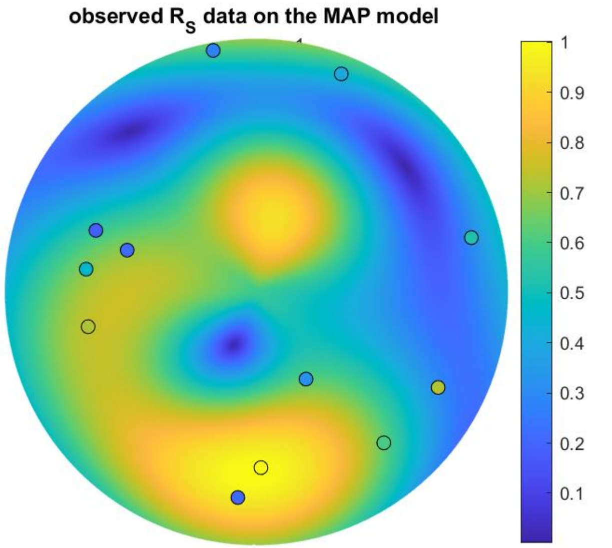
MAP model
strike, dip, slip
115+-3, 65+-1, -105+-1;
327+-4, 29+-1, -61+-2



(c)



(d)

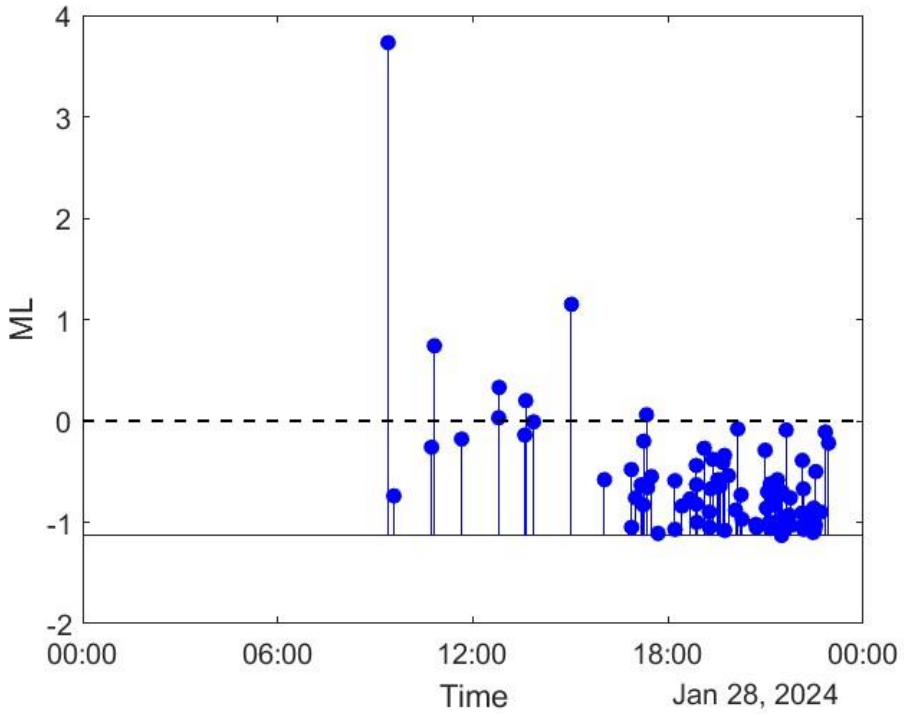


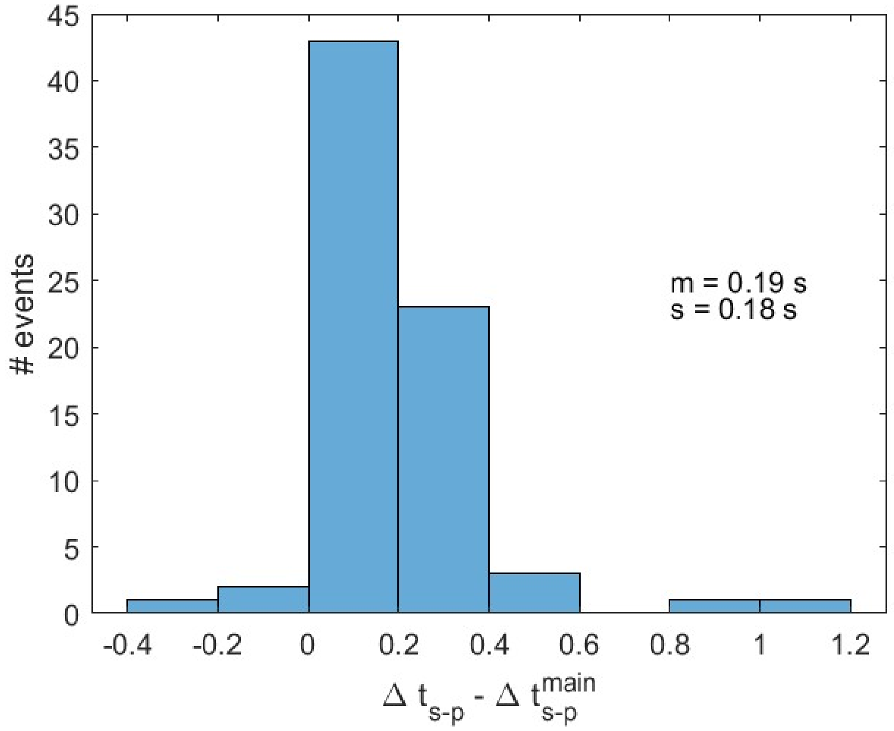
Focal mechanism solution shows a nearly pure normal fault mechanism. Inversions performed using only polarities (a) and P and S amplitudes together with polarities (b-d) provide overall consistent focal mechanisms.

Event Aftershocks

The manual catalog contains only one ML 1.4 aftershock (~ 6h from the main event). We searched for earthquakes hidden in the noise integrating the machine learning detector EQTransformer (Mousavi et al., 2020) and the template matching technique EQCorrscan (Chamberlain et al. 2018) at the stations close to the main event.

We were able to extract a high number of aftershocks (**86**) emerging only at the station SCL3, with magnitude bewteen -1.0 and 1.2. No foreshocks have been detected.





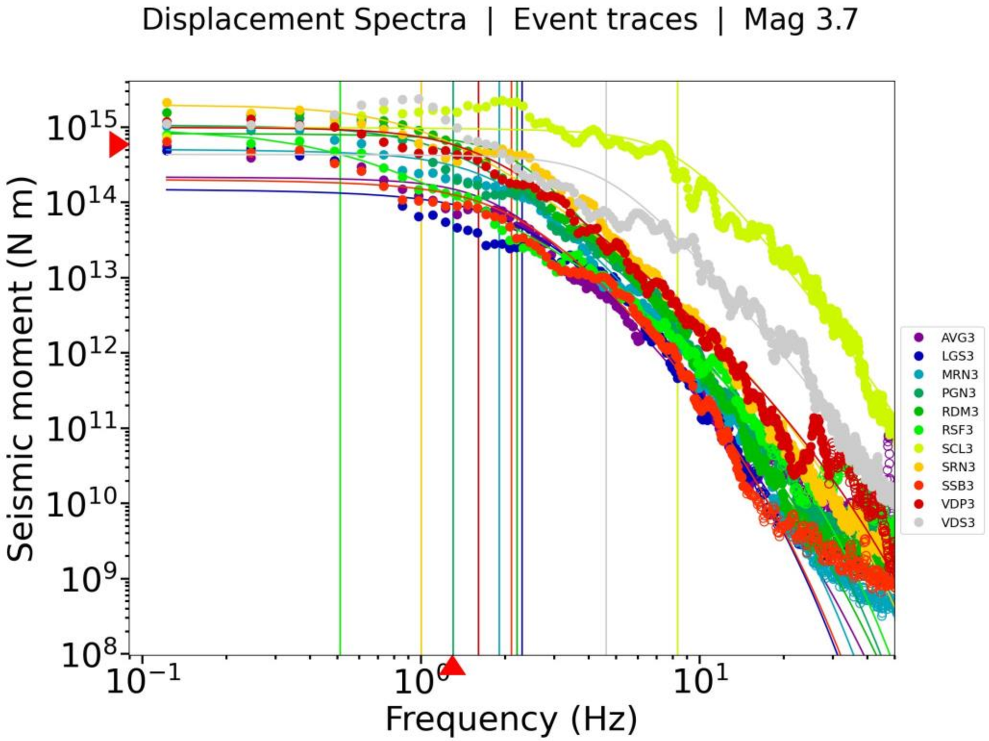
Analyzing the $t_s - t_p$ for the detected events and comparing it with the difference observed for the mainshock, we can estimate an average spatial extent of the seismicity of ~1.3 km ($v_s = 3.0\ km/s$)

Seismic Moment, Moment Magnitude, Rupture radius and Stress Drop

Frequency Domain source parameters

- Data have been preprocessed to remove the instrumental response, then a time window of $8s$ has been selected around the S-pick, starting $0.5s$ before the arrival.
- Local attenuation in the spectral modeling is corrected using a regional quality factor Q=230.

M_w	δM_w	f_c	δf_c	γ	$\delta\gamma$	$\Delta\sigma\ (MPa)$	$\delta\Delta\sigma(MPa)$	$r\ (m)$	$\delta r\ (m)$
3.78	0.03	1.29	0.08	2.75	0.04	1.1	0.2	610	40



Source parameters are resolved at **12 stations** of the network.

Moment magnitude estimations between $M_w 3.38$ and $M_w 4.13$, with an averaged value $(M_w 3.78 \pm 0.03)$.

Most of corner frequencies estimates range in the bandwidth $\mathbf{0.5Hz}$ to $\mathbf{2.5Hz}$; **VDS** and **SCL** stations exhibit **significantly higher** $\boldsymbol{f_c}$, suggesting possible along-strike directivity.

Final estimate leads to a stress drop of $(\mathbf{1.1 \pm 0.2})\boldsymbol{MPa}$ using the law from Kaneko & Shearer (2014).

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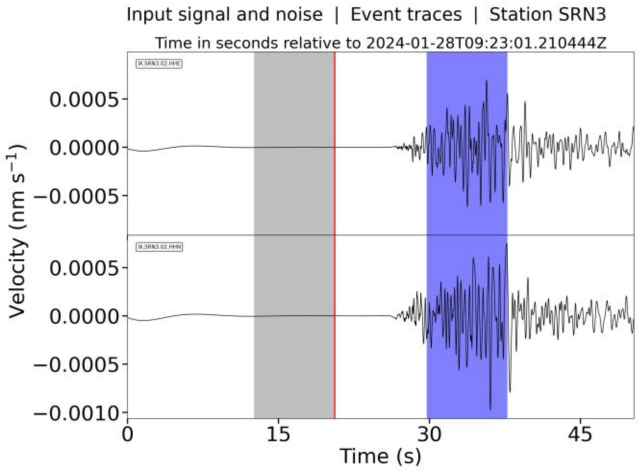
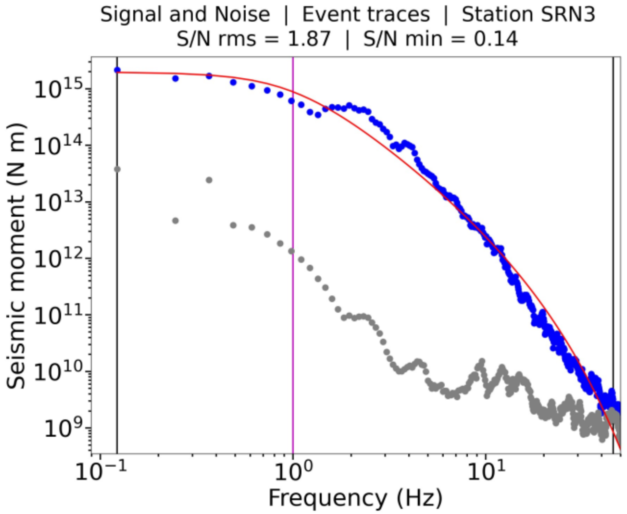
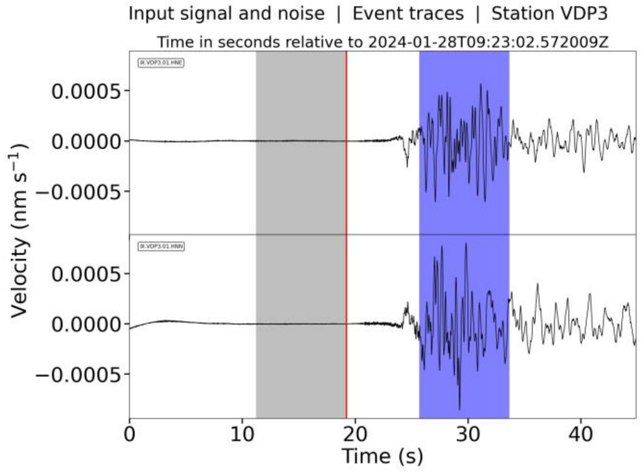
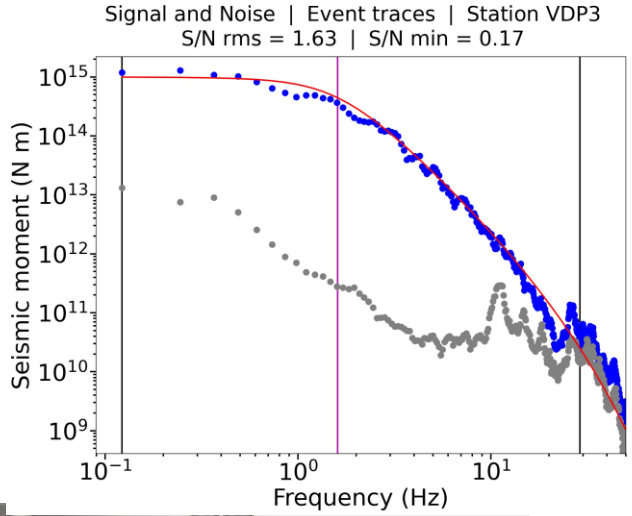
Frequency Domain source parameters: examples of records and displacement spectra









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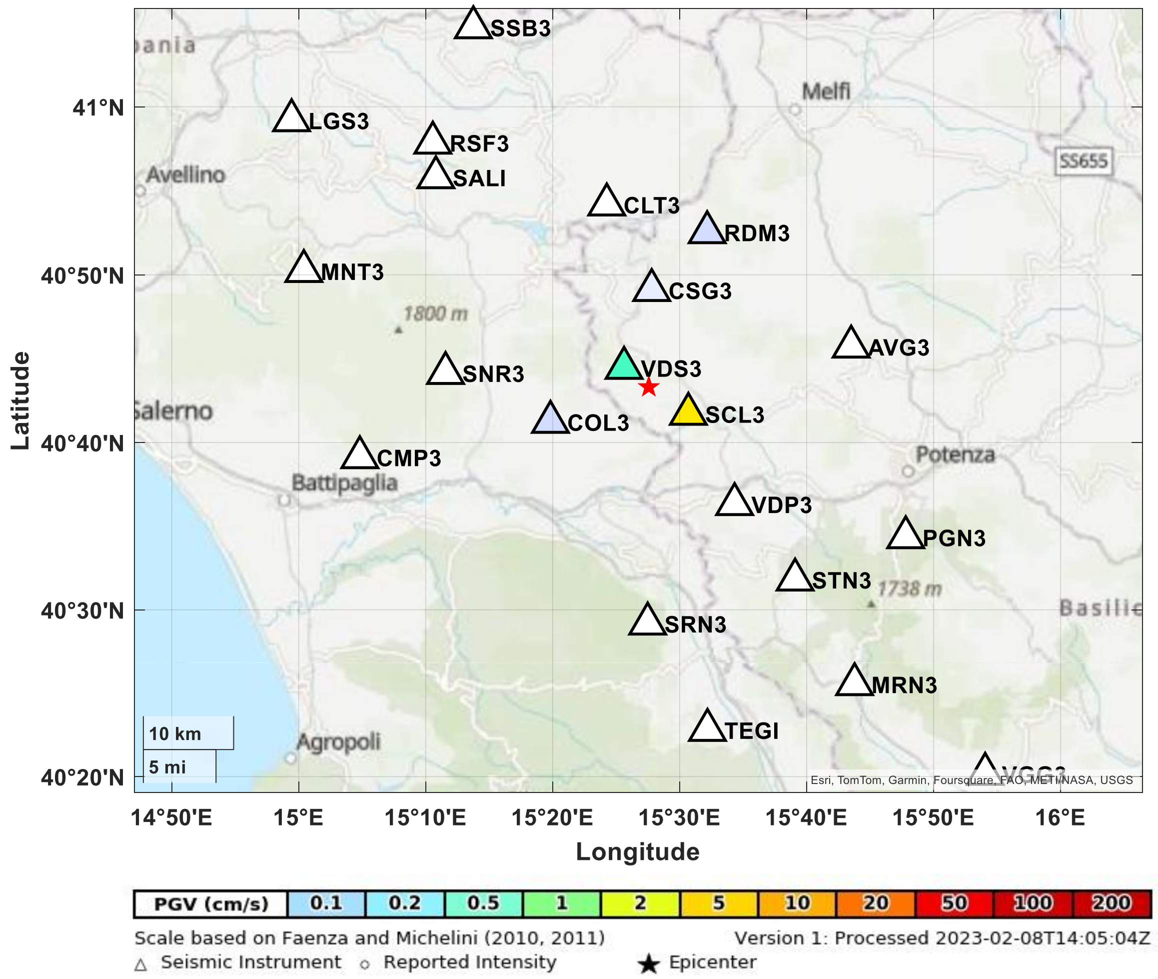
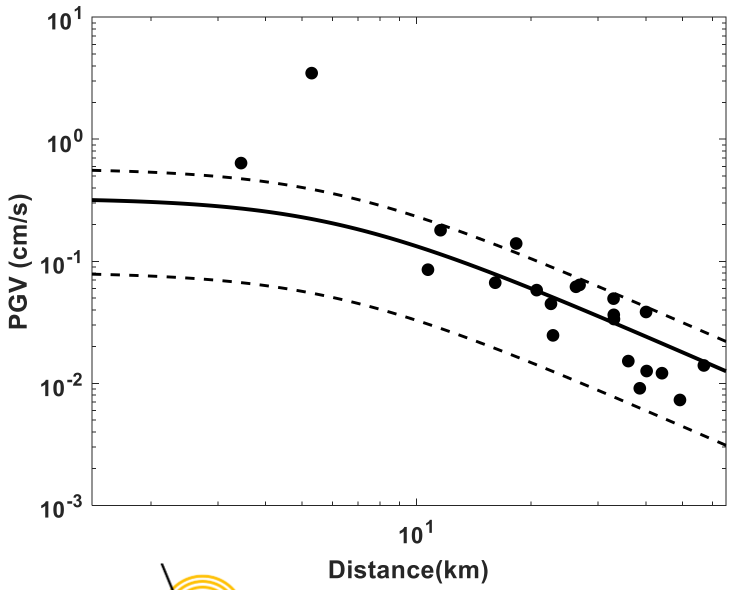
Strong Ground Shaking Prediction – Shake Maps

Strong Ground motion (PGV)

PGV from integrated accelerometers



- Average epicentral distance $\sim 28.0\ km$
  - Min distance IX.VDS3 $- 3.5\ km$
  - Max distance IX.VGG $- 56.9\ km$
- PGV range
  - $PGV_{min} = 7.3 \cdot 10^{-3}\ cm/s$ (IX.LGS3)
  - $PGV_{max} = 3.5\ cm/s$(IX.SCL3)



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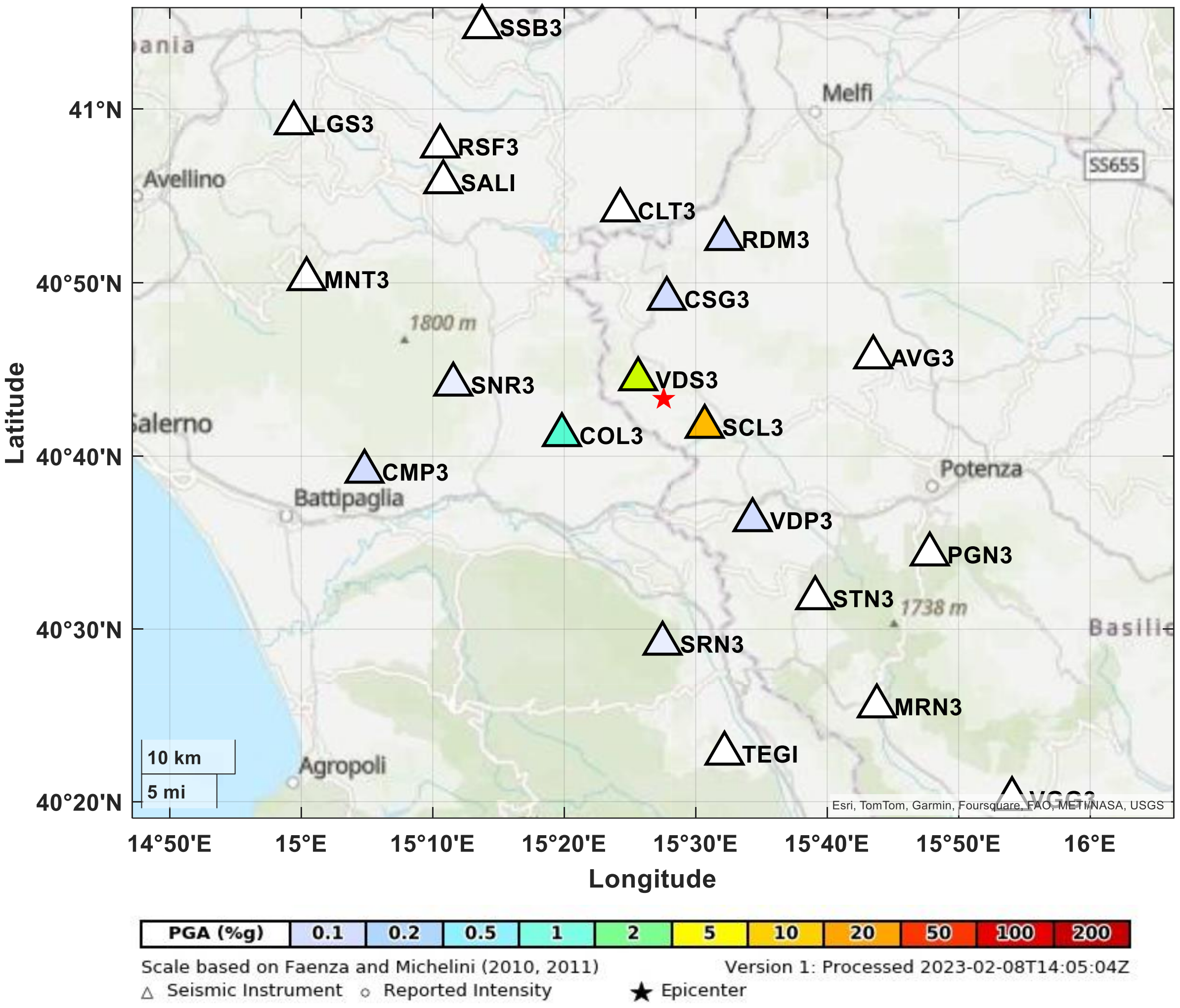
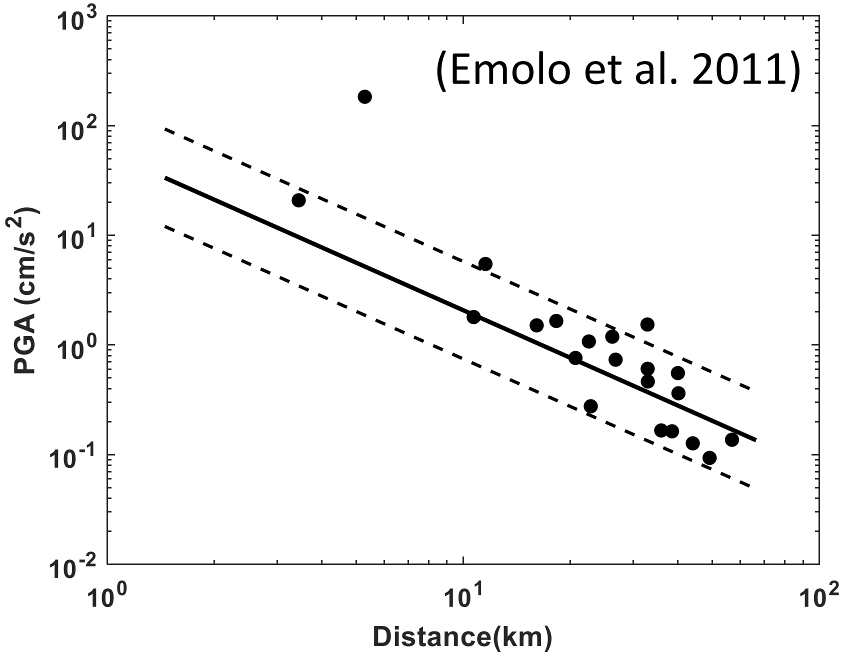
Strong Ground Motion (PGA)



- PGA range
  - $PGA_{min} = 9.5 \cdot 10^{-3}\%g$ (IX.LGS3)
  - $PGA_{max} = 18.7\%g$ (IX.SCL3)



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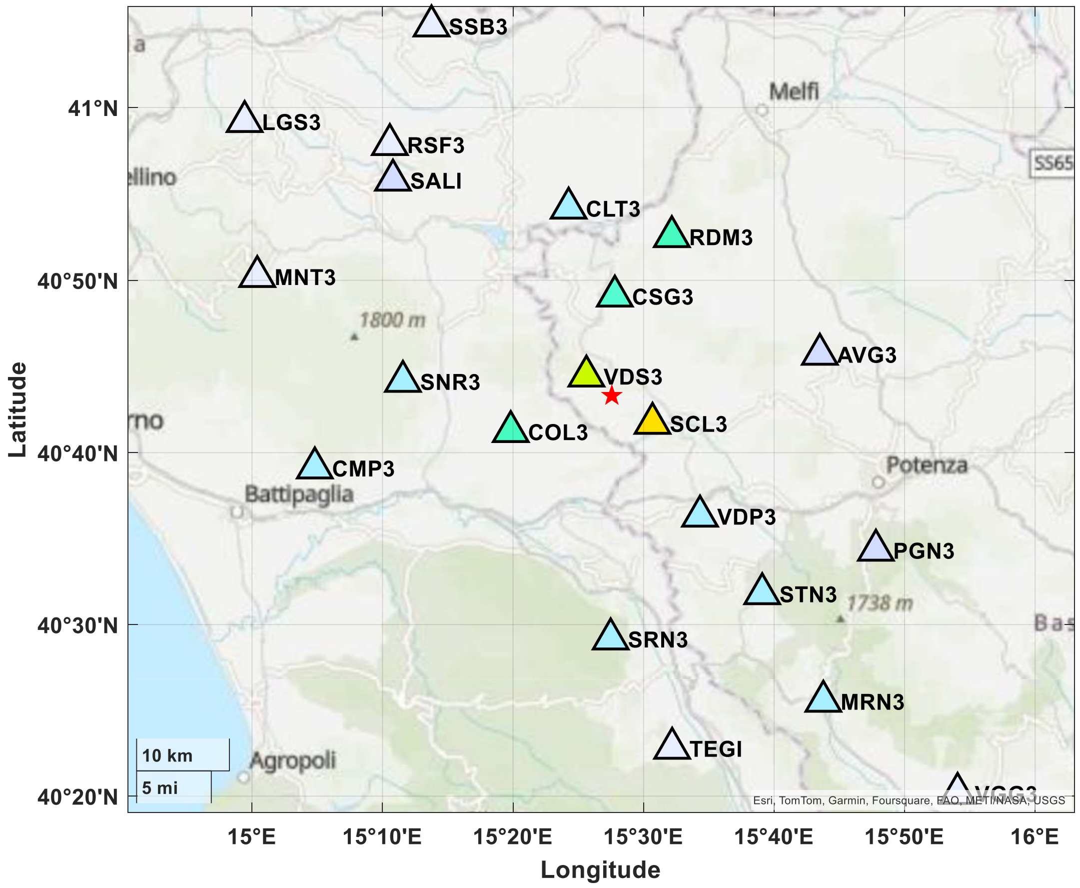
Strong Ground motion (IMM)



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0556	0.212	0.808	1.97	4.82	11.8	28.7	70.1	>171
PGV(cm/s)	<0.0178	0.0775	0.337	0.898	2.39	6.37	17	45.2	>120
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Faenza and Michelini (2010, 2011) Version 1: Processed 2023-02-08T14:05:04Z

△ Seismic Instrument ○ Reported Intensity ★ Epicenter

$IMM_{max} = VI$ (6.4 - IX.SCL3)

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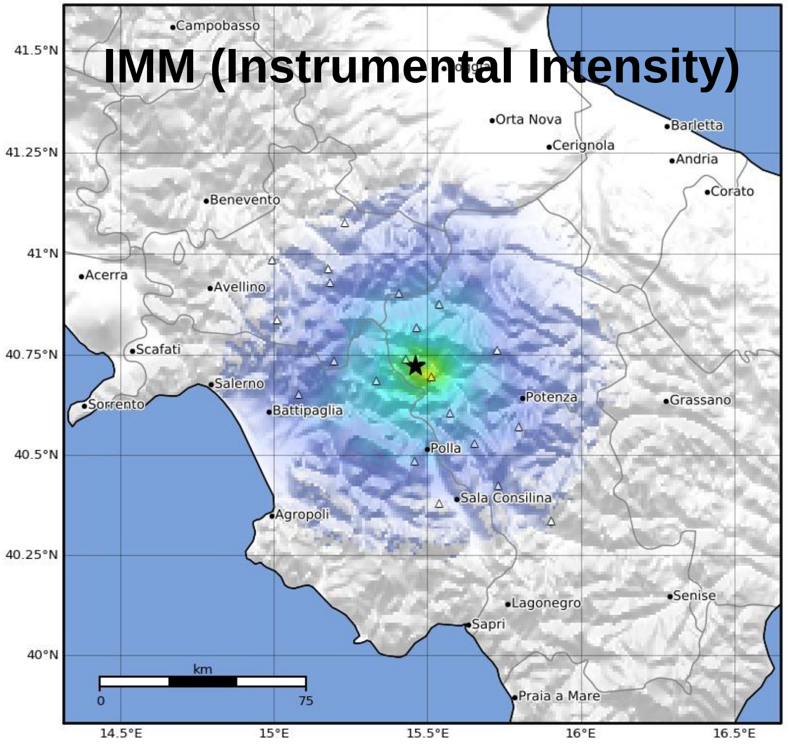
Irpinia Near-Fault Observatory

Strong Ground motion (ShakeMaps)

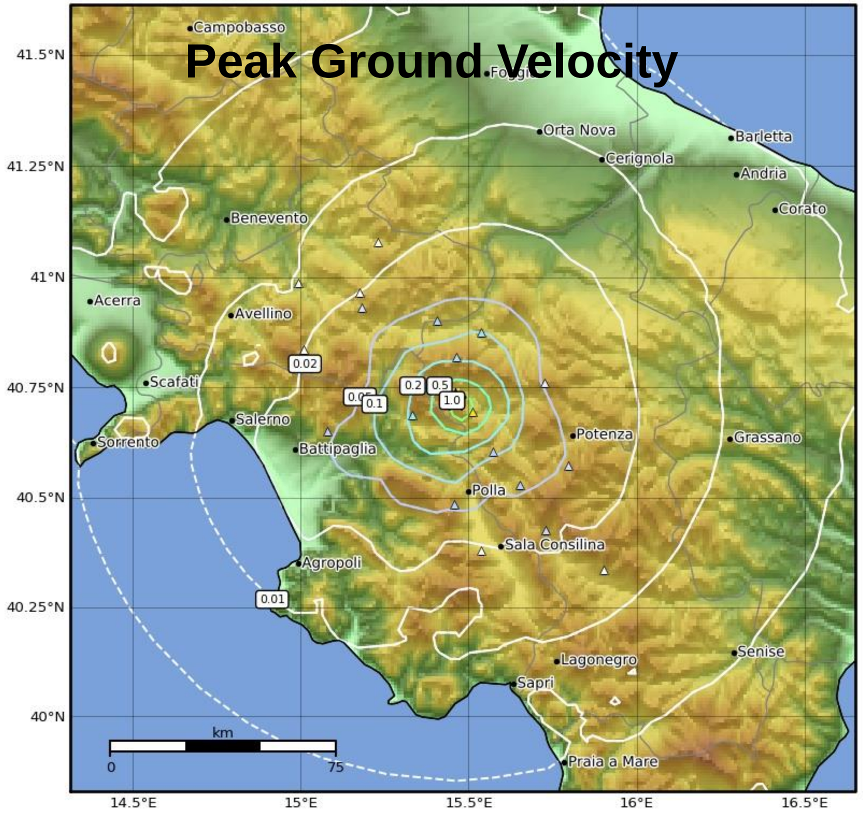
Macroseismic Intensity Map UNINA
ShakeMap: Ml 3.8 Ricigliano (SA)
Jan 28, 2024 09:23:21 UTC M3.8 N40.72 E15.46 Depth: 4.3km ID:17612r_isnet



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0556	0.212	0.808	1.97	4.82	11.8	28.7	70.1	>171
PGV(cm/s)	<0.0178	0.0775	0.337	0.898	2.39	6.37	17	45.2	>120
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Faenza and Michelini (2010, 2011) Version 1: Processed 2024-01-29T14:30:38Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter

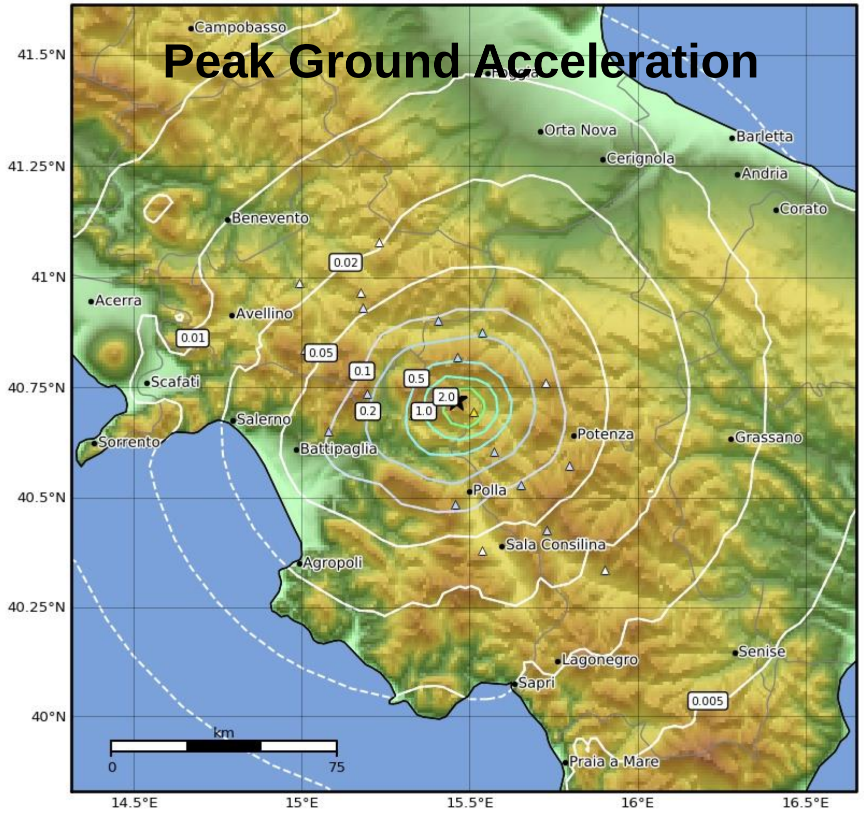
Peak Ground Velocity Map UNINA
ShakeMap: Ml 3.8 Ricigliano (SA)
Jan 28, 2024 09:23:21 UTC M3.8 N40.72 E15.46 Depth: 4.3km ID:17612r_isnet



PGV (cm/s)	0.1	0.2	0.5	1	2	5	10	20	50	100	200

Scale based on Faenza and Michelini (2010, 2011) Version 1: Processed 2024-01-29T14:30:38Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter

Peak Ground Acceleration Map UNINA
ShakeMap: Ml 3.8 Ricigliano (SA)
Jan 28, 2024 09:23:21 UTC M3.8 N40.72 E15.46 Depth: 4.3km ID:17612r_isnet



PGA (%g)	0.1	0.2	0.5	1	2	5	10	20	50	100	200

Scale based on Faenza and Michelini (2010, 2011) Version 1: Processed 2024-01-29T14:30:38Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter

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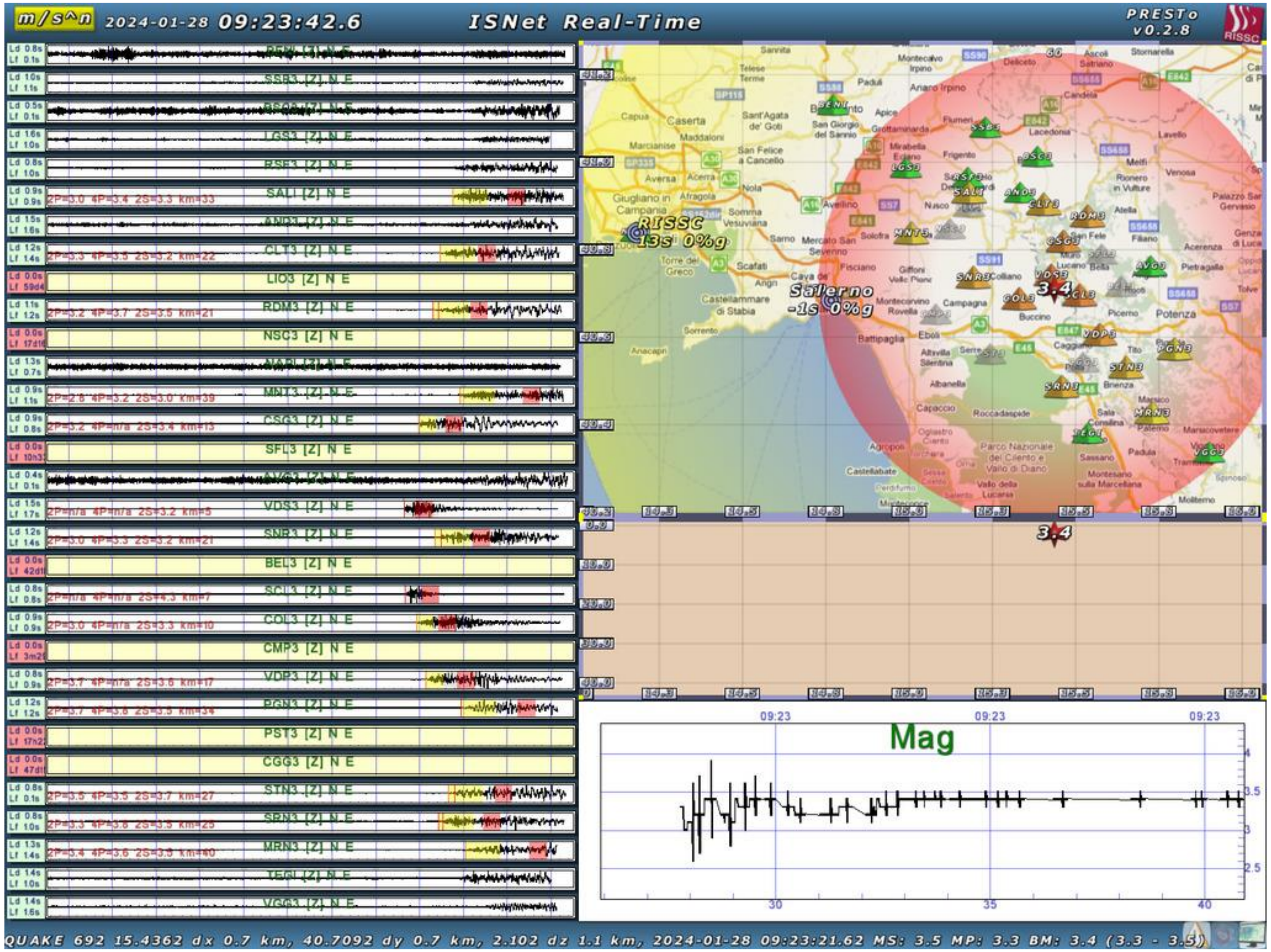
Earthquake Early Warning Testing

PRESTo – Probabilistic and Evolutionary Early Warning System

QuakeUP – Shaking-Forecast Based Earthquake Early Warning System

SAVE – Onsite Alert Level warning system

PRESTo Early Warning System (source-based)



ML 3.7, Ricigliano (SA)
40.7219, 15.4595, 4.3 km
2024-01-28 09:23:21.6 (UTC)

FIRST ALERT AFTER 6.3 sec from T0
(4.4 sec from 1st pick, 5 stations)
ΔMAG : -0.4
ΔLOC_epi : 1.8 km
ΔLOC_dep : 6.1 km

STABLE ALERT AFTER 12.2 sec from T0
(10.3 sec from 1st pick, 14 stations)
ΔMAG : -0.3
ΔLOC_epi : 2.4 km
ΔLOC_dep : 2.2 km

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Final Automatic Message from PRESTo

Il sistema di Early Warning **PRESTo**, in fase di sperimentazione presso il RISSC-Lab,
ha rilevato automaticamente un evento:

ML: **3.4**
Data: **2024-01-28 09:23:21.62 (UTC)**
Località: **San Gregorio Magno (SA)**
Google Map

utilizzando **14 stazioni** della rete **ISNet - Irpinia Seismic Network.**

La prima informazione su magnitudo e localizzazione dell'evento è stata disponibile al tempo:

2024-01-28 09:23:27.87 (UTC)

Cioè circa **4.6** secondi dopo il primo arrivo P rilevato alla stazione VDS3 al tempo:

2024-01-28 09:23:23.24 (UTC)

In allegato il rapporto dettagliato e l'istantanea.

Per una completa statistica degli eventi rilevati da **PRESTo** nella fase di sperimentazione,
consultare il bollettino on-line.

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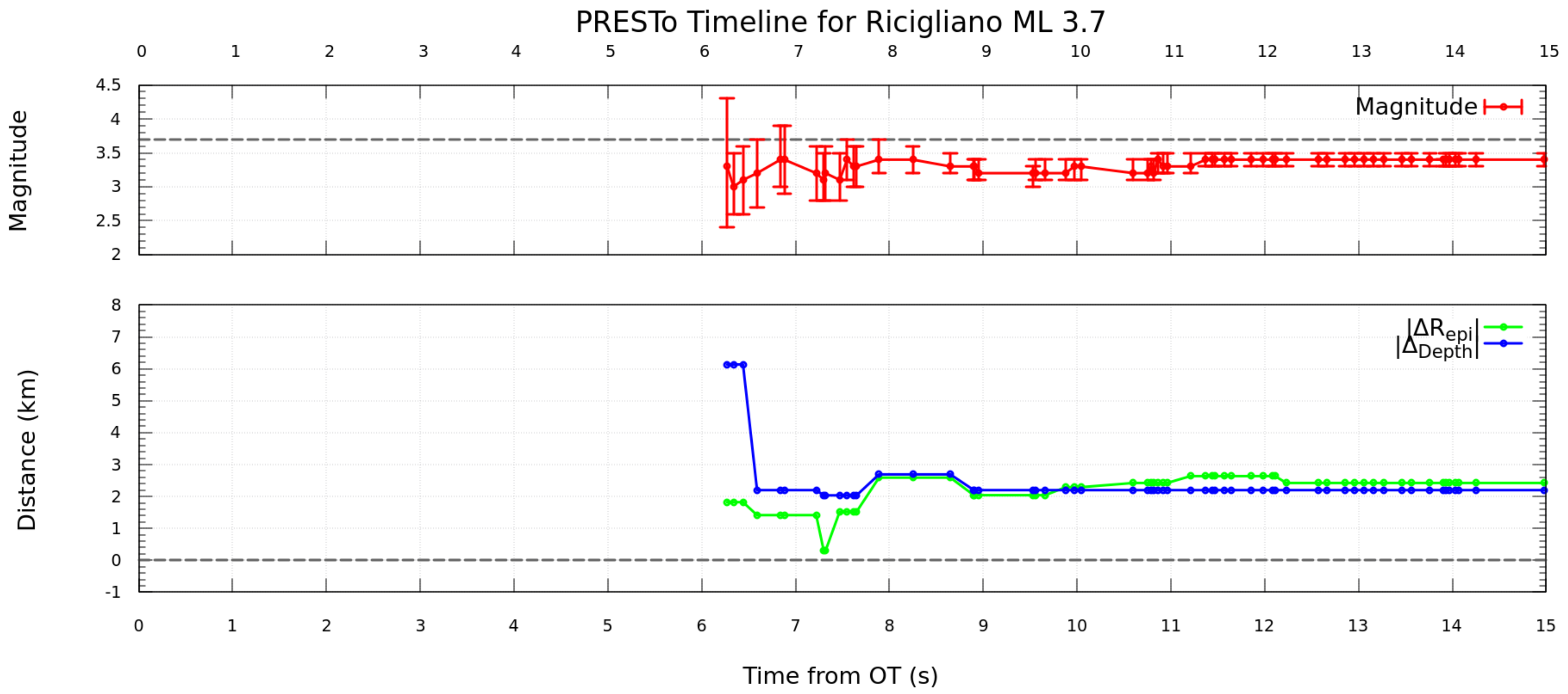
Real Time PRESTO evolution from CREW

Magnitude

Epicenter

Depth



Comparison of PRESTo estimates with 3D location and ISNet ML (dashed lines)

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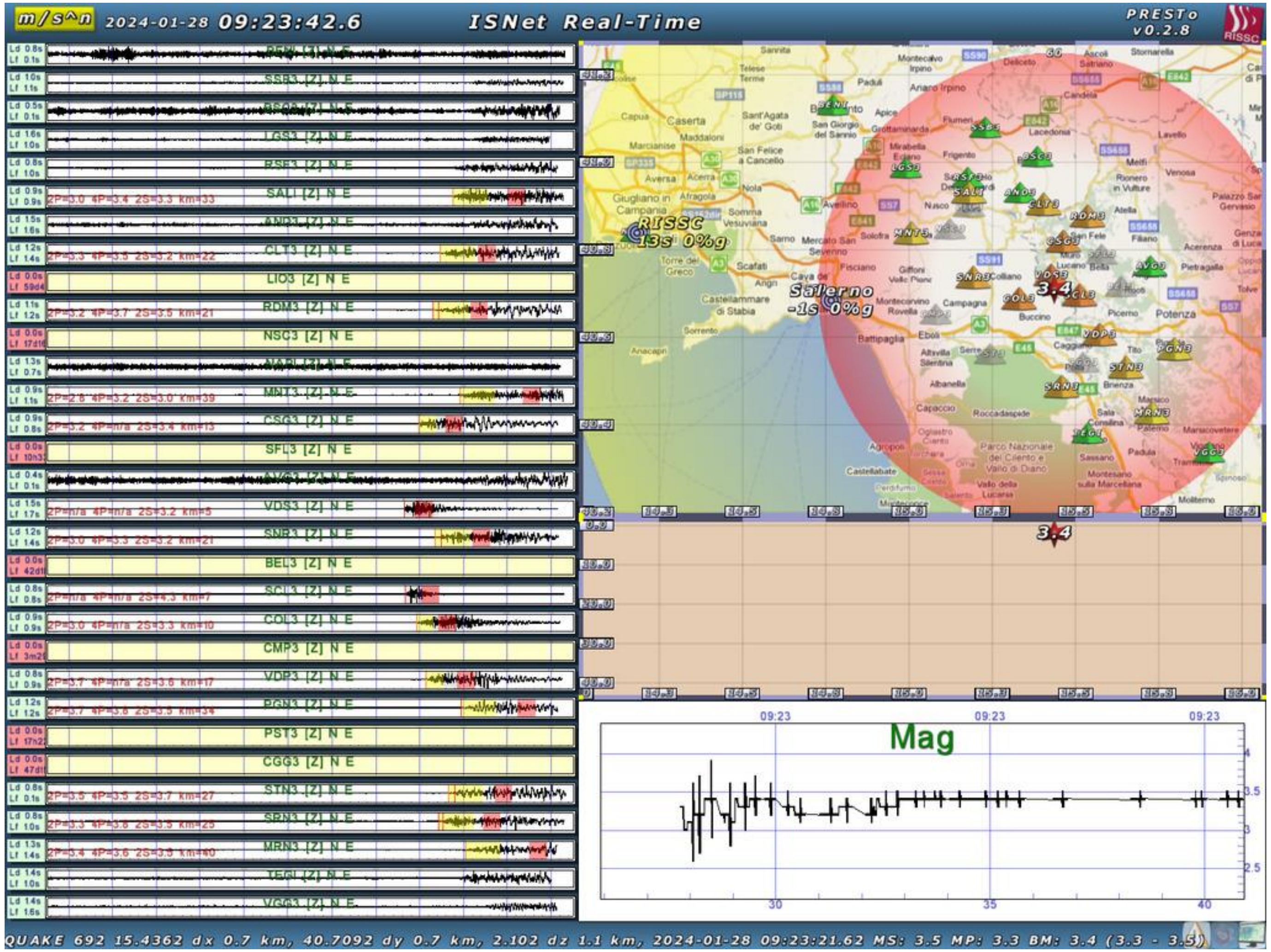
Data latency from PRESTo



Num.	Station	Latency (s)
1	AND3	1,00
2	AVG3	0,93
3	BEL3	-
4	BENI	0,97
5	BSC3	1,06
6	CGG3	-
7	CLT3	1,05
8	CMP3	-
9	COL3	0,98
10	CSG3	1,03
11	LGS3	1,87
12	LIO3	-
13	MNT3	0,98
14	MRN3	1,01
15	NAPI	1,04
16	NSC3	-
17	PGN3	1,01
18	PST3	-
19	RDM3	1,01
20	RSF3	0,99
21	SALI	1,09
22	SCL3	0,99
23	SFL3	-
24	SNR3	0,97
25	SRN3	0,99
26	SSB3	1,07
27	STN3	1,00
28	TEGI	1,85
29	VDP3	1,00
30	VDS3	1,03
31	VGG3	1,38

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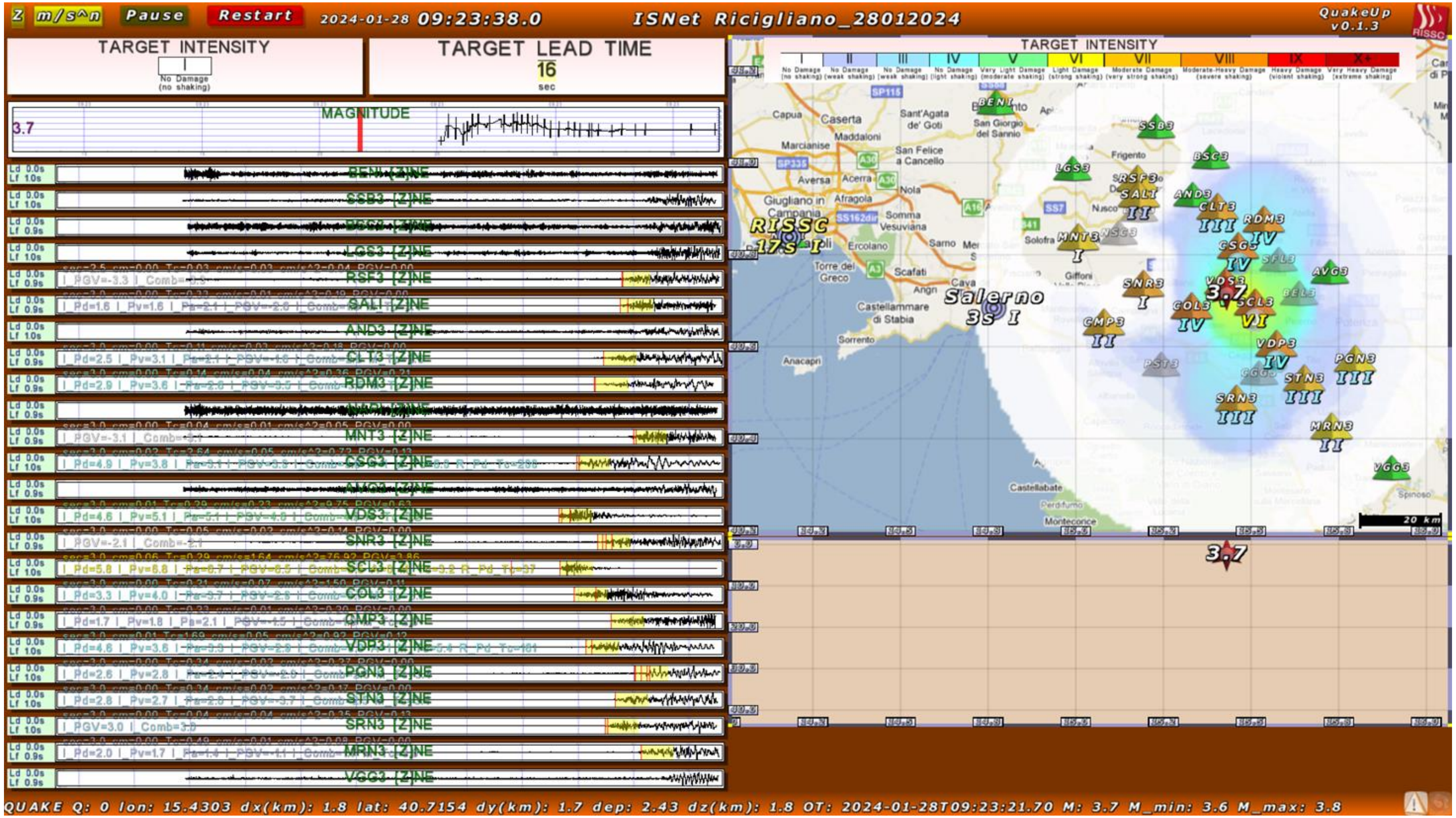
QUAKE-UP Early Warning System (impact-based)

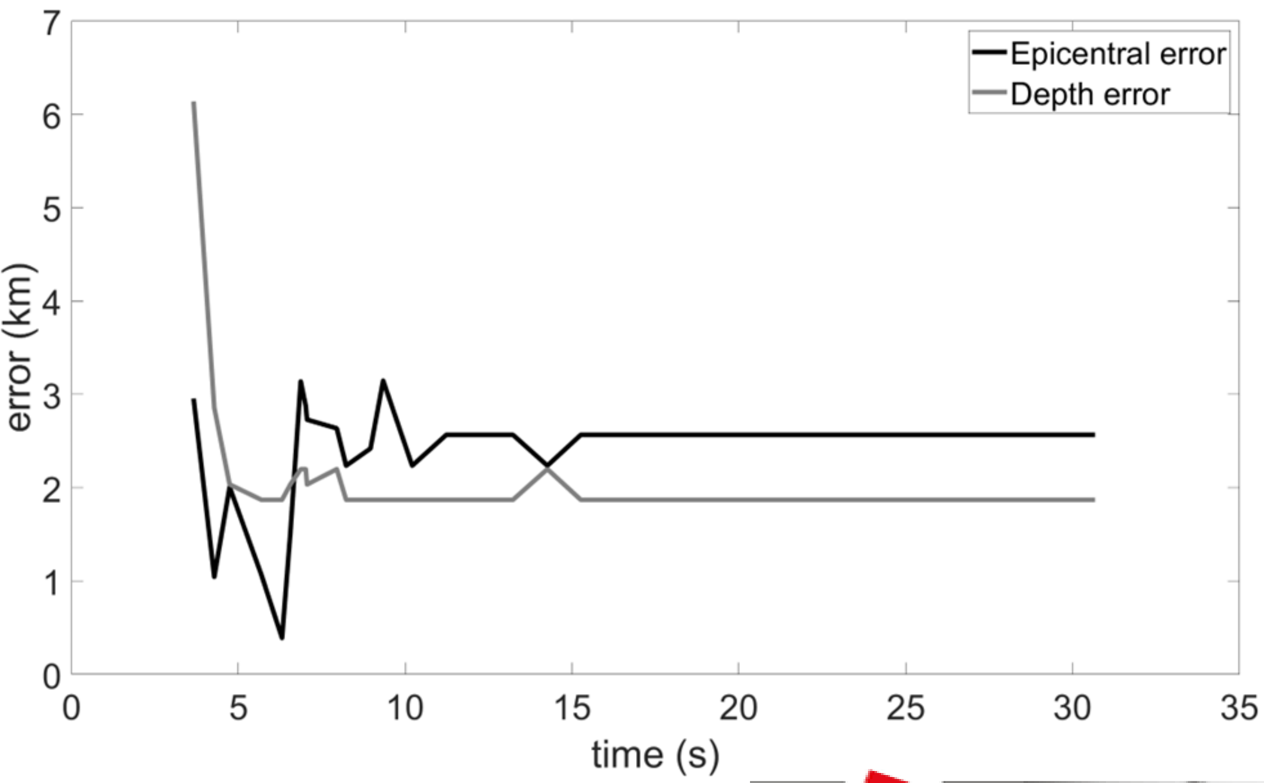


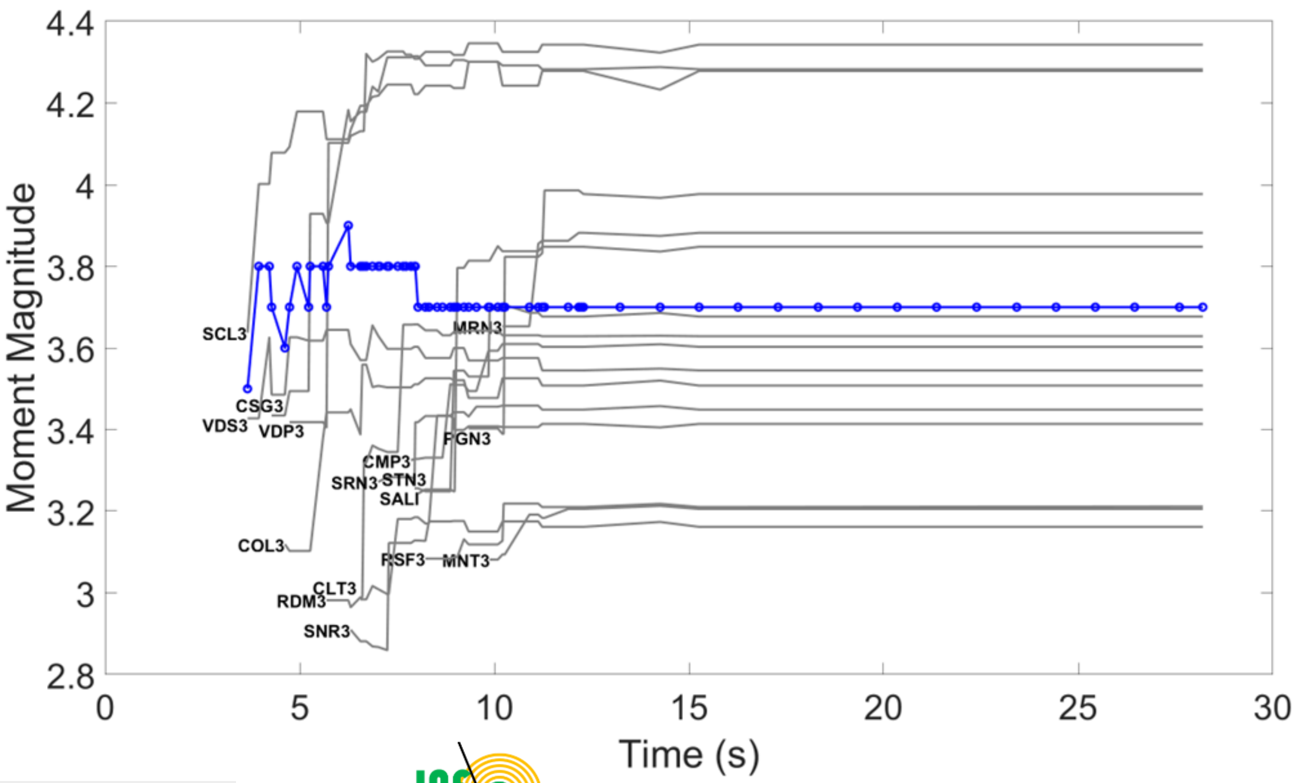
Screenshot of QuakeUp as resulting from the offline playback of the recorded waveforms.

About 4 s after the Origin Time of the event, the system is able to predict the expected shaking in the area of interest, using measured early P-wave amplitudes and predictions from an empirical GMPE.

QUAKE-UP Location and Magnitude Timelines

Time evolution of location errors and magnitude estimate from QuakeUp. Left plot shows the location errors, with respect to the 3D location results. Right plot shows the magnitude estimate at each station (gray lines) and the average value (blue line). Both location errors and magnitude estimate become pretty stable after about 8 seconds from the O.T.





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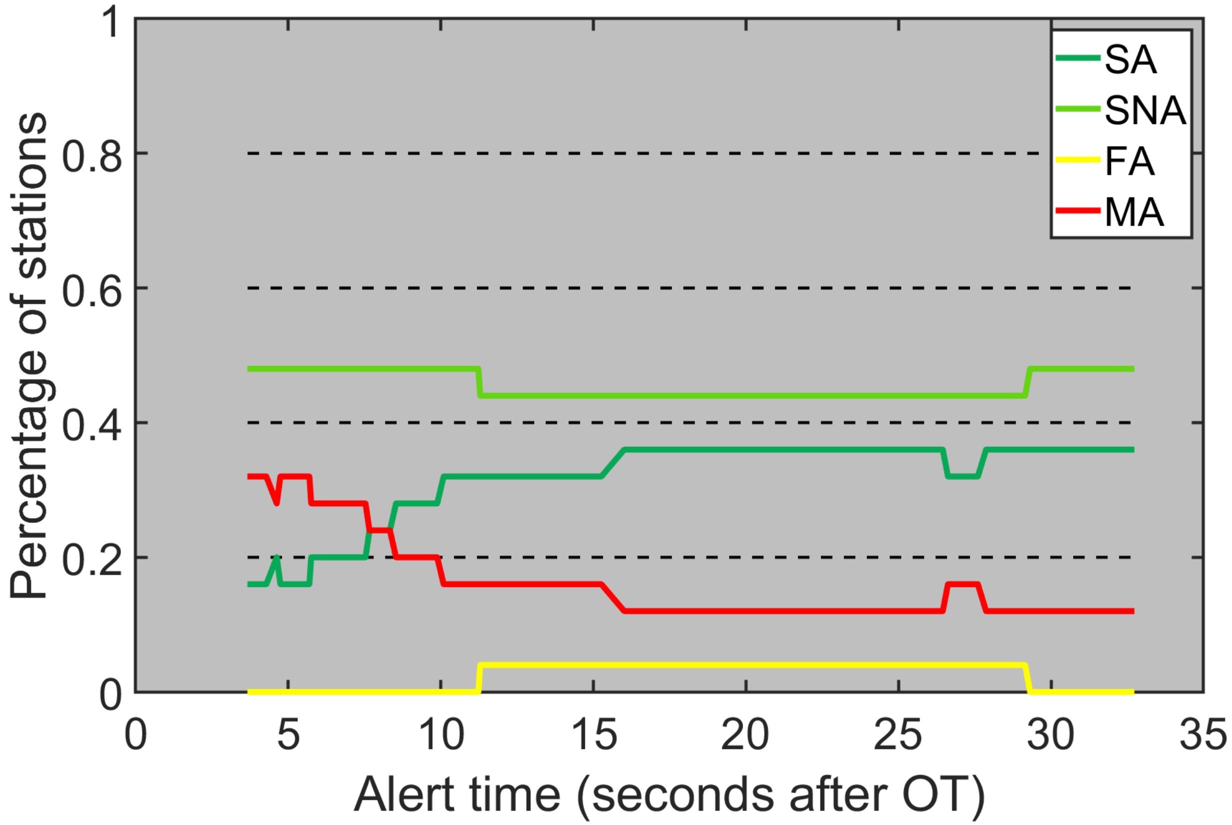
QUAKE-UP Impact Estimates

Using a **threshold intensity of III**, we define 4 alert categories, based on the comparison between the predicted and the observed intensity: **SUCCESSFUL ALERTS (SA)**, **SUCCESSFUL NON-ALERTS (SNA)**, **FALSE ALERTS (FA)** and **MISSED ALERTS (MA)**. Their definition is provided in the table, while their evolution with time is shown on the right plot. With the passing of time, the relative percentage of FA and SNA decreases.

Successful Alert (SA)	$I_{MM}^{pred} \geq I_{MM}^{thre}$ & $I_{MM}^{obs} \geq I_{MM}^{thre}$
Successful No-Alert (SNA)	$I_{MM}^{pred} < I_{MM}^{thre}$ & $I_{MM}^{obs} < I_{MM}^{thre}$
Missed Alert (MA)	$I_{MM}^{pred} < I_{MM}^{thre}$ & $I_{MM}^{obs} \geq I_{MM}^{thre}$
False Alert (FA)	$I_{MM}^{pred} \geq I_{MM}^{thre}$ & $I_{MM}^{obs} < I_{MM}^{thre}$



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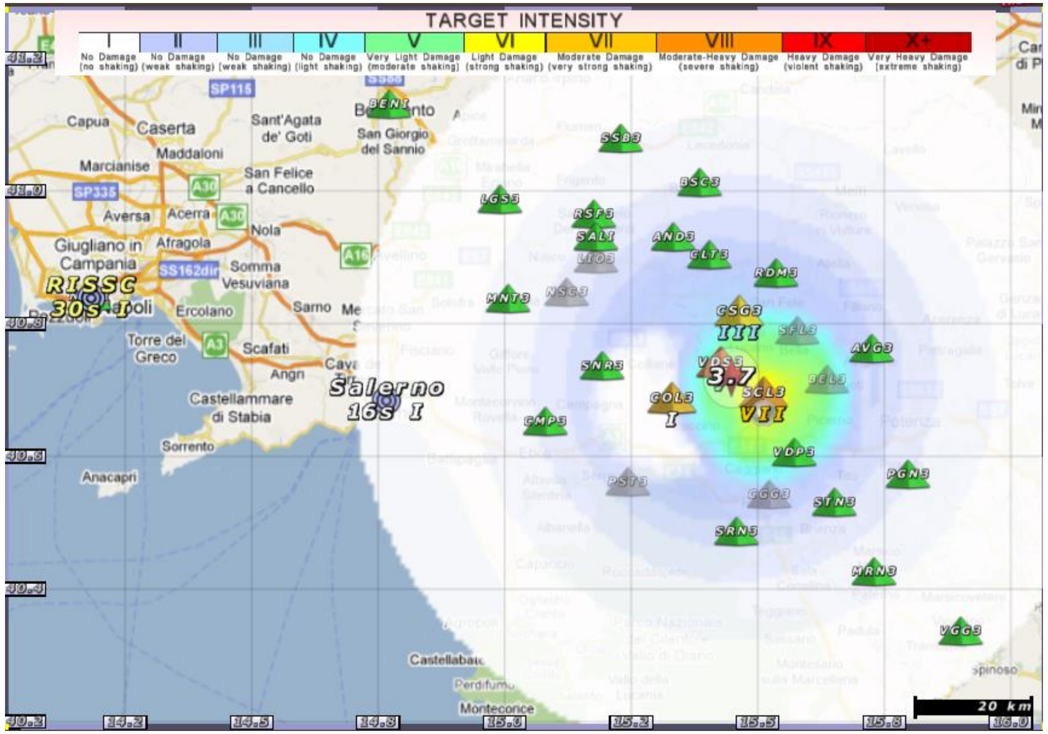
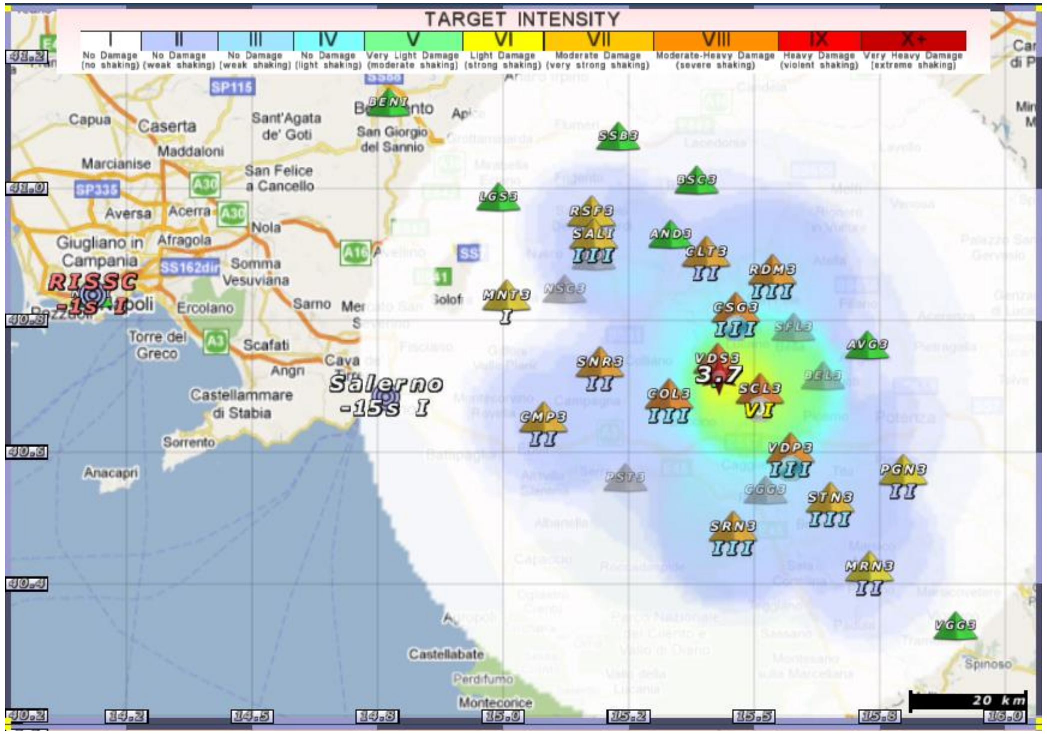
QUAKE-UP Impact Estimates

We show here the first (left) and the last (right) shake maps, as provided by QuakeUp. The predicted intensities are obtained form measured early P-wave amplitudes and from an empirical GMPE. The regional shake map well reproduces the real shaking distribution, since the very first estimate.





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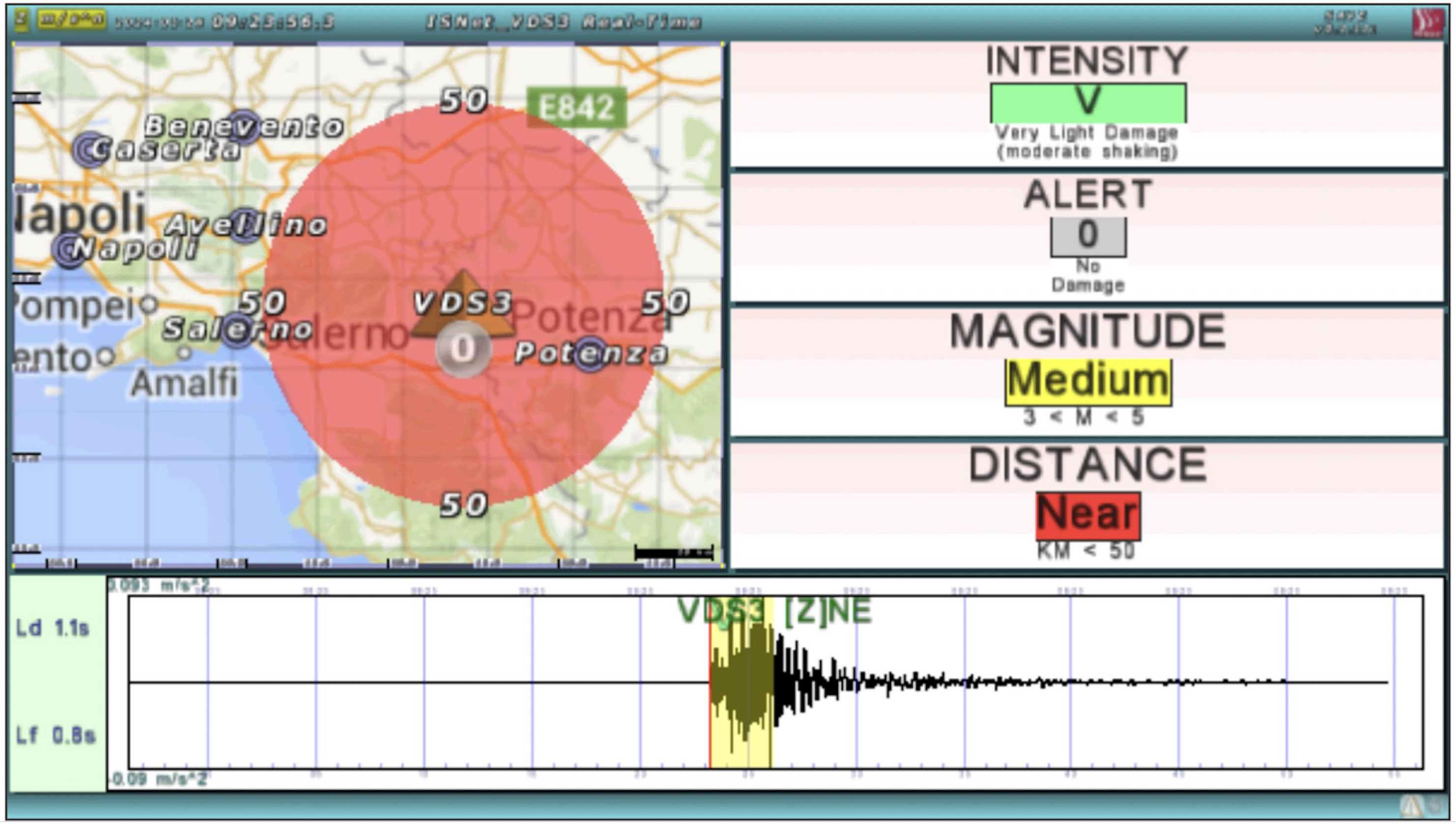
Real Time Performance of the onsite early warning system SAVE at the station VDS

On-Site estimates of Intensity, Alert Level, Magnitude and Distance as provides by SAVE@VDS station (epicentral distance 4 km). All the estimates are obtained using the vertical component of acceleration waveforms and using the first 3 seconds of recorded P-wave signal.

SAVE Screenshot



The system was able to compute both the Pd amplitude and the Tauc parameter, and was able to provide estimates of magnitude, distance and intensity ranges.

The **estimated intensity (through the Pd) was V**

The **observed intensity (through PGV) was V.**

The event was correctly classified as a **medium magnitude** event **nearby** the station.

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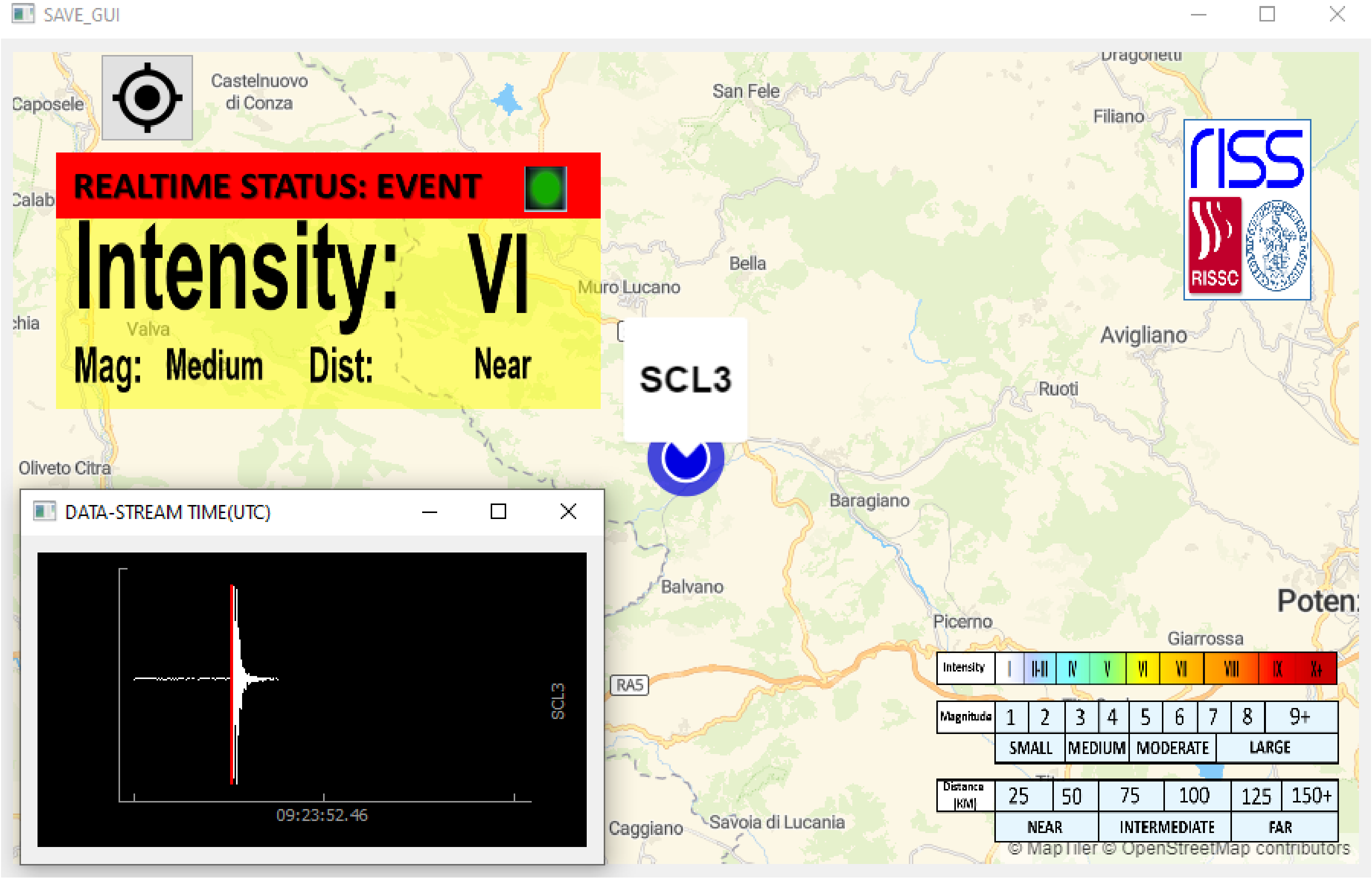
Offline Performance of the onsite early warning system SAVE at the station SCL

On-Site estimates of Intensity, Alert Level, Magnitude and Distance as provides by SAVE@SCL station (epicentral distance 5 km), through the playback of recorded waveforms. All the estimates are obtained using the vertical component of acceleration waveforms and using the first 3 seconds of recorded P-wave signal.



The system was able to compute both the Pd amplitude and the Tauc parameter, and was able to provide estimates of magnitude, distance and intensity ranges.

The **estimated intensity (through the Pd) was VI**
The **observed intensity (through PGV) was VI.**
The event was correctly classified as a **medium magnitude** event at an **intermediate distance** from the station.

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SismUp

SismUp received the following alert from PRESTo:

- Mag: 3.4, Time: 2024-01-28 09:23:21

The picture shows the screenshot of the app, on a smartphone located at Nocera Inferiore (epicentral distance of 68 km), during the event.

3 smartphones received the alert for this event.
The smartphones were located at Naples, Scafati and Nocera Inferiore.
The smartphones received the warning within an average time of 1.5 s

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Summary

- The 2024, January 28 (ML 3.7, Mw 3.8) Ricigliano earthquake occurred at the northern tip of the 20s segment of the 1980, MS 6.9 earthquake.

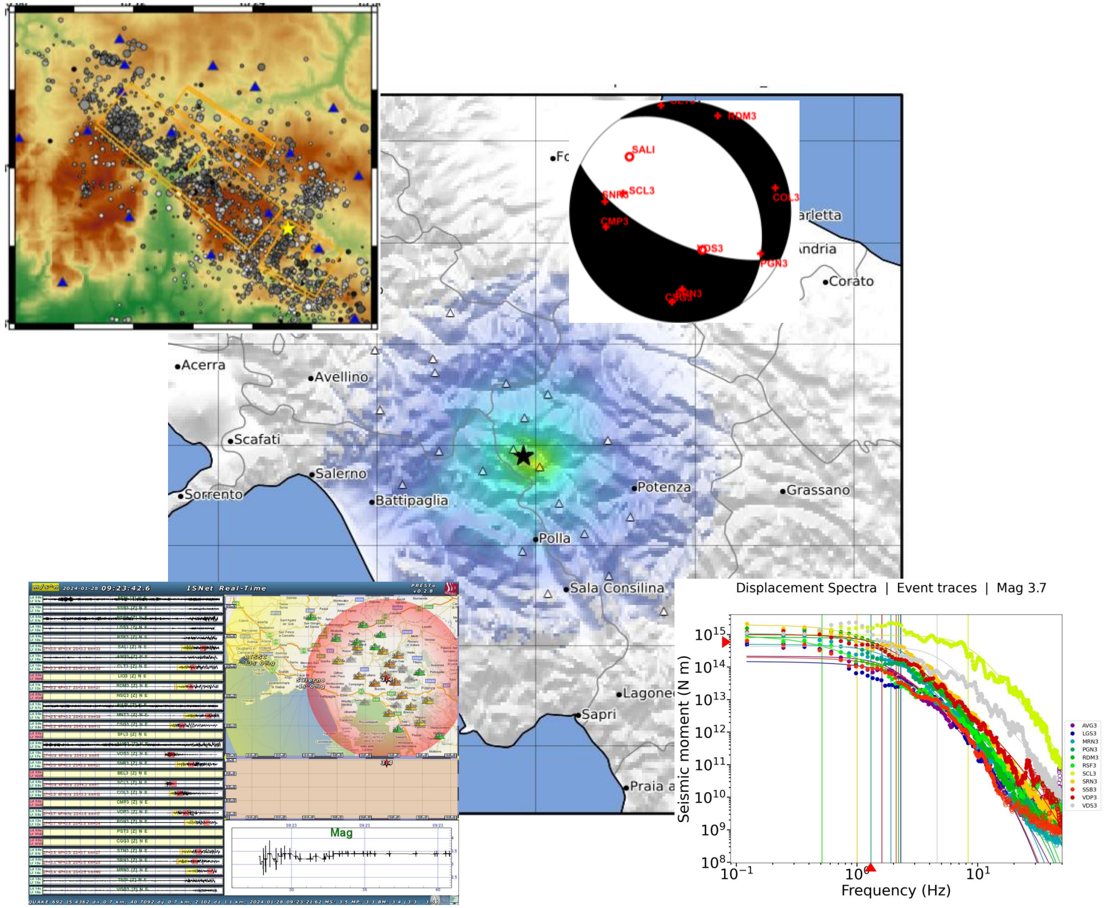
- The event occurred at 09:23 (UTC), 40.7219 lat. and 15.4595 long. at a depth of 4.3 km. The well constrained location (rms of 0.2 s and 500 m of location errors) is in a volume of high density of events, already interested in the past by seismic sequences

- The focal mechanism solution shows a normal faulting. The nodal planes and the source mechanism are consistent with the regional tectonic stress field and the past seismicity.

- Moment magnitude $M_w(3.78 \pm 0.03)$ and corner frequency $(1.29 \pm 0.08)\mathrm{Hz}$ suggest for an involved rupture area around $1.2km^2$, with a stress drop of $(1.1 \pm 0.2)MPa$.

- A maximum Instrumental intensity of VI has been recorded with max recorded PGA $:= 19\%g$ and max PGV$= 3.5\ cm/s$.

- Earthquake early warning testing: the 3 methods (PRESTo, QuakeUP and SAVE) showed a very good performance in terms of first alert (about 4-6 sec after the OT) and impact prediction. QuakeUp is able to estimate the IMM V-VI perceived shaking zone using P-wave after only 4 seconds from the OT. Real time on-site system SAVE allowed to correctly estimate IMM V and related alert level at VDS3 station.



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Useful Links:

ISNet http://isnet.unina.it/

ISNet Bulletin http://isnet-bulletin.fisica.unina.it/cgi-bin/isnet-events/isnet.cgi

CREW: https://lccepos.fisica.unina.it/

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