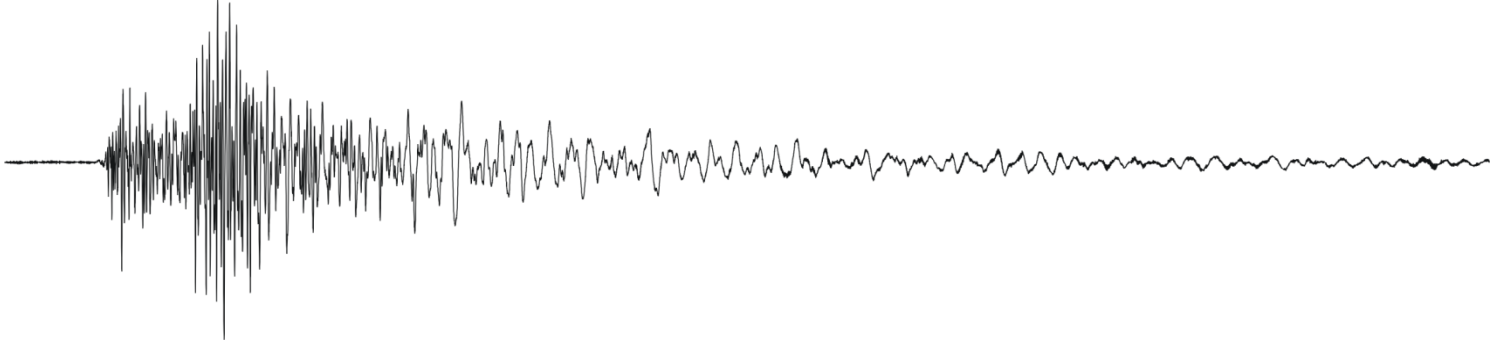


Seismic sequence Rocca San Felice 04-06/07/2020

Gaetano Festa, Guido Maria Adinolfi, Francesco Carotenuto, Alessandro Caruso, Simona Colombelli, Grazia De Landro, Luca Elia, Antonio Emolo, Sergio Gammaldi, Antonio G. Iaccarino, Antonio Iorio, Sahar Nazeri, Rosario Riccio, Guido Russo, Antonio Scala, Matteo Picozzi and Aldo Zollo

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

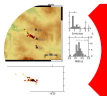
Università degli studi di Napoli Federico II

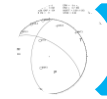
Irpinia Near-Fault Observatory

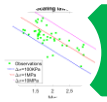
Summary


Data

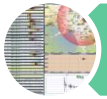

Seismotectonic setting


Location and Refined Catalog

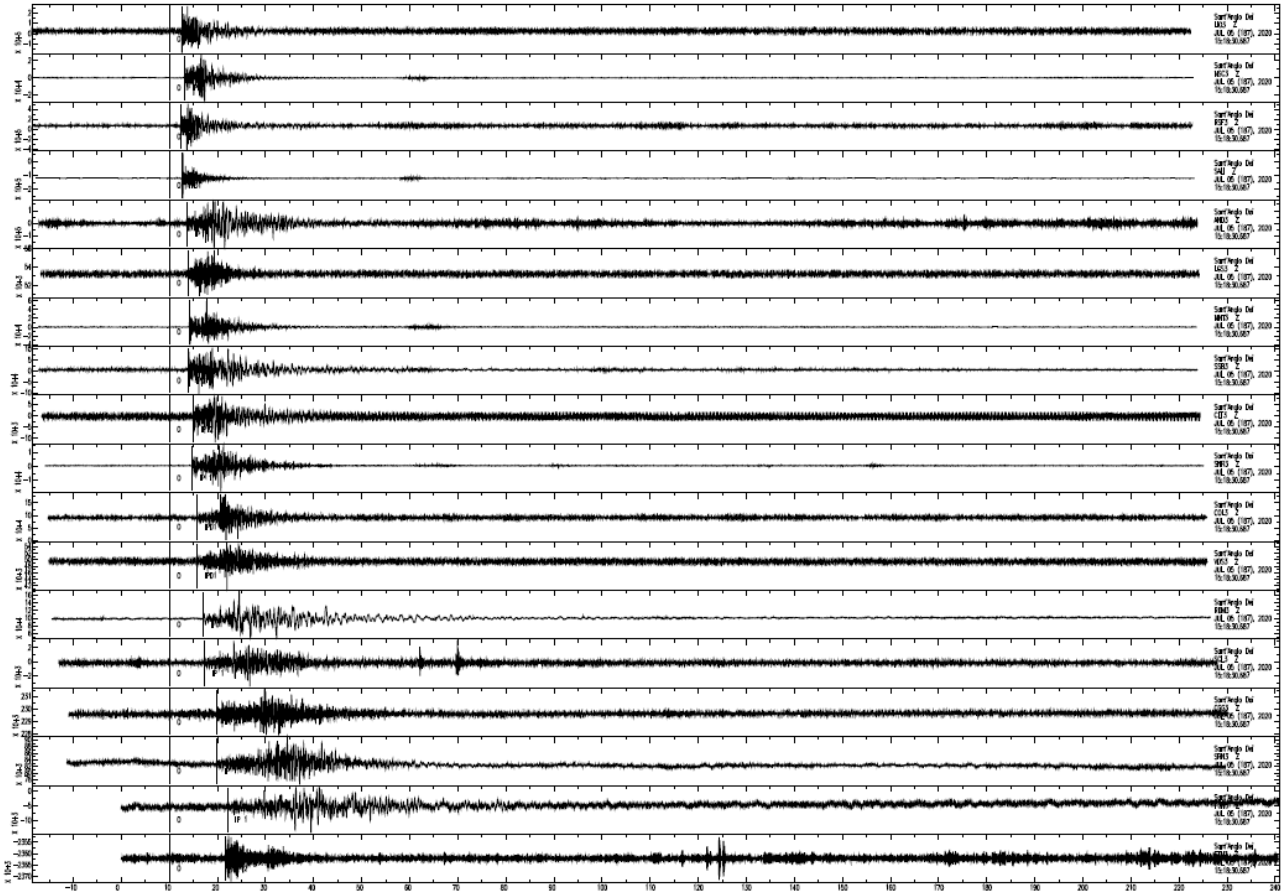

Focal mechanisms


Source Parameters


Ground motion

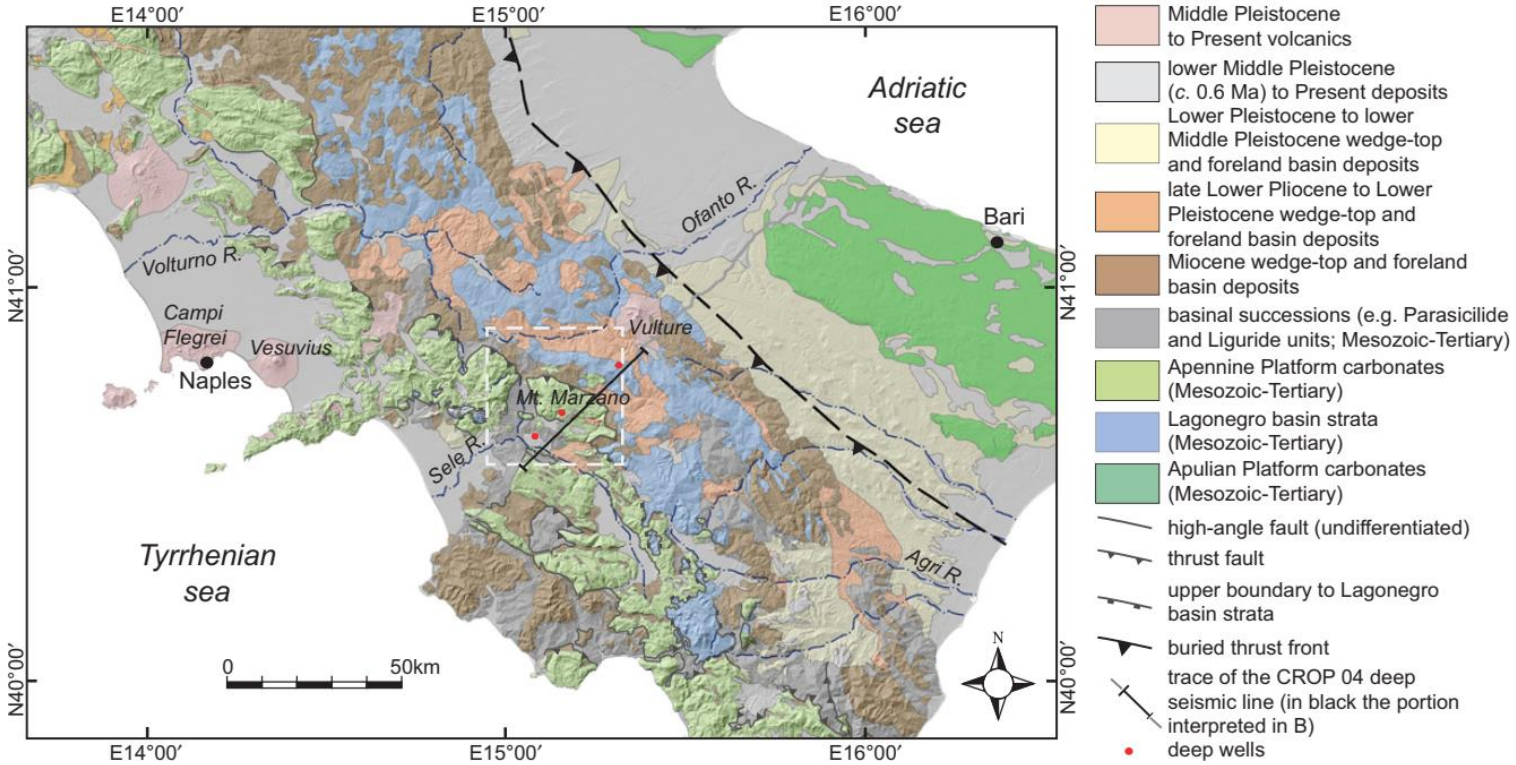

Earthquake Early Warning

Seismic records at ISNet



Here you see an example of **seismic waveforms (vertical component)** recorded at the stations of ISNet, for the event of M2.7, (5/7/2020-15:18) in the distance **range 3-70 km.** Even at the farthest stations the waveforms show a **large signal to noise ratio.**

Geological Setting



The sequence 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 A*scione et al.* (*2013*).

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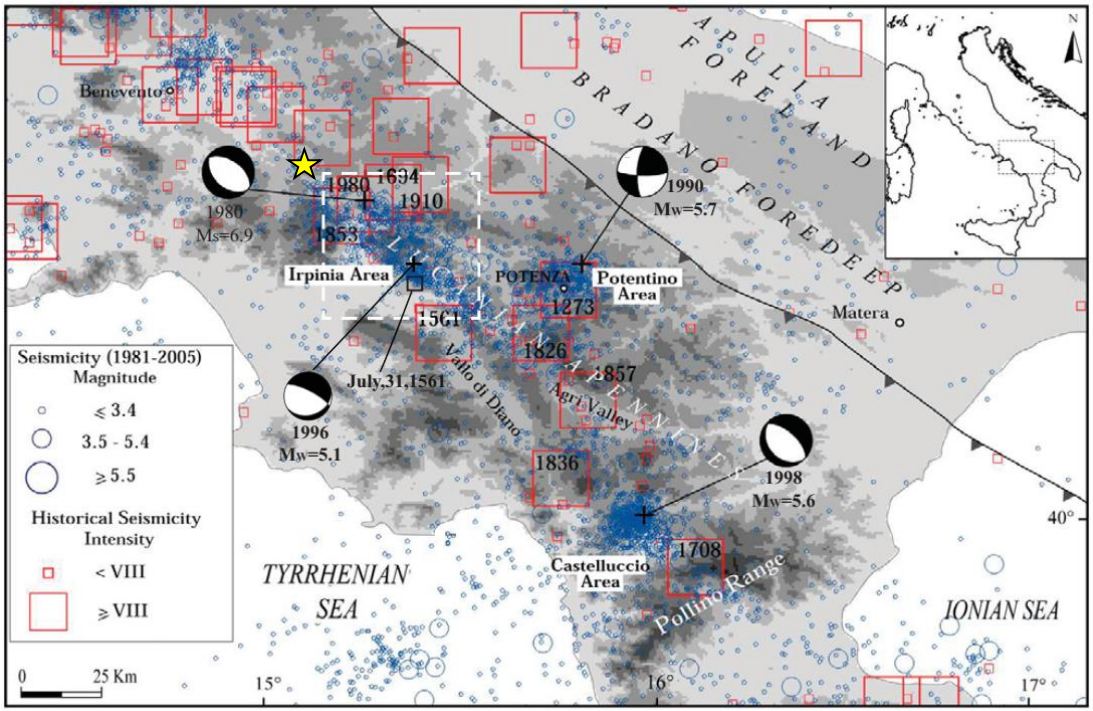
Historical and Instrumental Seismicity



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 Rocca San Felice seismic sequence is indicated by the yellow star.

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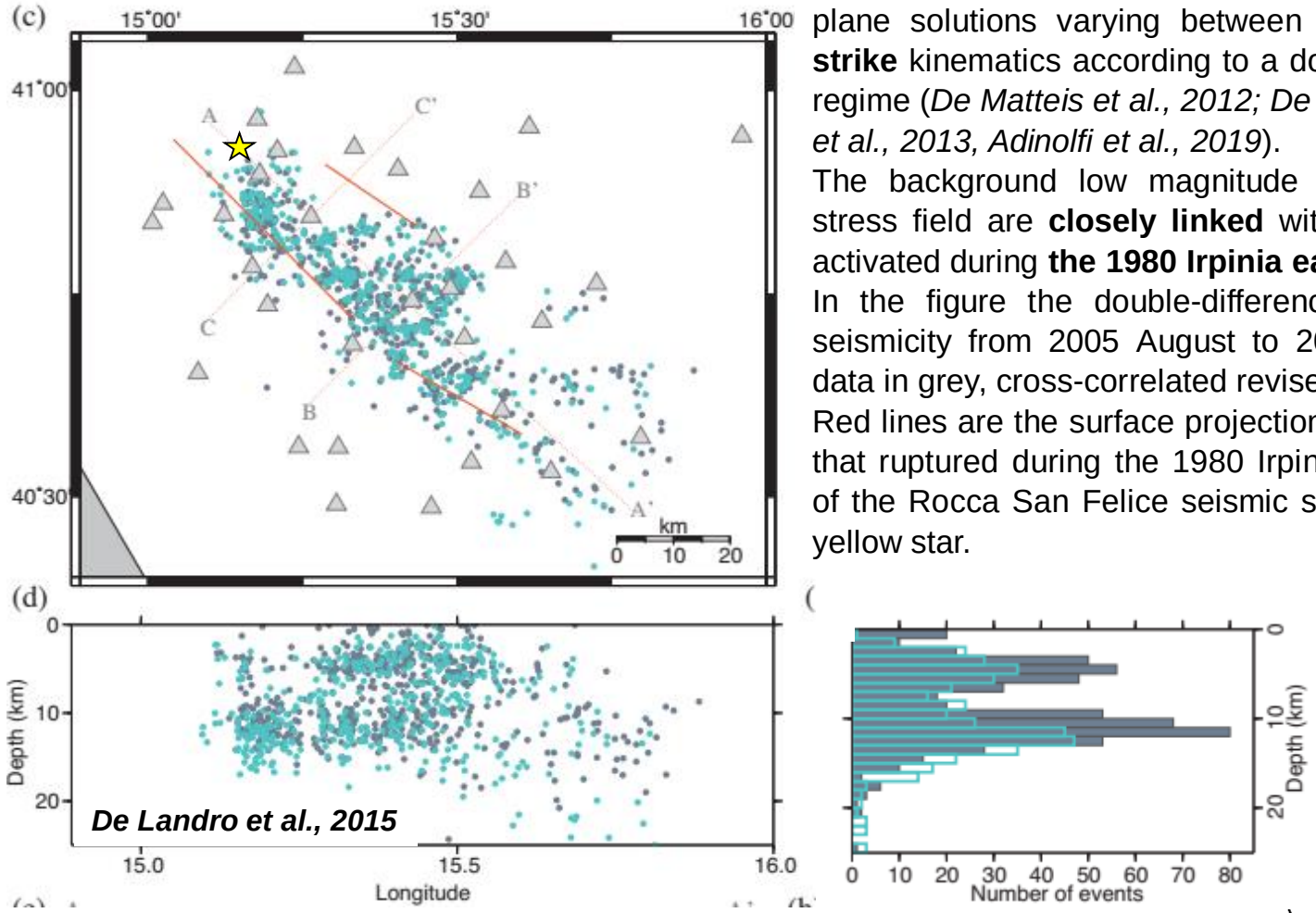
Instrumental Seismicity

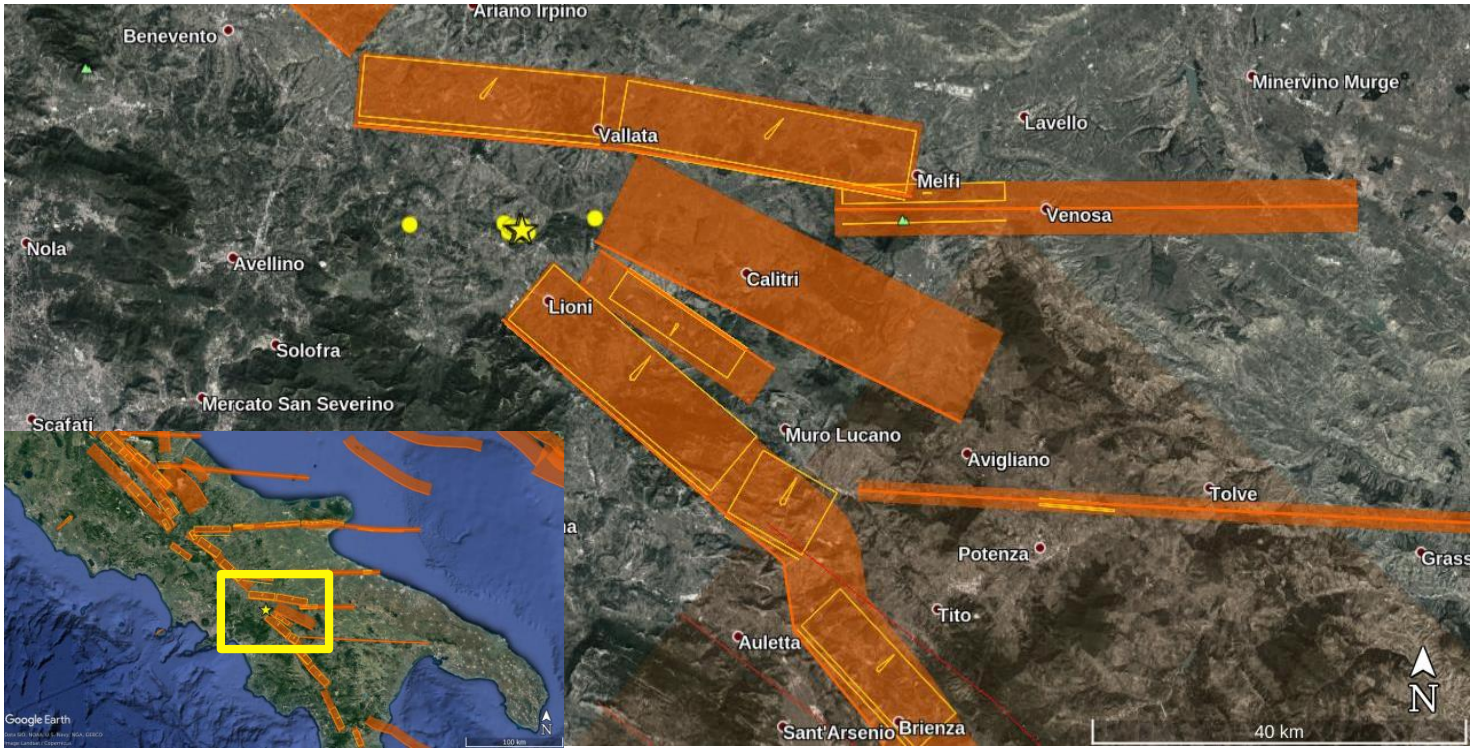
The present-day low-magnitude seismicity (**ML < 3.3**) occurs mainly in the upper 15 km of the crust and shows fault plane solutions varying between **pure-normal** and **normal-strike** kinematics according to a dominant SW–NE extensional regime (*De Matteis et al., 2012; De Landro et al., 2015; Ascione et al., 2013, Adinolfi et al., 2019*).

The background low magnitude seismicity and the related stress field are **closely linked** with the major fault segments activated during **the 1980 Irpinia earthquake**.

In the figure the double-difference earthquake locations of seismicity from 2005 August to 2011 April (manually revised data in grey, cross-correlated revised in turquoise) are reported. Red lines are the surface projection of the three fault segments that ruptured during the 1980 Irpinia earthquake. The location of the Rocca San Felice seismic sequence is indicated by the yellow star.



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*). Rocca San Felice **seismic sequence occurred near the northern 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 seismic sequence is indicated by yellow circles and stars.

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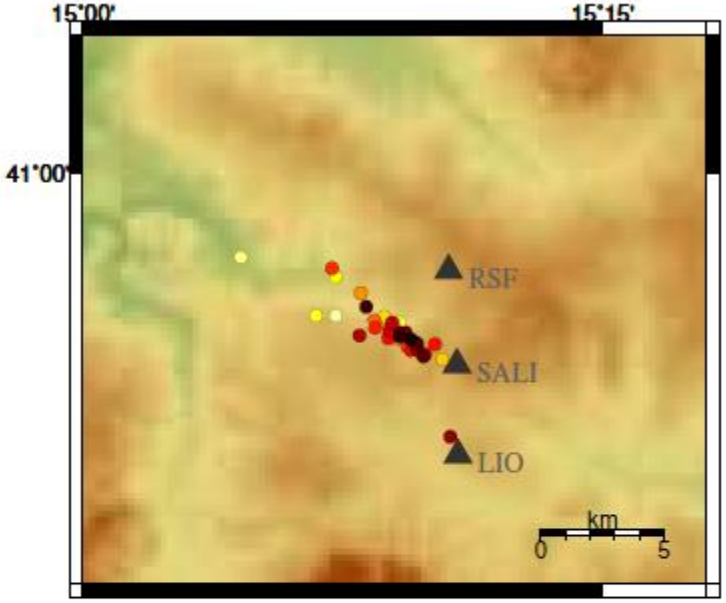
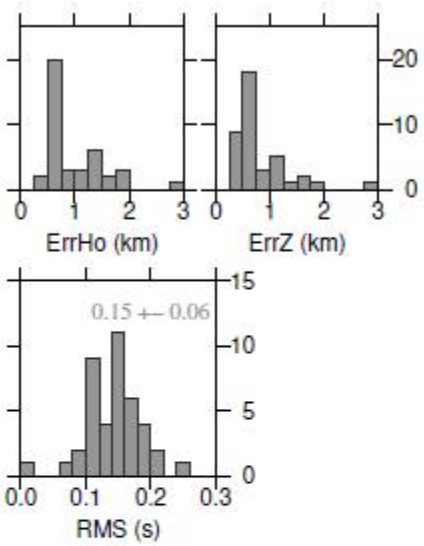
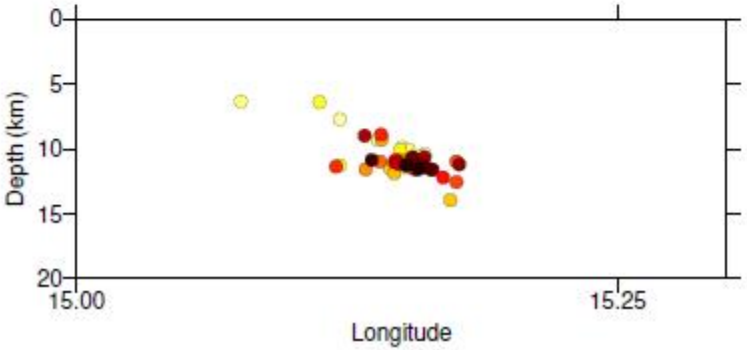
3D Absolute locations







The absolute locations of 43 automatically detected events have been computed using the software **NLLoc** (*Lomax et al., 2009*) . The inversion is performed in the **3D velocity model** for the area (*Amoroso et al., 2014*); P and S picks are manually measured. The color scale in the Figure corresponds to the time occurrence of the events (from yellow-time=0 to red-time=2days). The resulting location shows events distributed along the NW-SE direction, over a narrow zone 4-5 km long. The location errors are within 1 km and RMS residuals within 0.2 s for most of the events.

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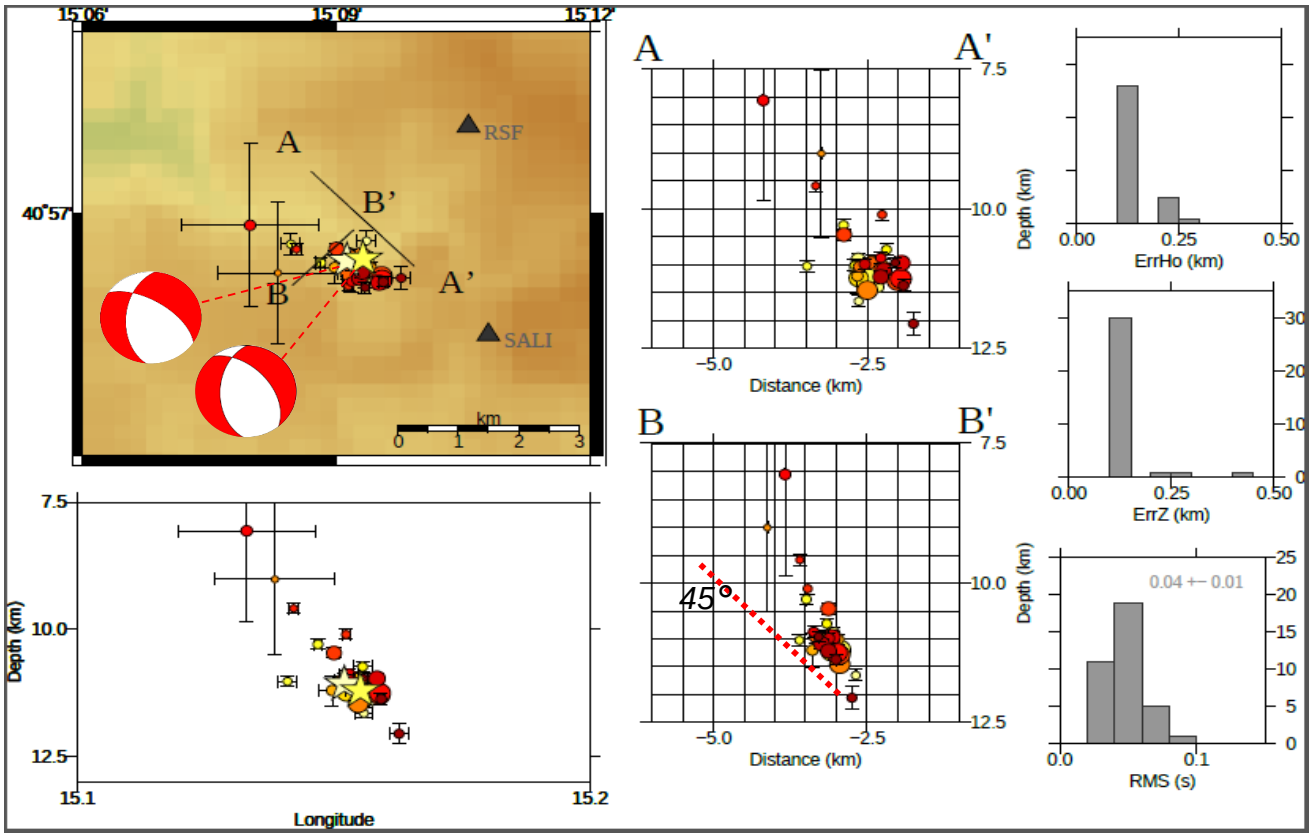
3D Double-Difference locations (1/2)



For this further refined analysis, 36 events have been selected, based on a threshold on the minimum number of picks and the quality of the absolute locations. The **double-difference locations** are obtained with the software **NLDiffLoc** (*De Landro et al., 2015*), in the 3D velocity model for the area (*Amoroso et al., 2014*), using the same manual picks. After relative relocation, events appear more clustered in space and they **clearly identify a NW-SE faulting zone** (extent; 1.5 km along-strike, 2 km along-dip) having an approximate **dip of 45°** (see sect BB')

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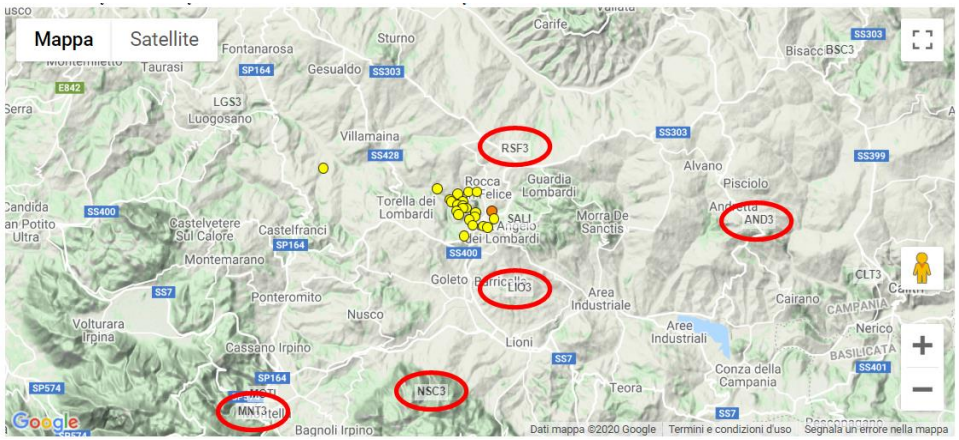
3D Double-Difference locations (2/2)

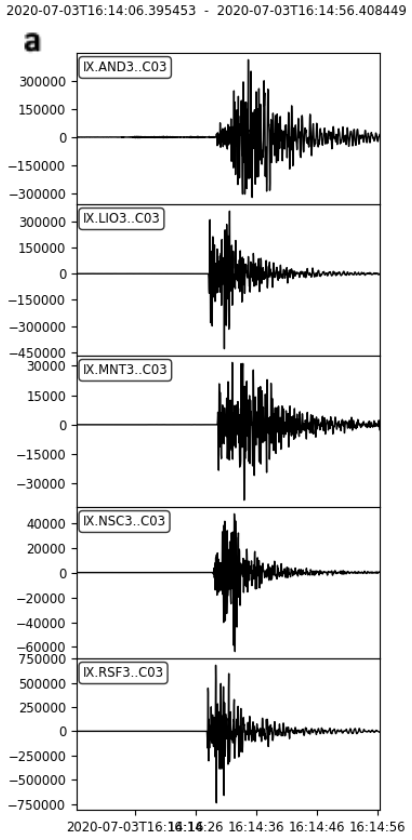
Main hints from the refined event location

- Events are clustered with an extension of the pattern **covering a size of 2-3 km** and an alignment in **the NW-SE** direction.
- Event depths are between **10 km and 12.5 km**. In section, the events clearly delineate a fault plane with a dip **of about 45°** and NE immersion.
- This result is **consistent with the focal mechanisms** of the two largest events and enables for plane selection (see slide 19 and following).
- Location errors are within **few hundred meters** for most of the events and **rms are within 0.1 s**

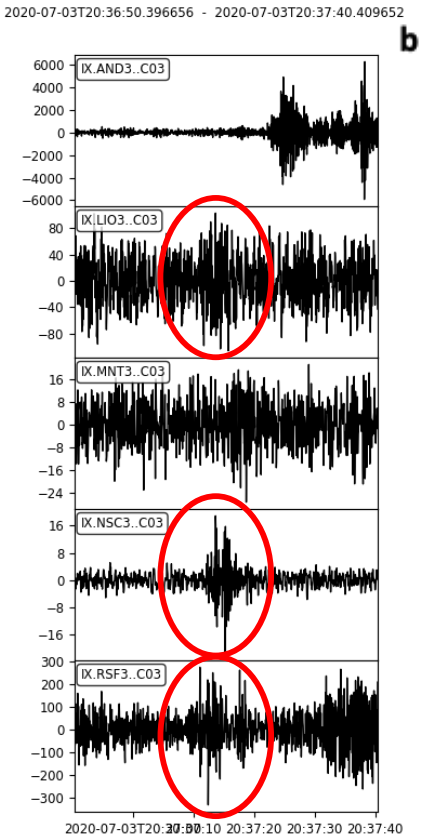
FAST catalog (1/2)



The automatic system of the network detected 43 events. We explored the **continuous helicorder** through the autocorrelation algorithm **FAST** (*Yoon et al., 2015, Bergen & Beroza 2018*) to improve the detection of microearthquakes. We used the vertical component of the velocimeters at **5 stations with a distance ranging from about 3 km to 17 km** from the sequence centroid. We retrieved **342 events** detected at least at 2 stations with a local magnitude ranging from **0.0 to 3.0**. On the right the waveforms for the main event (panel a - M 3.0 07/03 16:14:25) and for an event of M 0.0 (panel b Ml=0.0 07/03 20:37:00).



Main event – M=3.0
Declared at 5 stations



Event Ml=0.0
Declared at 3 stations

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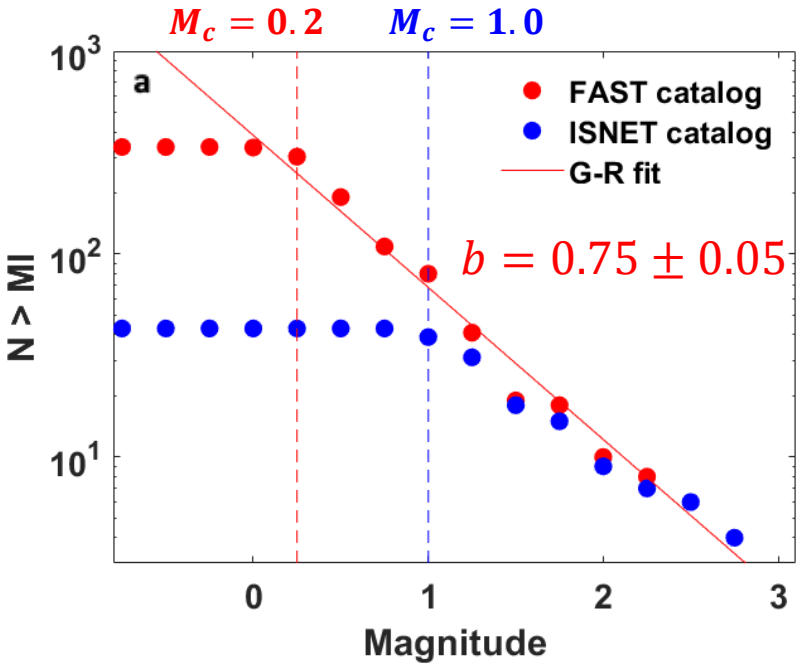
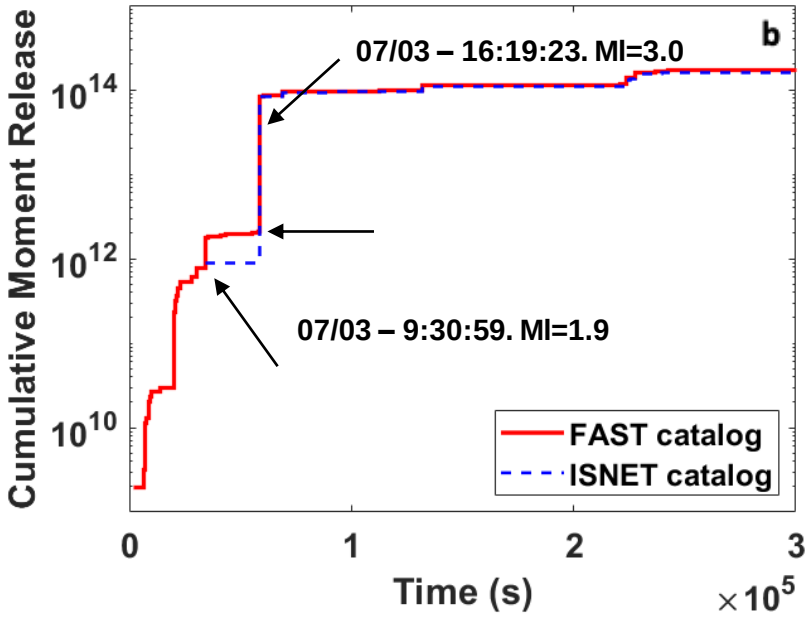
FAST catalog (2/2)





We investigated the **magnitude-frequency distribution** for the refined catalog, comparing it with the ISNET automatic catalog (panel a). We estimated a **magnitude of completeness of 0.2**, almost 1 unit smaller than the value from the automatic detections (1.0). We also reported the **b-value** estimate of **b=0.75±0.05** This is significantly larger than the value inferable from the automatically detected events (0.57±0.03). The latter estimate cannot be considered a robust estimate due to the scarcity of events. **The cumulative seismic moment release** (panel b) is not significantly different for the two catalogs yielding an equivalent **total magnitude of M 3.5.** However, we can recognize a sequence of events preceding the two largest (ML 3) events in the sequence, started about **14 hours before** the first event detected by the automatic procedures of ISNet (Ml=1.9 – 23 events).

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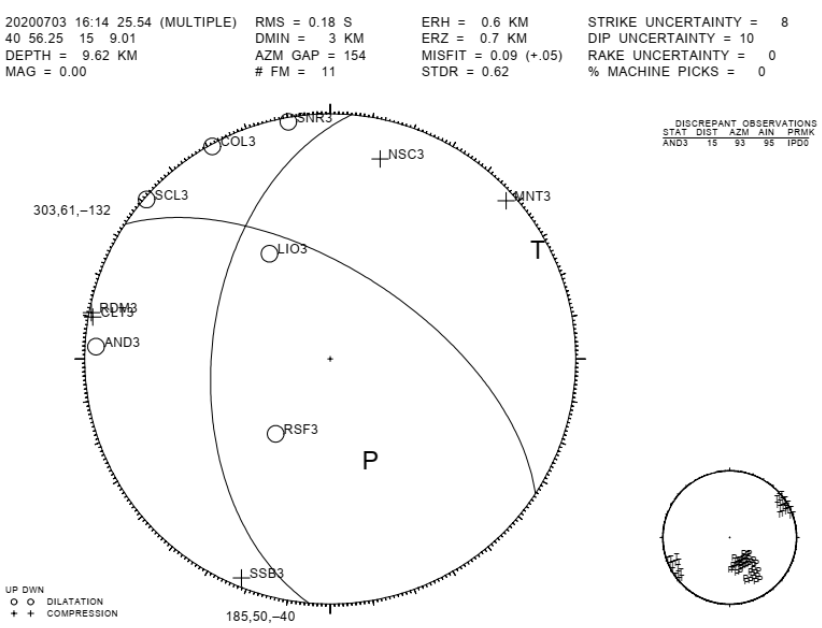
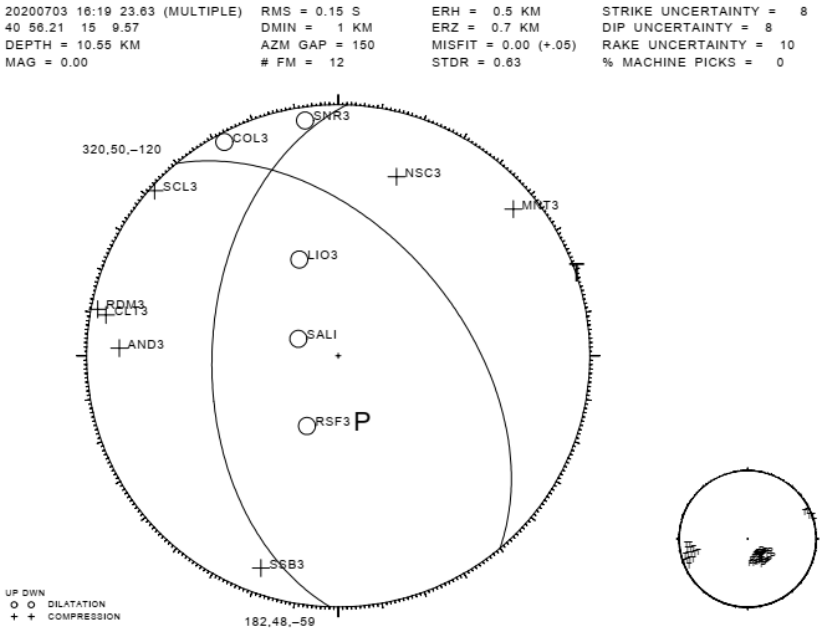
Focal Mechanisms



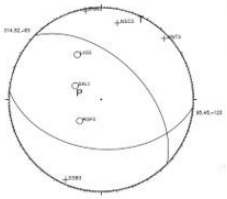
2020-07-03 16:14
ML 3.0



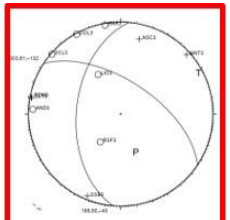
2020-07-03 16:19
ML 3.0

We computed the focal mechanism solutions from inversion of **P-wave polarities** using the FPFIT code (*Rosenberg and Oppenheimer, 1985*). The solutions for the two main earthquakes of the sequence are shown in the Figure. The solutions show a similar **normal-fault kinematics** with a minor strike-slip component. The entire set of solutions is shown in the following slide.

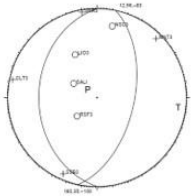
Focal Mechanism Catalog



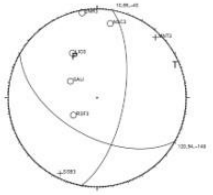
2020-07-03 09:30
ML 1.9



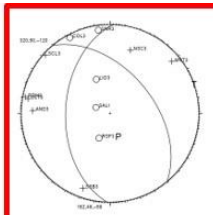
2020-07-03 16:14
ML 3.0



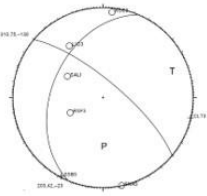
2020-07-03 16:18:11
ML 1.9



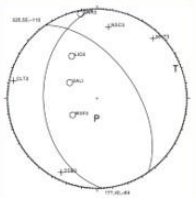
2020-07-03 16:18:55
ML 1.4



2020-07-03 16:19
ML 3.0



2020-07-03 18:00
ML 1.2



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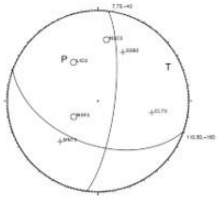
ML 2.6



2020-07-03 19:47
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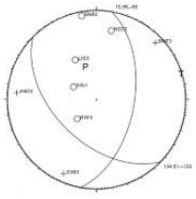
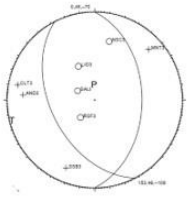


2020-07-03 20:50
ML 1.6



2020-07-04 00:44
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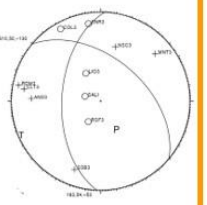
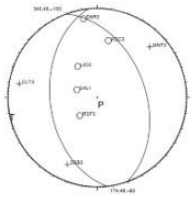
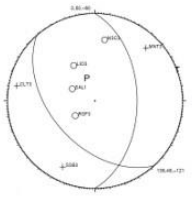


2020-07-04 12:34
ML 2.7



2020-07-05 13:23
ML 1.8



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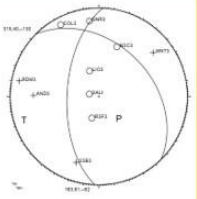

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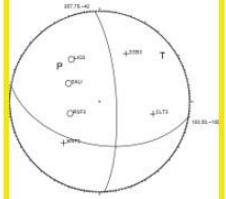

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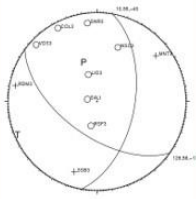

2020-07-05 15:18
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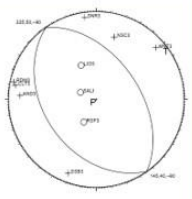

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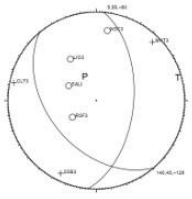

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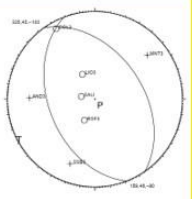
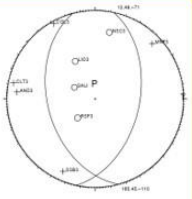
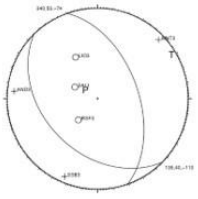


2020-07-05 19:12
ML 2.1



2020-07-05 19:19
ML 2.1



2020-07-06 05:18
ML 1.4

ML = 3.0

2.5 <ML <3.0

2.0 < M_L < 2.5

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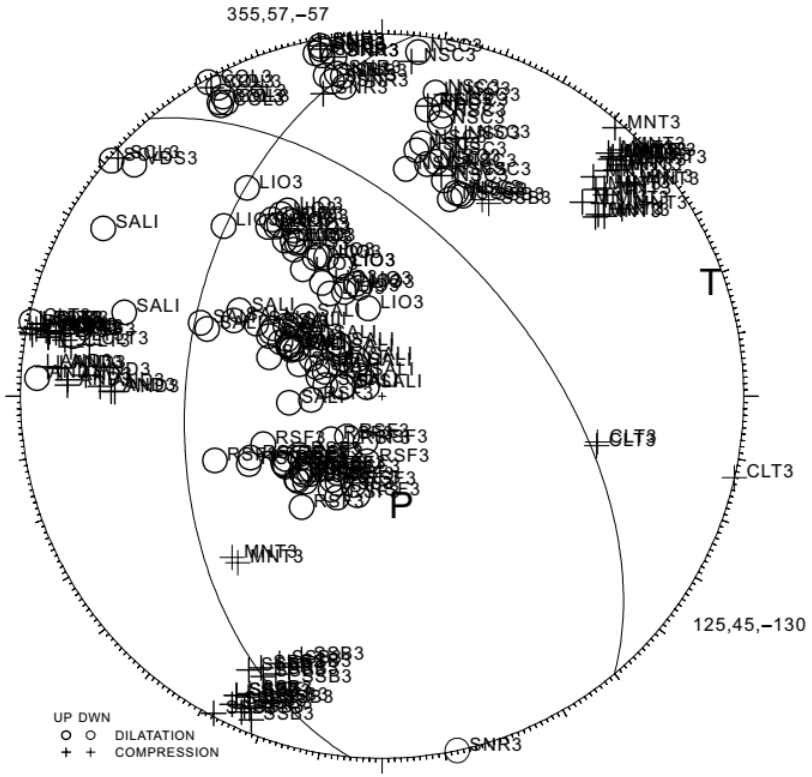
Composite Focal Mechanisms



Station	Polar.	No.	Polar.	No.
AND3	*UP*	9	*DOWN*	1
CLT3	*UP*	16	*DOWN*	1
COL3	*UP*	1	*DOWN*	6
LIO3	*UP*	0	*DOWN*	30
MNT3	*UP*	27	*DOWN*	0
NSC3	*UP*	8	*DOWN*	18
RDM3	*UP*	6	*DOWN*	0
RSF3	*UP*	1	*DOWN*	33
SALI	*UP*	0	*DOWN*	38
SCL3	*UP*	1	*DOWN*	1
SNR3	*UP*	4	*DOWN*	11
SSB3	*UP*	22	*DOWN*	0
VDS3	*UP*	0	*DOWN*	1

We finally computed **a composite focal mechanism** solution from the inversion of P-wave polarities for the two main earthquakes of the sequence. On the same focal sphere, we represent all the **available 235 polarities**. We see that some stations show a change in the polarity along the sequence: these stations are near the focal planes and constrain the mechanism.

Focal Mechanisms - Summary

- **21 fault plane solutions** are computed from the inversion of P-wave polarities for earthquakes with magnitude ranging between 1.2 and 3.0.

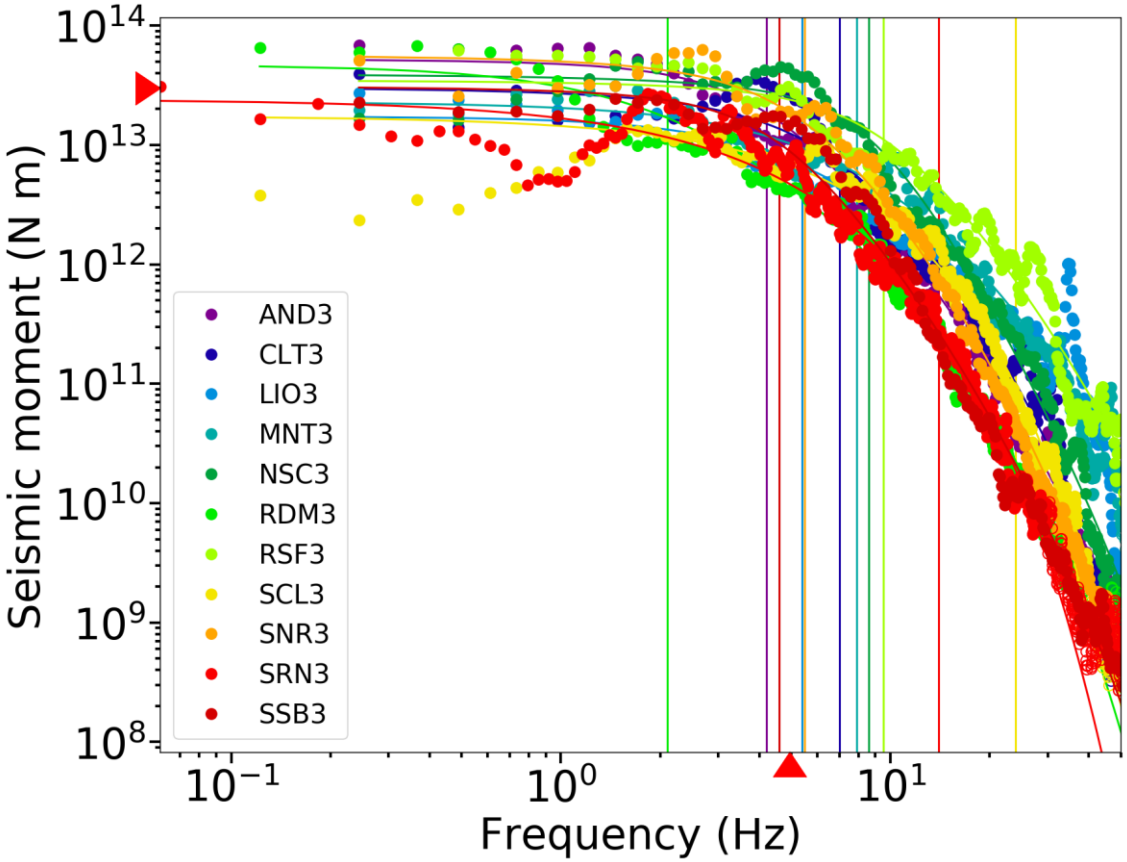
- Fault plane solutions show **normal fault kinematics** with a minor, variable strike-slip component. Despite the uncertainty of the solutions due to the small number of available data and the small size of the events, a good agreement between the solutions can be noted.

- A large group of seismic stations show the same P-wave polarity highlighting a similar rupture kinematics and fault plane geometry during the evolution of seismic sequence.

- Focal mechanism solutions of the main earthquakes show the activation of a **NW-SE striking** fault structure **with 50°-60° dip**, in a good agreement with seismogenic sources of the Irpinia region.

- Considering the earthquake locations of the seismic sequence, **the NE-dipping nodal plane can be considered as the preferential plane** along which the seismic sequence originated. In fact, its geometry is in good agreement with spatial hypocentre distribution.

Source Parameters – SPAR (1/3)



Source parameters have been computed for the 43 events of the sequence, automatically detected by the ISNet management system. **Displacement amplitude spectra** from observations have been modelled using a generalized Brune source model, through the software **SPAR** (*Supino et al., 2019*). For the event in the Figure we estimated an average moment magnitude of Mw=2.91 ±0.02, a corner frequency of fc=5.0 ±0.2 Hz and a spectral fall-off of gamma=2.42 ±0.04.

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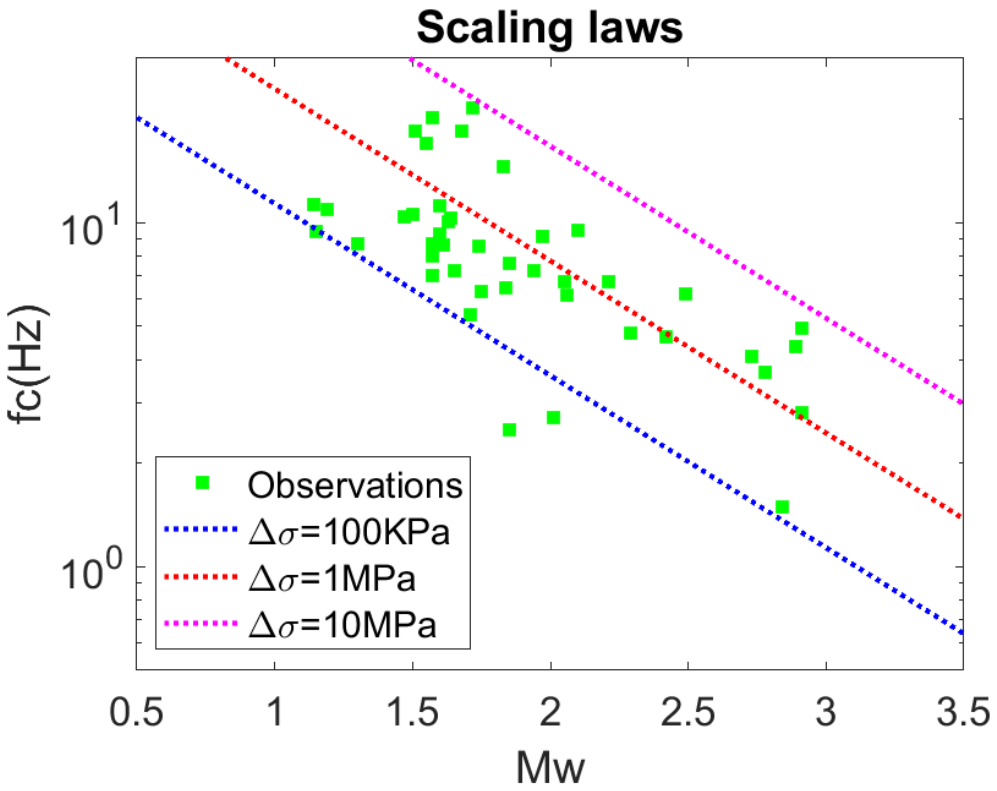
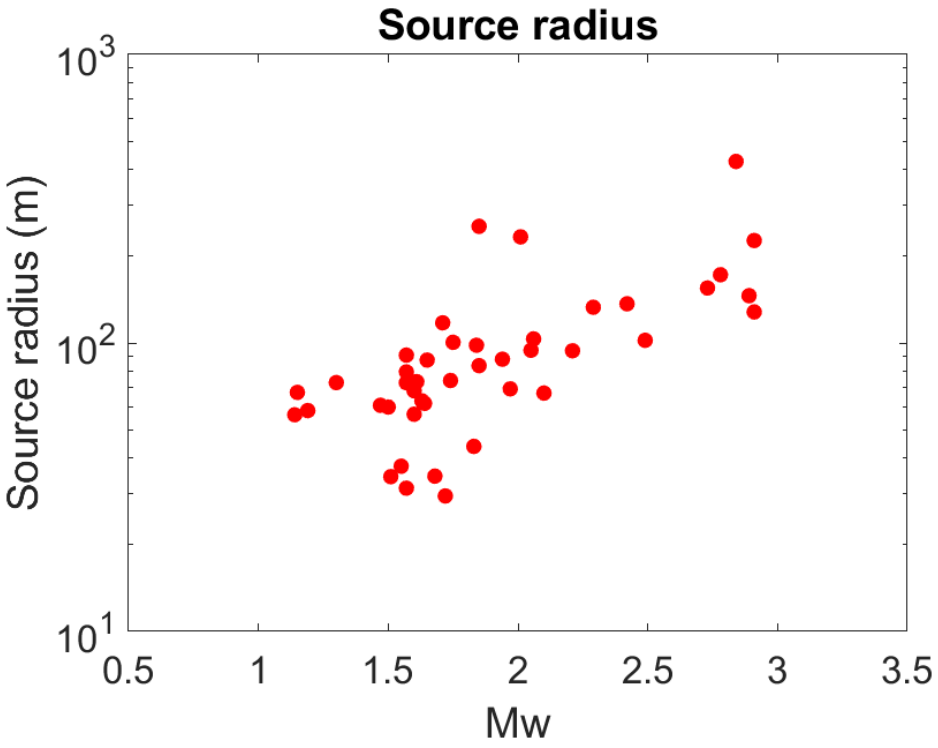
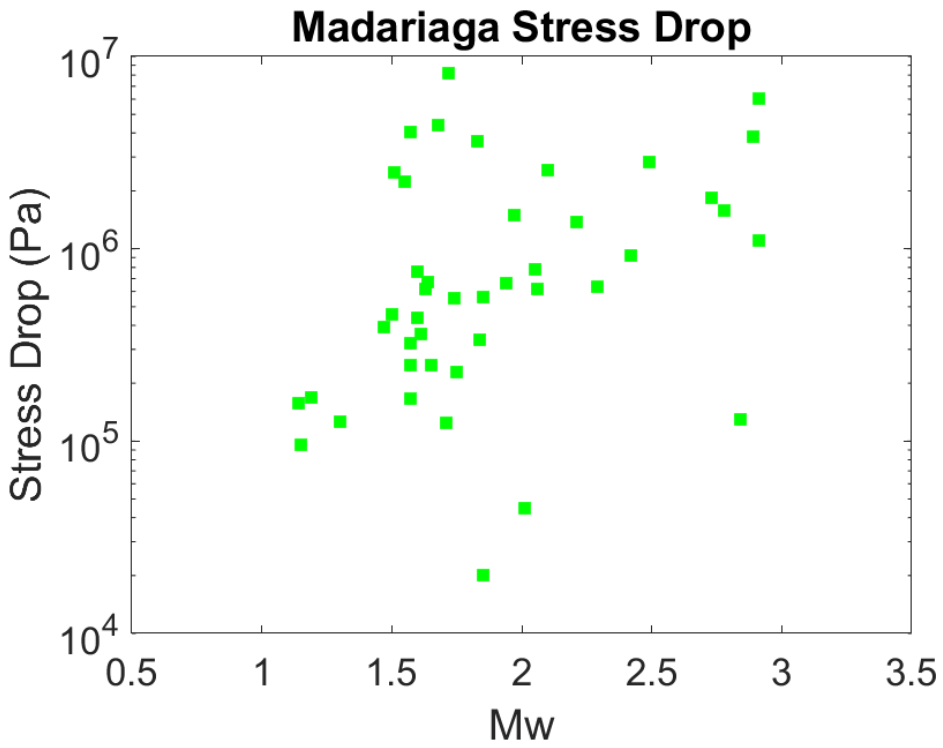
Source Parameters – SPAR (2/3)



The corner frequency vs Mw plot shows that the **self-similarity can be assumed for the sequence**, with an average stress drop of **0.64 MPa**. The stress drop has been computed using the circular rupture model of Madariaga. For the main events in the sequence, the stress drop is larger: we found **an average stress drop of 1.0 MPa** for events with magnitude **M>2**. For small magnitude events, the estimation of the corner frequency can be affected by the limited bandwidth and the anelastic attenuation effect.

Source Parameters – SPAR (3/3)

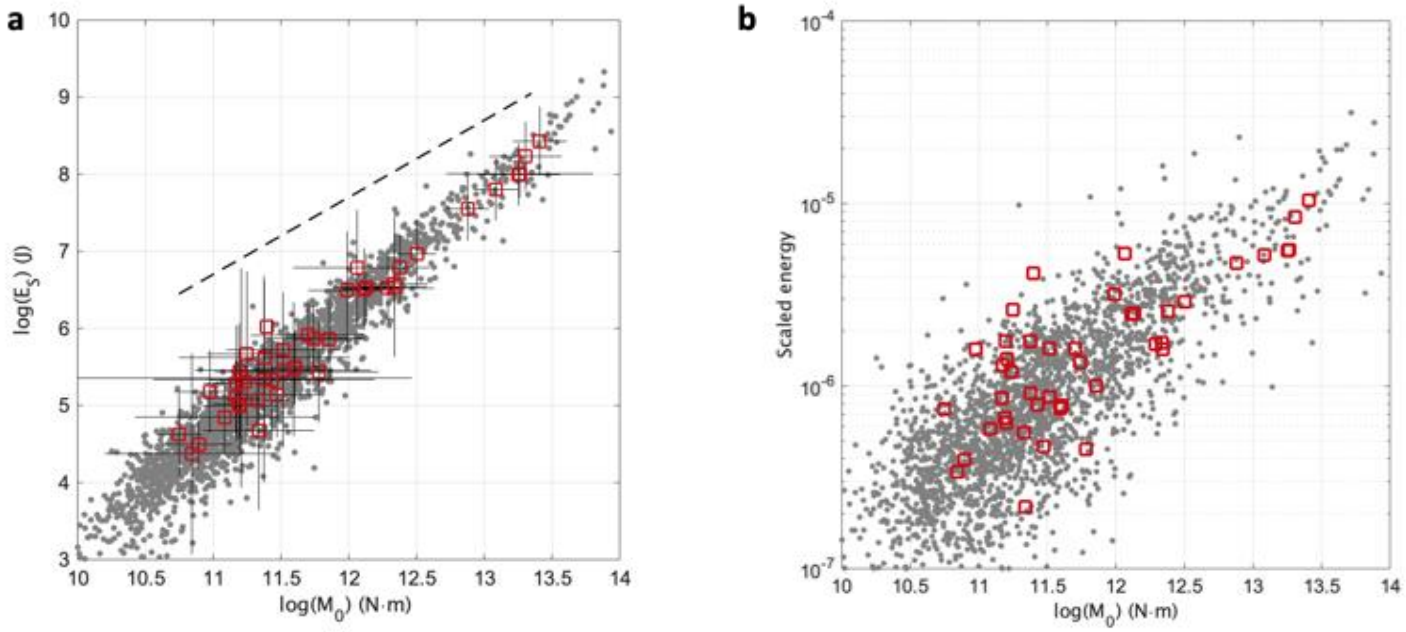




We found that the source radius ranges from **150-400 m** for the largest magnitude events in the sequence and between **30-60 m for a M1.5 events**. The stress drop plot in the right panel shows scattered points (over about two orders of magnitude) , with no specific trend with moment magnitude.

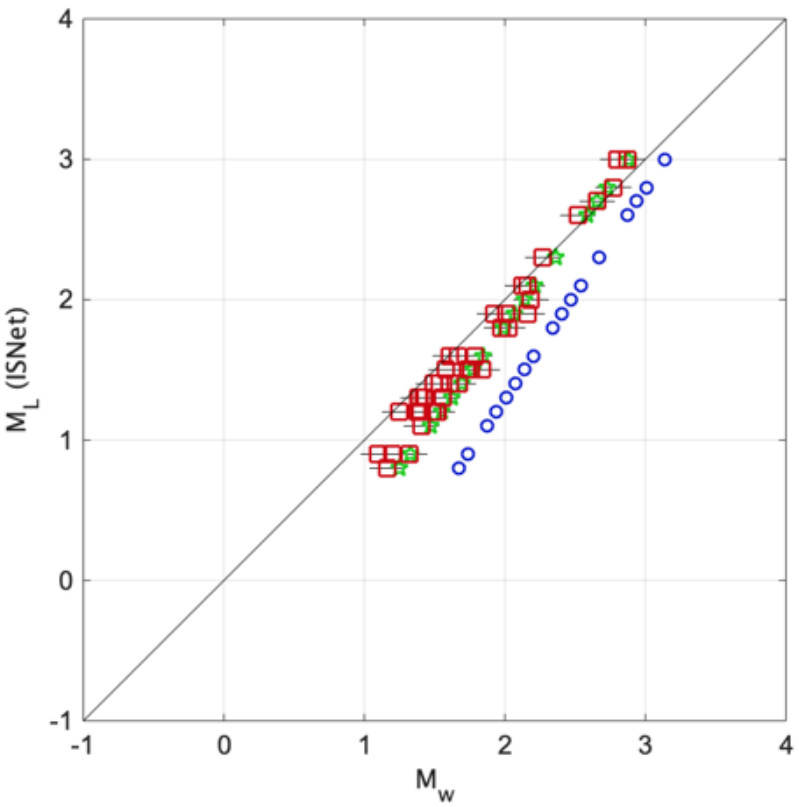
Source Parameters – TimeFit (1/2)

We have also estimated M_0 and E_S from the S-wave time windows applying the procedure in the time domain proposed by *Picozzi et al.* (*2018*) and (*2019*). **The energy-to-moment scaling** observed for the sequence is in good agreement with values estimated for the Irpinia seismicity. Figure (a) shows that the seismicity of the present sequence exhibits **smaller stress-drop** than that assumed by Kanamori as global average (from 2 to 6 MPa, dashed line): the diverse slope here suggests a possible deviation from self-similar behavior. Also the scaled energy increases as a function of the M_0 (Figure b).



Source Parameters – TimeFit (2/2)

We finally computed the **moment magnitude** (M_w) for the earthquakes of the sequence and compared these estimates with the **local magnitude** (M_L) from ISNet bulletin. As shown in the Figure to the side, the **M_L- M_w** scaling is linear but does not follow a 1:1 line. If we compute theoretical M_w values from ML using a model calibrated by *Malignini and Munafò* (*2018*), for Italy (blue dots), we observe a deviation from experimental data. On the contrary, these latter are in very good agreement with theoretical values obtained starting from M_L, and using the relation calibrated by *Bobbio et al.* (*2009*) for the Irpinia region. These results suggest that M_0 estimates are robust. Also the moment magnitude **shows a +0.2 shift** with respect to the local magnitude at small magnitudes (1<M<2)



Source Parameters

Hints from source parameters

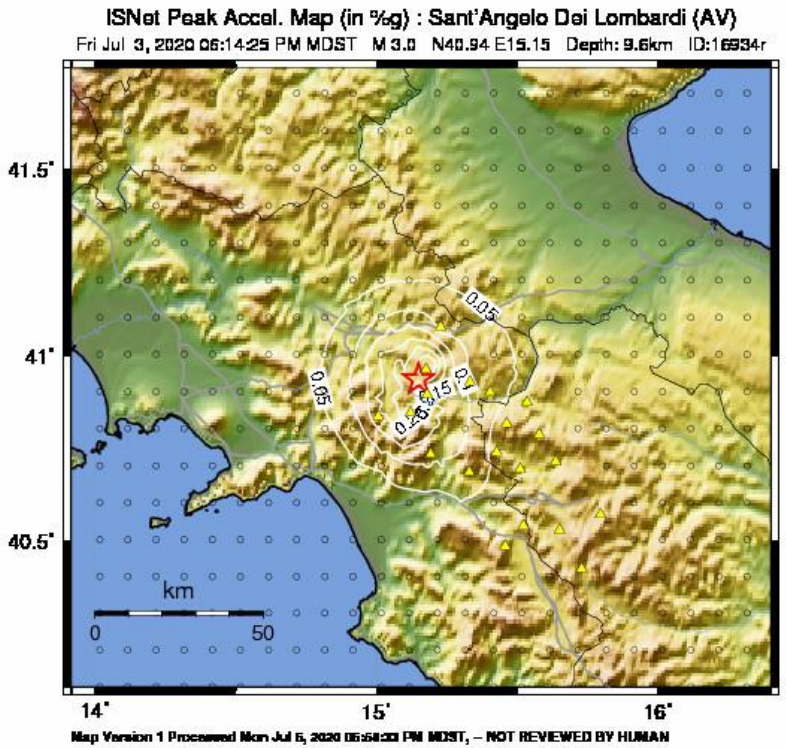
- Events show corner frequencies that scale with seismic moment. For M>2 the scaling is consistent with self-similarity and an average stress drop of **1.0 MPa. W**hen including all the events, the average stress drop is 0.64 MPa.

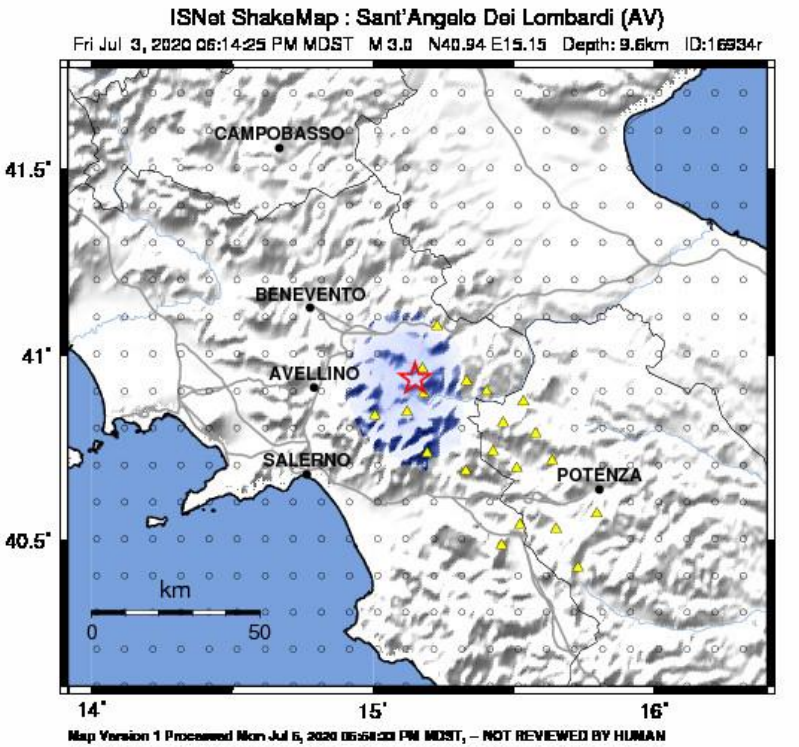
- Source radius ranges between **30-60m for a M1.5** event and **150-400 m for a M 3** event.

- **Radiated energy increases with seismic moment** at a faster rate than global average estimates, and **at lower dynamic stress drops**.

- **Moment magnitude** of the events is consistent with **local magnitude**, with a **0.2 shift** at small magnitudes.

PGA-Intensity – ShakeMap – M3.0
3/7/20 – 16:14





PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-8.2	8.2-16	16-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Here we represent the PGA and Intensity maps computed with ShakeMap software for the M3.0 event (3/7/2020 at 16.14). The plots **show maps slightly elongated** along the NS direction, indicating a source/path effect

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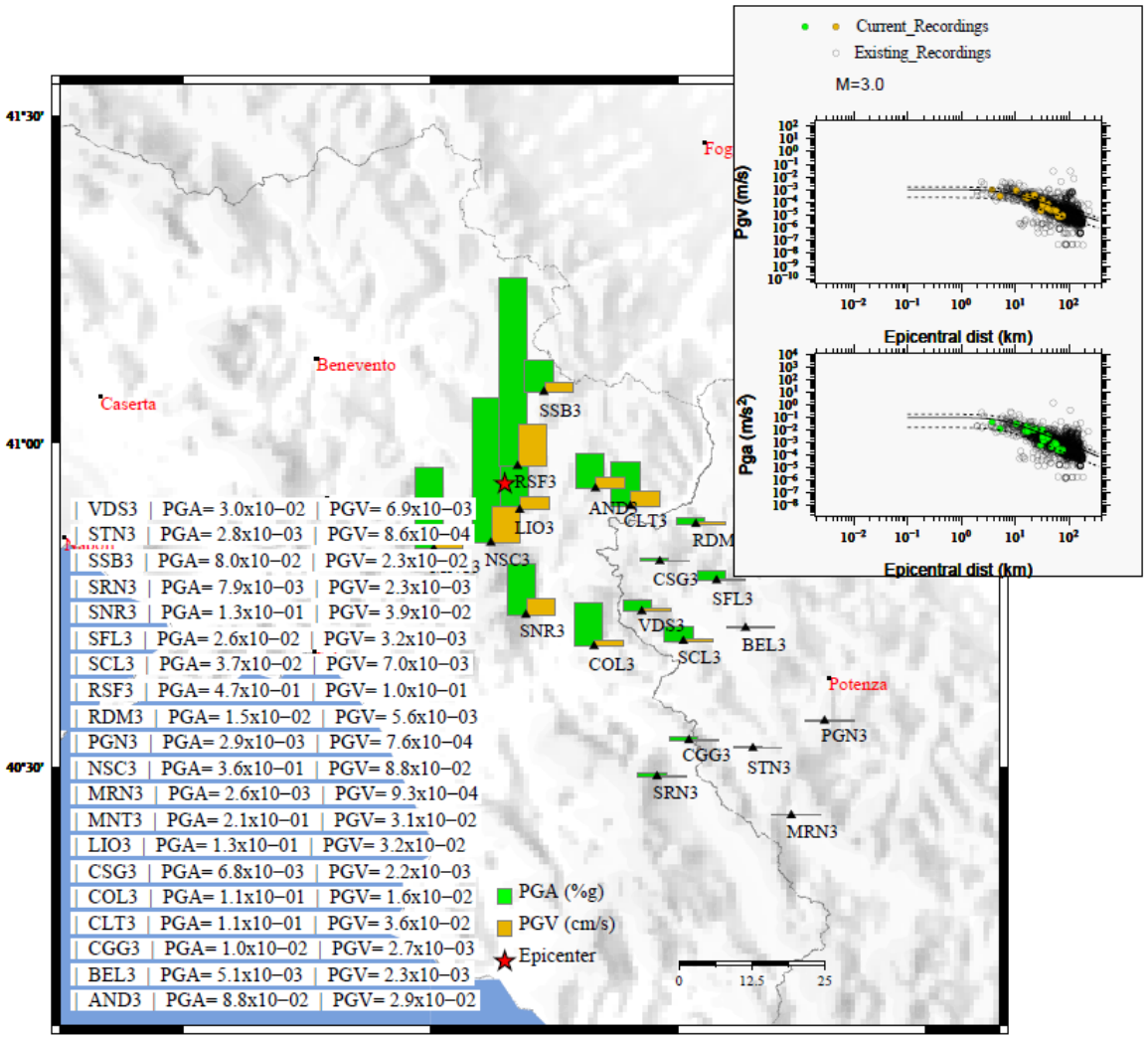
GMPE - M3.0
3/7/20 – 16:14



VDS3	PGA= 3.0x10−02	PGV= 6.9x10−03
STN3	PGA= 2.8x10−03	PGV= 8.6x10−04
SSB3	PGA= 8.0x10−02	PGV= 2.3x10−02
SRN3	PGA= 7.9x10−03	PGV= 2.3x10−03
SNR3	PGA= 1.3x10−01	PGV= 3.9x10−02
SFL3	PGA= 2.6x10−02	PGV= 3.2x10−03
SCL3	PGA= 3.7x10−02	PGV= 7.0x10−03
RSF3	PGA= 4.7x10−01	PGV= 1.0x10−01
RDM3	PGA= 1.5x10−02	PGV= 5.6x10−03
PGN3	PGA= 2.9x10−03	PGV= 7.6x10−04
NSC3	PGA= 3.6x10−01	PGV= 8.8x10−02
MRN3	PGA= 2.6x10−03	PGV= 9.3x10−04
MNT3	PGA= 2.1x10−01	PGV= 3.1x10−02
LIO3	PGA= 1.3x10−01	PGV= 3.2x10−02
CSG3	PGA= 6.8x10−03	PGV= 2.2x10−03
COL3	PGA= 1.1x10−01	PGV= 1.6x10−02
CLT3	PGA= 1.1x10−01	PGV= 3.6x10−02
CGG3	PGA= 1.0x10−02	PGV= 2.7x10−03
BEL3	PGA= 5.1x10−03	PGV= 2.3x10−03
AND3	PGA= 8.8x10−02	PGV= 2.9x10−02

When we represent the peak amplitudes (**PGA and PGV**) for the stations, we observe maximum peak amplitudes for stations nearby the epicenter. Along the Apennine direction, south of the epicentre, the peak amplitudes are larger than in the Anti-Apennine direction. On average **peak amplitudes match the GMPEs** retrieved for the area (*Emolo et al., 2011)*. However, PGV values show a faster decrease with amplitude, likely owing to larger attenuation.

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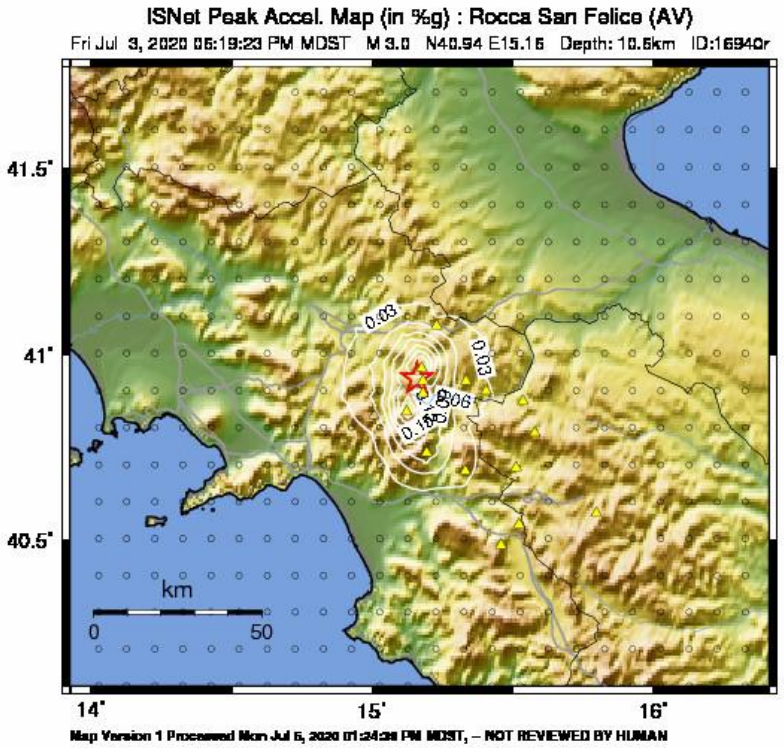
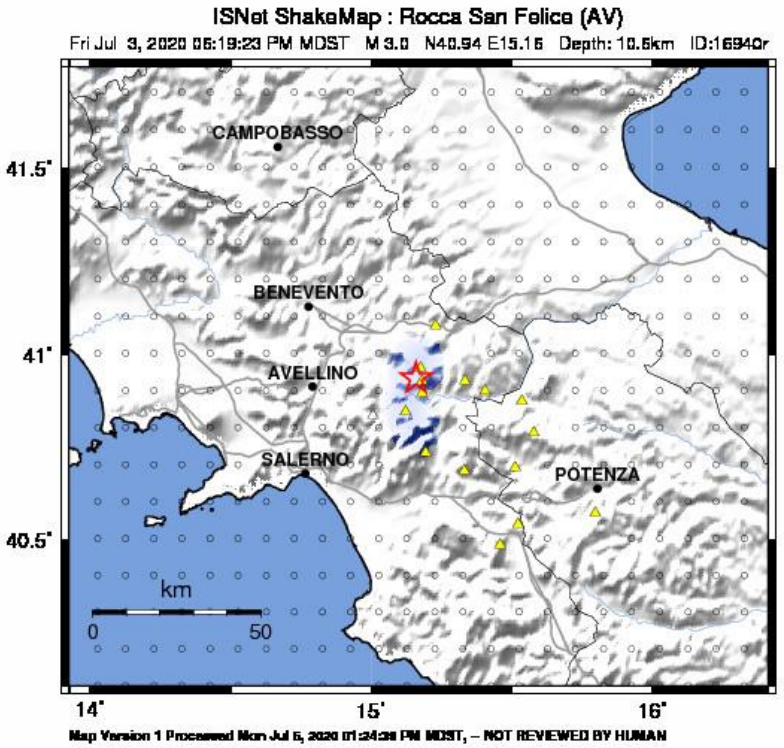
PGA-Intensity – ShakeMap – M3.0
3/7/20 – 16:19





PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

When analysing the ground motion for the other M 3.0 event (3/7/20 16:19), both PGA and Intensity maps computed with ShakeMap software **show maps elongated** along the NS direction, and a smaller amplitude than for the previous event of same magnitude.

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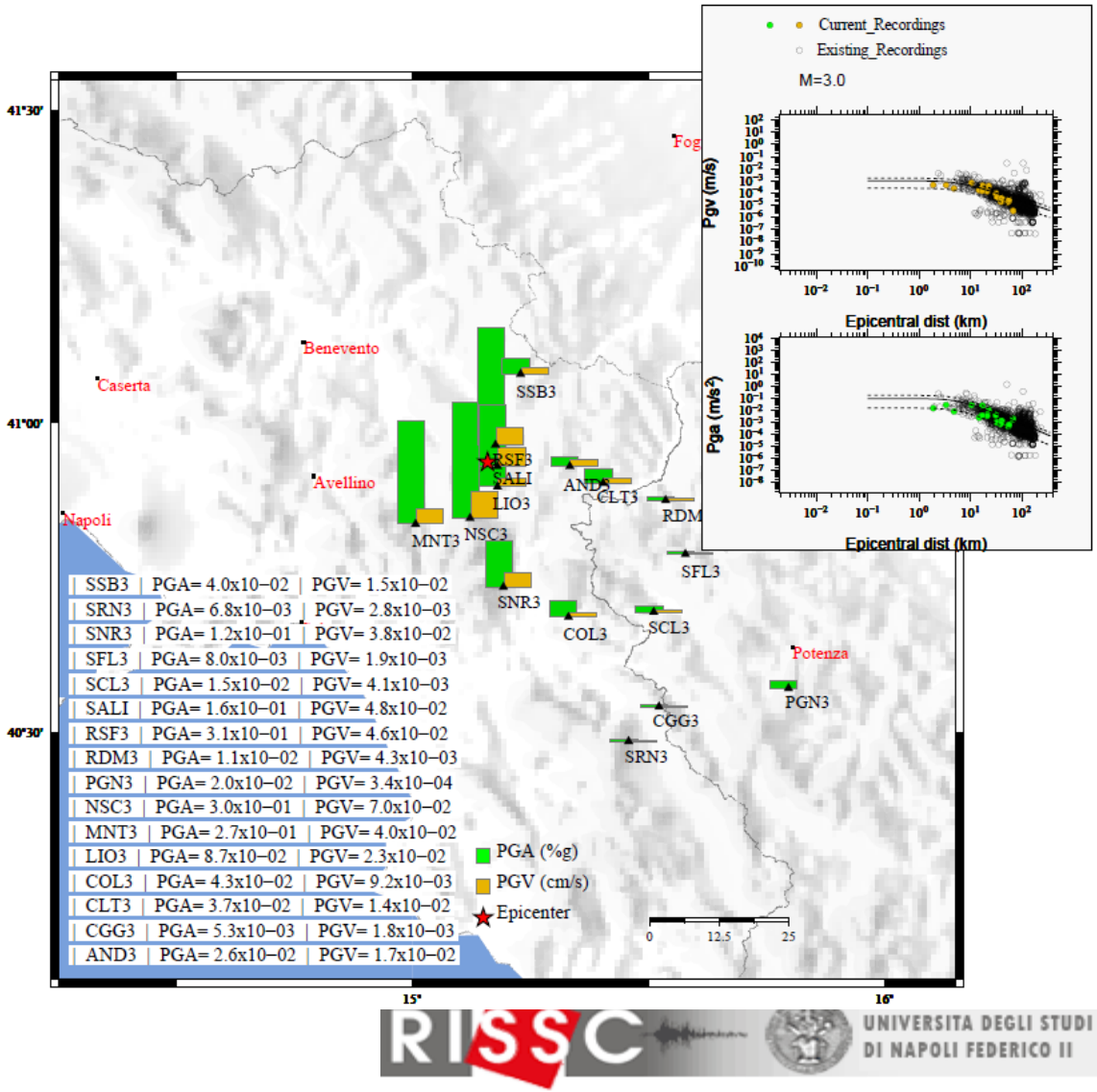
GMPE – M3.0
3/7/20 – 16:19



The amplitudes for this second event show a similar pattern than for the previous event, but **amplitudes are significantly smaller** mainly for lateral stations. This difference may be ascribed to the **diverse stress drop**: for the first event the stress drop is **6.1 MPa** while for the second event is **1.1 MPa**.

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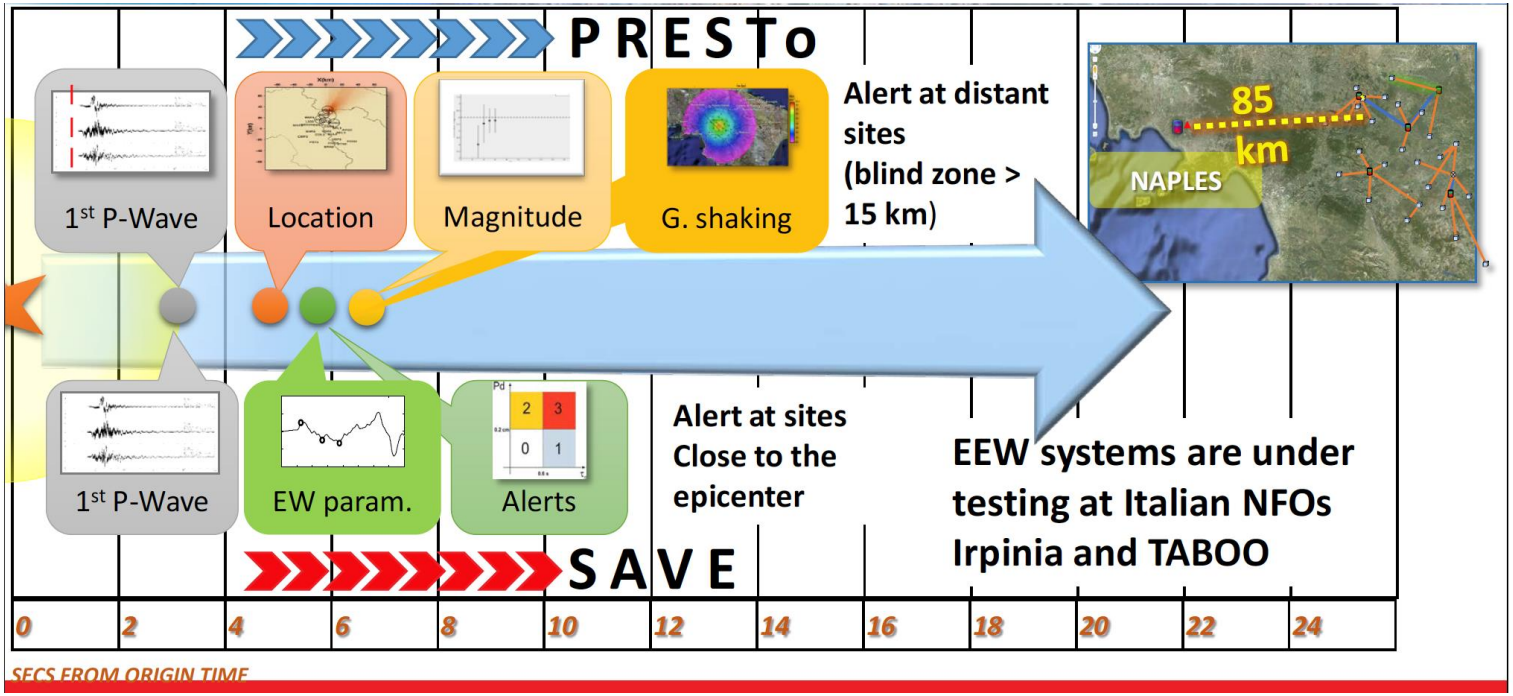
PRESTo and SAVE EEWS



Here we present the results for the **early warning systems** running in real-time on the Irpinia seismic network.
In the regional system **PRESTo** (*Satriano et al., 2010*) the alert results from the analysis of signals recorded by a network of stations and the prompt estimation of location, magnitude and ground shaking prediction through specific GMPEs. In the onsite system **SAVE** (*Caruso et al., 2017*) the alert is obtained from a single station analysis and it is based on the direct estimation of the predicted intensity at the site as given by the measure of the first P-wave amplitude. The blind zone is the region within which the strong shaking waves arrive before the alert.

Overall performance of PRESTo

Event ID	ML	Mw	MPRESTo	DM_first
16975	1.4	2	1.5	0.1
16973	2.1	2.4	2.1	0
16972	2.1	2.3	2.5	0.4
16967	2.8	2.9	3.4	0.6
16964	2	2.3	2	0
16963	2.8	2.9	3	0.2
16962	1.9	2.2	1.9	0
16961	1.8	2.2	1.2	-0.6
16958	1.3	1.8	1.2	-0.1
16956	2.7	2.8	3.1	0.4

MAIN OUTCOMES:

@ **FIRST Alert estimate:**

DeltaM: from 0 to 0.6

Average DeltaM = **0.26**

First Magnitude estimate on average available in **3.9s** from the first P-wave detection

The PRESTo EWS detected **10 events** of the sequence with M between 1.8 and 2.9; during the first day of the sequence, a temporary failure of the real-time communication prevented from a correct operation of the early warning system. For each event, the table shows the comparison between the local (M_L) and moment (M_w) magnitude (as computed by ISNet) and the estimated magnitude by PRESTo at the first alert. The difference between MPRESTo and M_L is also shown. We found that the first magnitude estimate is available on average **after 3.9s after the first P wave detection.**

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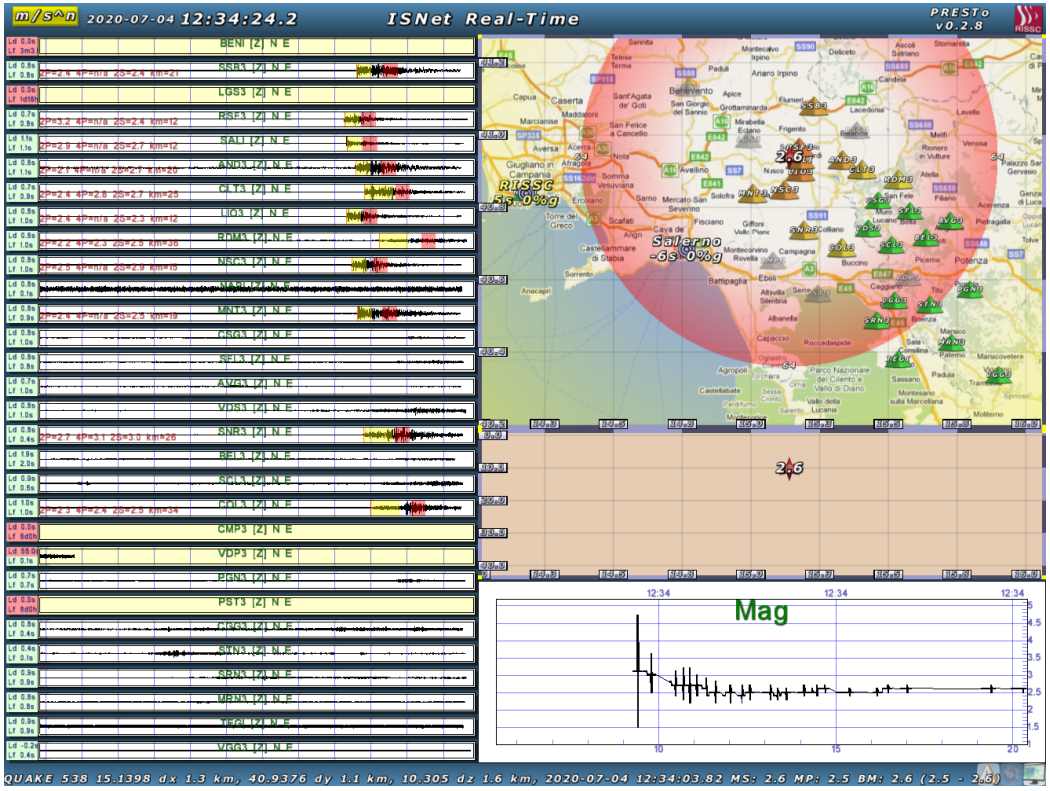
Real-Time Performance of PRESTo for M2.7, 04-07 12:34 event



FIRST PRESTo estimate:
6 sec after the origin time
MAG error: +0.4
LOC_epi error : 8 Km
LOC_dep_error: 6 km

END of earthquake
PRESTo estimate:
18 sec after origin time
MAG error : -0.1
LOC_epi error : 1.21 Km
LOC_dep_error: 1.8 km

DATA LATENCY:

- **23 stations with average data latency = 0.99 s**
- **3 stations with latency > 30s (problems)**
- **3 stations non available (problems)**

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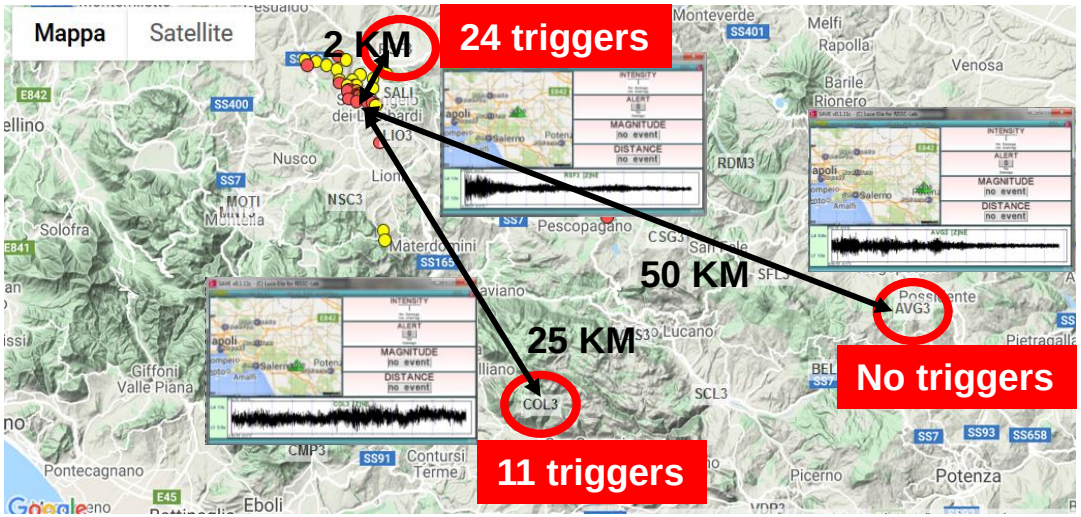
SAVE during the M3.0, 07-03 16:14 event



- Three stations were operational during the sequence: RSF3, COL3 and AVG3, at different distances from the sequence hypocenters.
- We recovered 24 detection at the closest station RSF3, 11 alerts at COL3 and no alerts at AVG3.
- SAVE correctly predicted the expected ground motion intensity for all of the sites.
- SAVE was not able to measure the τ_c parameters, thus not providing any information about event magnitude.

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ISNet_EWApp

The ISNet EWapp (*Colombelli et al., 2020*) currently being tested by 7 users in the RISSC lab, broadcast the alert related to 21 events of the sequence to the users smartphones, located in Naples, Avellino and Nocera Inferiore. For all the events, the intensity never overcame the threshold of intensity IV at the location of the smartphones.

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