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Intermediate-term narrow-range earthquake forecasting: an interdisciplinary tool based on seismological and geodetic observations

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The analysis: motivation and goals

- **Earthquakes cannot be predicted with high precision, but algorithms exist for intermediate-term middle-range prediction of main shocks above a pre-assigned threshold, like CN algorithm.**
- **Alarms can be issued, which:**
  - ✓ refer to areas with linear dimensions of hundred kilometres and having duration of several months to years;
  - ✓ are not compatible with evacuation or red alert
  - ✓ anyway, can be very **useful for many effective prevention actions** (e.g. planning of interventions, retrofitting, temporary safety measures)

Open question: can additional independent information reduce this uncertainty in space and time?

The analysis: motivation and goals

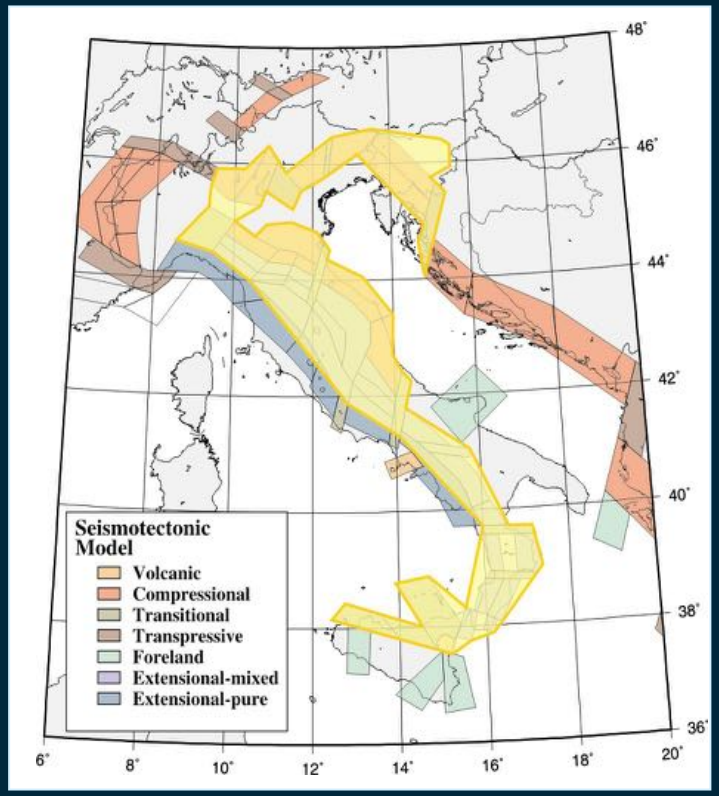
- **For the last decades GPS and SAR are providing valuable information about ground/crustal deformations, continuously improving resolution in space and time.**
- **We explored whether the additional independent information may come from space geodesy techniques:**
  - ✓ Building on earlier experience of the seismological and geodetic information integration (e.g. ASI-SISMA project)
  - ✓ following **a new approach**, where the seismotectonic setting and seismicity patterns are used as prior information within the geodetic data analysis
- **We carried out two exercises on the seismic crises of Emilia (2012) and Amatrice (2016), performing a retrospective analysis of GPS and SAR data**

Seismological Data Analysis

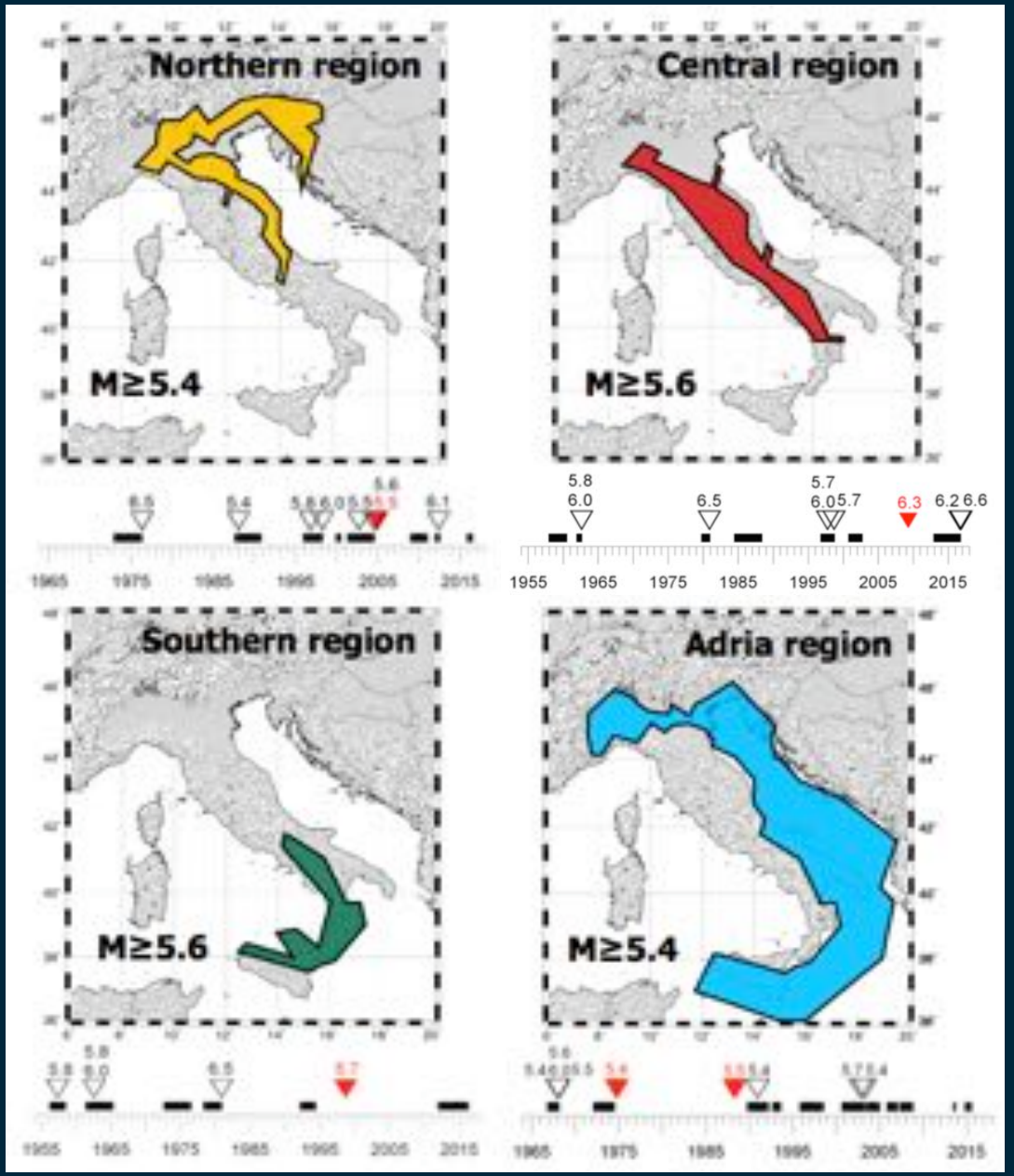
Real-time testing of premonitory CN seismicity patterns in Italy

http://mitp.ru/en/cn/CN-Italy.html

Tectonic setting and CN regionalization for Italy



CN analyses the seismic activity inside a set of four predefined regions, outlined according to the seismotectonic zoning (Scandone et al., 1994, Meletti et al. 2000).



Peresan (2018). AGU Book on Pre-earthquake processes, Ch. 9.
Peresan et al., (2005). Earth Sci. Rev.

A recent forecast: Albania Earthquakes

M6.4 26.11.2019
M5.6 21.09.2019

CN alert: 1 Sept. 2019 – 1 Jan. 2020

https://www.emsc-csem.org

Citizen Response		Date & Time UTC	Latitude degrees		Longitude degrees		Depth km	Mag[+]	Region name
					1				
732	V	2019-11-27 14:45:26.3 *4hr 59min ago*	41.57	N	19.45	E	15	5.3	ADRIATIC SEA
311	V	2019-11-26 06:08:22.9	41.58	N	19.33	E	10	5.4	ADRIATIC SEA
45	VI	2019-11-26 03:03:00.1	41.47	N	19.53	E	10	5.3	ALBANIA
78	VI	2019-11-26 02:59:24.1	41.40	N	19.54	E	10	5.1	ALBANIA
1371	VII	2019-11-26 02:54:11.6	41.38	N	19.47	E	10	6.4	ALBANIA
143	VI	2019-09-21 14:15:53.9	41.41	N	19.45	E	10	5.1	ADRIATIC SEA
793	VI	2019-09-21 14:04:27.6	41.37	N	19.45	E	20	5.6	ALBANIA

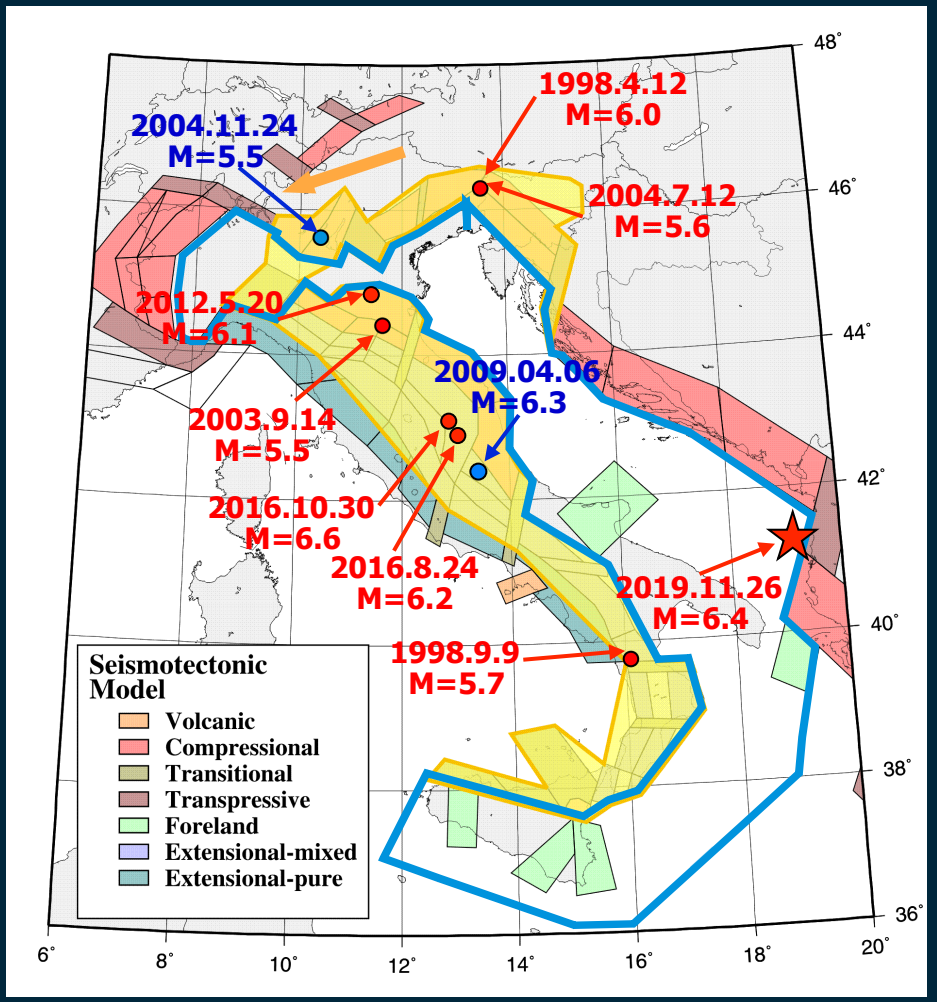
Intermediate-term middle-range earthquake forecasts

CN algorithm

Real-time testing 1998-2020

Earthquakes occurred within the space-time-magnitude volume monitored by CN since 1998

Date	Latitude, °N	Longitude, °E	Depth, km	M_{prio}	CN	CN Region
1998.04.12	46.24	13.65	10	6.0	Yes	North
1998.09.09	40.03	15.98	10	5.7	Yes	Centre, South
2002.10.31	41.78	14.87	10	5.7	Yes	Adria
2003.03.29	43.26	15.49	33	5.4	Yes	Adria
2003.09.14	44.33	11.45	10	5.6	Yes	North
2004.07.12	46.30	13.64	7	5.7	Yes	North
2004.11.24	45.63	10.56	17	5.5	No	North
2009.04.06	42.33	13.33	8	6.3	No	Centre
2012.05.20	44.90	11.23	6	6.1	Yes	North
2016.08.24	42.72	13.19	4	6.2	Yes	Centre
2016.10.30	42.85	13.09	10	6.6	Yes	Centre
2019.11.26	41.38	19.47	10	6.4	Yes	Adria



Updated to May 2020

http://mitp.ru/en/cn/CN-Italy.html

Intermediate-term middle-range earthquake forecasts

Space-time volume of alerts in CN application in Italy

Experiment	Space-time volume of alert (%)	n/N	Confidence level (%)
Retrospective* (1954 – 1963)	41	3/3	93
Retrospective (1964 – 1997)	26	10/12	>99
Forward** (1998 – 2020)	32	10/12	>99
All together (1954 – 2020)	30	23/27	>99

* Central and Southern regions only
** Adria region since 2005

Algorithm CN forecasted 23 out of the 27 strong earthquakes occurred in the monitored zones of Italy, including Adria region, with about 30% of the considered space-time volume occupied by alerts

(updated to May 2020
Next updating July 2020)

The archive of CN forecasts in Italy can be viewed at:
http://www.mitp.ru/en/cn/CN-Italy.html

e-mail: aperesan@inogs.it

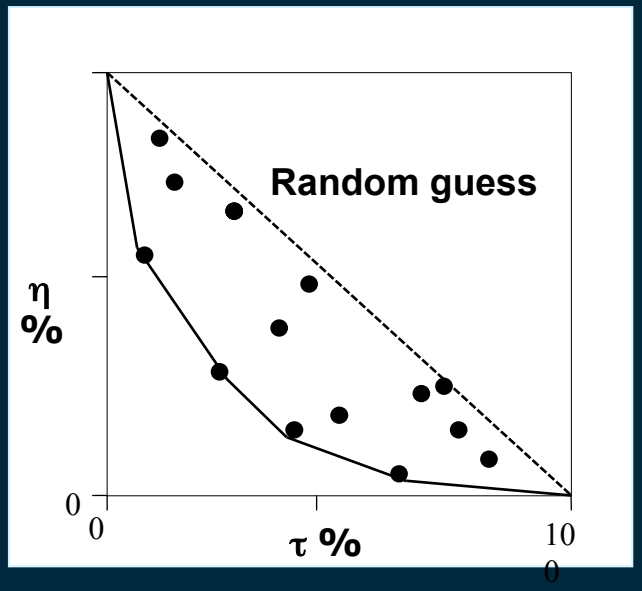
Intermediate-term middle-range earthquake forecasts

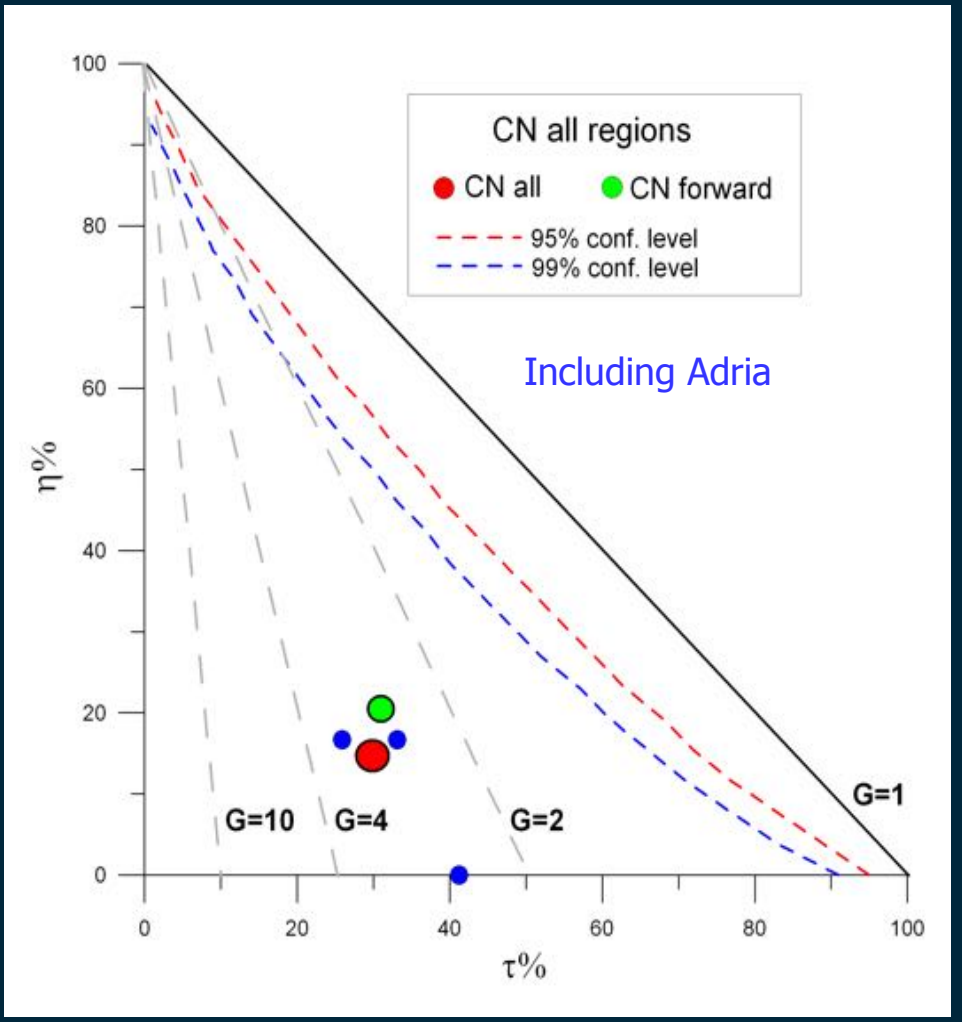
Evaluation of prediction results

The quality of prediction results can be characterised by using two parameters (*Molchan, 1997*) **:**

η : the rate of failures-to-predict (*n/N*)

τ : the space-time volume of alert





Peresan (2018), AGU Book on "Pre-Earthquake Processes"

CN forecasts in Italy
(updated to May 2020)

Integrating information from different observables

Geodetic data analysis along selected transects

Crespi, Kossobokov, Panza & Peresan
(PAGEOPH, 2019)

Integrated data analysis: GPS data

- **For the last decades GPS and SAR are providing valuable information about ground/crustal deformations, continuously improving resolution in space and time.**
- **We explore whether the synergic use of GPS and seismological information can reduce uncertainty of predictions following a new approach:**
  - ✓ the seismotectonic setting and seismicity patterns are used as prior information within the geodetic data analysis
  - ✓ the velocity and strain pattern are analysed along 1D transects, properly oriented with respect to the tectonic regions monitored by CN
- **We carry out two exercises on the seismic crises of Emilia (2012) and Amatrice (2016), performing a retrospective analysis of GPS and SAR data**

The new approach – the idea

GPS is used to estimate **not the standard 2D velocity and strain field**

BUT

the **velocity and strain pattern along transects**, properly **oriented with respect to the tectonic regions monitored by CN** (accounting for the known seismotectonic setting), used as prior information

Transect width (typically few tens of km) is selected balancing two criteria:

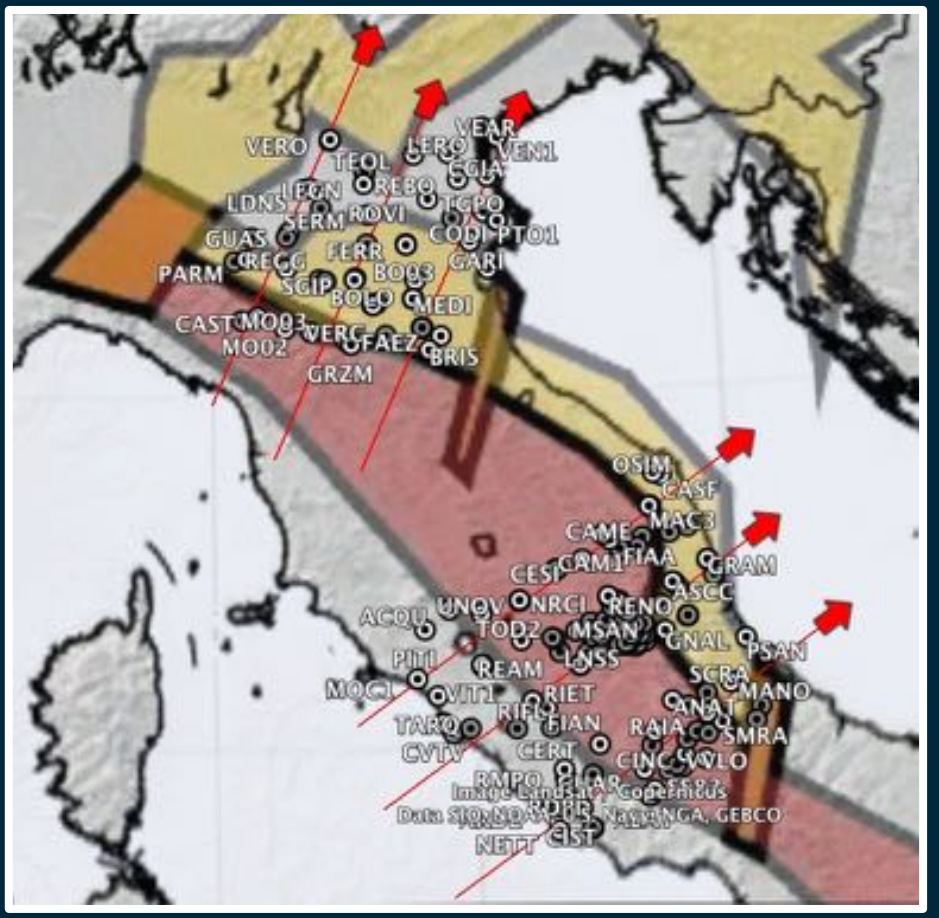
- include a substantial number of GPS stations
- focus on an area with a homogeneous tectonic setting (as much as possible)

The new approach – the experiments

We considered **6 transects**, 50 km wide, consistent with CN zonation:

- 3 for Emilia
  (EQs: 20 May 2012, Mw=6.0
  29 May 2012, Mw=5.7)
- 3 for Amatrice
  (EQ: 24 Aug 2016, Mw=6.2)

Each of selected GPS stations is included in one transect only

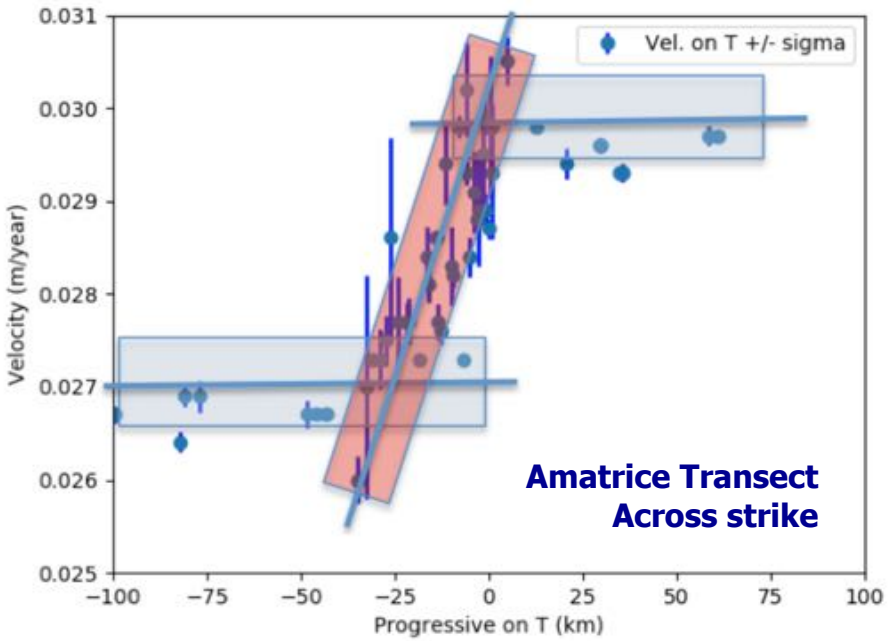


Would GPS data have been able to highlight the strain accumulation in preparation of the Emilia and Amatrice earthquakes?

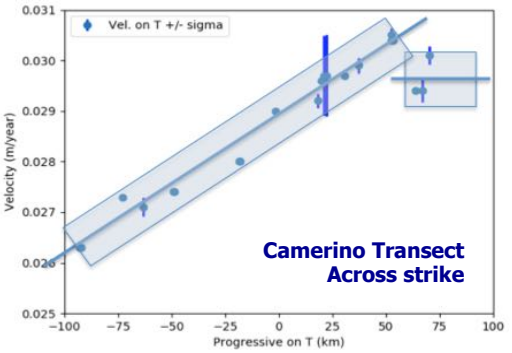
The results – counterexamples and uncertainties

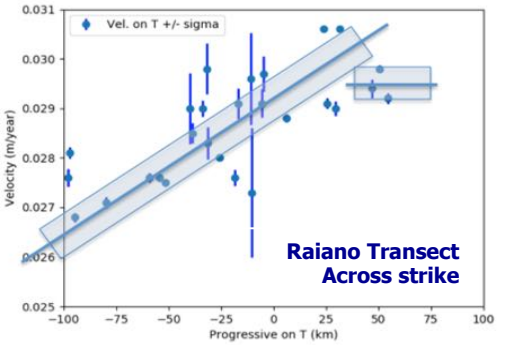
- **Standard outcomes:** tectonic extension across the Central Italy Apennines
- **Geodetic signature** for the Amatrice **across-strike transect**

Central Italy



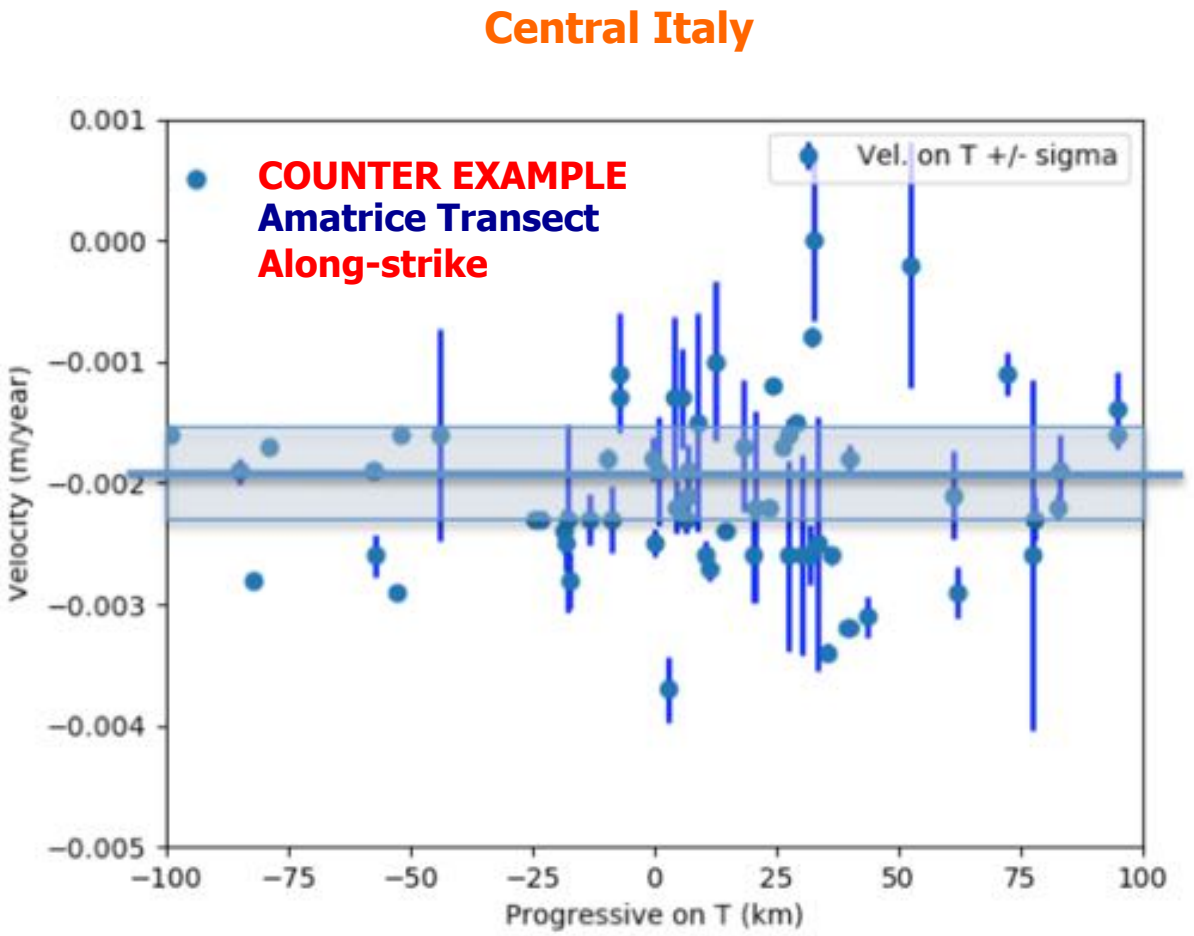
Imposing the same trend identified for Raiano and Camerino data, does not explain Amatrice across-strike observations…





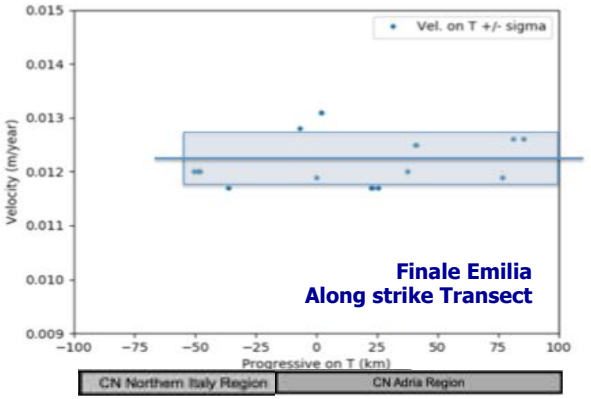
The results – counterexamples and uncertainties

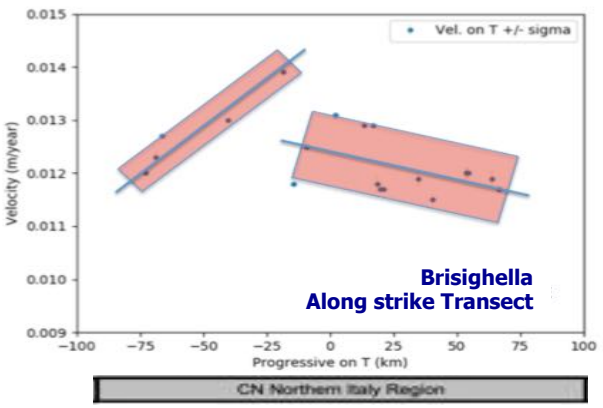
- **Standard outcomes:** tectonic extension across the Central Italy Apennines
- **No geodetic signature** for the Amatrice **along-strike transect**

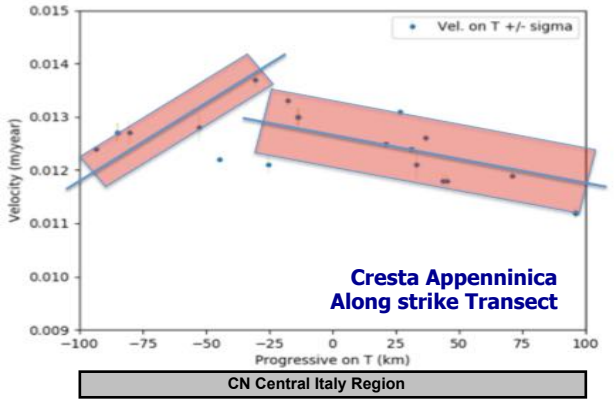


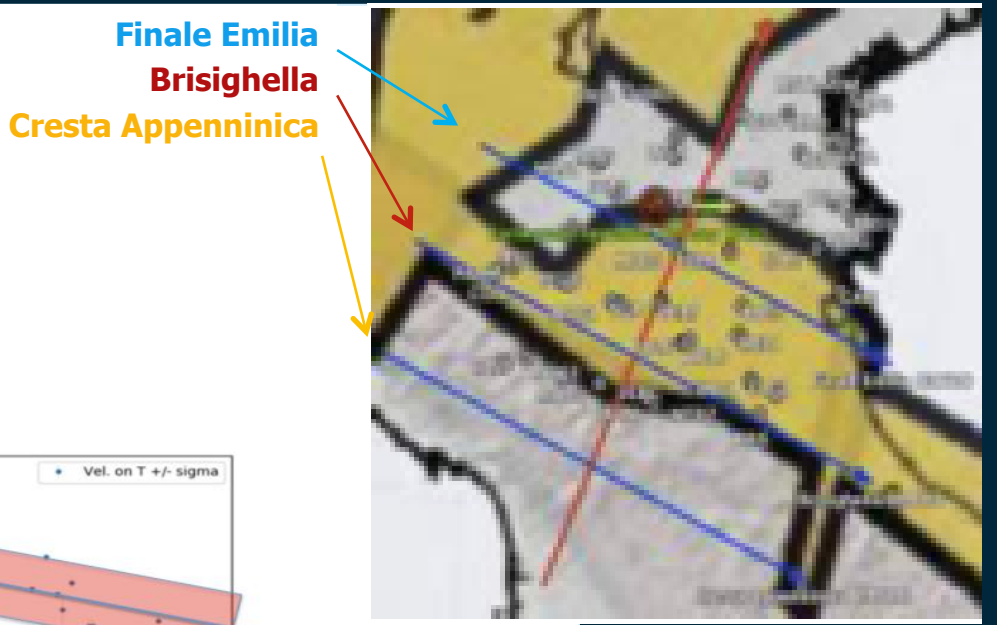
The results – Emilia transects

- Clear **geodetic signature** in the Brisighella and Cresta Appenninica along-strike transects, pretty **coherent** both **with the strike-slip focal mechanism** and **with the 29 May 2012 earthquake location**
- **No geodetic signatures** in Finale Emilia **along-strike transect**





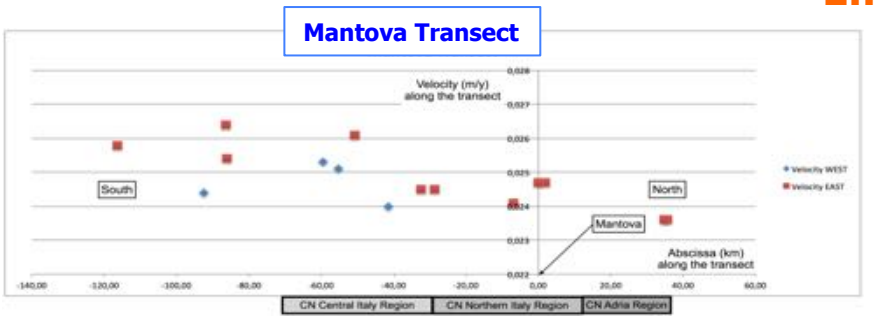


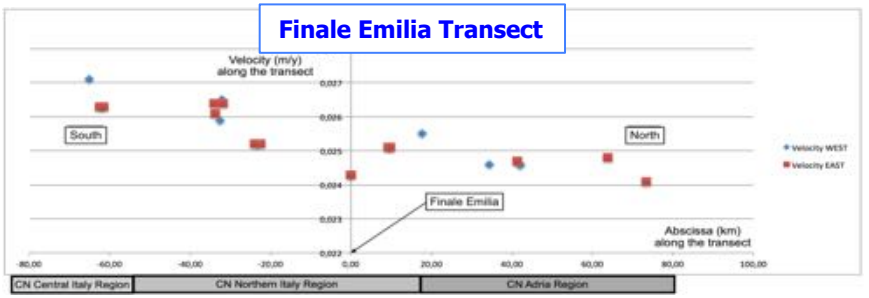


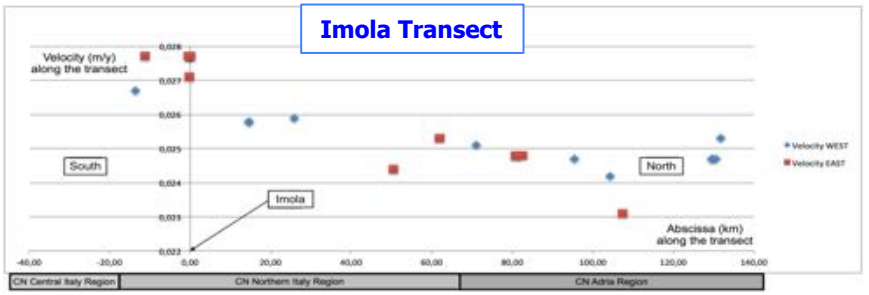
The results – Emilia transects

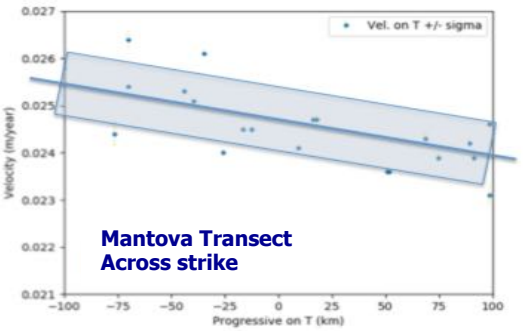
- **No geodetic signature** is observed for **across-strike transects**
- **Standard outcomes:** tectonic shortening moving northward from the Apennines to the Po Valley

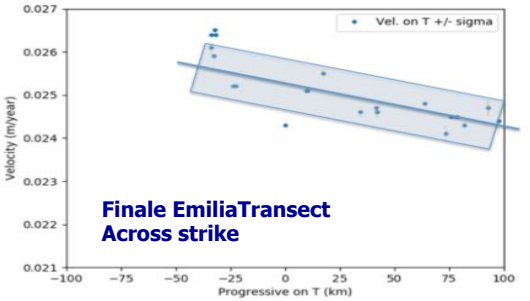
Emilia

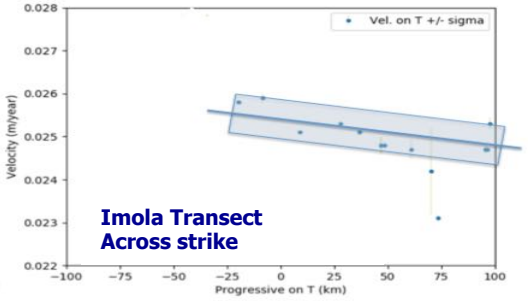












The results – Do we know Emilia ST setting?

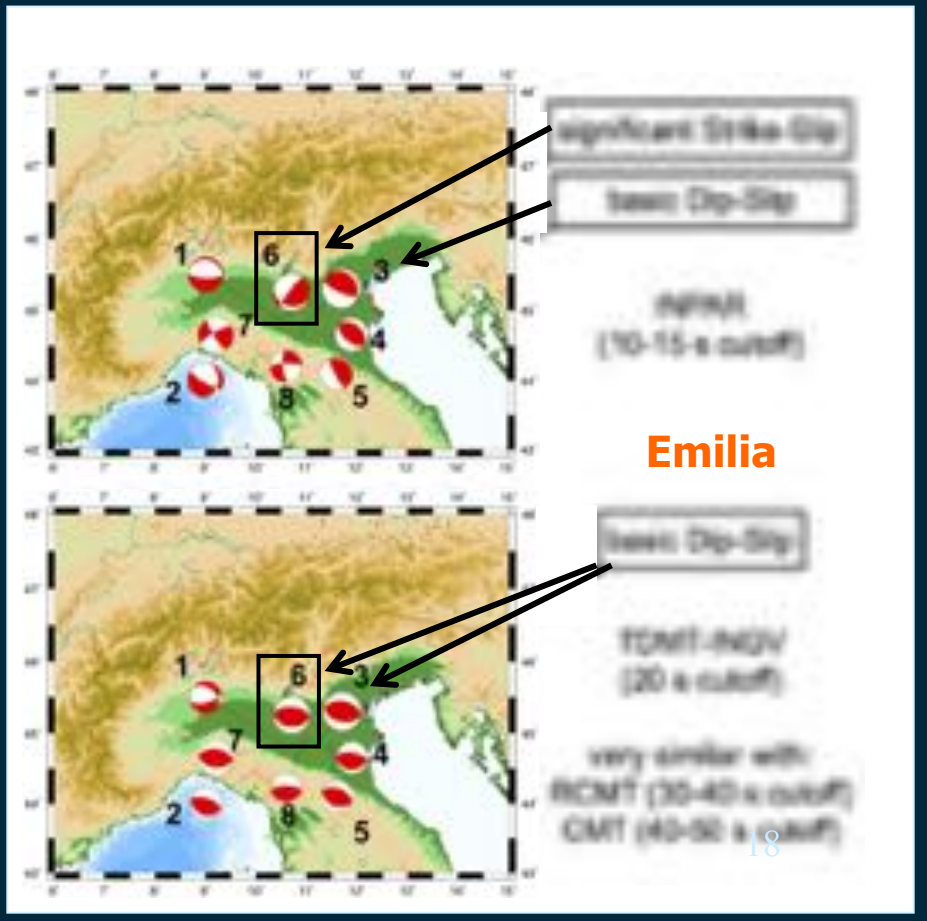
We got coherent and incoherent results across-strike:

- Central Italy (normal faults - transects across-strike): both CN alert and geodetic signature
- Emilia (thrust??? - transects across-strike???): CN alert but no geodetic signature

We checked the focal mechanisms for the two strongest Emilia May 2012 events (3: 20 May; 6: 29 May):

- relevant inconsistency for the event on 29 May 2012
- strike-slip possibly due to a strain accumulation parallel to strike

We found a geodetic signature for along-strike transects (orthogonal to the previous ones), compatible with a strike-slip mechanism



For further details see:

Crespi, M., Kossobokov, V., Panza, G.F., Peresan, A. (2019)

"Space-Time Precursory Features within Ground Velocities and Seismicity in North-Central Italy".

Pure and Applied Geophysics, DOI: 10.1007/ s00024-019-02297-y

Pure Appl. Geophys.

https://doi.org/10.1007/s00024-019-02297-y

Pure and Applied Geophysics

Space-Time Precursory Features within Ground Velocities and Seismicity in North-Central Italy

MATTIA CRESPI,[1] VLADIMIR KOSSOBOKOV,[2,8] GIULIANO F. PANZA,[3,4,5,6,8] and ANTONELLA PERESAN[7,8]

Abstract—Earthquakes cannot be predicted with ultimate precision, so that the progressive reduction of the prediction uncertainty in space and time is an evergreen and challenging task, both from the scientific point of view for the intrinsic complexity of seismic phenomenon and for its high societal relevance. To this aim, algorithms (like CN, M8 and M8S) based on objective recognition of seismicity patterns have been already tested for some decades for intermediate-term middle-range prediction of strong earthquakes above a pre-assigned magnitude threshold. Here, moving from some preliminary ideas, we propose an integrated approach to earthquake prediction, based on the synergy of high-density geodetic observations and seismological information, defining a new paradigm for time dependent hazard assessment scenarios. Through a wider and more refined retrospective analysis, duly involving the accuracy analysis of the newly available geodetic results, space–time precursory features are highlighted within ground velocities and seismicity, analyzing the 2016–2017 seismic crisis in Central Italy and the 2012 Emilia sequence. Overall, it is demonstrated that the proper integration of seismological and geodetic information can achieve what here is called *intermediate-term narrow-range earthquake prediction*. The extent of the alarmed areas, identified for the strong earthquakes by earthquake prediction algorithms based on seismicity patterns, can be significantly reduced from linear dimensions of a few hundred to a few tens of kilometers, leading to an improved more specific implementation of low-key preventive actions, like those recommended by UNESCO as early as in 1991.

Key words: Neo-deterministic seismic hazard assessment, seismicity patterns, geodetic signatures, earthquake prediction, intermediate-term narrow-range, low-key preventive actions.

1. Introduction

Earthquakes cannot be predicted with ultimate precision, so that the progressive reduction of the prediction uncertainty in space and time is an evergreen and challenging task, both from the scientific point of view for the intrinsic complexity of seismic phenomenon and for its high societal relevance.

To this aim, algorithms based on seismicity patterns (like CN, M8 and M8S) exist for some decades for intermediate-term middle-range prediction of earthquakes above a pre-assigned magnitude threshold. The algorithms have been rigorously tested in Italy and elsewhere, and their results may be properly used for the implementation of low-key preventive actions, like recommended by UNESCO as early as

Towards a systematic interdisciplinary analysis

- With these results acquired, a **systematic analysis of velocity variations** (together with their accuracy) is in progress, by defining **a set of transects uniformly distributed**, as far as possible, along and across major seismotectonic features of the Italian region, with a spacing of about 40-50 km and properly covering the regions monitored by CN algorithm.
- As a rule most of the transects contain information that appear to be useful for earthquake forecasting purposes. The few exceptions, naturally connected with the local very limited extension of land, are in Calabria and Western Sicily.

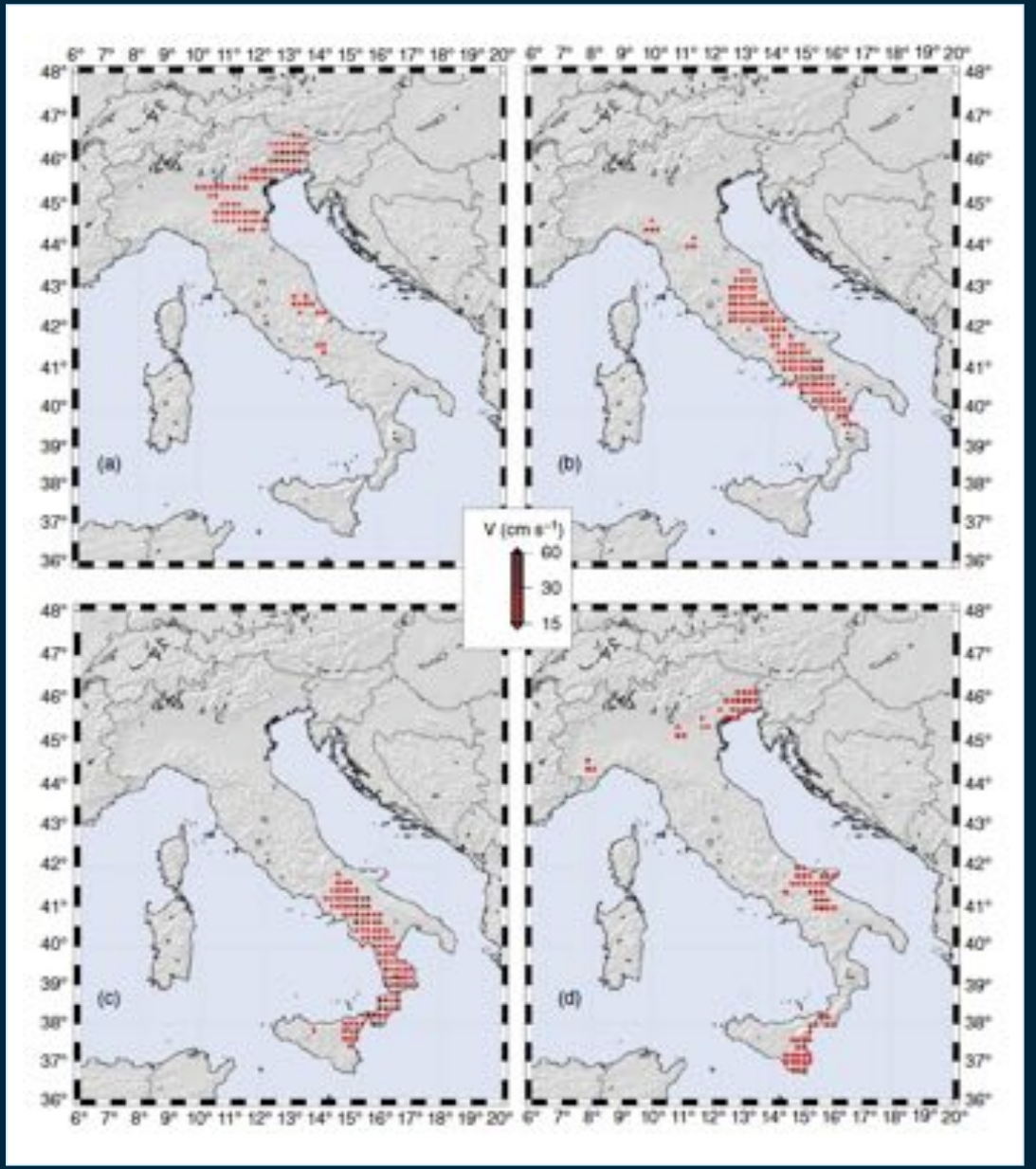
Developing an intermediate-term narrow-range forecasting tool

- The results obtained so far indicate that the combined analysis of intermediate-term middle-range earthquake predictions, like **CN (time dependent within decadal interval)**, with those from the processing of adequately dense and permanent **GNSS network data (time independent within the same decadal interval)**, may allow to **highlight in advance the localized strain accumulation**.
- Accordingly **the extent of the alarmed areas**, identified based on seismicity patterns at the intermediate scale can be **significantly reduced** from few hundred to few tens of kilometres.

Integrated time-dependent seismic hazard scenarios

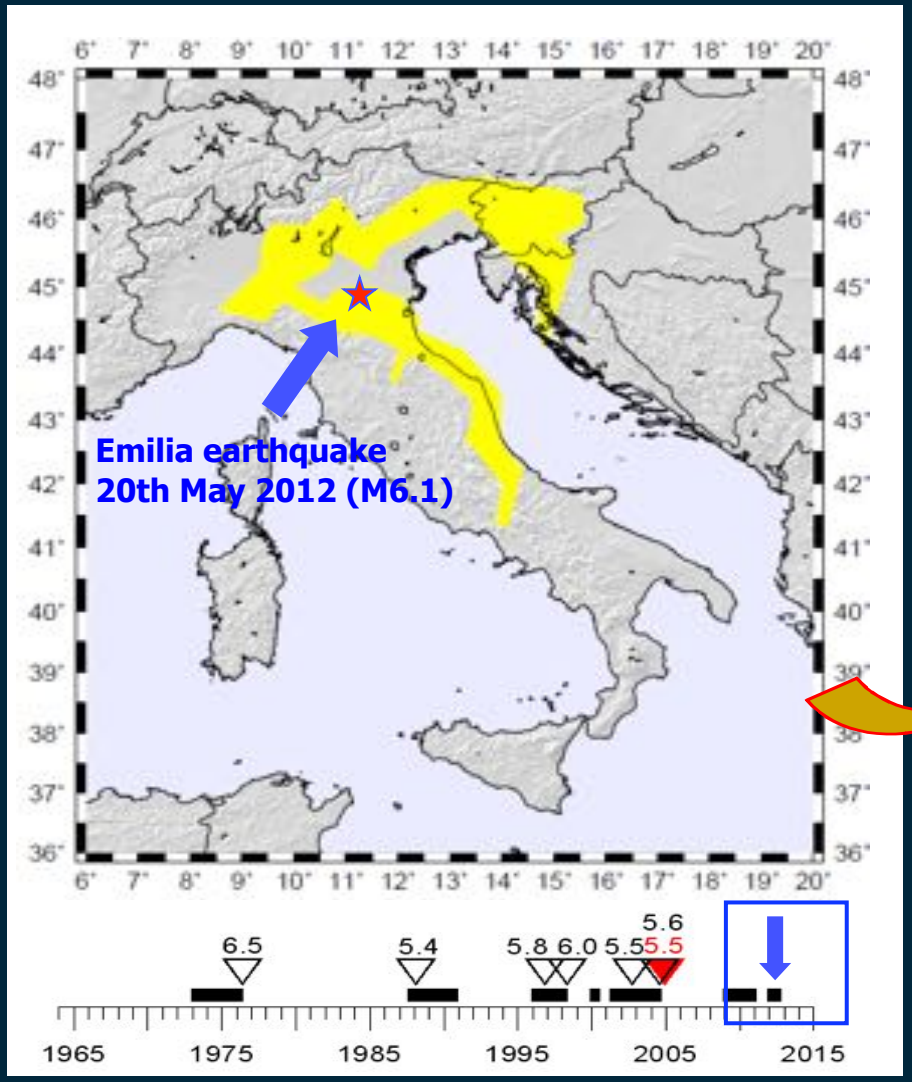
Time-dependent ground shaking scenarios

Ground shaking scenarios for the 4 CN zones in the Italian peninsula, when alerted.



PGV ≥ 15 cm/s corresponds to Intensity **X** (MCS) (Indirli et al., 2011)

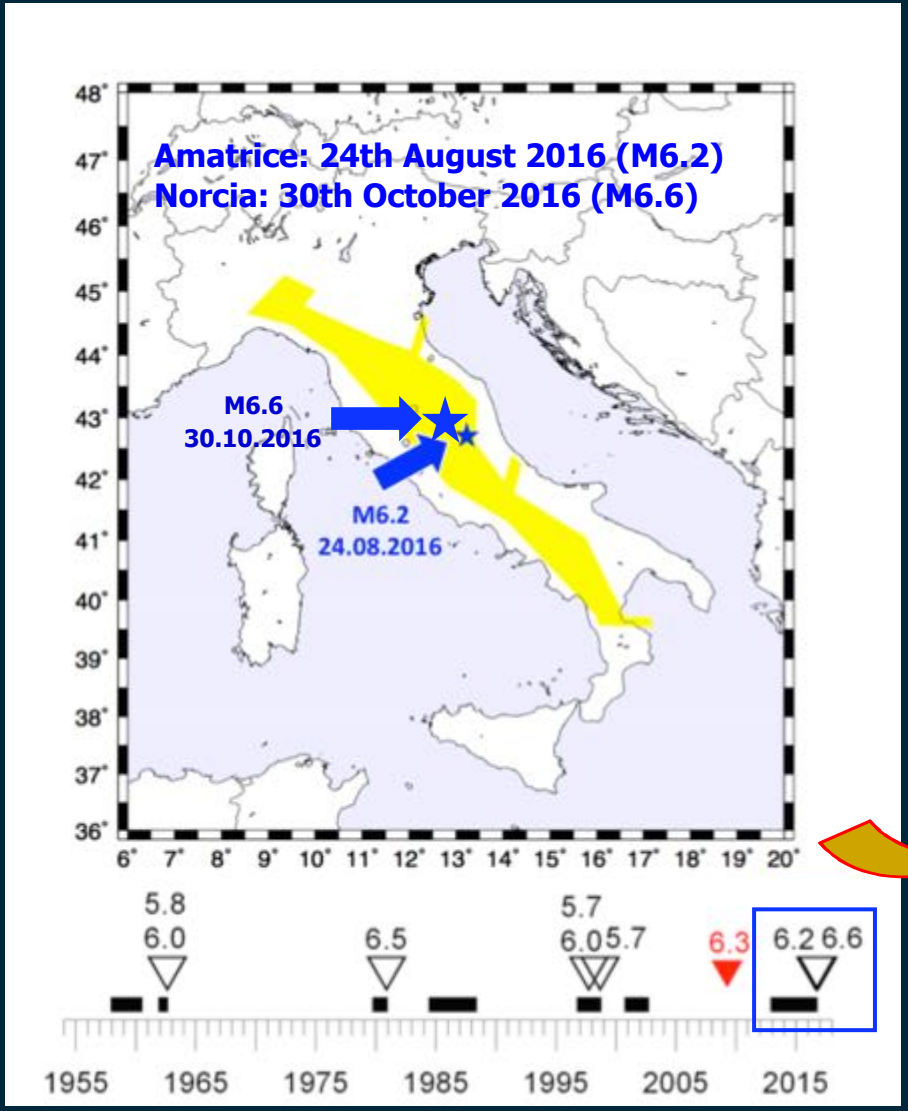
Time-dependent ground shaking scenarios

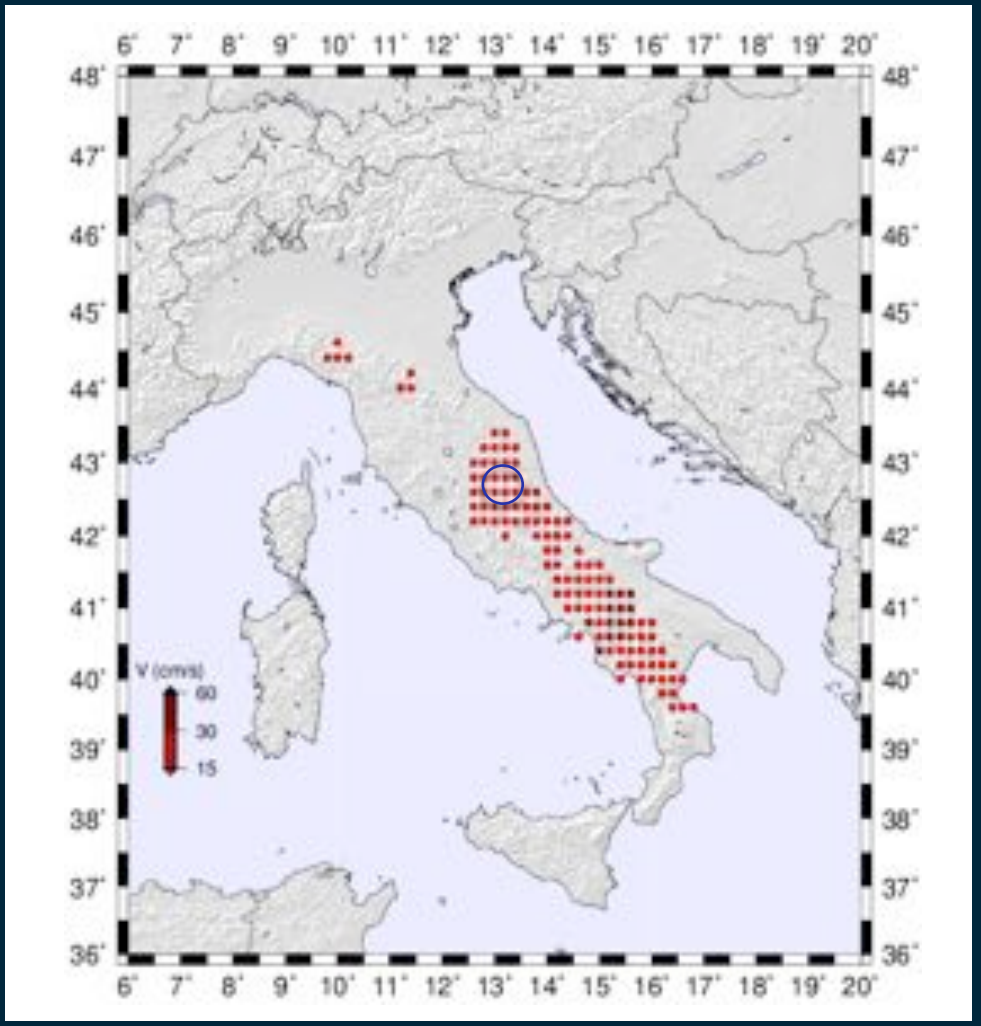


Time-dependent ground-shaking scenario associated with CN Northern Region, as defined **before the Emilia Earthquake (20 May 2012)**

Northern Region (yellow) alerted by **CN algorithm** for an earthquake with **M≥5.4**, in the time interval 1.3.2012-1.9.2012

Time-dependent ground shaking scenarios



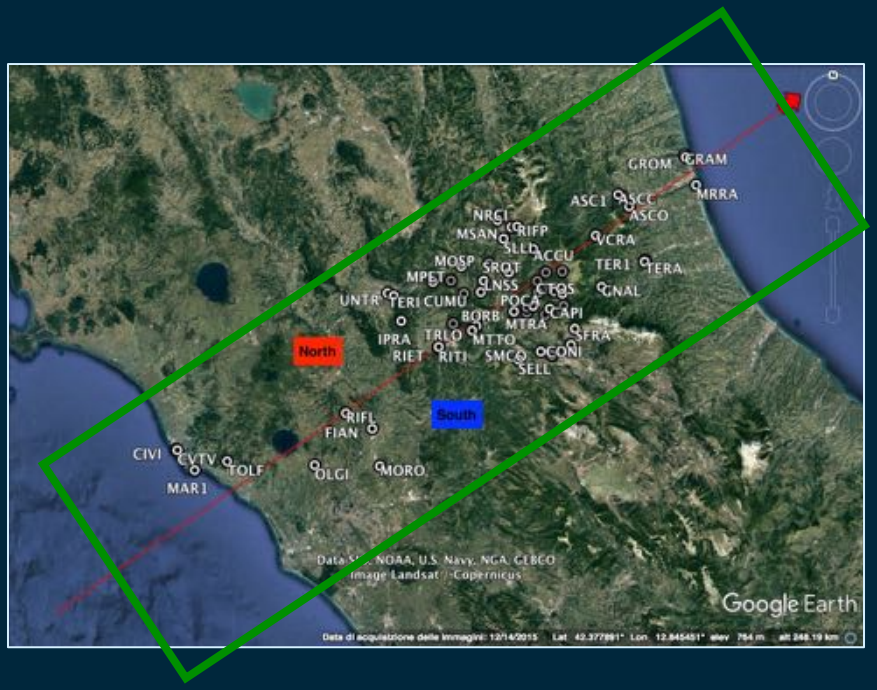


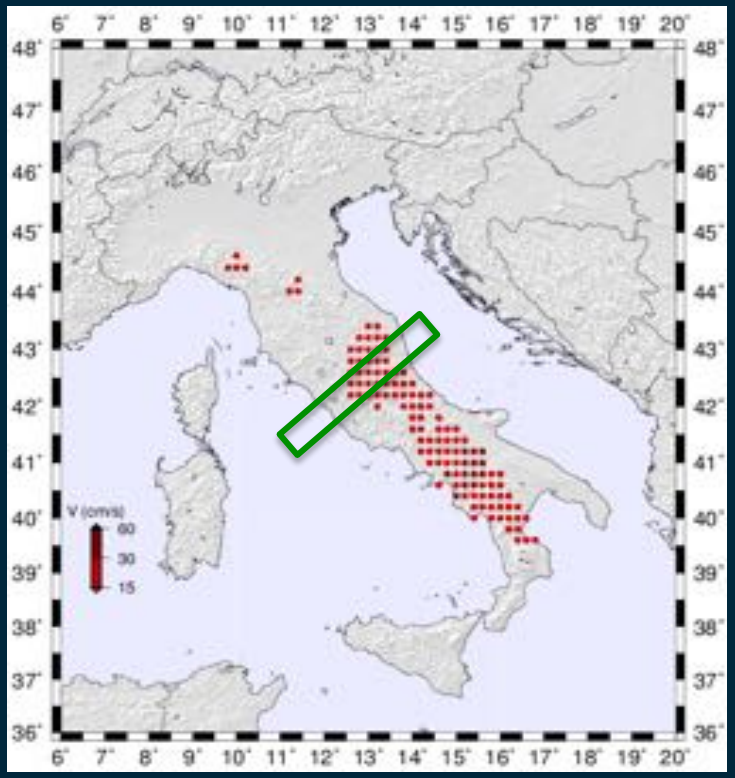
Time-dependent ground-shaking scenario associated with CN Central Region, as defined before the Amatrice , Visso and Norcia earthquakes.

Central Region (yellow) alerted by CN algorithm for an earthquake with M≥5.6, in the time interval 1.11.2012-1.11.2016

Integration with Earth-Observation data

- CN alarms are used to guide the processing of GPS and inSAR observations
- **Intersections of transects with geodetic signatures** and **CN related scenarios** can significantly **reduce the size of the areas**, where preventive actions should be focused





Panza, Peresan, Sansò, Crespi, Mazzoni, Nascetti (2017)

Conclusions

The retrospective 1D analysis of geodetic data (GPS and SAR) along properly oriented transects suggests that:

- GPS time series several years long may highlight geodetic signatures of strain accumulation in areas within CN alarmed zones and which were struck by earthquakes
- Geodetic signatures are stable over time, so the related strain accumulation is a relatively long-term phenomenon

- Integration of geodetic signatures and CN information can significantly reduce the space uncertainty of the alarmed areas => intermediate-term narrow-range forecasts

References

- **Crespi, M., Kossobokov, V., Panza, G.F., Peresan, A. (2019) -** ***"Space-Time Precursory Features within Ground Velocities and Seismicity in North-Central Italy".*** **Pure and Applied Geophysics, DOI: 10.1007/s00024-019-02297-y**
- **Peresan A. (2018) -** ***"Recent developments in the detection of seismicity patterns for the Italian region". In: "Pre-Earthquake Processes: A Multi-disciplinary Approach to Earthquake Prediction Studies",*** **Eds: D.Ouzounov, S.Pulinets. K.Hattori, P.Taylor. Chapter 9, Volume 234, AGU Geophysical Monograph Series. Wiley and Sons. pp. 149-172. DOI: 10.1002/9781119156949.ch9.**
- **Panza G.F., Peresan A., Sansò F., Crespi M., Mazzoni A., Nascetti A. (2018) - "*How geodesy can contribute to the understanding and prediction of earthquakes*". In: "Satellite Positioning for Geosciences". Rend. Fis. Acc. Lincei., 13 pp., doi:10.1007/ s12210-017-0626-y**
- **Panza G. F., A. Peresan, A. Magrin, F. Vaccari, R. Sabadini, B. Crippa, A. M. Marotta, R. Splendore, R. Barzaghi, A. Borghi, L. Cannizzaro, A. Amodio, S. Zoffoli (2013) – *"The SISMA prototype system: integrating Geophysical Modeling and Earth Observation for time-dependent seismic hazard assessment."* Natural Hazards. DOI 10.1007/ s11069-011-9981-7**
- **Peresan A., V. Kossobokov, L. Romashkova, G.F. Panza (2005) - *"Intermediate-term middle-range earthquake predictions in Italy: a review".* Earth Science Reviews, 69 (1-2), 97-132.**