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

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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.

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 1991 (Kantorovich and Keilis-Borok 1991; Keilis-Borok and Soloviev 2003; Panza 2010; Peresan et al. 2005, 2012).

Also, for at least 3 decades space geodesy techniques like GPS (now GNSS—Global Navigation Satellite Systems) and (for a comparable period) SAR satellite sensors can provide valuable and unprecedented information about the crustal deformations on a continuously increasing space density, and time rate and length basis. In this respect, data from about 20000 GNSS stations have been analysed and a global map of tectonic strain has been produced, which is publicly available in Kreemer et al. (2014). This data bank will be improved in the near future, thanks to (a) the full deployment of the GNSS constellations

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now under development (Beidou, Galileo, QZSS), (b) the availability of lower and lower cost GNSS receivers and (c) the recent and coming SAR satellite sensors (Sentinel-1, ALOS-2, Gaofen-3, COSMO-Skymed second generation).

It is therefore natural to investigate if a proper integration of the newly available geodetic observations with the validated seismological information and methods can be established, in order to better constrain in space and time the current earthquakes prediction (Kossobokov and Soloviev 2015; Kossobokov et al. 2015; Kossobokov 2017; Peresan 2018) that may lead to an improved focalization of possible prevention actions.

Some years ago, a first attempt was made focusing on the Central and Southern Apennines (Italy) in the framework of project SISMA, funded by Italian Space Agency (ASI), to jointly use seismological tools, like CN earthquake prediction algorithm and scenario earthquakes, and geodetic methods and techniques, like GPS and SAR, to effectively constrain priority areas where to concentrate prevention and seismic risk mitigation actions (Panza et al. 2013b). However, at that time, enough spatially dense and long coordinate time series coming from geodetic techniques were not available yet for the investigated area. Therefore, only recently, benefiting of the last years development and of GNSS permanent networks and data processing, it was possible to recognize the kind of relevant information, which can be supplied by geodesy and seismology (Panza et al. 2018). This complementary difference is the key feature of their integration, which defines a new paradigm for time dependent hazard assessment scenarios, whose novelty relies on:

- the unprecedented quality and density of available GNSS observations;
- the way the GNSS data are processed;
- the use of well established methods for seismic data analysis that have been already validated and provide a first level information, to be refined using results from GNSS analysis.

Here we move from the preliminary results presented in Panza et al. (2018) to develop a wider and refined retrospective analysis of ground velocities and seismicity related to the 2016–2017 seismic crisis in Central Italy and the 2012 Emilia earthquake. The main focus is placed on the capability of the proposed geodetic data processing method to supply useful information to strengthen the earthquake prediction, considering that algorithms like CN are well established and validated for some decades (Peresan 2018). In Sect. 2 the state-of-the-art of the geodetic data processing method, its application to the two investigated areas and the still open issues are discussed. In Sect. 3 the main features of CN algorithm are summarized and the results obtained in the two study areas are illustrated. Section 4 discusses the integration of the geodetic and seismological information and evidences the novel results. Finally, Sect. 5 summarizes the relevant conclusions and supplies future research prospects.

2. Time Independent Narrow-Range Signatures for Earthquake Prediction: A Geodetic GNSS-Based Approach

2.1. The Approach

A still open question is if the valuable information provided since at least 3 decades by GPS (now GNSS) about the crustal deformation can be useful to deepen the understanding of the earthquake preparation process, and to contribute to improve the assessment of the seismic hazard, even at local scale; it is just this scale which has the highest societal relevance.

In fact, under the hypothesis that earthquakes occur where strain energy has accumulated, GNSS can give such a contribution if they are able to reliably estimate the accumulation of strain, complementing the intermediate-term middle-range information provided by the monitoring of seismicity patterns.

However, there are large gaps in the GNSS observations coverage in many areas. Even in the most advanced countries, where there are the densest GNSS networks (Japan, USA), the station spacing ranges between 10 and 50 km, still generally too large to clearly sort out locked, accumulating strain faults from those that creep steadily. This is even

more difficult in transition zones between tectonic plates, as, for example, the Italian Apennines.

Therefore, in this study we do not consider the standard approach, where the analysis of the GPS data is devoted to estimate the 2D velocity and strain field in the study area, since it is a too low-resolution and numerically weak procedure. On the contrary, at present it appears reasonable that spatially more accurate and useful results can be retrieved from GNSS if independent additional information is introduced, capable to indicate *what* is relevant to monitor (i.e. grossly where and when). This additional information is especially relevant while waiting for a denser coverage of space geodesy techniques (hopefully, not only GNSS in the future) continuously monitored benchmarks, which could be only progressively achieved in the future, due to logistic and budget constraints.

The key point is to properly select this independent a priori information. It has to be linked to the physics of earthquake preparation and it has to be able for guiding the GNSS monitoring and improving its power, without constraining too much the geodetic results. This in order to avoid that GNSS data can act only as a mere (thus non-informative) confirmation of the a priori information itself.

This information can be found in the main well known tectonic setting, able to indicate preferential directions along which to look for strain accumulation. Therefore, the main trend of the known tectonic setting can act as a priori information, reducing the strain accumulation exploration space from 2D to 1D. This dimensional reduction may naturally improve the spatial resolution and accuracy of the geodetic results, provided a sufficient number of geodetic benchmarks (here, GNSS stations) are available along the selected directions.

In practice, the analysis of the GNSS data aims to estimate the 1D velocity with its error bar and to derive velocity variation and strain pattern along transects aligned according to the selected directions and approximately 50 km wide. The transects width has been chosen as a reasonable compromise between the opposite needs to consider a substantial number of GNSS stations and to improve the spatial resolution, meanwhile guaranteeing that the tectonic setting across the transects is as much as possible

homogeneous (Panza et al. 2018). Overall, the area corresponding to each transect is defined on the basis of two kinds of quantitative information: the direction along which to look for strain accumulation selected on the basis of the known tectonic setting, the width (here chosen at 50 km) dependent on the number of available GNSS stations.

2.2. The Applications in Italy

In the following applications a systematic retrospective analysis has been performed along a number of transects located both along and across-strike, with respect to the dominant tectonic trend characterizing the regions (Fig. 1) currently monitored by the CN algorithm (Peresan et al. 1999; Peresan 2018). This analysis (including stability tests) has been carried out considering GPS time series preceding the 2012 Emilia earthquake and the 2016 Central Italy seismic crisis, which were associated with a CN alarm declared for Northern and Central regions, respectively. In details, the available geodetic data analysed in this study are from GPS (Devoti et al. 2014; Devoti and Riguzzi 2018), consisting of International Terrestrial Reference Frame (ITRF) daily coordinates time series (with non uniform interval for all stations) before the events (Emilia: end of May 2005 to end of March 2012, Central Italy: beginning of January 2005 to middle of August 2016), but with non-uniform interval for all stations.

Velocity variation and related strain accumulation are highlighted, with due consideration of the errors involved in GPS data and the consequent velocity estimated accuracy. In particular, velocities along transects were piece-wise linearly buffered considering their accuracies, whose evaluation is not a simple issue (Devoti et al. 2017) since the simple covariance propagation within least squares estimation is not able to account for model error. Therefore, we decided to perform this evaluation on the basis of the comparison of two different official solutions (coordinates and their covariance matrices) coming from EPN (European Permanent Network) (Bruyninx et al. 2012) and RING (INGV RING Working Group 2016) on common GNSS permanent stations. These solutions are routinely generated with slight different models/software but using the same GPS
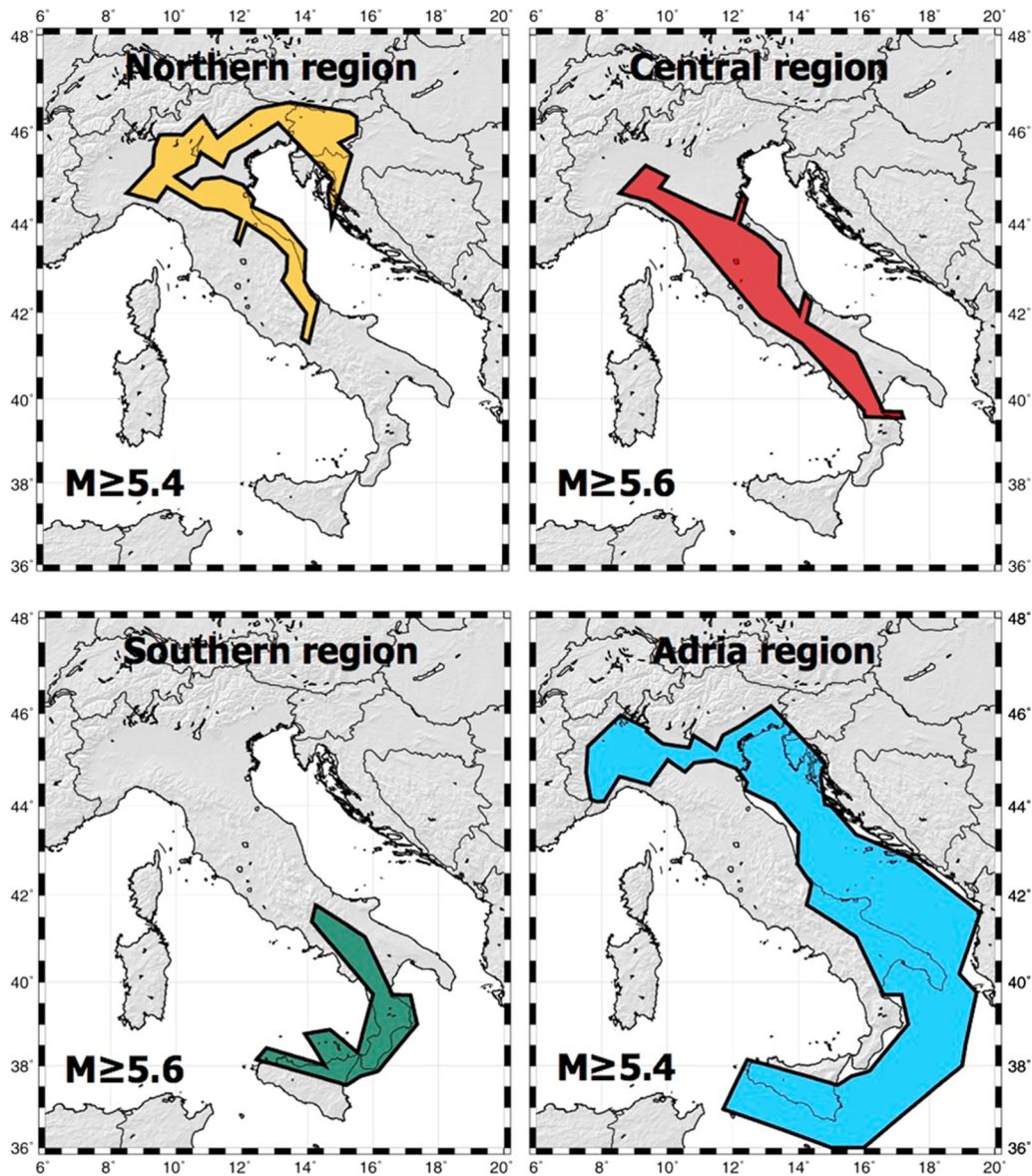
Figure 1
Regionalization used in the CN prediction experiment in Italy (after Panza et al. 2018 and references therein). The regionalization is composed by four partially overlapping regions, based on the seismotectonic model. The magnitude threshold identifying the target earthquakes is given for each region

observations. In such a way, also the slight effects of different processing models are at least approximately evaluated and taken into account.

Each buffer is defined around the robust piecewise linear interpolation of velocities (RANSAC algorithm Fischler and Bolles 1981); its width is taken equal to 6 times the Median Absolute Deviation (6 MAD), that is equal to 6 times the standard deviation for the normal distribution. This width ranges within 0.6 mm/year and 1.3 mm/year for all the considered transects.

2.2.1 The 2016–2017 Seismic Crisis in Central Italy

We consider three transects across-strike (Amatrice, Camerino and Raiano), approximately 180–200 km long crossing the Apennines from the Tyrrhenian to the Adriatic sea along the direction of maximum tectonic extension (approximate azimuth 55°), with the axis passing, respectively through Amatrice, Camerino and Raiano, and just one transect along-strike (Amatrice along), approximately 200 km long orthogonal to the direction of maximum tectonic extension (azimuth 145°). No other along-strike transects parallel to the Amatrice along one were considered, due to the severe lack of GNSS stations both westward and eastward (Fig. 2).

Comparing the velocity behaviours (Fig. 3) of the three transect across-strike, it is at first evident the well-known tectonic extension across the Central Italy Apennines and the expected velocity reduction, between Amatrice area and the Adriatic coast, which experiences tectonic shortening Scrocca et al. (2003). Anyway, in case of Amatrice transect it is also evident a velocity peak in the area between Rieti and Amatrice; this is a robust indication supported by the sufficiently dense distribution of GPS stations (a large part non-permanent ones) (Devoti et al. 2017) along the transect, mainly in the area between Rieti and Amatrice. This geodetic signature represents an anomaly in the Amatrice transect with respect to the surrounding regional trend. In fact the extensional trend identified for Camerino and Raiano data, even if supported by a lower number of GPS stations with respect to the Amatrice transect, does not mimic at all Amatrice across-strike velocity pattern. In the Amatrice along-strike transect, no significant velocities are detected (Fig. 4).
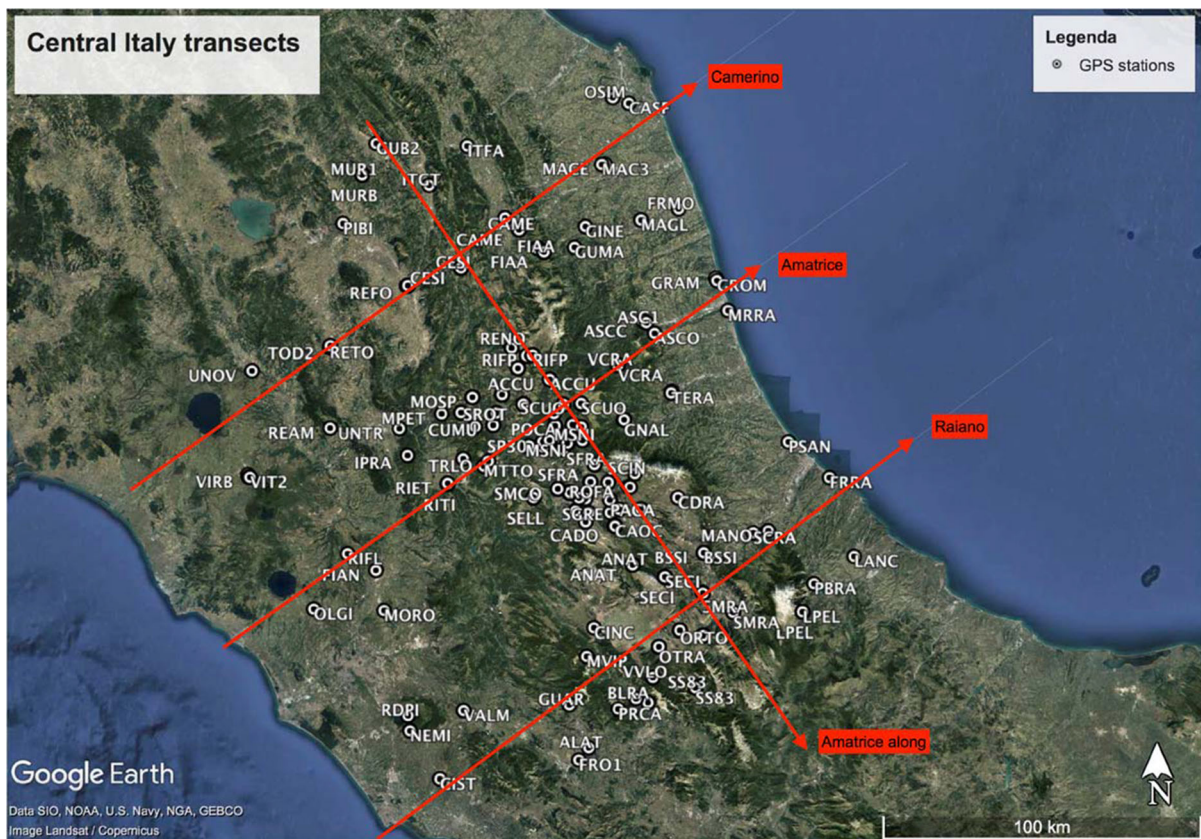

Figure 2
The four transects (across-strike: Amatrice, Camerino, Raiano; along-strike: Amatrice along) considered for the retrospective analysis of the 2016–2017 seismic crisis in Central Italy
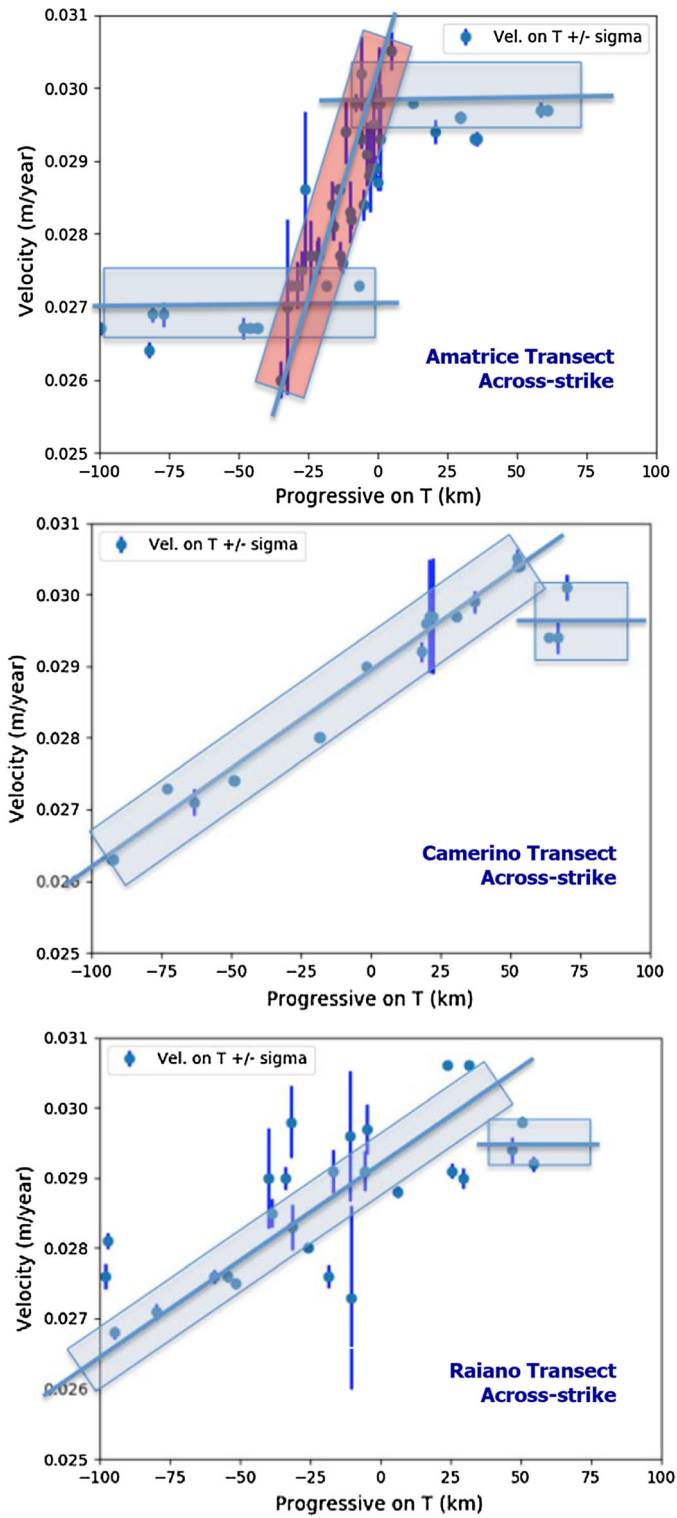
Figure 3
Velocity patterns within the Amatrice, Camerino and Raiano across-strike transects (velocities at GPS stations are indicated with their error bars 6 MAD wide)
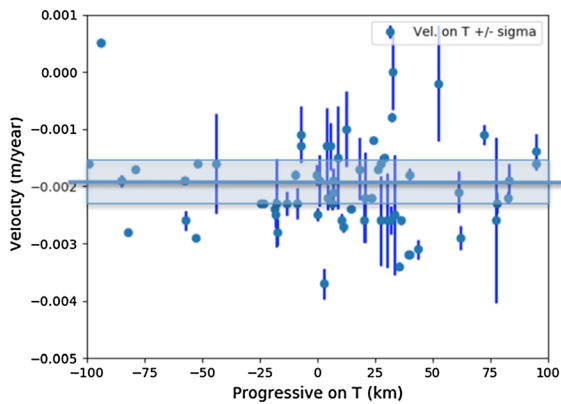
Figure 4

Velocity patterns within the Amatrice along-strike transect (velocities at GPS stations are indicated with their error bars 6 MAD wide)

The GPS data have been further analysed, in order to investigate if the mentioned peak velocity gradient in the area between Rieti and Amatrice changed significantly with time, during the whole time interval, beginning of January 2005–middle of August 2016 for which significant data are available (time stability analysis). To this aim, only the GPS stations active and reliable for about 2/3 of the whole time interval have been considered; this strict condition allowed for the selection of 14 GPS stations. Considering the possible effects of the strong earthquake occurred in L'Aquila (6 April, 2009) on some GPS stations (jump in the positions time series) the whole interval has been split into two sub-intervals, before and after the 2009 L'Aquila earthquake (an example for VCRA station in Fig. 5). A rather consistent behaviour before and after the L'Aquila earthquake has been assessed for all the selected 14 GPS stations: no significant change with time has been detected for the velocity in the area between Rieti and Amatrice, which result to be a long term stable pattern with respect to the length of the GPS permanent station coordinate time series.

Overall, a time independent (long term) geodetic signature, represented by an anomalous velocity peak, was highlighted only along the Amatrice across strike transect; this geodetic signature is well coherent with the extensional focal mechanism and the location of the Amatrice earthquake on 24 August 2016.

2.2.2 The 2012 Emilia Sequence

We consider three transects across strike (Mantova, Finale Emilia and Imola), approximately 130–160 km long in Northern Italy, from the Apennines to the Po Valley along the direction of maximum tectonic shortening (approximate azimuth 25°), with the axis passing, respectively through Mantova, Finale Emilia and Imola, and three transects along strike (Finale Emilia along, Brisighella, Apennine Crest), approximately 150–200 km long orthogonal to the previous ones (azimuth 115°) (Fig. 6).

In spite of the fact that the number of GPS stations is remarkably lower than in the case of the Amatrice transect, these six transects supply some information that may support the validity of our findings. As a matter of fact, at first, no significant acceleration peaks are evident in the across strike transects (Fig. 7); some velocity discontinuities could be seen in two (Brisighella, Apennine Crest) out of three along-strike transects (Fig. 8). These outcomes could be in agreement with the CN alarm for the Emilia 2012 earthquake, which started on March 1st 2012, and well consistent both with the strike-slip focal mechanism and the location (approximately coincident with the area where discontinuities in the velocity are observed) of the 29 May 2012 earthquake, as estimated according to INPAR approach (Bruyninx et al. 2012) (Fig. 9). The assessment of this hypothesis requires accumulation of more data.

Overall, time independent (long term) geodetic signatures, represented by velocity discontinuities, are possibly seen in the along-strike Brisighella and Apennine Crest transects; these geodetic signatures are coherent with strike-slip focal mechanism and location of the 29 May 2012 Emilia earthquake.

2.2.3 Discussion

The developed analysis on the selected transects allow us to identify in Amatrice, across strike; Apennines crest and Brisighella, along-strike transects reliable geodetic signatures, represented by velocity anomalies (peaks, discontinuities), thus associated to strain rate distribution in space, whose time independence is assessed in several years (even
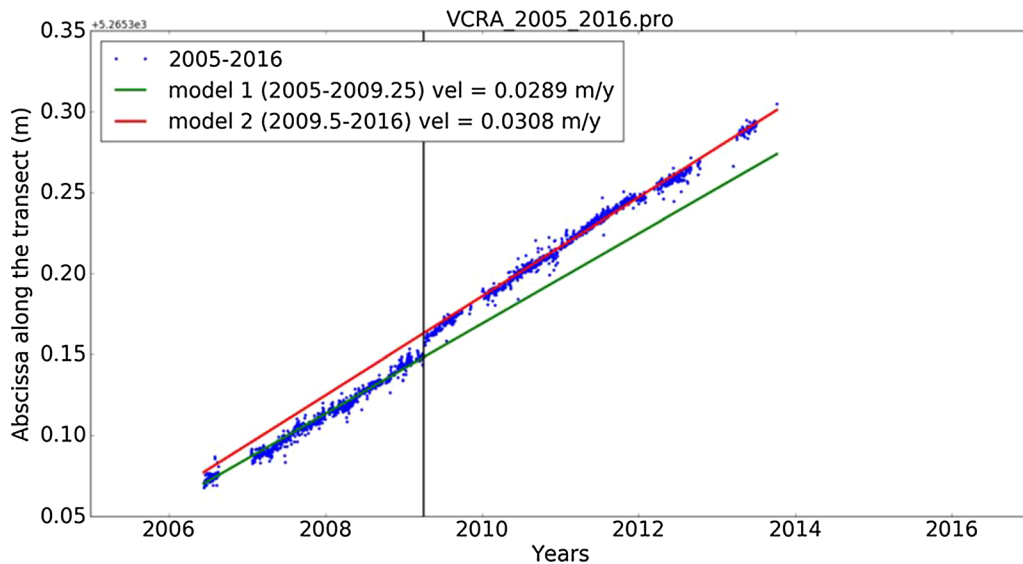
Figure 5
GPS station VCRA—linear robust velocities estimation along the Amatrice transect before and after the L'Aquila 2009 earthquake

more than 10) preceding the occurrence of the studied earthquakes.

At first, it is important to note that this time independence holds both in case of extensional (Central Italy) and shortening (Emilia) tectonic setting.

Moreover, it is relevant to underline that the highlighted time independent (long term) geodetic signatures, are well coherent with the focal mechanisms and the locations of the occurred earthquakes. In this respect, these geodetic signatures highlight the strain accumulation in preparation of the Emilia and Amatrice earthquakes.

3. Intermediate-Term Middle-Range Earthquake Prediction: Neo-Deterministic CN and M8 Approaches

Italy is the only country worldwide where the two independent, globally tested, CN and M8S algorithms are simultaneously applied since about 2 decades. These algorithms were originally formulated based on retrospective analysis of seismicity in the California–Nevada region (for CN) and preceding the greatest earthquakes with magnitude $M \geq 8$ worldwide (for M8), respectively, hence their names. CN and M8 are structured according to the general scheme of pattern recognition; robust quantification of the seismicity patterns is obtained through a set of empirical functions of seismicity, each representing a reproducible precursor, whose definition has been guided by the theory of complex systems and laboratory experiments on rocks fracturing (e.g. Keilis-Borok 1996; Rotwain et al. 1997). The M8S algorithm is a modification of M8 designed for a stabilized application in regions of moderate seismicity where earthquake catalog does not provide enough data for evaluation of the original estimates of seismic transients (Kossobokov et al. 2002). A detailed description of the algorithms and their rigorous prospective testing in Italy is provided in Peresan et al. (2005); see also Peresan (2018) for a recent expansion and review.

CN and M8S algorithms deal with multiple sets of seismic transients for identifying Time of Increased Probability (TIP) for a region where a strong event is likely to occur. The forecast/prediction rules are clearly specified so that, if an earthquake with magnitude above a predefined threshold $M \geq M_0$ (i.e. so-called "target event") occurs, it can be readily judged whether it falls within or outside the anticipated space–time-magnitude volume, namely if it has been predicted or not. The predefined rules make
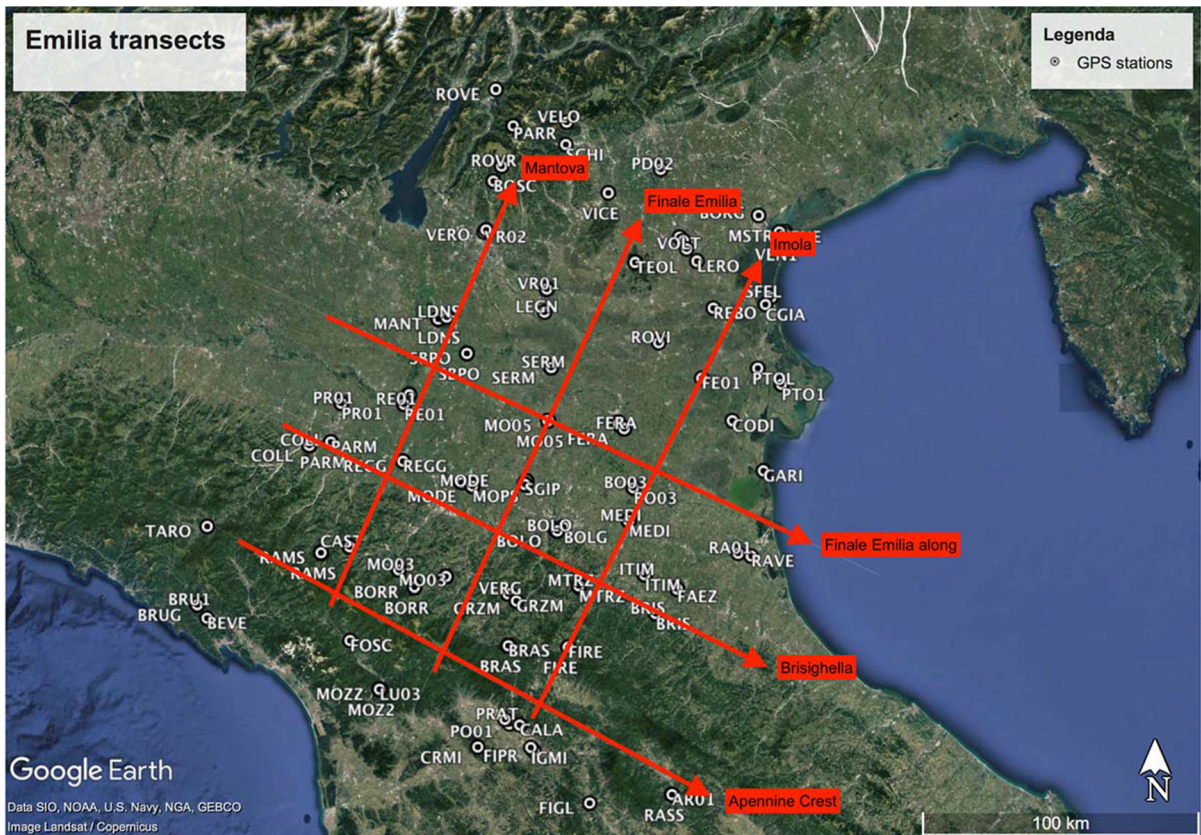
Figure 6
The six transects (across-strike: Mantova, Finale Emilia, Imola; along-strike: Finale Emilia along, Brisighella, Apennine Crest) considered for the retrospective analysis of the 2012 Emilia earthquakes

"falsifiable" both CN and M8S algorithms and permit assessing their performances by systematically recording, for a sufficiently long time, the number of successful predictions and failures to predict, along with the number and duration of alarms.

The real-time prediction experiment is ongoing in the Italian region and its surroundings, aimed at truly prospective testing of the forecasts by the M8S and CN algorithms. Specifically, CN predictions are regularly updated every 2 months since 1998 and a complete archive of predictions is available at: http://www.mitp.ru/en/cn/CN-Italy.html. Similarly, M8S predictions are updated every 6 months since 2002 and the archive of related predictions is available at: http://www.mitp.ru/en/m8s/M8s_italy.html. Current predictions are also made available on-line since 2003; to prevent their improper use, these predictions are accessible to professionals at password-protected

website. The obtained results already permitted a preliminary assessment of the statistical significance of the M8S and CN predictions, as shown hereinafter (see Molchan et al. 2017 for a detailed discussion).

3.1. Algorithm M8S in Italy

The algorithm M8S analyses seismicity within a set of overlapping circles of investigation, CI's, with a common radius proportional to the preparation zone size of the target events (Peresan et al. 2005). M8S forecasts for Italy are performed for three different magnitude ranges, namely M5.5 +, M6.0 +, and M6.5 +, where M_0 + indicates the magnitude range: $M_0 \leq M_0 < M_0 + 0.5$. Predictions are updated every 6 months. Algorithm M8S forecasted 17 out of 30 target earthquakes, which occurred within the area alerted for the relevant magnitude range, with about
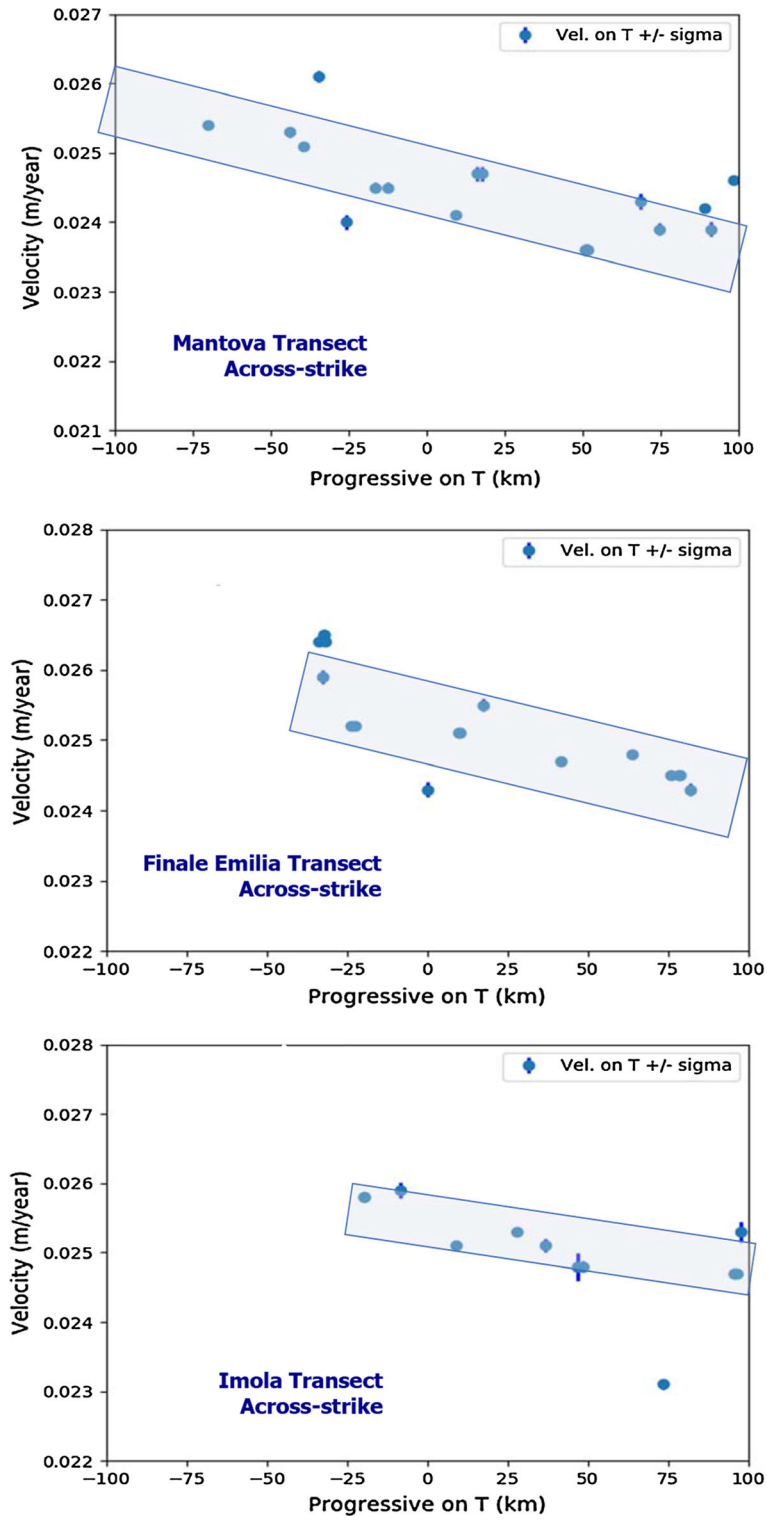
Figure 7
Velocity patterns within the Mantova, Finale Emilia and Imola across-strike transects (velocities at GPS stations are indicated with their error bars 6 MAD wide)
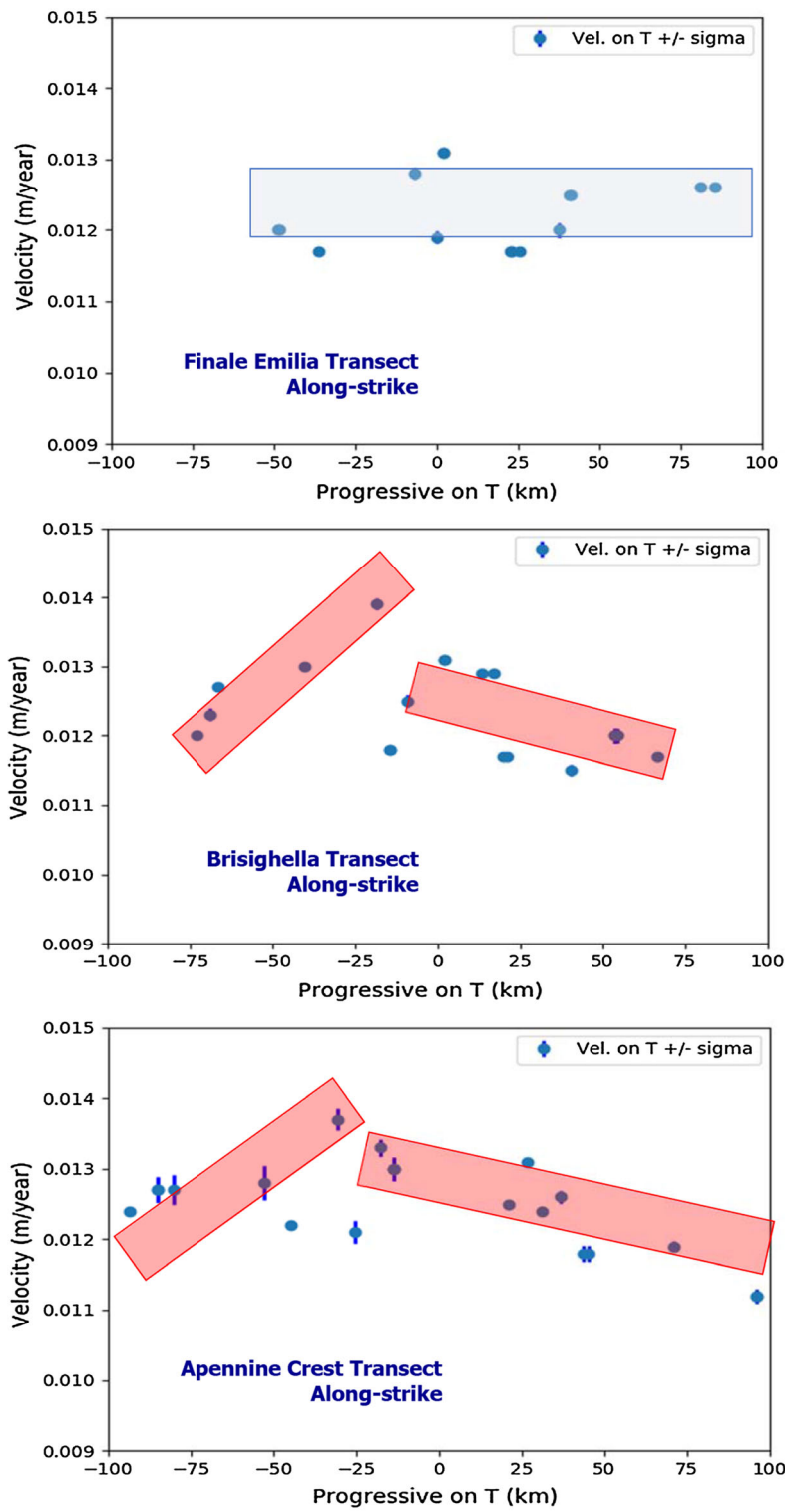
Figure 8
Velocity patterns within the Finale Emilia along, Brisighella and Apennine Crest along-strike transects (velocities at GPS stations are indicated with their error bars 6 MAD wide)
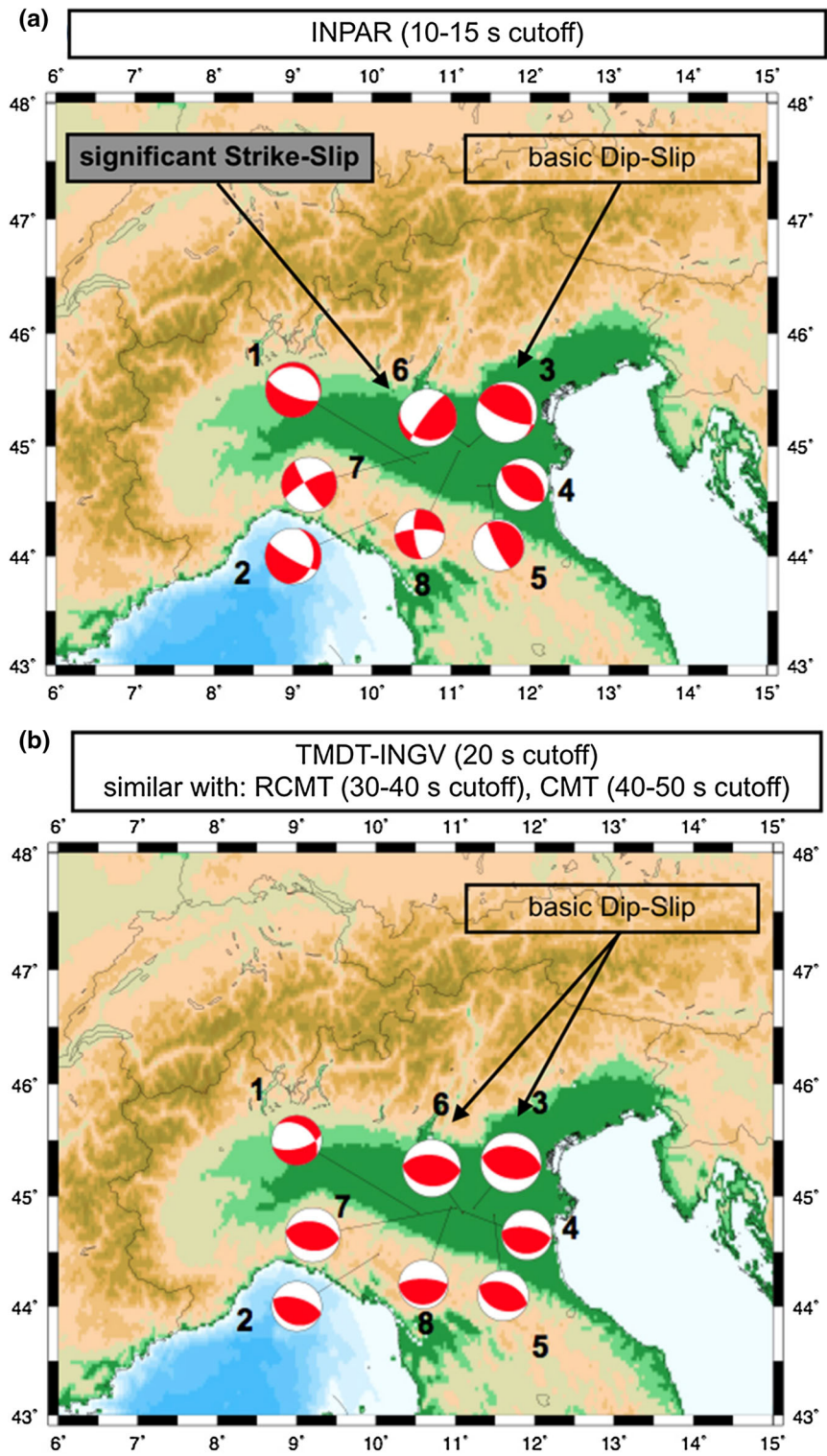
Figure 9

Focal mechanisms and earthquake locations as estimated by **a** INPAR and **b** TDMT-INGV for relevant earthquakes in Northern Italy, including the events on 20 May 2012 (number 3) and 29 May 2012 (number 6)

Table 1

Space–time volume of alarms (STV) for M8S application in Italy, for the three magnitude ranges defined by M6.5 +, M6.0 + and M5.5 +

Experiment	M6.5 +		M6.0 +		M5.5 +		
	STV (%)	n/N	STV (%)	n/N	STV (%)	n/N	Confidence level (%)
Retrospective (1972–2001)	35	2/2	39	1/2	38	9/14	95.8
Forward (2002–2018)	22	0/1	29	0/3	14	5/9	99.6
All together (1972–2018)	30	2/3	35	1/5	29	14/23	99.9

The confidence level of forward predictions for M5.5 + is above 99%

N total number of target events, n number of predicted earthquakes

30% of the overall space–time volume of alarms which accounts for actual distribution of seismic foci (Table 1). The confidence level of M5.5 + predictions since 2002 has been estimated to be above 99% (that is, the probability of obtaining similar results by random guessing, is below 1%); no estimation is yet possible for other magnitude levels, due to the extremely small number of target events. Further details about M8S results are provided in Peresan et al. (2015, 2016).

3.2. Algorithm CN in Italy

The algorithm CN analyses the seismic activity inside a set of four predefined regions (polygons), outlined according to the seismotectonic zoning (Peresan 2018). CN predictions are regularly updated every 2 months, since 1998. So far CN forecasted 22 out of the 26 target earthquakes, which occurred within the monitored zones of Italy, including Adria region, with about 30% of the considered space–time volume occupied by alarms (Table 2). The confidence level of CN forecasts has been estimated to be above 99%, so that the probability of receiving similar results by random guessing is far below 1%. A detailed discussion about CN results, including a list of target events, is available in (Peresan 2018).

The alarms, which refer to areas with linear dimensions of 100 km and having a duration of several months to years, are not compatible with evacuation or red alert, but can be very useful for many effective low key prevention actions (Kantorovich et al. 1974; Kantorovich and Keilis-Borok 1991; Peresan et al. 2012, Davis et al. 2012).

Note that at the meeting of the Commissione Grandi Rischi (CGR) of May 4th 2012, the reliability

Table 2

Space–time volume of alarm (STV) for CN application in Italy and its surroundings

Experiment	Space–time volume of alarm, STV (%)	n/N	Confidence level (%)
Retrospective[a] (1954–1963)	41	3/3	93.1
Retrospective (1964–1997)	26	10/12	> 99.9
Forward[b] (1998–2018)	33	9/11	99.9
All together (1954–2018)	30	22/26	> 99.9

During the period 1954–1963 only Central and Southern regions were analysed. Forward predictions for the Adria region begin in 2005

N total number of target events, n number of predicted earthquakes

[a]Central and Southern regions only

[b]Adria is considered since 2005

of CN alarm that was declared for "Northern (Italy) region" was questioned, but the May 21st 2012 earthquake in Emilia tragically confirmed the alarm. Similar predictions have been made before the earthquakes of Amatrice and Norcia (Peresan et al. 2016; Peresan 2018).

The probability gain of CN predictions is around 3, i.e. the occurrence probability of a target earthquake increases by a factor of 3 during the alarm, with respect to "normal conditions" (Peresan et al. 2015). For example, in the "Northern (Italy) region" as defined by CN (see Fig. 1) the probability of a target earthquake occurrence within 1 year, increases from 15% (average probability in normal conditions, with no predictive information) to 48% (during alarms). Similarly, in "Central region" during an alarm the probability of a target earthquake increases

by about a factor 4 (from about 12 to 45%). Given the statistic achieved so far by CN algorithm, the probability of observing a target earthquake when no alarm is declared within the region is pretty small, i.e. about 2–3%. Thus, although being characterized by uncertainties at the intermediate space–time scale, CN predictions are robust and significant, as they are validated by the rigorous prospective testing started in 1998 (and by the shared prediction experiment, after 2003) and provide not negligible probabilities of strong earthquake occurrence. A summary of the CN predictions since 1998 is given in Table 3.

4. Intermediate Term Narrow-Range Earthquake Prediction: The Benefit of Geodesy and Seismology Synergy

It is clear from the two previous paragraphs that both geodetic and seismological information are of high value for earthquake prediction, but in different ways with respect to space and time.

As a matter of fact, it was at first evidenced that geodetic signatures in geodetic time series are stable over long time, in the order of 10 years or more, so that they are basically time independent, at the time scale of interest here, in both the considered tectonic settings, extensional for Central Italy and shortening for Emilia. Secondly, these signatures can

Table 3

Summary of CN prediction in Italy since 1998

Date	Latitude (°)	Longitude (°)	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**

The earthquakes occurred during the period of real-time monitoring (i.e. since 1998 for North, Centre and South regions and since 2005 for Adria region) are evidenced in bold

display a very large space dependence, highlighting velocity anomalies (peaks, discontinuities) in space and the related strain accumulation, provided that a proper processing is carried out, just considering as prior information the knowledge about the tectonic settings. This prior information basically drives the orientation of the transects along which to look for the possible geodetic signatures. On the other hand, the neo-deterministic approach, for seismic hazard assessment (NDSHA), starting with pattern recognition of TIP by CN and M8S is able to supply time dependent information at the intermediate space and time scales (i.e. few 100 km in space, and several months to years in time) on the basis of seismological analyses.

This is the why it is important to integrate these information, in order to get the highest benefit from their synergy. The possibility of integration was already investigated, but following an essentially different approach, which was based on a more limited geodetic information and was using a whole set of precursors, in order to assess the relationship of geodetic precursors to future earthquakes (Sobolev et al. 1991; Zavyalov 2005). In this study, instead, the focus is placed on the possibilities offered by newly available improved geodetic observations, whose analysis is guided by a specific, well established set of seismic precursors.

The application of the integrated geodetic-seismological approach to the considered events indicates that it is possible to clearly highlight the velocity variation and the related strain accumulation along the Amatrice transect, focusing on an area of about only 5000 km^2 around Amatrice, included within the much wider Central region alarmed by CN since November 1st, 2012 (Fig. 10). Similar conclusions can be drawn for the 2012 Emilia earthquake, where the Apennines Crest and Brisighella transects show some discontinuity of the velocity, with the related strain accumulation, in an area of few thousand square kilometers, again included in the much wider Northern region alarmed by CN algorithm since March 1st, 2012 (Fig. 11). Anyway, the assessment of this hypothesis requires the accumulation of more data.

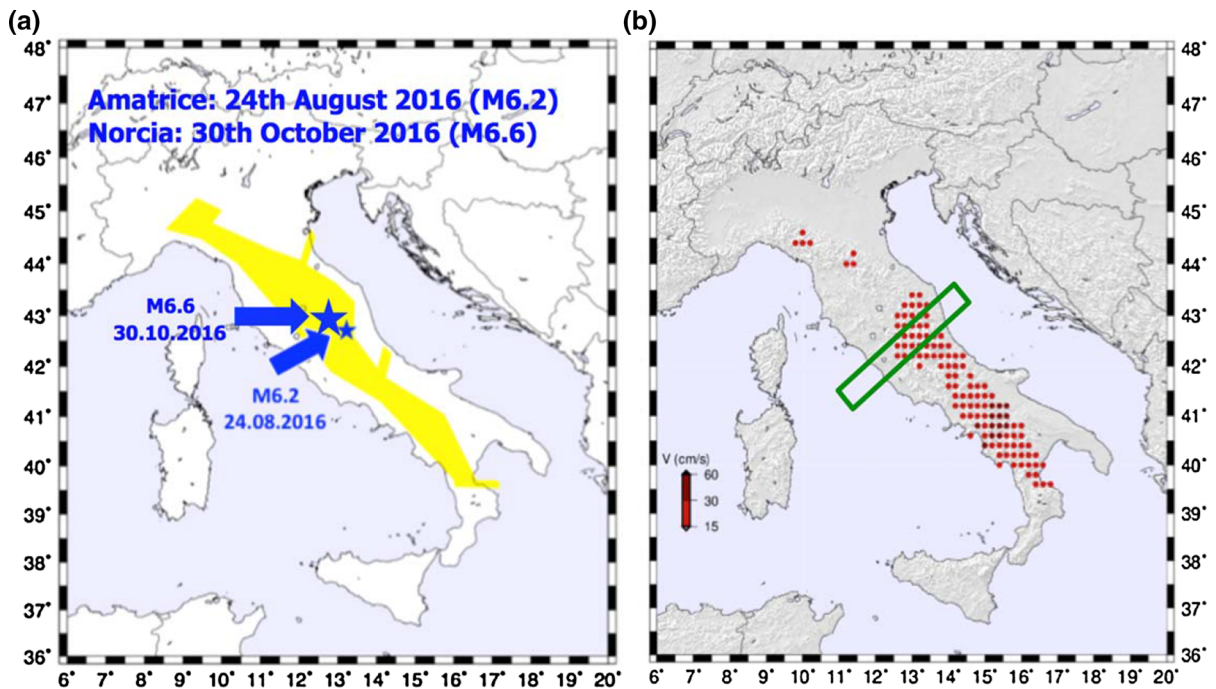Although earthquakes cannot be still predicted with ultimate precision, the results obtained so far

Figure 10
Synergic analysis of seismological and geodetic information: **a** CN alarmed area (yellow polygon) and epicenters of the Amatrice and Norcia earthquakes (blue stars); **b** intersection of Amatrice transect with geodetic signature (green rectangle) and CN related NDSHA ground shaking scenario (Panza et al. 2013a) associated with CN alarmed area, leading to a reduced zone (the rectangle) where preventive actions should be focused

show that the proper integration of seismological and geodetic information defines a new paradigm for time dependent hazard scenarios, achieving what is referred here as *intermediate-term narrow-range earthquake prediction* (see Table 1). Classification of earthquake predictions in Ismail-Zadeh and Kossobokov 2011). Accordingly, the extent of the alarmed areas, identified by CN and M8S based on seismicity patterns at the intermediate scale (i.e. linear dimensions of a few hundred kilometers for strong earthquakes of magnitude 6 or more), can be significantly reduced based on independent information from geodesy. These predictions, even if not ultimate and still not suitable to issue red alert, may enable an improved and reliable implementation of low-key preventive actions recommended by UNESCO (Fig. 12).

5. Conclusions and Future Perspectives

This study proposes an integrated approach to earthquake prediction, based on the synergic use of

geodetic and seismological information. NDSHA and CN procedures belong to the very exclusive class of algorithms validated by decades of prospective analysis (Peresan 2018; Rugarli et al. 2018); a number of methods proposed in literature are based on few retrospective case studies, and almost never prospectively validated. Full formalization of the integrated approach that includes GNSS/GPS data analysis is in progress. We present here fundamental original observations, aimed at future formalization and testing. Here the approach capability is assessed with examples and counterexamples in the Italian region. In fact, the new approach to GNSS data analysis relies on unprecedented density and quality of geodetic observations, which are available nowadays and were not available decades ago. The short time span of available high quality and density observations over the Italian territory now limits, if not prevents, a sound retrospective analysis, that will be the natural subject of future studies wherever appropriate.

This novel scheme is able to fully exploit the information content of the available data coming
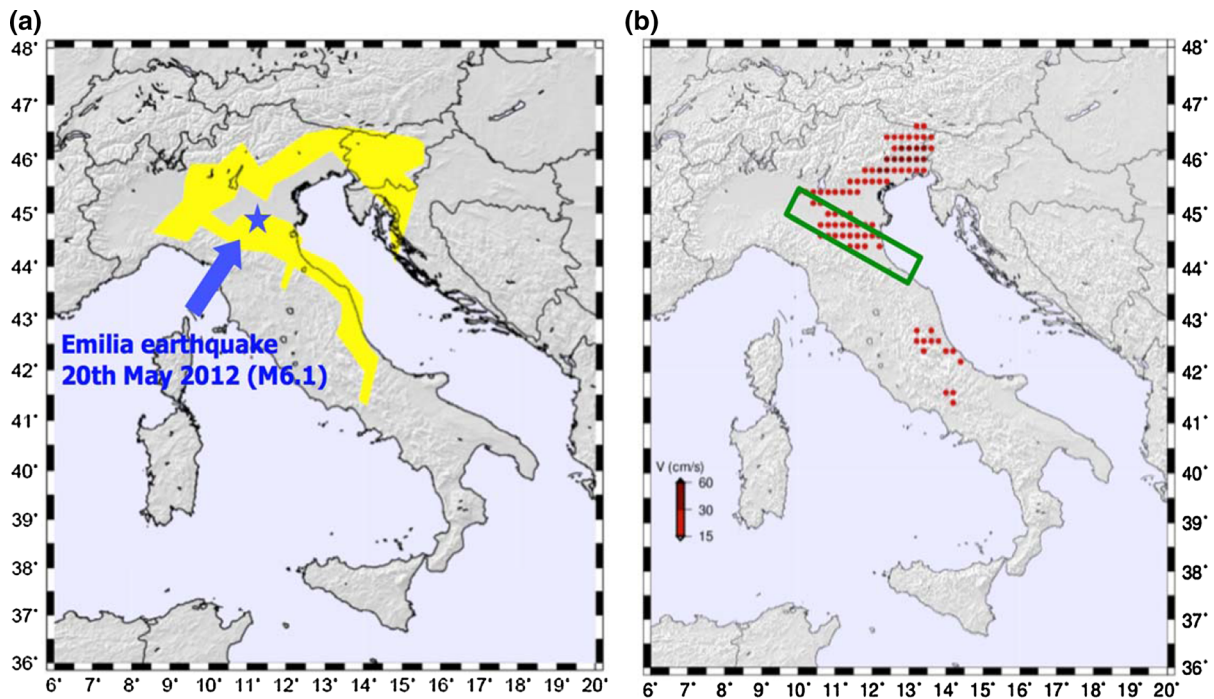
(a)

(b)

Figure 11

Synergic analysis of seismological and geodetic information: **a** CN alarmed area (yellow polygon) and epicenters of the Amatrice and Norcia earthquakes (blue stars); **b** intersection of Brisighella and Apennine Crest transects (green rectangle) with geodetic signature and CN related NDSHA ground shaking scenario (Panza et al. 2013a) associated with CN alarmed area, leading to a reduced zone (the rectangle) where preventive actions should be focused

from seismological and geodetic analysis, in order to delineate, as precisely as possible, the regions where to concentrate prevention actions and seismic risk mitigation planning has been developed.

Moving from the preliminary ideas and results presented in Panza et al. (2018), through a broader and refined retrospective analysis, duly involving the accuracy analysis of the geodetic results, the space-time precursory features are highlighted within ground velocities and seismicity. This is done analyzing the 2016–2017 seismic crisis in Central Italy and the 2012 Emilia sequence. The obtained results evidence that the integration of geodetic signatures and CN information can significantly reduce the space uncertainty of the alarmed areas, and thus improve the NDSHA time-dependent assessment of seismic hazard.

In conclusion, although earthquakes cannot be still predicted with ultimate precision, the proper integration of seismological and geodetic information

may allow achieving what can be referred as *intermediate-term narrow-range earthquake prediction,* with a time uncertainty of several months to years and a space uncertainty of tens of kilometers. This type of prediction, even if not ultimate and not suitable to issue red alerts, may lead to an improved reliable implementation of low-key preventive actions like those recommended by UNESCO.

Future research perspectives can be outlined based on the outcomes of the present research.

At first, new transects in Italy (e.g. southern Apennines, Irpinia, Calabria) should be considered, and additional retrospective analyses should be developed. Similarly, other regions in the world could be considered and analyzed, depending on data availability.

In addition, from a purely geodetic point of view, the number and the density of the monitored sites should be increased, benefiting of both GNSS and SAR data: the densification of GNSS permanent
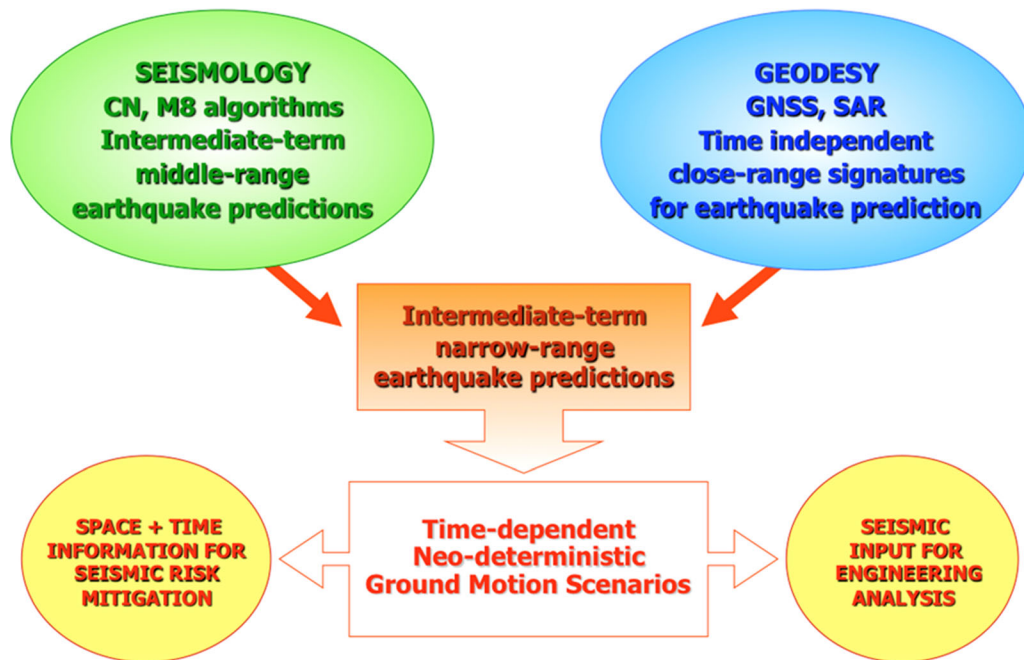
Figure 12
Synoptic scheme of the proposed integration of seismological and geodetic information towards improved earthquake prediction and hazard assessment

network should be pursued, also considering the coming (in few months) low-cost dual frequency multi constellation receivers, and a new deeper analysis of ascending and descending SAR stack imagery from COSMO-SkyMed and Sentinel-1 should be carried out, for a possible significant densification of the monitored geodetic benchmarks where possible. At the same time, rigorous prospective testing should be set up and duly continued, to allow for ultimate assessment of the effectiveness of the proposed integrated approach.

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