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State of the art on short-term earthquake forecasting and preparation in Italy: a preface

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ABSTRACT Main outcomes are reported of the first year of activity of the DPC-INGV-S3 project devoted to explore present situation of earthquake forecasting studies in Italy. The general paradigm beyond the project is that earthquakes are part of a large scale process whose ongoing features can only be detected by considering multi-parametric monitoring of large areas carried on for relatively long time spans. The focus of the first year of activity was on the analysis of the state of the art concerning a number of observables potentially of interest: deep fluids piezometry, seismicity, gaseous ground emissions and temperature, electromagnetic perturbations, short-term geodetic deformation and crustal elastic properties. To evaluate the actual heuristic potential of the above observables as expression of ongoing seismogenic processes, the reappraisal and exploitation of significant data sets collected in the past and relative to these were of main concern. Along these features, deterministic and statistical procedures for medium-term earthquake forecasting were also considered as a tool for detecting areas most interesting for future monitoring activity.

Key words: earthquake prediction.

1. Introduction

In the frame of the guidelines defined in the general agreement between the Department of Civil Protection and National Institute of Geophysics and Volcanology (DPC and INGV respectively) for the period 2012-2021, three new research projects were planned aiming at exploiting more advanced researches carried on in Italy to improve preparedness to future seismic events and supporting risk reduction programs. One of these projects focuses on "short-term earthquake prediction and preparation" and represents, from the cultural point of view, a strong discontinuity with respect to the main trend of seismological researches performed in Italy in the last 30 years.

After the strong interest on this topic that has followed the successful Haicheng prediction (1975), researches and field experiments were promoted in all developed countries (Hough, 2010). After about 15 years of studies, frustration prevailed having the Parkfield failed prediction experiment (1980-1990) as a paradigmatic example of unsuccessful prediction (false alarm). In Italy, in particular after the devastating Irpinia earthquake in southern Italy (November 23, 1980), the problem of earthquake forecasting assumed the form of a public harsh debate that invested both the scientific community and public opinion. In 1985 (January 23), a short-term (three days) seismic alarm was issued for the Garfagnana zone (northern Tuscany) but no seismic event occurred. Mainly due to the lack of preparedness of local population and a possibly negligence in communication [the alarm was abruptly issued during the TV prime time, see Pastore (1987)] this "false alarm" involved significant disruption to normal life, with associated costs and stresses and was again the source of a dramatic public debate (involving legal consequences for scientists and authorities). Since that, partially due to the lack of outstanding results, partially for the negative uncontrolled reactions experienced in 1980s and partially for the global trend involving the U.S.A. and most of other western countries, no coordinated research project was planned in Italy and no significant funding was provided for this kind of researches. A paradigmatic position denying any possibility of earthquakes forecast became the mainstream (at least as concerns communication outside of the scientific community) and the word "forecasting" itself became at some extent "impolite". A common misunderstanding is probably at the base of this apodictic position. In fact, it answers to a wrong question: the problem is not if the forecast is possible but, instead, what kind of forecast we are able to provide (Albarello and Meletti, 2012).

Actually, "earthquake forecasts" that are being provided concern long-term predictions and are widely considered for anti-seismic design of buildings: seismic hazard maps (http://esse1.mi.ingv.it/) actually represent a "forecast" for the maximum reasonable ground shaking expected in a future exposure time. Scarce attention was instead devoted by the scientific community to middle- and short-term prediction studies, probably also due to the lack of outstanding results ("no results – no money" vs. "no money-no results"). Beyond the lack or scarcity of financial support for researches, this situation also generated a "no-man land" that was occupied by any kind of "enthusiastic volunteers" in many cases out of any systematic scientific control. This generated the dramatic situation arisen during the 2009 L'Aquila seismic crisis with a frontal crash of the scientific community on one side (denying any possibility of reliable earthquake forecasting) and "self-made" answers to the growing demand coming from public opinion.

After that event, an International Commission on Earthquake Forecasting for Civil Protection was established to provide an "external" referee about the status of knowledge about earthquake prediction (Jordan *et al.*, 2011). The outcome of this commission was a "state of the art" review (see also Cicerone *et al.*, 2009) but, more straightforwardly, also a number of important recommendations. Among these, it was stated that "*A basic research program focused on the scientific understanding of earthquakes and earthquake predictability should be part of a balanced national program to develop operational forecasting (Recommendation C)"* and *"DPC should continue its directed research program on development of time-independent and time dependent forecasting models, with the objective of improving long-term seismic hazard maps that are operationally oriented (Recommendation D)"*. Of course, *"Forecasting methods intended for operational use should be scientifically tested against the available data for reliability and skill, both retrospectively and prospectively. All operational models should be under continuous prospective testing (Recommendation F1)"*. This position (that can be defined as "well-disposed scepticism" in contrast with "wishful data mining" that characterized early researches) also reflects a renewed interest towards this kind of studies in the U.S.A. and other countries (e.g., Kagan, 1997; Kagan and Jackson, 2000; Johnson, 2009). These, at least partially, are the result of the unsatisfactory status of seismic hazard assessment studies, that at presents are mainly linked to time-independent estimates provided in the frame of 40-year old Cornell-McGuire approaches (see, e.g., Mucciarelli and Albarello, 2012; Stein *et al.*, 2012).

In general, earthquake forecasting develops along two main branches: seismic hazard assessment (SHA) and earthquake prediction (EP). A major difference between SHA and EP is the target of forecasting: while SHA focuses on the ground motion scenario, EP aims at the definition of time and location of future seismic sources activations. Furthermore, SHA studies mainly concern long-term forecasting (tens of years or more) while EP focuses on middle-short-term forecasting (years to minutes). There are significant methodological differences underlying these two kinds of studies. In the common practice, SHA is mainly characterized by phenomenological approaches relying on the stochastic modelling of the underlying seismogenic process parameterized by considering past seismic history (statistical approach). On the other side, EP is mainly carried on by identifying observable phenomena able to characterize the present status of ongoing seismogenic processes potentially responsible for future damaging earthquakes (deterministic approach). Of course, deterministic and statistical approaches should be considered as end-members of a continuum spectrum of procedures where deterministic and statistical arguments contribute at a different extent. As an example, deterministic approaches to SHA have been proposed (e.g., Zuccolo *et al.*, 2011) and purely statistical approaches to EP exist in the literature (e.g., Marzocchi and Lombardi, 2009).

Beyond the differences stated above, however, being both SHA and EP provided by considering uncertain and incomplete information, their respective outcomes have a probabilistic form to express the actual degree of belief associated to each forecast. Thus, no solution of continuity exists between SHA and EP. Both SHA and EP must be prone to empirical validation procedures (e.g., Schorlemmer and Gerstenberger, 2007; Albarello and D'Amico, 2015) to warrant their respective reliability. Actually, EP tools represent a fundamental integration to refine SHA outcomes as concerns middle and short-term forecasting. In particular, they could help in defining priorities for choosing areas where more urgent are risk reduction interventions and improving emergency preparedness.

In this general view and as a result of the new climate surrounding the topic of earthquake forecasting, DPC and INGV decided to promote new explorative studies on earthquake forecasting (both in the long, middle and short-term) to provide national institutions of new tools for earthquake hazard assessment. This DPC-INGV-S3 project ("Short-term earthquake forecasting and preparation") was the result of this initiative. In the following, the conceptual background, the rationale of the project and the main research lines are illustrated to introduce outcomes provided by the research groups operating in the frame of the project during the first year of activity and reported in the papers included in the present special issue.

2. The conceptual background

The preliminary step for the definition of an effective research project devoted to earthquake forecasting is the identification the classes of observables of potential interest among those that in the last years were the argument of researches and experimental observations [see, for an extensive review, Cicerone *et al.* (2009)].

The first class of observables that was the subject of major scientific interest in the last years (Jordan *et al.*, 2011) is that related to seismicity studies carried on by considering stochastic models and tools. The second class concerns monitoring of underground fluids [radon (Rn), piezometry of confined aquifers] and variations of physical/mechanical properties of the crust (electrical conductivity, thermal anomalies, regional scale strain field variations, Vp/Vs ratios, seismic anisotropy, etc.) from surface measurements. The third class concerns large scale remote sensing (ground displacements, variations in the electromagnetic field, thermal radiation studies, etc.) from satellite data. These classes include quite different and complementary phenomena, all potentially related to the seismogenic process. In front of this wide spectrum of possible observations, there is the general lack of a well accepted and experimentally sound physical model linking the active seismogenic process to each of the observables listed above (Mulargia and Geller, 2003).

Recent data (Amoruso and Crescentini, 2012) suggest that nucleation of earthquakes affects a relatively small volume around the potential hypocenter (less than 100 km^3 in the case of the 2009 L'Aquila earthquake) and this makes highly problematic, except than in very peculiar situations, the direct monitoring from the surface of preparation phenomena. This could explain the lack of clear one-to-one correspondences between "anomalies" of any kind and the subsequent earthquake generation (Jordan *et al.*, 2011). On the other hand, several authors (e.g., Kagan, 1994; Main, 1995, 1996) suggest that the seismogenic process is "critical" in nature (e.g., Kagan, 1992; Turcotte, 1992) being the effect of small scale mechanical interactions of a multitude of elementary seismogenic structures (e.g., Sacks and Rydelek, 1995; Castellaro and Mulargia, 2001). This kind of systems exhibits a strong sensitivity to small variations of the tectonic environment hosting the potential seismogenic structure. In particular, small strain field variations (of the order of 0.1 μstrain), could severely modify the local seismic hazard (e.g., Rydelek and Sacks, 1999). In this view, identification of observables able to provide short-term indications about incoming earthquakes seems to require a change in the cultural paradigm that characterizes this kind of studies (Albarello, 2005): instead of a "silver bullet" relative to any forecasting "anomaly", one should search for multi-parametric indexes able to capture short-term variations of the regional strain field that have the earthquake as a possible effect. Here, "anomalies" are not expected to be generated by the earthquake nucleation process, but reflecting larger scale (both in time and space) crustal phenomenon (Rydelek e Sacks, 1990; Viti *et al.*, 2003; Pollitz *et al.*, 2006; Ryder *et al.*, 2007; Mantovani *et al.*, 2010, 2012).

Thus, forecasting of local/punctual phenomena as a seismic event requires the multi-parametric analysis involving different events scattered in space and time. This purpose, gathering data for different sources becomes mandatory along with availability of suitable processing techniques also based on Artificial Intelligence Strategies (e.g., Buscema and Benzi, 2011).

This paradigm displaces the attention from the search of single "anomalies" of any considered observable, to the collection of data sets aimed at reconstructing regional scale processes responsible for the expected earthquake. In this way, it may become possible retrieving a more coherent and straightforward perspective that will allow overcoming difficulties and conflicts that endlessly dominated the seismological debate in the last years.

3. The rationale of the DPC-INGV-S3 project

A major difference of research projects devoted to EP with respect to those relative to SHA is the lack of previous experiences (at least in Italy) of coordinated researches devoted to this topic. This aspect was discussed during several Italian scientific meetings (e.g., Albarello and Meletti, 2012) pointing out that the main limitation of researches so far carried on in the field of short-term earthquake forecasting relies on the lack of standardized observational data having sufficiently extended coverage both in time and space and specifically collected to monitor earthquake generation processes. In the recent years, despite of the fact that many institutions or single researchers performed generous attempts in this direction, no systematic, well supported and coordinated effort was devoted to monitoring observables of potential interest. In order to select the most interesting ones four basic issues have to be considered:

- multi-parametric observations over wide areas should be preferred since these are potentially able to provide an integrated image of ongoing geodynamic processes responsible for the incoming earthquake;
- economic suitability of monitoring procedures is of major concern (low operating costs) to allow long-term monitoring (well beyond the project duration);
- availability of physical models (whether incomplete) accounting for the possible association of the observable and ongoing seismogenic processes;
- possibility to falsify hypotheses concerning the above association on the basis of empirical tests.

A further constraint came from the strong temporal (one year possibly extended to further two years) and financial constraints (less than 300 K€). This made mandatory a preliminary selection of possible activities to be developed in the frame of the project. Three main research lines were identified:

1. review of the state of the art and reappraisal of data collected in the last years about observable and phenomena possibly related with ongoing seismogenic process. These data will be merged to provide a comprehensive multi-parametric database for retrospective validations and fixing observational protocols and standards;
2. retrospective empirical validation of patterns proposed as representative of ongoing seismogenic processes;
3. location of future monitoring networks relative to validated observables for an effective “forward” validation test.

In each research line, specific tasks were identified and funds allocation was provided (Table 1).

After a public call, 28 research proposals were submitted. Few words about the selection criteria adopted for the proposals to be included in the project:

- due to the financial limitations, no acquisition of new instrumental tools was allowed; the short time span of concern did not allow new monitoring campaigns in support of the proposed technique; thus, the bulk of the project is the reappraisal of data sparsely and independently collected in the last years by a number of institutions (not only academic) to provide a comprehensive multi-parametric database for retrospective validations and fixing observational protocols and standards;
- exploration of new promising research lines, internationally considered as feasible and so far less considered in Italy for monitoring seismogenic processes were favoured;

- following indications provided by DPC, two specific geographical areas (Po Plain and southern Apennines) were focused on: this implied that research project relative to possible observations only carried on outside the areas of interest were not considered for funding;
- observables relative to wide areas (e.g., those provided by observation networks or remote sensing) and characterized by good temporal continuity were of special interest;
- application of statistical testing procedure to validate effectiveness of proposed observations for monitoring the seismogenic process was considered of paramount importance;
- of major importance was defining areas most prone to next future earthquakes and where institution of specific observational networks will allow, in the next years, more effective testing of proposed protocols.

Table 1 - Scientific organization of the S3 project.

RESEARCH LINE	TASK	TOPIC	FUNDS (KEURO)
WP 1	Task 1	Deep seated underground fluids	44
	Task 2	Variations in the mechanical properties of the crust from seismic measurements	40
	Task 3	Seismicity patterns	20
	Task 4	Variations in the crustal displacements and strain field from satellite measurements	45
	Task 5	Variations in the electromagnetic field from ground based measurements	43
	Task 6	Variations of ground thermal emissions from satellite measurements	30
WP 2	Task 7	Application of validation protocols to available observations	18
WP 3	Task 8	Medium/short term forecasting of areas most prone to future seismic activations in the Po Plain and southern Apennines	30

By taking these criteria into account, 10 Research Units (RUs) were established including public companies (ARPA-Emilia-Romagna) research institutions (INGV, OGS, and CNR-IMAAA), and universities (Bologna, Basilicata, Bari, Siena, and Trieste): more than 70 researchers were involved.

4. Main results

Expected outcomes of the project were planned in the form of deliverables. In essence, three main kinds of deliverables were planned, corresponding to three main work packages (WPs). The first kind of deliverable (WP1) aimed at providing DPC of an effective overview of most recent experiences in Italy and elsewhere to evaluate what has been done and what could be done. A result was also the definition of best practice to monitor the relevant observables. This is a basic aspect in a research field where well-grounded scientific research is mixed to enthusiastic and fanciful experiences. Results of this WP had the form of deliverables respectively devoted to hydro-geochemical, seismological, geodetic, electromagnetic and thermal emission data. Four of them are reported in the present volume [see the contributions by Cenni *et al*. (2015), Martinelli (2015), Piccinini *et al*. (2015), Riggio and Santulin (2015), Tolomei *et al*. (2015), Tramutoli *et al*. (2015a)].

The second kind of deliverable of this WP was a database collecting observations actually available in the Italian area relative to each kind of observable. The population of an extensive database of parameters of interest represents the core of the whole project. Actually, no validation procedure can be performed in the lack of a reliable database of information collected on sufficiently wide areas and long times. In particular, key aspects of the expected database were:

1. clear and exhaustive characterization of the site and of sampling procedures;
2. maximum possible time coverage, irrespective to the occurrence of earthquakes (spot sampling just after the earthquakes has not been considered;
3. maximum spatial coverage, well beyond the two areas of potential interest;
4. construction of a comprehensive georeferenced database.

A basic difficulty met by some RUs for gathering data, was that data are widely dispersed over the territory and managed by a number of public and private companies that are not interested in sharing data and provide uniform formats. This is particularly true as concerns hydrogeochemical and Rn observations. Details concerning the structure of the database can be found in the project website (https://sites.google.com/site/ingvdpc2012progettos3/home) built on purpose for disseminating results of the project and inform the seismological community about ongoing acitivites. An example of the problems encountered in this work can be found in the contribution provided by Martinelli *et al*. (2015) in this volume and concerning the hydrogeochemical database.

A preliminary analysis of possible interrelation of any anomalous pattern and earthquakes was also attempted by considering each observable separately. Examples in this line are reported in this volume [see the contributions by Balasco *et al*. (2015), Buscema *et al*. (2015), Fidani and Martinelli (2015), Tramutoli *et al*. (2015b)]. The aim of this analysis was evaluating the capability of single observables to capture eventual pre-seismic signals. This analysis was planned to be performed in two distinct phases. In the first phase, any research group tried to identify anomalous patterns as much as possible without considering the occurrence of earthquakes. This identification had to be performed after the removal of spurious effects (e.g., meteo-climatic conditions) by each group. The anomalous pattern eventually identified for any observable had to be used to attempt "predictions" relative to any area and time interval. These pieces of information had to be passed to an independent research group having in charge testing these predictions against a seismic catalogue developed on purpose. This clear separation between the data-mining phase (identification of anomalous patterns) and testing against earthquake occurrence is necessary to avoid possible biases that are characteristic of this kind of analyses (anomalies are defined as a function of earthquake occurrences). Results obtained in this work packages (WP2) are described by Mulargia *et al*. (2015) in this volume. As a whole, the analysis performed in the frame of the project suggests that proposed precursors when considered separately are unable to provide useful results. In fact, no conclusive data supporting a significant empirical association with earthquakes were presented. Two different attitudes resulted from this outcome. The first one states that this result is in line with basic conceptual premises of the S3 project (no "silver-bullet" exists for earthquake forecasting) but this does not exclude the possibility that multi-parametric precursory patterns (not considered in the first year of activity due to lack of time) can provide more reliable results. The second position is much less optimistic, stating that the lack of statistical evidence supporting effectiveness of the proposed precursors discourages further studies in this direction except as concerns earthquake clustering. In fact, despite of the fact that no conclusive indication was provided during the project in support of this phenomenon as a reliable precursor, it can be considered the only physical phenomenon for which a significant association with impending mechanical failure has been demonstrated [see, for a discussion, Geller *et al.* (1997) and Mulargia and Geller (2003)]. The composition of these alternative views into a single shared position was not possible in the frame of the S3 project.

The third kind of activity (WP3) concerned the analysis of available evidence to evaluate heuristic potential of available observations to detect areas most probably expected as earthquake prone in the next years and that could be of major interest for future monitoring activities. The contributions provided by Peresan *et al.* (2015) and Viti *et al.* (2015) in the present issue outlines procedures and results obtained in this field.

5. Conclusions

After many years, during which earthquake forecasting was considered as impossible, a national research project specifically devoted to this controversial topic has been established in Italy and directly supported by national institutions (DPC) interested in defining operational forecasting tools. Despite of the limitations imposed by the relatively small funding and the short-term horizon (1 year possibly extended to further two years), this project represented a great cultural novelty in the seismological research in Italy. A new scientific paradigm supports this project that aims at overcoming methodological difficulties that undermined previous attempts in this direction. The common work allowed involved researchers to share awareness that significant progresses can be attained only by well-defined experimental protocols and validation procedures, focused on the multi-parametric observation of ongoing seismic phenomena: no single precursor is expected to be able to provide useful information. Collecting data and defining “anomalous” patterns independently from the actual occurrence of earthquakes has been accepted as a basic element for effective testing of claimed forecasts.

A basic contribution of the S3 project, that could be of major help for Civil Protection purposes is the availability of a comprehensive geo-referenced database concerning observations relative to a number parameters potentially related to the seismogenic process (observables). This database includes both most traditional observations (deep seated fluids, Rn emissions, electromagnetic and satellite thermal data, seismicity) and more recent proposals (seismic noise analysis, transients detection by GPS data, pre-seismic deformations by InSAR observations). All the considered data are characterized by a good time-space coverage (provided by the full exploitation of databases existing in the Italian area) and by an optimal cost-benefit ratio that makes them useful for monitoring large areas for long time. Best practices relative to data collection and processing were also defined and provided to DPC in the form of specific deliverables.

A key aspect of this collection is that monitoring has been performed (as much as possible) independently from earthquake occurrences: pre, peri, and post-seismic observations were collected. Furthermore, data are well distributed all over the Italian territory and this will allow their exploitation for a number of possible purposes (environmental studies, etc.).

Basic features of this data base are:

1. well defined experimental procedures, that is necessary to evaluate actual reliability of collected information;
2. maximum time-space coverage;
3. accessibility warranted by the implementation of the database into a Geographical Information System.

The database includes a huge amount of observations (of the order of 10^7 as whole) and its compilation required a big effort by involved RUs to gather and merge data provided by a number of different institutions. This collection probably represents the most extensive data base relative to earthquake related phenomena actually available for research applications in western countries. These efforts also revealed the lack of systematic observations in many parts of the Italian area and the absence of standardized protocols. Many of these protocols, representative of the state of the art, have been defined in the frame of the project and could be of help in planning future observation campaigns.

As concerns Civil Protection purposes, this database could be of primary importance for at least three reasons:

1. it makes accessible to the scientific community a huge amount of data that are sparsely stored in a number of different databases;
2. it allows multivariate and multi-parametric analyses to identify transient phenomena representative of ongoing seismogenic processes;
3. it allows the definitions of suitable validation protocols for proposed precursory patterns.

A second major outcome that results from data processing and analyses carried out during the project is the shared acknowledgment that, to be optimistic, single observables and relevant "anomalies" (defined in some ways) can only represent a very weak short-term precursor of future events. In fact, none significant and empirically robust anomalous pattern was revealed among the considered parameters before the important seismic sequences that struck the Po Plain and northern Calabria (Pollino). This is true both concerning more traditional parameters and the ones here considered for the first time. At least partially, this lack of evidence could be due to incompleteness of collected information (e.g., no Rn measurements were available for sites in the two zones), insufficient data analysis (no systematic data-mining activity was attempted to exploit with advanced data processing the huge amount of data collected during the project), or to the fact that considered earthquakes have been considered not large enough to generate anomalous patterns in some of the proposed observables. On the other hand, since the one here presented constitutes the major effort never produced in Italy to identify precursory patterns in a large set of parameters and by taking as well into account that the unpredicted events can produce significant damages (and thus they cannot be considered as minor), the lack of significant results casts a shadow over the possibility that single parameter can provide effective forecasts.

From this outcome, some of the participants in the project infer that the lack of empirical evidence supporting any physical link of the selected observables with earthquakes also prevents the possibility that these, when jointly analyzed, may be more effective. Other participants, instead, claim that this result is in line with the idea underlying the whole S3 project that no direct one-to-one link exists between a single observable and the earthquake occurrence. Furthermore, they suggest that all "single parameter" approaches do not allow to fully appreciate the informative contribute that the same parameter could offer, instead, in a multi-parametric real-time monitoring scheme. In fact, when this kind of approach is considered for testing, avoiding false positives is much more important than catching all events. For this reason, the identification of anomalous transients in the time series of a single observable is performed by applying the highest level of significance (e.g., 3-sigma and more) which, in an integrated multi-parametric scheme could be instead avoided. From this point of view, the absence of anomalous transients in the analysis of single time series, can be positively considered in terms of robustness against false alarm proliferation without exclude possible improvement achievable by using the same parameter within an integrated multi-parametric scheme suitable for incorporating (without increasing false positives rate) also anomalous transients at lower level of significance. The hypothesis to explore is to consider multi-parameter indices to identify patterns of precursors of different origins. Artificial Neural Networks are models that can be of help to verify this hypothesis. Actually, limitations imposed by a one-year research activity mainly devoted to data gathering, did not allow exploring actual feasibility of combined parameters to better constrain probability of future seismic occurrences.

Another aspect, only marginally explored during the S3 project, was the possibility of middle-term forecasting (months to years) on the basis of the analysis of medium, long-term series of measurements (tens of years) relative to specific observables (e.g., piezometric data relative to deep seated fluids or geodetic observations) or by considering phenomenological and deterministic approaches to delineate future scenarios. Some results were obtained in the S3 project by considering a pattern recognition approach and seismotectonic modelling accounting for systematic interactions of peri-Adriatic seismic sources and spatio-temporal regularity patterns of strong earthquakes. Both these approaches were supported by empirical evidence but no attempt was actually performed in the frame of the project to validate them systematically in a prospective way.

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