Foreword

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This volume collects papers representing the results of research performed under Task 4 of a project funded by the Italian Civil Defence Department in 2005,¹ “INGV-DPC Project S2 – Assessing the seismogenic potential and the probability of strong earthquakes in Italy” (Slejko and Valensise 2005). The goal of this task was to characterize the behavior of a given set of Italian seismogenic sources, using the most updated results obtained from the project itself, and to assign each source a probability of generating a significant earthquake. Nine Research Units² participated in the activities of S2-Task4 in the period 2005–2007, using different and sometimes even contradictory methods and techniques. All the teams were required to use common, fixed databases, in order to make their results comparable. This forced the authors to adopt input data as they became available before the end of the project.³

We invited a number of the researchers to extend or revise their Task 4 reports to make them suitable for a special volume, in the hope of mak-

ing the techniques and results more widely known. Most of the invited authors accepted; a few sought to publish elsewhere. Some results presented here are different from the ones obtained in 2007, at

¹The 2004–2006 Agreement between the Dipartimento della Protezione Civile (DPC) and the Istituto Nazionale di Geofisica e Vulcanologia (INGV) includes the execution of a series of Projects in Seismology and Volcanology. Details can be found at <http://progettosv.rm.ingv.it/>.

²The Research Units (RU) funded in S2-Task4 were: RU 4.1, led by Akinci – INGV, Rome; RU 4.2, Di Giovambattista – INGV, Rome; RU 4.3, Cinti – INGV, Rome; RU 4.4, Garavaglia – Politecnico, Milan; RU 4.5, Godano – University of Naples; RU 4.6, Mantovani – University of Siena; RU 4.7, Murru – INGV, Rome; RU 4.8, Peruzza – OGS, Trieste; RU 4.9, Rotondi – CNR IMATI, Milan. The budget of S2-Task4 is 380,000 Euro, corresponding to about 25% of the total budget of S2-2005 Project.

³The reference data bases are as follows: for the seismogenic sources, DISS V.3.0.2 released on Sept, 2006 (<http://diss.rm.ingv.it/diss/ReleaseNotes.html>); partial revision to source geometry has been performed with the release of DISS 3.0.4, and source areas (SA) have been renamed in composite sources (CS) with the latest 3.1.0 (Basili et al. 2008; DISS Working Group 2009); for the M5.5+ earthquakes, the catalog CPTI V.04 released on March, 2004, (217 B.C. -2002 A.D.) (Gruppo di Lavoro CPTI 2004); the catalog CSI V.1.1 (Castello et al. 2006), released on Aug, 2006 is the reference data base for instrumental seismicity of the last decades (1981–2002); afterward, instrumental data are taken from the bulletins (Italian Seismic Bulletin 2009).

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the project end, owing to the review process for this volume. In every case, understanding, organization, and expression improved and the context more clearly put forth.

The S2-Task4 project addressed three themes: occurrence of an impending earthquake based on 1 - instrumental seismological data, 2 - physical models, and 3 - statistical analysis of earthquake and fault data. Theme 1 represents the approach of characterizing aftershock statistics; theme 2 of modeling deformation and fault interaction; theme 3 of quantifying probability using statistical methods. The first theme is represented by a single article; the other themes are represented by three articles each. Below we summarize the results of each article.

1 Theme 1: Occurrence of an independent earthquake based on instrumental seismological data

Console et al. (2010a, this issue) use a well-known epidemic model incorporating short-term clustering (ETAS Epidemic Type Aftershock Sequence) to analyze 33 target events having magnitudes 5 or above, using the 1990–2006 Italian instrumental earthquake catalog. The retrospective forecast aims at quantifying predictability in the evolution of earthquake sequences. Space and time analyses of the completeness represent by-products of these studies, and have an important impact on seismic hazard assessment.

About 1/3 of the studied events exhibit a probability gain of at least 10 relative to a time-invariant Poisson model, the highest probability gains being associated with swarm-like sequences.

The retrospective forecasting shows good statistical properties, but the high rate of false alarm in prospective forecasts limits the method's reliability in real-time seismic monitoring, except in the case of predicting major aftershocks after a main event.

Further analyses, in particular ones based on bulletins since April 15, 2006, when the Italian National Seismic Network achieved a significant increase in magnitude completeness, are expected to clarify whether short-term clustering is able to predict impending major events.

2 Theme 2: Occurrence of a significant earthquake based on physical models

Interest in the second theme was high, inasmuch as the research was expected to shed light on the issue of whether sources behaved independently, a simplification that is assumed in nearly all the seismic hazard estimates done in the past in Italy (e.g. seismic regulation map based on area sources and stationary condition by Gruppo di Lavoro (2004); fault-based and time-dependent study in Central Italy, e.g. by Pace et al. (2006)).

Slejko et al. (2010, this issue) sought to estimate occurrence probability for strong earthquakes, making up for the relatively incomplete fault coverage in some parts of Italy by calibrating source occurrence rate from geodetic estimates and finite-element modeling. Assuming a characteristic fault model with characteristic magnitudes of 6.0 and 6.5, they were able to calculate and compare Poisson occurrence probabilities over the next 30 years for known and hypothetical fault sources over the whole of Italy, based on geophysical or on geodetic calculations.

In general, they found that the more dangerous faults are predominantly those located in the southern Apennines. The larger 30-year probabilities for magnitudes 6.0 range from 0.07 to 0.21 from the geophysical calculations and 0.08 to 0.22 from the geodetic calculations, a similar span. But for common faults the ratio of geodetic to geophysical probabilities ranged from 1:2 to 4:1, with median near 1:1, indicating some hope for better calibration with future improved methods.

The larger probabilities for magnitudes 6.5 range from 0.006 to 0.03 for the geophysical calculations and from 0.02 to 0.09 for the geodetic computations. For common faults the ratio ranged from 1:2 to more than 10:1, with median near 3:1. It is not yet clear why the discrepancy is larger for the larger magnitudes, but it may be related to the relatively broad area used in the geodetic estimation.

Mantovani et al. (2010, this issue), using a construction of the geodynamic and tectonic settings of the northern and southern Apennines, suggest a strong influence from the latter to the former and from the southern Dinarides to the southern Apennines. Over the time studied (about

700 years), two thirds of the earthquakes in the southern Apennines follow an earthquake in the southern Dinarides within 3 to 5 years (and in the past 150 years, all of them). A prediction for a southern Apennines earthquake based on the occurrence of a prior earthquake in the southern Dinarides, would have had a success rate of more than 50 percent. The mechanism is hypothesized to be that of post-seismic relaxation being propagated from the one area to the other.

The tectonic relationship between the earthquakes in the southern Apennines and northern Apennines and events in the seismic history seem also to suggest the possibility of anticipating events in the northern Apennines following events in the southern Apennines, but over longer time frames, although systematic predictions in space and time have not yet been formalized and tested.

These rather dramatic results suggest priorities in time and space for deployment of special geodetic and geophysical studies after the occurrence of events that might stress the tectonically connected areas.

Console et al. (2010b, this issue) assess the perturbation of earthquake probability for fault interaction on 32 receiver faults in Central and Southern Italy. Static Coulomb stress change, in its two components of permanent and transient effects, is computed using 118 triggering sources of M5.0+ earthquakes derived from the historical and instrumental catalogue; most of the events being pre-instrumental, the authors used rectangular faults with uniform slip distribution, and regional focal mechanisms. For each receiver fault, *Electronic Supplementary Material* shows the Coulomb failure stress change maps caused by all earthquakes occurring after a fault's last characteristic event. The permanent and temporary perturbations are converted into a shift in the time elapsed since the previous earthquake, and finally this shift is applied to a previously parameterized renewal model of occurrence modeled by a Brownian Passage Time (BPT) distribution. The perturbation of probability of having a characteristic earthquake in the next 30 years shows that the effect of earthquake interaction is small if compared with the intrinsic uncertainties assigned to mean recurrence time of faults. Probabilities are only very sensitive when the faults are highly

periodic and the elapsed time is about equal to the mean recurrence time. Since most of the faults are modeled with very high periodicity, this makes the impact of recent earthquakes on nearby faults negligible in most of the cases.

A posteriori, we note the highest increase of probability for fault interaction was assigned to two sources (ITGG027 and ITGG016) near the area of the L'Aquila 2009 earthquake. The causative fault of this event is not mapped, and two other well-known sources are not modeled in this study, as they lack the date of the last event. The role of the fault catalogue is confirmed to be crucial, and even if cascade events are not suggested by both this study and another one recently published (Marzocchi et al. 2009), this sector of Central Apennines deserves additional investigations, using different fault models.

3 Theme 3: Occurrence of a significant earthquake based on statistical analysis of earthquake and fault data

Garavaglia et al. (2010, this issue) applied statistics on interevent times of M5.3+ earthquakes occurring from 1600 to 2002. Events have to belong to the same DISS seismogenic areas, and intertimes are grouped into eight macro regions having similar style of faulting and amount of deformation. The sample becomes thus statistically acceptable for estimation of parameters in a mathematical model of interoccurrence times given by a mixture of exponential and Weibull distributions. Such a model is motivated by its capacity to jointly incorporate quasi-periodic, Poissonian and clustered events. The authors use four different estimation procedures to parameterize the mixture; they also perform credibility tests using Monte Carlo simulation to compare competing models. The *Electronic Supplementary Material* collects all the details of model parameters, and earthquake forecasts for the seismogenic areas, in different time periods, from January 1, 2003. In the perspective of a renewal model, the relative ranking of an impending M5.3+ earthquake is roughly maintained both in a 5-years and a 30-year perspective. Sources show large fluctuations in

probabilities inside the same macro region, while different methods are, in general, in agreement.

A posteriori, $M \sim 5.3+$ earthquakes in the years since the starting time of the forecast⁴ occurred inside sources not having the highest conditional probability, or outside of sources modeled in the study. Nevertheless, their probabilities are always above the source mean value (35–40% in 30 years with the different methods), a situation that points to about 1/3 of the sources mapped in DISS 3.0.2, and notably all the sources of MR 4, where the 2009 L'Aquila sequence occurred. Spatial criteria for computing intertimes remain a key element in this kind of analyses.

Akinci et al. (2010, this issue) sought to determine from among central Apennine fault sources those most likely to fail in the next 30 years based on a time dependent model for the characteristic earthquake model, accommodating uncertainties in moment, slip rate, and sharpness parameter for periodic recurrence. A broad estimate of the geologic slip rate uncertainties for one category of faults was narrowed somewhat by a one-dimensional Bayesian inversion to find an average slip rate which would best predict the historical rate of events in the catalog associated with that category of faults. Alternative sharpness parameters (0.3, 0.5, and 0.7) were derived from those few faults having multiple occurrences and from consideration of worldwide data. Finally, adopting weights for the sharpness parameters and for Poisson estimates, final 30-year occurrence probabilities were obtained for each fault.

Poisson occurrence probabilities ranged from 0.8 to 7 percent; time-dependent probabilities ranged from less than 0.01 percent to 16 percent.

Weighted average probabilities ranged from 0.4 to 6 percent, with the most likely faults (with one exception) being those with low maximum magnitudes and hence shorter return periods. The authors conclude that using the sensitivity results rather than the averages is a better choice for the selection of faults for future study and setting priorities on mitigation.

Peruzza et al. (2010, this issue) developed a procedure to parameterize a renewal model for a characteristic event of DISS geologic sources indirectly. Applying error propagation theory to magnitude and slip rate, they obtain mean recurrence times and aperiodicity coefficients starting from the geometry and kinematics assigned to the faults. Using a BPT distribution function they compute the probability of a maximum-sized event conditional on the time elapsed since the last one; they argued that about 20% of the given sources (115) exhibit a time-dependent probability higher than the equivalent Poissonian probability. Relative ranking of source probabilities is not heavily influenced by the variability in aperiodicity factor assigned to sources, though the absolute values are very sensitive to it. Critical, too, is the assignment of elapsed time to sources not having it, and some troubles when dealing with the tails of the distribution could arise from an improperly implemented numerical precision in the probability calculation.

The sources most likely to rupture are mainly faults of intermediate maximum magnitude having an elapsed time in the range 70%–120% of the mean recurrence time. *Electronic Supplementary Material* collects results obtained throughout the study period by some methodological implementations and using different releases of the reference faults database; an interactive notebook in Mathematica® for exploring some widely used distribution functions in earthquake probability is freely available too.

The results obtained by the two last papers on individual seismogenic fault sources (GG sources) are comparable. The conditional probability using renewal process and BPT distribution function is strongly influenced by the uncertainties on slip rate and on the date assigned to the most recent event. Different procedures have been developed to take into account the uncertainties,

⁴At July 2009, they are: the Monghidoro earthquake of Sept, 14 2003, $M_w = 5.3$ (located in DISS 3.02 ITSA027, inside MR3) at <http://www.mi.ingv.it/eq/030914/index.html>; the Salò earthquake of Nov, 24 2004 $M_L = 5.4$ (ITSA048 in MR2) at <http://www.iesn.org/speciali/garda/garda.htm>; the Parma earthquake of Dec, 23 2008, $M_L = 5.2$ (SA027 in MR 3); the devastating L'Aquila earthquake of April, 6 2009 $M_w = 6.3$ and its aftershocks (bridging the ITSA's 025 and 040, in MR 4). Other events are located outside the national borders, and overseas.

but if we do not consider earthquake sources for which the date of the last event is unknown (for which Akinci et al. adopted a fixed elapsed time of about 1,300 years, while Peruzza et al. chose ~10,000 years), the estimates are rather similar.

The highest priority in data parameterization has now to be given to the definition of a reasonable—even if uncertain – elapsed time for all sources for which this information is not given at present.

4 General observations on the import of the paper in this volume

In our opinion future research should be governed by the following considerations.

- 1) For faults, focus on about 1/3 of the mapped GG sources, those having long-lasting quiescence, to better determine elapsed times, and those having $M \sim 6.0$ with elapsed time longer than one-half the recurrence time. For source areas, focus on about 1/3 of the mapped SA sources, having time-dependent probabilities of occurrence greater than time-independent values.
- 2) For assessing interoccurrence time forecast probabilities, use alternative groups of inter-times for sources grouped using a variety of simple spatial kernels.
- 3) Forecasting from evolution of earthquake clusters should be attempted in several high-likelihood areas, especially those in the vicinity of recent damaging events.
- 4) Similarly, physical modeling for earthquake probability from fault interactions should be assessed in the vicinity of recent events. Seismic hazard methods should begin incorporating these modified occurrence probabilities in characterizing source rates.
- 5) Inasmuch as absolute values for occurrence probabilities seem to be sensitive to details of assumptions, while relative probabilities appear to be more stable, the latter should be the focus in application to civil defense priorities.

5 Observation in the light of Bayes' Law

Inasmuch as the focus of task 4 was the assessment of earthquake probabilities in the context of prediction of future damaging events, it is helpful to examine the impact of these studies on such prediction, using Bayes' Law.

What makes an earthquake prediction forecast reliability low is the small background probability of an earthquake. What makes a forecast probability more reliable is the occurrence of a predictor event which is more likely to be followed by an interval containing an earthquake rather than a time interval with no earthquake. In our opinion it is not widely appreciated that a precursory event nearly always found before an earthquake is not necessarily a good predictor unless the same event is very rarely found before a non-earthquake period.

Let the precursory event be denominated by E and the earthquake event by Q. We are interested by the probability that, given E, Q occurs, that is $P(Q|E)$, when $P(E|Q)$ is close to 1. The two probability expressions are related by the Bayesian expression,

$$P(Q|E) = \frac{P(E|Q) P(Q)}{P(E)}.$$

This expression asserts that the reliability of the earthquake forecast, $P(Q|E)$, is equal to the background earthquake probability times the ratio expressing the relative frequency with which earthquakes are preceded by the precursory event compared to the relative frequency that any similar time period is preceded by the precursory event. If the event is not precursory, that is, that it occurs with equal frequency before all time periods as before earthquakes, the ratio is one, and there is no increase in earthquake probability given the event.

The reliability can be rewritten,

$$\begin{aligned} & \frac{P(E|Q) P(Q)}{P(E|Q) P(Q) + P(E|\bar{Q}) P(\bar{Q})} \\ &= \frac{1}{1 + \frac{P(E|\bar{Q}) P(\bar{Q})}{P(E|Q) P(Q)}} \end{aligned}$$

where $\bar{Q}$ is a non-earthquake interval. From this equation, we can see that the ratio in the denominator must be small for the reliability of the earthquake forecast to be large; in particular, inasmuch as the probability of a non-earthquake interval is likely to be considerably larger than 0.5, the probability that events, E , must occur much less frequently before non-earthquake intervals than before earthquake intervals. In particular,

$$\frac{P(E|\bar{Q})}{P(E|Q)} \leq \frac{P(Q)}{P(\bar{Q})}$$

that is, that the relative frequency of the event before non-earthquake intervals be equal or less than the relative frequency of earthquake intervals to non-earthquake intervals.

Suppose, for instance that earthquakes are preceded by swarms (E) about half the time, that is, $P(E|Q) \sim 0.5$, and that swarms are followed by earthquakes about one-third the time, that is $P(Q|E) \sim 0.33$. And suppose also that the background probability of a significant earthquake in a given area and period of time is $1/30$. Manipulation of the above expressions results in the estimate that

$$P(E|\bar{Q}) \leq \left(\frac{1}{29}\right) (0.5)$$

or less than $1/60$. To our knowledge such statistics have not been investigated for swarms of small earthquakes or for radon anomalies, and hence it is difficult to assess the likely reliability of forecasts based on swarm or radon anomalies.

The studies in this report offer a way of increasing earthquake prediction reliability by increasing the background occurrence probability above that given by the Poisson assumption. In particular, according to the work of Mantovani et al. (2010, this issue), the occurrence of a significant event in the Dinarides offers relatively high $P(Q)$ values for making predictions using Bayes' law and common precursors.

Another way to increase the reliability of an earthquake prediction is to increase the time span of the prediction and the area covered, or to decrease the earthquake magnitude, each of which increase $P(Q)$. A drawback is that prediction win-

dows of a large fraction of a year are likely to be disruptive in their effects on a civil population.

6 Observation in the light of the L'Aquila earthquake

Preceding the L'Aquila earthquake, sources in the Central Apennines were highlighted as relatively more likely to have earthquake occurrences. Paper 4 highlighted Sulmona and Norcia. Paper 5's source areas have high likelihood sources in the Central Apennines, Papers 6 and 7 point to Sulmona and Ovindoli and some other historical sources. The Mantovani paper also suggests increased likelihood of events in the northern Apennines, given an event in the southern Apennines.

Indeed, on May 2008, some Research Units of the ended S2 Project passed on a list of seven priority areas (Peruzza et al. 2008) to a new S2 Project, proposed in the frame of the ongoing 2007–2009 Agreement between DPC and INGV (Marzocchi and Faccioli 2008); here, time-dependent statistics jointly with rough risk estimators suggest additional investigations. The first and the last of the priority areas have been already hit by damaging earthquakes.

It seems to us that the assessment of earthquake occurrence in the vicinity of L'Aquila should be a high research priority for some of the methods of this volume, especially for highlighted sources. Conditions for higher reliability predictions should also be recognized, and collection of precursor statistics be begun.

Finally, we hope that this volume will increase not only researcher awareness but also civil defence and public awareness, particularly with the assessment of mitigation procedures in the wake of a precursory forecast.

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