1.1 Prior to the 6 April 2009, L'Aquila earthquake: state of knowledge and seismological hypotheses

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1.1.1 Research in the 1990's: lessons from the 1997 Colfiorito earthquakes

On 12 September 1999, just over 10 years ago, the authoritative newspaper Corriere della Sera (Fig. 1) published a preview of the results of a study that had been initiated several years earlier by scientists of ING (Istituto Nazionale di Geofisica), a research institution that was soon to become INGV (Istituto Nazionale di Geofisica e Vulcanologia). With understandable and certainly well motivated hesitation and with the help of Franco Foresta Martin, the author of the article, the ING scientists informed the general public about the existence of a list of seismogenic zones, selected among many, where they believed a potentially destructive earthquake would be more likely to occur. Although the matter was treated with sense of touch, for the evident assumption of responsibility that the article involved, the statements contained in the article were bold and did not seem to allow for any doubt or replies. Nevertheless the claims were robust as they were essentially based on a simple comparison between the existence and the distribution of the active tectonic structures and their known seismic history. On the one hand this comparison was based on the knowledge being quickly accumulated on the main seismogenic sources of the peninsula, including data on the instrumental seismicity, their main seismotectonic parameters and the distribution of the active tectonic stress; on the other hand it relied on a very extended record of historical seismicity, probably the richest in the world. The areas of the peninsula that showed unequivocal signs of recent tectonic activity but had not been the locus of significant earthquakes in historical times – recall that the length of the Italian seismic catalogue allows this type of evaluations to be pushed up to the Middle Ages – were considered "lacune sismiche", a loose translation of the English expression *seismic gaps*.

As stated earlier, the research that would have brought to the identification of the seismic gaps was based on many years of data and conceptual development – more than two decades in the case of historical earthquakes – but experienced a strong acceleration caused by the 1997 Umbria-Marche (central Apennines) earthquake sequence. The main events of the sequence were somehow "expected", both in terms of their location and for their magnitude, their focal mechanism and even for the modes of seismic release (the sequence comprised three subsequent, similarly large shocks and a number of large aftershocks). At least in retrospect the region appeared to be free from major historical seismicity; or rather, it really looked as a *gap*, an unruptured portion of the crust between the big seismogenic sources responsible for the 1328 Cascia and 1703 Norcia earthquakes to the southeast and those responsible for the 1747 and 1751 Gualdo Tadino-Nocera Umbra earthquakes to the northwest. The 1997 sequence appeared to fit in that free stretch of the Apennines seismogenic belt, which was gradually filled starting from its northern portion with the two destructive shocks of 26 September, then in the southernmost portion with an additional destructive shock on 14 October, and finally again in the north with a significant shock near Gualdo Tadino on 5 April 1998. This gap-filling process was so regular that when some of the authors of this paper were consulted by the Italian Commissione Grandi Rischi to understand if the 5 April shock could be an indication of a further extension of the sequence toward the northwest, it was easy to predict that this was unlikely as the gap had been filled; twelve years later that evaluation still remains valid.

The 1997 experience was perhaps the onset of a new phase of the research on damaging earthquakes; a phase for which the mentioned article of Corriere della Sera represented a first verification point. Most people – not just scien-

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Fig. 1
The article by Franco Foresta Martin that appeared on the weekly scientific supplement of the Italian newspaper Corriere della Sera on 12 September 1999.

24 DOMENICA 12 SETTEMBRE 1999 Corriere della Sera

Corriere Scienza
UOMO/TECNOLOGIA/NATURA

Le aree sono classificate ad alto rischio perché da troppo tempo non sono soggette a movimenti sismici

Le quattro zone dove si aspettano i terremoti

Sono distribuite sugli Appennini, l'arco calabro e la Sicilia orientale

C'è una nuova mappa dell'Italia sismica, elaborata dai ricercatori dell'Istituto nazionale di geofisica (Ing), che riassume le conoscenze più aggiornate sulle faglie in grado di generare i forti terremoti italiani. In questa mappa gli studiosi hanno potuto evidenziare le cosiddette lacune sismiche, cioè le aree sismiche in cui da tempo non si verificano forti terremoti e che, quindi, sono esposte a terremoti significativi in futuro. Presentata in un recente convegno a Erice, la mappa rappresenta un approccio innovativo alla valutazione della pericolosità sismica del nostro Paese. «Tradizionalmente, la valutazione della pericolosità sismica si basa sulla identificazione di aree in cui i terremoti tendono ad avere sempre le stesse caratteristiche, individuate dalle informazioni contenute nei cataloghi storici e dai dati geologici — spiegano i ricercatori Ing —. Gli studi intrapresi negli ultimi anni puntano anche alla identificazione e descrizione delle faglie attraverso studi di sismologia storica, paleosismologia e sismologia strumentale. Poi, con l'aiuto di un modello fisico-matematico, si tenta di capire come si ripetono i forti terremoti».

Uno studio dell'Istituto nazionale di geofisica

A tutto questo si è aggiunto ora il concetto nuovo di lacuna: la ricerca del terremoto che non c'è e che, invece, ci dovrebbe essere. «Si è potuto accertare — aggiungono gli studiosi — che in un sistema di faglie l'attivazione avviene con la rottura in tempi successivi di segmenti, ognuno dei quali è lungo da alcune decine di chilometri fino a diverse centinaia di chilometri. Se uno di questi segmenti, già interessato da terremoti nel lontano passato, è rimasto immobile per molti secoli, mentre i segmenti adiacenti si sono attivati, allora possiamo supporre di essere in presenza di una lacuna sismica».

L'individuazione delle lacune sismiche lungo una fascia sismogenetica non può portare alla previsione di un terremoto, cioè all'indicazione precisa di quando esso avverrà, tuttavia costituisce un importante risultato scientifico e un elemento per orientare le strategie di prevenzione. Così poteva essere, ma non è stato, in Turchia, dove il disastroso terremoto di Izmit si è scaricato in una lacuna segnalata con largo anticipo dai sismologi.

In Italia gli studi dei sismologi hanno portato, finora, all'identificazione di diverse zone a elevata pericolosità sismica. Nell'ambito di esse sono presenti alcune lacune sismiche in cui il deficit di energia, accumulato negli ultimi secoli, sarà colmato con il verificarsi di forti terremoti. Le principali lacune evidenziate dagli studiosi ricadono in una fascia che comprende la dorsale appenninica, l'arco calabro e la Sicilia orientale. Le magnitudo massime dei terremoti attesi dovrebbero essere inferiori a 6.5 nell'Appennino settentrionale, e intorno a 7 nell'Italia meridionale, di gran lunga inferiori, quindi, alla magnitudo del recente terremoto turco, ma egualmente preoccupanti, date le condizioni del nostro patrimonio edilizio storico.

«Vorremmo sottolineare — precisano i ricercatori dell'Ing — che le lacune finora identificate sono solo una parte di quelle che presumiamo esistano. Questa mappa, infatti, rappresenta solo il punto di partenza per comprendere le modalità di accumulo e rilascio dell'energia sismica, e per identificare le lacune ancora sconosciute».

Franco Foresta Martin

L'unica arma è la prevenzione

Ma esiste davvero la possibilità scientifica di individuare le zone dov'è più alta la probabilità che si verifichi un terremoto? Lo abbiamo chiesto al professor Franco Barberi, sottosegretario alla Protezione civile.

«Io sono convinto di sì. Fra i vari possibili approcci, ritengo che quello dell'individuazione delle lacune sismiche sia uno dei più promettenti. Infatti, sono stato io stesso a chiedere all'Istituto nazionale di geofisica, e alla comunità scientifica in genere, di affrontare queste ricerche».

La valutazione del rischio sismico in Italia, ricorda Barberi, finora si basava essenzialmente sulla statistica degli accadimenti e sulla vulnerabilità del patrimonio edilizio. Sappiamo che oltre il 40% del territorio è considerato a rischio e oltre il 60% degli edifici è giudicato inadeguato. «Il quadro è preoccupante — osserva Barberi — e l'unico modo per difendersi è attuare una politica di prevenzione consistente nell'adeguamento edilizio. Ma il fabbisogno finanziario è gigantesco. Allora ci chiediamo: di fronte a risorse limitate, dove intervenire prima? Le lacune ci offrono un possibile criterio, che giudichiamo valido anche perché si è visto che funziona».

Barberi ricorda che, analizzando il modo con cui si è liberata l'energia nei recenti terremoti italiani, ultimo quello Umbro-Marchigiano del 1997-98, le scosse si sono succedute nei vari segmenti di faglia in modo tale da colmare le lacune. «Fermo restando che dobbiamo controllare tutto il territorio esposto al rischio sismico, rivolgiamo maggiore attenzione alle zone vicine alle lacune sismiche. Gli incentivi per il consolidamento dei vecchi edifici, la predisposizione dei piani di emergenza con l'individuazione di aree di sgombero, l'informazione alla popolazione, sono fra le misure che sollecitiamo». **(F.F.M.)**

tists but also administrators and politicians – were becoming increasingly aware of the importance of establishing priorities among the various seismic zones, especially in a country where seismicity is both widespread and potentially destructive such as Italy. Prioritizing the different seismic zones would have afforded the best possible use of the limited public resources available for seismic retrofitting of the areas that were more at risk. In a short note entitled "Our only weapon is prevention" (Fig. 1) published next to the mentioned Corriere della Sera article (Fig. 1), Prof. Franco Barberi, at that time head of the National Civil Protection Department (DPC), stated that:

"...our only line of defense is to implement a prevention policy focused on improving existing constructions. But the financial need is huge. Then the question becomes: given the limited resources, where should we start from? The gaps give us a possible criterion that we consider valid because it has proved to work."

The L'Aquila earthquake of 6 April 2009 seems to confirm that indeed that criterion works; the zone of *"...L'Aquila, between Rieti and Sulmona..."* was identified as one of the four areas of the peninsula where a destructive earthquake

was more likely to occur. The anticipated magnitude was larger than 6.5: luckily the 6 April earthquake was smaller than that, but this magnitude was attained repeatedly in nearby areas through history.
This line of thinking was adopted in the planning of subsequent research efforts, and in particular of those funded by the Civil Protection Department in the frame of the 2000-2003 agreement with INGV. This agreement was the first to acknowledge INGV as new entity that incorporated former ING and the National Group for the Defense from Earthquakes (GNDT), the latest expression of the significant research effort on Italy's seismic risk in Italy developed by the Consiglio Nazionale delle Ricerche.
Because of its high level of seismicity and seismic hazard, western Abruzzo has continued to be the object of several research efforts at different scales and with different goals, as well as of intense seismological and geodetic monitoring activity. In the following we summarize the main outcomes of these efforts, most of which were funded by the 2000-2003, 2004-2006 and 2007-2009 (ongoing) agreements between by the Civil Protection Department and the INGV.

1.1.2 Research funded by the Civil Protection Department (2000-2003)

The project "Earthquake probabilities in Italy between the year 2000 and 2030: elements for the definition of the priorities of the interventions of reduction of seismic risk", led by Alessandro Amato and Giulio Selvaggi of INGV, was the first project of a series that aimed at assessing the likelihood of destructive earthquakes (M >5.5) all over the Italian territory. The project was concluded in 2004: texts, images and final reports are available from http://portale.ingv.it/l-ingv/progetti.
The project generated a large number of observations and analyses on different aspects of seismogenic processes in Italy, serving as a basis for the elaboration of the seismogenic zoning model ZS9 (Meletti et al., 2008) used in the preparation of the National Seismic Hazard Map MPS04 (MPS Working Group, 2004). Most importantly, and in keeping with its title, the project outlined a limited number of seismogenic zones that are more likely to generate a strong earthquake in the near future. Most of these zones overlap with the seismic gaps identified in 1999. The conclusions of the project stated that:

> *"… the first evaluations of "time-dependent hazard"outlined some areas where the introduction of individual faults (and the associated geometric and kinematic parameters) in the calculations led to an hazard increase, at least in comparison with conventional evaluations such as those contained in the National Seismic Hazard Map MPS04... The areas identified include the Northeastern Alps (between Friuli and Veneto), the Adriatic Coast of Marche and Emilia, the Latium-Abrutii Apennines, an area located between Molise and Puglia, and the southeastern part of Sicily…"*

Data collected during the project were used by Pace et al. (2006) for an innovative analysis of seismic hazard of Central Italy. Their results were expressed in terms of 90% probability of non-exceedance of specified ground shaking levels over the interval 2004-2054, calculated at the nodes of a regular grid (Fig. 2). This time-dependent analysis differed substantially from conventional hazard analyses, that generally express probabilities that are independent of time. The analysis was launched inside the project even though it was published only two years

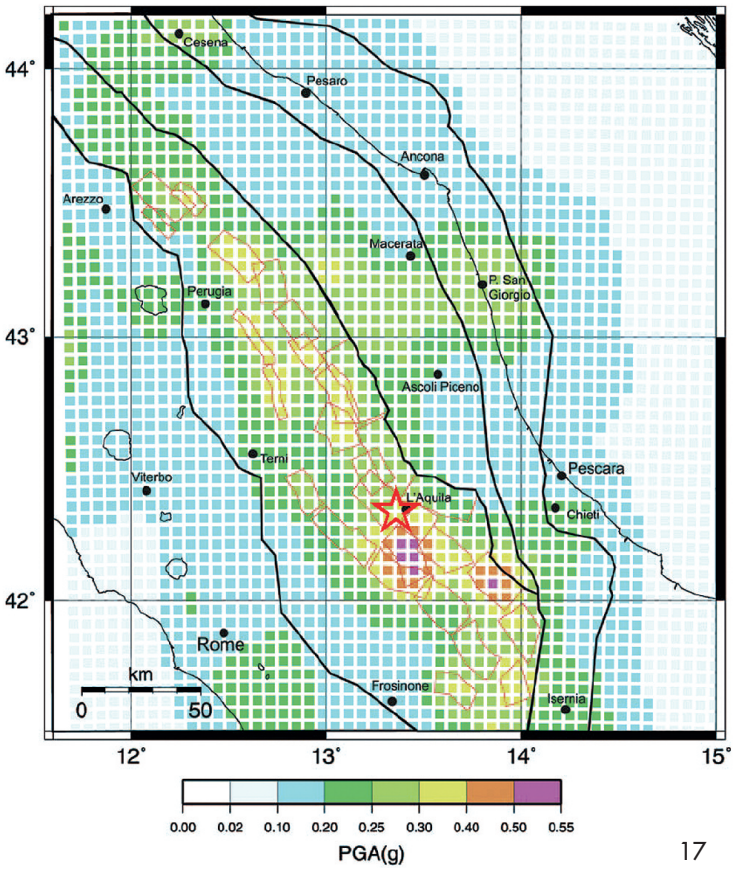


Fig. 2
Expected ground shaking in central Italy from Pace et al. (2006). See text for further details.

after its completion.
It is important to stress that, with the only exception of the data that contributed to the elaboration of the National Seismic Hazard Map, all the outcomes of that project are strictly scientific results that are not immediately suitable for an application by the Civil Protection authorities. Nevertheless the analysis published by Pace and co-authors shows a high probability for a strong shock in a relatively small region located to the south of L'Aquila, a region that overlaps for two thirds the area struck by the 6 April earthquake.

1.1.3 The INGV National Seismic Hazard Map (2004)

The National Seismic Hazard Map prepared by INGV in 2004 (MPS Working Group, 2004: http://zonesismiche.mi.ingv.it/) is the ultimate result of a complex series of scientific, technical and legal accomplishments. Stucchi et al. report extensively on the National Seismic Hazard Map elsewhere in this volume. For the purpose of this paper we just want to recall that that the map was preceded by a study conducted in 1998 on behalf of the Civil Protection Department by a working group formed by experts from all institutions dealing with seismic hazard (Gavarini et al., 1999). This study proposed that 6 municipalities of the L'Aquila area (Barete, Cagnano Amiterno, Capitignano, Montereale, Pizzoli, Tornimparte) be assigned to Zone 1, but maintained that L'Aquila itself be assigned to Zone 2, as in the previous seismic code. The new map, that was based on substantially better input data and a more innovative work methodology than the 1998 study, put L'Aquila – the only regional capital and one of the few province-towns (together with Messina and Reggio Calabria) – in Zone 1, along with many of the municipalities struck by the 6 April earthquake.

1.1.4 Research funded by the Civil Protection Department (2004-2006)

The 2004-2006 INGV-DPC Agreement was aimed at funding research that would return immediate application results. Special emphasis was given to the activities pertinent to the publication of the Seismic Hazard Map and the research on the so-called "probable earthquakes".
The project "Follow-up of the assistance to the Civil Protection Department for the completion and the management of the seismic hazard map foreseen by the Ordinanza PCM 3274/2003 and planning of further developments", initially co-ordinated by Gian Michele Calvi, Eucentre, and Massimiliano Stucchi, INGV, and completed by Carlo Meletti, INGV, has developed several seismic hazard applications and created an online seismic hazard database. This served as a basis for the definition of the new national Technical Regulations for Buildings, which become effective in July 2009. Further results of that project, with specific reference to the area of L'Aquila area, are presented by Stucchi et al. elsewhere in this volume.
The project "Evaluation of the seismogenic potential and probability of a large earthquake in Italy", led by Dario Slejko, INOGS, and Gianluca Valensise, INGV, started off from the results obtained by the project "Probable earthquakes in Italy between year 2000 and 2030..." and was completed in July 2007 (final report: http://portale.ingv.it/l-ingv/progetti). The project used the Italian *Database of Individual Seismogenic Sources* (DISS) and a set of strain and slip rates to estimate the likelihood of an earthquake of $M > 5.5$ over the entire national territory. The probabilities were calculated either following a time-independent approach and using a time-dependent scheme. The latter approach resulted in a list of seismogenic sources that not only are generally very active, but are also "late" from the point of view of the seismic release.
In the framework of this project Steven Ward (California University, Santa Cruz), in collaboration with different research units, proposed a scheme of time-independent probability (Fig. 3). The same technique had been used by Ward for the same calculations on California (Ward, 2007). The elaboration was based on 81 *Composite Seismogenic Sources* of DISS, version 3.0.2 (DISS Working Group, 2007; Basili et al., 2008) and on slip rates obtained by Salvatore Barba using a finite elements model within the same project, and returned 100-year probabilities for each source. The elaboration assigned particularly high probabilities to the central Apennines around L'Aquila, to the Campanian-Lucanian Apennines, the Stretta di Catanzaro in central Calabria and much of eastern Sicily.
A particularly interesting time-dependent elaboration was completed by Renata Rotondi of CNR-IMATI (Milan) in the framework of Task 4 of the same project (Fig. 4). The elaboration used

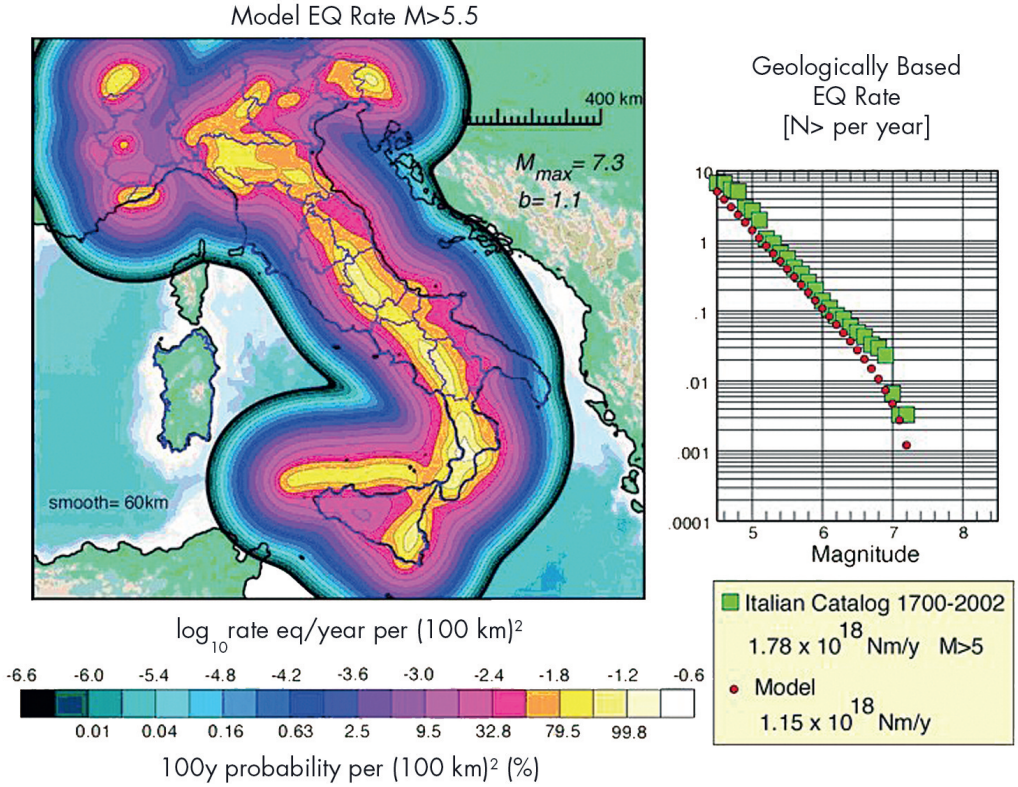


Fig. 3
100-years time-indedepent probabilities of significant earthquakes in Italy. Elaboration by Steven Ward in the framework of the project "Evaluation of the seismogenic potential and probability of a large earthquake in Italy". See text for further details.

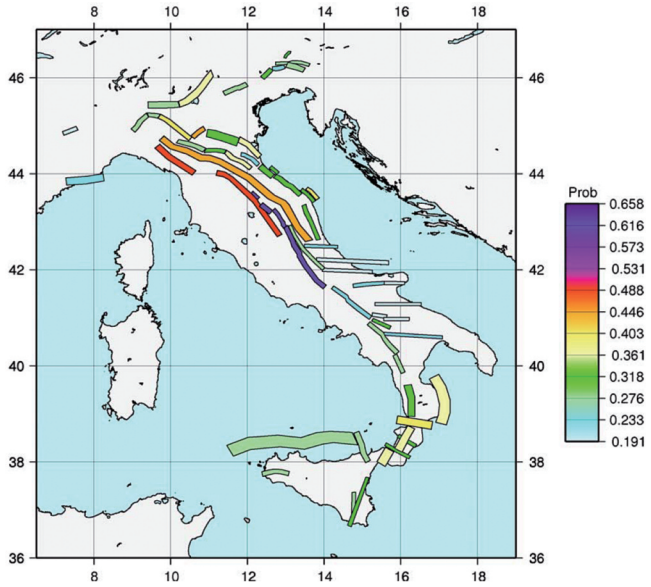


Fig. 4
Time-dependent probability of the occurrence of a magnitude 5.5 or larger earthquake. Elaboration by Renata Rotondi in the framework of the project "Evaluation of the seismogenic potential and probability of large earthquake in Italy". See text for further details.

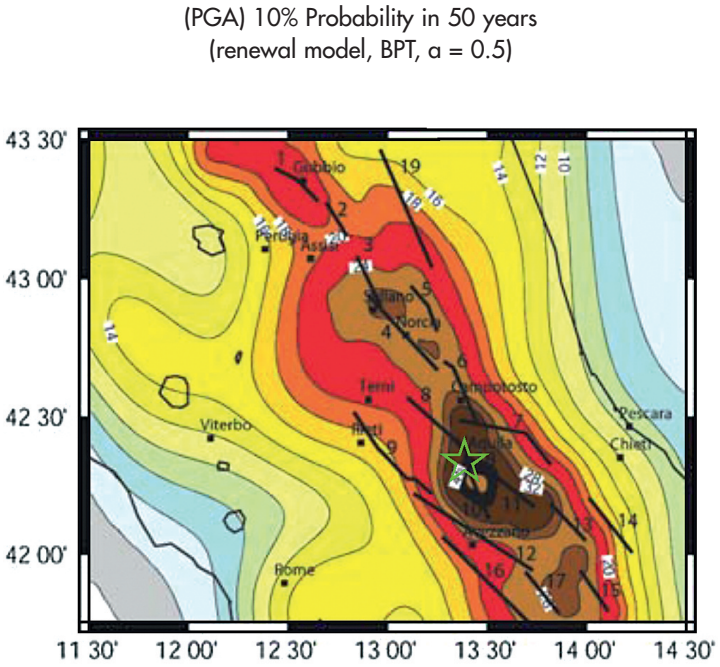
both results obtained from other research units of the same project and results obtained during the previous project "Earthquake probabilities in Italy between year 2000 and 2030...". Also this elaboration was based on the 81 *Composite Seismogenic Sources* of version 3.0.2 of DISS (DISS Working Group, 2007; Basili et al., 2008). The time dependence was based on estimates of the seismic moment already released by each source area, which in its turn was based on the considerable record of the Italian historic seismicity contained in the CPTI catalogue (Working group CPTI, 2004). Geological and historical data were analyzed through a stochastic technique that returned the probability of a damaging earthquake for each source area for the interval 2003-2033 (Fig. 4). Higher probabilities reflect a level of observed seismicity lower than expected and viceversa. An especially high probability was estimated for the seismogenic source ITSA025 "Norcia-Ovindoli-Barrea", that includes L'Aquila. As mentioned earlier this was

strictly a research result, and what is more, a result on a "frontier theme" as is earthquake prediction. It is worth noting, however, that other elaborations obtained in the same project suggested systematically high probabilities for the ITSA025.

The results of this project include a paper by Akinci et al. (2009) that by mere coincidence was published in April 2009, just a few days before the earthquake, but was actually completed in 2008. The paper contains time-dependent probabilities of strong ground shaking calculated over a large portion of the Central Apennines (Fig. 5). The elaboration was based on a rather complex technique that returns slightly different results for different choices of the input parameters. Similarly to the National Sesimic Hazard Map, the results are expressed in terms of acceleration levels that have a 10% probability of being exceeded in the next 50 years. Also this elaboration shows a peak of expected ground shaking in an area located just to the south of L'Aquila.

The activities that began within the 2000-2003 DPC-INGV Agreement and continued through the 2004-2006 Agreement are currently the object of the project "Determination of the seismogenic potential in Italy for the calculation of seismic hazard", coordinated by Salvatore Barba, INGV, and Carlo Doglioni, Rome University La Sapienza, under the 2007-2009 Agreement.

Fig. 5
Expected ground shaking in central Italy from from Akinci et al. (2009). See text for further details.



1.1.5 Medium term forecast: statistical techniques

Since 2005 the INGV website has hosted a page containing probabilities of occurrence for earthquakes of magnitude 5.5 or larger within a time window of 10 years (http://www.bo.ingv.it/~earthquake/ITALY/forecasting/M5.5+/). As the probabilities are strictly time-dependent, the maps are updated every 1st of January and after each earthquake of magnitude 5.5 or larger. The model used for the forecast is based on the space and time clustering of earthquakes that can inferred from the Italian earthquake catalogue (Faenza et al., 2003; Cinti et al., 2004). The web page contains maps obtained by computing probabilities at the nodes of a regular grid superimposed on a seismotectonic model of Italy. All processed maps, starting from 2005, show a very high probability for a damaging earthquake over a region that includes the L'Aquila area. In particular the map computed for 2009 (Fig. 6), published on 1 January 2009, shows that the seismotectonic district within which the 6 April earthquake occurred had the sixth highest probability out of 61 districts; notice that 34 of such districts exhibit significant probability values (see Map A on the left-hand side of Fig. 5). If one considers the spatial density of probability on a grid having 51 junctions (see Map B on the right-and side of the same figure), the junction closest to the region struck by the 6 April earthquake has the second highest density of probability.

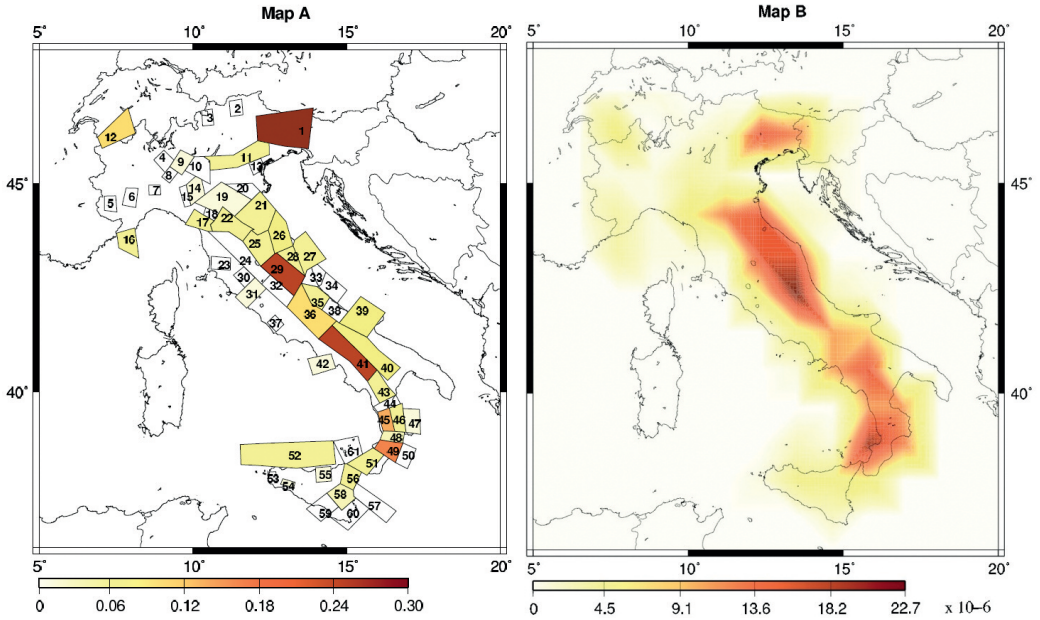


Fig. 6
Probability of occurrence of a magnitude 5.5 or larger shock calculated on 1 January 2009 for 61 homogeneous seismotectonic zones (left) and at the 51 nodes of a regular grid (right). The map was obtained through the analysis of the space-time clustering of Italian seismicity. The 6 April earthquake falls in zone 36.

1.1.6 Conclusions

All the results and elaborations that we have briefly described show that the scientific community, and in particular that represented by INGV researchers, had identified L'Aquila and its surroundings as a very likely candidate for a damaging earthquake, probabilities being rather high even for the first decades of this century. The following scheme shows the different available lines of evidence, listed in chronological order over the decade that preceded the April 6 earthquake.

1998 - *The new "Proposal of seismic zoning" for Italy requested by the Civil Protection Department confirms the high level of seismic hazard for L'Aquila and its surroundings.*

1999 - *The Aquilano district is identified as one of the four Italian areas that have the highest probability of being struck by a damaging earthquake, with a potential for magnitude up to 6.5.*

2004 - *As a result of an intense three-year research effort, L'Aquila is assigned a very high probability of a damaging earthquake over the interval 2000-2030.*

2004 - *The new National Seismic Hazard Map indicates that L'Aquila and much of it province, including many of the municipalities struck by the 6 April shock, should be classified in Zone 1 (higher hazard level) rather than Zone 2.*

2007 - *A new technique developed for California identifies a corridor running parallel to the axis of the central Apennines and centered on L'Aquila as one of the Italian areas having the highest probability of a significant earthquake.*

2007 - *A time-dependent technique is used to estimate a high probability for a significant earthquake in the interval 2003-2033 over a seismogenic source running parallel to the axis of the central Apennines and centered on L'Aquila.*

2008 - *Detailed geological observations highlight a significantly higher probability for a damaging shock in the Aquilano than in surrounding areas of the central Apennines.*

2009 - *The analysis of the probability of an earthquake of magnitude 5.5 or larger in the Aquilano district returns values that are among the largest nationwide. This condition has occurred consistently since 2005, i.e. from the beginning of regularly released analyses.*

Given these circumstances, it is not surprising that the sequence that started near L'Aquila in January 2009 generated anxiety throughout the entire seismological community. On 17 February, after a few weeks of continuous activity and based on the knowledge acquired on the local seismicity, the scientist on duty at the INGV 24-hour monitoring center in Rome issued the following report:

> *"Starting from the beginning of the year the INGV National Seismic Network has recorded many low-magnitude earthquakes around the city of L'Aquila. So far over 110 earthquakes have been located, all with magnitude smaller than 2.6, some of which are felt by the population. Most of the earthquakes are located in a very small area (4-5 km across), while another small group of events falls about 15 km to*

the northwest. The hypocentral depth is in the interval 5 to 15 km, that corresponds to the typical depth range of central Apennines seismicity. The mode of seismic release is typical of an "earthquake swarm", a sequence that lacks a real mainshock and is characterized by an irregular distribution in the time of the strongest shocks.

In the past the area under examination has been the locus of significant earthquakes. More specifically the recent activity locates between the southern end of the fault that generated the 1703 earthquake (intensity X of the MCS scale; equivalent magnitude 6.7) and the northern end of the fault commonly associated with the 1349 earthquake in current fault catalogues (e.g. DISS) and known as "Ovindoli-Piani di Pezza Fault".

During the past few years the area has not been hit by significant earthquakes. Based on the present level of knowledge it can be stated that the current sequence has not altered the probability for a damaging earthquake. It is important to recall that all affected municipalities fall in Zone 1 or Zone 2 of the national seismic classification".

The wording used was necessarily formal, this being an official report to the Seismic Survey Office of the Civil Protection Department. Nevertheless what the message really meant to say was that:

- *Aquilano is a well-known seismic district that has a high probability of generating damaging shocks.*
- *The seismic sequence that started in January has not reduced such probability; if it increased it, this increase was too small to justify any possible intervention by the authorities.*

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