Operational Earthquake Forecasting

State of Knowledge and Guidelines for Utilization

Report by the

International Commission on Earthquake Forecasting for Civil Protection

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Preface

This report by the International Commission of Earthquake Forecasting for Civil Protection responds to a request from the Italian government to assess the scientific knowledge of earthquake predictability and provide guidelines for the implementation of operational earthquake forecasting. As defined here, "operational forecasting" involves two key activities: the continual updating of authoritative information about the future occurrence of potentially damaging earthquakes, and the officially sanctioned dissemination of this information to enhance earthquake preparedness in threatened communities.

Although considerable research is being devoted to the science of short-term earthquake forecasting, the standardization of operational procedures is in a nascent stage of development. The problem is challenging because large earthquakes cannot be reliably predicted for specific regions over time scales less than decades. Therefore, short-term forecasts of such events never project high probabilities, and their incremental benefits for civil protection—e.g., relative to long-term seismic hazard analysis—have not been convincingly demonstrated. Under these circumstances, governmental agencies with statutory responsibilities for earthquake forecasting have been cautious in developing operational capabilities of the sort described in this report.

Nevertheless, public expectations that any valid information about enhanced seismic risk will be made available and effectively utilized are clearly rising. Experience shows that information vacuums can spawn informal predictions and misinformation, and that relying solely on informal communications between scientists and the public invites confusion. In this context, the deployment of systematic and transparent procedures for operational earthquake forecasting must be seriously considered.

Italian earthquake experts are in the forefront of the research needed for the implementation of operational earthquake forecasting. This report highlights their accomplishments and provides a roadmap for building upon their current efforts. While written for this purpose, the Commission hopes that its study will be useful not only in Italy, but also in other seismically active regions where operational earthquake forecasting may be warranted.

The report was written prior to the damaging aftershock of 22 February 2011 in Christchurch, New Zealand, and the catastrophic Tohoku earthquake of 11 March 2011 off the Pacific coast of Japan, and no attempt was made to revise its content in the light of these events. However, they underline the need for authoritative information about time-dependent seismic hazards, especially in the wake of major earthquakes, and their implications, as currently understood, do not contradict the Commission's findings and recommendations.

Many scientists in a number of countries have contributed to the report, and the Commission is grateful for their help. The report was improved by a number of peer reviews, and we are grateful for their recommendations. Prof. Paolo Capuano of the University of Salerno deserves a special word of thanks for his assistance to the Commission in all aspects of its work, including meeting arrangements, report preparations, and a special website that enhanced its internal correspondence. The Commission would also like to recognize the generous support of the Italian Department of Civil Protection, especially the encouragement of Dr. Guido Bertolaso and Prof. Mauro Dolce.

Thomas H. Jordan
Commission Chair

Abstract

Following the 2009 L'Aquila earthquake, the Dipartimento della Protezione Civile Italiana (DPC), appointed an International Commission on Earthquake Forecasting for Civil Protection (ICEF) to report on the current state of knowledge of short-term prediction and forecasting of tectonic earthquakes and indicate guidelines for utilization of possible forerunners of large earthquakes to drive civil protection actions, including the use of probabilistic seismic hazard analysis in the wake of a large earthquake. The ICEF reviewed research on earthquake prediction and forecasting, drawing from developments in seismically active regions worldwide. A *prediction* is defined as a deterministic statement that a future earthquake will or will not occur in a particular geographic region, time window, and magnitude range, whereas a *forecast* gives a probability (greater than zero but less than one) that such an event will occur. Earthquake predictability, the degree to which the future occurrence of earthquakes can be determined from the observable behavior of earthquake systems, is poorly understood. This lack of understanding is reflected in the inability to reliably predict large earthquakes in seismically active regions on short time scales. Most proposed prediction methods rely on the concept of a *diagnostic precursor*; i.e., some kind of signal observable before earthquakes that indicates with high probability the location, time, and magnitude of an impending event. Precursor methods reviewed here include changes in strain rates, seismic wave speeds, and electrical conductivity; variations of radon concentrations in groundwater, soil, and air; fluctuations in groundwater levels; electromagnetic variations near and above Earth's surface; thermal anomalies; anomalous animal behavior; and seismicity patterns. The search for diagnostic precursors has not yet produced a successful short-term prediction scheme. Therefore, this report focuses on operational earthquake forecasting as the principle means for gathering and disseminating authoritative information about time-dependent seismic hazards to help communities prepare for potentially destructive earthquakes. On short time scales of days and weeks, earthquake sequences show clustering in space and time, as indicated by the aftershocks triggered by large events. Statistical descriptions of clustering explain many features observed in seismicity catalogs, and they can be used to construct forecasts that indicate how earthquake probabilities change over the short term. Properly applied, short-term forecasts have operational utility; for example, in anticipating aftershocks that follow large earthquakes. Although the value of long-term forecasts for ensuring seismic safety is clear, the interpretation of short-term forecasts is problematic, because earthquake probabilities may vary over orders of magnitude but typically remain low in an absolute sense (< 1% per day). Translating such low-probability forecasts into effective decision-making is a difficult challenge. Reports on the current utilization operational forecasting in earthquake risk management were compiled for six countries with high seismic risk: China, Greece, Italy, Japan, Russia, United States. Long-term models are currently the most important forecasting tools for civil protection against earthquake damage, because they guide earthquake safety provisions of building codes, performance-based seismic design, and other risk-reducing engineering practices, such as retrofitting to correct design flaws in older buildings. Short-term forecasting of aftershocks is practiced by several countries among those surveyed, but operational earthquake forecasting has not been fully implemented (i.e., regularly updated and on a national scale) in any of them. Based on the experience accumulated in seismically active regions, the ICEF has provided to DPC a set of recommendations on the utilization of operational forecasting in Italy, which may also be useful in other countries. The public should be provided with open sources of information about the short-term probabilities of future earthquakes that are authoritative, scientific, consistent, and timely. Advisories should be based on operationally qualified, regularly updated seismicity forecasting systems that have been rigorously reviewed and updated by experts in the creation, delivery, and utility of earthquake information. The quality of all operational models should be evaluated for reliability and skill by retrospective testing, and they should be under continuous prospective testing against established long-term forecasts and alternative time-dependent models. Alert procedures should be standardized to facilitate decisions at different levels of government and among the public. Earthquake probability thresholds should be established to guide alert levels based on objective analysis of costs and benefits, as well as the less tangible aspects of value-of-information, such as gains in psychological preparedness and resilience. The principles of effective public communication established by social science research should be applied to the delivery of seismic hazard information.

Operational Earthquake Forecasting: State of Knowledge and Guidelines for Utilization

I. Introduction

Operational earthquake forecasting comprises procedures for gathering and disseminating authoritative information about the time dependence of seismic hazards to help communities prepare for potentially destructive earthquakes. Seismic hazards are known to change with time, in part because earthquakes release energy and suddenly alter the conditions within fault systems that will lead to future earthquakes. Statistical and physical models of earthquake interactions have begun to capture many features of natural seismicity, such as aftershock triggering and the clustering of seismic sequences. These models can be used to estimate future earthquake probabilities conditional on a region's earthquake history.

At the present time, earthquake probabilities derived from validated models are too low for precise short-term predictions of when and where big quakes will strike; consequently, no schemes for "deterministic" earthquake prediction have been qualified for operational purposes. However, the methods of probabilistic earthquake forecasting are improving in reliability and skill, and they can provide time-dependent hazard information potentially useful in reducing earthquake losses and enhancing community preparedness and resilience.

This report summarizes the current capabilities of probabilistic earthquake forecasting in Italy and elsewhere. It offers recommendations about how to validate and improve operational forecasting procedures and how to increase their utility in civil protection.

A. Charge to the Commission

The International Commission on Earthquake Forecasting for Civil Protection ("the Commission" or ICEF) was authorized by Article 6 of Ordinanza del Presidente del Consiglio dei Ministri no. 3757, issued on 21 April 2009. The Commission was appointed by Dr. Guido Bertolaso, head of the Dipartimento della Protezione Civile (DPC), with the following statement of charge:

1. *Report on the current state of knowledge of short-term prediction and forecasting of tectonic earthquakes.*
2. *Indicate guidelines for utilization of possible forerunners of large earthquakes to drive civil protection actions, including the use of probabilistic seismic hazard analysis in the wake of a large earthquake.*

The Commissioners are geoscientists from China, France, Germany, Greece, Italy, Japan, Russia, United Kingdom, and United States with wide experience in earthquake forecasting and prediction.

B. L'Aquila Earthquake

The L'Aquila earthquake disaster of 6 April 2009 illustrates the challenges of operational earthquake forecasting. The mainshock, moment magnitude 6.3, struck central Italy in the vicinity of L'Aquila, the capital of the Abruzzo region, at 3:32 am local time, killing over 300 people and destroying or rendering uninhabitable approximately 20,000 buildings (**Figure 1.1**). The quake injured at least 1,500 residents and temporarily displaced more than 65,000. Many of the region's cultural sites were badly damaged or destroyed, including the historic centers of Onna, Paganica, and Castelnuovo.

Figure 1.1. The 6 April 2009 earthquake caused extensive damage in the L'Aquila region, killing over 300 people and temporarily displacing more than 65,000 from their homes.

From the perspective of long-term seismic hazard analysis, the L'Aquila earthquake was no surprise. It occurred within a broad zone of historical seismicity, about 30 km wide, that runs along the Central Apennines. The probabilistic seismic hazard model of Italy, published in 2004 [*1*], identified this zone as one of the country's most seismically dangerous (**Figure 1.2**).

The seismotectonic environment of the earthquake, described in Appendix A, involves a complex system of normal faults that is accommodating northeast-southwest extension of the Apennines. The earthquake was caused by a rupture of the Paganica fault, a member of the Middle Aterno fault system, along about 18 km of its length [*2*]. This southwest-dipping normal fault had been identified as an active structure prior to the earthquake, but it was only roughly mapped and had not been included in the Italian Database of Individual Seismogenic Sources [*3*].

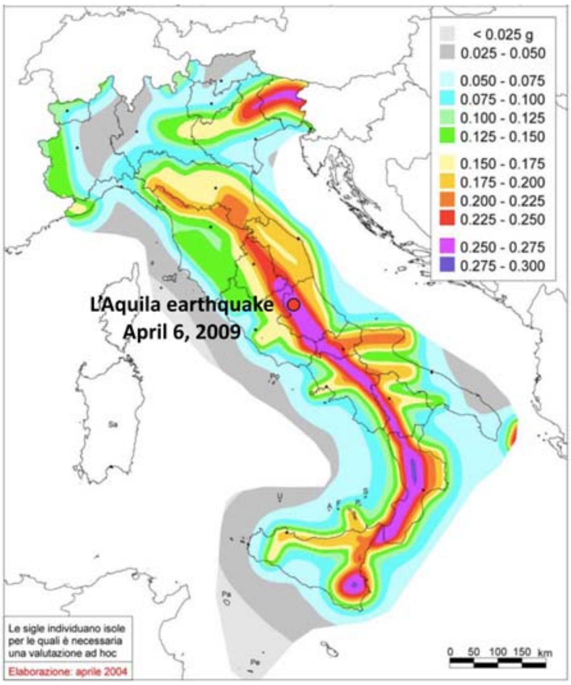

Figure 1.2. The probabilistic seismic hazard map for Italy [*1*], showing the location of the L'Aquila earthquake of 6 April 2009. The colors indicate the ground acceleration with a 10% probability of exceedance in 50 years, measured in units of surface gravitational acceleration, $g = 9.8\ m/s^2$.

The earthquake triggered seismic activity along the Middle Aterno fault system, as well as along the Laga fault system to the north (**Figure 1.3**). In the following months, thousands of aftershocks were recorded over an area of more than 5,000 square kilometers. Six had moment magnitudes of 5 or larger, and the two strongest aftershocks, which occurred on April 7 (moment magnitude 5.6) and April 9 (moment magnitude 5.4), caused additional damage. Beginning on the morning of April 7, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) produced 24-hour forecasts of aftershock activity as a scientific test. Statistical tests have since shown that these short-term forecasts reliably tracked the space-time evolution of the aftershock sequence with significant skill [*4*].

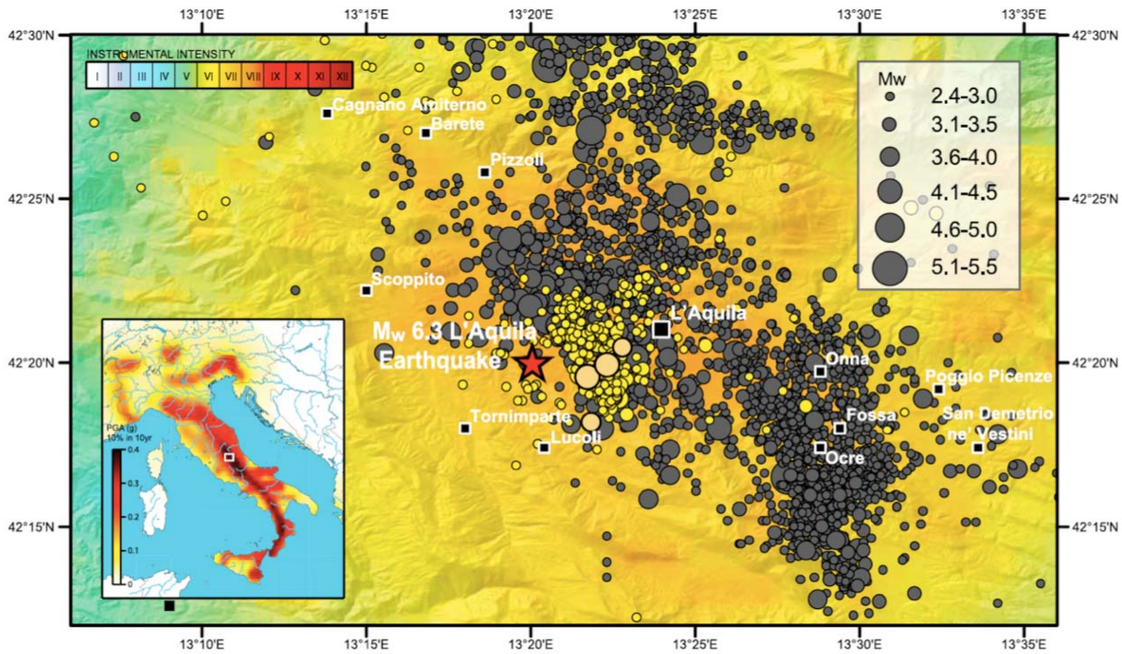

Figure 1.3. Map of the region affected by the 6 April 2009 L'Aquila M_W 6.3 earthquake (red star), including the ground motion predicted by the ShakeMap approach, the foreshocks between 1 November and 6 April (yellow), aftershocks between 6 April and 1 May (gray), and the settlements (black squares). Inset shows the national seismic hazard map [*1*] with the white box indicating the region in the main panel. Figure from van Stiphout et al. [*261*].

The skill of seismic forecasting prior to April 6 has been a controversial subject, at least from a public perspective [*5*]. Seismic activity in the L'Aquila area increased in January 2009 (**Figure 1.4**). A number of small earthquakes were widely felt and prompted school evacuations and other preparedness measures. The largest event of foreshock sequence, on March 30, had a local magnitude of 4.1. Two foreshocks of local magnitude 3.5 and 3.9 occurred within a few hours of the mainshock. In this context, "foreshock" is a strictly retrospective label; an event can be so designated only after the mainshock has been identified, which requires that the seismic sequence be completed (see §II.A). The seismological information available prior to the L'Aquila mainshock was insufficient for such a determination.

The situation preceding the mainshock was complicated by a series of earthquake predictions issued by Mr. G. Giuliani, a resident of L'Aquila and a technician of Istituto Nazionale di Astrofisica working at the Laboratori Nazionali del Gran Sasso [*6*]. These predictions, which had no official auspices, were reported through the media and described as being based on radon concentrations measured with gamma-ray detectors [*7*]. At least two of the predictions (on February 17 and March 30) were false alarms. No evidence examined by the Commission indicates that Mr. Giuliani transmitted to the civil authorities a valid prediction of the mainshock before its occurrence. However, his predictions during this period generated widespread public concern and official reactions. At the time, representatives of the DPC and INGV stated that (a) there were no scientifically validated methods for earthquake prediction, (b) such swarm activity was common in this part of Italy, and (c) the probability of substantially larger earthquakes remained small. The Commissione Nazionale per la Prevenzione e Previsione dei Grandi Rischi (CGR), which provides the government with authoritative information about hazards and risk (see §IV.C), was convened by the DPC on March 31.

It concluded that “there is no reason to say that a sequence of small-magnitude events can be considered a sure precursor of a strong event.”

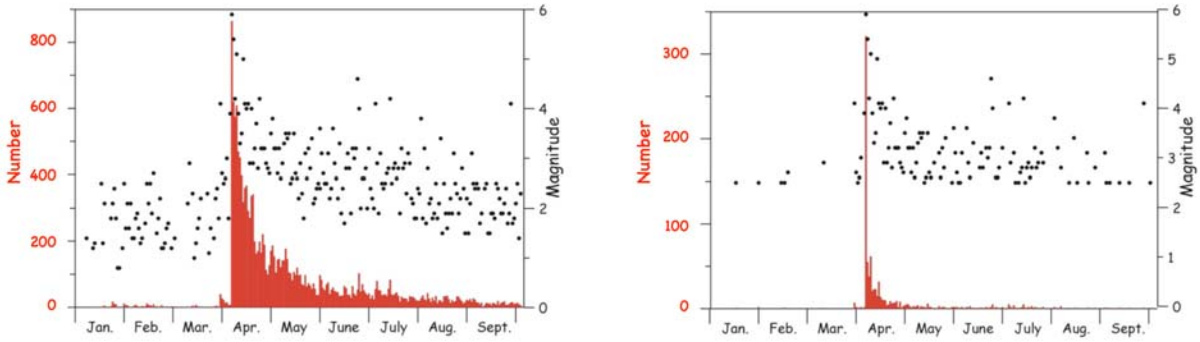

Figure 1.4. Time sequence of earthquakes in L’Aquila area from January 2009 through September 2009. (a) Total number of events located each day, in red (left scale); black dots show the highest magnitude event for each day (right scale). (b) Same plot filtered to include only events with magnitudes of 2.5 and greater. (Data from INGV.)

The L’Aquila experience raised a number of general questions pertaining to large earthquakes in Italy and elsewhere. What are the best available scientific methods for forecasting large earthquakes and their aftershocks in seismically active regions? Can large earthquakes be forecast with short-term probabilities that are high enough and reliable enough to aid in civil protection? How should government authorities use scientific information about earthquake probabilities to enhance civil protection? How should this information be communicated to the public?

C. Conduct of the Study

The Commission was convened and received its mandate from Dr. Bertolaso and Prof. Mauro Dolce (Chief of Evaluation, Prevention, and Mitigation, DPC Seismic Risk Office) in L’Aquila on 12-13 May 2009. The Commission was briefed on the L’Aquila sequence by DPC and INGV at the DPC headquarters, and it was taken on an air survey of the damaged area and a land survey of the historical center of L’Aquila. The Commission interviewed Mr. Giuliani, who requested an opportunity to describe his research on radon emissions as precursors to earthquakes. A work plan for the Commission was established with four main objectives:

- Evaluate the science of earthquake prediction and forecasting and its current ability to aid in civil protection.
- Assess the state-of-the-art of operational earthquake forecasting, drawing from developments in seismically active regions worldwide.
- Provide a roadmap for incorporating new scientific understanding into validated models that can be used in operational earthquake forecasting.
- Produce a report with findings and recommendations written in plain language for a general audience but based on concepts couched in a well-defined terminology.

The first meeting ended with a press conference.

The Commission held its second meeting at the German Research Centre for Geosciences (GFZ) Headquarters in Potsdam on June 5; the chair joined through a videolink to the Southern California Earthquake Center (SCEC) in Los Angeles. The mandate was discussed, main chapters of the report were outlined, and a task list was articulated that included a timetable and assignments to each member.

The third meeting was convened via audio-conference on July 15. The Commission discussed draft sections on the science of earthquake prediction and forecasting and summaries of national earthquake forecasting operations in China, Japan, Russia, and Greece. An overview of Italian earthquake sequences was requested.

The fourth meeting took place at the DPC headquarters in Rome on August 31 through September 2. The Commission met with Prof. Barberi (Vice President of the National Commission for the Prediction and Prevention of Major Risk), Prof. Boschi (President of INGV), and Dr. Curcio (Head of DPC Emergency Management) to discuss the research on seismic hazards and risk in Italy and to solicit their advice on earthquake forecasting procedures. The Commission chair assigned new tasks for preparation of the final report, which was structured into five main sections. The discussions focused on the fourth section, which details the Commission's key findings and recommendations.

The Commission held its final meeting at the DPC headquarters in L'Aquila, September 30 to October 2. A summary of the report, including the Commission's key findings and recommendations, was released at a press conference held near the end of the meeting [*8*]. The Commission concluded the meeting with a visit to reconstruction sites in L'Aquila.

Production of the complete ICEF report (this document) was coordinated by telecons and emails. A preliminary version was presented by the chair to Dr. Bertolaso and Prof. Dolce during a visit to the DPC headquarters in Rome on 2 July 2010, and the final version submitted to DPC on 1 December 2010.

D. Organization of the Report

The report comprises four main sections:

§I. *Introduction*: describes the charge to the Commission, the L'Aquila earthquake context, and the Commission's activities in preparing the report.

§II. *Science of Earthquake Forecasting and Prediction*: lays out definitions and concepts, summarizes the state of knowledge in earthquake forecasting and prediction, and discusses methods for testing forecasting models and validating forecasting procedures.

§III. *Status of Operational Earthquake Forecasting*: reports on how governmental agencies in China, Greece, Italy, Japan, Russia and United States use operational forecasting for earthquake risk management.

§IV. *Key Findings and Recommendations*: states the Commission's key findings and makes specific recommendation regarding policies and actions that can be taken by DPC to improve earthquake forecasting and its utilization in Italy.

§V. *Roadmap for Implementation*: summarizes the actions needed to implement the main recommendations in Italy.

The latter two sections reproduce the findings, recommendations, and roadmap originally released by the Commission on 2 October 2009 [*8*]. Two appendices are also included in the report:

A. Seismotectonic Environment of the L'Aquila Earthquake
B. Index of Acronyms and Abbreviations

II. Science of Earthquake Forecasting and Prediction

Earthquake forecasting and prediction is a highly technical field with a rich literature and vigorous research activities in many countries. The Commission has surveyed this research with the aim of assessing the methodologies for operational earthquake forecasting that are either currently deployed or might be feasibly developed for civil protection in the next several years. The report includes a brief synopsis of published results, emphasizing applications to Italian seismicity. It summarizes some interesting areas for future research but avoids detailed speculations on the long-term prospects for earthquake prediction.

A. Definitions and Concepts

Most damaging earthquakes are caused by the rupture of preexisting faults at depths less than 50 km, where past earthquakes have already weakened the brittle rocks within an active fault zone. An earthquake occurs when slowly increasing tectonic stresses cause the fault to fail suddenly. The rupture is a dynamic process, spreading rapidly from a small fault patch—the *nucleation zone*—across the fault surface (or multiple surfaces), displacing the earth on either side of the fault and radiating energy in the form of seismic waves.

Earthquake forecasting and prediction involve statements about the location, time, and magnitude of future fault ruptures. The spatial location of a rupture is usually taken to be the point at depth on a fault where the rupture nucleated—the *hypocenter*—and its temporal location is taken to be the *origin time* of its first dynamic motion [*9*]. For large earthquakes with rupture dimensions of tens of kilometers or more, other specifications of location, such as the space-time centroid of the fault slip, may be employed.

The most standardized and reliable measure of earthquake size is its *moment magnitude*, abbreviated M_W, which is based on the physical concepts of seismic moment [*10*] and seismic energy [*11*]. Moment magnitude can differ significantly from other magnitude scales in common use, such as the "local magnitude" M_L, which is derived from amplitudes recorded on nearby seismographs. For example, M_L of the L'Aquila earthquake was originally reported as 5.8, half a unit less than its M_W of 6.3, and later revised to 5.9 [*12*]. Such variations are common and generally reflect differences in the way that local magnitude scales have been calibrated, as well as variations in the amplitudes of seismic waves due to rupture orientation, rupture complexity, and geological heterogeneities.

1. Earthquake Phenomenology

The big earthquakes that dominate seismic energy release are very rare events. In space-time domains of sufficient size, the number of earthquakes greater than generic magnitude M is observed to follow a Gutenberg-Richter scaling relation, $\log_{10} N = a - b\mathrm{M}$ [*13*]. The *a-value* in this logarithmic relation gives the earthquake rate. The slope, or *b-value*, is usually close to unity, so that event frequency decreases tenfold for each unit increase in magnitude. Therefore, in an active fault system over the long-term, approximately 10,000 magnitude-2 earthquakes will occur for every magnitude-6 event.

In seismically active regions monitored with dense seismometer networks, Gutenberg-Richter scaling is observed down to very small magnitudes ($M_W < 0$). This supports an inference from laboratory experiments that the minimum size of fault rupturing—the *inner scale* of fault dynamics—is very small (< 10 m) [*14*]. Any finite seismometer network can only locate earthquakes large enough to be detected above the ambient noise level, so that seismicity catalogs will be incomplete for earthquakes less than some *completeness threshold*. In the L'Aquila area, for example, the completeness threshold at the time of the 6 April 2009, earthquake was approximately M_L1.5 [*15*].

Because fault systems are finite in size, Gutenberg-Richter scaling cannot persist to arbitrarily large magnitudes. Above some upper cutoff magnitude, the event frequency must drop towards zero more rapidly than exponentially in magnitude, defining a spatial *outer scale* of the rupture process. This maximum magnitude, which depends on the geometry and tectonics of the fault system, can be difficult to estimate accurately [*16*].

Earthquakes have a tendency to occur closely in time and space as earthquake clusters or sequences (**Figure 2.1**). If the biggest earthquake is substantially larger than other earthquakes in the sequence, it is called the *mainshock*. Once a mainshock is defined in an earthquake sequence, earthquakes that occurred before the mainshock origin time and close to the mainshock hypocenter are called *foreshocks*, and those that occurred after the mainshock are called *aftershocks*. When the rate of seismicity is high but no mainshock stands out, the sequence is called an *earthquake swarm*.

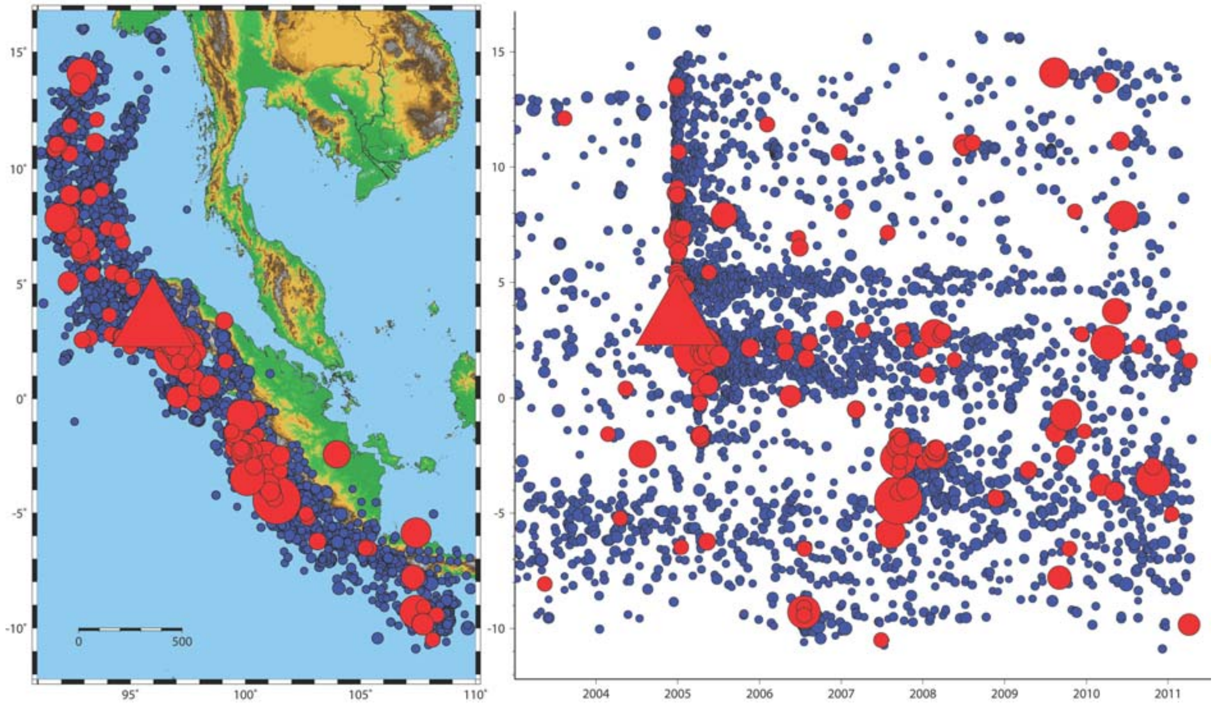

Figure 2.1. Sequence of earthquakes along the Indonesian subduction zone, beginning with the M_W 9.2 Sumatra earthquake of 26 December 2004 (red triangle) and continuing through early 2011. The vertical axis is latitude in geographic degrees. Red dots are the initiation points of events with $M_W \geq 7$; blue circles are smaller events. The Sumatra mainshock was followed by a very large aftershock, the M_W 8.7 Nias event of 28 March 2005, which was anticipated by calculations of stress loading south of mainshock epicenter [see ref.*195*]. This space-time plot illustrates the statistics of earthquake triggering; in particular, it shows how aftershocks generate their own aftershock sequences. Figure by J. Donovan and T. Jordan.

Foreshocks, mainshocks, and aftershocks are retrospective designations; they can only be identified as such after an earthquake sequence has been completed. Moreover, individual events in a sequence cannot be physically distinguished from the *background seismicity* unrelated to the mainshock. Background seismicity can add considerable uncertainty to the process of delimiting of foreshock and aftershock sequences in space and time, as can the overlapping of seismic sequences.

Almost all big earthquakes produce aftershocks by *stress triggering*, which may be caused by permanent fault slip and related relaxation of the crust and mantle (quasi-static triggering) or by the passage of seismic waves (dynamic triggering) [*17*]. The number of aftershocks is observed to increase exponentially with the magnitude of the mainshock (Utsu scaling) [*18*], and the aftershock rate is observed to decrease approximately inversely with time (Omori scaling) [*19*].

The scaling relations of Gutenberg-Richter, Utsu, and Omori can be combined into a stochastic model of seismicity, called an *Epidemic Type Aftershock Sequence (ETAS)* model, in which sequences comprise multiple generations of triggered events and can be initiated by spontaneous background seismicity [*20*]. ETAS-type models recognize no physical differences among foreshocks, mainshocks, and aftershocks (other than location, time, and magnitude), yet they can reproduce many of the short-term statistical features observed in seismicity catalogs, including aftershock magnitudes and rates, aftershock diffusion, and some statistical aspects of retrospectively-identified foreshock sequences [*21*, *22*].

Long-term earthquake statistics are commonly represented in terms of the average number of events in a specific space-magnitude window, or in terms of the average time between successive ruptures of a entire fault segment, sometimes assumed to be *characteristic earthquakes* with approximately the same fault slip [*23*]. According to the elastic rebound theory of the earthquake cycle (see §II.B.1), this *mean recurrence interval* is the time required to accumulate the fault strain that will be released in next characteristic earthquake. The mean recurrence interval of a fault segment can be calculated by dividing the slip expected in a characteristic earthquake, which scales with segment length, by the long-term slip rate of the fault, which can be estimated from geologic or geodetic observations.

Owing to several effects, including incomplete stress release, variations in rupture area, and earthquake-mediated interactions with other faults, the earthquake cycle is not periodic, and time between successive earthquakes can be highly irregular. To account for this variation, earthquake recurrence is often modeled as a stochastic *renewal process* described by a mean recurrence interval and a coefficient of variation [*24*].

2. Seismic Hazard and Risk

Earthquakes proceed as cascades in which the primary effects of faulting and ground shaking may induce secondary effects, such as landslides, liquefaction, and tsunami. *Seismic hazard* is a forecast of how intense these natural effects will be at a specified site on Earth's surface during a future interval of time. In contrast, *seismic risk* is a forecast of the damage to society that will be caused by earthquakes, usually measured in terms of casualties and economic losses. Risk depends on the hazard but is compounded by a community's *exposure*—through its population and built environment—and its *vulnerability*, the fragility of its built environment to shaking and secondary hazards, such as fires and dam failures [*25*]. Risk, when measured as an expected total loss that includes economic aftereffects, is lowered by *resilience*, how quickly a community can recover from earthquake damage [*26*].

Risk analysis seeks to quantify future losses in a framework that allows the impact of policies and investments relevant to risk reduction to be evaluated. Risk quantification is a difficult problem, because it requires detailed knowledge of the natural and built environments, as well as highly uncertain predictions of how regions will continue to develop economically. Owing to the exponential rise in the urban exposure to seismic hazards, the risk levels in many regions are rising rapidly [*27*].

In most regions of Italy, seismic risk is driven by the damage caused by seismic shaking. Quantifying the hazard due to shaking is the goal of *probabilistic seismic hazard analysis* (PSHA). Various *intensity measures* can be used to describe the shaking experienced during an earthquake; common choices are peak ground acceleration and peak ground velocity. PSHA estimates the *exceedance probability* of an intensity measure: the probability that the shaking will exceed some measure at a particular geographic site over a time interval of interest, usually several decades or more [*28*].

A plot of the exceedance probability as a function of the intensity measure is called the *hazard curve* for the site. From hazard curves, engineers can estimate the likelihood that buildings and other structures will be damaged by earthquakes during their expected lifetimes, and they can apply the performance-based design and seismic retrofitting to reduce structural fragility to levels appropriate for life-safety and operational requirements. A *seismic hazard map* is a plot of the intensity measure as a function of the site position for fixed probability of exceedance [*29*, *30*]. Official seismic hazard maps are now produced by many countries, including Italy (see Figure 1.2), where they are used to specify seismic safety criteria in the design of buildings (e.g., through building codes), lifelines, and other infrastructure, as well as to guide disaster preparedness measures and set earthquake insurance rates.

PSHA involves the estimation of two different types of probabilities: the probability for the occurrence of a distinct earthquake source (fault rupture) during the time interval of interest, and the probability that the ground motions at a site will exceed some intensity for that particular fault rupture. The first is obtained from an *earthquake rupture forecast*, whereas the second is computed from ground motion prediction model or *attenuation relationship*, which quantifies the distribution of ground motions as they attenuate with distance away from the source [*31*].

The Commission focused its study on the forecasting of earthquake ruptures, rather than the ground motions they produce, because the latter involves scientific issues beyond the scope of the Commission's mandate. However, the goal of operational earthquake forecasting—to provide communities with authoritative information about how seismic hazards are changing in time—clearly requires the ability to express earthquake rupture forecasts in terms of ground motions. Issues regarding strong-motion forecasting are briefly discussed in §II.D.

3. Probabilistic Forecasting and Deterministic Prediction

This report considers methods for forecasting and predicting earthquakes that belong to a predetermined class of *target ruptures*: fault slip events within a specified magnitude range that could hypothetically occur within a specified space-time domain. For most operational purposes, the spatial domain is taken to be a contiguous geographic region comprising the seismogenic volume of the lithosphere, and the temporal domain is a finite, continuous time interval.

Earthquake occurrence is often represented as a *marked point process* in which each event is specified by an origin time, hypocenter, and magnitude [*32*]. These are only a minimal set of observables, however. A forecast or prediction may be *fault-based*, specifying the likelihoods that certain faults (or seismogenic volumes around the faults) will rupture, and thus may require other observations, such as estimates of the rupture surface and slip direction, for an evaluation of its performance.

Predictions and forecasts both make statements about future earthquake activity based on information available at the time; that is, they provide *prospective* (before-the-fact) rather than *retrospective* (after-the-fact) earthquake information. In this report, the Commission distinguishes between a prediction and a forecast using a strict dichotomy. A prediction involves casting an *alarm*—an assertion that one or more target ruptures will occur in a specified subdomain of space (subregion) and future time (subinterval). Predictions are therefore prospective *deterministic* statements: if a target event occurs in the alarm subdomain, the prediction is a true alarm; otherwise it is a *false alarm* (or type-I error). If a target event occurs in a subdomain without an alarm, the error is a *failure-to-predict* (or type-II error). A prediction can also be cast as an *anti-alarm*, a deterministic statement that no target rupture will occur in a subdomain [*33*].

Forecasts are prospective *probabilistic* statements: they specify the probabilities that target events will occur in space-time subdomains. The probability in a particular subdomain is a number P that ranges between 0 (no chance of a target event) and 1 (certainty of a target event). A *time-independent* forecast is one in which the subdomain probabilities depend only on the long-term rates of target events; the events are assumed to be randomly distributed in time, and the probabilities of future events are thus independent of earthquake history or any other time-dependent information. Time-independent forecasts are useful for long-term seismic hazard analysis.

In a *time-dependent* forecast, the probabilities $P(t)$ depend on the information $I(t)$ available at time t when the forecast is made. The most useful information for operational forecasting has come from seismic catalogs and the geologic history of surface ruptures (§II.B.3). Examples related to different forecasting time windows include ETAS forecasts, based on short-term earthquake triggering statistics [*20*], and stress-renewal forecasts, based on long-term elastic rebound theory. In the latter type, which has been developed most thoroughly for California's San Andreas fault system [*34*], the rupture probability of a fault segment depends on the date of the last rupture according to a statistical distribution of recurrence intervals estimated from historical and paleoseismic records. Both types of forecasts must be updated as significant earthquakes occur within the fault system.

An earthquake prediction requires making a choice to cast, or not cast, an alarm. There are two basic approaches to this decision problem. The first is to find a deterministic signal, or pattern of signals, in $I(t)$ that can predict future earthquakes; i.e., to identify a *diagnostic precursor* that ensures with high probability that a target event will occur in a specific subdomain. The search for diagnostic precursors has so far been unsuccessful (§II.B.2).

The second approach is to cast deterministic predictions based on probabilistic forecasts. If the probability of a target event during a fixed forecasting interval is $P(t)$, the decision rule might be to cast a regional alarm for the subsequent interval whenever this time-dependent probability exceeds some threshold value P_0. If the probability model is accurate, the consequence of choosing a higher or lower threshold can be evaluated in terms of the anticipated false-alarm and failure-to-predict error rates. However, if $P(t)$ is low at all times, which is typical in forecasting large earthquakes over short periods, at least one of the prediction error rates will always be high, regardless of the decision rule. Such predictions always contain less information than the forecasts from which they were derived. Consequently, for most decision-making purposes, probabilistic forecasting provides a more complete description of prospective earthquake information than deterministic prediction [*35*, *36*].

4. Temporal Classification

Forecasts and predictions can be classified according to the time span of their applicability, which depends on the temporal scales of the natural processes that govern earthquake occurrence, such as hypothesized precursory phenomena, as well as more practical considerations, such as the time needed to enact civil protection measures in response to different types of predictions and forecasts. In the terminology used here, a forecast or prediction is said to be *long-term* if its time span is several years to many decades, *medium-term* if its span ranges from months to years, and *short-term* if its span is a few months or less.

The time span of a prediction is simply the interval of the alarm window. For probabilistic forecasts, the span is given by the length of time over which the subdomain probabilities are estimated, which is often a parameter of the forecasting model. For instance, from a time-independent forecast, one can produce event probabilities for arbitrarily intervals by assuming the events occur randomly in time [*37*]. The probabilities of large earthquakes from a time-independent forecast are always small for intervals short compared to the assumed earthquake recurrence interval.

A short-term alarm with a window less than a week or so is sometimes called an *imminent prediction*. Public attention is focused, quite naturally, on the desire for imminent predictions that would allow the evacuation of dangerous structures and other aggressive steps for civil protection. The most famous case of an imminent prediction was the Haicheng earthquake of 4 February 1975, in which a large population was evacuated in the hours before the mainshock. The Haicheng prediction is credited with saving many lives [*38*], although the formality and auspices of the prediction have been questioned [*39*, *40*] and similar schemes have not led to other comparable successes.

5. Uncertainties in Forecasting and Prediction

Statements about future earthquakes are inherently uncertain, and no forecast or prediction can be complete without a description of this uncertainty. Because uncertainty is expressed in terms of probabilities, both deterministic predictions and probabilistic forecasts need to be stated and evaluated using probabilistic concepts.

A forecast gives the probability an event will occur, which is an expression of uncertainty. This probability is almost never zero or unity, because natural variability in the system behavior introduces *aleatory* uncertainty, represented by the forecast probabilities. Aleatory variability is an intrinsic feature of a system model, but it will vary with the information that conditions the state of the system. For example, a forecast based on long-term seismicity rates might yield a 0.01% chance that a target earthquake will occur in a small subdomain of space and time and a 99.99% chance that it will not. Another forecast that incorporates additional information, say the recent occurrence of small earthquakes that could be foreshocks, might increase the event probability to, say, 1%, in the same subdomain. The aleatory uncertainty of the latter is greater, because the added information (recent seismicity) makes the prediction that no target event will occur less certain [*41*]. But its *probability gain* relative to the former, given by the ratio of the event forecast probabilities, is high: the likelihood of a target event has gone up by a factor of 100. A related concept is *information gain*, given by the logarithm of the probability gain factor [*42*]. In operational earthquake forecasting, new information can yield high probability gains, although the absolute probabilities usually remain low (see section II.D).

Incorrect models of earthquake processes and other errors in the forecasting method introduce *epistemic* uncertainties. Epistemic uncertainties are represented by probability distributions on the forecasting probabilities. Often, though not always, these are expressed in logic trees that incorporate a degree of variability due to alternative forecasting models. The relative weights of the alternatives are assigned from previous experience or, in lieu of adequate data, by expert opinion about model validity [*43*].

6. Operational Fitness

The *quality* of a forecasting or prediction method depends on how well it corresponds to the observations collected during many trials. Assessing the quality of a method is a multifaceted problem involving many attributes of performance [*44*]. Two attributes, reliability and skill, are highlighted in this report. *Reliability* evaluates the statistical agreement between the forecast probabilities of target events and the observed frequencies of those events (e.g., the mean observation conditional on a particular forecast). Reliability is an absolute measure of performance. *Skill*, on the other hand, assesses the performance of one method relative to another. Measures of skill can be used to evaluate a candidate method, say a short-term earthquake forecast, relative to a standardized reference method, such as a time-independent forecast [*42*, *45*]. To be useful, a method must demonstrate some degree of reliability and skill.

Various pitfalls have been encountered in the evaluation of method quality. Many amateur (and even some professional) predictions are stated only vaguely and qualitatively, because they are then more likely to be found reliable just by chance. Reliable earthquake predictions can always be made by choosing the alarm windows wide enough or magnitude thresholds of the target events low enough. For instance, the statement that an earthquake greater than magnitude 4 will occur somewhere in Italy during the next year is a very reliable prediction—the probability that it will be a correct alarm is almost certain. On the other hand, it is not a skillful prediction; any time-independent forecast calibrated to the instrumental seismicity catalog for Italy would also attach a probability very near unity to this statement [*46*]. Inflated estimates of skill can be easily obtained by choosing a reference forecast that is overly naïve; e.g., based on the (false) assumption that earthquakes are randomly distributed in time and space [*47*].

The worthiness of a method for operational applications—its *operational fitness*—depends on the method's quality, but also on its consistency and value to decision makers [*48*]. In this report, *consistency* will be primarily used to describe the compatibility of methods that range over different spatial or temporal scales; e.g., the consistency of short-term forecasting models with long-term forecasts. The *value* of a method describes the realizable benefits (relative to costs incurred) by individuals or organizations who use the forecasts to guide their choices among alternative courses of action [*49*]. The process of establishing the operational fitness of a forecasting method in terms of its quality, consistency, and value is here called *validation* [*50*].

B. Research on Earthquake Predictability

Earthquake predictability is the degree to which event populations in future domains of space, time, and magnitude can be determined from hypothetical observations. According to Gutenberg-Richter scaling, long-term observations of small earthquakes delineate the faults capable of producing large earthquakes. Therefore, *where* large earthquakes will occur can be predicted to a fairly high degree if sufficient seismicity and geologic data are available. (The Commission notes, however, that surprises have been frequent in poorly delineated fault systems.) Geologic and geodetic data on fault-slip and deformation rates can be balanced against seismic moment release to constrain the mean recurrence intervals of large earthquakes and thus determine *how frequently* they will occur. The difficult problem is to predict *when* large earthquakes will actually happen. The history of the subject can be traced into antiquity, but the modern scientific approach began with the development of the elastic rebound theory by H. F. Reid and others about a century ago [*51*].

1. Predictability of the Earthquake Cycle

Elastic rebound is a physical theory based on the idea that two crustal blocks move steadily with respect to each other, slowly increasing the shear stress on the fault that forms their tectonic boundary until the fault reaches its yield stress and suddenly ruptures. During the rupture, the friction on the fault drops, and the two blocks rebound elastically, springing back toward their undeformed state and reducing the shear stress to a base stress near zero [*52*]. The elastic energy is dissipated as heat and seismic waves that radiate from the fault, as well as by rock fracture during rupture. After the drop in shear stress, the slip velocity rapidly decreases, the friction recovers, and the fault locks up. The relative block motion continues unperturbed by the earthquake, and the shear stress begins to rise slowly once again.

The elastic rebound model is too simplistic to explain many salient aspects of earthquake phenomenology, but it does provide a framework for describing some important physical concepts important to the research on earthquake predictability, including the characteristic earthquake and seismic gap hypotheses that underlie many long-term, time-dependent forecasting models.

Characteristic earthquake hypothesis. In the ideal situation of a single, isolated fault segment where the yield stress and the tectonic loading remain constant, earthquakes have been hypothesized to be characteristic; i.e., repeating ruptures will have similar properties, such as fault slip (proportional to stress drop) and moment magnitude (proportional to slip times fault area) [*23*]. The earthquake cycle should then be periodic with a constant recurrence interval, which can be estimated knowing the relative velocity between the blocks and the slip in a characteristic earthquake or, more directly, from the statistics of repeating events. According to this hypothesis, earthquake occurrence on an individual fault does not follow a Gutenberg-Richter relationship, and the rates of large events cannot be simply extrapolated from the rates of small ones.

In the real world, the earthquake cycle is not strictly periodic, of course. The data for a particular fault segment will show a variation in the recurrence intervals that can be measured by a coefficient of variation. The data for estimating recurrence intervals come from three types of earthquake catalogs: instrumental, based on seismographic recordings; historical, based on non-instrumental written records; and paleoseismic, based on the geologic record of prehistoric events [*53*]. The instrumental catalogs are the most accurate in terms of occurrence times and magnitudes, but they are limited to the last hundred years or so—less than the mean recurrence intervals of most active faults. For example, the more active normal faults in the Abruzzo region are inferred to have mean recurrence intervals of 500-2000 years [*54*]. Historical records in civilized regions like Italy can extend earthquake catalogs over one or two thousand years, and, for some faults, paleoseismic studies can provide information about the largest events over even longer intervals. However, the accuracy and completeness of the earthquake catalogs degrade quickly with event age [*55*].

Retrospective analyses of instrumental, historical, and paleoseismic earthquake catalogs yield coefficients of variation that range from 0.1, a nearly periodic sequence, to 1.0, the value expected for a Poisson (random) distribution [*56*]. These estimates are often highly uncertain and can be biased by epistemic uncertainties in the catalogs [*57*]. There can also be a high variation in the moment magnitudes of earthquakes in observed sequences, which also represents a departure from the characteristic model. In some cases, faults show evidence of multiple modes of periodicity [*58*].

A number of prospective experiments have attempted to use the periodicity of the earthquake cycle to predict characteristic earthquakes and examine their possible precursors. Three projects established in the 1980s have provided important perspectives:

- A prediction experiment in the Tokai region of central Honshu was initiated in 1978 by the Large-Scale Earthquake Countermeasures Law enacted by the Japanese government. The last major earthquake had occurred in 1854, and historical studies had estimated the mean recurrence interval for large ($M \approx 8$) earthquakes in this highly populated region to be 117 years with a coefficient of variation of approximately 0.2 [*59*].
- In 1984, the Parkfield prediction experiment was established along a section on the San Andreas fault in central California. The Parkfield segment had ruptured in similar $M \approx 6$ earthquakes six times since 1857, the last in 1966. Using a characteristic earthquake model with a mean recurrence interval of 22 years and a coefficient of variation of about 0.2, the U.S. Geological Survey estimated that the next Parkfield earthquake would occur before January, 1993, at a 95-percent level of confidence [*60*].
- The German-Turkish Project on Earthquake Prediction Research was established in 1984 in the Mudurnu Valley, at the western end of the North-Anatolian Fault Zone. The recurrence interval for $M \approx 6$ earthquakes along this test section was estimated to be 15-21 years, and the last such event had occurred in 1967. The coefficient of variation was also about 0.2, but the magnitude range used for this estimate was quite large ($5.1 \leq M \leq 7.2$) [*61*].

Instrumentation deployed in these regions as part of the prediction experiments was especially designed to search for short-term precursors, about which more will be said later. A basic finding is that none of the target events occurred within the prediction windows derived from the characteristic earthquake hypothesis. The Izmit M7.4 earthquake ruptured the North Anatolian fault west of Mudurnu Valley in 1999, outside the prediction window [*62*], and an M6 earthquake ruptured the Parkfield segment in 2004, more than ten years beyond the prediction window [*63*]. At the time of writing, the anticipated Tokai event had not yet occurred [*64*].

<u>Seismic gap hypothesis</u>. The elastic rebound model implies that, immediately after a characteristic earthquake, the probability of another on the same fault segment should be very low and then slowly increase through the process of stress renewal as time elapses. Consequently, faults on a plate boundary that have not had a characteristic earthquake for a significant fraction of their recurrence interval can be identified as *seismic gaps*, sites where the probability of a future earthquake is high and increasing [*65*]. The seismic gap hypothesis was articulated in the 1960s, developed into qualitative forecasts in the 1970s, and formulated as a quantitative forecasting model by the early 1990s [*66*].

Testing of the seismic gap hypothesis has focused on circum-Pacific plate boundaries, where the slip rates are high and the recurrence intervals are expected to be relatively short. Some support for the use of seismic gaps as a forecasting method has been published [*66*, *67*], but serious shortcomings of the hypothesis have also been pointed out. In particular, the data suggest that the seismic potential is lower in the gaps and higher in plate-boundary segments where large earthquakes have recently occurred; i.e., plate boundary zones are not made safer by recent earthquakes [*68*].

Refinements that account for systematic spatial variations in the aseismic slip on faults may improve gap-based forecasting. Geodetic data from Global Positioning System (GPS) networks can assess whether a fault segment is locked or slipping aseismically. For example, the 27 February 2010 Maule earthquake in Chile (M_W 8.8) appears to have been a gap-filling rupture of a locked subduction megathrust [*69*] (**Figure 2.2**).

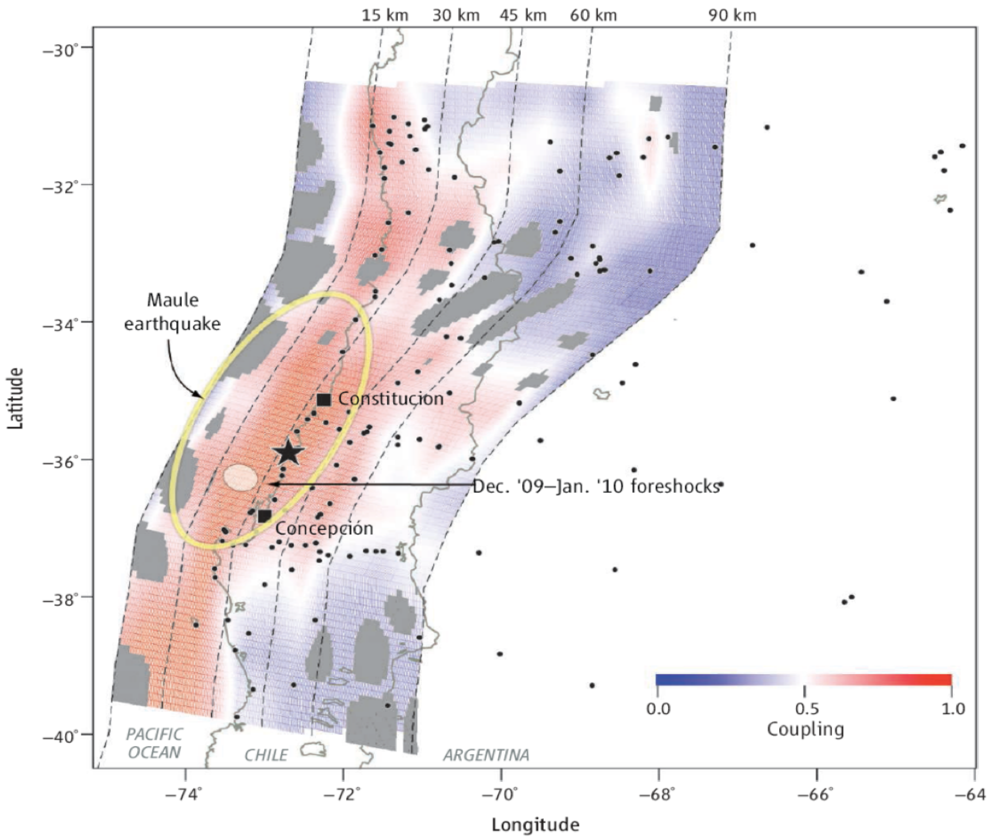

Figure 2.2. Stress accumulation in central Chile before the Maule earthquake on 27 February 2010. The map shows the degree of coupling (or locking) of the plate interface between the Nazca and South American plates. The dark red areas include the rupture zone (yellow ellipse). Dots are the GPS sites used to generate the image. The large black star is the epicenter of the earthquake. The small ellipse is the area where foreshocks were observed from December 2009 to January 2010. Figure from Madariaga et al. [*69*].

Complicating factors. Many other factors have been shown to complicate Reid's simple picture of the earthquake cycle. For example, ruptures may not completely relax the stress on a fault segment; i.e., the stress drop may be only a fraction of the total elastic stress. Consequently, earthquakes are not strictly characteristic. However, if the yield stress were to remain constant, they could be still *time-predictable* [*70*], because the time needed to return the stress to the (constant) fault strength could be estimated from the fault slip in the last event. If the base stress remains constant, but the yield stress is variable, then earthquakes would not time-predictable, but they could be *slip-predictable* because the slip in the next earthquake could be estimated from the time elapsed since the last earthquake. Time-predictable and size-predictable models have been commonly employed in long-term time-dependent forecasting [*71*], but their validity has been questioned through more stringent statistical tests, in particular for the Italian region [*72*].

Earthquake predictability is also compromised by the complexity of fault systems, which display a scale-invariant hierarchy or a *fractal geometry*. Faults are almost never the isolated, planar entities as assumed in simple models of block boundaries; rather, they form discontinuous branching structures distributed in a three-dimensional volume of the seismogenic lithosphere [*73*]. This geometrical complexity, in concert with stress heterogeneities and earthquake-mediated stress interactions, helps to explain the universality of the Gutenberg-Richter frequency-magnitude distribution.

It has been proposed that earthquakes are scale-invariant phenomena describable by the theory of self-organized criticality [*74*]. According to this hypothesis, the crust is maintained by long-term plate tectonic forcing in a critical state, where small ruptures can propagate into much larger ones at any time, thus eliminating the predictability of individual events [*75*]. This hypothesis is consistent with Gutenberg-Richter scaling, the relatively small stress drops of earthquakes compared to ambient tectonic stresses, the fractal distributions of faults, and the ability of small stress perturbations to trigger earthquakes [*76*], as observed in hydraulic fracturing experiments in deep boreholes [*77*]. Self-organized criticality cannot be strictly maintained in a finite fault system, however. The largest ruptures will span the entire system and drop the stress below a critical state, creating zones of relative quiescence until the stress rebuilds by tectonic loading [*78*].

2. Search for Diagnostic Earthquake Precursors

Regularity of an earthquake cycle is not a necessary condition for predictability. An alternative prediction strategy is to monitor physical, chemical, or biological changes that can be related to the preparatory phase of fault rupture. A precursory change is diagnostic if it can predict an impending event's location, time, and magnitude with high probability and low error rates.

Searches for diagnostic precursors—the "silver bullets" of earthquake prediction [*79*]—have been wide ranging, and the results often controversial. In the late 1980s, the Sub-Commission on Earthquake Prediction of the International Association for Seismology and Physics of the Earth's Interior (IASPEI) established a peer-review procedure for precursor evaluation. Out of the 40 nominations evaluated by the IASPEI Sub-Commission by 1994, 31 were rejected, 5 were placed on a Preliminary List of Significant Precursors, and 4 were judged "undecided" owing to lack of data and adequate testing [*80*]. Three of five listed as significant precursors were derived from seismicity patterns, one was based on ground-water chemistry and temperature, and one was based on a measurement of ground-water levels. The latter two precursors were observed only in single instances and only tentatively accepted for further investigation. In a 1997 review, the IASPEI Sub-Commission chair concluded, "It is not clear that any of these proposed precursors are understood to the point that they can now be used for prediction; they are simply a collection of phenomena which have a better than average chance of becoming useful in earthquake prediction some day" [*81*].

The debate on earthquake precursors intensified in the late-1990s [*82*]. Critical reviews written at that time [*75*, *83*, *84*] and in the subsequent decade [*40, 51*, *85*] concluded that none of the proposed precursors considered by the IASPEI Sub-Commission or otherwise published in the scientific literature has been demonstrated to be diagnostic in the sense used here. Cicerone et al. [*86*] have recently provided a face-value compilation of published observations for many types of precursors.

In this section, the Commission briefly summarizes the recent research on several classes of earthquake precursors, including changes in strain rates, seismic wave speeds, and electrical conductivity; variations of radon concentrations in groundwater, soil, and air; fluctuations in groundwater levels; electromagnetic variations near and above Earth's surface; thermal anomalies; anomalous animal behavior; and seismicity patterns.

Strain-rate changes. Geodetic networks can observe strain across systems of active faults up to plate-tectonic dimensions. Strainmeters and tiltmeters measure deformations on much shorter baselines (≤ 1 km). They are typically more sensitive to short-term, localized changes in strain rate than continuously monitored networks of GPS stations or other satellite-based geodetic methods.

The origin time of an earthquake marks dynamic breakout, when the fault rupture attains the speed and inertia needed to generate seismic waves. According to laboratory experiments and theoretical models, the nucleation process leading up to dynamic breakout should occur in a region of higher effective stress and involve the concentration of slip on fault patches that have a characteristic dimension and at a slip rate that increases inversely with the time to dynamic breakout [*87*]. Strainmeters have thus far shown no significant precursory changes in strain rate during the nucleation of large earthquakes, which places limits on the scale of the nucleation zone. Before L'Aquila earthquake, two laser strainmeters located about 20 km from the epicenter did not record precursory signals; the data from these two strainmeters constrain the pre-rupture slip in the hypocentral region to have a moment that is less than 0.00005% (5×10^{-7}) of the mainshock seismic moment [*88*] (**Figure 2.3**).

Similarly stringent constraints on nucleation precursors have come from strainmeters in California that were situated near the epicenters of the 1989 Loma Prieta earthquake (M_W 7.1) [*89*], the 1992

Landers earthquake (M_W 7.3) [*90*], and the Parkfield 2004 earthquake (M_W 6.0) [*91*]. In Japan, the 2003 Tokachi-oki earthquake (M_W 8.0) showed no precursor signals on the strainmeters and tiltmeters located near the source region [*92*].

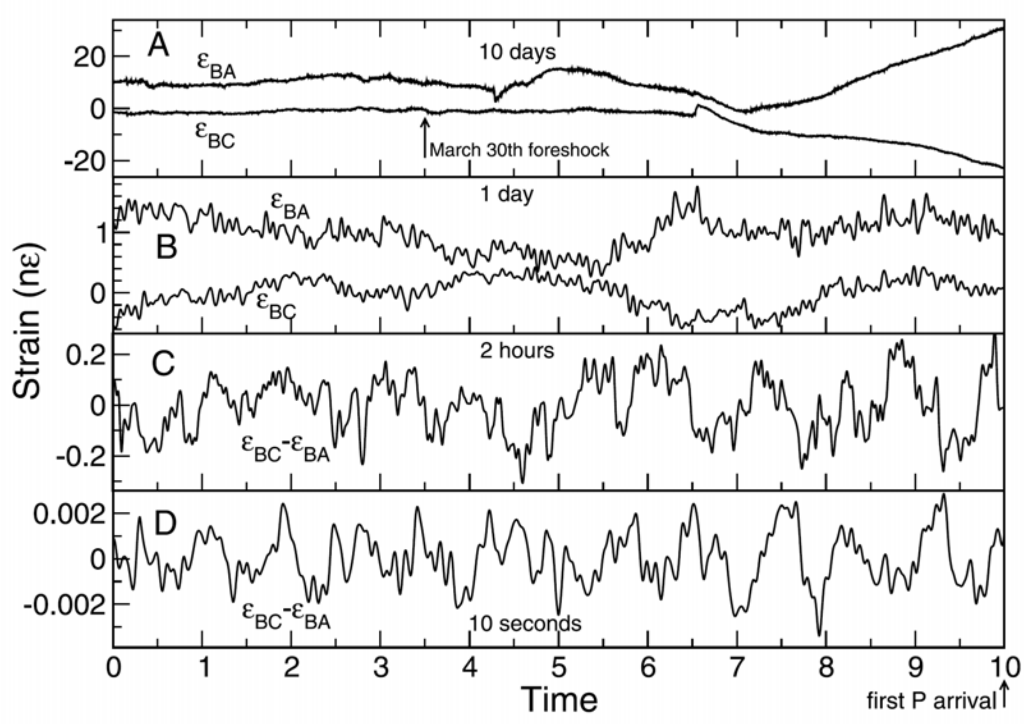

Figure 2.3. Pre-seismic strain recorded on two 90-m laser interferometers (BA and BC) located 1400 m underground at the Laboratori Nazionali del Gran Sasso, approximately 20 km northeast of the 6 April 2009 L'Aquila earthquake. (A) Last ten days before the mainshock in 1-day time units. (B) Last day before the mainshock in 0.1-day time units. (C) Last two hours before the mainshock in 0.2-hour time units. (D) Last ten seconds preceding the first P arrival in 1-s time units. Records have been filtered to the appropriate band after removal of Earth tides, microseisms, environmental effects, and post-seismic offsets due to foreshocks. Each plot ends at the first P arrival from the mainshock. These data constrain the pre-rupture nucleation slip in the hypocentral region of the L'Aquila earthquake to have a moment that is less than 0.00005% (5×10^{-7}) of the mainshock seismic moment. Figure from A. Amoruso & L. Crescentini [*88*].

These results constrain the nucleation scale for dynamic breakout to be a few tens of meters or less, and they are consistent with the hypothesis that this scale is comparable for all earthquakes, big and small; i.e., most seismogenic ruptures start in more or less the same way. If this hypothesis is correct, the pre-seismic strains associated with rupture nucleation at depth would usually be too small to be detected at the surface and, even if observed, would not be diagnostic of the eventual rupture size. In other words, earthquake magnitude depends more on the physical processes that propagate and arrest, rather than nucleate, the rupture.

Another class of precursor is the strain-rate change caused by transient movements on faults too slow to radiate much seismic energy. Slow-slip events have been observed in many subduction zones [*93*] and, more rarely, in continental fault systems [*94*]. Intriguing observations indicate that a large, slow event may have preceded the great 1960 Chile earthquake (M_W 9.5) [*95*] and that slow precursors to large earthquakes may be common on oceanic transform faults [*96*]. Aseismic transients appear to be involved in the excitation of seismic swarms on transform faults in continental and oceanic lithosphere [*97*], as well as in subduction zones [*98*]. However, slow precursors to large continental earthquakes have not been detected by strainmeters or in the geodetic data.

Seismic velocity changes*.* It is possible that precursory changes in stress and strain are too small to be directly observed, but are coherent enough to induce changes in rock properties that can be observed in other types of precursory signals, such as temporal variations in *P*-wave and *S*-wave travel times. In the 1970s, substantial (~10%) changes in the velocity ratio V_P/V_S were reported before earthquakes in California and the Soviet Union [*99*], and the observations were attributed to the dilatant microfracturing of rocks and associated fluid diffusion prior to failure [*100*]. However, better theoretical models incorporating laboratory rock dilatancy, microcracking, and fluid flow did not support to the hypothesized V_P/V_S time history [*101*], and repeated measurements showed only small (less than 1-2%) and poorly reproducible V_P/V_S anomalies [*102*].

An extensive search for seismic velocity variations related to seismic activity has been performed at Parkfield using both natural and artificial sources. Cross-borehole travel-time measurements at the San Andreas Fault Observatory at Depth (SAFOD) have detected small decreases in *S* velocities before two small earthquakes near the boreholes, hypothesized to be caused by precursory changes in microcrack density [*103*]; however, the data are limited, and a causal relationship has not been demonstrated. Other high-resolution seismic experiments have shown clear co-seismic and post-seismic changes in the near-fault velocities associated with the 2004 Parkfield earthquake, but no significant pre-seismic changes [*104*, *105*].

The seismic velocities in cracked and oriented rocks can be anisotropic. Stress changes can, in principle, induce measureable change in the magnitude and orientation of the seismic anisotropy. Observations of *S*-wave splitting (birefringence) have been used to predict earthquakes in Iceland, with one reported success for a single M5 event [*106*]. However, the statistical basis for the forecast has been challenged on a number of counts [*107*]. Relatively few independent observations have been reported for other regions, and at least two published reports are negative [*108*, *109*].

<u>Electrical conductivity changes</u>. The minerals that constitute crustal rocks are generally poor conductors of electricity. At large scales, the electrical conductivity of dry crustal rocks is therefore low, and the rock conductivity is primarily controlled by the distribution of crustal fluids [*110*]. Stress changes are capable of opening and closing the microcracks in rocks, causing the migration of fluids and consequent changes in electrical properties. Stress-induced variations in the electric conductivity of rocks have been extensively studied in laboratory experiments [*111*]. Two behaviors have been reported. In one, the conductivity increased with increasing shear stress, reaching maximum at the time of a sudden release of shear stress and returning to a lower value immediately afterwards. In another, resistivity again decreased with increasing stress, but decreased further upon the sudden drop of shear stress.

The electrical conductivity structure of the crust can be monitored using the underground (telluric) currents induced primarily by externally forced changes in Earth's magnetic field, but also from anthropogenic and hydrologic sources. Changes in electrical conductivity prior to earthquakes have been reported since the early 1970s [*112*]. A number of field experiments have explored for conductivity changes prior to earthquakes [*113*]. For example, a telluric array designed to detect conductivity variations has monitored the San Andreas fault at Parkfield, California, since 1988 [*114*]. No precursory changes have been observed for any of the M > 4.0 earthquakes near Parkfield since 1989, although short-term, co-seismic fluctuations, probably from electrokinetic signals, were observed for some of them. In particular, the M_W 6.0 Parkfield earthquake of 28 September 2004 did not produce any observed electrical precursor [*104*]. In Japan, unusual geoelectrical potential change were observed before the volcano-seismic activity in 2000 in Izu volcano islands; these phenomena have been interpreted as electrical activity from the critical stage before one of M > 6 events in the swarm [*115*]. Although the monitoring of transient electric potentials can be useful for studying fluids in fault zones, there is no convincing evidence that such techniques have detected diagnostic precursors.

<u>Radon emission</u>. The main isotope of radon, ^{222}Rn, is an inert, radioactive gas with a half-life of 3.8 days, produced by the decay of ^{238}U. Radon is continuously emitted from uranium-bearing rocks; it dissolves in groundwater and concentrates in soil gas. Because radon is inert, it does not combine with other elements to form compounds, and because of its short half-life, it cannot diffuse to large distances from its source [*116*]. Extensive research on radon emission as an earthquake precursor started after a strong, short-term increase in the radon concentration of groundwater was reported near the epicenter of a M5.3 earthquake in Tashkent, Uzbekistan, in 1966 [*117*].

Laboratory experiments in the early 1980s showed that radon emission increases significantly during rock fracturing, consistent with the dilatancy-diffusion theory [*118*]. Radon has since been monitored as a potential earthquake precursor in a number of active fault systems, and retrospective studies have been reported a number of positive correlations [*119*]. Cicerone et al. [*86*] have summarized 159 observations of changes gas emissions associated with 107 earthquakes; 125 of these were changes in radon emission from 86 earthquakes. In Japan, for example, changes in the radon concentrations of ground water were observed in data collected before the 1978 Izu-Oshima earthquake [*120*] and the 1995 M_W 6.9 Kobe earthquake [*121*].

Short-term pre-seismic anomalies have been reported across a wide range of epicentral distance (up to about 1000 km), time before event (from hours to months), and event magnitude (from less than M_W 1.5 to M_W 7.9). No significant correlation among these parameters has been demonstrated [*86*], nor has a causal connection been established between radon anomalies and the preparation phase of earthquake nucleation [*122*,*123*]. Local conditions, including porosity and permeability, are important factors in controlling the radon emission from a rock and its concentration in groundwater and soil gas [*124*]; geologic heterogeneity can therefore lead to strong spatial and temporal variations unassociated with tectonic processes. The preseismic anomalies account for only about 10% of the total observed anomalies. They have been rarely recorded by more than one or two instruments, and often at distant sites but not at sites closer to the epicentral area. Systematic studies of false alarms and failures-to-predict are rare. Long data sequences, spanning tens of years, are available for Iceland [*125*] and the San Andreas fault [*126*]; thus far, they do not offer support to the hypothesis that radon anomalies are diagnostic precursors.

In the L'Aquila region of central Italy, measurements of the radon content of groundwater and air have been performed at the underground Laboratori Nazionali del Gran Sasso to study local deformation process, in co-operation with the National Institute of Nuclear Physics and University Roma-Tre. The measurements span from March, 1998, to June, 1999. Six spike-like events in water-air ratio of radon were identified during this time and two local seismic events (March 1998, M_L 4.7 and June 1998, M_L 3.1) occurred within a 100-km radius [*127*]. The authors suggest a possible correlation, but there have been no further attempt to validate the methodology.

Since 2000, independent experiments have been carried out in the same region by Mr. G. Giuliani, a technician working at the Gran Sasso facility, using a gamma-ray detector of his own design. He has claimed to have reported anomalous increases of the radon concentration before earthquakes of L'Aquila sequence, although his claims in the media appear to be inconsistent [*7*]. Giuliani discussed his radon measurements with the Commission during its first meeting in May 2009. The Commission was not convinced of any correlation between his radon observations and seismic activity, finding unsatisfactory the way in which anomalies were identified above the background and noting the lack of quantitative procedures to substantiate any correlation. So far, Giuliani's results have not been published in a peer-reviewed scientific journal [*128*].

<u>Hydrological changes</u>. Hydrological variations can be caused by fluid movements through interconnected fissures in response to tectonic stress changes. Ground shaking as well as permanent co-seismic and post-seismic deformation has been observed to alter stream flow and water levels in wells through the consolidation of surficial deposits, fracturing of rock masses, aquifer deformation, and the clearing of fracture-filling material; the areal extent of these effects correlates with earthquake magnitude [*129*].

Observations of hydrological precursors a few hours to several months before some moderate to large earthquakes have been published [*86*, *130*], though systematic studies are lacking. Correlations of precursory water-level changes with distance from the epicenter and event magnitude are weak [*86*] and inconsistent with plausible precursory mechanisms. A possible case of variations of uranium concentrations and of water flow in a spring in the L'Aquila region was also reported retrospectively [*131*], but a causal relationship with the seismic sequence and the April 6 main shock has not been established.

<u>Electromagnetic signals</u>. There are a number of physical mechanisms that could, in principle, generate electromagnetic (EM) phenomena during the preparatory phase of an earthquake: electro-kinetic phenomena, e.g., from dilatancy-induced fluid flow; signals from the stress-induced migration of solid-state defects, such as Freund's *p*-hole hypothesis [*132*]; electrical effects associated with micro-cracking, including piezoelectric discharge [*133*]; and air ionization produced by radon emanation [*134*].

Precursory phenomena have been investigated across a wide range of EM frequencies, in the laboratory and in the field [*135*]. The hypothesized signals have been classified into two major groups [*133*, *136*]: (a) signals emitted from within the focal zones, such as telluric currents and magnetic fields at ultra-low frequencies (ULF: 0.001-10 Hz), extremely/very low frequencies (ELF/VLF: 10 Hz-30 kHz), and low frequencies (LF: 30-300 kHz); and (b) anomalous EM transmissions related to atmospheric or ionospheric coupling to the lithosphere. (A third form of EM radiation, infrared emissions from thermal anomalies, is discussed in the next subsection.)

Electric phenomena observed for earthquakes in Japan, Greece, and Indonesia have been dominantly co-seismic; i.e., observed during or immediately after the arrival of the seismic waves [*137*, *138*]. Laboratory experiments have shown that changes in the physical state of solids can be accompanied by electromagnetic emissions that peak at the dynamic failure time [*139*], but it is not clear how laboratory results scale up to large ruptures in a heterogeneous crust, or whether pre-seismic deformations are sufficient to generate sensible signals [*140*].

Satellites have detected anomalous VLF signals in the ionosphere near earthquake source regions [*141*], including L'Aquila [*142*]. This seismo-ionospheric coupling has been mainly described as changes in the *F2* layer critical frequency some days before or after the earthquake. When averaged over a large set of events, the amplitude of the pre-seismic signal is small (-8 dB) compared to the noise level, and the conditional statistics of retrospective precursor detection are too weak to provide any probability gain in earthquake forecasting [*143*].

The most convincing EM precursors have been ULF magnetic anomalies recorded before the 1989 M_W 7.1 Loma Prieta earthquake [*144*] and the 1993 M_W 7.7 Guam earthquake [*145*]. However, recent reanalysis has indicated that these particular anomalies were likely to have been caused by solar-terrestrial interaction [*146*] or sensor-system malfunction [*147*]. Observations from a station of the University of L'Aquila, only 6 km from the 6 April 2009 epicenter, did not indicate any type of ULF precursor [*148*].

Electro-telluric signals, which propagate through the ground, have been studied in Greece for several decades by the VAN team (named after P. Varotsos, K. Alexopoulos & K. Nomikos). They have suggested that such "seismic electric signals" (SES) precede earthquakes and, if recorded on a properly calibrated set of monitoring stations, can provide short-term diagnostic precursors for ruptures in specified source regions [*149*]. Although observational support for the VAN method has been published [*150*], subsequent testing has failed to validate the optimistic SES prediction capability claimed by the authors [*151*].

Earthquake lights and other fiery phenomena have been attributed to strong electric fields in the atmosphere near the nucleation zones of earthquakes [*152*], including the L'Aquila mainshock [*153*]. Earthquake lights have been reported just before, during, and immediately after strong ($M > 5$) shallow earthquakes, more commonly at night [*154*]. Most have been observed near the quake epicenters, but some at distances of 100 km or more. Systematic studies with good temporal control relative to earthquake origin times are lacking. Based on the anecdotal observations, less than 5% of strong shallow ruptures appear to be preceded by earthquake lights. Little progress has been made in explicating the specific physical mechanisms that generate such phenomena, although the *p*-hole model is a contender [*155*].

Thermal anomalies. Satellite remote sensing of thermal infrared radiation (TIR), usually in the 8-13 micron band, has been used to search for thermal anomalies associated with earthquakes. A number of retrospective observations of TIR signals precursory to large events have been published [*156*], including a precursor to the 2009 L'Aquila earthquake [*157*]; the anomaly amplitudes are typically 2º-4ºC over regions spanning hundreds of kilometers. One explanation of these signals is enhanced radon emission, which causes water condensation and latent heat release [*158*]. An alternative is infrared luminescence from charged particles transferred from the lithosphere to the atmosphere, as predicted by the *p*-hole hypothesis [*159*].

Serious issues can be raised regarding the efficacy of these methodologies in earthquake prediction. Detection of TIR anomalies is limited by the spatial and temporal sampling of the earthquake regions afforded by the satellite-based sensors. The data processing is quite complex and must account for large variations in near-surface temperatures associated with solar cycles and atmospheric, hydrological, and other near-surface variations. There has been no precise characterization of what constitutes a TIR earthquake precursor. Purported precursors show poor correlations with earthquake epicenters and irregular scaling with earthquake magnitude. The background noise (TIR signal not associated with earthquake activity) has not been systematically characterized; in some studies claiming positive results, the analysis of the regional background has been limited to temporal intervals that are small multiples of the precursor duration. In contrast, a systematic survey of satellite data collected over a seven-year interval in California found that the natural variability of TIR anomalies was too high to allow statistically significant correlations with seismic activity [*160*]. Owing to these methodological problems, the retrospective identification of TIR anomalies with large earthquakes remains unconvincing. No studies have been published that prospectively test the reliability and skill of TIR methods.

The Commission concludes that TIR anomalies have not been demonstrated to be diagnostic earthquake precursors, and that no significant probability gain in forecasting has been validated by TIR techniques.

Anomalous animal behavior. A ever-popular subject of investigation is anomalous animal behavior observed before earthquakes [*161*]. In some cases, purported precursory behaviors have been discounted by systematic studies [*162*]. Animals, including humans, do respond to signals that they can feel, such as small earthquakes that might be foreshocks [*163*]. Anecdotal evidence suggests that some animal species may have evolved “early warning” systems that allow individuals to respond in the few seconds prior to the onset of strong shaking, most probably triggered by the weak shaking of the first-arriving *P* wave [*164*]. Geobiologists have also speculated on the evolution of sensory systems that could detect more subtle precursory signals [*165*]. However, there is no credible scientific evidence that animals display behaviors indicative of earthquake-related environmental disturbances that are unobservable by the physical and chemical sensor systems available to earthquake scientists.

Seismicity patterns. Foreshocks and other patterns of seismicity are an important class of physical phenomena that can be readily observed by seismic networks and have been extensively investigated as precursors. As individual events, foreshocks have not displayed special rupture characteristics that allow them to be discriminated *a priori* from background seismicity and therefore cannot be used as diagnostic precursors. On average worldwide, about 15% of the mainshocks are accompanied by one or more foreshocks within 1 unit of the mainshock magnitude in a time-space window of 10 days and 75 km, but this rate varies substantially with the type of faulting [*166*]. The foreshock rates for regions such as Italy and California are similar to those predicted by earthquake triggering models such as ETAS that do not distinguish among foreshocks, mainshocks, and aftershocks [*20*] (see §II.D.4).

The absence of simple foreshock patterns precludes their use as diagnostic precursors, which is not surprising given the nearly universal scaling relations that characterize earthquake statistics. Models that allow much more complexity (many free parameters) have been investigated using powerful numerical techniques that can consider data in all their possible combinations [*167*]. Such *pattern recognition* methods have the potential to discern any repetitive patterns in seismic activity that might be caused by precursory processes, even if the physical mechanisms are not fully understood. Pattern recognition methods depend on having reasonably complete and homogeneous earthquake catalogs of sufficiently long duration to define the background seismicity rate.

Among the most notable examples in this class of phenomenological methods are the Magnitude-8 (M8) and California-Nevada (CN) codes, which have been applied systematically to forecasting global and regional seismicity since the early 1990s [*168*]. As input, these methods use a variety of metrics calculated from earthquake catalogs, usually after the catalog has been “declustered” in an attempt to remove aftershocks. Purely empirical functions with many parameters are fit to the seismicity data in a retrospective statistical analysis of catalogs. The predictions are deterministic: alarms are based on a time of increased probability of target event. Typically, alarms are issued for periods of months or years in geographically extended areas; e.g. the CN alarms for Italy cover areas comparable to or greater than the area of Switzerland [*169*].

Prospective tests of the M8, CN, and related pattern-recognition models (M8S, MSc) have been conducted over the past two decades by V. Kossbokov and his colleagues [*170*], and the results through mid-2010 are shown on a Molchan diagram [*171*] in **Figure 2.4**. Two conclusions can be drawn from this testing: (a) When an adequate sample of target earthquakes is available ($N > 10$), these prediction methods show skill that is statistically significant with respect to time-independent forecasts constructed by extrapolating spatially smoothed, catalog-derived earthquake rates to larger magnitudes. (b) However, the prediction methods achieve only small probability gains, in the range 2-4 relative to these time-independent reference forecasts (Figure 2.4). One unresolved issue is the degree to which this apparent probability gain could be compromised by inadequate declustering.

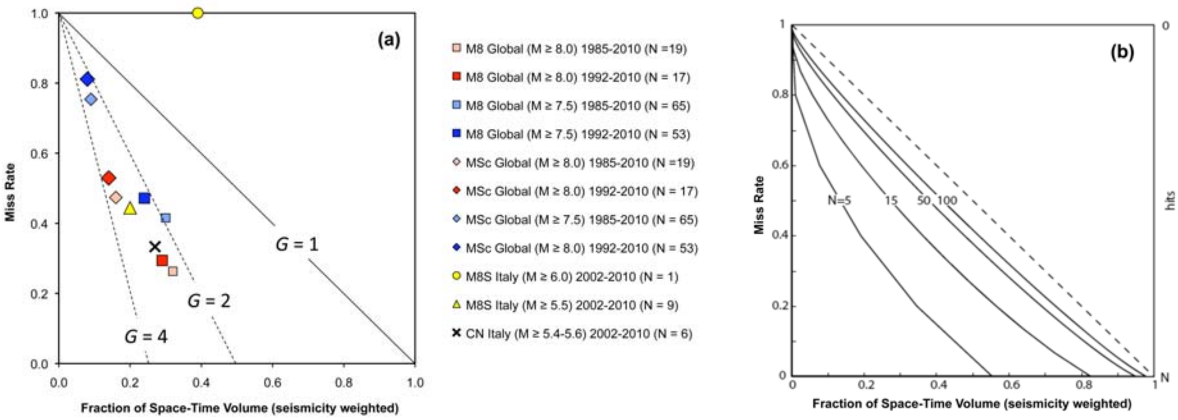

Figure 2.4. (a) Results of Kossobokov's [*170*] testing of the earthquake predictions based on the M8, MSc, M8S, and CN pattern-recognition algorithms, plotted on a Molchan diagram of failure-to-predict fraction (miss rate) vs. fraction of space-time volume occupied by alarms. The latter is weighted by the seismicity rate of the time-independent reference forecast. The legend for each test describes the algorithm, testing region, magnitude threshold, testing interval, and number of target events observed during the interval (*N*). Solid diagonal line corresponds to no probability gain relative to the reference forecast (probability gain factor *G* of unity); dashed lines correspond to *G* = 2 and 4. (b) Molchan diagram showing how the one-sided 95% confidence limits vary with sample size *N* [*45*]. All prediction results for *N* > 10 show significant probability gain; i.e., the hypothesis *G* = 1 can be rejected with high confidence (> 99%). Data courtesy of V. Kossobokov.

The large alarm areas, high error rates (e.g. 30-70% false alarms), and relatively low probability gains limit the practical utility of these methods as deterministic prediction tools. Moreover, there is significant controversy about the testing methodology and the time-independent forecast used as the reference in the tests [*172*]. The extrapolation of the catalog data from small to large magnitudes introduces a large uncertainty into the reference model that includes a systematic underestimation of the background rate due to finite temporal sampling effects (the statistics of small numbers) [*173*], which systematically biases the apparent skill to higher values. (This is a generic problem with skill scores in any technique judged against the background rate where there is no palaeoseismic or other data to constrain the occurrence rate of extreme events.)

A class of pattern-recognition models aims to forecast earthquakes events from the space-time clustering smaller events, exemplified by the RTP algorithm (reverse tracing of precursors) [*174*] and RTL algorithm (distance, time and length) [*175*]. The methods examine differences in event location, origin time, and size to detect correlations. Variants of this method aim for shorter-term forecasts by looking for the near simultaneous occurrence of two or more earthquakes separated by a large distance [*176*, *177*]. Prospective tests have not demonstrated significant skill for predictions made by this class of models relative to time-independent forecasts, nor with respect to standard earthquake triggering models, such as ETAS, that account for salient aspects of earthquake clustering.

The pattern informatics (PI) method uses as input deviations from average event or moment rates at different locations [*178*,*179*], a choice motivated by the long-range interactions expected in near-critical systems [*180*]. The output, based on an association of small earthquakes with future large earthquakes, is a long-term forecast from which alarm regions can be delineated. Good performance in prospective earthquake prediction has been claimed by the authors [*181*]; however, an independent analysis for California indicated that the PI method does not show significant skill relative to a relative intensity (RI) reference model based on the binning of historical seismicity [*45*].

<u>Proxies for accelerating strain</u>. The critical point concept, as well as more mechanistic concepts such as accelerated stress-corrosion cracking or rate- and state-dependent friction observed in the laboratory, predict a time-reversed Omori law acceleration of seismicity prior to long-range rupture [*182*, *183*]. The best known example of this class of models is accelerated moment release (AMR), which has been applied to long-term forecasting, mainly retrospectively [*184*]. The method calculates the cumulative sum of the square root of the seismic moment or energy ("Benioff strain"). Though physically appealing in principle, AMR has yet to demonstrate forecasting reliability and skill. The use of Benioff strain reduces signal fluctuations, introducing another parameter; the use of cumulative data applies a strong smoothing filter, introducing strong autocorrelations that significantly bias the

results [*185*]. This may explain why a recent search for *decreasing* rate of Benioff strain prior to large earthquakes produced retrospective results comparable to the search for an increasing rate [*186*].

<u>Summary</u>. The search for diagnostic precursors has thus far been unsuccessful. This silver-bullet strategy for earthquake prediction is predicated on two hypotheses: (1) large earthquakes are the culmination of progressive deformation sequences with diagnostic precursory changes in the regional stress and strain fields, and (2) diagnostic information about an impending earthquake can be extracted from observations that are sensitive to these precursory stress and strain changes. Neither of these hypotheses has been empirically validated.

Research on precursory behavior has contributed substantially to the understanding of earthquake processes, and it should be part of a fundamental research program on earthquake predictability. As described throughout this report, much has been learned from the earthquake monitoring and deep drilling at Parkfield, California [*187*]. The establishment of similarly well-instrumented "natural laboratories" in regions of high seismicity are an effective strategy for gaining new insights into earthquake predictability.

There is also considerable room for methodological improvements in this type of research. Much of the speculation about predictability has been based on inadequate statistical analysis of retrospective correlations between proposed precursors and subsequent earthquakes. Often the correlations have been guaranteed by allowing considerable variation in the signal properties that qualify as precursors, as well as wide (and physically implausible) ranges of earthquake magnitude, epicentral distance, and precursory time interval. The retrospective data coverage has rarely been sufficient to characterize the background noise or evaluate the statistics of false alarms and failures-to-predict. Where such coverage is available, proposed prediction schemes show high error rates.

In fact, few prediction schemes have been formulated in a manner that allows rigorous testing. Models that are properly formulated for testing usually involve many parameters. Their values must be assumed or calibrated with retrospective data. Prediction success has often been over-estimated by retrospective testing that was not independent of the data used in the retrospective model-tuning. Prospective testing of formalized models has been infrequent, and, where such tests have been carried out (e.g., in Parkfield, California), the predictions have failed to demonstrate reliability and skill relative to baseline forecasts.

Several hypothesized precursors have been plausibly conceptualized from laboratory observations but remain untested by adequate observations in nature. The scalability of the purported phenomena is by no means obvious; for example, strain data confirm that the scale ratio of rupture area to nucleation area for large earthquakes is much smaller than the volume of dilatant damage relative to sample size in laboratory tests, which appears to limit the size of signals associated with pre-seismic rock dilatancy.

Whether large earthquakes can be triggered by large aseismic transients, or whether diagnostic patterns of slow slip events and episodic tectonic tremor can foretell megathrust earthquakes in subduction zones, exemplify plausible hypotheses that should be evaluated by basic research. The Commission is not optimistic that the search for diagnostic precursors will provide an operational basis for deterministic earthquake prediction anytime soon. However, it holds open the possibility that observations of physical precursors described in this section can improve methods for probabilistic forecasting [*188*].

C. Predictability of Fault Interaction

One of the most striking features of seismicity is the clustering of earthquakes, as manifested in foreshock-mainshock-aftershock sequences, seismic swarms, and sequences of large earthquakes observed to propagate along major fault systems. The most obvious physical process responsible for this spatiotemporal clustering is fault interaction: stress changes on one fault caused by slip (seismic or aseismic) on another fault. The regularity of seismic clustering phenomena suggests that it may be possible to infer changes in earthquake probabilities from models of fault interaction.

1. Earthquake-Mediated Interaction

A special case is *earthquake-mediated* fault interaction, in which the stress changes on a receiver fault are forced by seismic waves propagating from the rupture (dynamic interaction) as well as by the permanent displacement of the source fault (quasi-static interaction) [*189*]. The quasi-static interaction can be modeled using the Coulomb failure function (CFF), which accounts for both the shear stress changes and the normal stress changes on the receiver fault [*190*]. An increment in shear stress in the direction of fault slip will bring the fault closer to failure, whereas an increment in normal stress (pressure on the fault surface) will increase the fault's frictional strength and thus inhibit failure. These increments depend on many details, such as the total slip of the source rupture, the distance between the source and receiver faults, the relative orientation of the faults, and the relationship between normal stress and pore pressure [*191*]. Their magnitudes are typically less than a few bars and are thus small compared to the stress drops of tens to hundreds of bars observed during fault rupture [*192*]. However, results of simulations carried out on an interacting fault systems show that CFF perturbations can alter seismicity patterns across many scales in space and time [*193*]. CFF models have been used to anticipate the spatial propagation of large-earthquake sequences along the North Anatolian fault [*194*] and the Indonesian Trench [*195*, *196*].

In a quasi-static model, fault ruptures cause instantaneous changes in the CFF. According to the prevailing theory of rock friction (rate- and state-dependent friction), an instantaneous stress change can excite earthquake sequences that decay according to a modified-Omori law [*197*]. This physical model of seismicity response has been calibrated retrospectively using long-term earthquake catalogs and incorporated into short- to medium-term earthquake forecasts in a number of seismically active areas (see §II.D.5).

Several technical limitations and physical issues confront the development of CFF-based methods. Short-term forecasting requires knowledge of the faults parameters that are not yet regularly available in real time. A reliable forecast also requires an estimation of the state of stress on a particular fault, usually made through a single-fault renewal process that only accounts for the time since the last event. Reality may be more complicated, because the stress interaction in a complex fault network may induce multi-modal recurrences that cannot be described by a single-fault recurrence model [*198*]. Numerical simulations of earthquake sequences in realistic fault geometries (*earthquake simulators*) are beginning to overcome this limitation (**Figure 2.5**) [*199*, *200*].

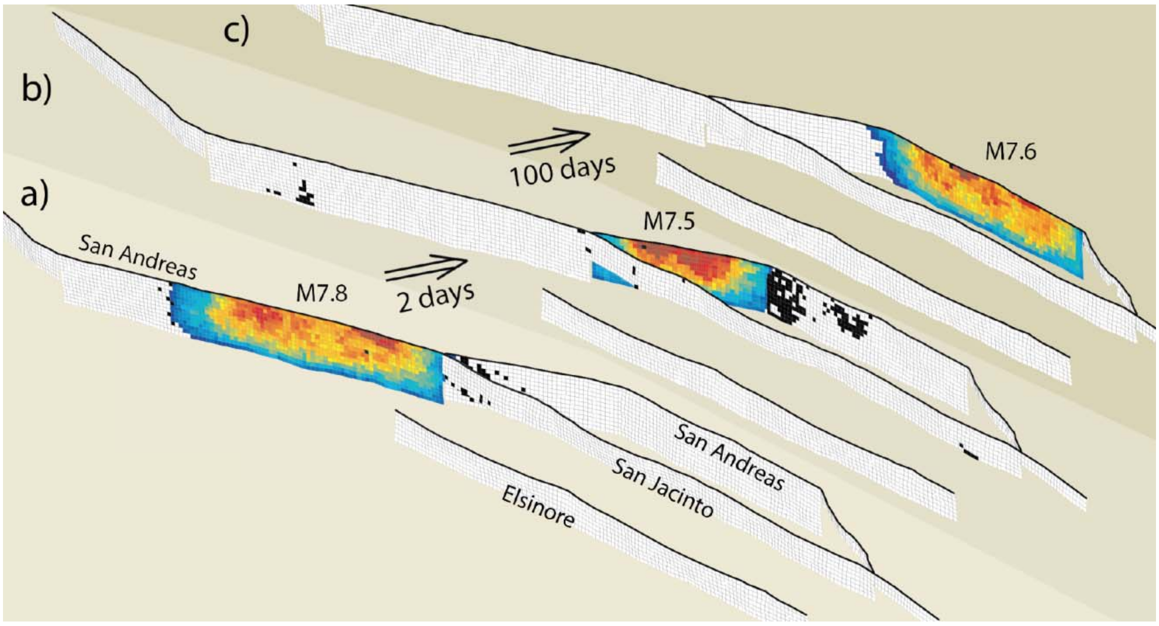

Figure 2.5. Example output from the *RSQSim* earthquake simulator [*200*] showing fault-slip in a cluster of large events on the southern San Andreas fault system. This simulation produced 220 events with magnitudes above 7, and about 10% of those were followed by one or more events above magnitude 7 within the following four years. In this example, three large earthquakes occurred in a 102-day period. Aftershocks on day-2 and day-100, following the first two events, are shown as black dots. Insights from such earthquake simulations may improve the probabilistic forecasting models. Simulation and figure by J. Dieterich and K. Richards-Dinger.

Various tests have compared the relative effects of dynamic interaction with quasi-static interaction [*201*]. The former may predominate over the latter at large distances and during early aftershock activity, when the event rates are high [*202*]. The dynamic stress changes caused by seismic waves interacting with the receiver fault can be considerably larger and more complex in time and space. Fully dynamical simulations of fault ruptures may provide a better quantification [*203*].

The viscoelastic and poroelastic responses of Earth's crust and upper mantle that follow fault slip also contribute to the CFF [*204*]. The post-seismic viscoelastic interaction decays more slowly with distance that the quasi-static effect, and it can take decades to attain its maximum value [*205*]. A better understanding of these responses through high-resolution geodesy and strainmeter observations could improve medium-term forecasting models.

2. Aseismic Transients

Slow slip on the source fault is another type of aseismic transient that can load or unload a receiver fault. The physical mechanisms that govern slow slip events are not yet understood, but a new mode of behavior of major seismogenic faults has been discovered in the Cascadia and Japan subduction zones, called *episodic tremor and slip* (ETS) [*206*]. ETS involves periodic slip of several centimeters on what is believed to be a transition zone between the creeping (velocity-strengthening) and seismogenic (velocity-weakening) part of the subduction megathrust. Recent theoretical work suggests that such behavior implies high pore fluid pressure and low effective normal stress [*207*]. The presence of highly pressurized pore fluids is supported by the spatial and temporal correlation of tremor with aseismic slip [*208*].

Slow slip events and tectonic tremor have been documented in other subduction zones around the world; some show ETS behavior, while others display less correlation between slow events and tremor [*209*]. ETS events on plate boundaries characterized by strike-slip and normal faulting have not yet been reported, but a growing number of studies have revealed both slow-slip events and tectonic tremor on the San Andreas fault in California [*210*, *211*, *212*].

The relationship of slow slip events and ETS to the occurrence of large earthquakes is a key area of research on earthquake predictability. If a causal mechanism can be established, potentially significant gains in forecasting probability may become available [*213*]. The main tools needed to investigate this relationship are co-mingled networks of continuously recording GPS receivers, strainmeters, and high-performance seismometers.

D. Probabilistic Forecasting Models

An earthquake forecasting model is a systematic method for calculating the probabilities of target events within future space-time domains. The models potentially useful for operational purposes have forecasting intervals T that can range from long-term (years or more) to short-term (months or less), and they differ in their assumptions about the statistical behavior of earthquakes, as well as in the information they incorporate into the forecasts. The methods based on non-seismic precursors have not yet demonstrated sufficient reliability and skill to be considered for operational forecasting (see §II.B). For this reason, all of the time-dependent models discussed in this section use observations of seismic activity to modify the baseline probabilities calculated from time-independent reference models.

The probability $P(t)$ from a time-dependent forecast at time t can be related to the time-independent probability P_{poisson} by a gain factor $G(t) = P(t)/P_{\text{poisson}}$ [*214*]. As illustrated below, the gain factors currently produced by short-term forecasting models can be quite high (G = 100-1000). However, in these situations, the forecasting intervals are typically much shorter than the recurrence intervals of large earthquakes (days compared to hundreds of years), and the values of $P(t)$ for potentially destructive events remain much less than unity [*215*]. This is just another way of stating that the extant forecasting models cannot provide high-probability earthquake predictions.

Although probability gain is a useful measure of forecasting power, comparisons among models can be tricky, because the values of G can depend strongly on the domain size as well as other details of the calculation. Few time-dependent models have thus far been tested against observations sufficient to validate reliability and skill (see §II.E). Many scientific issues about how to assimilate the data from ongoing seismic sequences into the models have not been resolved; consequently, comparable seismicity-based forecasts that employ different modeling assumptions can display order-of-magnitude differences in $P(t)$. Large uncertainties must also be attached to the time-independent reference models. For these reasons, the illustrative values of G given here are labeled *nominal probability gains* to indicate that they are highly uncertain and largely unvalidated.

1. Stationary Poisson Models

The reference forecasts used to calculate time-dependent probability gains assume large earthquakes are independent events that happen randomly in time at the long-term rate; i.e., the probabilities

$P_{poisson}$ for any forecast interval T are given by a stationary Poisson distribution and are thus independent of the forecast time t [*37*]. The rate depends on magnitude, usually according to a tapered or truncated Gutenberg-Richter distribution, and it can vary with geographic position. The spatial dependence of the earthquake rate can be estimated using several types of information, including instrumental and historical catalogs, geodetic strain measurements, and geologic data on deformation rates.

Time-independent forecasts are the basis for long-term probabilistic seismic hazard analysis [*28*]. A particular class comprises fault-based models, in which the principal earthquake sources are localized on mapped faults and assigned occurrence rates consistent with the long-term fault slip rates. Fault-based models have been used in constructing the U.S. and Japanese national seismic hazard maps [*29*, *216*]. The official long-term earthquake forecast for Italy (see Figure 1.2) is a time-independent model based on a seismotectonic zonation of the country [*1*]. Each zone is characterized by a homogeneous seismicity rate and a truncated Gutenberg-Richter distribution consistent with historical and instrumental seismicity catalogs. The upper cutoff magnitude in the frequency-magnitude distribution is estimated primarily from the sizes of the largest active faults and from historical seismicity.

A fundamental uncertainty in long-term earthquake forecasting comes from the short sampling intervals available in the instrumental seismicity catalogs and historical records used to calibrate the time-independent models, which is reflected in the large epistemic uncertainty in earthquake recurrence rates. These uncertainties can be reduced by better instrumental catalogs, improved geodetic monitoring, and geologic field work to identify active faults, their slip rates, and recurrence times.

2. Characteristic Earthquake Models

A class of long-term models introduces time dependence by assuming a nearly periodic cycle of characteristic earthquakes (§II.B.1) and calibrating the cycle from the seismic history of a region. A simple model is a renewal process in which the expected time of the next event depends only on the date of the last event [*56*, *217*]. The times between successive events are considered to be independent and identically distributed random variables. When a rupture occurs on the segment, it resets the renewal process to its initial state. As in the case of time-independent models, earthquakes are characterized only by an occurrence time, fault-segment location, and magnitude; the complexities of the rupture process, such as the location of the hypocenter on the fault segment, are usually ignored. The aperiodicity of the recurrence intervals observed in real fault systems is introduced stochastically through a coefficient of variation in the renewal process.

More complex models can be built by allowing the state variable in the renewal process to depend on large earthquakes that are off the fault segment but close enough to affect the stress on the segment. Such a model was included in the WGCEP 2003 forecast for the San Francisco Bay Area to account for the "stress shadow" of the 1906 San Francisco earthquake [*218*]. The WGCEP 2003 study also considered a time-predictable model of the earthquake cycle that incorporated information about the slip in the last event.

The UCERF2 time-dependent forecast for California (**Figure 2.6**) incorporates renewal models for the major strike-slip faults of the San Andreas system. The mean UCERF2 probability of large earthquakes on fault sections that have not ruptured for intervals comparable to or exceeding the mean recurrence times can be up to a factor of two greater than the time-independent probability for the same sections. For instance, the UCERF2 model for Coachella section of the San Andreas fault, which last ruptured circa 1680, shows a nominal probability gain factor of $G = 1.7$ for $M \geq 7$ events at $T = 30$ years.

Few fault segments have earthquake records sufficiently long and accurate to test the characteristic earthquake model, including its predicted deviation from Gutenberg-Richter scaling [*219*]. Early evidence for the characteristic earthquake hypothesis came from paleoseismic research on the San Andreas fault in California [*23*], although the more recent data have been used to argue against this hypothesis [*220*, *221*]. Other examples of paleoseismic records that show evidence against a single recurrence time come from the Yammouneh fault system in Lebanon [*222*] and the Aksu thrust fault in China [*223*]. As noted in §II.B.1, the closely related seismic gap hypothesis has also failed prospective testing against circum-Pacific earthquake observations [*68*].

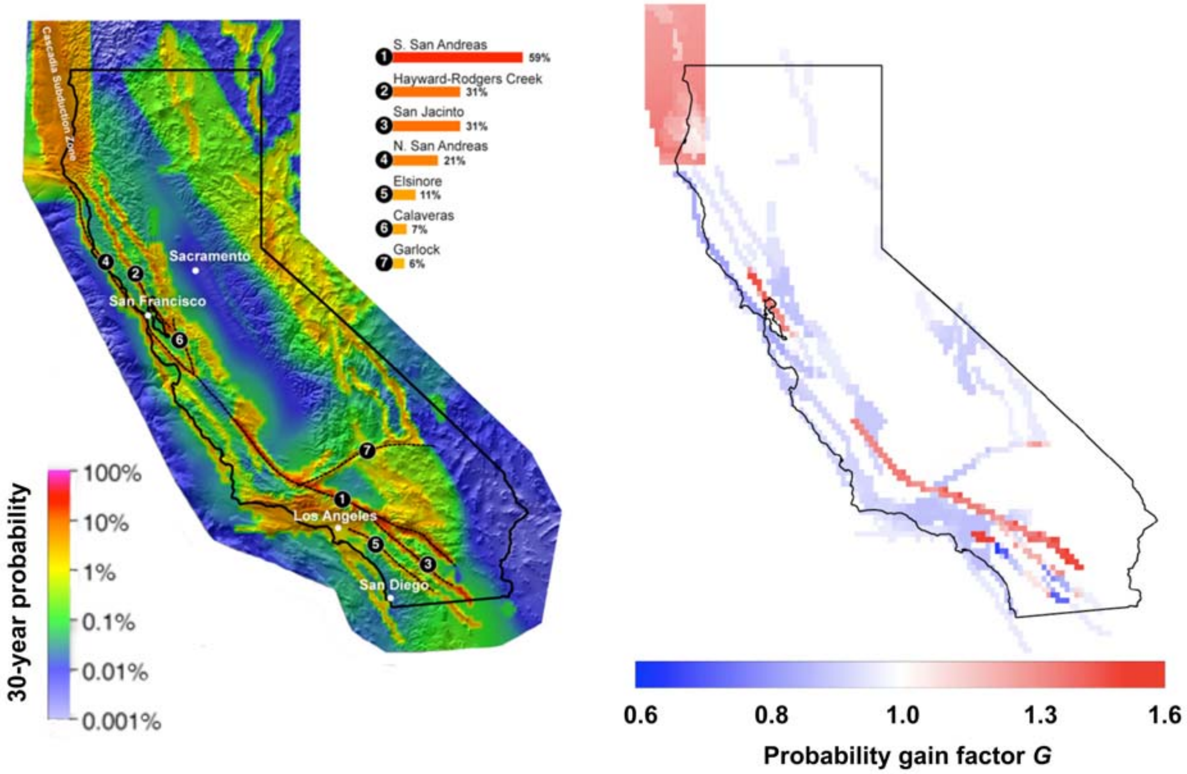

Figure 2.6. Left map shows the 30-year participation probabilities from the Uniform California Earthquake Rupture Forecast, Version 2 (UCERF2) , derived for ruptures with magnitudes greater than or equal to 6.7 [*34*]. Participation probabilities are computed for ruptures occurring in 0.1º x 0.1º geographic cells. Right map shows probability gain factor of the time-dependent UCERF2 forecast relative to a time-independent reference forecast.

The characteristic earthquake hypothesis has been incorporated into two recent seismic hazard models for Central Italy [*54*, *224*], and efforts are underway to develop time-dependent national models [*225*]. Preliminary results indicate that the time-dependent, fault-based models do not yield significant probability gains relative to time-independent models.

3. Earthquake Triggering Models

Earthquake triggering models attempt to capture the behavior of earthquake-mediated fault interactions through empirical statistical relationships that reproduce the observed properties of earthquake clustering. In particular, the excitation and decay of aftershock sequences obey nearly universal scaling relations (§II.A.1). The triggering rate scales exponentially with the magnitude of the parent event (Utsu scaling) and decays approximately inversely with time (Omori scaling); the frequency of the daughter events falls off exponentially with magnitude (Gutenberg-Richter scaling).

A number of different formulations have been applied to short-term earthquake forecasting. In single-generation models, all aftershocks are presumed to be triggered by a single mainshock [*226*]. An example is the Short-Term Earthquake Probability (STEP) model, which the U.S. Geological Survey has applied to operational forecasting in California since 2005 [*227*]. STEP uses aftershock statistics to make hourly revisions of the probabilities of strong ground motions (Modified Mercalli Intensity ≥ VI) on a 10-km, statewide grid. The nominal probability gain factors in regions close to the epicenters of small-magnitude (M = 3-4) events are on the order of 10-100 relative to the long-term base model (**Figure 2.7**).

In multiple-generation models, no distinction is made between mainshocks and aftershocks. All earthquakes trigger other earthquakes according to the same set of scaling relations; i.e., each aftershock generates its own aftershocks. This subclass includes Epidemic-Type Aftershock Sequence (ETAS) models [*20, 21*]. Because all earthquakes in an ETAS model can trigger aftershocks, the durations of earthquake sequences are not related to the underlying Omori decay in a straightforward way. The modified Omori law (a generalized form of the Omori scaling relation [*19*]) usually leads to a rapid reduction of the triggering rate in a few days, whereas the effective duration of the earthquake sequence can be extended by many factors, including the minimum magnitude considered, the assumed rate of independent (background) earthquakes, and the Utsu scaling exponent. As in the single-generation case, the model variants depend on how the parameters in the scaling law are related to one another [*22*, *228*] and how the of daughter events are spatially distributed with respect to the parent event [*202*].

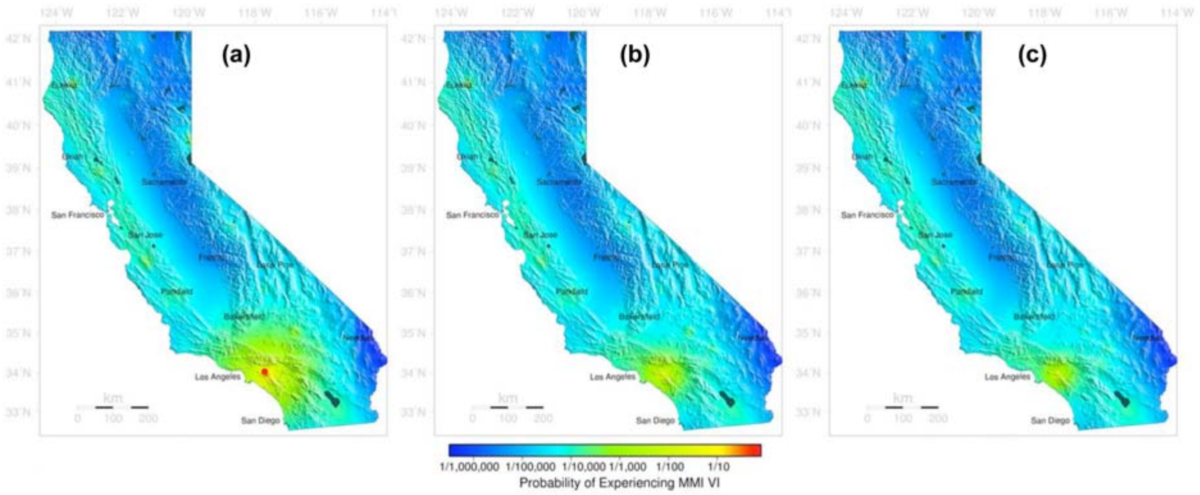

Figure 2.7. Short-term earthquake probability (STEP) maps published on-line by the U.S. Geological Survey following the M5.4 Chino Hills earthquake, which occurred in the Los Angeles region on 29 July 2008 at 11:42 local time. (a) STEP map released at 13:00 local time, 1 hr 18 min after the mainshock. Red dot is epicenter; yellow region indicates area where the probability of intensity VI shaking is more than 10 times the background model (blue colors). (b) STEP map released at 13:00 local time on 30 July 2008. (c) STEP map released at 13:00 local time on 1 August 2008, about three days after the earthquake. The decrease in the local shaking probability reflects the modified Omori scaling of aftershock decay used in this short-term forecast.

Retrospective calculations using ETAS models to track the short-term (1-day) evolution of seismic sequences in California [*229*] and Italy [*230*] show nominal probability gains on the order of 10-100, similar to single-generation aftershock models such as STEP. This gain has been validated by some prospective experiments, such as those conducted in California by the Collaboratory for the Study of Earthquake Predictability and in tracking the space-time evolution of the aftershocks following the L'Aquila earthquake (**Figure 2.8)** [*4*].

Both the single-generation and multiple-generation triggering models allow for the possibility that an earthquake can generate an aftershock with a larger magnitude than the parent, and they can therefore be used to model foreshock probabilities. If each event is taken to be an independent sample from a Gutenberg-Richter distribution, as usually assumed, the probability of such an occurrence is small, typically about 10%, which is consistent with global foreshock statistics [*166*].

Retrospective ETAS calculations for the day before the L'Aquila mainshock yield probability gains of 5-25 in a large area (~3600 km^2) around the hypocenter. In other words, according to an ETAS model, the occurrence of a L'Aquila-size event was 5-25 times more likely on 6 April 2009 than forecast in this area from the long-term reference model [*4*]. The nominal probability gain increases to about 100 if the forecast is restricted to the more limited region of the L'Aquila foreshocks (~100 km^2), but the 1-day probability remains much below 1% [*231*]. Similar values have been obtained retrospectively for other sequences that have occurred elsewhere in Italy.

However, in these and most other applications of ETAS-like models, earthquakes are represented as samples of a marked point process (§II.A.1), not as spatially extended sources, and the distribution of daughter events is assumed to be spatially isotropic relative to the hypocenter of the parent. Moreover, the probability gains do not account for the proximity of earthquakes to major faults. These simplifications regarding the spatial aspects of triggering limit the forecasting performance of short-term triggering models. Extending the models to fault-based earthquake forecasting may provide addition probability gain relative to long-term reference models, provided sufficient fault and seismicity data are available to calibrate the time-dependent models for specific fault systems.

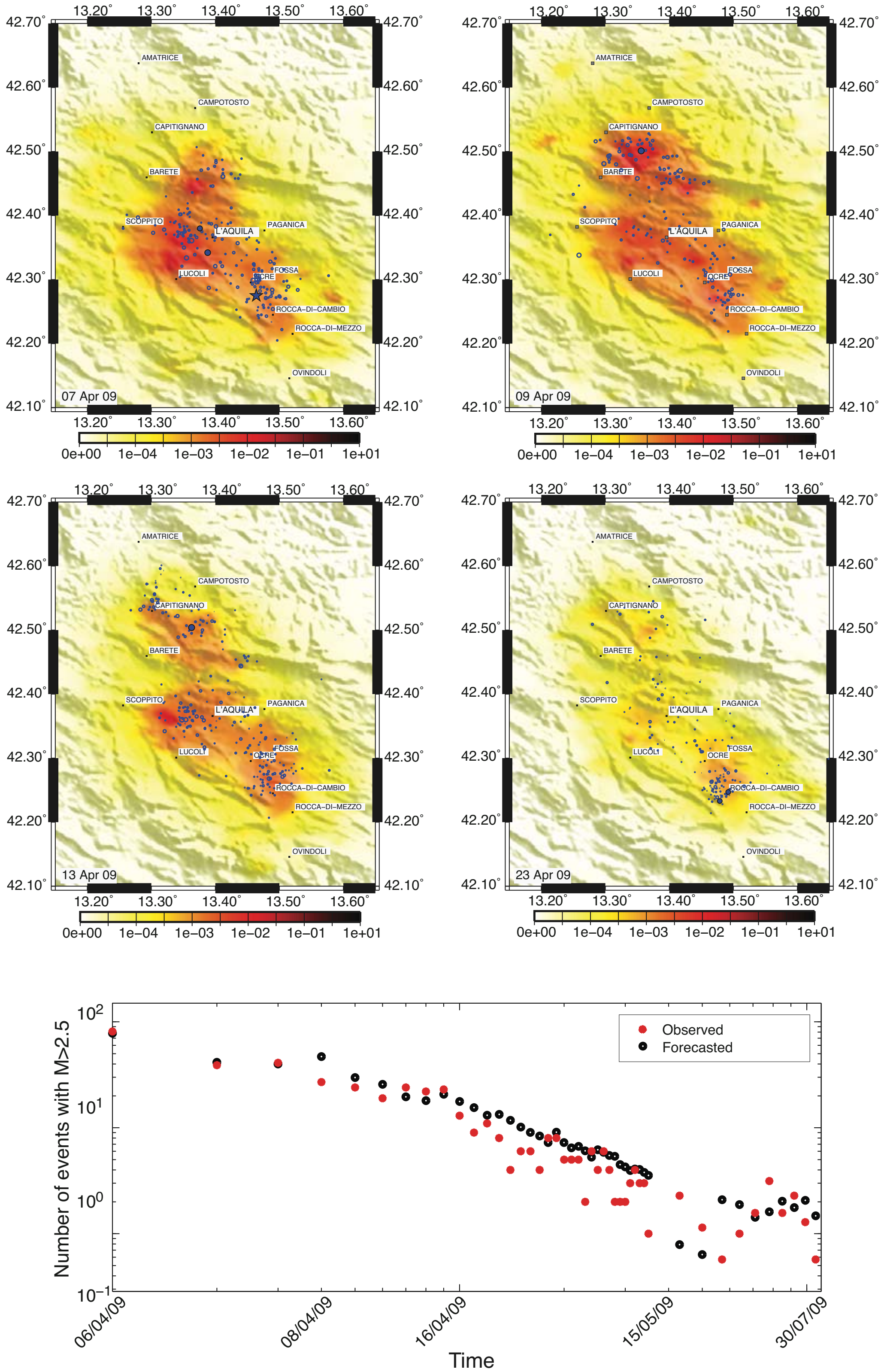

Figure 2.8. Comparison of observed seismicity with the 1-day ETAS forecasts issued prospectively by INGV after the L'Aquila mainshock [*4*]. The maps show the expected daily number of events per square kilometer above magnitude 4 on four different dates during the first month. The blue dots are the earthquakes with $M_L \geq 2.5$ that occurred during the forecasting time windows; the dimensions of the dots are scaled with magnitude. The lower plot shows the daily observed number of events of $M_L \geq 2.5$ (red circles) and the daily forecast number of events (black circles) for the entire aftershock zone; the scales are logarithmic. [Figure by W. Marzocchi.]

4. Empirical Foreshock Probability Models

ETAS-like models do not distinguish among foreshocks, mainshocks, and aftershocks in terms of the earthquake source process; a foreshock is just an earthquake in a sequence that happens to be proximate to, but precedes, a larger event. In an ETAS model, the probability of such a foreshock can be directly calculated from the same scaling relations used to represent the aftershock activity [*22*]. However, if the preparation process leading to large earthquakes also increases the likelihood of smaller events, then the foreshock statistics will not necessarily be consistent with the aftershock statistics.

A clear example can be found on mid-ocean ridge transform faults, where subseismic transients generate seismic swarms and sometimes trigger large earthquakes [96]. Consequently, the ratio of foreshock to aftershocks per mainshock can be several orders of magnitude higher than predicted by an ETAS model, and simple foreshock-based prediction schemes can achieve probability gains on the order of 1000 [*232*]. Similar behavior has been observed for seismic swarms in the Salton Trough of southern California, a region of high heat flow that is transitional between the San Andreas fault system and the ridge-transform tectonics of the Gulf of California [97].

Empirical foreshock probability (EFP) models provide a statistical basis for earthquake forecasting that can account for this and other types of precursory behavior. EFP models, originally developed for application to the southern San Andreas fault system by Agnew & Jones [*233*], rely on a Bayesian treatment of the statistical observations of target earthquakes, foreshocks associated with those target events (retrospectively identified), and background seismicity. This generic form of EFP, which define foreshocks as earthquakes that occur 3 days before a mainshock and less than 10 km from the mainshock epicenter, has been used for operational forecasting in California by the U. S. Geological Survey and the California Earthquake Prediction Evaluation Council for the past 20 years (see §III.F).

The nominal probability gains attained by this method can reach 100-1000, somewhat higher than the gains calculated for ETAS models. However, the epistemic uncertainties are large, primarily owing to assumptions regarding the frequency-magnitude distribution and the relationship between the rates of target earthquakes and background seismicity, which opens to question the statistical significance of this discrepancy [*234*].

In Italy, for example, a survey of major earthquakes ($M_L \geq 5.5$) during the last 60 years indicates that 6 of 26 have been preceded by foreshocks, if the latter are restricted to events of M_L = 4.0-5.4 within 10 km and 3 days of the mainshocks. This ratio (0.23) is similar to that calculated from an ETAS model (0.24) [*235*]. In the L'Aquila case, the EPF method yields a retrospective, 3-day mainshock probability of about 0.8%, which corresponds to a nominal probability gain of about 8-10 relative to the preferred ETAS model. Given the epistemic uncertainties in both types of model, the statistical significance of this difference must be considered as marginal.

5. Coulomb Stress Change Models

The probability of triggering in this class of models depends on the stress perturbations from previous earthquakes, described by the Coulomb failure function, as well as the stress loading by steady block movement. The models cover a wide range of temporal forecasts, from short-term to long-term. As discussed in §II.C.1, the most recent models estimate the variation of the seismic rate (from a background value) induced by a static stress variation embedded in a rate- and state-dependent model. Specifically, these models convert a sudden stress increase induced by a large fault rupture into a factor that multiplies the background seismic rate relative to a population of nearby receiving faults. This causes a sudden jump in seismicity rate that decays inversely with time and eventually recovers; the duration of the transient is inversely proportional to the fault stressing rate.

The modified seismic rate calculated in this manner can be transformed into a time-dependent probabilistic forecast. Coulomb stress change models have been used to construct medium-term earthquake forecasts case studies in Istanbul [*236*], Tokyo [*237*], the Wenchuan region [*238*], and other regions. Evaluations of these recent models are not yet available; a full prospective analysis of skill and reliability may take decades. A global study, based on a representative sample of earthquakes with known fault-plane orientations found that only 61% of the triggered events occurred in areas of increased Coulomb stress [*239*]. Similarly, an analysis of all the CMT catalogue events showed no strong directional dependence of triggering frequency relative to the orientation of the potential mainshock fault planes [*240*].

The same class of models has been proposed for daily forecasts after a large event. The operational application of these models has thus far been limited by the lack of precise data on the mainshock faulting geometry and slip distribution until several days after the event. Retrospective tests suggest that Coulomb models do not perform as well as the ETAS models in the short term [*241*]. As previously noted, there is some controversy concerning the relative importance of static and dynamic triggering.

6. Medium-Term Forecasting Models

Medium-term forecasts, such as the CFF-based models described above, occupy a gray zone where the earthquake triggering concepts that underlie short-term forecasts and the stress renewal concepts that underlie long-term forecasts are of questionable applicability. Better physical models are needed to unify forecasting methods across these domains and resolve the inconsistencies.

In lieu of a physics-based understanding, seismologists have pursued a variety of statistical investigations in attempts to forecast seismic activity on time scales of months to years. Prediction methods based on pattern-recognition analysis yield probability gains of 2-4 relative to time-independent forecasts (see Figure 2.4). Using similar pattern-recognition analysis to calibrate probabilistic forecasting models might provide increases in medium-term gain of this order, but the performance would likely remain considerably below the nominal gains of 100-1000 achieved by short-term clustering models.

The development of medium-term forecasting models formulated using more transparent statistical assumptions has therefore been a high priority for seismological research. Two examples are the EEPAS (Every Earthquake is a Precursor According to Scale) and the double branching model. The EEPAS model [*242*] is a method of forecasting earthquakes based on the notion of a “precursory scale increase” at all scales of the seismogenic process. The rate density of future earthquake occurrence is computed directly from past earthquakes in the catalogue. The EEPAS model calibrated to the New Zealand earthquake catalogue has been retrospectively tested on catalogs from California and Japan [*243*, *244*]. The nominal probability gain for earthquakes of $M \geq 5$ is about 8 relative to a time-independent reference model; combining EEPAS with the STEP model increases the nominal probability gain by a factor of two [*244*].

The double branching model [*245*] is a time-dependent model in which each earthquake stochastically generates other earthquakes through two branching processes with different space-time scales. The first is an ETAS process that describes the short-term triggering of aftershocks due to coseismic stress transfer. The second branching process works at larger space-time scales and aims to describe further correlations among events. An application to the Italian territory for M_W 5.5 or larger has shown a probability gain of about 3 compared to a time-independent smoothed seismicity [*246*].

E. Validation of Earthquake Forecasting Methods

Validation is the process of establishing the operational fitness of a forecasting method in terms of the method’s quality, consistency, and value (§II.A.4). The specific criteria for operational fitness will depend on the region and the purposes for issuing forecasts. In this section, the Commission summarizes some of the key issues that will need to be addressed in the operational implementation of the forecasting methodologies.

1. Evaluation of Forecast Quality

The quality of a forecasting method is the agreement between the forecasts and the observations accumulated over many trials. Statistical measures of agreement, such as absolute measures of reliability and relative measures of skill, can be constructed from the joint probability distribution among the forecasts and observations [*48*, *247*]. Quantitative methods for evaluating forecast quality are well developed in meteorology, where weather systems can be synoptically mapped and continuously tracked, allowing forecasting models to be routinely tested against rich sets of observations.

Observational limitations make the evaluation of earthquake forecasts inherently more difficult. The precise characterization of earthquake activity requires dense networks of seismometers with high bandwidth and dynamic range. Such instrumental systems have been available for only a few decades, and they have yet to be installed in many seismic areas. In most regions, the catalogs of well-located seismicity are too short to sample the rare, large earthquakes that dominate fault system activity, which limits the ability to calibrate forecasting models and retrospectively test them against existing data.

By the same token, substantial difficulties confront the prospective testing of forecasts for the extended periods needed to sample regional seismic behavior [*79*]. While retrospective testing can be useful in rejecting candidate models, prospective testing is necessary to fully evaluate forecasting quality. Individual scientists and research groups rarely have the resources (or patience) to sustain such long-term experiments. Because the models typically involve complex parameterizations, the publication of forecasting experiments in regular scientific journals usually does not provide sufficient information for independent evaluations of performance. Moreover, active researchers are constantly seeking to improve their procedures, sometimes by tweaking their parameters, sometimes by wholesale changes to their algorithms. The forecasts thus become moving targets, frustrating comparative evaluations. Disagreements about the performance of different methods have often arisen from the lack of standards in data specification and testing procedures (e.g., use of inconsistent magnitude scales).

These persistent problems motivated the Southern California Earthquake Center (SCEC) and U.S. Geological Survey to set up a Working Group on Regional Earthquake Likelihood Models. The five-year RELM project, which began in 2006 [*248*], is comparing the performance of time-independent earthquake forecasting models in California using standardized testing procedures that quantify forecast reliability and skill [*249*, *250*].

Based on this experience, an international partnership has been formed to develop the Collaboratory for the Study of Earthquake Predictability [*79*, *251*]. CSEP is an infrastructure for the prospective testing of earthquake forecasts and predictions with four primary components:

- <u>Testing regions</u>: natural laboratories comprising active fault systems with adequate, authoritative data sources for conducting prediction experiments.
- <u>Community standards</u>: rules for the registration and evaluation of scientific prediction experiments.
- <u>Testing centers</u>: facilities with validated procedures for conducting and evaluating prediction experiments.
- <u>Communication protocols</u>: procedures for conveying scientific results and their significance to the scientific community, government agencies responsible for civil protection, and the general public.

Regional experiments involving both time-independent and time-dependent models are now underway in California, New Zealand, Japan, and Italy, and will soon be started in China. A program for global testing has also been initiated. The testing centers run forecasting experiments using a common software system that automatically updates short-term, seismicity-based models and evaluates the forecasts on a regular schedule [*252*]. Both likelihood-based tests [*249*] and alarm-based tests [*45*] have been implemented.

The CSEP testing procedures follow strict "rules of the game" that adhere to the principle of reproducibility: the testing region, the authoritative data sources, including the seismicity catalog, and the conventions for model evaluation are established before, and maintained throughout, an experiment. An experiment re-run at any time by any researcher will therefore produce the same results. All models submitted to CSEP are required to be properly documented (preferably in the form of source code for the executable model), and they can be calibrated using retrospective data for each region; however, any data used for calibrating the models retrospectively are not employed in model evaluations. The model and any updating methods are fixed; authors cannot modify or interact with their models after an experiment has begun, and they are not involved in conducting the statistical tests. Thus, the forecasts are truly "blind", and the validation is independent of the proponent. Although the main focus is on the prospective testing of forecasts [*253*], the reproducibility of CSEP experiments provides a unique capability for retrospective testing.

Prospective forecast testing in the Italian region was initiated by CSEP on 1 August 2009 under an agreement among INGV, which leads the Italian effort, ETH Zürich, which hosts the European CSEP testing center, and SCEC, which develops and maintains the collaboratory software. More than 30 time-independent and time-dependent models have been submitted for testing using an authoritative seismicity catalog provided by INGV [*254*]. Examples of the long-term models are shown in **Figure 2.9**. The variability evident in the model comparison is a manifestation of the large epistemic uncertainties that should be associated with forecasting models of this type.

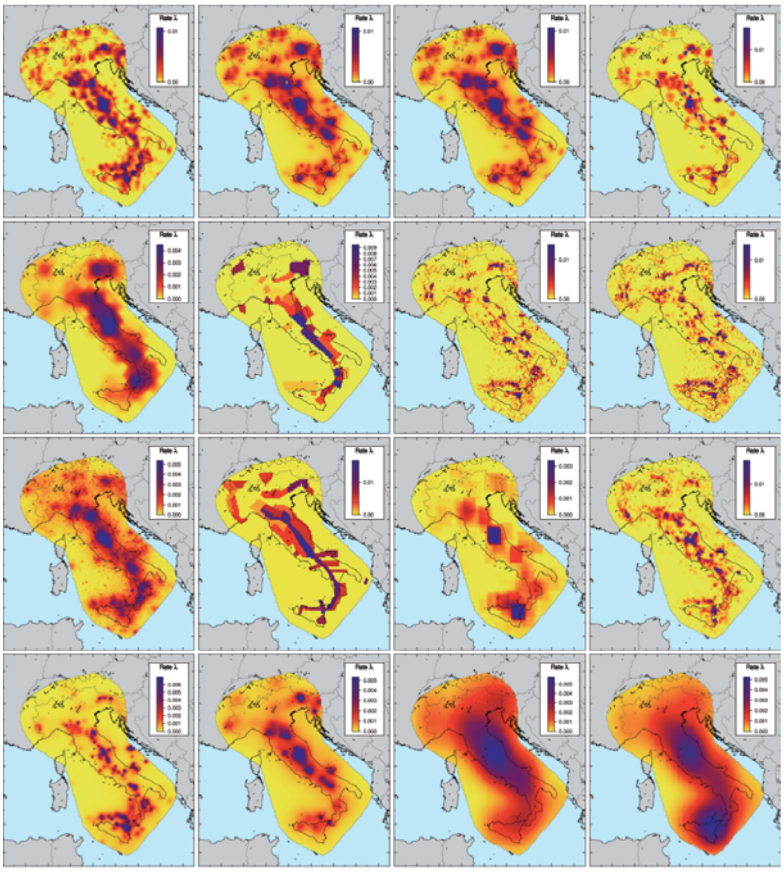

Figure 2.9. Sixteen of the long-term earthquake forecasting models for Italy submitted for prospective testing to the Collaboratory for the Study of Earthquake Predictability [*254*]. Color coded are the rates of forecast events for the next 5 years (note that the color scales are not the same). Prospective testing of these models commenced on August 1, 2009, and will last for 5 years.

CSEP provides an infrastructure that can be adapted for the rigorous empirical testing of operational forecasting models [*255*]. A key requirement for this purpose is the establishment of *reference forecasting models*, against which the skill of candidate models can be evaluated. The reference forecasts should include the time-independent model officially used by DPC in long-term seismic hazard analysis, as well as any short-term or medium-term models qualified by DPC for operational purposes. Criteria for the operational qualification should include estimates of reliability that quantify the epistemic uncertainties in the models, as well as demonstrated skill relative to the time-independent forecasts. The adaptation of CSEP to the testing of operational forecasts faces other of conceptual and organizational issues. For example, the long-term models, especially fault-based models, may have to be reformulated to permit rigorous empirical testing.

CSEP evaluations are currently based on comparisons of earthquake forecasts with seismicity data. From an operational perspective, however, forecasting value can be better represented in terms of the strong ground motions that constitute the primary seismic hazard. This approach has been applied in the STEP model, which forecasts ground motion exceedance probabilities at a fixed shaking intensity, and should be considered in the future formulation and testing of operational models. The coupling of physics-based ground motion models, such as SCEC's CyberShake simulation platform [*256*], with earthquake forecasting models offers new possibilities for developing ground motion forecasts.

2. Spatial and Temporal Consistency

The consistency of operational earthquake forecasting methods applied across spatial and temporal scales is an important issue for dynamic risk management [*257*]. The decision problems informed by operational forecasting often involve trade-offs among multiple targets and time frames. What resources should be devoted to short-term disaster preparations relative to the long-term investments in seismic safety engineering? In which regions should investments be concentrated, and how should changes in seismic activity be used to alter this resource distribution? Inconsistencies among the forecasting methods can hamper decision-making pertinent to such questions.

The consistency problem is related to scientific issues regarding earthquake predictability. Different statistical assumptions underlie the most widely used time-dependent forecasting models. Long-term, time-dependent forecasts, such as those developed by the Working Group on California Earthquake Probabilities [*34, 218*], are based on quasi-periodic renewal models in which earthquake sequences are less clustered in time than expected for a random (Poisson) distribution, whereas short-term forecasts, such as STEP [*227*] and ETAS [*20*], are based on triggering models in which sequences are more clustered than Poisson. The triggering models do not yet account for the localization of seismicity on major faults, which are assumed to the primary sources of large earthquakes in the renewal models.

These temporal and spatial inconsistencies arise because most current forecasting methods are primarily empirical, derived from the stochastic modeling of seismicity data rather than physical modeling of the underlying faulting processes. The development of physics-based earthquake simulators that can properly account for stress interactions in complex fault systems has the potential to unify earthquake forecasting methods over a much wider range of spatial and temporal scales [*199, 200*]. The development of better medium-term forecasting models is a critical aspect of this unification.

Until the scientific challenges related to physics-based forecasting can be overcome, spatial and temporal consistency will have to be achieved through a statistical approach. For example, when integrated over sufficiently long intervals, the probabilities from short-term forecasting models should be consistent with those of long-term forecasts. The current practice of using the long-term forecasts to specify background seismicity rates for the short-term models—e.g., as in the STEP model for California—does not necessarily achieve this consistency, because the seismicity fluctuations introduced by earthquake triggering can occur on time scales comparable to the recurrence intervals of the largest events [*200*]. Modification of both the long-term and short-term models will be required to ensure their compatibility on intermediate time scales. Ideally, model development should be integrated across all time scales of forecast applicability.

3. The Valuation Problem

As documented in this report and emphasized elsewhere [*35, 36, 258*], probabilistic forecasts are the best means for transmitting scientific information about future earthquake occurrence to decision-makers in a way that appropriately separates hazard estimation by scientists from the public protection role of civil authorities. Earthquake forecasts possess no intrinsic societal value; rather, they acquire value through their ability to influence decisions made by users seeking to mitigate seismic risk and improve community resilience to earthquake disasters.

The time scale of a forecast is clearly very significant in determining its value to decision-makers. The long-term earthquake forecast for Italy gives a probability of approximately 15% that there will be a magnitude-6 earthquake somewhere in the country during the next year. This forecast provides important input to building codes, because the seismic hazard is high when integrated over the decades of a building's lifetime, but it is less valuable for informing the day-to-day decisions of emergency managers, because on any given day, the chances of a potentially damaging shock are very low.

The societal value of seismic safety measures based on long-term forecasts has been repeatedly demonstrated [*259*]. The M_W 7.0 Haiti earthquake of 12 January 2010 caused immense destruction and loss of life in a region where large earthquake were anticipated but the built environment was not constructed to withstand intense seismic shaking. In contrast, the M_W 8.8 Chile earthquake of 27 February 2010 caused substantially less damage and loss of life relative to its size, in large part because Chile enforces high seismic safety standards.

The potential value of protective actions that might be prompted by short-term forecasts is far less clear. Most previous work on the public utility of short-term forecasts has anticipated that they would deliver high probabilities of large earthquakes; i.e., that deterministic predictions would be possible [*260*]. This expectation has not been realized. While the probability gains of short-term, seismicity-based forecasts can be high (> 100 relative to long-term forecasts), the probabilities of large, potentially destructive earthquakes typically remain low (< 1% per day).

The benefits and costs of preparedness actions in high-gain, low-probability situations have not been systematically investigated in Italy or elsewhere. Value assessments can be classified as *ex* *post*—determining the actual value of the forecasts after the observations have become available—and *ex ante*—determining the expected value of the forecasts before the observations have become available [*49*]. Ex ante assessments of earthquake forecasting value deserve special attention, because they are needed to establish objective, quantitative, and transparent protocols for decision-making before a seismic crisis occurs [*261*].

Economic valuation is one basis for prioritizing how to allocate the limited resources available for short-term preparedness. If the threat level rises, civil authorities can choose to do nothing or to take action. The actions might range from low-cost measures—augmenting scientific monitoring of the hazard, placing emergency services on alert, and notifying the public of an increased hazard level—to high-cost disaster preparations, such as closing seismically vulnerable facilities (e.g., substandard, high-occupancy buildings) and mass evacuations.

A rational approach to decision problems of this type can be illustrated by a simple cost-loss model for optimizing binary decisions [*261*]. Suppose a decision-maker has to choose between two actions: either (a) protect, or (b) do not protect. The cost of protection is C. In the absence of protection, the decision-maker incurs a loss $L > C$ if an adverse hazard state arises. The time interval between the act of protection and the occurrence of the adverse hazard state is assumed to be sufficiently short that financial discounting is negligible. If the probability of the adverse hazard state arising within a specified time window is P, the policy that minimizes the expected expense is (a) if $P > C/L$, but (b) if $P < C/L$. The minimal expense is then the lower of the two amounts, C and PL.

Many factors complicate this rational approach. A consensus on the monetary value of society's most precious assets, such as human life and treasured historical structures, can be difficult to achieve, making their incorporation into formal cost-loss calculations problematic. Official actions based on scientific forecasts can also incur intangible costs, such as loss of credibility when the response to a seismic crisis is judged by the public *a posteriori* as an over-reaction (false alarm) or an under-reaction (failure to predict). This problem is compounded by the fact that the epistemic uncertainties in the short-term probability estimates are bound to be high, allowing considerable latitude in the official response. Moreover, the assessments of forecast value must take into account the information available to decision-makers in the absence of the forecasts [*49*]. Probability gain of a short-term forecast with respect to a long-term forecast may overestimate the effective information gain.

The importance of correct and clear information to the media and the public must be emphasized. Most people, including reporters, are not familiar with the concept of probability, and experience shows that probabilistic forecasts can be easily misinterpreted. A vigorous program of public education on the utility and limitations of low-probability forecasting should be a basic component of a program to mitigate seismic risk.

III. Status of Operational Earthquake Forecasting

In developing guidelines for the implementation of operational forecasting systems, the Commission drew from the experience of various countries that maintain or are developing operational systems and protocols. This section summarizes the current capabilities and procedures in six seismically active countries, including Italy, as reported by the Commissioners from those countries. These summaries were written to answer the following questions:

- Which organizations have statutory responsibility for providing authoritative earthquake information to civil protection agencies and to the public, and which for evaluating earthquake forecasts and predictions?
- Which forecasting capabilities can be considered operational? To what extent is short-term, local forecasting consistent with long-term, regional forecasting? Are the forecasts based on probabilistic models? Do the models include fault representations?
- How are operational forecasts currently translated into alerts and actions for civil protection?
- What technical developments in operational forecasting can be anticipated in the near future?

A. China (Chen)

China is one of the most seismically active countries in the world; destructive earthquakes pose a major threat to lives and property in almost all of the Chinese territory [*262*]. The 1556 Guanzhong (Huaxian, Shan'xi) earthquake killed 830,000 people, more than any other quake in recorded history. During the twentieth century, Chinese earthquake deaths were more than 50% of the total worldwide. The 1920 Haiyuan earthquake caused 230,000 deaths, and the 1976 Tangshan earthquake (M_S 7.8) killed 242,000 people and seriously injured another 164,000. Those killed or missing in the 2008 Wenchuan earthquake (M_S 8.0) numbered nearly 90,000.

China has carried out an extensive research program aimed at earthquake prediction and the prevention and mitigation of earthquake disasters [*263*]. In 1966, the Xingtai earthquake (M_S 7.2), caused 8,064 fatalities and 38,000 serious injuries in a densely populated area. Three years later, the State Council established the Central Working Group on Seismological Works for coordinating earthquake monitoring and prediction [*264*]. The group was reorganized into the State Seismological Bureau (SSB) in 1971, and its name was changed to China Seismological Bureau in 1998; the English translation was changed into China Earthquake Administration (CEA) in 2004. Most of the provincial governments also established earthquake administrations for leading and coordinating the prevention and mitigation of earthquake disasters at the local level. The CEA organizes annual meetings on the evaluation of future earthquake likelihood for the coming year. At these meetings, earthquake predictions and forecasts based on the comprehensive analysis of multi-disciplinary observations and models are discussed, and a report is sent the State Council that identifies earthquake-prone areas for intensified monitoring during the coming year.

The program for the prevention and mitigation of earthquake disasters comprises four basic components: earthquake science and technology, earthquake monitoring and prediction, earthquake disaster prevention, and earthquake disaster emergency management. It is recognized that the realization of these four aspects relies on legislative as well as other actions. Earthquake predictions and forecasts in China are classified into long-term (decades), medium-term (years), short-term (months to weeks) and imminent (weeks to days and even hours). Short-term forecasting of strong aftershocks also has a strong programmatic role.

In 1957, Li Shan-bang led the compilation of the *1:5,000,000 Map of Seismic Zonation of China* in cooperation with seismologists from the former Soviet Union [*265*]. The first preliminary Chinese building code in seismic regions was published in 1959, sponsored by Liu Hui-xian. From 1972 to 1977, the State Seismological Bureau compiled the second version of the *1:3,000,000 Seismic Intensity Zoning Map in China*, based on the concepts of long-term earthquake forecasting. This zoning map, which represented the most likely seismic intensities in the future 100 years under average soil conditions, was approved by the Construction Committee of Chinese Government as basis of engineering seismic design for small to middle-sized projects. Further accumulation of seismic data and developments in science and technology led the State Seismological Bureau to compile the third version of the *Seismic Intensity Zoning Map in China* (scale 1:4,000,000) to meet the needs of new seismic design; completed in 1990, it was based on macro-seismic intensity and the probabilistic method of seismic hazard analysis. The inhomogeneity of seismicity in space and time was considered, and the results from studies of medium-term and long-term earthquake prediction were incorporated. The latest (fourth) version was issued in 2001 and is cast in terms of ground motion parameters.

The Chinese seismologists also took active part in the Global Seismic Hazard Assessment Program (GSHAP), initiated by the United Nation as a demonstration project for the International Decade of Natural Disaster Reduction (IDNDR, 1990-1999). The first global seismic hazard map based on a consistent probabilistic seismic hazard analysis was published in 1999 [*30*].

The "Law of the People's Republic of China on Protecting Against and Mitigating Earthquake Disasters" was enacted in 1997 as an endeavor to involve the public in earthquake prevention and mitigation [*266*]. A revision enacted on 27 December 2008 became operational on 1 May 2009. Accordingly, the government issued the "Act on the Management of Earthquake Prediction," with the aim to regulate the procedures for the evaluation and release of earthquake predictions and forecasts, especially imminent earthquake predictions, and to strengthen the role of experts and minimize the social cost that may be caused by non-scientific earthquake predictions.

In the practice of medium-term, short-term, and imminent earthquake prediction, a number of observational techniques have been explored, including the monitoring of seismicity, ground deformation, stress, gravity, geoelectricity, geomagnetism, groundwater flow, and geochemistry. Owing to the lack of a thorough understanding of the physics of earthquake occurrence, earthquake prediction in China has been mainly empirical.

In the last four decades, Chinese seismologists have acquired experience in medium-term and long-term earthquake prediction. By using an empirical approach, the Haicheng earthquake was successfully predicted by the Chinese seismologists, and the casualties and loss were greatly reduced [*267*]. The Haicheng earthquake prediction consisted of four stages (long-term, medium-term, short-term, and imminent) based on the geological, historical seismological studies, observations of geodetic deformation and macroscopic anomalous phenomena. The foreshock activity of the Haicheng earthquake played an important role in issuing imminent-term predictions and evacuation orders.

However, using the same empirical approach, Chinese seismologists failed to predict the 1976 Tangshan earthquake (M_S 7.8). The lessons learned from the successes and failures in earthquake prediction have promoted Chinese seismologists to reflect on the methodology and philosophy in earthquake prediction research. More and more Chinese seismologists, as well as the public at large, recognize the difficulties encountered in this research, especially in the study of short-term and imminent earthquake predictions [*268*]. A better understanding of the regularities of earthquake occurrence and the characteristics of earthquake precursors is needed, and research efforts should be intensified in a number of areas, particularly in the collection of improved observations.

B. Greece (Papadopoulos)

Greece and its adjacent areas are the most seismically active regions in the Western Eurasia. Strong earthquakes ($M \geq 6$) occur with a mean repeat time of about one year. In the last six decades, the most lethal have been the 12 August 1953 earthquake (M_S 7.2) in the Ionian Sea and the 7 September 1999 earthquake (M_w 5.9) in the capital city of Athens, which killed 476 and 143 people, respectively [*269*]. The antiseismic policy in Greece is coordinated by the Earthquake Planning and Protection Organization (EPPO), which is a public authority operating under the supervision of the Ministry of Infrastructure, Transportation, and Networks (ITN). EPPO is also responsible for the evaluation of earthquake forecasting and prediction procedures. However, the immediate response to strong and damaging earthquakes, such as rescue operations, housing, humanitarian and financial support, is coordinated by the General Secretary for Civil Protection (GSCP), supervised by the Ministry for Citizen's Protection.

The national telemetric seismograph system is monitored round-the-clock by the Institute of Geodynamics, National Observatory of Athens (NOAGI), which is a public research center under the supervision of the General Secretary for Research and Technology of the Ministry of Education and Lifelong Learning [*270*]. The Universities of Athens, Thessaloniki, and Patras contribute to the seismic monitoring by transmitting to NOAGI the data from their own seismic network in real-time. NOAGI has the statutory responsibility for providing earthquake information to civil protection agencies and the public. As soon as the source parameters of an $M \geq 4$ earthquake are determined, the event is publicly announced, and the information is transmitted in parallel to EPPO and GSCP. Earthquakes of $M < 4$ are not routinely announced unless they cause social concern in local communities.

A cornerstone of the long-term antiseismic policy in Greece is the Antiseismic Building Code. The code was first established at national level in 1959 and has since been improved several times; it is based on a time-independent evaluation of the seismic hazard derived from a seismogenic zonation developed by a consensus involving the Greek several seismological institutions. The latest version of the code, released in 2003, is stated in terms of three levels of seismic hazard at the national scale [*271*]. Alternative approaches for the seismic hazard assessment included the use of incomplete earthquake data files [*272*], Bayesian methods [*273*] and comparisons of time-independent with time-dependent models [*274*]. A review can be found in [*275*].

Greece has not yet established an official program for the operational forecasting or prediction of earthquakes, although research on various methods has been underway since the early 1980s. The two most important types are based on: (a) the recognition of seismicity patterns, such as seismic gaps, migration of earthquake epicenters, long-term seismicity acceleration, and short-term foreshocks, as well as probabilistic models of seismicity [*276*]; and (b) the detection of changes in the Earth's electric field, such as the VAN method [*277*]. The latter has been very controversial, however [*278*]. Only a few earthquake prediction statements (EPSs) based on seismicity patterns were submitted to EPPO since the 1980s. However, in the same time interval, and particularly up to 1999, hundreds of EPSs produced by the VAN team were submitted either to EPPO, to other Greek governmental bodies, or to scientists in Greece and abroad. Many of those EPSs were also announced by Greek or foreign (e.g. French) media, causing considerable concern among the Greek population. In the last several years, the VAN group has posted their predictions on an archival database hosted by Cornell University (USA); these postings have not received official review or evaluation.

In view of the social problems caused by the VAN predictions, the Greek government authorized EPPO in 1992 to establish the Permanent Special Scientific Committee for the Assessment of Seismic Hazard and the Evaluation of Seismic Risk (hereafter called the "Committee"). In its current form, the Committee president, the vice president, members, and an administrative secretary are appointed by the Minister of ITN, based on recommendations by the EPPO. The Committee comprises experts in several disciplines such as seismology, solid-Earth geophysics, tectonics, geodesy, engineering geology, and civil engineering. One member is appointed by and represents GSCP. Committee appointments are for two years and can be extended for an additional year.

The Committee's current mandate is to evaluate earthquake forecasts and predictions, long-term as well as short-term, and also to assess seismicity during earthquake crises; e.g. after strong earthquakes or during persistent seismic sequences, such as swarms. In addition, the Committee makes recommendations to the Government and EPPO regarding special countermeasures that go beyond routine actions. The Committee is convened by its president or at the request of the president of EPPO or the Minister of ITN, and it operates on internal rules established by the consensus of its members. According to these internal rules, the Committee president can invite external experts to Committee sessions. The Committee convenes for the evaluation of an earthquake forecast or prediction only if it has been officially submitted; therefore, predictions that have appeared in the mass media or in scientific journals or conferences, but have not been submitted to the Committee, are typically not evaluated.

Since its founding in 1992, the Committee has recommended that special measures be undertaken in response to submitted EPSs in only few cases. These have been of two types. The first includes scientific response, such as intensification of instrumental monitoring in the EPS target area, further data analysis, and verification of results. The second type includes operational measures; e.g., updating of emergency plans and instructions to local authorities for the seismic crisis management. The Committee has never favored the public announcement of earthquake predictions. Overall, the activities of the Committee have proven to be useful from both a scientific and a social point of view.

In a recent case (January, 2008), a prediction published in a peer-reviewed journal [*279*] was subsequently submitted to the Committee for evaluation. The prediction method was based on observations of space-geodetic anomalies in conjunction with accelerated Benioff strain, interpreted in terms of a dilatancy model; the target area, which had a dimension greater than 50 km, included the Ionian islands of Zakynthos and Cephallonia. The published prediction stated, "If this interpretation is correct, it may foreshadow the occurrence of a very strong earthquake(s) [around M=7] sometime during 2007 to 2008 in the above designated area." After discussions with the leading author, and with the help of an external expert in space geodesy, the Committee concluded that, in view of ambiguities related to the calibration of the geodetic station and the large uncertainties involved in the measurements, the prediction was not useful from practical point of view. In addition, the Committee recommended intensification of the instrumental monitoring of the target area. The publicity received by the prediction (which was not through the Committee process) caused social concern in the Ionian islands for an extended period. No strong earthquakes (M > 6) had occurred in the target area and adjacent regions by the end of 2010.

It is noteworthy that, in 1994, the Council of Europe established the European Advisory Evaluation Committee for Earthquake Prediction (EAECEP), which operated within the framework of the "Open Partial Agreement" of the Council of Europe for the mitigation of natural and technological hazards. EAECEP engaged in various activities (e.g., evaluation of earthquake simulations), and it was convened at least once—in 1995 in Athens, Greece—to evaluate EPSs by the VAN group. After 2001, however, EAECEP became inactive.

C. Italy (Marzocchi & Gasparini)

Italy is one of the most seismically active countries in the European-Mediterranean region, and earthquakes have frequently caused extensive damage and casualties (e.g., Belice 1968: 231 deaths; Friuli 1976: 978 deaths; Irpinia: 2914 deaths). Destructive events have repeatedly motivated governments to tackle the problem of defending people and property from earthquakes. This activity was strongly improved after the Friuli (1976) and Irpinia (1980) earthquakes with the founding of the country's first Ministry of Civil Protection in July 1981.

Civil protection activities are currently based on the Law #225/1992 (passed in 1992). This law established the National Civil Protection Service, which integrates the emergency response to a catastrophic event across all public and private organizations. These organizations include fire brigades, army, volunteers, scientific communities, as well as ministries, local administrations and owners of strategic utilities. Operational coordination at the national level is the responsibility of the Department of Civil Protection (Dipartimento della Protezione Civile, or DPC). This coordination has become progressively more important; Law #112/1998 set out rules for the decentralization of civil protection in Italy, assigning to regions and provinces specific roles for civil protection activities and to municipalities the primary local responsibility for disaster planning and management.

According to Law #225/1992, the level at which decisions are made after an event depends on the event's severity as rated on the following scale:

A. Natural events or events related to human activities that can be confronted by interventions within the means of individuals, competent institutions, and administrations, following ordinary laws.

B. Natural events or events related to human activities that, owing to their nature and extent, require a coordinated intervention of more competent institutions and administrations, following ordinary laws.

C. Natural disasters, catastrophes, or other kinds of events that, owing to their intensity and extent, need to be confronted with extraordinary means and powers.

Events A and B are dealt with at local level, by the affected municipality or region. Events C are dealt with by the National Civil Protection Service, under the coordination of the Prime Minister through DPC. Therefore, the DPC is charged at national scale with risk forecasting and loss prevention, as well as with emergency management and response.

The main purpose of the National Civil Protection Service is to safeguard human life and health, and to protect communities, goods, national heritage, and the environment from various types of disasters, natural or man-made. The DPC develops:

- activities devoted to the causes of disasters, the identification of risks, and the definition of areas at risk;
- activities aimed at reducing damage due to disasters, including those based on knowledge gained by forecasting; and
- interventions for the rehabilitation of communities and the recovery of normal life conditions.

To perform these tasks, the DPC has interacted with the scientific community by means of the National Commission for the Prediction and Prevention of Major Hazards (Commissione Nazionale per la Prevenzione e Previsione dei Grandi Rischi, or CGR) and through "competence centers"—scientific institutions that provide services, information, data, technical and scientific contributions, and elaborations on specific topics—to share the best practices in risk assessment and management.

The first formal CGR was appointed in 1982 (Interdisciplinary Scientific Commission) and tasked to collaborate with the Ministry of Civil Protection on problems regarding prediction and prevention of risks. After several changes, the CGR was defined by Law #225/1992 as a central advisory body of the National Civil Protection Service. During the 1990s, the CGR became very large, comprising eight sections (seismic, nuclear, volcanic, hydrogeologic, chemical, transport, cultural heritage, health risks) with more than 80 members. The CGR was reorganized under the Law #21/2006, which defines the CGR as the technical-scientific advisory body for the DPC with the main task of providing opinions and proposals in the different areas of risk. The CGR currently has 21 members, although, if needed, it can refer to a list of experts for all the risks of interest. In emergencies, the CGR can be convened within one day.

The National Institute of Geophysics and Volcanology (Istituto Nazionale di Geofisica e Vulcanologia, or INGV) is the DPC competence center for seismic and volcanic risk. This research institute is a component and operational structure of the National Service of Civil Protection, and it operates in a continuous collaboration with the DPC through three-year agreements, under which the DPC defines and funds seismic and volcanic monitoring and the evaluation of the seismic and volcanic hazards, including the production of long-term seismic hazard maps.

The first probabilistic seismic hazard map of Italy was developed in the late 1970s [*280*] and enforced in the national seismic classification between 1981 and 1984. A revised map updating the seismic classification was released in 1998 [*281*], but it was not put into force until 2003. At present, INGV provides long-term seismic hazard maps for the entire country. The most recent hazard map was released in 2004 [*282*] and enforced by an ordinance of the Prime Minister in 2006; it is the official reference for the seismic classification of the Italian territory and the seismological basis for the design seismic actions of the current (2008) building code. The seismic hazard is currently defined in terms of peak ground acceleration (PGA) and spectral acceleration values for various probabilities of exceedance. This information is stored in a database that is freely accessible to all users via the web [*1*].

Underlying the 2004 hazard map is a comprehensive seismic hazard model that takes into account the variability of the seismicity, the seismogenic potential, and the seismic energy propagation in different areas of Italy. The model is based on a time-independent earthquake forecast; i.e., earthquakes are assumed to occur as independent events, random in time. Although the Italian catalog of seismogenic faults continues to be improved since its first version [*283*], the knowledge of these faults remains incomplete, owing to the complex tectonics of Italy; therefore, this information has not yet been used in the offcial hazard model.

Operational procedures for short-term forecasting and protocols for the use of such forecasts have not yet been established in Italy.

D. Japan (Yamaoka)

In Japan, two government organizations, the Japan Metrological Agency (JMA) and Headquarters for Earthquake Research Promotion (HERP) in the Ministry of Education, Culture, Sports, Science and Technology, have responsibility for operational earthquake forecasting. JMA has the operational responsibility for predicting the hypothetical Tokai earthquake, aftershock forecasting, earthquake early warning, and tsunami warning [*284*]. HERP is responsible for providing the public with appropriate information on earthquake risk, implemented through the following tasks [*285*]: (1) planning of comprehensive and basic policies; (2) coordination of budgets and other administrative work with relevant government organizations; (3) establishment of comprehensive surveys and observational plans; (4) collection, analysis, and the comprehensive evaluation of survey results collected by universities and related institutions; and (5) public announcements based on comprehensive evaluations. Under the third task, HERP has the operational responsibility for (a) monthly reports on evaluation of seismic activity in Japan, (b) long-term evaluation of inland and off-shore earthquakes, and (c) national seismic hazard maps for Japan.

Historically, Japan has suffered many natural disasters, especially earthquakes. The government has promoted research on earthquake forecasting and prediction since it was established in its modern form in 1868. A national program for earthquake prediction, started in 1965, aimed for the detection and elucidation of precursory phenomena of earthquakes. In a report presented at the 1976 meeting of the Seismological Society of Japan, a megathrust earthquake (M ~ 8) was predicted for the Suruga Trough along the Japan's southern coast; this so-called "Tokai seismic gap" was known to have ruptured in the great earthquakes of 1707 and 1854 and was thought to be ripe for failure at any time [*286*]. Because the region potentially affected by the anticipated Tokai earthquake was central to Japan's economy, including its biggest industrial area and its main transportation corridor, the government enacted the "Large-Scale Earthquake Disaster Countermeasure Act" in 1978.

Based on this law, the Japan Meteorological Agency (JMA), National Research Institute of Earth Science and Disaster Prevention (NIED), Geospatial Information Authority of Japan, and the Geological Survey of Japan maintain an intensive observational network principally composed of strainmeters, seismometers, GPS stations, and groundwater sensors in and around the Tokai region and the anticipated source region of the Tokai earthquake. JMA monitors all of the data continuously and has the statutory responsibility to predict the Tokai earthquake in the short term, in consultation with a panel of experts. The prediction scheme is deterministic, based on pre-slip on the upper interface of the Philippine Sea plate [*287*]. Once a short-term prediction has been made, the Prime Minister will announce an earthquake warning [*288*]. Beginning in 2001, in response to requests from many local governments, JMA revised its procedures to include three stages for the release of public information: an earthquake report, an earthquake advisory, and an earthquake warning [*289*]. These announcements are based primarily on the number of strainmeters that detect anomalies showing possible pre-slip in the source area of the Tokai earthquake; the actions to be taken at each stage are specified in detail for traffic services, shops, offices, schools, as well as emergency sections.

In spite of continuous research efforts in Japan, little evidence has been found for precursors that are diagnostic of impending large earthquakes, including the Tokai event (which has not yet happened). In 1995, the Hyogoken-Nanbu (Kobe) earthquake, M_W 6.9, killed 6,434 people and destroyed over 100,000 buildings and houses. The Japanese government recognized that insufficient information on the earthquake environment of Kobe area was available prior to the catastrophe, and therefore established HERP. The Earthquake Research Committee of HERP convenes regular meetings, once per month, to evaluate seismic activity. In case of significant earthquakes, the committee holds emergency meetings to assess the activity and release the latest information to the public.

Operational procedures for issuing short-term forecasts and predictions have not been established, except locally in the case of the Tokai earthquake (based on the Large-Scale Earthquake Disaster Countermeasure Act and its modifications) and, more recently, for earthquake swarms in the eastern Izu Peninsula [*290*]. In addition, since 1998, following a report by the HERP entitled "Probabilistic evaluation of aftershocks," JMA has used the Omori-Utsu model for the probabilistic forecasting of large aftershocks (M ≥ 5 or 6) that will occur in 3 or 5 days.

The earthquake prediction research program is now aimed at a comprehensive understanding of the earthquake cycle and at forecasting using physical models of earthquake occurrence [*291*]. The program emphasizes the importance of developing predictive simulations in combination with monitoring of crustal activities. HERP coordinates the cooperative research and monitoring of earthquakes distributed among various institutions in Japan, including JMA, NIED, Geospatial Information Authority of Japan, the Geological Survey of Japan, and the national universities.

The first ten years of HERP activity produced information essential for disaster mitigation. The most important results have been the long-term forecasting of earthquake occurrence and the potential for strong ground motions. One of the main products has been the evaluation of the long-term earthquake potential of active crustal and subduction-zone faults [*292*]. To date, HERP has sponsored studies of the past activity of 110 active inland faults and about 30 source regions of subduction-zone earthquakes around Japan. The results have been published along with the probabilities of earthquake occurrence in the next 10 and 30 years, based on a statistical analysis the seismic record as well as geological surveys. The subduction-zone probabilities are better constrained, because the recurrence intervals of large earthquakes in these source regions are relatively short, on the order of a century. However, high uncertainties still exist for the earthquake probabilities on inland faults, where the slip rates are lower and the recurrence intervals correspondingly longer. In fact, all of four of the large inland earthquakes that have occurred after the publication of the evaluation happened where no fault-specific evaluation had been made [*293*].

The evaluation of earthquake source regions has been used to produce new seismic hazard maps for Japan; the first series was released in 2005 [*294*], and an updated series published in 2009.

Both probabilistic seismic hazard maps and scenario earthquake shaking maps are publicly available via the NIED website [*295*]. The maps have been calculated on a 250-m grid across the entire country, and they account for the amplification of strong motion due to local ground conditions. The hazard maps are now updated yearly, based on the occurrence of new earthquakes as well as new research results. The hazard maps are used in many aspects of the Japanese disaster reduction program; e.g., the promotion of retrofitting of the older houses and buildings, the formulation of emergency response plans by national and local governments, and the calculation of insurance rates.

Under the auspices of HERP, the Geospatial Information Authority of Japan has deployed more than 1300 GPS stations across the Japanese islands, and NIED has deployed more than 700 high-sensitivity seismic stations [*296*]. When combined with the existing stations operated by the national universities and JMA, total number of seismic stations exceeds 1200 [*297*]. These observational networks have provided the data for many new research results. The geodetic data have been used to map the heterogeneous strain distribution within Japan, leading to the delineation of strain-accumulation regions where many historical earthquakes have occurred. Slow slip events on the subduction interface have also been discovered using the GPS network. Detailed analysis shows that regions of slow slip tend to be complementary to regions of seismic slip, supporting the asperity model for earthquakes along the subduction zones. Analysis of the tremendous volume of seismic data recorded by the high-sensitivity seismic network has led to the discovery of episodic tremor that accompanies some slow slip events (see §II.C.2). These findings have improved the understanding of earthquake processes in convergent tectonic environments, and they have furthered the goal of medium-term earthquake forecasting based on physical models that are constrained by high-quality network data.

Since 2007, JMA has begun to provide residents in Japan with earthquake early warning (EEW). EEW is a system that detects an earthquake occurrence with nearby seismometers, determines the magnitude and hypocenter as quickly as possible, and informs the public of a strong tremor before it arrives at more distant sites [*298*]. JMA transmits the EEW information through a number of media, including TV, radio, and internet. In spite of the limitations of EEW (e.g., residents near the earthquake epicenter may not receive a warning before the strong tremor), most people have welcomed the operational system. The media repeatedly instruct the public of the actions to be taken in the case of an EEW [*299*].

E. Russia (Sobolev)

Earthquake forecasting and prediction has been pursued for many years in Russia's seismically active regions, which extend from the Far East (Primorye, Sakhalin, Kuril Islands, Kamchatka, and Komandor Islands), the Lake Baikal region (with its extension to Stanovoy ridge on the East), Yakutia, the Altai and Sayan mountains, and the Greater Caucasus. Between 1991 and 2010, ten earthquakes of magnitude 7.5 or larger have occurred in the territory of the Russian Federation.

The Russian Expert Council for Earthquake Prediction and Earthquake Hazard Assessment (REC), was established in 1994 as part of a Federal Targeted Program entitled "Development of the Federal System for Seismological Observations and Prediction of Earthquakes." In 2002, a joint decision of the Ministry of the Russian Federation for Civil Defense, Emergencies and Elimination of Consequences of Natural Disasters (Emercom of Russia) and the Russian Academy of Sciences modified the name to the Russian Expert Council for Earthquake Prediction and Earthquake Hazard and Risk Assessment (with the same acronym, REC), and regional branches were established for Northern Caucasus in Mahachkala, Siberia in Irkutsk, Kamchatka in Petropavlovsk-Kamchatskiy, and Sakhalin in Youzhno-Sakhalinsk.

Russian scientists have been very active in developing methods for earthquake prediction and forecasting; a particular focus has been on medium-term predictions [*300*]. In a number of cases, prospective information from medium-term forecasts has been transferred to governmental authorities via legally approved channels. The procedures can be illustrated by activities in the Far East, which comprise some of the most dangerous earthquake zones of the Russian territory. Since 1965, the concepts of the seismic cycle and seismic gaps have been used for the long-term prediction of strong earthquakes in the Kurile-Kamchatka Arc [*301*]. A special program was initiated by the Russian Federation Government Decree of September 6, 1995, "On preparation of the Kamchatka region for possible earthquake." Under this program, the probabilities of events with M > 6 are issued for 5-year windows. For example, in the current window (2008-2013), an earthquake with M > 7.5 is expected near Petropavlovsk-Kamchatskiy, the biggest city on Kamchatka, with a probability of 50% [*302*]. Special efforts are underway to decrease the expected social and economic losses in this urban area.

Among the largest earthquakes to occur within the Russian territory in last 20 years are the Kronotskoe earthquake of 5 December 1997 (M 7.8), on the Kamchatka Peninsula, and Simushirskoe earthquake of 15 November 2006 (M 8.2), in Kuril Islands. Several algorithms and methods based on the space-time and energy characteristics of seismicity were aimed at medium-term earthquake forecasting in these regions [*303*].

The modified M8 algorithm and repeated trilateration measurements were used for the medium-term prediction of the Kronotskoe earthquake. A zone of high probability (ZHP) for a M ≥ 7.5 target event in the 1993-1998 period was delineated as a 660 km × 660 km square in an Open File Report of the Institute of Volcanology, transmitted in a letter from Institute of Volcanology to the REC on 14 March 1996 [*304*]. The Kronotskoe earthquake took place 20 months later near the center of the ZHP.

The RTL algorithm, based on seismic quiescence and subsequent activation phenomena, was used to forecast both the Kronotskoe and Simushirskoe earthquakes. RTL graphs and a map of the anomalous zone (100 km × 200 km) were delivered to the REC on 27 August 1996; the magnitude of target event was estimated as M ≈ 7. The Kronotskoe earthquake took place 16 months later in the marginal part of the anomalous zone. In the case of the Simushirskoe event, RTL graphs and the map of the anomalous zone (200 km × 200 km) were delivered to the REC on 10 October 2002; the target magnitude was estimated to be M > 7. The Simushirskoe earthquake took place 49 months later in the marginal part of the anomalous zone.

The successful predictions of these two earthquakes were mentioned among the main achievements of Russian Academy of Sciences in 1997 and 2006. Some preventive actions (including the training of soldiers) were implemented by Ministry Emergency Situations in both cases. This ministry has statutory responsibility for providing risk mitigation and earthquake preparedness on territory of Russian Federation.

A scientific program aimed at earthquake prediction was created by Academy of Sciences of USSR in 1980 [*305*]. Three main topics were suggested: an integrated geological and geophysical study of seismic regions, earthquake precursors, and a system of controlled earthquakes. A proposal was made to set up an observation system in the country comprising base seismic stations and local forecasting networks. The latter include a seismo-forecasting observatory and 10-15 integrated observation points. Three multidisciplinary test sites are in operation on Russian territory at this time, in Kamchatka, Sakhalin, and Baikal, where seismicity, deformation of Earth's surface, hydrodynamic, electromagnetic and geochemical fields are recorded. Analyses of these observations are focused on two objectives: first, to promote fundamental research aimed at gaining better insight into earthquake source processes and the origin of precursors; secondly, to set up integrated systems capable of real-time data processing and analysis.

The local commissions with responsibility for the evaluation of earthquake precursors comprise members of scientific institutes and specialists of the Geophysical Survey of the Russian Federation. These commissions meet periodically. The protocols of the meetings and appropriate materials are sent to the REC but are not typically released to the public. Forecasts and predictions can be sent to the REC by any person or organization in Russia without a special mandate. Official protocols for the use of forecasts for civil protection actions have not yet been developed. As of this time, no short-term predictions have been approved by the REC.

F. United States (Jordan)

The U. S. Geological Survey (USGS) has the federal responsibility for earthquake monitoring, earthquake hazard assessment, and earthquake forecasting in the United States. Its National Seismic Hazards Mapping Project (NSHMP) provides long-term seismic hazard maps for the entire country [*306*]. The first maps based on probabilistic seismic hazard models were released in 1996, and they were updated with new seismic, geologic, and geodetic information in 2002 and again in 2008 [*29*]. The models have been produced by a consensus-building process that involves the end-users of the hazard analysis, as well as the state geological surveys and academic research organizations.

The NSHMP model is used as the hazard basis for the seismic elements in model building codes, although the process in indirect because code regulations are established and enforced at the state and local level, rather than the national level. (The state and local jurisdictions typically adopt relevant sections of the model codes without extensive revision.) The 1996 national hazard model was used in developing the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and*

Other Structures [*307*]. These NEHRP Provisions were incorporated extensively into model codes, including the International Building Code and the National Fire Protection Association 5000 Code. This cycle is repeated every few years to incorporate changes in hazard assessments and advances in building seismic safety research. The 2008 revision of the national seismic hazard model was used to revise the NEHRP Provisions in 2009, which were used in turn by the American Association of Civil Engineers to recommend changes to model codes. The next generation of model codes, to be published in 2012, is expected to adopt these recommendations. The NSHMP model is also used in setting insurance rates, design of critical facilities, earthquake loss studies, retrofit prioritization, and land-use planning.

The NSHMP model is primarily based on a time-independent earthquake rupture forecast; i.e., earthquakes are assumed to occur as independent events, random in time. In places where the information is sufficient, such as within most of the Pacific-North America plate boundary zone, faults are used to represent the dominant earthquake sources.

Beginning in 1988, a series of Working Groups on California Earthquake Probabilities have released time-dependent forecasts for the San Andreas fault system that account for the date of the last major earthquake [*308*]. The Uniform California Earthquake Rupture Forecast, Version 2 (UCERF2; see Figure 2.6), is a mixture of time-dependent and time-independent elements. UCERF2 was developed to be consistent with the NSHMP 2008 forecast; i.e., they share the same time-independent earthquake rate model [*34*]. The 2008 NSHMP model for Alaska included a time-dependent treatment of the Denali fault [*309*].

Under the Stafford Act of 1978 (Public Law 93-288), the USGS Director is delegated responsibility to issue timely warnings of potential geologic disasters. To support the Director's responsibility in this area, the National Earthquake Prediction Evaluation Council (NEPEC) was initially created by the USGS Director in 1978 and then formally established by the United States Congress in 1980 under Sec. 101 (e)(2) of Public Law 96-472.

NEPEC's name and original charter reflect a time when geoscientists were optimistic about feasibility of high-probability earthquake prediction. NEPEC activities waned in the mid-1990s, and the council was dormant for a period of about ten years. It was revived by the USGS in 2006 and its charter was renewed in 2008 and again 2010. According to the 2006 revision of its charter [*310*], the council's duties are to:

- provide objective and critical review, by a uniform process, of any scientific data or interpretation of scientific data that might warrant issuance of a formal USGS prediction of a specific earthquake, or that might warrant a formal USGS position other than a prediction (e.g., negative evaluation or advisory);
- recommend to the appropriate scientists any actions that might be desirable or required to clarify or verify the basis for a prediction;
- maintain an accurate record of predictions evaluated and evidence pertinent to them; and
- provide the Director a timely and concisely written review of the evidence relevant to a prediction of any potentially damaging earthquake (usually those of magnitude 5 or greater) and a written recommendation as to whether the evidence is sufficiently clear that an official prediction by the Director should be issued or, if not, what other official position, if any, the Director should take.

In recent years, NEPEC has reviewed the NSHMP and other developments in seismic hazard analysis (e.g., the UCERF models), as well as scientific research on short-term earthquake forecasting, such as the testing infrastructure of the Collaboratory for the Study of Earthquake Predictability (CSEP). Thus far, the USGS and NEPEC have not established protocols for operational forecasting on a national level.

However, operational earthquake forecasting is routinely practiced in California under the auspices of the USGS and the California Emergency Management Agency (CalEMA), which convenes the California Earthquake Prediction Evaluation Council (CEPEC). This council of experts was formally established in 1976, and its mission includes the review of scientific research on seismic and volcanic forecasting in California, the assessment of phenomena that may be earthquake or volcanic eruption precursors, and the evaluation of major earthquakes and volcanic activity to better understand their scientific significance and societal impacts.

Although initially oriented toward high-probability predictions, CEPEC procedures have been adapted to low-probability forecasting [*215*]. Following major earthquakes in the state, or in other situations of rapidly evolving seismic activity, CEPEC generally (though not consistently) adheres to a notification protocol established for the southern San Andreas fault system in 1991 [*311*]. The protocol categorizes alerts for major earthquakes (M ≥ 7) at four levels of 3-day probability: D (0.1-1%), C (1-5%), B (5-25%), and A (> 25%). Since the adoption of the protocol nearly 20 years ago, the Level-A probability threshold of 25% has never been reached [*312*], and the Level-B threshold of 5% has been exceeded only twice (after the 23 April 1992 Joshua Tree (M_W 6.1) and 28 September 2004 Parkfield (M_W 5.9) earthquakes. Level-C alerts have been issued on about ten occasions. In the more common Level-D situations, formal alerts have not been posted.

An instructive Level-C alert was issued for southern California in March 2009, just a few weeks before the L'Aquila earthquake. A swarm of more than 50 small earthquakes occurred over a period of several days within a few kilometers of the southern end of the San Andreas fault, near Bombay Beach, California. The largest event in the sequence, a M4.8 earthquake on March 24, was also the largest that had been located within 10 km of the southern end of the San Andreas fault since instrumental recording began in 1932. Because this segment of the San Andreas had not ruptured since circa 1680, the mean UCERF2 30-yr probability of a M ≥ 7 rupture was fairly high, about 24%, corresponding to a probability rate of 3×10^{-5} per day.

CEPEC met by teleconference three and a half hours after the M4.8 event and issued a brief report to CalEMA that included the following statement: "CEPEC believes that stresses associated with this earthquake swarm may increase the probability of a major earthquake on the San Andreas Fault to values between 1 to 5 percent over the next several days. This is based on methodology developed for assessing foreshocks on the San Andreas Fault. This potential will rapidly diminish over this time period." The short-term probability estimated by CEPEC thus corresponded to a nominal gain factor of about 100-500 relative to the time-dependent UCERF2 model [*313*]. The CEPEC advisory was transmitted to the CalEMA field offices in southern California (though not until a full day later) and used by CEPEC members in responding to the considerable public interest. As expected, no larger earthquake followed the M4.8 Bombay Beach event.

CEPEC has generally relied on generic short-term earthquake probabilities or *ad hoc* estimates calculated informally, rather than probabilities based on operationally qualified, regularly updated seismicity forecasting systems [*215*]. The procedures are unwieldy, requiring the scheduling of meetings or telecons, which lead to delayed and inconsistent alert actions. Moreover, how the alerts are used is quite variable, depending on decisions at different levels of government and among the public. For example, the 2001 Bombay Beach M4.1 earthquake led to a formal public advisory from the State but the 2009 M4.8 earthquake, which was even closer to the San Andreas fault, did not.

The dissemination of operational forecasts in California has become more automated. For every earthquake recorded above M5.0, the California Integrated Seismic Network, a component of the USGS Advanced National Seismic System, automatically posts on the web the probability of a M ≥ 5 aftershock and the number of M ≥ 3 aftershocks expected in the next week. These alerts are also sent to selected organizations, such as CalEMA, via email.

An important operational system for California is the Short-Term Earthquake Probability (STEP) model, an aftershock forecasting web service provided by the USGS since 2005 [*227*]. STEP uses aftershock statistics to make hourly revisions of the probabilities of strong ground motions (Modified Mercalli Intensity ≥ VI) on a 10-km, statewide grid. The nominal probability gain factors in regions close to the epicenters of small-magnitude events (M < 5) are often 10-100 relative to the long-term base model and can locally rise by three orders of magnitude following major events (see Figure 2.7). The probability gain that STEP calculates from current seismicity is relative to the time-independent NSHMP model for California. However, as described in §II.E.2, using a long-term forecast to specify background seismicity rates for a short-term model introduces a potential inconsistency, because the long-term rate can be biased upward by short-term triggering. Also, the STEP probability gain does not depend on the proximity of the seismicity to major faults, which is probably a poor approximation and further exemplifies how it might be improved. STEP models for California and other regions are being tested in CSEP against alternative short-term forecasting methods.

In the next version of the Uniform California Rupture Forecast (UCERF3), scheduled for release in 2012, the WGCEP plans to integrate long-term probabilities from fault-based renewal models with short-term probabilities from seismic triggering and clustering models. Development of this integrated model will address the consistency problem and provide new capabilities for operational earthquake forecasting. A recognized challenge is the adaptation of fault-based models like UCERF into a CSEP environment, which will be necessary for rigorous, comparative testing.

G. Summary and Discussion

The Commission's overview of operational earthquake forecasting in seismically active countries highlights a broad range of decision-making practices. Nevertheless, some common points can be identified:

- Long-term time-independent earthquake forecasting models are the basis for seismic hazard mapping in all six countries surveyed in this report. Long-term time-dependent forecasting models have been developed for Japan and specific areas in China and United States.
- Short-term forecasting of aftershocks is practiced by several countries, but operational earthquake forecasting has not been fully implemented (i.e., regularly updated and on a national scale) in any of the countries that have been surveyed. Vigorous research on probabilistic forecasting and its operational applications is being supported by all countries.
- In a few seismically active regions, notably in California, routine use is made of operational earthquake forecasting. The forecasts of major quakes are based on the statistical evaluation of seismicity. Forecasters typically operate in a low-probability environment, rarely projecting short-term probabilities for major events greater than a few percent. The use of formalized models is limited, however, and the public dissemination of forecasting information appears to be sporadic.
- In most countries, scientific assessments are provided to decision makers by groups of earthquake specialists who have access to a continuous flow of data coming from earthquake monitoring facilities. In all countries, the monitoring facilities are managed by earthquake specialists.

Based on the experience accumulated in seismically active regions with high populations, the Commission endorses a systematic approach to operational earthquake forecasting that is founded on the general principles of transparency, consistency, and objectivity. The public should be provided with open sources of information about the short-term probabilities of future earthquakes that are authoritative, scientific, consistent, and timely. These sources need to properly convey the aleatory and epistemic uncertainties in the operational forecasts. Experience also supports the following conclusions:

- Earthquake probabilities should be based on operationally qualified, regularly updated seismicity forecasting systems. All operational procedures should be rigorously reviewed and updated by experts in the creation, delivery, and utility of earthquake forecasts.
- The quality of all operational models should be evaluated for reliability and skill by retrospective testing, and the models should be under continuous prospective testing against established long-term forecasts and a wide variety of alternative time-dependent models.
- Short-term models used in operational forecasting should be consistent with the long-term forecasts used in probabilistic seismic hazard analysis.
- Alert procedures should be standardized to facilitate decisions at different levels of government and among the public. Earthquake probability thresholds should be established to guide alert levels based, when feasible, on objective analysis of costs and benefits.

In establishing these probability thresholds, consideration should be taken of the less tangible aspects of value-of-information, such as gains in psychological preparedness and resilience [*314*]. Authoritative statements of risk can provide a psychological benefit to the public by filling information vacuums that can lead to informal predictions and misinformation. The regular issuance of such statements conditions the public to be more aware of ongoing risk and to learn how to make appropriate decisions based on the available information. It provides an effective defense against rumors of an impending earthquake, which are often spawned in the wake of seismic activity and are becoming more rapidly amplified through social media such as Twitter [*215*]. And it can address the public's increasing expectation that, using high-bandwidth communications, governments will deliver, nearly instantaneously, authoritative information about public risk. Sociological research provides relevant guidance regarding the ways and means by which this information should be developed and delivered [*315*].

IV. Key Findings and Recommendations

In adherence to its charge, the Commission has reviewed the knowledge about earthquake predictability and its current implementation in prediction and forecasting methods, and it has described in general terms the assessments of quality, consistency, and value that are needed to guide the operational utilization of such methods. This section states the Commission's key findings and makes specific recommendations regarding policies and actions that can be taken by DPC to improve earthquake forecasting and its utilization in Italy [*316*]. The Commission recognizes that Italian earthquake science is already moving forward in high gear, and its recommendations are intended to help DPC and its partner organizations increase this momentum and utilize research results for the public welfare. The Commission's findings and recommendations, though addressed to the Italian DPC, have been cast in a general form to enhance their utility in other countries with high seismic risk.

A. Need for Probabilistic Earthquake Forecasting

The public needs information about future earthquakes. However, earthquake generation is a very complex process occurring in an underground environment that is very difficult to observe. Given the current state of scientific knowledge, individual large earthquakes cannot be reliably predicted in future intervals of years or less. In other words, reliable and skillful deterministic earthquake prediction is not yet possible.

Any information about the future occurrence of earthquakes contains large uncertainties and, therefore, can only be evaluated and provided in terms of probabilities. Probabilistic earthquake forecasting can convey information about future earthquake occurrence on various time scales, ranging from long term (years to decades) to short term (months or less). Probabilistic forecasting is a rapidly evolving field of earthquake science.

<u>Recommendation A</u>: DPC should continue to track the scientific evolution of probabilistic earthquake forecasting and deploy the infrastructure and expertise needed to utilize probabilistic information for operational purposes.

B. Earthquake Monitoring

Earthquake monitoring has improved considerably since the digital revolution began several decades ago. Owing to investments in digital seismic and geodetic technology, new data on earthquake processes are accumulating rapidly. However, many of the key processes that control fault rupture are still poorly known, such as the stresses that act on faults to produce earthquakes and the slow motions that sometimes accompany (and may precede) rapid fault failures. It is very likely that further judicious investments in observational technologies and data collection programs will benefit the operational capabilities of earthquake forecasting.

Not all of the high-quality information from seismic networks run by different agencies is currently available to DPC. Strain-rate monitoring and other types of geodetic analysis are also distributed across several agencies that process the data using independent methods.

<u>Recommendation B1</u>: DPC should coordinate across Italian agencies to improve the flow of data, in particular seismic and geodetic monitoring data, into operational earthquake forecasting.

<u>Recommendation B2</u>: Particular emphasis should be placed on real-time processing of seismic data and the timely production of high-quality earthquake catalogs and strain-rate maps.

The determination of earthquake properties in near real time is a capability critical for short-term operational forecasting, including aftershock forecasting and forecasting during seismic swarms. Earthquake catalogs and strain-rate maps are essential products for developing long-term forecasts.

Well-instrumented "natural laboratories," such as Parkfield in the U.S. and Tokai in Japan, have provided high-quality and high-density observations of earthquake generation processes, including precursory processes, which have proven useful in testing scientific hypotheses about earthquake predictability. Natural laboratories in Italy could provide unique observations relevant to the types of earthquakes that occur in its tectonic situation.

<u>Recommendation B3</u>: Opportunities for establishing well-instrumented natural laboratories for studying earthquake generation processes should be supported.

C. Research on Earthquake Predictability

Despite over a century of scientific effort, the understanding of earthquake predictability remains immature. This lack of understanding is reflected in the inability to predict large earthquakes in the deterministic short-term sense. The Commission has identified no method for the short-term prediction of large earthquakes that has been demonstrated to be both reliable and skillful.

In particular, the search for precursors that are diagnostic of an impending earthquake has not yet produced a successful short-term prediction scheme. The Commission has critically reviewed the scientific literature on phenomena proposed as diagnostic precursors, including strain-rate changes, changes in seismic wave velocities, electromagnetic signals, changes in groundwater levels and flow, radon anomalies, and acoustic emissions. In well-monitored regions, retrospective analyses of data collected prior to large earthquakes, including the L'Aquila mainshock of 6 April 2009, show no convincing evidence of diagnostic precursors.

In many cases of purported precursory behavior, the reported observational data are contradictory and unsuitable for a rigorous statistical evaluation. One related problem is a bias towards publishing positive rather than negative results, so that the rate of false negatives (earthquake but no precursory signal) cannot be ascertained. A second is the frequent lack of baseline studies that establish noise levels in the observational time series. Because the signal behavior in the absence of earthquakes is often not characterized, the rate of false positives (signal but no earthquake) is unknown. Without constraints on these error rates, the diagnostic properties of the signal cannot be evaluated.

Methods that use patterns of regional seismicity to predict large earthquakes have been the subject of considerable research. A subclass based on pattern recognition techniques are being tested prospectively, and some may show probability gain relative to long-term earthquake forecasts. However, error rates and the large areal extent of the predictions do not yet provide the diagnostic capability needed for operational predictions.

Despite this negative assessment, the search for diagnostic precursors should not be abandoned, and more fundamental research on the underlying earthquake processes is required. Current knowledge about earthquake precursors is poor, and many intriguing observations have yet to be fully explored. Among the important recent discoveries are transient deformations that propagate along some plate-boundary faults at rates much slower than ordinary seismic ruptures. Research on these phenomena will improve the understanding of earthquakes and may produce results with implications for operational earthquake forecasting.

<u>Recommendation C</u>: 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.

Although the search for diagnostic precursors should continue as a component of basic research, the Commission is not optimistic that diagnostic precursors will provide an operational basis for deterministic earthquake prediction in the near future. The best operational strategy is to accelerate the development of probabilistic earthquake forecasting.

D. Development of Long-Term Forecasting Models

The simplest, most widely-used long-term forecasting models assume earthquakes happen randomly in time, i.e. the system of seismicity has no memory. Such time-independent models are currently the most important forecasting tools for civil protection against earthquake damage, because they provide fundamental information about where earthquakes will occur, how big they can be, and how often they may happen. Such forecasts are the foundation for the seismic hazard mapping that guides earthquake safety provisions of building codes, performance-based seismic design, and other risk-reducing engineering practices, such as retrofitting to correct design flaws in older buildings. As the experience across many countries demonstrates, stringent building codes and seismic retrofitting regulations are the most effective measures communities can adopt to ensure seismic safety.

The time-independent earthquake forecast for Italy, which was published in 2004, identified the L'Aquila region to be amongst those with the highest potential for expected ground shaking. In recent earthquakes, some areas experienced ground shaking at a level that was higher than that expected, especially close to the fault and on specific sites whose geological and soil characteristics amplified the ground motion, perhaps because the current seismic hazard map of Italy does not take into account site amplification effects and near-fault wave propagation effects.

In addition, the current hazard map is based on earthquake sources distributed in seismogenic volumes, rather than on sources assigned to mapped faults. Moving towards a fault-based rupture forecast of the sort that underlies the seismic hazard models for Japan and the United States could improve the time-independent forecast. However, the tectonic complexity of Italy makes a complete enumeration of individual faults difficult. Research is underway on 'fault-system' representations that aggregate individual faults into source volumes, a plausible intermediate step.

One class of earthquake forecasts accounts for some long-term memory of past events, which makes the earthquake probability time-dependent. For example, after one earthquake on a fault segment, another earthquake on that segment may be less likely until enough time has elapsed to build sufficient stress for another rupture. Owing to Italy's tectonic complexity, this type of renewal modeling is difficult to apply and remains in the research phase. A second class of time-dependent model is based on the long-term space-time clustering of earthquakes observed in historical catalogues.

A fundamental uncertainty in long-term earthquake forecasting is the short sampling interval available from instrumental seismicity catalogs and historical records. Even though Italy has a long recorded history of earthquakes, the recurrence intervals are still highly uncertain. Field work to identify active faults, their slip rates, and recurrence times is needed.

Recommendation D: 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.

E. Development of Short-Term Forecasting Models

On short time scales, say less than a few months, earthquake sequences show a high degree of clustering in space and time; one earthquake can trigger others. The probability of triggering increases with initial shock's magnitude and decays with elapsed time according to simple (nearly universal) scaling laws. This description of clustering explains many of the statistical features observed in seismicity catalogs, such as aftershocks, and it can be used to construct forecasts that indicate how earthquake probabilities change over the short term.

Properly applied, short-term aftershock forecasts have operational utility, because they allow civil protection authorities and the population at large to anticipate the aftershocks that inevitably follow large earthquakes. Aftershock forecasting can likely be improved by incorporating more information about main shock deformation patterns and geological settings, such as more detailed descriptions of local fault systems.

Recommendation E1: DPC should emphasize the deployment of an operational capability for forecasting aftershocks.

The models of earthquake triggering and clustering used in aftershock forecasting can be more generally applied to short-term earthquake forecasting. Additional information from the retrospective analysis of foreshocks, earthquake swarms, and other aspects of seismicity behavior can be used to improve the estimates of short-term earthquake probabilities.

Recommendation E2: DPC should support development of earthquake forecasting methods based on seismicity changes to quantify short-term probability variations.

F. Validation of Earthquake Forecasting Methods

Forecasting models considered for operational purposes should demonstrate reliability and skill with respect to established reference forecasts, such as long-term, time-independent models. Many proposed schemes for earthquake forecasting can be rejected as candidates for operational use because they show no significant probability gain relative to the reference forecast.

Validation of reliability and skill requires objective evaluation of how well the forecasting model corresponds to data collected after the forecast has been made (prospective testing), as well as checks against data previously recorded (retrospective testing). Experience has shown that such evaluations are most diagnostic when the testing procedures conform to rigorous standards and the prospective testing is blind. An international collaboration to establish the standards and infrastructure for the comparative testing of earthquake forecasting models is underway, and Italian scientists are participating.

Recommendation F1: 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 F2: The international infrastructure being developed to test earthquake forecasting methods prospectively should be used as a tool for validating the forecasting models for Italy.

At present, most validation efforts are based on evaluating the correspondence of the earthquake forecasts directly with seismicity data. However, from an operational perspective, the demonstration of forecasting value may best be cast in terms of ground motions. In other words, the evaluation of earthquake forecasts is best done in conjunction with the testing of seismic hazard forecasts against observed ground motions.

G. Utilization of Earthquake Forecasts

The utilization of earthquake forecasts for risk mitigation and earthquake preparedness requires two basic components: scientific advisories expressed in terms of probabilities of threatening events, and protocols that establish how probabilities can be translated into mitigation actions and preparedness.

An effective structure for assisting decision-makers is to have an expert panel that convenes on a regular basis to engage in planning and preparation and to interpret the output of forecasting models and any other relevant information. The responsibilities of such a panel include the timely synthesis of information necessary for situation assessments during seismic crises and also in “peacetime.” It also provides a mechanism for the evaluation of ad hoc earthquake predictions.

Recommendation G1: An independent panel of experts should be created to evaluate forecasting methods and interpret their output. This panel should report directly to the head of DPC.

One of the outstanding challenges in the operational use of probabilistic forecasts is in translating them into decision-making in a low-probability environment. Most previous work on the public utility of earthquake forecasts has anticipated that they would deliver high probabilities of large earthquakes, i.e., deterministic predictions would be possible. This expectation has not been realized. Current forecasting policies need to be adapted to a low-probability environment such as in Italy. Although the value of long-term forecasts for ensuring seismic safety is fairly clear, the interpretation of short-term forecasts is problematic because earthquake probabilities may vary over orders of magnitude, but they typically remain low in an absolute sense.

To date, there is no formal approach for converting earthquake probabilities into mitigation actions. One strategy that can assist decision-making is the setting of earthquake probability thresholds for mitigation actions. These thresholds should be supported by objective analysis, for instance by cost/benefit analysis, in order to justify actions taken in a decision-making process.

Recommendation G2: Quantitative and transparent protocols should be established for decision-making that include mitigation actions with different impacts that would be implemented if certain thresholds in earthquake probability are exceeded.

H. Public Communication of Earthquake Information

Providing probabilistic forecasts to the public in a coordinated way is an important operational capability. Good information keeps the population aware of the current state of hazard, decreases the impact of ungrounded information and contributes to reducing risk and improving preparedness. Using web-based technology, probabilistic earthquake forecasts can be made available to the public on a continuous basis, not only during crises, but also at times when the probability of having a major event is low. This would educate people about seismicity variations, enhance the effectiveness of public communication in case of an extreme event, reduce unjustified criticism, and have a positive influence on public willingness to participate in civil protection system. Experience from various earthquake prone areas has shown that direct information through official websites accessible to the public, as well as special TV programs, are effective and well accepted ways to communicate. The principles of effective public communication have been established by social science research and should be applied in communicating seismic hazard information.

<u>Recommendation H</u>: DPC, in accordance with social-science principles on effective public communication and in concert with partner organizations, should continuously inform the public about the seismic situation in Italy based on probabilistic forecasting.

V. Roadmap for Implementation

The Commission has identified several interrelated activities that could improve the scientific basis for, and the reliability of, operational earthquake forecasting. This section summarizes some of the actions needed to implement the main recommendations of this report in Italy. However, the Commission does not provide specific guidance about how DPC and its partners should organize their collaboration to accomplish such recommendations.

The development of any new operational protocol requires progress in three phases. First is a research phase, during which exploratory science is promoted, information is collated, and forecasting models are constructed. This should be followed by a testbed phase, where forecast models are compared in terms of their quality and consistency, followed by an implementation phase that includes verification of forecast value that can be used in turn to define thresholds for civil protection actions. Clearly, any practical use of forecasting methods must be done in an appropriate policy framework, one that can weigh costs against benefits and potential gains against possible risks.

A. Underway

A number of actions are underway or have been initiated by DPC, INGV, and the other relevant Italian organizations:

- Encourage basic research on earthquakes and their predictability.
- Continue a directed research program on the development of long-term seismic hazard maps in order to provide a basic reference model against which others may be judged for predictive power.
- Sustain the development and implementation of capabilities to integrate seismic and geodetic data streams collected by different organizations to provide a real-time processing infrastructure, so that basic data and information derived from it can be provided consistently and quickly.
- Gain experience from the exercise of forecasting aftershocks as the best current example of a relatively skilled, low-probability forecast, and anticipate the potential use of other forms of forecasting based on observation of earthquake clustering.
- Encourage the relevant agencies to participate in global testing programs to quantify reliability and skill in earthquake forecasting with current knowledge.
- Continuously inform the public by providing accessible, appropriate and timely information on the current status of earthquake hazard based on probabilistic forecasting.

B. Outstanding Actions

The Commission has established that the science of forecasting has progressed to the stage where probability gains above background can be made, albeit almost always in a low-probability environment. A variety of forecasting models have been proposed that quantify the probability, and a global effort is currently under way to establish the reliability and skill of such models. The Commission recommends anticipating the emergence of such scientifically-tested forecasting models by the following actions:

- Convene a scientific advisory structure reporting to the head of DPC to provide expert advice and updates at regular intervals and rapidly at times of crisis.
- Determine how scientific results on forecasting capability may be provided to decision-makers in a useful way. This could be done by a working group, with representation of the relevant agencies, and social scientists as well as seismologists, reporting to the scientific advisory structure.
- Deploy an appropriate infrastructure to utilize low-probability forecasting for operational purposes.

Implementation must be orchestrated in a way that reduces the vulnerability of society and improves community resilience. While the responsible scientific research on earthquake predictability should be encouraged and operational forecasting capabilities should be developed, these activities cannot substitute for civil protection actions well in advance of earthquakes, for example in the design and planning of new buildings, or retrofitting of older ones identified as being at risk. Preparing properly for earthquakes means being always ready for the unexpected, which is a long-term proposition.

Appendices

Appendix A. Seismotectonic Environment of the L'Aquila Earthquake

The seismicity in Abruzzo increased above its long-term average in January 2009 [*317*]. The earthquake sequence included an M_L4.1 event on March 30, located at 42.32ºN, 13.3ºE, 10 km depth. The main L'Aquila event occurred at 01:32:40.4 UT on April 6 with a hypocenter located at 42.342ºN, 13.380ºE, 8.3 km depth [*318*], close to the March 30 foreshock. The mainshock was caused by normal faulting with a southwesterly dip of about 45° and an extension axis roughly perpendicular to the Central Apennines belt. The fault rupture, which propagated upward and to the southeast, produced most of its slip and aftershocks below 2 km depth [*319*]. Some minor surface faulting was observed along a 2.5-km trace with a maximum vertical displacement of 10 cm [*320*]. In the following months, thousands of aftershocks were recorded over an area of more than 5,000 square kilometers.

The seismicity of the region has been documented for over a thousand years—one of the longest historical records in the world [*321*]. The larger historical events in the Umbria-Marche-Abruzzi region define a broad, seismically active zone of normal faulting, about 30-km wide, which is accommodating northeast-southwest extension of the Central Apennines chain [*322*, *323*, *324*]. In the vicinity of L'Aquila, the largest historical events preceding 2009 were the 1703 l'Aquila and 1915 Avezzano earthquakes, which have inferred recurrence times of 500-2000 years [*54*].

The association between earthquakes and faults in this tectonically complex region of Italy is the subject of much current research and debate [*54*, *224*, *322*]. The mainshock of April 6 was located on the previously identified, but poorly mapped, Paganica fault [*325*]. Foreshock activity was particularly strong in the 10 days before the mainshock [*326*]. Aftershock activity was triggered along *en echelon* normal faults of the Middle Aterno fault system, as well as along the similar Laga fault system to the north. Relocations of the foreshocks suggest that some of the foreshock activity involved normal faulting antithetic to the Paganica fault.

A major effort to study deformation of Central Italy is underway using both temporary and permanent Global Positioning System (GPS) sensors. Immediately after the March 30 event, the GPS network was reinforced with new stations that recorded the mainshock. The primary finding of the long-term GPS observations is that the Apennines are stretching in northeast-southwest direction by about 3 mm/year [*323, 327*]. Using the width of 30 km gives an average strain of about 10^{-8} per year [*327*], roughly an order of magnitude less that the strain rates observed across the San Andreas fault system in California or the subduction zone in the Northern Chile. Geological estimates of strain rates vary substantially depending on the time period and regions covered by the estimates, but they are in general agreement with GPS measurements.

In summary, the seismotectonics of the Central Apennines is characterized by diffuse and moderate seismicity with a number of normal fault segments identified by both paleoseismic and historical seismicity [*54*]. Some of the segments are known to be active, but not all have had historical earthquakes associated with them. The Paganica fault, the source of the L'Aquila earthquake of April 6, is a typical instance of a fault with poorly known historical activity.

Appendix B. Index of Acronyms and Abbreviations

AMR	accelerated moment release
CalEMA	California Emergency Management Agency
CEA	China Earthquake Administration
CEPEC	California Earthquake Prediction Evaluation Council
CSEP	Collaboratory for the Study of Earthquake Predictability
CFF	Coulomb failure function
CN	California-Nevada (prediction algorithm)
CGR	Commissione Nazionale per la Prevenzione e Previsione dei Grandi Rischi
DPC	Dipartimento della Protezione Civile (Italy)
EAECEP	European Advisory Evaluation Committee for Earthquake Prediction
EEPAS	Every Earthquake is a Precursor According to Scale (forecasting model)
EEW	earthquake early warning
ELF/VLF	extremely/very low frequency (EM waves of 10 Hz-30 kHz)
EM	electromagnetic
EFP	empirical foreshock probability (forecasting model)
EPPO	Earthquake Planning and Protection Organization" (Greece)
ETAS	Epidemic Type Aftershock Sequence
ETH Zürich	Eidgenössische Technische Hochschule Zürich (Switzerland)
ETS	episodic tremor and slip
G	probability gain factor
GSHAP	Global Seismic Hazard Assessment Program
GPS	Global Positioning System
GSCP	General Secretary for Civil Protection (Greece)
HERP	Headquarters for Earthquake Research Promotion (Japan)
IASPEI	International Association for Seismology and Physics of the Earth's Interior
ICEF	International Commission on Earthquake Forecasting for Civil Protection
IDNDR	International Decade of Natural Disaster Reduction (1990-1999)
INGV	Istituto Nazionale di Geofisica e Vulcanologia (Italy)
ITN	Ministry of Infrastructure, Transportation, and Networks (Greece)
JMA	Japan Meteorological Agency
LF	low frequency (EM waves of 30-300 kHz)
M8	Magnitude-8 (prediction algorithm)
M_L	local magnitude
M_W	surface-wave magnitude
M_W	moment magnitude
MSc	Mendocino scenario (prediction algorithm)
NEHRP	National Earthquake Hazard Reduction Program (United States)
NEPEC	National Earthquake Prediction Evaluation Council (United States)
NIED	National Research Institute of Earth Science and Disaster Prevention (Japan)
NOAGI	National Observatory of Athens, Institute of Geodynamics (Greece)
NSHMP	National Seismic Hazard Mapping Program (United States)
P	probability of a target earthquake in a specified space-time domain
$P_{poisson}$	probability of a target earthquake in a specified space-time domain computed from a time-independent model assuming events are random in time
PI	pattern informatics (prediction algorithm)
PGA	peak ground acceleration
REC	Russian Expert Council for Earthquake Prediction and Earthquake Hazard and Risk Assessment
RELM	Regional Earthquake Likelihood Models
RTP	reverse tracing of precursors (prediction algorithm)
SCEC	Southern California Earthquake Center (United States)
SES	seismic electric signals
SSB	State Seismological Bureau (China)
STEP	Short Term Earthquake Probability (forecasting model)

T	time interval of an earthquake forecast or prediction
UCERF	Uniform California Earthquake Rupture Forecast
ULF	ultra-low frequency (EM waves of 0.001-10 Hz)
USGS	United States Geological Survey
VAN	P. Varotsos, K. Alexopoulos & K. Nomikos (research team)
V_P	compressional wave velocity
V_S	shear wave velocity
WGCEP	Working Group on California Earthquake Probabilities
ZHP	zone of high probability

References

Abrahamson, N. A., and K. M. Shedlock (1997). Overview, Seismol. Res. Lett., 68, 9-23.
Aceves, R. L., S. K. Park, and D. J. Strauss (1996). Statistical evaluation of the VAN method using the historic earthquake catalog in Greece, Geophys. Res. Lett., 23, 1425-1428, doi:10.1029/96GL01478.
Japan Meteorological Agency, Earthquake Early Warnings, http://www.jma.go.jp/jma/en/Activities/eew.html.
Japan Meteorological Agency, Prediction of the Tokai Earthquake, http://www.jma.go.jp/en/quake_tokai/.
Aggarwal, Y. P., L. R. Sykes, Armbrust.J, and M. L. Sbar (1973). Premonitory changes in seismic velocities and prediction of earthquakes, Nature, 241, 101-104.
Agnew, D. C., and L. M. Jones (1991). Prediction probabilities from foreshocks, J. Geophys. Res., 96, 11959-11971.
Akhoondzadeh, M., M. Parrot, and M. R. Saradjian (2010). Electron and ion density variations before strong earthquakes (M > 6.0) using DEMETER and GPS data, Natural Hazards and Earth System Sciences, 10, 7-18.
Aki, K. (1981). A probabilistic synthesis of precursory phenomena, in Earthquake Prediction, D. W. Simpson and P. G. Richards, editors, 556-574, American Geophysical Union, Washington DC.
Aki, K. (1989). Ideal probabilistic earthquake prediction, Tectonophysics, 169, 197-198.
Akinci, A., F. Galadini, D. Pantosti, M. Petersen, L. Malagnini, and D. Perkins (2009). Effect of time dependence on probabilistic seismic-hazard maps and deaggregation for the Central Apennines, Italy, Bull. Seismol. Soc. Amer., 99, 585-610.
Alessio, G., L. Alfonsi, C. A. Brunori, F. R. Cinti, R. Civico, L. Cucci, G. D'Addezio, R. De Ritis, E. Falcucci, U. Fracassi, A. Gasparini, S. Gori, A. Lisi, S. Mariano, M. T. Mariucci, P. Montone, R. Nappi, D. Pantosti, A. Patera, S. Pierdominici, M. Pignone, S. Pinzi, S. Pucci, P. Vannoli, A. Venuti, F. Villani, and E. W. Grp (2010). Evidence for surface rupture associated with the Mw 6.3 L'Aquila earthquake sequence of April 2009 (central Italy), Terr. Nova, 22, 43-51.
Allen, C. R., editor (1980). Earthquake Prediction and Public Policy, National Academy of Sciences, Washington, D.C., 152 pp.
Allen, C. R., and D. V. Helmberger (1973). Search for temporal changes in seismic velocities using large explosions in southern California, in Proceedings of the Conference on Tectonic Problems of the San Andreas Fault System, R.L. Kovach and A. Nur, eds., Stanford University Publications in Geological Science 13, Stanford, pp. 436-452.
Amoruso, A., and L. Crescentini (2010). Limits on earthquake nucleation and other pre-seismic phenomena from continuous strain in the near field of the 2009 L'Aquila earthquake, Geophys. Res. Lett., 37, L10307, doi:10.1029/2010GL043308.
Anderson, J. G. (1981). Consequence of an earthquake prediction on statistical estimates of seismic risk, Bull. Seismol. Soc. Amer., 71, 1637-1648.
Anzhong, J., and Anonymous (1985). Some results of observations and studies on earth resistivity in China, Eos, Transactions, American Geophysical Union, 66, 1066-1067.
Anzidei, M., E. Boschi, V. Cannelli, R. Devoti, A. Esposito, A. Galvani, D. Melini, G. Pietrantonio, F. Riguzzi, V. Sepe, and E. Serpelloni (2009). Coseismic deformation of the destructive April 6, 2009 L'Aquila earthquake (central Italy) from GPS data, Geophys. Res. Lett., 36, L17307, doi:10.1029/2009GL039145.
Armbruster, J., and M. L. Sbar (1973). Premonitory changes in seismic velocities and prediction of earthquakes, Nature, 241, 101-104
Asada, T. (1982). Earthquake prediction techniques: their application in Japan, University of Tokyo Press, Tokyo.
Aster, R. C., P. M. Shearer, and J. Berger (1990). Quantitative measurements of shear wave polarizations at the Anza Seismic Network, Southern California: Implications for shear wave splitting and earthquake prediction, J. Geophys. Res., 95, 12449-12473.
Aster, R. C., P. M. Shearer & J. Berger (1991). Reply, J. Geophys. Res. 96, 6415-6419.
Atzori, S., I. Hunstad, M. Chini, S. Salvi, C. Tolomei, C. Bignami, S. Stramondo, E. Trasatti, A. Antonioli, and E. Boschi (2009). Finite fault inversion of DInSAR coseismic displacement of the 2009 L'Aquila earthquake (central Italy), Geophys. Res. Lett., 36, L15305, doi:10.1029/2009GL039293.
Bagnaia, R., A. D'Epifanio, and S. Sylos Labini (1992). Aquila and subsequent events: an example of Quaternary evolution in Central Apennines, Quaternaria Nova, 2, 187-209.

Baird, G. A., and P. S. Kennan (1985). Electrical response of tourmaline rocks to a pressure impulse, Tectonophysics, 111, 147-154.

Bak, P., and C. Tang (1989). Earthquakes as a self-organized critical phenomenon, J. Geophys. Res., 94, 15635-15637.

Bakun, W., K. Breckenridge, J. Bredehoeft, R. Burford, W. Ellsworth, M. Johnston, L. Jones, A. Lindh, C. Mortensen, R. Mueller, C. Poley, E. Roeloffs, S. Schulz, P. Segall, and W. Thatcher (1987). Parkfield, California, earthquake prediction scenarios and response plans, U. S. Geological Survey Open-File Report 87-192.

Bakun, W. H., B. Aagaard, B. Dost, W. L. Ellsworth, J. L. Hardebeck, R. A. Harris, C. Ji, M. J. S. Johnston, J. Langbein, J. J. Lienkaemper, A. J. Michael, J. R. Murray, R. M. Nadeau, P. A. Reasenberg, M. S. Reichle, E. A. Roeloffs, A. Shakal, R. W. Simpson, and F. Waldhauser (2005). Implications for prediction and hazard assessment from the 2004 Parkfield earthquake, Nature, 437, 969-974.

Bakun, W. H., and A. G. Lindh (1985). The Parkfield, California earthquake prediction experiment, Science, 229, 619-624.

Barsukov, O. M., and O. N. Sorokin (1973). Variations in apparent resistivity of rocks in the seismically active Garm region, Izvestiya, Academy of Sciences, USSR, Physics of the Solid Earth, 10, 685-687.

Basili, R., G. Valensise, P. Vannoli, P. Burrato, U. Fracassi, S. Mariano, M. M. Tiberti, and E. Boschi (2008). The Database of Individual Seismogenic Sources (DISS), version 3: Summarizing 20 years of research on Italy's earthquake geology, Tectonophysics, 453, 20-43.

Ben-Zion, Y., K. Dahmen, V. Lyakhovsky, D. Ertas, and A. Agnon (1999). Self-driven mode switching of earthquake activity on a fault system, Earth Planet. Sci. Lett., 172, 11-21.

Berkhemer, H., J. Zschau, and O. Ergunay (1988). The German-Turkish Project on earthquake prediction research, concept and first results, in Proceedings of the ECE/UN Seminar on Prediction of Earthquakes, C. S. Olivera, ed., Lisbon, 579-601.

Biasi, G. P., and R. J. Weldon (2009). San Andreas Fault Rupture Scenarios from Multiple Paleoseismic Records: Stringing Pearls, Bull. Seismol. Soc. Amer., 99, 471-498.

Bird, P., Y. Y. Kagan, and D. D. Jackson (2002). Plate tectonics and earthquake potential of spreading ridges and oceanic transform faults, in Plate Boundary Zones, Geodyn. Ser., 30, edited by S. Stein and J. T. Freymueller, pp. 203–218, AGU, Washington, D. C.

Boettcher, M. S., A. McGarr, and M. Johnston (2009). Extension of Gutenberg-Richter distribution to M-W-1.3, no lower limit in sight, Geophys. Res. Lett., 36, L10307, doi:10.1029/2009GL038080.

Bonanno, G. A., S. Galea, A. Bucciarelli, and D. Vlahov (2007). What predicts psychological resilience after disaster? The role of demographics, resources, and life stress, Journal of Consulting and Clinical Psychology, 75, 671-682.

Borcherdt, R. D., M. J. S. Johnston, G. Glassmoyer, and C. Dietel (2006). Recordings of the 2004 Parkfield earthquake on the General Earthquake Observation System array: Implications for earthquake precursors, fault rupture, and coseismic strain changes, Bull. Seismol. Soc. Amer., 96, S73-S89, doi: 10.1785/0120050827.

Borok, V. I. K., V. G. (1986). Periods of high probability of occurrence of the world’s strongest earthquakes, in Mathematical Methods in Seismology and Geodynamics, edited by A. L. L. V.I. Keilis-Borok, pp. 48-57, Allerton Press, New York.

Boschi, E., E. Guidoboni, G. Ferrrari, D. Mariotti, G. Valensise & P. Gasperini (2000). Catalogue of strong Italian earthquakes from 461 B.C. to 1997, Ann. Geofis., 43, 609-868.

Bowman, D. D., and G. C. P. King (2001). Accelerating seismicity and stress accumulation before large earthquakes, Geophys. Res. Lett., 28, 4039-4042.

Bowman, D. D., G. Ouillon, C. G. Sammis, A. Sornette, and D. Sornette (1998). An observational test of the critical earthquake concept, J. Geophys. Res., 103, 24359-24372.

Bozkurt, S. B., R. S. Stein, and S. Toda (2007). Forecasting probabilistic seismic shaking for greater Tokyo from 400 years of intensity observations, Earthquake Spectra, 23, 525-546.

Brudzinski, M. R., H. R. Hinojosa-Prieto, K. M. Schlanser, E. Cabral-Cano, A. Arciniega-Ceballos, O. Diaz-Molina, and C. DeMets (2010). Nonvolcanic tremor along the Oaxaca segment of the Middle America subduction zone, J. Geophys. Res., 115, B00A23, doi:10.1029/2008JB006061.

Building Seismic Safety Council (2003). NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, Federal Emergency Management Agency Publication 450, 338 pp.

Campbell, W. H. (2009). Natural magnetic disturbance fields, not precursors, preceding the Loma Prieta earthquake, J. Geophys. Res., 114, A05307, doi:10.1029/2008JA013932.

Chen, K. H., R. Bürgmann, and R. M. Nadeau (2010). Triggering effect of M 4-5 earthquakes on the earthquake cycle of repeating events at Parkfield, California, Bull. Seismol. Soc. Amer., 100, 522-531.

Chen, Q. F., and K. L. Wang (2010). The 2008 Wenchuan Earthquake and Earthquake Prediction in China, Bull. Seismol. Soc. Amer., 100, 2840-2857, doi:0.1785/0120090314.

Chen, Y. T., C. Z. Chen, and B. Q. Wang (1992). Seismological studies of earthquake prediction in China: a review, in Earthquake Prediction, M. Dragoni and E. Boschi, editors, pp. 71-109, Il Cigno Galileo Galilei, Roma, Italy.

Chen, Y. T., C. Z. Zhu, and Z. L. Wu (2002). Seismology in China in the 20th century, in International Symposium Science and Technology in Modern China: Retrospect and Prospect, 1, 331-342.

Chen, Z. L. (1986). Earthquake prediction research in China: status and prospects, *J. Phys. Earth,* 34, S1-S11.

Chen, Z. L. (2001). Review and prospects of the progress of seismological science and technology in China, Earthquake Research in China, 17, 231-245 (in Chinese with English abstract).

Chiarabba, C., A. Amato, M. Anselmi, P. Baccheschi, I. Bianchi, M. Cattaneo, G. Cecere, L. Chiaraluce, M. G. Ciaccio, P. De Gori, G. De Luca, M. Di Bona, R. Di Stefano, L. Faenza, A. Govoni, L. Improta, F. P. Lucente, A. Marchetti, L. Margheriti, F. Mele, A. Michelini, G. Monachesi, M. Moretti, M. Pastori, N. P. Agostinetti, D. Piccinini, P. Roselli, D. Seccia, and L. Valoroso (2009). The 2009 L'Aquila (central Italy) M(W)6.3 earthquake: Main shock and aftershocks, Geophys. Res. Lett., 36, L18308, doi:10.1029/2009GL039627.

Chiarabba, C., L. Jovane, and R. DiStefano (2005). A new view of Italian seismicity using 20 years of instrumental recordings, Tectonophysics, 395, 251-268.

Chu, J. J., X. T. Gui, J. G. Dai, C. Marone, M. W. Spiegelman, L. Seeber, and J. G. Armbruster (1996). Geoelectric signals in China and the earthquake generation process, J. Geopkys. Res.,101, 13,869-13,882.

Chyi, L. L., T. J. Quick, T. F. Yang, and C. H. Chen (2005). Soil gas radon spectra and earthquakes, Terrestrial Atmospheric and Oceanic Sciences, 16, 763-774.

Cicerone, R. D., J. E. Ebel, and J. Britton (2009). A systematic compilation of earthquake precursors, Tectonophysics, 476, 371-396.

Cifuentes, I. L., and P. G. Silver (1989). Low frequency source characteristics of the great 1960 Chilean earthquake, J. Geophys. Res., 94, 643-663.

Cocco, M., and J. R. Rice (2002). Pore pressure and poroelasticity effects in Coulomb stress analysis of earthquake interactions, J. Geophys. Res., 107, ESE 2-1 to 2-17, doi:10.1029/2000JB000138.

Console, R., M. Murru, and G. Falcone (2010). Probability gains of an epidemic-type aftershock sequence model in retrospective forecasting of M > 5 earthquakes in Italy, J. Seismology, 14, 9-26.

Cornell, C. A. (1968). Engineering seismic risk analysis, Bull. Seismol. Soc. Amer., 58, 1583-1606.

Cornell, C. A., and S. R. Winterstein (1988). Temporal and magnitude dependence in earthquake recurrence models, Bull. Seismol. Soc. Amer., 78, 1522-1537.

Crampin, S. (1999). A successful stress-forecast: an addendum to 'Stress-forecasting: a viable alternative to earthquake prediction in a dynamic Earth', Trans. R. Soc. Edinb., 89, 231-231.

Crampin, S., T. Volti & R. Stefansson (1999). A successful stress-forecast earthquake, Geophys. J. Int., 138, F1-F5.

Cutter, S. L., L. Barnes, M. Berry, C. Burton, E. Evans, E. Tate, and J. Webb (2008). A place-based model for understanding community resilience to natural disasters, Global Environ. Chang., 18, 598-606.

D'Agostino, N., A. Avallone, D. Cheloni, E. D'Anastasio, S. Mantenuto, and G. Selvaggi (2008). Active tectonics of the Adriatic region from GPS and earthquake slip vectors, J. Geophys. Res., 113, doi:101229/2008JB005860.

Daeron, M., Y. Klinger, P. Tapponnier, A. Elias, E. Jacques, and A. Sursock (2007). 12,000-year-long record of 10 to 13 paleoearthquakes on the Yammouneh fault, Levant fault system, Lebanon, Bull. Seismol. Soc. Amer., 97, 749-771.

Delahaye, E. J., J. Townend, M. E. Reyners, and G. Rogers (2009). Microseismicity but no tremor accompanying slow slip in the Hikurangi subduction zone, New Zealand, Earth Planet. Sci. Lett., 277, 21-28, doi:10.1016/j.epsl.2008.09.038.

Deng, J. S., and L. R. Sykes (1997). Evolution of the stress field in southern California and triggering of moderate-size earthquakes: A 200-year perspective, J. Geophys. Res., 102, 9859-9886.

Dieterich, J. H. (1978). Preseismic fault slip and earthquake prediction, J. Geophys. Res., 83, 3940-3948.

Dieterich, J. H. (1994). A constitutive law for rate of earthquake production and its application to earthquake clustering, J. Geophys. Res., 99, 2601-2618.

Dieterich, J. H., and K. B. Richards-Dinger (2010). Earthquake recurrence in simulated fault systems, Pure Appl. Geophys., 167, 30-48, doi:10.1007/s00024-010-0094-0.

Doser, D. I., K. B. Olsen, F. F. Pollitz, R. S. Stein, and S. Toda (2009). The 1911 M ~6:6 Calaveras earthquake: Source parameters and the role of static, viscoelastic, and dynamic coulomb stress changes imparted by the 1906 San Francisco Earthquake, Bull. Seismol. Soc. Amer., 99, 1746-1759, doi:10.1785/0120080305.

Einarsson, P., P. Theodórsson, Á. R. Hjartardóttir, and G. I. Guðjónsson (2008). Radon changes associated with the earthquake sequence in June 2000 in the South Iceland Seismic Zone, Pure Appl. Geophys., 165, 63-74, doi:10.1007/978-3-7643-8738-9_5.

Ellsworth, W. L., M. V. Matthews, R. M. Nadeau, S. P. Nishenko, P. A. Reasenberg, and R. W. Simpson (1999). A physically-based earthquake recurrence model for estimation of long-term earthquake probabilities, U. S. Geological Survey Open-File Report 99-522.

EMERGEO Working Group (2010). Evidence for surface rupture associated with the Mw 6.3 L'Aquila earthquake sequence of April 2009 (central Italy), Terra Nova, 22, 43-51, doi:10.1111/j.1365-3121.2009.00915.x.

Emmermann, R., and J. Lauterjung (1997). The German Continental Deep Drilling Program KTB: Overview and major results, J. Geophys. Res., 102, 18179-18201.

Eneva, M., D. Adams, N. Wechsler, Y. Ben-Zion and O. Dor (2008). Thermal Properties of Faults in Southern California from Remote Sensing Data, Report sponsored by NASA under contract to SAIC No. NNH05CC13C, March, 2008, 70pp.

Enomoto, Y., H. Hashimoto, N. Shirai, Y. Murakami, T. Mogi, M. Takada, and M. Kasahara (2006). Anomalous geoelectric signals possibly related to the 2000 Mt. Usu eruption and 2003 Tokachi-Oki earthquakes, Physics and Chemistry of the Earth, 31, 319-324.

Evernden, J. F., editor (1976). Abnormal animal behavior prior to earthquakes, National Earthquake Hazards Reduction Program, 429-429 pp., U. S. Geol. Surv., Menlo Park, Calif., USA.

Fedotov, S. A. (1965). Zakonomernosti raspredeleniya sil'nykh zemletryaseniy kamchatki, kuril'skikh ostrovov i severo-vostochnoy yaponii. Regularities of the distribution of strong earthquakes in Kamchatka, the Kurile islands, and northeastern Japan, Akad. Nauk SSSR Inst. Fiziki Zemli Trudy, 36(203), 66-93.

Fedotov, S. A. (1968). On seismic cycle, opportunities of quantitative seismic regionalization and long-term seismic forecast, Seismic regionalization in USSR, Moscow, Nauka, 121-150.

Fedotov, S. A., A. V. Solomatin, and S. D. Chernyshev (2008). Aftershocks and the Rupture Zone of the M-S=8.2, November 15, 2006 Middle Kuril Is. Earthquake and a Long-Term Earthquake Forecast for the Kuril-Kamchatka Arc for the Period from April 2008 to March 2013, J. Volcanol. Seismol., 2, 375-394.

Fedotov, S. A. et al. (1999). Prediction of Ktronotsky earthquake December 5, 1997, M = 7.8-7.9, Kamchatka, and of its strong aftershocks, Volcanology and Seismology, 597-613.

Felzer, K. R., R. E. Abercrombie, and G. Ekstrom (2004). A common origin for aftershocks, foreshocks, and multiplets, Bull. Seismol. Soc. Amer., 94, 88-98.

Felzer, K. R., and E. E. Brodsky (2006). Decay of aftershock density with distance indicates triggering by dynamic stress, Nature, 441, 735-738.

Fidani, C. (2010). The earthquake lights (EQL) of the 6 April 2009 Aquila earthquake, in Central Italy, Natural Hazards and Earth System Sciences, 10, 967-978, doi:10.5194/nhess-10-967-2010.

Field, E. H. (2007). Overview of the working group for the development of regional earthquake likelihood models (RELM), Seismol. Res. Lett., 78, 7-16.

Field, E. H., T. E. Dawson, K. R. Felzer, A. D. Frankel, V. Gupta, T. H. Jordan, T. Parsons, M. D. Petersen, R. S. Stein, R. J. Weldon, II, and C. J. Wills (2008). The uniform California earthquake rupture forecast, version 2 (UCERF 2), Open-File Report - U. S. Geological Survey, 96-96.

Field, E. H., T. E. Dawson, K. R. Felzer, A. D. Frankel, V. Gupta, T. H. Jordan, T. Parsons, M. D. Petersen, R. S. Stein, R. J. Weldon, and C. J. Wills (2009). Uniform California Earthquake Rupture Forecast, Version 2 (UCERF 2), Bull. Seismol. Soc. Amer., 99, 2053-2107.

Field, E. H., T. H. Jordan, and C. A. Cornell (2003). OpenSHA; a developing, community-modeling environment for seismic-hazard analysis, Seismol. Res. Lett., 74, 198-198.

Fleischer, R. L. (1981). Dislocation model for radon response to distant earthquakes, Geophys. Res. Lett., 8, 477-480.

Frankel, A. D., C. S. Mueller, T. P. Barnhard, D. M. Perkins, E. V. Leyendecker, N. Dickman, S. L. Hanson, and M. G. Hopper (1996). National seismic-hazard maps; documentation June 1996, U. S. Geological Survey Open-File Report 1996-532.

Frankel, A. D., M. D. Petersen, C. S. Mueller, K. M. Haller, R. L. Wheeler, E. V. Leyendecker, R. L. Wesson, S. C. Harmsen, C. H. Cramer, D. M. Perkins, and K. S. Rukstales (2002). Documentation for the 2002 update of the national seismic hazard maps, U. S. Geological Survey Open-File Report 2002-420.

Fraser-Smith, A. C., A. Bernardi, P. R. McGill, M. E. Ladd, R. A. Helliwell, and O. G. Villard (1990). Low frequency magnetic field measurements near the epicenter of the M_S-7.1 Loma Prieta earthquake, Geophys. Res. Lett., 17, 1465-1468.

Freed, A. M. (2005). Earthquake triggering by static, dynamic, and postseismic stress transfer, Ann. Rev. Earth Plant. Sci., 33, 335-367.

Freund, F., M. A. S. da Silva, B. W. S. Lau, A. Takeuchi, and H. H. Jones (2007). Electric currents along earthquake faults and the magnetization of pseudotachylite veins, Tectonophysics, 431, 131-141, doi:10.1016/j.tecto.2006.05.039.

Freund, F., and D. Sornette (2007). Electro-magnetic earthquake bursts and critical rupture of peroxy bond networks in rocks, Tectonophysics, 431, 33-47, doi:10.1016/j.tecto.2006.05.032.

Freund, F. T. (2007a). Pre-earthquake signals – Part I: Deviatoric stresses turn rocks into a source of electric currents, Natural Hazards and Earth System Sciences, 7, 535–541.

Freund, F. T. (2007b). Pre-earthquake signals – Part II: Flow of battery currents in the crust, Natural Hazards and Earth System Sciences, 7, 543-548.

Freund, F. T., A. Takeuchi, and B. W. S. Lau (2006). Electric currents streaming out of stressed igneous rocks – A step towards understanding pre-earthquake low frequency EM emissions, Phys Chem. Earth, 31, 389-396.

Freund, F. T., A. Takeuchi, B. W. S. Lau, A. Al-Manaseer, C. C. Fu, N. A. Bryant, and D. Ouzounov (2007). Stimulated infrared emission from rocks; assessing a stress indicator, eEarth, 2, 7-16.

Fu, C. Y., and H. X. Liu (1956). Prevention of Earthquake Disasters**,** Twelve-Year National Long-Term Plan for Science and Technology Development (1956-1967), Project No. 33 (in Chinese).

Fujita, K., T. Katsura, and Y. Tainosho (2004). Electrical conductivity measurement of granulite under mid- to lower crustal pressure-temperature conditions, Geophys. J. Int., 157, 79-86.

Fujiwara, H., S. Kawai, S. Aoi, N. Morikawa, S. Senna, K. Kobayashi, T. Ishii, T. Okumura, and Y. Hayakawa (2006). National seismic hazard maps of Japan, Bulletin of the Earthquake Research Institute Tokyo, 81, 221-232.

Galadini, F., and P. Galli (2000). Active tectonics in the central Apennines (Italy) – Input data for seismic hazard assessment, Natural Hazards, 22, 225-270.

Galli, P., F. Galadini, and D. Pantosti (2008). Twenty years of paleoseismology in Italy, Earth-Sci. Rev., 88, 89-117.

Gasparini, P., and M. S. M. Mantovani (1978). Radon anomalies and volcanic eruptions, J. Volcanol. Geother. Res., 3, 325-341.

Geller, R. J., editor (1996), Debate on "VAN", Geophys. Res. Lett., 23, 1291-1452.

Geller, R. J. (1997). Earthquake prediction: a critical review, Geophys. J. Int., 131, 425-450.

Geller, R. J., D. D. Jackson, Y. Y. Kagan, and F. Mulargia (1997). Earthquakes cannot be predicted, Science, 275, 1616-1618.

Gerstenberger, M. C., L. M. Jones, and S. Wiemer (2007). Short-term aftershock probabilities: Case studies in California, Seismol. Res. Lett., 78, 66-77.

Gerstenberger, M. C., S. Wiemer, L. M. Jones, and P. A. Reasenberg (2005). Real-time forecasts of tomorrow's earthquakes in California, Nature, 435, 328-331.

Giardini, D., G. Grunthal, K. M. Shedlock, and P. Z. Zhang (1999). The GSHAP Global Seismic Hazard Map, Ann. Geofisica, 42, 1225-1230.

Glover, P. W. J., and F. J. Vine (1992). Electrical conductivity of carbon bearing granulite at raised temperatures and pressures, Nature, 360, 723-726.

Glover, P. W. J., and F. J. Vine (1994). Electrical conductivity of the continental crust, Geophys. Res. Lett., 21, 2357-2360.

Gokhberg, M. B., V. A. Morgounov, T. Yoshino, and I. Tomizawa (1982). Experimental measurement of electromagnetic emissions possibly related to earthquakes in Japan, J. Geophys. Res., 87, 7824-7828.

Gomberg, J., N. Beeler, and M. Blanpied (2000). On rate-state and Coulomb failure models, J. Geophys. Res., 105, 7857-7871.

Gomberg, J., P. Bodin, and P. A. Reasenberg (2003). Observing earthquakes triggered in the near field by dynamic deformations, Bull. Seismol. Soc. Amer., 93, 118-138.

Gomberg, J., J. L. Rubinstein, Z. G. Peng, K. C. Creager, J. E. Vidale, and P. Bodin (2008). Widespread triggering of nonvolcanic tremor in California, Science, 319, 173.

Grandori, G., and E. Guagenti (2009). Prevedere I terremoti: la lezione dell'Abruzzo, Ingegneria Seismica, 26, 56-62.

Grant, R. A., and T. Halliday (2010). Predicting the unpredictable; evidence of pre-seismic anticipatory behaviour in the common toad, J. Zool., 281, 263-271, doi:10.1111/j.1469-7998.2010.00700.x.

Grant Ludwig, L., S. O. Akciz, G. R. Noriega, O. Zielke & J. R. Arrowsmith (2010). Climate-modulated channel incision and rupture history of the San Andreas fault in the Carrizo Plain, Science, 327, doi:10.1126/science.1182837.

Graves, R., T. Jordan, S. Callaghan, E. Deelman, E. Field, G. Juve, C. Kesselman, P. Maechling, G. Mehta, K. Milner, D. Okaya, P. Small, and K. Vahi (2010). CyberShake: A Physics-Based Seismic Hazard Model for Southern California, Pure Appl. Geophys., 167, 1-15, doi: 10.1007/s00024-010-0161-6.

Greenhough, J., A. F. Bell, and I. G. Main (2009). Comment on "Relationship between accelerating seismicity and quiescence, two precursors to large earthquakes" by Arnaud Mignan and Rita Di Giovambattista, Geophys. Res. Lett., 36, L17303.

Gruppo di Lavoro (2004). Redazione della mappa di pericolosità sismica prevista dall'Ordinanza PCM 3274 del 20 marzo 2003, Rapporto conclusivo per il Dipartimento della Protezione Civile, INGV, Milano-Roma, April, 2004, 65 pp. + 5 appendices; http://zonesismiche.mi.ingv.it/.

Gruppo Nazionale di Difesa dei Terremoti (1999). Censimento di vulnerabilità degli edifici pubblici strategici e speciali nelle regioni Abruzzo, Basilicata, Calabria, Campania, Molise, Puglia e Sicilia Orientale, 3 vols., Dipartimento della Protezione Civile.

Gu, G. X., editor (1983a). Catalogue of Chinese Earthquakes (1831BC -AD1969), The Scientific Publishing House, Beijing, 894 pp. (in Chinese).

Gu, G. X., editor (1983b). Catalogue of Chinese Earthquakes (AD1970-1979), Seismological Press, Beijing, 664 pp. (in Chinese).

Gutenberg, B., and C. F. Richter (1956). Magnitude and energy of earthquakes, Ann. Geofisica, 9, 1-15.

Hamada, K. (1993). Statistical evaluation of the SES predictions issued in Greece: alarm and success rates, Tectonophysics, 224, 203-210.

Hamilton, R., chair, and the IDNDR Scientific and Technical Committee (1997). Report on early warning capabilities for geological hazards, International Decade for Natural Disaster Reduction Secretariat, Geneva, Switzerland, 35 pp.

Han, J., and M. Kamber (2006). Data mining: Concepts and techniques, 2nd edition, 800 pp., Morgan Kaufmann Publishers, San Francisco.

Hardebeck, J. L., K. R. Felzer, and A. J. Michael (2008). Improved tests reveal that the accelerating moment release hypothesis is statistically insignificant, J. Geophys. Res., 113, B08310, doi:10.1029/2007JB005410.

Harris, R. (1998). The Loma Prieta, California, earthquake of October 17, 1989; forecasts, U. S. Geological Survey Professional Paper1550-B, B1-B28.

Harris, R. A., and S. M. Day (1993). Dynamics of fault interaction: parallel strike-slip faults, J. Geophys. Res., 98, 4461-4472.

Harris, R. A., and R. W. Simpson (1992). Changes in static stress on southern California faults after the 1992 Landers earthquake, Nature, 360, 251-254.

Harris, R. A., and R. W. Simpson (1998). Suppression of large earthquakes by stress shadows: a comparison of Coulomb and rate-and-state failure, J. Geophys. Res., 103, 24,439-24,451.

Harris, R. A., R. W. Simpson, and R. B. Hermann (1996). Stress relaxation shadows and the suppression of earthquakes; some examples from California and their possible uses for earthquake hazard estimates, Seismol. Res. Lett., 67, 40-40.

Harte, D., and D. Vere-Jones (2005). The entropy score and its uses in earthquake forecasting, Pure Appl. Geophys., 162, 1229-1253.

Hauksson, E. (1981). Radon content of groundwater as an earthquake precursor: Evaluation of worldwide data and physical basis, J. Geophys. Res., 86, 9397-9410.

Hauksson, E., and J. G. Goddard (1981). Radon earthquake precursor studies in Iceland, J. Geophys. Res., 86, 7037-7054.

Hayakawa, M., R. Kawate, O. A. Molchanov, and K. Yumoto (1996). Results of ultra-low-frequency magnetic field measurements during the Guam earthquake of 8 August 1993, Geophys. Res. Lett., 23, 241-244.

Healy, J. H., V. G. Kossobokov and J. W. Dewey (1992). A test to evaluate the earthquake prediction algorithm, M8, USGS Open-File Report 92-401, 23 pp. with 6 Appendices.

Heinicke, J., U. Koch, and G. Martinelli (1995). CO_2 and radon measurements in the Vogtland area (Germany) – a contribution to earthquake prediction research, Geophys. Res. Lett., 22, 771-774.

Heki, K., and S. Miyazaki (2001). Plate convergence and long-term crustal deformation in Central Japan, Geophys. Res. Lett., 28, 2313-2316.

Helmstetter, A., Y. Y. Kagan, and D. D. Jackson (2006). Comparison of short-term and time-independent earthquake forecast models for southern California, Bull. Seismol. Soc. Amer., 96, 90-106, doi:10.1785/0120050067.

Helmstetter, A., G. Ouillon, and D. Sornette (2003). Are aftershocks of large Californian earthquakes diffusing?, J. Geophys. Res., 108, 2483-2507.

Helmstetter, A., and D. Sornette (2002). Subcritical and supercritical regimes in epidemic models of earthquake aftershocks, J. Geophys. Res., 107, doi: 10.1029/2001JB001580.

Helmstetter, A., and D. Sornette (2003). Foreshocks explained by cascades of triggered seismicity, J. Geophys. Res., 108, 2457, doi:10.1029/2003JB002409.

Hirata, N. (2004). Past, current and future of Japanese national program for earthquake prediction research, Earth Planets and Space, 56, xliii-l.
Hobara, Y., and M. Parrot (2005). Ionospheric perturbations linked to a very powerful seismic event, Journal of Atmospheric and Solar-Terrestrial Physics, 67, 677-685, doi:10.1016/j.jastp.2005.02.006.
Holliday, J. R., D. L. Turcotte, and J. B. Rundle (2008). A review of earthquake statistics: Fault and seismicity-based models, ETAS and BASS, Pure Appl. Geophys., 165, 1003-1024, doi:10.1007/s00024-008-0344-6.
Holub, R. F., and B. T. Brady (1981). The effect of stress on radon emanation from rock, J. Geophys. Res., 86, 1776-1784.
Hori, T., N. Kato, K. Hirahara, T. Baba, and Y. Kaneda (2004). A numerical simulation of earthquake cycles along the Nankai Trough in southwest Japan: lateral variation in fictional property due to the slab geometry controls the nucleation position, Earth Planet. Sci. Lett., 228, 215-226.
Hough, S. (2009). Predicting the Unpredictable: The Tumultuous Science of Earthquake Prediction, Princeton University Press, Princeton, New Jersey, 272pp.
Hu, Y. X. (1990). Synthetic Probabilistic Method of Seismic Hazard Analysis, Seismological Press, Beijing, 185 pp. (in Chinese).
Hubert-Ferrari, A., J. Suppe, J. Van der Woerd, X. Wang, and H. F. Lu (2005). Irregular earthquake cycle along the southern Tianshan front, Aksu area, China, J. Geophys. Res., 110, B06402.
Huc, M., and I. G. Main (2003). Anomalous stress diffusion in earthquake triggering: Correlation length, time dependence, and directionality, J. Geophys. Res., 108, 2324, doi:10.1029/2001JB001645.
Ide, S., and G. C. Beroza (2001). Does apparent stress vary with earthquake size?, Geophys. Res. Lett., 28, 3349-3352.
Igarashi, G., S. Saeki, N. Takahata, K. Sumikawa, S. Tasaka, Y. Sasaki, M. Takahashi, and Y. Sano (1995). Ground-water radon anomaly before the Kobe earthquake in Japan, Science, 269, 60-61, doi:10.1126/science.269.5220.60.
Igarashi, G., and H. Wakita (1995). Geochemical and hydrological observations for earthquake prediction in Japan, J. Phys. Earth, 43, 585-598.
Ihmle, P. F., and T. H. Jordan (1994). Teleseismic search for slow precursors to large earthquakes, Science, 266, 1547-1551.
Ishibashi, K. (1977). Re-examination of a great earthquake expected in the Tokai district, central Japan—possibility of the ‘Suruga Bay earthquake’, Rep. Coord. Comm. Earthquake Pred., 17, 126-132 (in Japanese).
Ishibashi, K. (1981). Specification of a soon-to-occur seismic faulting in the Tokai District, central Japan, based upon seismotectonics, in Earthquake Prediction: An International Review, D. W. Simpson and P. G. Richards, editors, American Geophysical Union, Washington, D.C., 297-332.
Ispido, T., and M. Mizutani (1981). Experimental and theoretical basis of electrokinetic phenomena to rock-water systems and its applications to geophysics, J. Geophys. Res., 86, 1763-1775.
Ito, K., and M. Matsuzaki (1990). Earthquakes as self organized critical phenomena, J. Geophys. Res., 95, 6853-6860.
Jackson, D. D. (1996). Hypothesis testing and earthquake prediction, Proc. Natl. Acad. Sci. USA, 93, 3772-3775.
Jackson, D. D., K. Aki, C. A. Cornell, J. H. Dieterich, T. L. Henyey, M. Mahdyiar, D. Schwartz, and S. N. Ward (1995). Seismic hazards in southern California - probable earthquakes, 1994 to 2024, Bull. Seismol. Soc. Amer., 85, 379-439.
Jackson, D. D., and Y. Y. Kagan (2006). The 2004 Parkfield earthquake, the 1985 prediction, and characteristic earthquakes: Lessons for the future, Bull. Seismol. Soc. Amer., 96, S397-S409.
Japan Meteorological Agency (2004). Examination of the possibility that the Tokachi-oki earthquake in 2003 accompanied a precursory slip, Jishin-Yochi Renrakukaihou, 71, 122-123.
Jin, A. (1985). Some results of observation and study of earth resistivity in China, *Eos Trans. AGU*, **66**, 1066 (abstract).
Johnston, M. J. S., R. D. Borcherdt, A. Linde, and M. T. Gladwin (2006). Continuous borehole strain and pore pressure in the near field of the 28 September 2004 M 6.0 Parkfield, California, earthquake: Implications for nucleation, fault response, earthquake prediction, and tremor, Bull. Seismol. Soc. Amer., 96(4), S56-S72.
Johnston, M. J. S., A. T. Linde, and D. C. Agnew (1994). Continuous borehold strain in the San Andreas fault zone before, during, and after the 28 June 1992, Mw 7.3 Landers, California, earthquake, Bull. Seismol. Soc. Amer., 84, 799-805.
Johnston, M. J. S., A. T. Linde, and M. T. Gladwin (1990). Near field high resolution strain measurements prior to the October 18, 1989, Loma Prieta Ms 7.1 earthquake, Geophys. Res. Lett., 17, 1777-1780.
Jolliffe, I. T., and D. B. Stephenson (2003). Forecast Verification - A Practitioner's Guide in Atmospheric Science, John Wiley & Sons, Chichester, 254pp.

Jones, L. M. (1996). Earthquake prediction: The interaction of public policy and science, Proc. Nat. Acad. Sci. USA, 93, 3721-3725.

Jones, L. M., K. E. Sieh, D. C. Agnew, C. R. Allen, R. Bilham, M. Ghilarducci, B. H. Hager, E. Hauksson, K. Hudnut, D. D. Jackson, and A. G. Sylvester (1991). Short-term earthquake hazard assessment for the San Andreas Fault in Southern California, Open-File Report - U. S. Geological Survey, 42-42.

Jordan, T. H., G. Beroza, C. A. Cornell, C. B. Crouse, J. Dieterich, A. Frankel, D. D. Jackson, A. Johnston, H. Kanamori, J. S. Langer, M. K. McNutt, J. R. Rice, B. A. Romanowicz, K. Sieh, P. G. Somerville (2003). Living on an Active Earth: Perspectives on Earthquake Science, National Academies Press, Washington, D.C., 418 pp.

Jordan, T. H. (2006). Earthquake predictability, brick by brick, Seismol. Res. Lett., 77, 3-6.

Jordan, T. H., Y.-T. Chen, P. Gasparini, R. Madariaga, I. Main, W. Marzocchi, G. Papadopoulos, G. Sobolev, K. Yamaoka & J. Zschau (2009). Operational earthquake forecasting: State of knowledge and guidelines for implementation, Findings and Recommendations of the International Commission on Earthquake Forecasting for Civil Protection, released by the Dipartimento della Protezione Civile, Rome, Italy, October 2, 2009.

Jordan, T. H. (2009). Earthquake system science: Potential for seismic risk reduction, Scientia Iranica, 16, 351-366.

Jordan, T. H., and L. M. Jones (2010). Operational earthquake forecasting: Some thoughts on why and how, Seismol. Res. Lett., 81, 571-574, doi:10.1785/gssrl.81.4.571.

Kagan, Y. Y. (1997a). Are earthquakes predictable?, Geophys. J. Int., 131, 505-525.

Kagan, Y. Y. (1997b). Seismic moment-frequency relation for shallow earthquakes: Regional comparison, J. Geophys. Res., 102, 2835-2852.

Kagan, Y. Y., and D. D. Jackson (1991). Seismic Gap Hypothesis: Ten years after, J. Geophys. Res., 96, 21419-21431.

Kagan, Y. Y., and D. D. Jackson (1995). New Seismic Gap Hypothesis: Five years after, J. Geophys. Res., 100, 3943-3959.

Kamigaichi, O., M. Saito, K. Doi, T. Matsumori, S. Tsukada, K. Takeda, T. Shimoyama, K. Nakamura, M. Kiyomoto, and Y. Watanabe (2009). Earthquake Early Warning in Japan: Warning the General Public and Future Prospects, Seismol. Res. Lett., 80, 717-726.

Kanamori, H. (2003). Earthquake prediction: an overview, in International Handbook of Earthquake and Engineering Seismology, 81B, 1205-1216, International Association of Seismology and Physics of the Earth's Interior, ISBN 0-12-440658-0.

Kanamori, H., and J. J. Cipar (1974). Focal process of the great Chilean earthquake May 22, 1960, Phys. Earth Planet. Inter., 9, 128-136.

Kao, H., S. J. Shan, H. Dragert, G. Rogers, J. F. Cassidy, and K. Ramachandran (2005). A wide depth distribution of seismic tremors along the northern Cascadia margin, Nature, 436, 841-844.

Katz, R. W., and A. H. Murphy (1997). Economic value of weather and climate forecasts, Cambridge University Press, Cambridge, UK, 222 pp.

Keilis-Borok, V., L. Knopoff, V. Kossobokov, and I. Rotvain (1990). Intermediate-term prediction in advance of the Loma Prieta earthquake, Geophys. Res. Lett., 17, 1461-1464.

Keilis-Borok, V. I., L. Knopoff, I. M. Rotwain, and C. R. Allen (1988). Intermediate-term prediction of occurrence times of strong earthquakes, Nature, 335, 690-694.

Keilis-Borok, V. I., and V.G. Kossobokov (1987). Periods of high probability of occurrence of the world's strongest earthquakes, Computational Seismology, 19, 45-53.

Keilis-Borok, V. I., and V. G. Kossobokov (1990). Premonitory activation of earthquake flow: Algorithm M8, Phys. Earth Planet. Inter., 61, 73-83.

Kelleher, J., L. Sykes, and J. Oliver (1973). Possible criteria for predicting earthquake locations and their application to major plate boundaries of Pacific and Carribean, J. Geophys. Res., 78, 2547-2585.

Kenner, S. J., and P. Segall (2000). Postseismic deformation following the 1906 San Francisco earthquake, J. Geophys. Res., 105, 13195-13209.

Kerr, R. A. (2007). Continuing Indonesian quakes putting seismologists on edge, Science, 317, 1660-1661.

Kilb, D., J. Gomberg, and P. Bodin (2000). Triggering of earthquake aftershocks by dynamic stresses, Nature, 408, 570-574.

King, C.-Y. (1978). Radon emanation on San Andreas fault, Nature, 271, 516-519.

King, C.-Y. (1986). Gas geochemistry applied to earthquake prediction: an overview, J. Geophys. Res., 91, 12269-12281.

King, C.-Y., B. S. King, W. C. Evans, and W. Zhang (1996). Spatial radon anomalies on active faults in California, Applied Geochemistry, 11, 497-510.

King, C.-Y., and A. Minissale (1994). Seasonal variability of soil gas radon concentration in central California, Radiation Measurements, 23, 683-692.

King, C.-Y., C. Walkingstick & D. Basler (1993), Radon in soil gas along active faults in central California, in: C. S. Gundersen & R. B. Wanty (eds.), *Field Studies of Radon In Rocks, Soils and Water*, U.S. Geol. Sur. Open File Report, 77-143.

King, C.-Y., W. Zhang, and Z. C. Zhang (2006). Earthquake-induced groundwater and gas changes, Pure Appl. Geophys., 163, 633-645.

Kirschvink, J. L. (2000). Earthquake prediction by animals; evolution and sensory perception, Bull. Seismol. Soc. Amer., 90, 312-323.

Kobayashi, A., T. Yamamoto, K. Nakamura, and K. Kimura, Short-term (2006). Slow slip events detected by the strainmeters in Tokai region in the period from 1984 to 2005, Zisin 2 (Journal Seismol. Soc. Japan, Second Series), 59, 19-27.

Konca, A. O., J. P. Avouac, A. Sladen, A. J. Meltzner, K. Sieh, P. Fang, Z. H. Li, J. Galetzka, J. Genrich, M. Chlieh, D. H. Natawidjaja, Y. Bock, E. J. Fielding, C. Ji, and D. V. Helmberger (2008). Partial rupture of a locked patch of the Sumatra megathrust during the 2007 earthquake sequence, Nature, 456, 631-635.

Kossobokov, V. G., P.N. Shebalin, J. H. Healy, J. W. Dewey and I. N. Tikhonov (1999). A real-time intermediate-term prediction of the October 4, 1994, and December 3, 1995, southern Kuril Islands earthquakes, in D. K. Chowdhury, editor, Computational Seismology and Geodynamics, 4, 57-63.

Kossobokov, V. G. (2006). Quantitative earthquake prediction on global and regional scales, in Recent Geodynamics, Georisk and Sustainable Development in the Black Sea to Caspian Sea Region, Proceedings, A. IsmailZadeh, editor, pp. 32-50, Amer Inst Physics, Melville, New York, USA.

Kossobokov, V. G., V. I. Keilisborok, and S. W. Smith (1990). Localization of intermediate-term earthquake prediction, J. Geophys. Res., 95, 19763-19772.

Kossobokov, V. G., L. L. Romashkova, V. I. Keilis-Borok, and J. H. Healy (1999). Testing earthquake prediction algorithms: statistically significant advance prediction of the largest earthquakes in the Circum-Pacific, 1992-1997, Phys. Earth Planet. Inter., 111, 187-196.

Kossobokov, V. G., and A. A. Soloviev (2008). Prediction of extreme events: Fundamentals and prerequisites of verification, Russ. J. Earth Sci., 10, ES2005, doi:10.2205/2007ES000251.

Lagios, E., V. Sakkas, P. Papadimitriou, I. Parcharidis, B. N. Damiata, K. Chousianitis, and S. Vassilopouiou (2007). Crustal deformation in the central Ionian islands (Greece): Results from DGPS and DInSAR analyses (1995-2006), Tectonophysics, 444, 119-145.

Langbein, J., R. Borcherdt, D. Dreger, J. Fletcher, J. L. Hardebeck, M. Hellweg, C. Ji, M. Johnston, J. R. Murray, R. Nadeau, M. J. Rymer, and J. A. Treiman (2005). Preliminary report on the 28 September 2004, M 6.0 Parkfield, California earthquake, Seismol. Res. Lett., 76, 10-26.

Larson, K. M., V. Kostoglodov, S. Miyazaki, and J. A. S. Santiago (2007). The 2006 aseismic slow slip event in Guerrero, Mexico: New results from GPS, Geophys. Res. Lett., 34, L13309, doi: 10.1029/2007gl029912.

Latoussakis, J., and G. N. Stavrakakis (1992). Times of increased probability of earthquakes of ML ≥ 5.5 in Greece diagnosed by algorithm M8, Tectonophysics, 210, 315-326.

Leary, P. C., P. E. Malin, R. A. Phinney, T. Brocher, and R. Voncolln (1979). Systematic monitoring of millisecond travel time variations near Palmdale, California, J. Geophys. Res., 84, 659-666.

Lee, S. P., editor (1960), Catalogue of Chinese Earthquakes, Vols. 1 & 2, The Scientific Publishing House, Beijing, 790 pp. (in Chinese with English abstract).

Li, R. A. (1986). The Haicheng earthquake, in: Z. J. Guo and X. L. Chen, editors, Earthquake Countermeasures, Seismological Press, Beijing, 321-336 (in Chinese).

Li, S. B. (1957). Instruction of Chinese intensity zoning map, Acta Geophysica Sinica, 6 (in Chinese with English abstract).

Li, Y. G., P. Chen, E. S. Cochran, J. E. Vidale, and T. Burdette (2006). Seismic evidence for rock damage and healing on the San Andreas fault associated with the 2004 M 6.0 Parkfield earthquake, Bull. Seismol. Soc. Amer., 96, S349-S363, doi:10.1785/0120050803.

Lighthill, M. J., editor (1996). A critical review of Van, World Scientific, Singapore, 376 pp.

Linde, A. T., M. T. Gladwin, M. J. S. Johnston, R. L. Gwyther, and R. G. Bilham (1996). A slow earthquake sequence on the San Andreas fault, Nature, 383, 65-68.

Linde, A. T., and I. S. Sacks (2002). Slow earthquakes and great earthquakes along the Nankai trough, Earth Planet. Sci. Lett., 203, 265-275.

Lindell, M. K., S. Arlikatti, and C. S. Prater (2009). Why people do what they do to protect against earthquake risk: perceptions of hazard adjustment attributes, Risk Anal., 29, 1072-1088.

Lisi, M., C. Filizzola, N. Genzano, C. S. L. Grimaldi, T. Lacava, F. Marchese, G. Mazzeo, N. Pergola, and V. Tramutoli (2010). A study on the Abruzzo 6 April 2009 earthquake by applying the RST approach to 15 years of AVHRR TIR observations, Natural Hazards and Earth System Sciences, 10, 395-406.

Liu, C. C., A. T. Linde, and I. S. Sacks (2009). Slow earthquakes triggered by typhoons, Nature, 459, 833-836.

Liu, K. K., T. F. Yui, Y. H. Yeh, Y. B. Tsai, and T. L. Teng (1984). Variations of radon content in groundwaters and possible correlation with seismic activities in northern Taiwan, Pure Appl. Geophys., 122, 231-244.

Liu, Y. J., and J. R. Rice (2005). Aseismic slip transients emerge spontaneously in three-dimensional rate and state modeling of subduction earthquake sequences, J. Geophys. Res., 110, B08307, doi: 10.1029/2004jb003424.

Liu, Y. J., and J. R. Rice (2009). Slow slip predictions based on granite and gabbro friction data compared to GPS measurements in northern Cascadia, J. Geophys. Res., 114, B09407, doi: 10.1029/2008jb006142.

Llenos, A. L., J. J. McGuire, and Y. Ogata (2009). Modeling seismic swarms triggered by aseismic transients, Earth Planet. Sci. Lett., 281, 59-69, doi;10.1016/j.epsl.2009.02.011.

Lohman, R. B., and J. J. McGuire (2007). Earthquake swarms driven by aseismic creep in the Salton Trough, California, J. Geophys. Res., 112, B04405, doi:10.1029/2006jb004596.

Lombardi, A. M., and W. Marzocchi (2009). Double Branching model to forecast the next M ≥ 5.5 earthquakes in Italy, Tectonophysics, 475, 514-523, doi:10.1016/j.tecto.2009.06.014.

Ludwig, L. G., S. O. Akciz, G. R. Noriega, O. Zielke, and J. R. Arrowsmith (2010). Climate-Modulated Channel Incision and Rupture History of the San Andreas Fault in the Carrizo Plain, Science, 327, 1117-1119.

Lyubushin, A., T. Tsapanos, V. Pisarenko, and G. Koravos (2002). Seismic hazard for selected sites in Greece: A Bayesian estimate of seismic peak ground acceleration, Natural Hazards, 83-98.

Ma, Z., Z. Fu, Y. Zhang, C. Wang, G. Zhang, and D. Liu (1990), Earthquake Prediction: Nine Major Earthquakes in China (1966-76), Seismological Press, Beijing.

Madariaga, R., M. Metois, C. Vigny, and J. Campos (2010). Central Chile Finally Breaks, Science, 328, 181-182.

Magsino, S. L., editor (2009). Applications of Social Network Analysis for Building Community Disaster Resilience: Workshop Summary, National Academies Press, Washington, D.C. 82 pp.

Main, I. (1996). Statistical physics, seismogenesis, and seismic hazard, Rev. Geophys., 34, 433-462.

Main, I. G. (1999). Applicability of time-to-failure analysis to accelerated strain before earthquakes and volcanic eruptions, Geophys. J. Int., 139, F1-F6.

Main I. G. (2006), A hand on the aftershock trigger, Nature, 441, 704-705.

Main, I. G., L. Li, J. McCloskey, and M. Naylor (2008). Effect of the Sumatran mega-earthquake on the global magnitude cut-off and event rate, Nature Geosci., 1, 142.

Mallman, E. P., and T. Parsons (2008). A global search for stress shadows, J. Geophys. Res., 113, B12304.

Marone, C. (1998). Laboratory-derived friction laws and their application to seismic faulting, Ann. Rev. Earth Planet. Sci., 26, 643-696.

Marzocchi, W., and A. M. Lombardi (2008). A double branching model for earthquake occurrence, J. Geophys. Res., 113, B08317, doi: 10.1029/2007jb005472.

Marzocchi, W., and A. M. Lombardi (2009). Real-time forecasting following a damaging earthquake, Geophys. Res. Lett., 36, L21302, doi: 10.1029/2009gl040233.

Marzocchi, W., L. Sandri, and E. Boschi (2003). On the validation of earthquake-forecasting models: The case of pattern recognition algorithms, Bull. Seismol. Soc. Amer., 93, 1994-2004.

Marzocchi, W., J. Selva, F. R. Cinti, P. Montone, S. Pierdominici, R. Schivardi, and E. Boschi (2009). On the occurrence of large earthquakes: New insights from a model based on interacting faults embedded in a realistic tectonic setting, J. Geophys. Res., 114, B01307, doi: 10.1029/2008jb005822.

Marzocchi, W., J. Selva, A. Piersanti, and E. Boschi (2003). On the long-term interaction among earthquakes: Some insight from a model simulation, J. Geophys. Res., 108, B11304, doi: 10.1029/2003jb002390.

Marzocchi, W., D. Schorlemmer, and S. Wiemer, editors (2010). An Earthquake Forecast Experiment in Italy, Ann. Geofisica, 53 (3), 163 pp.

Marzocchi, W., and J. Zhuang (2011). Statistics between mainshocks and foreshocks in Italy and Southern California, Geophys. Res. Lett, 38, L09310, doi:10.1029/2011GL047165.

Mazzotti, S., and J. Adams (2004). Variability of near-term probability for the next great earthquake on the Cascadia subduction zone, Bull. Seismol. Soc. Amer., 94, 1954-1959.

McCalpin, J. (2009). Paleoseismology, 2nd edition, Academic Press, 613pp.

McCann, W. R., S. P. Nishenko, L. R. Sykes, and J. Krause (1979). Seismic gaps and plate tectonics: seismic potential for major boundaries, Pure Appl. Geophys., 117, 1082-1147.

McCloskey, J., S. S. Nalbant, and S. Steacy (2005). Indonesian earthqauake: Earthquake risk from co-seismic stress, Nature, 434, 291.

McEvilly, T. V., and L. R. Johnson (1974). Stability of P and S velocities from central California quarry blasts, Bull. Seismol. Soc. Amer., 64, 343-353.

McGuire, J. J. (2008). Seismic cycles and earthquake predictability on east pacific rise transform faults, Bull. Seismol. Soc. Amer., 98, 1067-1084.

McGuire, J. J., M. S. Boettcher, and T. H. Jordan (2005). Foreshock sequences and short-term earthquake predictability on East Pacific Rise transform faults, Nature, 434, 457-461, doi:10.1038/nature03377.

McGuire, J. J., P. F. Ihmlé, and T. H. Jordan (1996). Time-domain observations of a slow precursor to the 1994 Romanche Transform earthquake, Science, 274, 82-85.

McGuire, J. J., and T. H. Jordan (2000). Further evidence for the compound nature of slow earthquakes: The Prince Edward Island earthquake of April 28, 1997, J. Geophys. Res., 105, 7819-7827.

Meletti, C., F. Galadini, G. Valensise, M. Stucchi, R. Basili, S. Barba, G. Vannucci, and E. Boschi (2008). A seismic source zone model for the seismic hazard assessment of the Italian territory, Tectonophysics, 450, 85-108.

Meyer, M. A., and J. M. Booker (2001). Eliciting and Analyzing Expert Judgment: A Practical Guide, SIAM, Philadelphia, PA.

Michael, A. J. (2011). Fundamental questions of earthquake statistics, source behavior, and the estimation of earthquake probabilities from possible foreshocks, Bull. Seismol. Soc. Amer., in press.

Michael, A. J., and L. M. Jones (1998). Seismicity alert probabilities at Parkfield, California, revisited, Bull. Seismol. Soc. Amer., 88, 117-130.

Mignan, A., G. C. P. King, and D. Bowman (2007). A mathematical formulation of accelerating moment release based on the stress accumulation model, J. Geophys. Res., 112, B11304, doi: 10.1029/2006jb004671.

Mileti, D. S., and J. D. Darlington (1997). The role of searching in shaping reactions to earthquake risk information, Social Problems, 44, 89-103.

Mileti, D. S., J. R. Hutton, and J. H. Sorensen (1981). Earthquake prediction response and options for public policy, University of Colorado Institute of Behavioral Science, Boulder, Colorado.

Miller, M. M., T. Melbourne, D. J. Johnson, and W. Q. Sumner (2002). Periodic slow earthquakes from the Cascadia subduction zone, Science, 295, 2423-2423.

Min, Z. Q., editor (1995). Catalogue of Chinese Historical Strong Earthquakes (23rd Century BC-AD1911), Seismological Press, Beijing, 514 pp (in Chinese).

Mogi, K. (1981). Seismicity in western Japan and long-term earthquake forecasting, in Earthquake Prediction: An International Review, D. W. Simpson & P. G. Richards, eds., American Geophysical Union, Washington, D.C., 43-51.

Mogi, K. (1985). Earthquake prediction, Academic Press, Tokyo; Orlando, Fla.

Mogi, T., Y. Tanaka, D. S. Widarto, E. M. Arsadi, N. T. Puspito, T. Nagao, W. Kanda, and S. Uyeda (2000). Geoelectric potential difference monitoring in southern Sumatra, Indonesia – Co-seismic change, Earth Planets and Space, 52, 245-252.

Mogro-Campero, A., R. L. Fleischer, R. S. Likes, and C. Y. King (1980). Changes in subsurface radon concentration associated with earthquakes, J. Geophys. Res., 85, 3053-3057.

Molchan, G. M. (1990). Strategies in strong earthquake prediction, Phys. Earth Planet. Inter., 61, 84-98.

Molchan, G. M. (1991). Structure of optimal strategies in earthquake prediction, Tectonophysics, 193, 267-276.

Molchan, G. M., and Y. Y. Kagan (1992). Earthquake prediction and its optimization, J. Geophys. Res., 97, 4823-4838.

Montgomery, D. R., and M. Manga (2003). Streamflow and water well responses to earthquakes, Science, 300, 2047-2049.

Morat, P., and J. L. Le Mouel (1987). Variation of the electrical resistivity of large rock samples with stress, Geophysics, 52, 1424-1430.

Morita, Y., S. Nakao, and Y. Hayashi (2006). A quantitative approach to the dike intrusion process inferred from a joint analysis of geodetic and seismological data for the 1998 earthquake swarm off the east coast of Izu Peninsula, central Japan, J. Geophys. Res., 111, doi: 10.1029/2005jb003860.

Mulargia, F., and P. Gasperini (1992). Evaluating the statistical validity beyond chance of VAN earthquake precursors, Geophys. J. Int., 111, 32-44.

Mulargia, F., and P. Gasperini (1995). Evaluation of the applicability of the time- and slip-predictable earthquake recurrence models to Italian seismicity, Geophys. J. Int., 120, 453-473.

Multidisciplinary Center for Earthquake Engineering Research (2008). MCEER Research: Enabling Disaster-Resilient Communities. Seismic Waves, November, pp. 1-2 [available at www.nehrp.gov/pdf/SeismicWavesNov08.pdf].

Murphy, A. H. (1986). Comparative Evaluation of Categorical and Probabilistic Forecasts: Two Alternatives to the Traditional Approach, Monthly Weather Review, 114, 245-249.

Murphy, A. H. (1993). What Is a Good Forecast? An Essay on the Nature of Goodness in Weather Forecasting, Weather and Forecasting, 8, 281-293.
Murphy, A. H., and R. L. Winkler (1987). A general framework for forecast verification, Monthly Weather Review, 115, 1330-1338.
Murray, J., and P. Segall (2002). Testing time-predictable earthquake recurrence by direct measurement of strain accumulation and release, Nature, 419, 287-291.
Murray, J. R., and P. Segall (2005). Spatiotemporal evolution of a transient slip event on the San Andreas fault near Parkfield, California, J. Geophys. Res., 110, B09407, doi: 10.1029/2005jb003651.
Nadeau, R. M., and D. Dolenc (2005). Nonvolcanic tremors deep beneath the San Andreas Fault, Science, 307, 389-389.
Nagao, T., Y. Enomoto, Y. Fujinawa, M. Hata, M. Hayakawa, Q. Huang, J. Izutsu, Y. Kushida, K. Maeda, K. Oike, S. Uyeda, and T. Yoshino (2002). Electromagnetic anomalies associated with 1995 Kobe earthquake, Journal of Geodynamics, 33, 401-411.
Nagao, T., Y. Orihara, T. Yamaguchi, I. Takahashi, K. Hattori, Y. Noda, K. Sayanagi, and S. Uyeda (2000). Co-seismic geoelectric potential changes observed in Japan, Geophys. Res. Lett., 27, 1535-1538.
Nanjo, K. Z., T. Ishibe, H. Tsuruoka, D. Schorlemmer, Y. Ishigaki, and N. Hirata (2010). Analysis of the Completeness Magnitude and Seismic Network Coverage of Japan, Bull. Seismol. Soc. Amer., 100, 3261-3268, doi:10.1785/0120100077.
National People's Congress of the People's Republic of China (2008). Law of the People's Republic of China on Protecting against and Mitigating Earthquake Disasters, 26 pp. (in Chinese with English translation).
National Research Council Committee on Estimating and Communicating Uncertainty in Weather and Climate (2006). Completing the forecast: characterizing and communicating uncertainty for better decisions using weather and climate forecasts, National Academies Press, Washington, D.C, 125 pp.
Němec, F., O. Santolik, and M. Parrot (2009). Decrease of intensity of ELF/VLF waves observed in the upper ionosphere close to earthquakes: A statistical study, J. Geophys. Res., 114, A04303, doi: 10.1029/2008ja013972.
Nersesov, I. (1970). Earthquake prognostication in the Soviet Union, Bull. New Zealand Soc. Earthq. Eng., 3, 108-111.
Nishenko, S. P. (1991). Circum-Pacific seismic potential: 1989-1999, Pure Appl. Geophys., 135, 169-259.
Nishenko, S. P., and L. R. Sykes (1993). Comment on "Seismic gap hypothesis: Ten years after", J. Geophys. Res., 98, 9909-9916.
Niu, F. L., P. G. Silver, T. M. Daley, X. Cheng, and E. L. Majer (2008). Preseismic velocity changes observed from active source monitoring at the Parkfield SAFOD drill site, Nature, 454, 204-208, doi:10.1038/nature07111.
Nosengo, N. (2010). Italy puts seismology in the dock, Nature, 465, 992-992.
Obara, K. (2002). Nonvolcanic deep tremor associated with subduction in southwest Japan, Science, 296, 1679-1681, doi:10.1126/science.1070378.
Obara, K., K. Kasahara, S. Hori, and Y. Okada (2005). A densely distributed high-sensitivity seismograph network in Japan: Hi-net by National Research Institute for Earth Science and Disaster Prevention, Review of Scientific Instruments, 76, 021301, doi:10.1063/1.1854197.
Ogata, Y. (1988). Statistical Models for Earthquake Occurrences and Residual Analysis for Point Processes, Journal of the American Statistical Association, 83, 9-27.
Ogata, Y. (1999). Seismicity analysis through point-process modeling: A review, Pure Appl. Geophys., 155, 471-507.
Ogata, Y., R. S. Matsu'ura, and K. Katsura (1993). Fast likelihood computation of epidemic type aftershock-sequence model, Geophys. Res. Lett., 20, 2143-2146.
Ogata, Y., and H. C. Zhuang (2006). Space-time ETAS models and an improved extension, Tectonophysics, 413, 13-23.
Oglesby, D. (2008). Rupture termination and jump on parallel offset faults, Bull. Seismol. Soc. Amer., 98, 440-447, doi:10.1785/0120070163.
Ohta, Y., M. Ohzono, S. Miura, T. Linuma, K. Tachibana, K. Takatsuka, K. Miyao, T. Sato, and N. Umino (2008). Coseismic fault model of the 2008 Iwate-Miyagi Nairiku earthquake deduced by a dense GPS network, Earth Planets and Space, 60, 1197-1201.
Ouillon, G., C. Castaing, and D. Sornette (1996). Hierarchical geometry of faulting, J. Geophys. Res., 101, 5477-5487.
Ouzounov, D., and F. Freund (2004). Mid-infrared emission prior to strong earthquakes analyzed by remote sensing data, Adv. Space Res., 33, 268-273.

Ozaki, M., S. Yagitani, I. Nagano, and K. Miyamura (2009). Ionospheric penetration characteristics of ELF waves radiated from a current source in the lithosphere related to seismic activity, Radio Science, 44, Rs1005, doi: 10.1029/2008rs003927.

Ozawa, S., H. Suito, and M. Tobita (2007). Occurrence of quasi-periodic slow-slip off the east coast of the Boso peninsula, Central Japan, Earth Planets Space, 59, 1241-1245.

Pace, B., L. Peruzza, G. Lavecchia, and P. Boncio (2006). Layered seismogenic source model and probabilistic seismic-hazard analyses in central Italy, Bull. Seismol. Soc. Amer., 96, 107-132.

Page, M. T., D. Alderson, and J. Doyle, J (2011). The magnitude distribution of earthquakes near Southern California faults, J. Geophys., in press.

Pantosti, D., D. P. Schwartz, and G. Valensise (1993). Paleoseismology along the 1980 surface rupture of the Irpinia fault - implications for earthquake recurrence in the southern Apennines, Italy, J. Geophys. Res., 98, 6561-6577.

Papadopoulos, G. A. (1988). Long-term accelerating foreshock activity may indicate the occurrence time of a strong shock in the western Hellenic Arc, Tectonophysics, 152, 179-192.

Papadopoulos, G. A. (2010). Comment on “The Prediction of two large earthquakes in Greece”, Eos, Trans. Am. Geophys. Union, 91,162.

Papadopoulos, G. A., M. Charalampakis, A. Fokaefs, and G. Minadakis (2010). Strong foreshock signal preceding the L'Aquila (Italy) earthquake (M sub(w) 6.3) of 6 April 2009, Natural Hazards and Earth System Sciences, 10, 19-24.

Papadopoulos, G. A., G. Drakatos, D. Papanastassiou, I. Kalogeras, and G. Stavrakakis (2000). Preliminary results about the catastrophic earthquake of 7 September 1999 in Athens, Greece, Seismol. Res. Lett., 71, 318-329.

Papadopoulos, G. A., G. Drakatos, and A. Plessa (2000). Foreshock activity as a precursor of strong earthquakes in Corinthos Gulf, Central Greece, Phys. Chem. Earth, 25, 239-245.

Papadopoulos, G. A. (1999). Luminous and Fiery Phenomena Associated with Earthquakes in the East Mediterranean,in M. Hayakawa, editor, Atmospheric & Ionospheric Electromagnetic Phenomena Associated with Earthquakes, TERRAPUB, Tokyo, 559-575.

Papadopoulos, G. A., and A. Kijko (1991). Maximum likelihood estimation of earthquake hazard parameters in the Aegean area from mixed data, Tectonophysics, 185, 277-294.

Papadopoulos, G. A., I. Latoussakis, E. Daskalaki, G. Diakogianni, A. Fokaefs, M. Kolligri, K. Liadopoulou, K. Orfanogiannaki, and A. Pirentis (2006). The East Aegean Sea strong earthquake sequence of October-November 2005: lessons learned for earthquake prediction from foreshocks, Natural Hazards and Earth System Sciences, 6, 895-901.

Papaioannou, Ch. A., and B. C. Papazachos (2000). Time-independent and time-dependent seismic hazard in Greece based on seismogenic sources, Bull. Seismol. Soc. Amer., 90, 22-33.

Papazachos, B. C., and P. E. Comninakis (1982). Long-term earthquake prediction in the Hellenic Trench Arc System, Tectonophysics, 86, 3-16.

Papazachos, B. C., and C. B. Papazachou (1997). The Earthquakes of Greece, Zitti Publ., Thessaloniki, Greece, 304 pp.

Papazachos, C., and B. Papazachos (2001). Precursory accelerated Benioff strain in the Aegean area, Annali Di Geofisica, 44, 461-474.

Park, S. K. (2002). Perspectives on monitoring resistivity changes with telluric signals at Parkfield, California: 1988-1999, J. Geodyn., 33, 379-399.

Park, S. K., M. J. S. Johnston, T. R. Madden, F. D. Morgan, and H. F. Morrison (1993). Electromagnetic precursors to earthquakes in the ULF band: A review of observations and mechanisms, Rev. Geophys., 31, 117-132.

Parrot, M., editor (2006). First results of the DEMETER micro-satellite, Planet. Space Sci., 54, 411-558.

Parrot, M., and M. J. S. Johnston, editors (1989). Seismoelectromagnetic effects, Phys. Earth Planet. Inter., 57, 1-177.

Parsons, T. (2002). Global Omori law decay of triggered earthquakes: Large aftershocks outside the classical aftershock zone, J. Geophys. Res., 107, 2199; doi:10.1029/2001JB000646.

Parsons, T., and E. L. Geist (2009). Is There a Basis for Preferring Characteristic Earthquakes over a Gutenberg-Richter Distribution in Probabilistic Earthquake Forecasting?, Bull. Seismol. Soc. Amer., 99, 2012-2019.

Parsons, T., S. Toda, R. S. Stein, A. Barka, and J. H. Dieterich (2000). Heightened odds of large earthquakes near Istanbul: An interaction-based probability calculation, Science, 288, 661-665.

Parsons, T., and A. A. Velasco (2009). On near-source earthquake triggering, J. Geophys. Res., 114, B10307, doi: 10.1029/2008jb006277.

Paté, M.-E., and H. C. Shah (1979). Public policy issues: Earthquake prediction, Bull. Seismol. Soc. Amer., 69, 1533-1547.

Peltzer, G., P. Rosen, F. Rogez, and K. Hudnut (1996). Postseismic rebound in fault step-overs caused by pore fluid flow, Science, 273, 1202-1204.

Peresan, A., G. Costa, and G. F. Panza (1999). Seismotectonic model and CN earthquake prediction in Italy, Pure Appl. Geophys., 154, 281-306.

Peresan, A., V. Kossobokov, L. Romashkova, and G. F. Panza (2005). Intermediate-term middle-range earthquake predictions in Italy: a review, Earth-Science Reviews, 69, 97-132.

Perfettini, H., and J. P. Ampuero (2008). Dynamics of a velocity strengthening fault region: Implications for slow earthquakes and postseismic slip, J. Geophys. Res., 113, B09411, doi: 10.1029/2007jb005398.

Petersen, M. D., A. D. Frankel, S. C. Harmsen, C. S. Mueller, K. M. Haller, R. L. Wheeler, R. L. Wesson, Y. Zeng, O. S. Boyd, D. M. Perkins, N. Luco, E. H. Field, C. J. Wills, and K. S. Rukstales (2008). Documentation for the 2008 update of the United States National Seismic Hazard Maps, U. S. Geological Survey Open-File Report 2008-1128.

Petrini, V., C. Bosi, G. Bigi, C. Eva, G. Grandori, E. Iaccarino, G. Luongo, D. Postpischl, A. Parturlon, M. Riuscetti, P. Sandone, R. Scarpa, M. Stucchi, and L. Vezzani (1981), Carta della pericolosità sismica, C.N.R. – PF Geodinamica.

Piersanti A., G. Spada, R. Sabadini, & M. Bonafede (1995), Global postseismic deformation, Geophys. J. Int., 120, 544-566.

Planinic, J., V. Radolic, B. Vukovic (2004). Radon as an earthquake precursor, Nuclear Instr. Methods Phys., Research A, 530, 568-574.

Plastino, W., and F. Bella (1999). Radon time series analysis at the Laboratori Nazionali del Gran Sasso, *L.N.G.S. Annual Report*, 199-203.

Plastino, W., P. P. Povinec, G. De Luca, C. Doglioni, S. Nisi, L. Ioannucci, M. Balata, M. Laubenstein, F. Bella, and E. Coccia (2010). Uranium groundwater anomalies and L'Aquila earthquake, 6th April 2009 (Italy), Journal of Environmental Radioactivity, 101, 45-50, doi:10.1016/j.jenvrad.2009.08.009.

Pollitz, F., W. H. Bakun, and M. Nyst (2004). A physical model for strain accumulation in the San Francisco Bay region: Stress evolution since 1838, J. Geophys. Res., 109, B11408, doi: 10.1029/2004jb003003.

Pollitz, F. F. (1992). Postseismic relaxation theory on the spherical earth, Bull. Seismol. Soc. Amer., 82, 422-453.

Pondrelli, S., S. Salimbeni, A. Morelli, G. Ekstrom, M. Olivieri, and E. Boschi (2010). Seismic moment tensors of the April 2009, L'Aquila (Central Italy), earthquake sequence, Geophys. J. Int., 180, 238-242.

Power, W. L., and T. E. Tullis (1995). Review of the fractal character of natural fault surfaces with implications for friction and the evolution of fault zones, in Fractals in the Earth Sciences, edited by C. C. Barton and P. R. L. Pointe, pp. 89-105, Plenum Press, New York, NY, USA.

Pulinets, S., and K. Boyarchuk (2004). Ionospheric precursors of earthquakes, Springer, Berlin, 315 pp.

Pulinets, S., D. Ouzounov, A. Karelin, K. Boyarchuk, and L. Pokhmelnykh (2006). The physical nature of thermal anomalies observed before strong earthquakes, Phys. Chem. Earth, 31, 143-153.

Pulinets, S. A. (2007). Natural radioactivity, earthquakes, and the ionosphere, Eos, Transactions, American Geophysical Union, 88, 217-218.

Quan, Y. D. (1988). The Haicheng, Liaoning province, earthquake of M7.3 of February 4, 1975, in Z. C. Zhang, editor, (1988), Earthquake Cases in China (1966-1975), Seismological Press, Beijing, 189-210 (in Chinese).

Raleigh, C. B., G. Bennett, H. Craig, T. Hanks, P. Molnar, A. Nur, J. Savage, C. Scholz, R. Turner, and F. Wu (1977). Prediction of the Haicheng earthquake, Eos Trans. Am. Geophys. Union 72, 236–272.

Reasenberg, P. A. (1999). Foreshock occurrence rates before large earthquakes worldwide, Pure Appl. Geophys., 155, 355-380.

Reasenberg, P. A., and L. M. Jones (1989). Earthquake hazard after a mainshock in California, Science, 243, 1173-1176.

Reasenberg, P. A., and L. M. Jones (1994). Earthquake aftershocks - update, Science, 265, 1251-1252.

Reid, H. F. (1911). The elastic-rebound theory of earthquakes, University of California Publications in Geological Sciences, 413-444.

Rhoades, D. A., and F. F. Evison (2004). Long-range earthquake forecasting with every earthquake a precursor according to scale, Pure Appl. Geophys., 161, 47-72.

Rhoades, D. A., and F. F. Evison (2005). Test of the EEPAS forecasting model on the Japan earthquake catalogue, Pure Appl. Geophys., 162, 1271-1290, doi:10.1007/s00024-004-2669-0.

Rhoades, D. A., and M. C. Gerstenberger (2009). Mixture Models for Improved Short-Term Earthquake Forecasting, Bull. Seismol. Soc. Amer., 99, 636-646, doi:10.1785/0120080063.

Rice, J. R. (1979). Theory of precursory processes in the inception of earthquake rupture, Gerlands Beitr. Geophys., 88, 91-127.

Rice, J. R., and J. W. Rudnicki (1979). Earthquake precursory effects due to pore fluid stabilization of a weakening fault zone, J. Geophys. Res., 84, 2177-2193.

Roache, P. J. (1998). Verification and validation in computational science and engineering, Hermosa Publishers, Albuquerque, New Mexico, 464pp.

Roberts, G. P., and A. M. Michetti (2004). Spatial and temporal variations in growth rates along active normal fault systems: an example from The Lazio-Abruzzo Apennines, central Italy, J. Struct. Geol., 26, 339-376.

Roberts, J. J., A. G. Duba, E. A. Mathez, T. J. Shankland, and R. Kinzler (1999). Carbon-enhanced electrical conductivity during fracture of rocks, J. Geophys. Res., 104, 737-747.

Roeloffs, E. A. (1988). Hydrologic precursors to earthquakes: a review, Pure Appl. Geophys., 126, 177-209.

Roland, E., and J. J. McGuire (2009). Earthquake swarms on transform faults, Geophys. J. Int., 178, 1677-1690, doi:10.1111/j.1365-246X.2009.04214.x.

Rong, Y. F., D. D. Jackson, and Y. Y. Kagan (2003). Seismic gaps and earthquakes, J. Geophys. Res., 108, doi:10.1029/2002JB002334.

Rubin, A. M. (2008). Episodic slow slip events and rate-and-state friction, J. Geophys. Res., 113, B11414, doi: 10.1029/2008jb005642.

Rundle, J. B., K. F. Tiampo, W. Klein, and J. S. S. Martins (2002). Self-organization in leaky threshold systems: The influence of near-mean field dynamics and its implications for earthquakes, neurobiology, and forecasting, Proc. Nat. Acad. Sci. USA, 99, Suppl. 1, 2514-2521.

Rundle, P. B., J. B. Rundle, K. F. Tiampo, A. Donnellan, and D. L. Turcotte (2006). Virtual California: Fault model, frictional parameters, applications, Pure Appl. Geophys., 163, 1819-1846, doi: 10.1007/s00024-006-0099-x.

Ryall, A., and W. U. Savage (1974). S-wave splitting: Key to earthquake prediction?, Bull. Seismol. Soc. Amer., 64, 1943-1951.

Rydelek, P. A., and I. S. Sacks (1999). Large earthquake occurrence affected by small stress, Bull. Seismol. Soc. Amer., 89, 822-828.

Sammis, C. G., and S. W. Smith (1999). Seismic cycles and the evolution of stress correlation in cellular automaton models of finite fault networks, Pure Appl. Geophys., 155, 307-334.

Savage, J. C. (1993). The Parkfield prediction fallacy, Bull. Seismol. Soc. Amer., 83, 1-6.

Schall, R. B. (1988). An evaluation of the animal-behavior theory for earthquake prediction, California Geology, 41, 41-45.

Scholz, C. H., L. R. Sykes, and Y. P. Aggarwal (1973). Earthquake prediction: a physical basis, Science, 181, 803-810.

Schorlemmer, D., M. C. Gerstenberger, S. Wiemer, D. D. Jackson, and D. A. Rhoades (2007). Earthquake likelihood model testing, Seismol. Res. Lett., 78, 17-29.

Schorlemmer, D., F. Mele, and W. Marzocchi (2010). A completeness analysis of the National Seismic Network of Italy, J. Geophys. Res., B04308, doi: DOI 10.1029/2008JB006097.

Schorlemmer, D., J. D. Zechar, M. J. Werner, E. H. Field, D. D. Jackson, T. H. Jordan, and R. W. Grp (2010). First results of the Regional Earthquake Likelihood Models experiment, Pure Appl. Geophys., 167, 859-876, doi:10.1007/s00024-010-0081-5.

Schwartz, D. P., and K. J. Coppersmith (1984). Fault behavior and characteristic earthquakes - examples from the Wasatch and San Andreas fault zones, J. Geophys. Res., 89, 5681-5698.

Schwartz, S. Y., and J. M. Rokosky (2007). Slow slip events and seismic tremor at circum-pacific subduction zones, Rev. Geophys., 45, 1-32, doi:8755-1209/07/2006RG000208.

Segovia, N., S. de la Cruz-Reyna, M. Mena, E. Ramos, M. Monnin, and J. L. Seidel (1989). Radon in soil anomaly observed at Los Azufres geothermal field, Michoacan; a possible precursor of the 1985 Mexico earthquake (Ms = 8.1), Nat. Hazards, 1, 319-329.

Seher, T., and I. G. Main (2004). A statistical evaluation of a 'stress-forecast' earthquake, Geophys. J. Int., 157, 187-193.

Seismological Committee of Chinese Academy of Sciences (1956), Chronological Table of Chinese Earthquakes, Vols. 1 and 2, The Scientific Publishing House, Beijing, 1,653 pp. (in Chinese).

Senior Seismic Hazard Analysis Committee (1997). Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts, U.S. Nuclear Regulatory Commission, U.S. Dept. of Energy, Electric Power Research Institute; NUREG/CR-6372, UCRL-ID-122160, Vol. 1-2.

Serpelloni, E., M. Anzidei, P. Baldi, G. Casula, and A. Galvani (2005). Crustal velocity and strain-rate fields in Italy and surrounding regions; new results from the analysis of permanent and non-permanent GPS networks, Geophys. J. Int., 161, 861-880, doi:10.1111/j.1365-246X.2005.02618x.

Shankland, T. J., A. G. Duba, E. A. Mathez, and C. L. Peach (1997). Increase of electrical conductivity with pressure as an indicator of conduction through a solid phase in midcrustal rocks, J. Geophys. Res., 102, 14741-14750.

Shebalin, P. (2006). Increased correlation range of seismicity before large events manifested by earthquake chains, Tectonophysics, 424, 335-349.

Shebalin, P., V. Kellis-Borok, A. Gabrielov, I. Zaliapin, and D. Turcotte (2006). Short-term earthquake prediction by reverse analysis of lithosphere dynamics, Tectonophysics, 413, 63-75.

Shelly, D. R. (2010). Periodic, Chaotic, and Doubled Earthquake Recurrence Intervals on the Deep San Andreas Fault, Science, 328, 1385-1388, doi:10.1126/science.1189741.

Shelly, D. R., G. C. Beroza, S. Ide, and S. Nakamula (2006). Low-frequency earthquakes in Shikoku, Japan, and their relationship to episodic tremor and slip, Nature, 442, 188-191.

Shimazaki, K., and T. Nakata (1980). Time-predictable recurrence model for large earthquakes, Geophys. Res. Lett., 7, 279-282.

Shimazaki, K., H. Sato, I. Nakabayashi, and H. Tanabe (2001). Recent progress in long-term earthquake forecasts in Japan, Chigaku Zasshi (Journal of Geography), 110, 816-827 (in Japanese with English abstract).

Shnirman, M., S. Schreider, and O. Dmitrieva (1993). Statistical evaluation of the VAN predictions issued during the period 1987-1989, Tectonophysics, 224, 211-221.

Silver, P. G., and N. J. Valette-Silver (1992). Detection of hydrothermal precursors to large northern California earthquakes, Science, 257, 1363-1368.

Singh, M., M. Kumar, R. K. Jain, and R. P. Chatrath (1999). Radon in ground water related to seismic events, Radiation Measurements, 30, 465-469.

Skordas, E., P. Kapiris, N. Bogris, and P. Varotsos (2000). Field experimentation on the detectability of co-seismic electric signals, Proceedings of the Japan Academy, Series B-Physical and Biological Sciences, 76, 51-56.

Slejko, D., L. Peruzza, and A. Rebez (1998). Seismic hazard maps of Italy, Annali Di Geofisica, 41, 183-214.

Sobolev, G. (2001). The examples of earthquake preparation in Kamchatka and Japan, Tectonophysics, 338, 269-279.

Sobolev, G. (2008). Seismological evidence for the nucleation of two strong earthquakes, Izvestiya-Physics of the Solid Earth, 44, 873-882.

Sobolev, G. A., T. L. Chelidze, A. D. Zavyalov, L. B. Slavina, and V. E. Nikoladze (1991). Maps of expected earthquakes based on a combination of parameters, Tectonophysics, 193, 255-265.

Sobolev, G. A., V.V. Ratushny, G. S. Kushnir (1990). A concept of earthquake prediction in USSR. Moscow, IFZ AN USSR, 171.

Somerville, P., and Earthquake Engineering Research Institute Panel (2003). Securing Society Against Catastrophic Earthquake Losses: A Research and Outreach Plan in Earthquake Engineering, Earthquake Engineering Research Institute, Oakland, California, 62 pp.

Sornette, A., and D. Sornette (1989). Self-organized criticality and earthquakes, Europhys. Lett., 9, 197-202.

Sornette, D., and C. G. Sammis (1995). Complex critical exponents from renormalization group theory of earthquakes - implications for earthquake predictions, J. Phys. I, 5, 607-619.

Sornette, D., and M. J. Werner (2005). Constraints on the size of the smallest triggering earthquake from the epidemic-type aftershock sequence model, Bath's law, and observed aftershock sequences, J. Geophys. Res., 110, B08304, doi: 10.1029/2004jb003535.

St-Laurent, F. (2000). The Saguenay, Quebec, earthquake lights of November 1988-January 1989, Seismol. Res. Lett., 71, 160-174.

St-Laurent, F., J. S. Derr, and F. T. Freund (2006). Earthquake lights and the stress-activation of positive hole charge carriers in rocks, Phys. Chem. Earth, 31, 305-312.

State Seismological Bureau (1981). Report on Chinese Seismic Intensity Zonation Map, Seismological Press, Beijing, 383 pp. (in Chinese).

State Seismological Bureau (1996). An Introduction to Chinese Seismic Intensity Zonation Map (1990), Seismological Press, Beijing, 176 pp. (in Chinese).

Stark, P. B. (1996). A few considerations for ascribing statistical significance to earthquake predictions, Geophys. Res. Lett., 23, 1399-1402.

Stark, P. B. (1997). Earthquake prediction: the null hypothesis, Geophys. J. Int., 131, 495-499.

Stein, R. S. (1999). The role of stress transfer in earthquake occurrence, Nature, 402, 605-609.

Stein, R. S., A. A. Barka, and J. H. Dieterich (1997). Progressive failure on the North Anatolian fault since 1939 by earthquake stress triggering, Geophys. J. Int., 128, 594-604.

Stein, R. S., G. C. P. King, and J. Lin (1992). Change in failure stress on the southern San Andreas fault system caused by the 1992 Magnitude = 7.4 Landers earthquake, Science, 258, 1328-1332.

Stein, R. S., G. C. P. King & J. Lin (1994), Stress triggering of the 1994 M = 6.7 Northridge, California, earthquake by its predecessors, Science, 265, 1432-1435.

Stein, R. S., S. Toda, T. Parsons, and E. Grunewald (2006). A new probabilistic seismic hazard assessment for greater Tokyo, Phil. Trans. Roy. Soc. A, 364, 1965-1986, doi: 10.1098/rsta.2006.1808.

Stothers, R. B. (2004). Ancient and modern earthquake lights in Northwestern Turkey, Seismol. Res. Lett., 75, 199-204.

Stucchi, M., A. Akinci, E. Faccioli, P. Gasperini, L. Malagnini, C. Meletti, V. Montaldo & G. Valensise (2004), Mappa di Pericolosità sismica del territorio Nazionale, http://zonesismiche.mi.ingv.it/documenti/rapporto_conclusivo.pdf (in Italian)

Sykes, L. R., and W. Menke (2006). Repeat times of large earthquakes: Implications for earthquake mechanics and long-term prediction, Bull. Seismol. Soc. Amer., 96, 1569-1596.

Szeliga, W., T. Melbourne, M. Santillan, and M. Miller (2008). GPS constraints on 34 slow slip events within the Cascadia subduction zone, 1997-2005, J. Geophys. Res., 113, B04404, doi: 10.1029/2007jb004948.

Takeuchi, N., N. Chubachi, and K. I. Narita (1997). Observations of earthquake waves by the vertical earth potential difference method, Phys. Earth Planet. Inter., 101, 157-161.

Talwani, P., W. S. Moore, and J. Chiang (1980). Radon anomalies and microearthquakes at Lake Jocassee, South Carolina, J. Geophys. Res., 85, 3079-3088.

Thomas, D. (1988). Geochemical precursors to seismic activity, Pure Appl. Geophys., 126, 241-266.

Thomas, J. N., J. J. Love, and M. J. S. Johnston (2009). On the reported magnetic precursor of the 1989 Loma Prieta earthquake, Phys. Earth Planet. Inter., 173, 207-215, doi:10.1016/j.pepi.2008.11014.

Thomas, J. N., J. J. Love, A. Komjathy, and O. P. Verkhoglyadsova (2010). On the reported ionospheric precursor of the 1999 Hector mine, California earthquake (abstract), American Geophysical Union Fall Annual Meeting, poster NH31A-1342, December, 2010.

Tiampo, K. F., J. B. Rundle, S. McGinnis, S. J. Gross, and W. Klein (2002). Mean-field threshold systems and phase dynamics: An application to earthquake fault systems, Europhys. Lett., 60, 481-487.

Tiampo, K. F., J. B. Rundle, S. A. McGinnis, and W. Klein (2002). Pattern dynamics and forecast methods in seismically active regions, Pure Appl. Geophys., 159, 2429-2467.

Toda, S. (2008). Coulomb stresses imparted by the 25 March 2007 M-w=6.6 Noto-Hanto, Japan, earthquake explain its 'butterfly' distribution of aftershocks and suggest a heightened seismic hazard, Earth Planets and Space, 60, 1041-1046.

Toda, S., and Y. Awata (2008). Does the 2007 Noto Hanto earthquake reveal a weakness in the Japanese national seismic hazard map that could be remedied with geological data?, Earth Planets and Space, 60, 1047-1052.

Toda, S., J. Lin, M. Meghraoui, and R. S. Stein (2008). 12 May 2008 M=7.9 Wenchuan, China, earthquake calculated to increase failure stress and seismicity rate on three major fault systems, Geophys. Res. Lett., 35, L17305, doi:10.1029/2008gl034903.

Toda, S., R. S. Stein, K. Richards-Dinger, and S. B. Bozkurt (2005). Forecasting the evolution of seismicity in southern California: Animations built on earthquake stress transfer, J. Geophys. Res., 110, B05S16, doi:10.1029/2004jb003415.

Toya, Y., K. F. Tiampo, J. B. Rundle, C. C. Chen, H. C. Li, and W. Klein (2010). Pattern informatics approach to earthquake forecasting in 3D, Concurr. Comput.: Pract. Exp., 22, 1569-1592, doi:10.1002/cpe.1531.

Tramutoli, V., V. Cuomo, C. Filizzola, N. Pergola, and C. Pietrapertosa (2005). Assessing the potential of thermal infrared satellite surveys for monitoring seismically active areas: The case of Kocaell (Izmit) earthquake, August 17, 1999, Remote Sens. Environ., 96, 409-426.

Tributsch, H. (1982). When the snakes awake: Animals and earthquake prediction, 248 pp., MIT Press, Cambridge, MA, USA.

Tsapanos, T. M. (2008). Seismicity and seismic hazard assessment in Greece, in E. S. Husebey, editor, Earthquake Monitoring and Seismic Hazard Mitigation in Balkan Countries, pp. 253-270, Springer.

Tyburczy, J. A., and D. K. Fisler (1995). Electrical properties of minerals and melts, in Mineral Physics and Crystallography: A Handbook of Physical Constants, American Geophysical Union, Washington, DC.

Ulomov, U. I., and B. Z. Mavashen (1971). Forerunners of the Tashkent earthquake, *Izv. Akad. Nauk*, USSR, 21, 180-200.

United Nations International Strategy for Disaster Reduction Secretariat (2009). *Global Assessment Report on Disaster Risk Reduction*, ISBN/ISSN: 9789211320282, 207 pp.

Utsu, T. (1961). A statistical study on the occurrence of aftershocks, Geophys. Mag., 30, 521-605.

Utsu, T. (1971). Aftershocks and earthquake statistics (III): Analyses of the distribution of earthquakes in magnitude, time, and space with special consideration to clustering characteristics of earthquake occurrence (1), J. Faculty Sci., Hokkaido Univ., Ser. VIII, 3, 379–441.

Utsu, T. (1978). Estimation of parameters in formulas for frequency-magnitude relation of earthquake occurrence; in cases involving a parameter c for the maximum magnitude, Jishin, 31, 367-382.

Utsu, T., and A. Seki (1955). Relation between the area of aftershock region and the energy of the mainshock, Zisin (J. Seismol. Soc. Japan), Ser. 2, 7, 233–240 (in Japanese).

Uyeda, S., and M. Kamogawa (2010). Reply to Comment on “The Prediction of Two Large Earthquakes in Greece” by G. A. Papadopoulos, Eos, Trans. Am. Geophys. Union, 91,163.

Uyeda, S., M. Kamogawa, and H. Tanaka (2009). Analysis of electrical activity and seismicity in the natural time domain for the volcanic-seismic swarm activity in 2000 in the Izu Island region, Japan, J. Geophys. Res., 114, B02310, doi: 10.1029/2007jb005332.

Uyeda, S., T. Nagao, and M. Kamogawa (2009). Short-term earthquake prediction: Current status of seismo-electromagnetics, Tectonophysics, 470, 205-213, doi:10.1016/j.tecto.2008.07.019.

Valensise, G., and D. Pantosti, editors (2001). Database of potential sources for earthquakes larger than M 5.5 in Italy, version 2.0, Ann. Geofis., 44, 797-964.

Vallianatos, F., D. Triantis, A. Tzanis, C. Anastasiadis, and A. Stavrakas (2004). Electric earthquake precursors: from laboratory results to field observations, Physics and Chemistry of the Earth, 29, 339-351.

van Stiphout, T., S. Wiemer, and W. Marzocchi (2010). Are short-term evacuations warranted? Case of the 2009 L'Aquila earthquake, Geophys. Res. Lett., 37, L06306, doi: 10.1029/2009gl042352.

Varnes, D. J. (1989). Predicting earthquakes by analyzing accelerating precursory seismic activity, Pure Appl. Geophys., 130, 661-686.

Varotsos, P., and K. Alexopoulos (1984). Physical properties of the variations of the electric field of the earthquake preceding earthquakes, Tectonophysics, 110, 73-98.

Varotsos, P., K. Alexopoulos, and M. Lazaridou (1993). Latest aspects of earthquake prediction in Greece based on seismic electric signals, II, Tectonophysics, 224, 1-37.

Varotsos, P., K. Alexopoulos, K. Nomicos, and M. Lazaridou (1986). Earthquake predictions and electric signals, Nature, 322, 120.

Varotsos, P., and M. Lazaridou (1991). Latest aspects of earthquake prediction in Greece based on seismic electric signals, Tectonophysics, 188, 321-347.

Varotsos, P. A. (2005). The physics of seismic electric signals, TerraPub, Tokyo, Japan, 338 pp.

VereJones, D. (1995). Forecasting earthquakes and earthquake risk, International Journal of Forecasting, 11, 503-538.

Vergnolle, M., A. Walpersdorf, V. Kostoglodov, P. Tregoning, J. A. Santiago, N. Cotte, and S. I. Franco (2010). Slow slip events in Mexico revised from the processing of 11 year GPS observations, J. Geophys. Res., 115, B08403, doi: 10.1029/2009jb006852.

Villante, U., M. De Lauretis, C. De Paulis, P. Francia, A. Piancatelli, E. Pietropaolo, M. Vellante, A. Meloni, P. Palangio, K. Schwingenschuh, G. Prattes, W. Magnes, and P. Nenovski (2010). The 6 April 2009 earthquake at L'Aquila: a preliminary analysis of magnetic field measurements, Natural Hazards and Earth System Sciences, 10, 203-214.

Virk, H. S. (1997). Radon studies for earthquake prediction, Himalayan Geol., 17, 91-103

Voisin, C., M. Campillo, I. R. Ionescu, F. Cotton, and O. Scotti (2000). Dynamic versus static stress triggering and friction parameters: Inferences from the November 23, 1980, Irpinia earthquake, J. Geophys. Res., 105, 21647-21659.

Wakita, H., Y. Nakamura, K. Notsu, M. Noguchi, and T. Asada (1980). Radon anomaly: possible precursor of the 1978 Izu-Oshima-Kinkai earthquake, Science, 207, 882-883, doi:10.1126/science.207.4433.882.

Wallace, L. M., and J. Beavan (2006). A large slow slip event on the central Hikurangi subduction interface beneath the Manawatu region, North Island, New Zealand, Geophys. Res. Lett., 33, L11301, doi:10.1029/2006gl026009.

Wang, K. L., Q. F. Chen, S. H. Sun, and A. D. Wang (2006). Predicting the 1975 Haicheng earthquake, Bull. Seismol. Soc. Amer., 96, 757-795.

Wang, S. Y., G. Wu & Z. L. Shi (1999). Catalogue of Modern Chinese Earthquakes (AD 1912-1990, M_S 4.7), China Science and Technology Press, Beijing, 637 pp. (in Chinese).

Ward, S. N. (1997). Dogtails versus rainbows: Synthetic earthquake rupture models as an aid in interpreting geological data, Bull. Seismol. Soc. Amer., 87, 1422-1441.

Washington, J. W., and A. W. Rose (1990). Regional and temporal relations of radon in soil gas to soil temperature and moisture, Geophys. Res. Lett., 17, 829-832, doi:10.1029/GL017i006p00829.

Wei, M., D. Sandwell, and Y. Fialko (2009). A silent M_W 4.7 slip event of October 2006 on the Superstition Hills fault, southern California, J. Geophys. Res., 114, B07402, doi:10.1029/2008jb006135.

Wesson, R. L., O. S. Boyd, C. S. Mueller, C. G. Bufe, A. D. Frankel, and M. D. Petersen (2007). Revision of time-independent probabilistic seismic hazard maps for Alaska, U. S. Geological Survey Open-File Report 2007-1043.

Whitcomb, J. H., J. D. Garmany, and D. L. Anderson (1973). Earthquake prediction: Variation of seismic velocities before the San Francisco earthquake, Science, 180, 632-635.

Woessner, J. H., S. Marzocchi, W. Werner, M. J. Lombardi, A. M. Catalli, F. Enescu, B. Cocco, M. Gerstenberger, M. C. Wiemer, S. (2011). A retrospective comparative forecast test on the 1992 Landers Sequence, J. Geophys. Res., in press.

Woith, H., M. Westerhaus, O. Ergünay, J. Zschau, B. Lühr, and C. Milkereit (2009). Lessons learned from the Turkish-German project on earthquake research, Second International Seminar on Prediction of Earthquakes, Lisbon, Portugal.

Working Group on California Earthquake Probabilities (1988), Probabilities of large earthquakes occurring in California on the San Andreas fault, U.S. Geological Survey Open-File Report 1988-398.

Working Group on California Earthquake Probabilities (1990), Probabilities of large earthquakes in the San Francisco Bay Region, California, U.S. Geological Survey Circular 1053.

Working Group on California Earthquake Probabilities (1995), Seismic hazards in southern California: probable earthquakes, 1994-2024, Bull. Seismol. Soc. Am. **85**, 379-439.

Working Group on California Earthquake Probabilities (2003), Earthquake Probabilities in the San Francisco Bay Region: 2002–2031, USGS Open-File Report 2003-214.

Working Group on California Earthquake Probabilities (2007), The Uniform California Earthquake Rupture Forecast, Version 2 (UCERF 2), USGS Open-File Report 2007-1437.

Wyatt, F. K., D. C. Agnew, and M. Gladwin (1994). Continuous measurements of crustal deformation for the 1992 Landers earthquake sequence, Bull. Seismol. Soc. Amer., 84, 768-779.

Wyss, M., editor (1991). Evaluation of proposed earthquake precursors, American Geophysical Union, Washington, DC, 94 pp.

Wyss, M. (1997). Second round of evaluations of proposed earthquake precursors, Pure Appl. Geophys., 149, 3-16.

Wyss, M., and M. Baer (1981). Seismic quiescence in the western Hellenic Arc may foreshadow large earthquakes, Nature, 289, 785-787.

Wyss, M., and D. C. Booth (1997). The IASPEI procedure for the evaluation of earthquake precursors, Geophys. J. Int., 131, 423-424.

Xie, Y. S., and M. B. Cai, (1987). Compilation of Historical Materials of Chinese Earthquakes, Vols. 1 to 5, The Scientific Publishing House, Beijing, 4,471 pp. (in Chinese).

Yamazaki, Y. (1965). Electrical conductivity of strained rocks, 1, Laboratory experiments on sedimentary rocks, Bulletin of the Earthquake Research Institute, 43, 783-802.

Yikilmaz, M. B., D. L. Turcotte, G. Yakovlev, J. B. Rundle, and L. H. Kellogg (2010). Virtual California earthquake simulations: simple models and their application to an observed sequence of earthquakes, Geophys. J. Int., 180, 734-742, doi: 10.1111/j.1365-246X.2009.04435.x.

Yulin, Z., Q. Fuye, and X. Tongchun (1990). The relationship between resistivity variation and strain in a load bearing rock soil layer, Dizhen Xuebao = Acta Seismologica Sinica, 12, 87-93.

Zhao, Y., F. Qian, and T. Xu (1991). The relationship between resistivity variation and strain in a load-bearing rock-soil layer, Acta Seismol. Sin., 4, 127-137.

Zhang, Z. C., editor (1988). Earthquake Cases in China (1966-1976), Seismological Press, Beijing, China, 222 pp (in Chinese).

Zhang, Z. C., editor (1990). Earthquake Cases in China (1976-1980), Seismological Press, Beijing, China, 421 pp (in Chinese).

Zechar, J. D., and T. H. Jordan (2008). Testing alarm-based earthquake predictions, Geophys. J. Int., 172, 715-724.

Zechar, J. D., D. Schorlemmer, M. Liukis, J. Yu, F. Euchner, P. J. Maechling, and T. H. Jordan (2010). The Collaboratory for the Study of Earthquake Predictability perspective on computational earthquake science, Concurr. Comput.-Pract. Exp., 22, 1836-1847, doi:10.1002/cpe.1519.

Zielke, O., J. R. Arrowsmith, L. G. Ludwig, and S. O. Akciz (2010). Slip in the 1857 and Earlier Large Earthquakes Along the Carrizo Plain, San Andreas Fault, Science, 327, 1119-1122.

Zoback, M., S. Hickman, and W. Ellsworth (2010). Scientific drilling into the San Andreas fault zone, Eos, Transactions, American Geophysical Union, 91, 197-199.

Zoller, G., S. Hainzl, and J. Kurths (2001). Observation of growing correlation length as an indicator for critical point behavior prior to large earthquakes, J. Geophys. Res., 106, 2167-2175.

Zongjin, M., F. Zhengxiang, Z. Yingzhen, W. Chengmin, Z. Guomin, and L. Defu (1990). Earthquake prediction; Nine major earthquakes in China (1966-1976), Seismological Press, Beijing.

End Notes

1 Gruppo di Lavoro (2004), available at http://zonesismiche.mi.ingv.it/. The source model for the 2004 Italian seismic hazard map has been published in Meletti et al. (2008).

2 Bagnaia et al. (1992).

3 Basili et al. (2008).

4 Marzocchi and Lombardi (2009). This application of an aftershock forecasting model appears to have been the first operational use of short-term forecasting methods in Italy. The assessment of "significant skill" is with respect to a time-independent forecast.

5 Grandori and Guagenti (2009).

6 The Commission interviewed Mr. Giuliani on 13 May 2009.

7 Mr. Giuliani made contradictory statements to the media before and after the mainshock of 6 April 2009; see http://www.youtube.com/INGVterremoti#p/u/13/c7-9lNkA-y4 for a compilation of Giuliani's interviews.

8 Jordan et al. (2009).

9 For example, seismic data for the L'Aquila mainshock estimate the epicenter (the point on the ground surface above the hypocenter) at 42.342ºN, 13.380ºE, the hypocenter depth of 8.3 km, and the origin time of 01:32:40.4 UT (03:32:40.4 local time).

10 Seismic moment M_0 is proportional to the area of faulting times the average fault displacement. Moment magnitude is defined by $M_W = 2/3 \log M_0 - 6.03$, where the units of M_0 are newton-meters (Nm). The seismic moment of the L'Aquila mainshock determined from teleseismic waves was about 3.4×10^{18} Nm, which corresponds to $M_W = 6.3$ (Pondrelli et al., 2009).

11 The seismic energy E radiated by fault rupture is observed to be approximately proportional to its seismic moment M_0 over many orders of magnitude, which implies $\log E \sim 3/2\, M_w$; therefore, a unit increase of moment magnitude corresponds to a 32-fold increase in seismic energy. On average $E/M_0 \approx 3 \times 10^{-5}$, which corresponds to an apparent stress of ~1 MPa (Ide and Beroza, 2001).

12 INGV (2009), La sequenza sismica de L'Aquilano - Aprile 2009, http://portale.ingv.it/primo-piano/archivio-primo-piano/notizie-2009/terremoto-6-aprile/copy_of_la-sequenza-sismica-dell-aquilano-aprile-2009/view?set_language=it.

13 Gutenberg and Richter (1956). Gutenberg-Richter scaling implies that event frequency falls off as a power law in seismic moment: $N \sim M_0^{-2b/3}$.

14 Marone (1998); Boettcher et al. (2009).

15 Schorlemmer et al. (2010). Analysis of the seismic bulletin since April 16, 2005, shows that the Italian National Seismic Network is complete at M_L2.9 for the entire territory, excluding the islands of Sardinia, Pantelleria, and Lampedusa. At the DPC reporting threshold of M_L2.5, the network may miss events in southern parts of Apulia and the western part of Sicily. In the Abruzzo region, as well as elsewhere in Central and Southern Apennines, the catalogs are complete to thresholds as low as M_L1.5.

16 T. Utsu (1978); Kagan (1997b); Bird et al. (2002).

17 Voisin et al. (2000); Kilb et al. (2000); Freed (2005).

18 The number of aftershocks N above some threshold magnitude M_0 generated by a mainshock of magnitude M scales as $\log_{10} \alpha(M - M_0)$, where the *triggering exponent* α is approximately constant (Utsu and Seki, 1955); Utsu (1971).

19 The *modified Omori scaling relation* states that the aftershock rate decays as a power law in time: $n(t) = K(t + c)^{-p}$, where K, c, and p are constants, and p is usually near unity (Utsu, 1961).

20 Ogata (1988); Ogata et al. (1993); Ogata and Zhuang (2006); Helmstetter and Sornette (2002); W. Marzocchi and Zhuang (2011).

21 Helmstetter et al. (2003); Sornette and Werner (2005).

22 Helmstetter and Sornette (2003); Felzer et al. (2004).

23 The term "characteristic earthquake" was coined to describe the repetition of earthquakes which have surface ruptures with similar characteristics, in particular similar surface displacements (Schwartz and Coppersmith, 1984). More recent research indicates that ruptures have complex displacement distributions with heterogeneities at every scale (e.g., Konca et al., 2008). Therefore, this report adopts a more general definition: characteristic earthquakes are ruptures of an entire fault segment with approximately equal average displacement; i.e., similar seismic moments.

24 In a renewal point process, the times between successive events are considered to be independent and identically distributed random variables. When a rupture occurs on the segment, it resets the renewal process to its initial state. The distribution of recurrence intervals is modeled as a probability density function parameterized by a mean recurrence interval and an *aperiodicity factor*; an estimate of the latter is the coefficient of variation (the standard deviation normalized by the mean recurrence interval). Examples include the log-normal, Weibull, and Brownian passage time (BPT) distributions. See Working Group on California Earthquake Probabilities (2003).

25 Jordan (2009).

26 Cutter et al. (2008), available at www.nehrp.gov/pdf/SeismicWavesNov08.pdf.

27 Somerville et al. (2003; available at http://www.eeri.org/cds_publications/research_plan_05-2003.pdf). A recent report by the United Nations International Strategy for Disaster Reduction Secretariat (2009) noted this problem: "As countries develop, and both economic conditions and governance improve, vulnerability decreases but not sufficiently rapidly to compensate for the increase in exposure, particularly in the case of very rapidly growing low-income and low-to-middle-income countries."

28 Cornell (1968).

29 Frankel et al. (1996, 2002, 2008); Wesson et al. (2007).

30 Giardini et al. (1999).

31 Abrahamson and Shedlock (1997); Field et al. (2003).

32 In this type of point process, the 'mark' is earthquake magnitude (Vere-Jones, 1995; Ogata, 1999).

33 Molchan and Kagan (1992).

34 Field et al. (2009).

35 A consensus in favor of a probabilistic representation of prospective information was reached some years ago in weather forecasting, where deterministic predictions are called 'categorical forecasts' (Murphy, 1986).

36 Jackson (1996).

37 If a region has a mean rate of target events equal to R (the inverse of the average recurrence interval), then the Poisson probability that one or more events will occur in the region is $P_{\text{poisson}} = 1 - e^{-RT}$ for any time interval T. For forecasting intervals short compared to the recurrence interval, $P_{\text{poisson}} \approx RT$. For example, the 3-day probability of an earthquake with a recurrence interval of 300 years is approximately 3×10^{-5}.

38 Raleigh et al. (1977).

39 Based on a comprehensive review of documents and other evidence, Wang et al. (2006) concluded that "the prediction of the Haicheng earthquake was a blend of confusion, empirical analysis, intuitive judgment, and good luck."

40 Hough (2009).

41 This type of uncertainty (Shannon uncertainty) is maximized when the event probability is 50%.

42 Harte and Vere-Jones (2005).

43 Senior Seismic Hazard Analysis Committee (1997).

44 Jollifre and Stephenson (2003).

45 Zechar and Jordan (2008).

46 In Italy, the average rate of earthquakes with $M_L \geq 4$ is about 16 per year (Chiarabba et al., 2005); therefore, the Poisson probability of having no such events in a future year is only about 10^{-7}.

47 Stark (1996, 1997).

48 Murphy (1993).

49 Katz and Murphy (1997).

50 In weather forecasting, the term "verification" is used in place of "validation" (e.g., Jollifre and Stephenson, 2003). Verification substantiates that a model "does what it is supposed to do" at a specified level of precision; e. g., the mathematics is correct and properly implemented, say, in a computer code. Validation establishes that a model adequately describes the behavior of real systems within its proposed domain of applicability and that its epistemic uncertainties are properly characterized. Verification can be accomplished by comparison with other models (e.g., through cross-validation), but validation requires the comparison of model results with observations.

51 Jordan et al. (2003).

52 Reid (1911).

53 *Paleoseismology* is the study of prehistorical earthquakes using information from the geologic record, such as disturbances of soil layers exposed by digging trenches across active faults; in favorable situations, the

disturbed layers can be dated using radiocarbon or other radiometric dating methods (McCalpin, 2009). For examples relevant to Italy, see Pantosti et al. (1993) and Galli et al. (2008).

54 Akinci et al. (2009).

55 Biasi and Weldon (2009).

56 Ellsworth et al. (1999); Sykes and Menke (2006); McGuire (2008).

57 Uncorrelated epistemic uncertainty in the dating of events will increase the apparent dispersion of recurrence intervals, but other types of uncertainty may reduce it. For example, paleoseismic catalogs cannot resolve events that are too closely spaced, and instrumental catalogs can be too short to measure the full variation in recurrence times if they are correlated on a temporal scale comparable to the catalog interval. Although dates in the historical catalogs are often well constrained, the magnitudes and locations of events can be highly uncertain, which opens them up to interpretation bias.

58 Ben-Zion et al. (1999).

59 Ishibashi (1981; K. Mogi (1981).

60 Bakun and Lindh (1985).

61 Berkhemer et al. (1988).

62 Woith et al. (2009).

63 Savage (1993); Jackson and Kagan (2006).

64 It is now appreciated that a characteristic earthquake model for recurrence of the anticipated Tokai event is too simple, because it does not account for strong interactions with interplate (Tonankai) earthquakes to the west, nor for plate-collision interactions to the east (Heki and Miyazaki, 2001); Hori et al. (2004).

65 In the terminology of Mogi (1985), these are “seismic gaps of the first kind”; he also identifies a second type as a gap in the seismicity of smaller magnitude events before a large earthquake.

66 Fedotov (1965); Kelleher et al. (1973); McCann et al. (1979); Nishenko (1991).

67 Nishenko and Sykes (1993).

68 Kagan and Jackson (1993); Kagan and Jackson (1995); Rong et al. (2003).

69 Madariaga et al. (2010).

70 Shimazaki and Nakata (1980).

71 Murray and Segall (2002).

72 Mulargia and Gasperini (1995).

73 Power and Tullis (1995); Ouilion et al. (1996).

74 Bak and Tang (1989); Sornette and Sornette (1989).

75 Geller et al. (1997); Kagan (1997a).

76 Main (1996).

77 Emmermann and Lauterjung (1997).

78. Sammis and Smith (1999); G. Zoller et al. (2001).

79 Jordan (2006).

80 Wyss (1991, 1997).

81 Wyss and Booth (1997).

82 Contributions to an extended on-line debate conducted in 1999 by *Nature Magazine* (I. Main, editor) can be found at http://helix.nature.com/debates/earthquake/equake-frameset.html.

83 Geller (1997).

84 Hamilton et al. (1997).

85 Kanamori (2003).

86 Cicerone et al. (2009).

87 Dieterich (1978); Rice (1979).

88 Amoruso and Crescentini (2010).

89 Johnson et al. (1990).

90 Wyatt et al. (1994); Johnston et al. (1994).

91 Johnston et al. (2006).

92 Japan Meteorological Agency (2004).

93 Linde and Sacks (2002); Schwartz and Rokosky (2007).

94 Linde et al. (1996).

95 Kanamori and Cipar (1974); Cifuentes and Silver (1989).

96 Ihmlé and Jordan (1994); McGuire et al. (1996); McGuire and Jordan (2000).

97 Lohman and McGuire (2007); Llenos et al. (2009); Roland & J. J. McGuire (2009).

98 Ozawa et al. (2007); Delahaye et al. (2009).

99 Nersesov (1970); Aggarwal et al. (1973); Whitcomb et al. (1973).

100 Scholz et al. (1973).

101 Rice and Rudnicki (1979).

102 Allen and Helmberger (1973); McEvilly and Johnson (1974); Leary et al. (1979).

103 Niu et al. (2008).

104 Langbein et al. (2005); Borcherdt et al. (2006).

105 Li et al. (2006).

106 Crampin et al. (1999).

107 Seher and Main (2004).

108 Ryall and Savage (1973).

109 Aster et al. (1990, 1991).

110 In unconsolidated sediments and sedimentary rocks, the conductivity increases almost quadratically with porosity (Archie's law), whereas in dry rocks, the conductivity generally decreases when porosity increases.

111 Morat and Le Mouel (1987); Glover and Vine (1992, 1994); Tyburczy and Fisler (1995); Shankland et al. (1997); Roberts et al. (1999); Fujita et al., (2004).

112 Barsukov and Sorokin (1973).

113 Asada (1982); Jin (1985); Chu et al. (1996).

114 Park (2002).

115 Uyeda et al. (2009).

116 Gasparini and Mantovani (1978).

117 Ulomov and Mavashen (1971).

118 Holub and Brady (1981).

119 Talwani et al. (1980); Mogro-Campero et al. (1980); Fleischer (1981); Liu et al. (1985); Segovia et al. (1989); Heinicke et al. (1995); Virk (1997); Singh et al. (1999); Planinic et al. (2004); Chyi et al. (2005).

120 Wakita et al. (1980).

121 Igarashi et al. (1995).

122 Theoretical models for geochemical precursors have been summarized by Thomas (1988).

123 Hauksson (1981).

124 Washington and Rose (1990).

125 Hauksson and Goddard (1981); Einarsson et al. (2008).

126 King (1978); King and Minissale (1994); King et al. (1993, 1996).

127 Plastino and Bella (1999).

128 Giuliani presented his results at the December 2009 annual meeting of the American Geophysical Union in San Francisco and the May 2010 annual meeting of the European Geophysical Union in Vienna.

129 Montgomery and Manga (2003).

130 King (1986); Roeloffs (1988); Ma et al. (1990); Silver and Vallette-Silver (1992); Igarashi and Wakita (1995); King et al. (2006).

131 Plastino et al. (2009).

132 Freund's (2007a,b) p-hole hypothesis states that, in silicate minerals containing water, hydroxyl pairs adjacent to cation vacancies undergo an electron transfer inside the mineral matrix by which two oxygen atoms transform from their usual 2– valence state to the 1– valence state, while two protons reduce to molecular H_2. The O^- undergo spin pairing to form peroxy bonds, $O_3Si/^{OO}\backslash SiO_3$. From the viewpoint of condensed-matter physics, an O^- in an O^{2-} matrix is a defect electron or "positive hole" (p-hole); i.e. a charge carrier that resides in and travels via the O 2p-dominated valence band. A peroxy bond represents a p-hole pair, electrically inactive and dormant. When the peroxy bond breaks under deviatoric stress, p-holes are released. These charge carriers are highly mobile and turn the mineral or rock momentarily into a p-type semiconductor. Further work to confirm this condensed-matter physics would be desirable.

133 Uyeda et al. (2009).

134 Pulinets (2007).

135 Yamazaki (1965); Ispido and Mizutani (1981); Gokhberg et al. (1982); Baird and Kennan (1985); Parrot and Johnston (1989); Zhao et al. (1991); Vallianatos et al. (2004).

136 Park et al. (1993).

137 Mogi et al. (2000); Nagao et al. (2000); Skordas et al. (2000); Takeuchi et al. (1997); Enomoto et al. (2006).

138 Hobara and Parrot (2005).

139 Freund et al. (2006); Freund (2007b); Freund et al. (2007); Freund and Sornette (2007).

140 Ozaki et al. (2009).

141 Parrot (2007).

142 Akhoondzadeh et al. (2010).

143 Němec et al. (2009); Thomas et al. (2010).

144 Fraser-Smith et al. (1990).

145 Hayakawa et al. (1996).

146 Campbell (2009).

147 Thomas et al. (2009).

148 Villante et al. (2010).

149 Varotsos et al. (1993); Varotsos and Lazaridou (1991)**;** Varotsos (2005).

150 Aceves et al. (1996); Shnirman et al. (1993); Hamada (1993).

151 Geller (1996); Lighthill (1996); Mulargia and Gasperini (1992).

152 Pulinets and Boyarchuk (2004); Nagao et al. (2002).

153 Fidani (2010).

154 Papadopoulos (1999); St-Laurent (2000); Stothers (2004).

155 St-Laurent et al. (2006).

156 Ouzounov and Freund (2004); Tramutoli et al. (2005).

157 Lisi et al. (2010).

158 Pulinets et al. (2006).

159 Freund et al. (2007).

160 Eneva et al. (2008). This report examined data from the MODIS and ASTER satellites from 2000 to 2007, as well as selected images from the airborne MASTER instruments. The authors state: “While we did observe occasional temperature increases before M > 4.5 earthquakes in California, such anomalies are common at other times as well, so we concluded that they cannot be used for earthquake prediction, including the case of the two largest events (M6.0 and M6.6) during the study period.”

161 Grant and Halliday (2010).

162 Schall (1988).

163 Evernden (1976).

164 Tributsch (1982).

165 Kirschvink (2000).

166 Reasenberg (1999); Marzocchi and Zhuang (2011).

167 Data-mining techniques of this type have been successfully applied in many scientific fields, usually in the visualization or detection of objects with well determined *a priori* properties that are otherwise beyond the resolution limit of the sensor; e.g. extracting the plate number of a speeding car from a blurry photograph (e.g., Han and Kamber, 2006).

168 Keilis-Borok et al. (1988); Keilis-Borok and Kossobokov (1990).

169 Peresan et al. (1999).

170 Healy et al. (1992); Kossobokov et al. (1999); Peresan et al. (2005); Kossobokov (2006); V. G. Kossobokov & A. A. Soloviev (2008).

171 Molchan (1990, 1991).

172 Marzocchi et al. (2003).

173 Main et al. (2008).

174 Shebalin et al. (2006).

175 Sobolev (2001).

176 Shebalin (2006).

177 Sornette and Sammis (1995).

178 Rundle et al. (2002); Tiampo et al. (2002).

179 Toya et al. *(*2010).

180 Tiampo et al. (2002).

181 According to Holliday et al. (2008), “This method was used by Rundle et al. (2002) to forecast m = 5 and larger earthquakes in California for the time period 2000–2010. This forecast successfully predicted the

locations of 16 of the 18 large earthquakes that have subsequently occurred.” This result is difficult to assess because the alarm regions corresponding to the predictions are not explicitly defined.

182 Varnes (1989).

183 Main (1999).

184 Bowman et al. (1998); Bowman and King (2001); Mignan et al. (2007).

185 Greenhough and Main (2009).

186 Hardebeck et al. (2008).

187 Zoback et al. (2010).

188 A statement by K. Aki (1989) provides guidance towards this research objective: “I would like to define the task of the physical scientists in earthquake prediction as estimating objectively the probability of occurrence of an earthquake within a specified space and time window, under the condition that a particular set of precursory phenomena were observed.”

189 Gomberg et al. (2003).

190 Stein et al. (1992, 1994); Harris and Simpson (1992); Toda et al. (2005).

191 Cocco and Rice (2002).

192 Stein (1999); Liu et al. (2009); Chen et al. (2010).

193 Rydelek and Sacks (1999); Deng and Sykes (1997); Harris et al. (1996); Harris and Simpson (1998); Marzocchi et al. (2003); Toda et al. (2005).

194 Stein et al. (1997).

195 McCloskey et al. (2005).

196 Kerr (2007).

197 Dieterich (1994); Gomberg et al. (2000).

198 Marzocchi et al. (2009).

199 Ward (1997); Rundle et al. (2006); Yıkılmaz et al. (2010).

200 Dieterich and Richards-Dinger (2010).

201 Mallman and Parsons (2008); Parsons and Velasco (2009).

202 Felzer and Brodsky (2006); Main (2006).

203 Harris and Day (1993); Oglesby (2008); Doser et al. (2009).

204 Pollitz (1992); Piersanti et al. (1995); Peltzer et al. (1996); Pollitz et al. (2004).

205 Kenner and Segall (2000).

206 Obara (2002); Miller et al. (2002); Kao et al. (2005); Szeliga et al. (2008).

207 Liu and Rice (2005, 2009); A. M. Rubin (2008); Perfettini and Ampuero (2008).

208 Shelly et al. (2006).

209 Wallace and Beavan, (2006); Larson et al. (2007); Delahaye et al. (2009); Brudzinski et al. (2010); Vergnolle et al. (2010).

210 Linde et al. (1996); Murray and Segall (2005); Lohman and McGuire (2007); Wei et al. (2009).

211 Nadeau and Dolenc (2005); Gomberg et al. (2008).

212 Shelly (2010).

213 For example, slow slip events in the Cascadian subduction zone show a 14-month periodicity, and Mazzotti & Adams (2004) have speculated that “during the 2-week slow-slip events, the weekly probability of a great earthquake is about 30 to 100 times as high as it is during any week of the rest of the year.”

214 G can vary from 0 to $1/P_{poisson}$; $G > 1$ corresponds to a probability gain, and $G < 1$ to a probability loss (Aki, 1981).

215 Jordan and Jones (2010).

216 Fujiwara et al. (2006).

217 Cornell and Winterstein (1988).

218 Working Group on California Earthquake Probabilities (2003).

219 Parsons and Geist (2009).

220 Zielke et al. (2010); Grant Ludwig et al. (2010).

221 Page et al. (2011).

222 Daeron et al. (2007).

223 Hubert-Ferrari et al. (2005).

224 Pace et al. (2006).

225 The S2 INGV/DPC project (led by E. Faccioli and W. Marzocchi) has developed several alternative models. The first is based on faults with independent characteristic earthquakes; the second introduces fault interactions using the Coulomb failure function, and the third filters the recurrent faults in space and adds time-independent background seismicity.

226 Reasenberg and Jones (1989, 1994).

227 Gerstenberger et al. (2005, 2007); daily forecasts available at http://earthquake.usgs.gov/earthquakes/step/.

228 Holliday et al. (2008).

229 Helmstetter et al. (2006).

230 Console et al. (2010).

231 Unpublished calculation by W. Marzocchi (2009).

232 McGuire et al. (2005).

233 Agnew and Jones (1991); Michael and Jones (1998).

234 Michael (2011).

235 Marzocchi and Zhuang (2011).

236 Parsons et al. (2000).

237 Stein et al. (2006); Bozkurt et al. (2007).

238 Toda et al. (2008).

239 Parsons (2002).

240 Huc and Main (2003).

241 Woessner et al. (2011).

242 Rhoades and Evison (2004).

243 Rhoades and Evison (2005).

244 Rhoades and Gerstenberger (2009).

245 Marzocchi and Lombardi (2008).

246 Lombardi and Marzocchi (2009).

247 In the most complete sense, forecast quality is characterized by the totality of statistical characteristics embodied in the joint probability distribution of forecasts and observations. This characterization corresponds to what in meteorology is called the *distributions-oriented approach* to validation (Murphy and Winkler, 1987).

248 Field (2007); see also papers in *Seismol. Res. Lett.* **78***, no. 1*, 2007.

249 Schorlemmer et al. (2007).

250 Schorlemmer et al. (2010).

251 Zechar et al. (2009).

252 Forecasting models currently under test in CSEP include time-independent models and time-dependent models updated at regular intervals (e.g., 1-day, 3-month, and 1-year); see http://www.cseptesting.org/.

253 The prospective nature of the testing is subject to one caveat: the CSEP experiments are lagged by the time needed to finalize the seismicity catalogs required for the testing, which can range from about one month up to a year or more. The INGV catalog used for CSEP testing in Italy is produced about eight months in arrears.

254 Marzocchi et al. (2010).

255 Website for the Collaboratory for the Study of Earthquake Predictability is http://eu.cseptesting.org/.

256 Graves et al. (2010).

257 National Research Council Committee on Estimating and Communicating Uncertainty in Weather and Climate Forecasts (2006).

258 In his review of how forecasts might be applied to earthquake risk reduction, Vere-Jones (1995) concludes: “Such considerations reinforce the view that the primary task of the scientist concerned with earthquake prediction should be the development of theories and models which allow such conditional probabilities to be explicitly calculated from past information. On the other hand the development of an alarm strategy, including the setting of suitable threshold levels and the actions which should follow an alarm, should not be the responsibility of the scientist, but of a group representing appropriate local and national authorities, with the scientist (not to mention the statistician) in an advisory role.”

259 A series of special studies about seismic vulnerability in Italy was published in 1999-2001 by the Gruppo Nazionale per la Difesa dai Terremoti (GNDT) as part of the project, “Progetto per la rilevazione della vulnerabilità del patrimonio edilizio a rischio sismico e di formazione di tecnici per l'attività di prevenzione sismica connessa alle politiche di mitigazione del rischio sismico nelle regioni dell'Italia meridionale," (e.g., GNDT, 1999); see http://gndt.ingv.it/Pubblicazioni/Censimenti.htm.

260 Paté and Shah (1979); Allen (1980); Anderson (1981); Jones (1996).

261 van Stiphout et al. (2010).

262 Zhang (1988, 1990); Chen et al. (1992).

263 Fu and Liu (1956); Chen (1986, 2001).

264 Chen et al. (2002).

265 Seismological Committee of Chinese Academy of Sciences (1956); Li (1957); Lee (1960); Gu (1983a,b); State Seismological Bureau (1981); Xie and Cai (1987); Hu (1990); Min (1995); State Seismological Bureau (1996); Wang et al. (1999).

266 National People's Congress of the People's Republic of China (2008).

267 Li (1986); Quan (1988); Wang et al. (2006).

268 Chen and Wang (2010).

269 Papazachos and Papazachou (1997); Papadopoulos et al. (2000).

270 The home page of NOAGI is http://www.gein.noa.gr/.

271 The Greek seismic hazard zonation map can be found in http://www.oasp.gr/index.php?option=com_content&view=article&id=47%3A 2010-02-05-11-20-24 & catid.

272 Papadopoulos and Kijko (1991).

273 Lyubushin et al. (2002).

274 Papaioannou and Papazachos (2000).

275 Tsapanos (2008).

276 Wyss and Baer (1981); Papazachos and Comninakis (1982); Papadopoulos (1988); Latoussakis and Stavrakakis (1992); Papadopoulos et al. (2000); Papazachos and Papazachos (2001); Papadopoulos et al. (2006).

277 Varotsos and Alexopoulos (1984); Varotsos et al. (1986, 1993).

278 Critical discussions of the VAN methodology and results can be found in Mulargia and Gasperini (1992), Geller (1996), and Lighthill (1996). A recent discussion is given by Papadopoulos (2010) and Uyeda and Kamogawa (2010).

279 Lagios et al. (2007).

280 Petrini et al. (1981).

281 Slejko et al. (1998).

282 Stucchi et al. (2004), available at http://zonesismiche.mi.ingv.it/documenti/rapporto_conclusivo.pdf (in Italian).

283 Valensise and Pantosti (2001); Meletti et al. (2008).

284 See the JMA website http://www.jma.go.jp/jma/indexe.html for details.

285 See HERP website http://www.jishin.go.jp/main/index-e.html for details.

286 Ishibashi (1977, 1981).

287 The ability of the real-time strainmeter array to detect an M_W 6 slow slip on the plate boundary has been demonstrated in Tokai region (Kobayashi et al., 2006). However, JMA does not claim that the prediction will be always successful, because detectable pre-slip has not been demonstrated to be a diagnostic precursor. Recent improvements on observation and theory indicate that there are intermediate regions between completely locked and stable sliding regions on plate boundary.

288 Procedures are outlined on the JMA website (http://www.jma.go.jp/en/quake_tokai/).

289 An earthquake report is to be issued when (1) a small anomaly is observed that is insufficient to be interpreted as being directly related to the occurrence of the Tokai Earthquake, or (2) a number of anomalies are observed that are interpreted as being irrelevant to the occurrence of the Tokai Earthquake (i.e. indicating no risk of such an earthquake). An earthquake advisory is to be issued when a number of anomalies are observed that are interpreted as indicating an increasing possibility of the Tokai Earthquake occurring. An earthquake warning is to be issued when anomalies are observed that are interpreted as indicating the Tokai Earthquake is expected to occur.

290 HERP and JMA have recently announced that they will forecast earthquake swarm activity of the eastern Izu peninsula, beginning in April, 2011. Earthquake swarms have occurred repeatedly in this region since 1978, and intensive observational research has revealed that the seismic activity is produced by magma injection into the crust as a dikes. The dike injections can be detected and evaluated by strainmeters deployed around the source area. A statistical study of past activity has shown a linear correlation between the strain change in the initial stage and subsequent swarm activity. The largest event and total number of earthquakes will be forecast from the amount of strain in the initial 24 hours, and the duration of the swarm activity will be forecast from the number of magma-injection events that have been detected. For the scientific background on these forecasting procedures (Morita et al., 2006).

291 N. Hirata (2004).

292 Shimazaki et al. (2001); see also the HERP website http://www.jishin.go.jp/main/index-e.html for details.

293 The 2005 Western Fukuoka earthquake (M_W 6.6), the 2007 Noto Hanto earthquake (M_W 6.7), and the 2007 Niigata Chuetsu-oki earthquake (M_W 6.6) occurred in near-coastal areas of the Japan Sea, where insufficient surveys had been conducted (Toda and Awata, 2008). The Iwate-Miyagi earthquake (M_W 6.9) occurred to the south of the evaluated fault, where little evidence for a surface fault trace had been found (Ohta et al., 2008).

294 Earthquake Research Committee, *National Seismic Hazard Maps for Japan (2005)*, Headquarters for Earthquake Research Promotion, Report issued on 23 March 2005, 158 pp., available in English translation at http://www.jishin.go.jp/main/index-e.html; Fujiwara et al. (2006).

295 The official versions of hazard maps are provided in Japanese by NEID at the Japan Seismic Hazard Information Station (J-SHIS) http://www.j-shis.bosai.go.jp/, which contains links to English-language versions. The probabilistic seismic hazard maps show exceedance probabilities above a fixed JMA shaking intensity for a 30-year period, and JMA intensities at a fixed exceedance probabilility for various return periods. The scenario earthquake shaking maps show JMA intensities for specified sources.

296 Obara et al. (2005).

297 Nanjo et al. (2010).

298 Kamigaichi, et al. (2009).

299 Details the JMA earthquake early warning procedures are posted on the website http://www.jma.go.jp/jma/en/Activities/eew.html.

300 Keilis-Borok and Kossobokov (1987); Kossobokov et al. (1990); Keilis-Borok et al. (1990); Kossobokov et al. (1999); Kossobokov and Soloviev (2008).

301 Fedotov (1965, 1968).

302 Fedotov et al. (2008).

303 Keilis-Borok and Kossobokov (1987); Kossobokov et al. (1990); Sobolev et al. (1991); Sobolev (2001).

304 Fedotov et al. (1999); Sobolev (2008).

305 Sobolev et al. (1990).

306 The program is managed by the U. S. Geological Survey's Earthquake Hazards Program; see http://earthquake.usgs.gov/hazards/.

307 Building Seismic Safety Council (2003).

308 Working Group on California Earthquake Probabilities (1988, 1990, 1995, 2003, 2007).

309 Wesson et al. (2007), available at http://pubs.usgs.gov/of/2007/1043/.

310 *Revised Charter of the National Earthquake Prediction Council*, signed by USGS acting director P. Patrick Leahy on 23 January 2006. The U.S. General Services Administration has since streamlined the requirements for chartering federal advisory councils; therefore, the 2010 edition of the NEPEC charter, signed by USGS Director M. McNutt, is briefer (and less informative) than the 2006 edition summarized in the text of this report.

311 Southern San Andreas Working Group (1991), Short-Term Earthquake Hazard Assessment for the San Andreas Fault in Southern California, USGS Open File Report 91-32. The probability thresholds in this report were adapted from those originally set for the Parkfield region of California by W. H. Bakun K. S. Breckenridge, J. Bredehoeft, R. O. Burford, W. L. Ellsworth, M. J. S. Johnston, L. Jones, A. G. Lindh, C. Mortensen, R J. Mueller, C. M. Poley, E. Roeloffs, S. Schulz, P. Segall & W. Thatcher (1987), *Parkfield, California, Earthquake Prediction Scenarios and Response Plans*, USGS Open File Report 87-192.

312 Level-A advisories were issued in several cases in the 1980's, prior to the Southern San Andreas Working Group report, two for the Parkfield region and two following M5 earthquakes in the Lake Elsman region (Harris, 1998, available at http://pubs.usgs.gov/pp/pp1550/pp1550b/pp1550b.pdf).

313 The CEPEC methodology was based on the formulation by D. Agnew & L. M. Jones (1991); for a recent review, see Michael (2011).

314 Bonanno et al. (2007); Magsino (2009).

315 Mileti et al. (1981); Mileti and Darlington (1997); Lindell et al. (2009).

316 These findings and recommendations are identical to those released by the Commission on 2 October 2009 (Jordan et al., 2009).

317 The seismicity of Italy is monitored by the Centro Nazionale Terremoti of INGV in Rome; data are publicly available at the CNT website, http://cnt.rm.ingv.it.

318 INGV bulletin (November, 2009); http://bollettinosismico.rm.ingv.it/2009_04_01/2009_04_01.lst.
319 Chiarabba et al. (2009); Anzidei, et al. (2009); Atzori et al. (2009).
320 EMERGEO Working Group (2010).
321 Boschi et al. (2000).
322 Galadini and Galli (2000).
323 D'Agostino et al. (2008).
324 Roberts and Michetti, (2004).
325 Bagnaia et al. (1992).
326 Papadopoulos et al. (2010).
327 Serpelloni et al. (2005).