DEPARTMENT OF THE INTERIOR
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Applications of the USGS Aftershock Sequence Model and Guidelines for Drafting Aftershock Forecasts

by

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1. Introduction

Many studies have sought patterns in earthquake occurence predictive of future strong earthquakes. Most of these studies have found that aftershock sequences – intense clusters of earthquakes in space and time associated with a mainshock – are the strongest non-random features in the seismicity. Aftershock sequences so strongly shape the seismicity that many investigators first attempt to identify and remove all aftershocks before searching for other patterns.

The fact that aftershocks occur in recognizable patterns in time, space and magnitude can be used to advantage. General laws describing the average occurence of aftershocks can be used as a basis for predicting, in a probabilistic sense, earthquakes after a mainshock. Two classes of earthquakes that may follow a mainshock are considered separately here. First are aftershocks smaller than the mainshock, which may themselves be strong enough to be hazardous. The second class are earthquakes larger than the mainshock that may follow it. (In this case, the original mainshock is retrospectively termed a foreshock.)

Probabilities of occurrence for both classes of earthquakes can be derived from the USGS aftershock model. The model is based on observations of the ongoing sequence and historic earthquake sequences. It can be applied in any seismically active region for which sufficient historic data have been compiled. At this time historic data have been compiled for California and central Japan; compilations for other regions are in progress.

It is the intention of the USGS to model earthquake sequences in real time following mainshocks in order to derive short term (days to months) probabilistic predictions of future earthquake activity. It is planned that this modeling will begin immediately after a mainshock, and may continue during the aftershock sequence. It is expected that this modeling will result in a set of reliable (statistically valid) short term estimates of the likelihood for additional damaging earthquakes – either strong aftershocks or a larger mainshock. It is the intention of the USGS that these probabilistic estimates will be expressed as concise statements, hereafter referred to as forecasts.

The first forecast, made immediately after the mainshock, will be based on the magnitude of the mainshock and on historic patterns of aftershock sequences. In California this forecast will be communicated first to OES, which has responsibility in California to disseminate hazard warnings to the public and to county and local officials. At later times during the earthquake sequence the USGS will make forecasts utilizing additional information about the aftershocks that have already occurred.

In the following sections of this memorandum we discuss factors considered pertinent to the formulation, design, application and dissemmination of these forecasts.

2. Areas of applicability of the aftershock model.

The range of applicability of the model reflects the range over which basic assumptions of the model are valid. (See Appendix I for a description of the model and assumptions.) The basic assumptions are (1) that earthquake sequences follow the modified Omori relation in time; and (2) that earthquake sequences follow an exponential (Gutenberg-Richter) magnitude distribution. With respect to the first assumption there is generally little dispute. Some researchers prefer an exponential time distribution, but to date so little is known about the physics controlling the time behavior of the aftershock process that there is no strong reason to reject the use of a modified Omori relation for our purposes.

With respect to the assumption of an exponential magnitude distribution, however, other models of earthquake occurence may either conflict or partially conflict. First, the idea that a given region is physically incapable of producing earthquakes greater than some specified magnitude truncates the model's magnitude distribution. The arguments for such a magnitude limit may vary with region and researcher, but sometimes a concensus for one exists. In these cases, the model can be modified to accomodate this additional constraint. Therefore, when the USGS considers the idea of a maximum magnitude in a given region to be a significant factor, it should adopt a truncated magnitude model. Such a situation occurred in the 6 March, 1989, Obsidian Buttes $M4.7$ earthquake sequence (see Appendix III).

Another potential conflict with the model can arise if an aftershock sequence is located near a fault segment that is thought, for independent reasons, to be close to failure (and, accordingly, has been assigned a high intermediate-term probability for a large earthquake). In these cases the aftershock model may underestimate the actual probability for large events in the sequence, and the model probability should be considered a lower bound. For example, the model probability of a $M \geq 5.5$ earthquake occurring in the 72-hour interval after a magnitude 3.5 event at San Ardo, near the Andreas fault, is less than 0.001. However, because of its proximity to the Parkfield segment (20 km northwest of Middle Mountain and within the Parkfield Alert Zone) most researchers would judge this result to be too low. For this case, the Parkfield earthquake prediction scenario estimates the probability of a characteristic Parkfield earthquake to be 0.028.

3. Design of the forecasts.

The set of earthquakes following a mainshock are known collectively as an aftershock sequence. Analogously, we refer to the set of probability forecasts that may follow a mainshock as a "forecast sequence". Obviously, one can construct many different forecast sequences – all equally correct in a numerical sense – but differing widely in frequency of issue, earthquake magnitudes and time intervals specified, wording emphasis and tone, audience targeted, method of dissemination, etc. The primary users of aftershock forecasts are officials responsible for emergency response and the media. How should the forecast sequence be designed to best address the information needs of the users?

Public officials need an immediate forecast of the short-term probability of a larger event for use in deciding whether to issue an earthquake hazard advisory. The generic model can provide such a forecast immediately after the mainshock. Public officials also need updates to this model at appropriate intervals after the mainshock. After the Loma Prieta earthquake the USGS issued updates twice a day for 8 days, then daily for the next 9 days, and then twice weekly for the next 4 weeks. This particular schedule, which evolved as the sequence progressed, reflected our day-to-day sense during the earthquake sequence of what was needed. We have not received criticism that those forecasts were either too frequent or too infrequent. Clearly, during the early stage of an earthquake sequence, relatively frequent forecasts are needed to reflect the high and rapidly decreasing hazard; later in the sequence, less frequent forecasts are needed.

The public's need for aftershock hazard forecasts is more difficult to assess. Dennis S. Mileti, Professor of Sociology and Director of the Hazards Assessment Laboratory, Colorado State University, discussed the public's hazard information needs and perceptions in his recent testimony to Congress after the Loma Prieta earthquake (Appendix IV). Mileti proposes that the individuals who receive hazard warnings go through a three-part process: hearing, perceiving (understanding, believing or personalizng) and responding. He states that all stages of this process are sensitive to many factors related to the information content and style of the warning (Appendix IV, page 4). Mileti's comments are very relevant to aftershock forecasts, and we recommend that they be used as guidelines in the design and wording of the forecasts.

One important idea Mileti brings out is that some people tend to discount the hazard of aftershocks: "Of course aftershocks occur after earthquakes; they are smaller, and if I and my house survived the mainshock, we'll survive the aftershocks." The idea that an aftershock can be damaging – possibly more damaging than the mainshock – is not always perceived.

The public needs to understand basic facts about the typical time behavior of an earthquake sequence. They should understand that the hazard will diminish with time and eventually return to a negligible level. At the same time, they need to understand that the specific times of aftershocks cannot be predicted, except in a probabilistic sense. An effective way to convey these ideas is through a sequence of regularly spaced (*e.g.,* daily) forecasts. The slowly decreasing probabilities in these forecasts make clear both the diminishing and enduring nature of the aftershock hazard.

Characterizing the hazard with probabilities. An earthquake sequence consists of very brief periods of very high hazard (earthquakes) separated by much longer intervals of no hazard. The intervals between earthquakes appear to be random. Experiencing such a random and spiky hazard-time function is rather unusual. Other situations with a similar hazard-time function include lightening in an electric storm, incoming artillary on the battlefield and tornados during a tornado watch. These situations tend to be anxiety-raising because of the random and spiky nature of the hazard. To characterize this hazard, we use probabilities, thereby converting a spiky hazard-time function into a smooth one.

But for an individual to accept these probabilities as a believable measure of the (random and spiky) aftershock hazard requires either mathematical sophistication or faith. While probabilities convey important information, they are technical and not easily interpreted and translated by individuals into hazard-mitigative actions. These ideas were alluded to in a draft Plan for Research resulting from the recent Beckman Center (January 15-16) Workshop in Irvine, California, and summarized by Thomas L. Henyey, Professor and Chairman of Geological Sciences, University of Southern California.

Describing the hazard with probabilities can be misleading because doing so leads people to focus on the probability assigned to an earthquake rather than on its potential effects. As the estimated probabilities drop with time, the public perception of the hazard decreases. However, a $M6$ aftershock that was assigned a 2% probability of occurring is just as damaging as a $M6$ earthquake that was given a 30% chance of occurring (*i. e.,* probabilities diminish, but earthquakes either happen or they don't). The appropriate response in the 2% case in many situations will be identical to that in the 30% case: prepare. To shift the focus away from probabilities and toward hazard mitigation actions we recommend that aftershock forecasts include a narrative describing the probable effects, in terms of expected additional damage, landslides, etc., expected as a result of the earthquakes that are being forecast.

Specification of the earthquake magnitude to be forecast. Obviously, forecasts should focus on earthquakes big enough to have damaging effects. This magnitude will vary depending on local geology and the degree of regional development, but a working threshhold might be $M \geq 5$. Confusion arose during the Loma Prieta earthquake sequence forecasts from the fact that probabilities were given for both $M \geq 5$ and $M \geq 6$ aftershocks. This was too much information. The facts that a hazard is present and slowly abating are effectively conveyed by consistent announcements of probabilities for one range of aftershock magnitudes. While it is true that in the Loma Prieta sequence a magnitude 6 aftershock would cause additional damage over a larger area than one of magnitude 5, this distinction may be too fine for assimilation during the chaotic times after a strong earthquake. Thus, in future situations of this kind we recommend including in the formal language of the forecast only the probability of $M \geq 5$ aftershocks. Additional information, for example, about the expected number of magnitude 4 earthquakes, or the expected duration of felt aftershocks, may also be included, outside the formal language of the forecast.

Specification of the time intervals in the forecast. The length of the interval over which the hazard's probability is calculated and expressed characterizes the hazard perhaps even more than the numerical value of the probability assigned to that interval. While the length of interval is formally a free parameter in the methodology, the choice of this length affects how individuals will perceive the warning, and how they will respond to it. I think it is most useful to characterize the aftershock hazard as a fairly long term one. Doing so implicitely sends a message that hazard mitigation actions that take a day, a few days or even a week to accomplish are still worth doing – that the hazard has a long time scale associated with it. Based on our experience with the Loma Prieta sequence, I recommend using an interval of 3 months for expressing earthquake probabilities. Specification of this time interval in the formal forecast casts the aftershock hazard into a framework in which the continued exercise of hazard-mitigative actions clearly makes sense.

Frequency of forecasts. At the start of the Loma Prieta sequence we calculated and announced 24-hour short term forecasts. Because the probabilities associated with this very short time window decrease rapidly in the beginning of the sequence we issued forecasts twice-daily for the first 8 days. Some members of the Irvine Workshop criticised that the forecast probabilities seemed to vary too fast or erratically the first week of the Loma Prieta sequence. This criticism was also raised by some councilmembers at the January, 1990 NEPEC meeting. I think the criticism is valid, and that at fault is the original choice of a 24-hour interval over which to estimate probabilities; it is too short. Adopting 3-month intervals allows the frequency of forecasts to be reduced; daily forecasts in the beginning of the sequence will be adequate. Day-to-day changes in the probabilities estimated for 3-month intervals will be relatively slow, and less confusing.

The frequency of forecasts should be tapered as the sequence progresses. Perhaps a useful guideline for when to stop issuing forecasts is when the long term (3-month) probability of a $M \geq 5$ aftershock is less than 20%. (For Loma Prieta, this was November 20, 1989; in fact we issued our last forecast on November 30.) Figure 1 illustrates the probabilities for three actual earthquake sequences in California, and for three generic sequences. The 20% rule would result in a brief (2-3 days) period of forecasts after a generic M6 event, and about a 1-month period of forecasts after a generic M6.5 event. In the case of a large earthquake sequence, a forecast sequence terminated by the 20% rule suggested above might later be augmented with one or more additional forecasts aimed at keeping the public aware that late aftershocks are possible. For example, a forecast in January or February, 1990, advising of the continuing possibility of a late aftershock to the Loma Prieta earthquake, could have provided the public with a basis for understanding the occurrence of the April 18 $M5.5$ aftershock near Watsonville.

Wording and tone of the forecasts. The language in the forecast should both reflect the hazard levels and suggest appropriate responses. Here again, many of Mileti's comments are relevant. Language that underscores the unpredictability of aftershocks should be included. Some measure of down-home, better-safe-than-sorry advice about the need for preparation would be useful. One important purpose of issuing forecasts is to personalize the risk and thus to stimulate appropriate hazard-mitigative measures by individuals. Simply stating the presence of a hazard may contribute more to raising anxiety levels than to stimulating useful preparatory responses. The widely-held perception that the period after a strong earthquake is too late for earthquake preparation must be corrected. Thus, we recommend including language in the forecast aimed at stimulating appropriate mitigative response throughout the aftershock sequence.

Caveats in the forecast. Some people are fairly sophisticated about the meaning of probabilities. We all know what "a 50% chance of rain" means, and appropriate response is obvious: close the windows, carry an umbrella. But, as discussed above, probabilities of aftershocks are not so easily interpreted. There are no 'earthquake clouds' visable to verify the forecast, and "what is one supposed to do, anyway?" The worst case of misunderstanding I can think of is one in which a person acts on the mistaken understanding that a particular aftershock forecast meant that no earthquake would occur, and as a result unnecessarilly suffers damage or loss of life when an earthquake does occur. In order to prevent misunderstandings and to help translate the information we put out into a useable form, I propose the following text for all forecasts.

> This forecast does not assure that an earthquake will or will not occur. The earthquake-related hazards remain higher than normal throughout the aftershock sequence. Because of the higher hazard, the Geological Survey recommends that earthquake preparation and response measures, such as those described in your local telephone directory, be taken now. It is not too late to take these actions, which can reduce your risk in aftershocks.

4. Dissemination of forecasts.

The USGS will disseminate aftershock forecasts at selected times during the earthquake sequence, beginning immediately after the mainshock. Transmittal will be by FAX (assuming telephone service is available). The order and timing of the FAX transmissions will reflect the priority needs of the recipients. In California, the first forecast (immediately after the mainshock) will be sent to the California Office of Emergency Services and other government agencies (FEMA, Army Corps of Engineers) responsible for emergency response. In order to give these agencies time to respond to the information they have received, we will impose a delay of one-half hour before transmitting the forecast to the media and other recipients. The distribution list for USGS aftershock forecasts released during the Loma Prieta earthquake sequence is given in Appendix VI. To faciliate effective transmission of the forecasts to the non-English speaking media and public, the USGS will provide appropriate translations.

5. Recommended situations for applying the model.

1. After a large ($M6 \sim M7$) earthquake the model may be used to estimate probabilities for smaller ($M \geq 5$) aftershocks. Use of the model in this situation is expected to result in a series of public forecasts. (Example: 1989 Loma Prieta earthquake sequence.)

2. After a moderate ($M5 \sim M6$) earthquake the model may be used (following guideines in Section 2) to estimate probabilities for a larger earthquake. Use of the model in this situation is expected to result in one or more private communications to OES, and possibly also public forecasts. (Examples: 1989 Lake Elsman and Obsidian Buttes earthquake sequences.)

3. After a large ($M6 \sim M7$) earthquake the model may be used (following guideines in Section 2) to estimate probabilities for a larger event. In these cases the model results should be used cautiously, and in conjunction with results from other models, including gap and characteristic earthquake models, and the Agnew-Jones foreshock probability model. Use of the model in this situation is expected to result in private communications to OES and/or other agencies or groups engaged in earthquake hazard assessment or response. Normally this use of the model in these situations will not result directly in public forecasts. (Example: memorandum to the NEPEC Working Group on Earthquake Probabilities, Appendix V.)

6. Example text for an aftershock forecast following a large ($M6 \sim M7$) *earthquake.*

This is a possible example of the simplified forecast proposed for use after a large earthquake. It was modified from actual text used after Loma Prieta. It is expected that additional language will be included in press releases, describing other aspects of the earthquake and aftershock hazard, beyond this formal forecast.

> The probability for aftershocks decreases with time most rapidly during the first week after the mainshock. Then, in the following weeks and months, the probability for aftershocks decreases more slowly. It is common for a strong aftershock to occur several weeks or months after a mainshock. To assess the chances for additional damaging aftershocks, scientists rely on the typical behavior of past California sequences, and on the behavior thus far of the [name, if available] earthquake sequence. The [name, if available] aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations we are able to forecast the chance of future strong aftershocks. As of [Wednesday, November 1], there is a [35%] chance in the next 3 months of an aftershock large enough to cause damage (magnitude 5.0 or larger). Also, in the next two months, the occurrence of [two] additional magnitude 4.0 or larger aftershocks would be typical.

7. Example text for a forecast of a larger earthquake following a moderate ($M5 \sim M6$) *earthquake.*

> Based on the past history of many earthquake sequences in California, the chance that today's magnitude 6 earthquake will be followed by a larger earthquake can be estimated. The chance that a similar or larger earthquake will occur in the next 7 days is about 5% The most likely area for such a follow-on event is within 10 miles of the epicenter of today's earthquake.

8. Example text for a forecast of a larger earthquake following a large ($M6 \sim M7$) earthquake.

See Appendix V.

9. Loma Prieta earthquake sequence – revisited.

In reviewing the use of the model to forecast aftershocks of the Loma Prieta earthquake we became aware of factors that introduced undesirable (some real, some artificial) variations in the estimated probabilities. These include a change on October 24 in the estimated mainshock magnitude from 6.9 to 7.1; artificial changes associated with a numerical calculation that was performed step-wise in time, with breaks at discrete times after the mainshock; changes associated with inconsistent specification of the time interval in the forecast; and natural variations of the seismicity during the first few days of the sequence, which appear to have contributed too strongly to the final result. Variance introduced by changes in the mainshock magnitude estimate cannot be avoided. The variance introduced by the step-wise calculation was simply fixed by replacing that section of computer code with a continuous calculation. Variance introduced by the inconsistent use of forecast intervals will be eliminated by adopting a single, 3-month interval in future applications. Variance associated with seismicity variations in the first few days is decreased by introducing additional smoothing into the Bayesian formulation. This is done by raising, by a factor that tapers from 3.0 to 1.0 over 7 days, the estimated variance of the posterior estimates of the sequence parameters. This has the effect of decreasing the weight given to the posterior estimates (and increasing the weight given to the generic values) during the first week of the sequence. Figures 2 and 3 illustrate this effect on the Loma Prieta sequence.

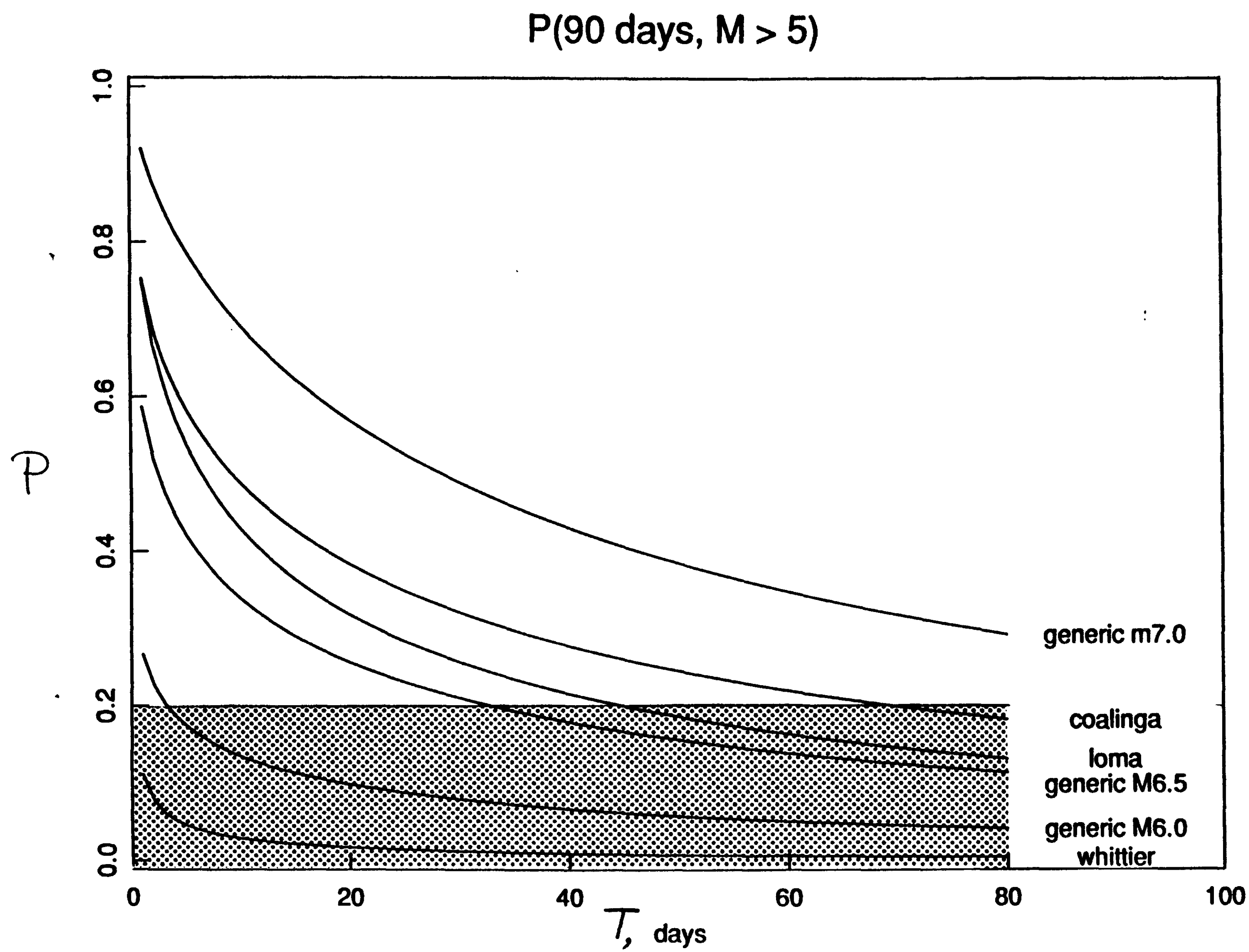

Figure 1. Probability (P) of one or more aftershocks of magnitude 5.0 or larger during a sliding 90-day window starting at the time, T, after the mainshock. Curves representing the Whittier Narrows (1987), Coalinga (1983) and Loma Prieta (1989) earthquakes are based on model calculations using the entire aftershock sequence, and do not, therefore, represent realtime estimates. They are presented this way to allow comparison with their generic counterparts. Shaded area below 20% probability illustrates cutoff times after which forecasts for each sequence would be terminated.

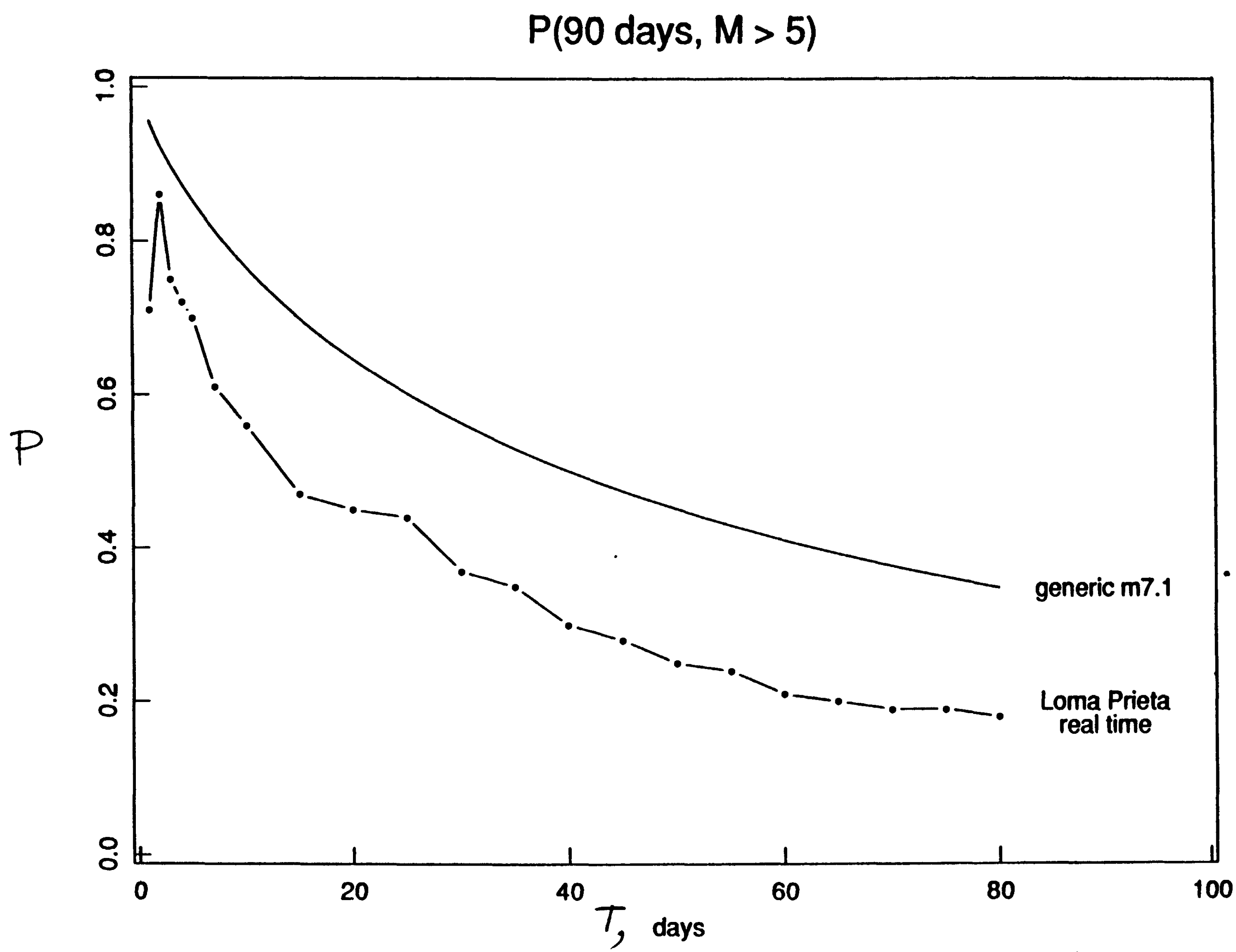

Figure 2. Real-time reconstruction of model probabilities calculated with available data from the Loma Prieta earthquake sequence. Shown are the interval probabilites for aftershocks ($M \geq 5.0$) in the sliding 90-day window beginning at time, T, after the mainshock. Data points (connected with line segments) are the actual real-time values that would now be obtained with the aftershock data available at the time T, using a mainshock magnitude of 7.1 throughout the sequence. When a mainshock magnitude of 6.9 is used, calculated probabilities for the first 6 days are 3 to 5 percent lower. Smooth curve is based on the generic model.

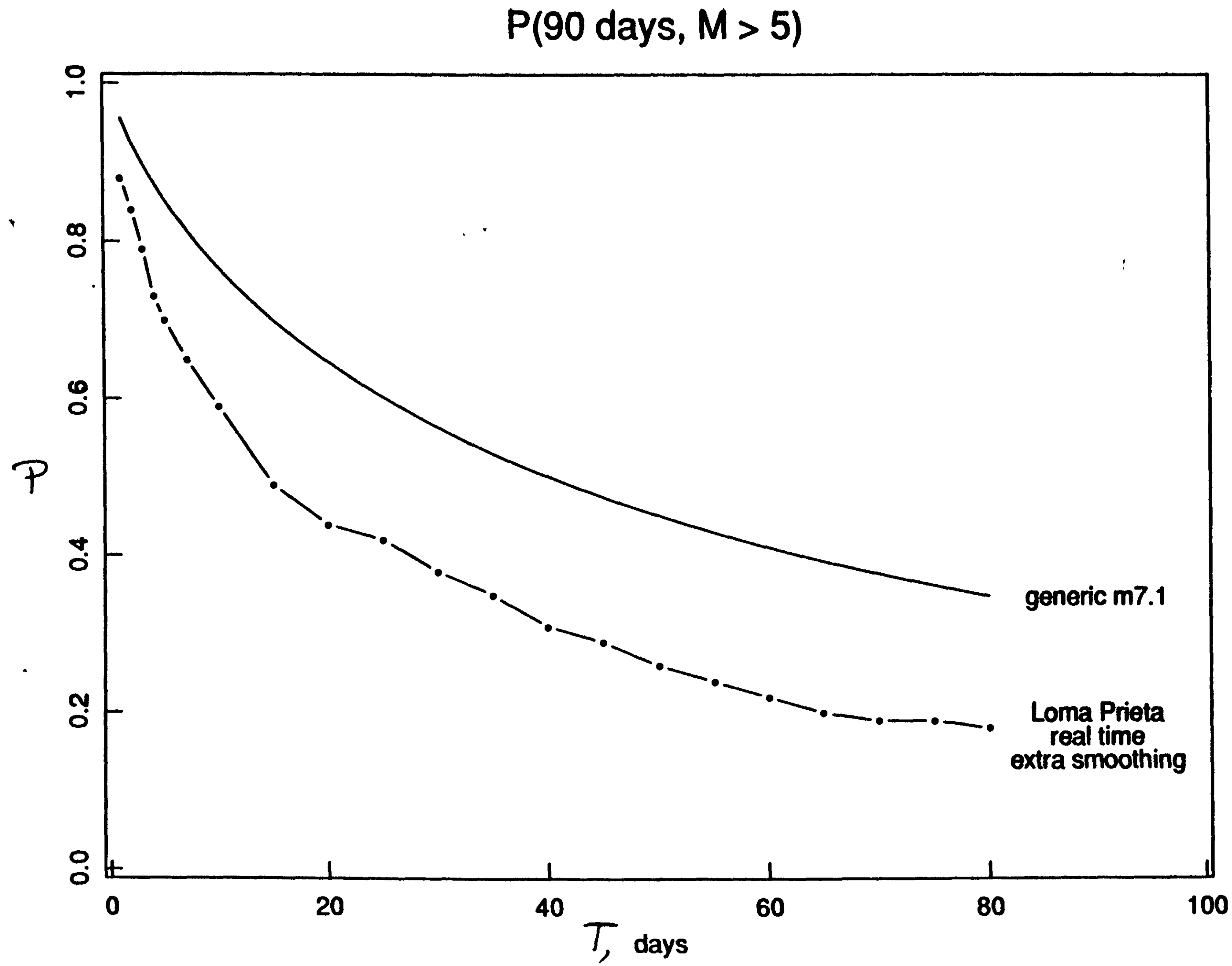

Figure 3. Same as Figure 2, but with additional smoothing added to the real-time results (see text).

APPENDICES

I. Original report in *Science* by P. Reasenberg and L. Jones on the aftershock model.

II. Technical comment in *Science* by P. Rydelek on the uncertainties in the model probabilities. Reply by P. Reasenberg and M. Matthews.

III. Technical comment in *Science* on applications of the model by P. Reasenberg and L. Jones.

IV. Testimony by Dennis Mileti before Congressional Field Hearing on the Loma Prieta earthquake.

V. Memorandum from P. Reasenberg to the NEPEC Working Group on Earthquake Probabilities.

VI. Distribution list for FAX transmissions of Loma Prieta aftershock forecasts.

VII. Press releases issued by the USGS in Menlo Park on the Loma Prieta earthquake and aftershocks, from 18 October – 30 November, 1989.

APPENDIX I.

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SCIENCE

Earthquake Hazard After a Mainshock in California

PAUL A. REASENBERG AND LUCILE M. JONES

Earthquake Hazard After a Mainshock in California

PAUL A. REASENBERG AND LUCILE M. JONES

After a strong earthquake, the possibility of the occurrence of either significant aftershocks or an even stronger mainshock is a continuing hazard that threatens the resumption of critical services and reoccupation of essential but partially damaged structures. A stochastic parametric model allows determination of probabilities for aftershocks and larger mainshocks during intervals following the mainshock. The probabilities depend strongly on the model parameters, which are estimated with Bayesian statistics from both the ongoing aftershock sequence and from a suite of historic California aftershock sequences. Probabilities for damaging aftershocks and greater mainshocks are typically well-constrained after the first day of the sequence, with accuracy increasing with time.

IN THE IMMEDIATE AFTERMATH OF A large earthquake in a populated region, numerous decisions will have to be made concerning the suspension and resumption of critical services, including the operation of utilities, industrial processes, transportation facilities, and schools. The need to resume these activities and to reoccupy structures that may have been weakened or partially damaged in the mainshock must be tempered by the expectation that one or more additional damaging earthquakes, including either a second, larger mainshock or one or more strong aftershocks, may occur (*1, 2*). Although most of the structural damage associated with an earthquake sequence occurs during the mainshock shaking, significant additional damage and loss of life has been sustained during strong aftershocks, particularly in structures weakened by the mainshock. Reliably assessing the extent of structural damage sustained in the mainshock for a particular structure may take several weeks or more. However, the need to reoccupy that structure may be urgent. To approach rationally the questions of when to resume certain activities and which structures to reoccupy, we must be able to assess the probabilities for the occurrence of both a larger mainshock and strong aftershocks.

The probability that a larger earthquake will follow an earthquake of a given magnitude has been estimated empirically for the southern California region from the occurrence rate of foreshocks (*3*). State and federal hazard evaluation and emergency response officials have included this assessment of the enhanced probability of a larger earthquake in responding to recent moderate events in California (*4*). We have developed a parametric model in which we describe stochastically an earthquake sequence and derive a probability for the occurrence of either a larger mainshock or a strong aftershock. Our model is based on data from California earthquakes, but can be applied elsewhere.

The distributions of aftershocks in space, time, and magnitude follow well-known stochastic laws (*2, 5–9*). Indeed, aftershocks can be identified only in a statistical fashion; they bear no known characteristics differentiating themselves from other earthquakes. In general, the rate of occurrence of earthquakes increases abruptly after a mainshock, and then decreases with time after the mainshock according to a power-law decay, while the earthquake magnitudes have an exponential distribution that is stationary in time (Fig. 1). We use these relations to model earthquake sequences and to estimate probabilities for the occurrence of strong aftershocks or larger mainshocks in any given time interval. We consider the combined probability that one or more additional earthquakes (strong aftershock or larger mainshock) will occur in a given magnitude range and time interval. We do not distinguish between the case of one such event occurring and that of more than one occurring; we assume that virtually all questions of public policy would have the same outcome in either case.

We model the aftershock process as a nonhomogeneous Poisson process in time with intensity, $N(t)$, obeying the modified Omori law (*7*)

$$N(t) = \frac{K}{(t + c)^p} \qquad (1)$$

where t is time after the mainshock, and K, c, and p are constants. We model the magnitude distribution following the Gutenberg-Richter relation

$$N(M) = A \cdot 10^{-bM} \qquad (2)$$

where M is the aftershock magnitude, and A and b are constants. Then the rate, λ, of aftershocks with magnitude M or larger, at the time t following a mainshock of magnitude M_m, may be expressed as

$$\lambda(t, M) = 10^{a + b(M_m - M)}(t + c)^{-p} \qquad (3)$$

where a, b, p, and c are constants. The probability, P, of one or more earthquakes occurring in the magnitude range ($M_1 \leq M < M_2$) and time range ($S \leq t < T$) is (*10*)

$$P = 1 - \exp\left[-\int_{M_1}^{M_2}\int_{S}^{T} \lambda(t, M)\,dt\,dM\right] \qquad (4)$$

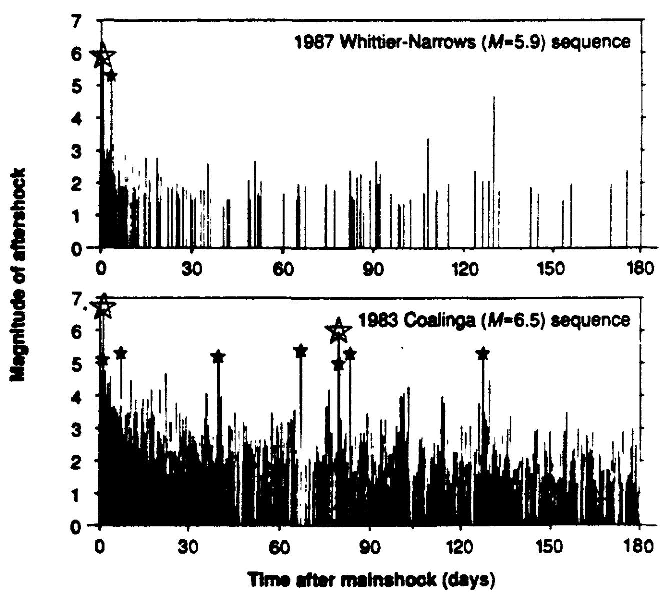

Fig. 1. Aftershock activity following two recent California earthquakes. (**A**) 1 October 1987 (M = 5.9) Whittier-Narrows earthquake. (**B**) 2 May 1983 (M = 6.5) Coalinga earthquake. Small stars indicate $M \geq 5.0$ events; large stars, $M \geq 5.5$ events.

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We estimate the interval probabilities $P(M_1, M_2, S, T)$ by evaluating Eq. 4 over selected time and magnitude intervals, using point estimates of the constant model parameters. Probabilities for aftershocks are obtained when $M_2 = M_m$. Probabilities for a larger mainshock are obtained when $M_1 = M_m$ and $M_2 = \infty$ (Tables 1 and 2).

We have estimated the parameters in Eq. 3 using earthquake data from California (*11–14*). We identified 62 aftershock sequences ($M_m \geq 5$) occurring from 1933 to 1987 using a cluster recognition algorithm (*10, 15*). Model parameters were estimated separately for each sequence with the method of maximum likelihood. We used all aftershocks with $M \geq M_m - 3$ to determine the fit to Omori's Law (parameters a and p); we used all aftershocks with $M \geq 2$ to determine parameter b (*16*). Mean parameter values determined for these 62 sequences are $\bar{b} = 0.90 \pm 0.02$, $\bar{p} = 1.07 \pm 0.03$, and $\bar{a} = -1.76 \pm 0.07$ (*17*) (Fig. 2). These values are similar to those obtained from comparable aftershock sequences worldwide. Ranges and median value of b are 0.51 to 1.33, median 0.83 for 13 sequences in Japan; 0.46 to 1.00, median 0.82 for 10 sequences in Southern California; and 0.56 to 1.36, median 0.82 for 10 sequences in Greece (7). The range of most commonly reported values of p worldwide is ~1.0 to ~1.4. Earthquake sequences in eastern California had significantly higher values of a than their counterparts in both the compressional regime of southern California and the strike-slip regime of central California, which implies that there is a higher probability for aftershocks in eastern California sequences (*18*). We refer to the distributions of parameter values determined for the 62 historic California sequences as the a priori distributions. The set of model parameters consisting of the medians of the a priori distributions ($a = -1.67$, $b = 0.91$, $p = 1.08$, $c = 0.05$) is termed the "generic California" model (Fig. 2; Table 1).

Estimated interval probabilities for the generic sequence indicate that most large aftershocks (those with magnitude one unit below the mainshock or greater) occur within a few weeks of the mainshock, and are approximately seven times as likely as a greater mainshock in any given interval (Table 1). For example, the estimated probability that at least one $M \geq 5.5$ earthquake will follow a $M = 6.5$ mainshock in a generic sequence during the 1-week interval beginning 0.01 day after the mainshock is 0.34. After 15 days, the 1-week probability drops to 0.03. The estimated probability for the occurrence of a larger mainshock in the 30-day interval beginning 0.25 days after the mainshock is 0.04 (*19*).

Primary support for the validity of the generic model for earthquakes with magnitude larger than the mainshock is obtained independently from the empirical frequency of foreshocks. During the first 7-day interval following $M \geq 5.0$ earthquakes in southern California, the probability (determined from the foreshock occurrence rate) that another earthquake of equal or greater magnitude will occur is 0.056 (*20*). The corresponding probability estimated with the generic California model is 0.049 (Table 1). The agreement between these estimates for the immediate probability of a larger mainshock provides some confidence that our model is approximately valid in this extended magnitude range. Thus, the generic model provides a useful starting point for estimating post-mainshock hazard in the absence of any information about a particular sequence other than the mainshock magnitude. However, departures from this generic behavior are expected in any given aftershock sequence.

Two recent earthquake sequences serve to illustrate such departures: the 1983 ($M = 6.5$) Coalinga earthquake and the 1987 ($M = 5.9$) Whittier-Narrows earthquake (*21–23*). The magnitude distributions for these sequences differed slightly ($b = 0.73$ for Whittier-Narrows, $b = 0.89$ for Coalinga). The Coalinga sequence was more productive in aftershocks ($a = -1.47$) than the Whittier-Narrows sequence ($a = -1.60$), and the decay in its rate of aftershocks was slower ($p = 1.06$ for Coalinga; $p = 1.50$ for Whittier-Narrows). These contrasts in model parameters account for substantial differences in the resulting probability estimates, both between these sequences and relative to the generic sequence, and illustrate the variation of hazard among California earthquake sequences (Table 2) (*24*). For example, the calculated probability for the occurrence of one or more $M \geq 4.9$ events at Whittier-Narrows during the 1-week beginning 1 day after the mainshock was 0.10 (Table 2); one aftershock in this magnitude range occurred 2.8 days after the Whittier-Narrows mainshock (Fig. 1A). At Coalinga, the estimated probability for one or more $M \geq 5.5$ events during the 90-days beginning 1 day after the mainshock was 0.39; one strong aftershock ($M = 5.8$) occurred at Coalinga 80 days after the mainshock (Fig. 1B).

A much more practical use of the model is the calculation of interval probabilities for aftershocks or larger mainshocks in real time during an ongoing aftershock sequence. The model parameters for an ongoing earthquake sequence can be estimated with Bayes rule (*25, 26*). We assume that the a priori estimates of each parameter, θ, are normally distributed with some mean value θ_0 and variance σ_0^2, and that the a posteriori estimate of the parameter, determined from a sample of size n, is normally distributed with some mean $\hat{\theta}$ and variance σ^2. Then the Bayesian estimate of θ, for a mean squared error loss function, is given by

$$\hat{\theta}_B = \left(\frac{\sigma_0^2}{\sigma_0^2 + \sigma^2/n}\right)\hat{\theta} + \left(\frac{\sigma^2/n}{\sigma_0^2 + \sigma^2/n}\right)\theta_0 \quad (5)$$

Thus, Bayesian estimates, $\hat{\theta}_B$, of the model parameters can be obtained throughout the sequence, with accuracy increasing with time after the mainshock. Immediately after the mainshock, the calculation of $\hat{\theta}_B$ heavily weights the a priori mean parameter value; during the course of the aftershock sequence, the a posteriori parameter estimates are increasingly weighted as the current data become more numerous and σ^2/n becomes small compared to σ_0^2. Monte Carlo simula-

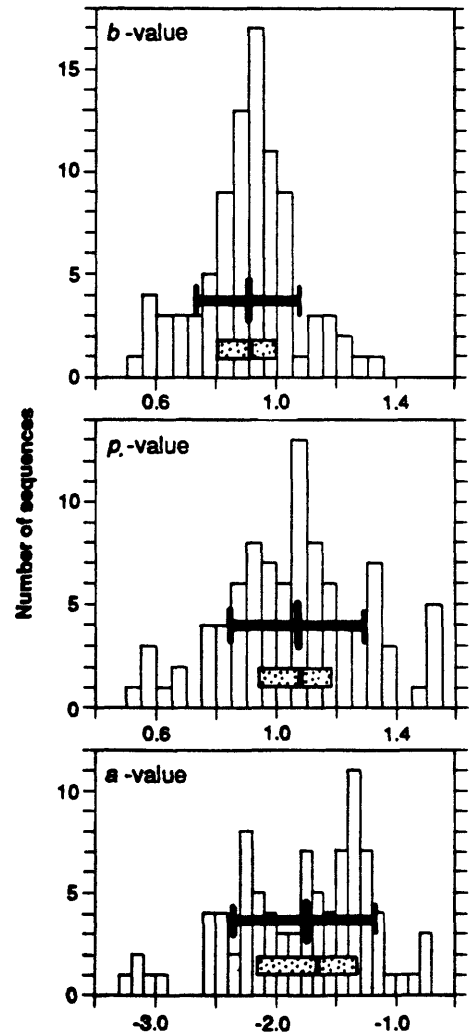

Fig. 2. Distributions of parameters (b, p, and a) determined for aftershock sequences following 62 ($M \geq 5.0$) mainshocks in California from 1933 to 1987. Solid bar indicates mean ± 1 sd. Shaded bar indicates median (central line) and upper and lower quartiles (end points) of distribution.

tions indicate that, for the generic California sequence, the a posteriori parameter estimates receive more than half the total weight within approximately 24 hours. Thus, immediately useful and increasingly accurate estimates of probabilities for aftershocks or larger mainshocks can be obtained during an ongoing earthquake sequence.

Our statistical model is completely general, and can be easily extended to other geographic or tectonic regions; only the a priori parameter values are particular to California. The ability to estimate parameters for an ongoing sequence, however, obviously depends on the availability of network processing with the capability to locate epicenters and to estimate magnitudes accurately in real time.

In the present model, the estimated values of the parameters are essentially determined from the smaller magnitude earthquakes. Justification for extending the model to larger magnitudes is provided by the close agreement between the estimated probability for larger mainshocks that we determined and the observed foreshock frequency in southern California. Furthermore, the model should be applicable at larger magnitudes for a self-similar process, and California seismicity is apparently self-similar over a wide range of magnitudes (27). Although there is some evidence that the Gutenberg-Richter magnitude relation may systematically underestimate the number of larger magnitude earthquakes worldwide (7), it adequately accounts for the California data.

We have adopted a simple inverse power-law time decay to describe aftershock rate. More sophisticated models with more parameters—such as trigger and epidemic models, models allowing for secondary or multiple aftershock sequences, and those based on a combination of power-law and exponential time decays—may be appropriate for modeling some complete sequences that include numerous observations (28, 29). However, we preferred to develop a simple model to ensure that the estimation of parameters is stable during the early hours of an ongoing aftershock sequence when precious few data are available from which to infer a larger number of parameters.

The simplification of the spatial distribution of aftershocks described above precludes any inference of the detailed spatial distribution of aftershocks or larger mainshock (30). However, from the standpoint of early hazard evaluation, detailed spatial resolution of the expected earthquake activity may be effectively limited by a lack of knowledge about the mainshock faulting process. As such data become available in the days following the mainshock, appropriate corrections to the isotropic results could be applied.

Table 1. Interval probabilities, $P(M_1, M_2, S, T)$ for the generic California aftershock sequence for strong aftershocks or larger mainshocks ($M_1 = M_m - 1$, $M_2 = \infty$), and for larger mainshocks only ($M_1 = M_m$, $M_2 = \infty$). Time intervals are described by S (interval start time, in days after the mainshock) and $(T - S)$ (duration, in days). Model parameters for the generic sequence are ($b = 0.91$, $p = 1.08$, $a = -1.67$, $c = 0.05$).

$(T-S)$	S								
	0.01	0.25	0.50	1	3	7	15	30	60
				Earthquakes with $M \geq M_m - 1$					
1	0.234	0.119	0.083	0.052	0.021	0.009	0.004	0.002	0.001
3	0.296	0.181	0.140	0.100	0.049	0.024	0.012	0.006	0.003
7	0.338	0.227	0.186	0.144	0.083	0.046	0.025	0.013	0.007
30	0.399	0.297	0.258	0.217	0.152	0.104	0.068	0.042	0.024
60	0.424	0.326	0.289	0.249	0.185	0.136	0.096	0.064	0.039
90	0.437	0.342	0.305	0.267	0.203	0.154	0.113	0.079	0.051
365	0.479	0.390	0.357	0.320	0.261	0.214	0.173	0.137	0.103
1000	0.504	0.420	0.388	0.353	0.297	0.252	0.212	0.177	0.142
				Earthquakes with $M \geq M_m$					
1	0.032	0.015	0.011	0.007	0.003	0.001	0.001	0.000	0.000
3	0.042	0.024	0.018	0.013	0.006	0.003	0.001	0.001	0.000
7	0.049	0.031	0.025	0.019	0.011	0.006	0.003	0.002	0.001
30	0.061	0.042	0.036	0.030	0.020	0.013	0.009	0.005	0.003
60	0.066	0.047	0.041	0.035	0.025	0.018	0.012	0.008	0.005
90	0.068	0.050	0.044	0.037	0.028	0.020	0.015	0.010	0.006
365	0.077	0.059	0.053	0.046	0.036	0.029	0.023	0.018	0.013
1000	0.083	0.065	0.059	0.052	0.042	0.035	0.029	0.024	0.019

Table 2. Interval probabilities, $P(M_1,M_2,S,T)$, for strong aftershocks or a larger mainshock ($M_1 = M_m - 1$, $M_2 = \infty$), following the 1987 ($M = 5.9$) Whittier-Narrows, CA, earthquake and the 1983 ($M = 6.5$) Coalinga, CA, earthquake. Time intervals are described by S (interval start time, in days after the mainshock) and $(T - S)$ (duration, in days). Model parameters for the Whittier-Narrows earthquake data were $a = -1.60$, $b = 0.73$, $p = 1.50$, and $c = 0.05$ and for the Coalinga earthquake data were $a = -1.47$, $b = 0.89$, $p = 1.06$, and $c = 0.05$.

$(T-S)$	S								
	0.01	0.25	0.50	1	3	7	15	30	60
				Whittier-Marrows (M = 5.9) Sequence; Earthquakes with $M \geq 4.9$					
1	0.393	0.141	0.084	0.044	0.012	0.004	0.001	0.000	0.000
3	0.431	0.185	0.123	0.074	0.026	0.010	0.004	0.001	0.000
7	0.448	0.208	0.146	0.095	0.040	0.017	0.007	0.003	0.001
30	0.465	0.232	0.171	0.120	0.062	0.034	0.017	0.009	0.004
60	0.470	0.238	0.178	0.127	0.069	0.040	0.023	0.012	0.006
90	0.472	0.241	0.181	0.130	0.073	0.043	0.025	0.015	0.008
365	0.476	0.248	0.188	0.138	0.080	0.051	0.033	0.021	0.013
1000	0.478	0.250	0.191	0.141	0.083	0.054	0.036	0.024	0.016
				Coalinga (M = 6.5) Sequence; Earthquakes with $M \geq 5.5$					
1	0.330	0.176	0.125	0.081	0.033	0.015	0.007	0.003	0.002
3	0.413	0.265	0.209	0.153	0.077	0.039	0.020	0.010	0.005
7	0.467	0.330	0.276	0.218	0.129	0.074	0.040	0.022	0.011
30	0.545	0.427	0.378	0.324	0.234	0.165	0.109	0.069	0.039
60	0.577	0.466	0.420	0.370	0.283	0.214	0.154	0.105	0.066
90	0.593	0.487	0.443	0.394	0.310	0.242	0.181	0.130	0.086
365	0.643	0.550	0.511	0.468	0.393	0.332	0.274	0.221	0.169
1000	0.673	0.588	0.552	0.513	0.444	0.387	0.334	0.283	0.233

REFERENCES AND NOTES

1. Utsu (2) defines "aftershock" as follows: "It is often observed that a number of earthquakes occur in a group within a limited interval of time and space. The largest earthquake in such a series is called the mainshock, and smaller ones occurring before and after the mainshock are called foreshocks and aftershocks respectively." Such a retrospective definition requires observation of the entire sequence (so that the largest earthquake in the series can be determined). In this study, we assume that a large earthquake has recently occurred, and refer to it as the "mainshock." We refer to smaller earthquakes that may follow it as "aftershocks," and any larger earthquake that may follow as a "larger mainshock."
2. T. Utsu, *J. Fac. Sci. Hokkaido Univ. Ser.* 7 **3**, No. 3 (1969).
3. L. M. Jones, *Bull. Seismol. Soc. Am.* **75**, 1669 (1985). Foreshocks in this study were limited to earthquakes within 10 km of the mainshock epicenter.
4. J. Goltz, *The Parkfield and San Diego Earthquake Predictions: A Chronology*, *Report of the Southern California Earthquake Preparedness Project* (Governor's Office of Emergency Services, Sacramento, CA, 1985).
5. T. Utsu, *Geophysics* **30**, 521 (1961).
6. _____, *J. Fac. Sci. Hokkaido Univ. Ser* 7 **3**, No. 4 (1970).
7. _____, *ibid.* **3**, No. 5 (1971).
8. _____, *ibid.* **4**, No. 1 (1972).
9. _____, *J. Phys. Earth* **22**, 71 (1974).

10. P. A. Reasenberg, *J. Geophys. Res.* **90**, 5479 (1985).
11. Data were obtained from catalogs prepared separately for southern and eastern California (*12*), northern California before 1971 (*13*), and northern California after 1971 (*14*). A variety of magnitude scales have been used in California. For mainshocks ($M \geq 5.0$), M_W (moment magnitude) was used when available; otherwise M_L (local magnitude) was used. For southern and eastern California aftershocks, we used M_L for ($M \geq 3.0$), and M_{CA} (coda amplitude magnitude) for ($M < 3.0$). For northern California aftershocks, we used M_L before 1970 and M_D (coda duration amplitude) after 1970.
12. D. D. Given, L. K. Hutton, L. M. Jones, *U.S. Geol. Surv. Open-File Rep. 87-488* (1987).
13. R. B. Darragh *et al.*, *Bull. Seismographic Stations Univ. Calif., Berkeley* **55**, 1–2 (1985).
14. S. L. Kirkman-Reynolds and F. W. Lester, *U.S. Geol. Surv. Open-File Rep. 86-157* (1987).
15. This algorithm identifies clusters of earthquakes in time and space. By defining the identified clusters as the set of aftershocks, we effectively eliminate the spatial part of the problem. Thus, from this point on, the analysis considers aftershocks as two-dimensional (time-magnitude) vectors.
16. We used $c = 0.05$ days, the value that minimizes χ^2 for the post-1970 data.
17. Errors are ± 1 standard deviation of the mean.
18. Subsets of sequences occurring in each tectonic regime in California were compared with the two-sample t test for difference in the mean of each parameter; $\bar{a}_{east} > \bar{a}_{north}$, $p < 0.02$ and $\bar{a}_{east} > \bar{a}_{south}$, $p < 0.005$.
19. Sensitivity of the calculated probabilities to variations in the model parameters was investigated. A 10% increase in a, b, c, or p, relative to the generic value, leads to probabilities for strong aftershocks at $S = 1$, $(T - S) = 365$ of 0.44, 0.35, 0.32, and 0.25, respectively, compared to the generic probability of 0.32 in Table 1. Corresponding probabilities for larger mainshocks are 0.068, 0.042, 0.046 and 0.035, compared to the generic probability 0.046 in Table 1.
20. L. M. Jones and P. A. Reasenberg, *Eos* **69**, 1305 (1988).
21. J. Bennett and R. Sherburne, Eds., *Calif. Div. Mines Geol. Spec. Pub. 66* (1983).
22. E. Hauksson *et al.*, *Science* **239**, 1409 (1988).
23. W. Ellsworth and M. Rymer, Eds., *U.S. Geol. Surv. Prof. Pap. 1487* (1988).
24. We obtained the probability estimates given in Table 2 using parameters estimated for the entire earthquake sequences; thus, they are generally better-determined than those that would have been obtained in real-time during the earthquake sequences. We present these best model estimates of aftershock probability rather than the real-time or "limited knowledge" estimates in order to best demonstrate the time- and magnitude-dependence of the calculated probabilities and to provide a uniform comparison of results for these contrasting earthquake sequences.
25. R. T. Hogg and A. T. Craig, *Introduction to Mathematical Statistics* (Macmillan, New York, 1978).
26. A. H. Bowker and G. J. Lieberman, *Engineering Statistics* (Prentice Hall, Englewood Cliffs, New Jersey, ed. 2, 1972).
27. Y. Y. Kagan and L. Knopoff, *J. Geophys. Res.* **86**, 2853 (1981).
28. Y. Ogata, *J. Phys Earth* **31**, 115 (1983).
29. ———, *J. Am. Stat. Assoc.* **83**, 9 (1988).
30. The empirical (isotropic) spatial distribution of strong aftershocks in California was determined from the California data. The median distance between $M \geq 5.0$ aftershocks and their mainshock epicenter is 5 km. The 80 percentile distance is 9 km.
31. We thank M. V. Matthews for providing technical assistance throughout the study, B. Ellsworth and Y. Ogata for helpful discussions and suggestions, and R. D. Brown, for initially stimulating our interest in this problem.

20 September 1988; accepted 23 December 1988

APPENDIX II.

SCIENCE

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California Aftershock Model Uncertainties

P. A. Reasenberg and L. M. Jones (*1*) have estimated probabilities for the occurrence of large aftershocks in varying time intervals after a mainshock in California. These probabilities were calculated from a proposed "generic California" model of aftershock occurrence. The model has four parameters (*a*, *b*, *c*, and *p*), which are determined from an average of 62 previous aftershock sequences that had occurred throughout California from 1933 through 1987. Their plan is to use the a priori generic model as an initial estimate for any aftershock sequence, but then to update the model parameters (and the probabilities) as real-time data about the frequency and magnitudes of the aftershocks become available. In their report, however, tables are provided for the probabilities of hazardous aftershocks that are based on either the a priori estimates of the generic model (*1*, table 1) or on the final a posteriori values from an aftershock sequence (*1*, table 2); thus the utility of the update scheme is not clearly demonstrated. Moreover, because of inherent uncertainties probability estimates based on the generic model alone (*1*, table 1) are suspect.

The deviations in the parameters of the generic model (SD's of 18 to 33%) are seen in the histograms in figure 2 of their report. (The histograms contain about 45% more data values than the quoted 62 aftershock sequences.) Here, chi-squared tests were applied to the histograms of the *a* and *p* parameters, with the result that the null hypothesis of Gaussian distributions can be rejected at the $P = 0.05$ significance level ($\chi^2_a = 40.8$, $P = 0.024$; $\chi^2_p = 32.7$, $P = 0.036$). In fact, the values in the histogram of the *a* parameter spanning nearly ±2 SD of the mean, produce a chi-squared statistic ($\chi^2 = 28.2$, $P = 0.059$) that does not formally reject the null hypothesis of a uniform distribution (5% significance level). The large uncertainties in these parameters can be shown to have a large effect on the estimated probabilities.

For example, consider estimating the probability of a large aftershock ($M \geq 5.5$) in the 24 hours immediately after a $M = 6.5$ mainshock in California. This would seem to be the time of the most value of the generic model, since Reasenberg and Jones have found that after about a day the model parameters are weighed more heavily by the real-time data from the aftershock sequence itself than by the a priori generic estimates. Allowing ±1 SD in the two parameters that tested non-Gaussian (*a* and *p*), their equation 4 results in a spread of the estimated probability from 4 to 88%, compared with the 23.4% they tabulated from the median values of the generic model.

As another example, consider the probability of a large aftershock in the time interval 3 to 30 days after a mainshock. Uncertainties of ±1 SD again in both *a* and *p* produce a spread of from 2 to 81%, compared with the tabulated value of 15.2%. According to Reasenberg and Jones, however, in this example the first 3 days of data after the mainshock can be used to update the parameters. This would presumably reduce the variance and thus decrease the spread in the above probability in accordance with the general scheme of going from table 1 to table 2 with real-time data. But in their report, no quantitative amount of variance reduction is given; thus no evaluation can be made of the reliability of the proposed update scheme in estimating probabilities for aftershocks.

In view of probable non-Gaussian statistics, the means of including the a priori generic averages into the update scheme is not readily apparent. In equation 5, Reasenberg and Jones suggest using a form of Bayes rule that assumes Gaussian statistics; this does not appear to be justified, and I believe alternative formulations or methods must be considered. A related question in non-Gaussian statistics is how close the mean value is to the most probable value of the data. As a worst-case illustration, consider rolling a die, that is, samples from a uniform distribution. An estimate, to any desired accuracy, of the mean value of the underlying stochastic process can be obtained by repeated rolls of the die. A histogram of the rolls provides constraints on the possible outcome of any roll of the die. But the next roll is unpredictable with any a priori model of the data. This illustration pertains to a discrete, limited process and obviously does not represent a continuous physical system, but the message is clear. In the aftershock model the *a* parameter is a measure of the production of aftershocks. The California average of *a* may therefore not be the best estimate (that is, the most probable) for describing aftershocks occurring in different tectonic settings of the state. Estimating model parameters from subsets of the data which focus on regional tectonics may actually prove more useful.

In addition to *a* and *p*, the other parameters (*b* and *c*), introduce even more uncertainty into the model. Therefore, the a priori generic model by itself appears to be unreliable in estimating probabilities of aftershocks because of poor constraints on some model parameters. Before the availability of real-time data, the generic model may have value as a predictive tool, but only in the broadest sense of assessing best- or worst-case scenarios for possible damaging aftershocks. To use it beyond its known time limitations, however, and without stating the important uncertainties, as in table 1 of Reasenberg and Jones, tends to give the apparent and misleading impression that aftershocks in California are reliably predictable.

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REFERENCES

1. P. A. Reasenberg and L. M. Jones, *Science* **243**, 1173 (1989).

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Response: Rydelek criticizes our approach (*1*) to modeling the post-mainshock earthquake hazard, citing the existence of large uncertainty in the generic model results and alleging the unsuitability of our application of Bayes rule for the estimation of probabilities at times after the mainshock. His comments question the overall utility of our model for hazard assessment, and his main point concerns the uncertainty in the probabilities for earthquakes estimated for the generic model.

We first correct a mistake and amend terminology in our original report. Rydelek notes that the number of observations in our original figure 2 exceeds the stated number of earthquake sequences used in our formulation of the generic model. The stated number, 62, is correct, as are the parameter means, medians, and standard deviations. Unfortunately, the histograms shown in that figure were incorrect and do not represent those 62 sequences. The correct histograms are shown in Fig. 1. This error does not affect the results we originally reported.

We have refered to our probability estimates as Bayesian because they have the form of the posterior mean in the case that both the prior and sampling distributions are Gaussian. The relevant probability distributions are not Gaussian, so our estimates do not derive formally from Bayes rules. We will therefore refer to them here as the Reasenberg-Jones (RJ) estimates, while noting that their statistical informality does not diminish their effectiveness in meeting the needs for which they are designed. Our ad hoc algorithm uses only first and second moments of observed distributions in a simple fashion to produce accurate reflections of our best current knowledge of the behavior of aftershock sequences. We do not believe that a more statistically formal alternative method would yield appreciably different results.

Rydelek is correct in stating that the variance in the a priori model parameters for California earthquake seqences (in our original figure 2) is the major source of uncertainty in the interval probabilities calculated for the generic model. We stated in our report that the generic model provides a useful starting point for estimating post-mainshock hazard but that departures from the generic behavior can be expected in any particular sequence. By definition, a generic model of a process—one based solely on the central tendencies of a priori distributions of the parameters representing the process—provides information about the expected value and standard deviation of a future observation. Our generic model provides estimates of the probability of earthquakes after a mainshock. We did not include in our original report an analysis of the uncertainties in the generic model probabilities. While we stated that these uncertainties decrease rapidly with time after the mainshock because of the inclusion of observations from the current earthquake sequence, we did not demonstrate this behavior. We now more fully explore this aspect.

We investigated the uncertainties in probabilities estimated from both the generic model and from an ongoing earthquake sequence at selected times after the mainshock by conducting a series of experiments employing a Monte Carlo technique. The RJ probability estimates are given by linear combination of a component estimated from the current aftershock sequence and a component reflecting the central tendency of past sequences. In the first experiment, we investigated the effect of a priori variability in the parameter distribution by randomly sampling such variability, rather than by taking a central value as the starting point. We examine Rydelek's example of estimating, at the time of the mainshock, the probability of aftershocks $M \geq 5.5$ in the 1-day interval immediately after a mainshock with magnitude $M_m = 6.5$. Five hundred sets of values for the model parameters, a, b, and p (2) were drawn at random from the empirical distributions for 62 California earthquake sequences (Fig. 1). From the resulting distribution of probabilities $P(M_1 = M_m - 1, M_2 = \infty, S = 0.01, T - S = 1)$ (3), we determined the quantile points corresponding to median and ±1 SD (Table 1). As Rydelek points out, the uncertainty in this probability is substantial: the ±1 SD range about the generic value (0.234) is 0.070 to 0.590. For the case of a larger mainshock in the 7-day interval immediately after a mainshock, $P(M_1 = M_m, M_2 = \infty, S = 0.01, T - S = 7)$. The ±1 SD range about the generic value (0.049) is 0.015 to 0.145 (Table 1).

Our second experiment was designed to evaluate the uncertainty in estimates of P at selected times after the mainshock. We generated an ensemble of 500 synthetic earthquake sequences with parameter values equal to the generic model. These sequences included aftershocks with magnitudes $M \geq M_m - 4$, corresponding, in the case of a $M_m = 6.5$ mainshock, to complete aftershock observation for $M \geq 2.5$ (4). At selected times after the mainshock we estimated the parameters for each synthetic sequence with a maximum likelihood (ML) method. We then computed the RJ estimates using randomly sampled values from the 62 empirical sequences used in this study. This procedure isolates the uncertainty in our estimates due to the inherent variability of past sequences. We determined from the resulting distribution of $P(M_1 = M_m - 1, M_2 = \infty, S, T - S$

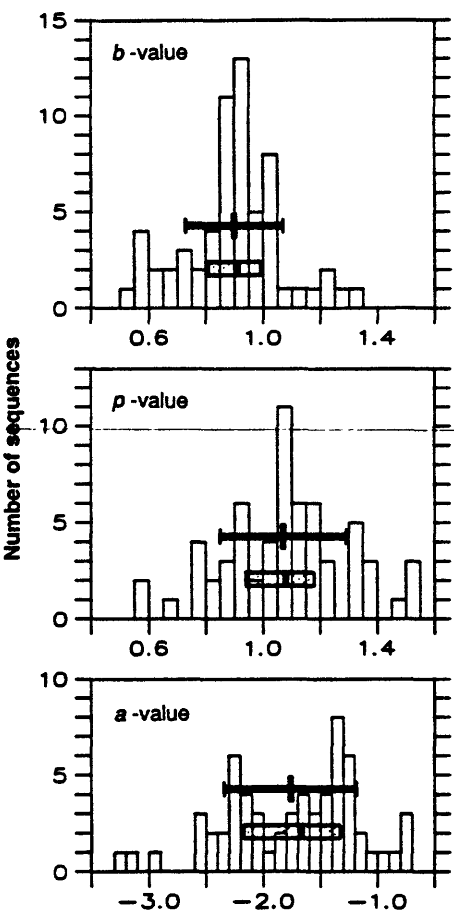

Fig. 1. Distributions of parameters (b, p, and a) determined for aftershock sequences after 62 ($M \geq 5.0$) mainshocks in California from 1933 to 1987. Solid bar indicates mean ± 1 SD. Shaded bar indicates median (central line) and upper and lower quartiles (end points) of distribution.

Table 1. Interval probabilities, $P(M_1, M_2, S, T)$, for strong aftershocks or larger mainshocks ($M_1 = M_m - 1$, $M_2 = \infty$), and for larger aftershocks only ($M_1 = M_m$, $M_2 = \infty$), estimated at the time of the mainshock (generic model, $S = 0.01$) and at selected times (S, in days) after the mainshock ($S = 0.25$, 0.5, and so forth). Generic model (GM) values are compared with results of the Monte Carlo (MC) experiment in which standard errors (±1 SD) of the model are estimated. Time intervals are described by S (interval start time, in days, after the mainshock) and $(T - S)$ (duration, in days).

Model or interval	S: 0.01	0.25	0.5	1	3	7	15	30
Earthquakes with $M \geq M_m - 1$								
$(T - S) = 1$								
GM	0.234	0.119	0.083	0.052	0.021	0.009	0.004	0.002
MC result	0.240	0.115	0.080	0.051	0.021	0.009	0.004	0.002
−1 SD	0.070	0.070	0.054	0.034	0.015	0.007	0.003	0.001
+1 SD	0.590	0.190	0.124	0.075	0.029	0.012	0.006	0.003
$(T - S) = 7$								
GM	0.338	0.227	0.186	0.144	0.083	0.046	0.025	0.013
MC result	0.340	0.220	0.185	0.145	0.082	0.047	0.025	0.013
−1 SD	0.100	0.130	0.115	0.095	0.056	0.033	0.019	0.001
+1 SD	0.710	0.350	0.270	0.205	0.114	0.063	0.033	0.017
Earthquakes with $M \geq M_m$								
$(T - S) = 1$								
GM	0.032	0.015	0.011	0.007	0.003	0.001	0.001	0.000
MC result	0.045	0.015	0.011	0.007	0.003	0.001	0.001	0.000
−1 SD	0.010	0.008	0.006	0.004	0.002	0.001	0.000	0.000
+1 SD	0.120	0.028	0.018	0.011	0.004	0.002	0.001	0.000
$(T - S) = 7$								
GM	0.049	0.031	0.025	0.019	0.011	0.006	0.003	0.002
MC result	0.060	0.030	0.024	0.018	0.011	0.006	0.003	0.002
−1 SD	0.015	0.016	0.014	0.011	0.007	0.004	0.002	0.001
+1 SD	0.145	0.060	0.041	0.031	0.016	0.009	0.005	0.002

= 1) quantile points at the selected times, S, corresponding to the expected probability and ±1 SD (Table 1). The standard error in P rapidly decreases with increasing time after the mainshock due to the inclusion of current data. For example, at $S = 1$ day after the mainshock, the ±1 SD range about the generic 1-day interval probability (0.052) is 0.034 to 0.075 (Table 1).

Rydelek suggests estimating parameters from subsets of the a priori data corresponding to particular tectonic regions. While this approach has potential merit, it was not very successful for the California data. Parameter estimates for subsets of the data corresponding to the strike-slip regime of central California, the compressional regime of southwestern California and the strike-slip and extensional regime of eastern California do not differ significantly from each other, with one exception. The a value for sequences in eastern California is significantly higher than in central or southwestern California, which indicates a higher productivity of aftershocks there. In future applications of our method to other areas, however, a search for regional or tectonic subsets of earthquake sequences that significantly differ in some parameter values could provide an improvement over the single generic model approach.

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REFERENCES AND NOTES

1. P. A. Reasenberg and L. M. Jones, *Science* **243**, 1173 (1989).
2. Model parameters a, b and p, defined in (*1*), describe the total number, magnitude distribution and time distribution of the aftershocks, respectively.
3. As defined in (*1*), M_1 and M_2 are, respectively, the lower and upper limits of a magnitude range, and S and T are, respectively, the lower and upper limits of a time interval, for which P is computed.
4. In practice, observation of earthquakes within the central and southern California U.S. Geological Survey networks is complete above approximately magnitude 1.5.

21 November 1989; accepted 30 November 1989

APPENDIX III.

SCIENCE

19 January 1990, Volume 247, pp. 345–346

PAUL A. REASENBERG AND LUCILE M. JONES

California Aftershock Hazard Forecasts

The first practical application for our model for real-time probabilistic hazard assessment (*1*) was provided by the 6 March 1989 *M*4.7 Obsidian Butte earthquake sequence in the northern Brawley Seismic Zone at the southern end of the Salton Sea, California (Fig. 1). The earthquake sequence was initially very active and included a relatively high proportion of large-magnitude aftershocks ($a = -0.5$, $b = 0.6$). As a

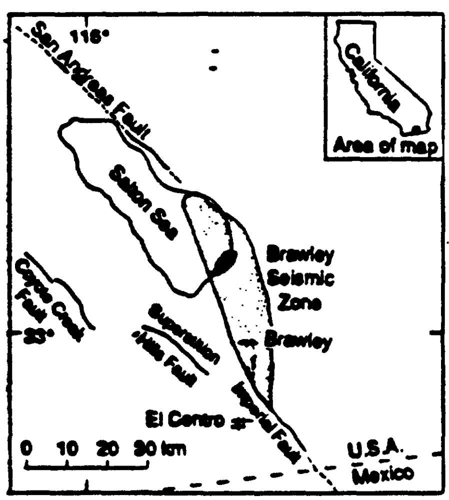

Fig. 1. Aftershock zone (black area at south end of the Salton Sea) of the 1989 Obsidian Butte earthquake sequence. The Brawley Seismic Zone (shaded area) is the site of numerous earthquake swarms in the cross over region between the San Andreas and Imperial faults.

result, the model-estimated probability for a larger ($M \geq 4.7$) earthquake during the first week in the sequence was relatively high—on the order of 0.30. Scientists familiar with the Brawley Seismic Zone generally felt that this estimate was reasonable. We did find, however, that other factors, in addition to those considered in the model, also warranted consideration.

One factor was the proximity (18 km) of the Obsidian Butte earthquakes to the intersection of the Brawley Seismic Zone and the San Andreas fault and the possibility that a great ($M \approx 8$) earthquake might be triggered by the Obsidian Butte sequence. The concensus was that the distance to the San Andreas fault was too great to warrant an upward revision of the model probability estimate for a great earthquake.

Another factor was that the Brawley Seismic Zone may not be capable of producing very large earthquakes because it is composed of numerous small faults, rather than a continuous long fault. If we assume that the largest possible earthquake in the Brawley Seismic Zone is *M*6.2 (the magnitude of the largest known historic event), then the model-estimated probability of a $M \geq 4.7$ earthquake decreases from 0.30 to 0.26.

The U.S. Geological Survey used the model to issue frequent public forecasts during the 17 October 1989 Loma Prieta earthquake sequence of probabilities of strong aftershocks within a day, a week, and 2 months. While this earthquake produced fewer aftershocks than expected for a generic *M*7.1 earthquake, the final model parameters determined for it ($a = -1.67$, $b = 0.75$, $p = 1.19$) all differ by less than 1 SD from their respective generic values (*2*, figure 1). We reported 24 hours after the earthquake that the chance of a $M \geq 5$ aftershock in the next day was 0.13 (none occurred). One week later that probability had decreased to 0.05, while the probability of a $M \geq 5$ aftershock over the next 2 months was 0.50 (none occurred). Forecasts were made first daily, and then less frequently, through 30 November 1989. These were issued to federal, state, and regional government agencies and were widely reported by Bay Area printed and electronic media. Public demand for and interest in aftershock forecasts was greatest immediately after the earthquake and remained high for about 2 weeks, decreasing as the felt aftershocks subsided.

Some local and regional government agencies requested model results particular to their needs during the first week of the sequence. The Port of Oakland requested estimates of probabilities for strong aftershocks in order to decide whether and when to reoccupy a damaged structure. The San Francisco Fire Department requested probabilities of strong shaking in the Marina and China Basin districts to guide decisions about equipment deployment and staffing levels in these damaged areas. Within the U.S. Geological Survey, scientists coordinating the regional deployment of strong motion portable seismographs frequently consulted model results in planning their experiment design and field strategy.

Our experience with the Obsidian Butte sequence and the Loma Prieta sequence has shown that the model can provide important information for real-time hazard assessment for earthquake sequences. Sensible real-time assessment of the seismic hazard during future earthquake sequences in California should also take into account relevant regional factors, including proximity to stressed fault segments, fault complications or gaps, and possible regional limitation of the maximum possible earthquake size.

In the Loma Prieta sequence, we found that regularly released short-term forecasts of expected aftershock activity were useful in meeting the high public demand for earthquake hazard information after a strong earthquake. We also saw that the press and public can easily misunderstand a probabilistic forecast; such public statements should be simple, clear, and consistent. Overall, however, we feel that our use of model probabilities to forecast the continuing earthquake hazard after the Loma Prieta earthquake was generally understood and widely accepted by the public, the press, and other government agencies.

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REFERENCES AND NOTES

1. P. A. Reasenberg and L. M. Jones, *Science* **243**, 1173 (1989).
2. P. A. Reasenberg and M. V. Matthews, *ibid.* **247**, 343 (1990).

21 April 1989; accepted 30 November 1989

APPENDIX IV

Testimony
by
Dennis S. Mileti
Professor of Sociology
Director, Hazards Assessment Laboratory
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before the

Subcommittee on Science, Research and Technology
Committee on Science, Space and Technology
U.S. House of Representatives

Field Hearing on

The Loma Prieta Earthquake: Lessons Learned
San Francisco, California
December 4, 1989

The purpose of this testimony is to respond to three questions posed by the Subcommittee. Three questions follow. First, is the National Earthquake Hazards Reducation Program (NEHRP) based on realistic assessments of human behavior? Second, have earthquake education efforts had the desired impact? Third, did different classes or ethnic groups react differently to the earthquake?

<u>Human Behavior Basis</u>

In the mid-1950s the nation embarked on a research and applications effort to develop preparedness for federal, state, and local government response to disaster. Fueled by concern over the Cold War, examination of disasters caused by natural events was thought to be a useful way to learn how to prepare for nuclear attack response. Investigations focused on a range of natural disaster-inducing phenomena, for example, hurricane, tornado, earthquake, flood, and volcano. It became soon apparent that these natural disasters were themselves worth preparing for and, in the decade since the accident at the Three-Mile Island nuclear reactor, focus in preparedness has also been pointed toward technological mishaps.

Preparedness lessons have accumulated, and a policy to foster and enhance applications at all governmental levels has been adopted, put into action, and then refined as new insights have been gained. Emergency preparedness, today, stands as its own professional specialty, is institutionalized in a variety of professional societies, has recruited membership from a wide interdisciplinary range of traditional sciences and fields, and is also a relatively big business.

Contemporary emergency preparedness rests on a too often unarticulated but nevertheless empirically validated theory about human behavior in emergencies. This theory brings satisfaction to those who helped see it developed, as well as to scholars in organizational sciences. It can be summarized as follows. First, response to community-wide emergencies is performed by bureaucracies (for example, fire and police departments; department of health and transportation; hospitals, the Red Cross and so on). Second, the effectiveness and efficiency of response is enhanced to the extent that the response of each bureaucracy is coordinated through some centralized command and control mechanism. Third, coordination is achieved if pre-event planning both within and between bureaucracies addresses items like activities, tasks, authority, priorities, decision making, role specification, resources, training, communications, and so on. These lessons have been hard won over the last three decades and for the most part they work.

However, contemporary emergency planning in the United States and the underlying theory on which it rests are not likely categorically applicable in reference to as yet unexperienced major cataclysmic events. The theory, policy to institutionalize it, and efforts to put it into practice are each biased by the empirical emergency experience in the U.S. over the last three or so decades.

This historical experience has been limited to natural and technological events which have been emergencies, but not disasters. Emergencies are events in which the bureaucratic response structures man has erected to respond to such mishaps can in fact respond. The ability of local bureaucratic response may be exceeded, but then state bureaucracies can converge to the site. In cases where local and state bureaucractic response abilities are both exceeded, then federal agencies and national organizations converge to do the necessary worl, for example search and rescue, provosion of life essentials, and so on. There simply has not been en emergency in the U.S. in the experience of anyone alive today in which this bureaucratic response paradigm has not worked or could not have worked were it in place. Yet, the nation now faces some future disasters in which we know that the ability of all bureaucracies, regardless of governmental level, to respond will be exceeded and convergence from outside the affected community by those who could help will be initially impossible. Existing emergency plans do not constitute full readiness for cataclysmic disasters such as a great urban earthquake.

Most historical events of great magnitude occurred long before people, their erected structures, and built environment were densely concentrated in the U.S. Our experience with emergency response excludes responses to these lower probability cataclysmic events. They happened long enough ago to not be part of the personal experience of emergency planners alive today, and then they affected sparse population settlements.

It is small wonder that preparedness in this nation is built on a centralized bureaucratic response paradigm. This approach is effective given our experience with emergencies over the course of at least the last couple of lifetimes. The best alternative for future cataclysmic disaster we have come up with has been to recommend to the public that it be ready to be on its own until enough time passes for the way to be cleared for emergency response organizations to get there, and emergency response can proceed in its bureaucratic and familiar way. The consequence may be a 72 hour response void in the case of the next great urban earthquake. One can only imagine what this void might be in the case of other cataclysmic events as yet unimagined.

A response void in the immediate aftermath of a cataclysmic disaster is unfortunate for a variety of reasons. For example, the first 24 hours after a major urban earthquake are critical from a medical viewpoint. Recent experience and medical research reveals that if the trapped are injured and not rescued within 24 hours that eventual death is somewhat certain.

There is an alternative planning theory that is not based on a centralized bureaucratic emergency response mode. It can fill the response voids that are the consequence of cataclysmic disasters in areas characterized by traditional response planning. This alternative is suggested by events which followed from the 17 October 1989 Loma Prieta Earthquake. It is also supported by empirical observations from other recent earthquake disasters, for example the 7 December 1988 earthquake in the Soviet Republic of Armenia.

The Loma Prieta Earthquake was an emergency to which emergency bureaucracies could respond in some communities (for example, San Francisco), but it was a disaster that exceeded the response capacity of emergency bureaucracies in other communities (for example, Watsonville and to some degree Santa Cruz). The latter communities more closely approximate the conditions to be found in a great urban earthquake. Indeed, in these communities isolated by the earthquake, there was overloading of the bureaucratic order found in modern society where people do not do things, but rather bureacracies do. For example, bureaucracies supply water, food, housing, work, electricity, education; bureaucracies rescue people, offer medical aid, treat the injured; and bureaucracies doing different things are usually coordinated in some general way through a system we know as government. The earthquake changed all that; bureaucracies were themselves earthquake victims, other bureaucracies took a while to converge to the scene, and when bureaucracies finally did appear they were not fully coordinated. What immediately emerged was a decentralized set of grassroots bureaucracies or work groups comprised of surviving victims. People organized themselves into emergency groups to do the work (search and rescue) that needed to get done.

The emergence and success of public grassroots groups to accomplish disaster response needs is not a new phenomenon nor is it unique to this earthquake. What is revealed by this experience is that reorganization of society in a catastrophic impacts earthquake did occur, and surviving victims in even such an extreme event took command of the response void left by overwhelmed emergency response bureaucracies.

Overall, this was a decentralized response as there was little coordination between groups. Additionally, work groups lacked knowledge about how to do the jobs on which they embarked in the most effective way. In a major cataclysmic earthquake in an urban setting in the U.S., it is likely that the 72 hour emergency response void will not be a void. It will be filled with grassroots groups from the public itself.

The U.S.A. has long ago mounted a national effort to mitigate the losses from and prepare to respond to the earthquake hazard. The National Earthquake Hazards Reduction Program has done much to move toward both goals, and major preparedness initiatives are underway in several regions both within and outside California. Planning is, however, not now focused in terms of how to take advantage of the inevitable contributions of victims in response to a major earthquake disaster until such time as traditional government bureaucratic response can converge to the site. There need not be a 72 hour response void until government can proceed with response as is planned. Planning can now focus on how to make the most of emergent grassroots response, and how to make them more effective at the tasks which they assume. The following shifts seem in order, at a minimum, in planning for response to a great urban earthquake in the U.S.A. in the first 72 hours.

First, the public should be viewed as a resource in the 72 hour void until government can arrive to offer help.

Second, attention should be paid about how to make public response more effective. For example, emphasis could be placed on what to say over the radio to surviving victims about how to best engage in search and rescue. This technical knowledge exists, it seems foolhardy to not plan to give it to those who will rescue the vast majority of people who get rescued.

Third, the initial things that we plan to send to the disaster site might not best be response bureaucracies. Instead, the first order of convergence could be the tools victims engaged in search and rescue need to do their work.

Finally, a general policy shift in disaster planning in general could be in order. Traditional organizations that spearhead disaster response planning could consider a shift in the theory which underlies disaster response planning in the U.S. The existing theory excludes the public from disaster response, and casts the public as a source of problems for which government bureaucracies must plan response solutions. Consequently, our planning could be excluding those with the largest disaster response roles. The role should not continue to be overlooked as the nation moves to enhance its readiness for a great urban earthquake.

These four possible shifts in the nation's approach to planning for response to a great quake should be researched in the context of the Loma Prieta Earthquake. The focus of this research is better placed on the areas that were isolated and experienced great impacts in this earthquake (for example, Watsonville) rather than communities where response bureaucracies were left relatively intact (for example, San Francisco and Oakland).

Public Education and Warnings

The existing research record on public disaster warning response is empirically rich and knowledge has been cumulative. For example, it has been learned that protective public behavior does not automatically flow from receiving warning information. The perception of risk which people hold is an intervening factor. Warnings work through people's cognitive processes to influence behavior. Effective warning systems disseminate public information that can be heard and lead diverse people to accurate cognitions and perceptions, and then to protective actions. These perceptions are shaped by two sets of factors. First, the characteristics of the information receiver, and second those of the information given or the warning itself.

Research findings suggest that people who receive warnings go through a sequential process that shapes their perception of risk and subsequent behavior. A simple model of this process is the sequence: (1) hear, (2) perceive (understand, believe, and personalize), and (3) respond (decide about alternative protective response actions and then perform them). The sequence described may not be the same for everyone. Each factor or stage in the sequence is affected by receiver and information (sender) factors. Additionally, people typically do not passively await the arrival of more information. Most people seek out more on their own. This has typically been referred to as the confirmation process.

Knowledge also exists about which information (sender) factors and receiver (person) factors influence each stage (hear, understand, believe, personalize, decide, respond) in the general process. Briefly, this research suggests that each stage of the process can be influenced by information/ warning factors like warning message content and style. Content factors include risk location, potential risk impacts, time to impact, and guidance about what people should do. Style factors include information specificity, consistency, accuracy, certainty, and clarity. Sender characteristics important to consider are channel, frequency, and source of the warning.

Research also documents the receiver (public) factors which influence the general hear-perceive-respond process. Four categories of characteristics are important. First, attributes of the receiver's environment when the warning is received include physical and social cues. Second, social attributes include network, resource, demographic and activity characteristics. Third, psychological attributes include pre-warning knowledge, locus of control, and experience. Fourth, physiological characteristics (for example, disabilities) can also impact the warning response process.

The Loma Prieta Earthquake was followed by several public aftershock warnings for damaging earthquakes. Some examples follow. The U.S. Geological Survey in Reston communicated with the Chairman of the California Earthquake Prediction Evaluation Council after the main shock. An earthquake aftershock warning was released to the press at 7:15 a.m. the morning of 18 October 1989 for a 6.0 R magnitude or larger aftershock within the first 24 hours following the main shock. It was given a 10% to 20% probability of occurrence; it was for the same locations affected by the main shock. A warning was also made public of a remote possiblity of a 7.0 R magnitude aftershock in the first 24 hours after the main shock in the San Francisco Examiner. At 5:00 p.m. on 18 October 1989 another 24 hour aftershock warning was issued. It came from the U.S. Geological Survey in Menlo Park. It was for the same areas. It warned of a 2%

probability of a 6.0 R magnitude aftershock and a 13% probability for a 5.0 R magnitude aftershock. The probability of a 6.0 R magnitude aftershock was decreased to 1% at 7:00 a.m. on 21 October 1989, and the probability of a 5.0 R magnitude aftershock was also reduced to 8%. Additional aftershock warnings occurred during the week after the main shock. On 24 October 1989 another warning was issued by the U.S. Geological Survey. It was for an earthquake "strong enough to cause additional damage, especially to structures weakened in last Tuesday's quake." This aftershock was given a 50% probability of occurrence for the time period of "in the next few weeks to two months." This warning is still in effect.

The process to reach and inform the public of aftershock risk, and how that public processed those warnings, was not likely similar to existing knowledge about pre-impact warnings. It appears to have been a greater problem to capture the public's attention because of the just experienced disaster than is typically the case before a disaster strikes.

Pre-impact warning studies suggest that public warning response could almost be diagrammed by the use of a normal curve. The bulk of the public in the center of the curve hear the warning, seek more information and eventually engage in a protective action. Some few people in the left-hand tail of the curve are not exposed to the warning. Additionally, some few people in the right-hand tail of the curve respond without seeking more information.

It is suspected that the Loma Prieta earthquake inverted this normal curve with the most members of the public in the tails, and the fewest in the center of the curve. It is now hypothesized that the left-hand tail of the curve was comprised of a large portion of the victim population who turned off the electronic media, did not read newspapers, and devoted all their attention to immediate disaster needs. Those citizens never heard the aftershock warnings. The right-hand tail of this inverted normal curve was also comprised of a large portion of the victim population. These people heard the aftershock warnings but the information was not perceived. The warnings, although heard, were lost in a flood of other post-impact emergency information; or the warnings were constrained from being translated into perceptions about risk requiring action because the victim public possessed pre-emergency knowledge about aftershocks. For example, "of course aftershocks occur after earthquakes; they are smaller, if I and my house survived the main shock, we'll survive the aftershock." The fewest victims fell in the center of the inverted normal curve. They heard the warnings, they perceived the risk, they sought more information, and they may or may not have taken mitigative actions.

Additionally, the factors that influence the process may have influenced the process differently. For example, pre-impact knowledge typically facilitates accurate warning perceptions and response. Yet knowledge about aftershocks may have constrained hearing warnings, forming accurate perceptions and their response.

The Loma Prieta Earthquake provides a unique opportunity to study the effectiveness of pre-disaster earthquake education, public response to aftershock warnings, and post-impact public education and interest in mitigation and preparedness. An initial assessment suggests that there may be much to learn in each of these areas. Minimally, this quake must have social scientists question the validity of existing theories on topics such as these in the context of an earthquake disaster environment with great impacts. These theories must be refined and then inform planning before, for example, aftershock warnings are issued to a public after a great urban earthquake. Such aftershocks could be large earthquakes which are themselves capable of destruction to the construted environment weakened by the main shock.

Social Class and Ethnicity

The Loma Prieta earthquake would illustrate that social class and ethnicity can play a major role in influencing how earthquake victims perceive, respond, and interpret the response of others and government in an earthquake. This topic, however, has not yet been researched. For example, ethnic identifiction was likely a major factor in altering access to and interpretation of public warnings for damaging aftershocks, and social class did influence participation in assessing available relief. Ethnic identification was a major factor in influencing public perception and response to the earthqake in Soviet Armenia.

Many of the areas in the United States that might experience a great earthquake are among the most ethnically diverse regions of the nation. Public response in the U.S. would likely be splintered and directed by the ethnic identification of victims. We know relatively little about how to prepare for such a multidirectional public response, nor have we clearly identified the problems that such a response would create, much less the plans that would address the problems.

It seems clear, however, that preparedness for response plans must take into account how ethnicity will impact the response to a great urban earthquake in the United States. The rich ethnic and socioeconomic diversity of the populations affected by the Loma Prieta earthquake provide a context to discover through research how these factors influence behavior.

General Conclusion

Researchers are famous for concluding that more research is needed. I am no exception to this general axiom. However, brief field investigations of this earthquake do suggest that there is a basis to question the applicability of well-trusted theories, assumptions and preparedness paradigms in the context of a great urban earthquake. Recent great earthquakes in other places (for example, Armenia, S.S.R.) also suggest that traditional theories and readiness approaches must be scientifically tested and refined for applicability in the context of a great urban earthquake. The Loma Prieta earthquake is the largest experienced in our own culture in almost a century. It provides an uninvited laboratory for research on human behavior and preparedness that should be conducted to inform and upgrade readiness for a great urban earthquake. I have only touched upon a few topical areas in this testimony that support my general conclusion. There are many others.

APPENDIX V.

Date: December 15, 1989

To: NEPEC Working Group on Probabilities

From: Paul Reasenberg

Subject: Long Range Forecast for Large Earthquakes after Loma Prieta

Using the Reasenberg-Jones model for aftershock probabilites to forecast the long-term probability for large earthquakes in the Bay Area after Loma Prieta requires a long leap of faith, or at least, some important assumptions. The model was developed from a learning set of mainshock-aftershock sequences. Foreshocks associated with these sequences were not considered. Thus, the model is based strictly on aftershock behavior, in which the aftershocks are, by experiment design, always smaller than the mainshock. An extension of the model has been suggested, in which the exponential distribution of magnitudes would be extended to aftershock magnitudes larger than the mainshock. While doing so is a valid modeling procedure, the following caveats should be stated.

1. The exponential distribution of magnitudes (Gutenberg-Richter law) appears to systematically underestimate the number of larger magnitude earthquakes worldwide (Utsu, 1971). While we have insufficient data to know if a similar underestimate results from our aftershock model, the possibility cannot be ruled out.

2. The R-J model is based on aftershocks smaller than the mainshock. It is an assumption that the self-similar behavior of the magnitude distribution exhibited on average by the smaller aftershocks will be followed by the larger-than-mainshock aftershocks. Even for aftershocks with magnitudes comparable to the mainshock, the seismogenic process in any particular case is obviously controlled by local physical constraints, not by laws reflecting average behavior. These constraints include the presence of neighboring Bay Area faults, the depth, topography and velocity of the ductile region, geometric and compositional barriers in the crust, and the stress footprint left in 1906.

With these caveats stated, here are the model probabilities for large aftershocks calculated using the model that best fits the Loma Prieta aftershocks to date ($a = -1.67$, $p = 1.19$, $b = 0.75$).

1-year interval: January 1, 1990 – Dec 31, 1990

$$P(M \geq 6.0) = 0.053$$
$$P(M \geq 7.0) = 0.010$$

2-year interval: January 1, 1990 – Dec 31, 1991

$$P(M \geq 6.0) = 0.067$$
$$P(M \geq 7.0) = 0.012$$

The attached graph illustrates the decay in the model probability for a $M \geq 7$ aftershock in a sliding 1-year window. The probability shown on the graph for the 1-year interval beginning 75 days after the mainshock (January 1, 1990) is slightly less than the corresponding figure (0.010) given above because the graph was prepared previously using slightly different model parameters. The baseline "blue book" probability of 0.0067 per year (20% probability in 30 years) is shown for reference.

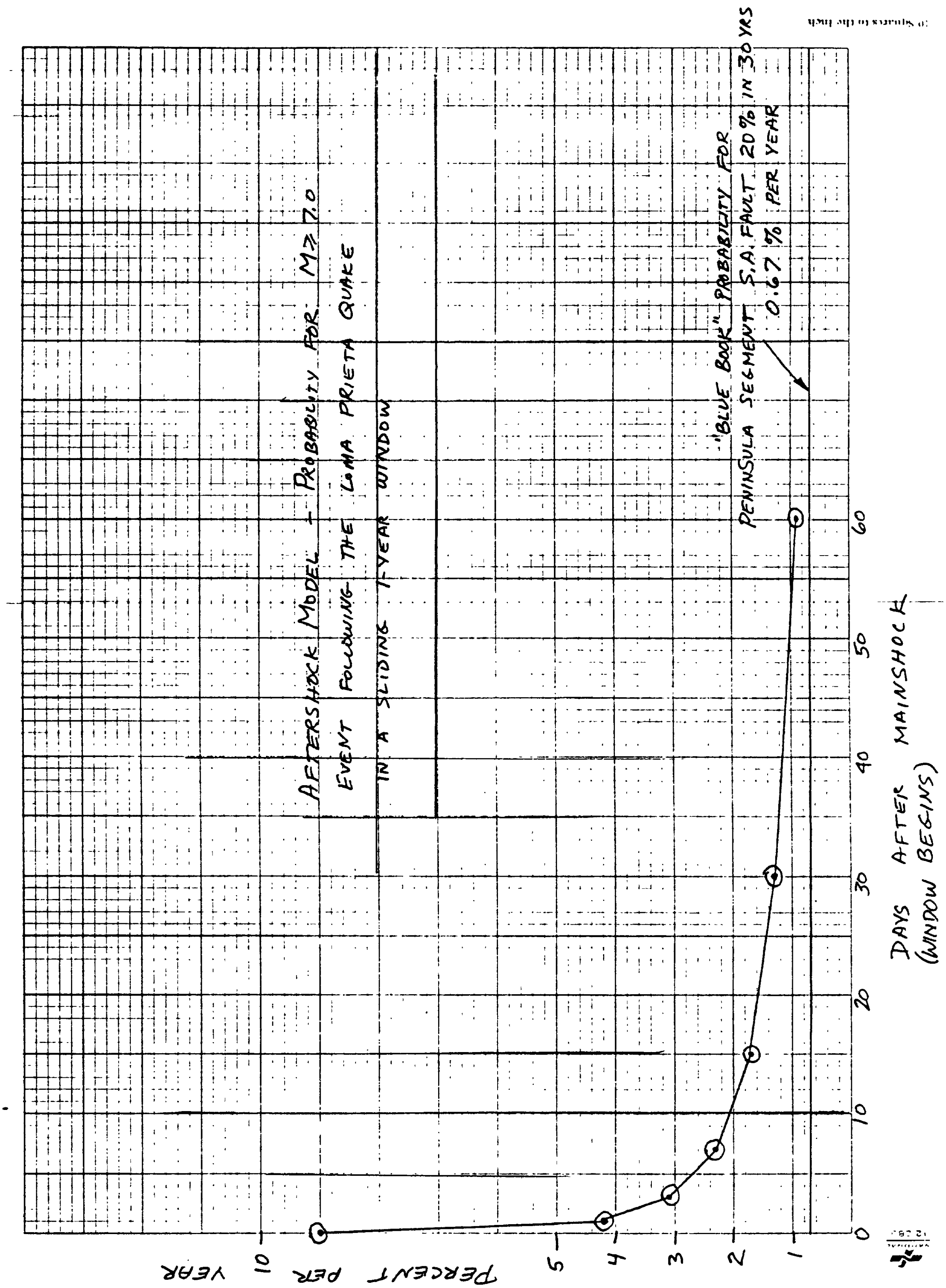
The Loma Prieta sequence produced fewer aftershocks (and had a lower b-value) than expected for a generic $M = 7.1$ earthquake. Accordingly, the above long range forecast includes lower probabilities than would be obtained with the generic model. Furthermore, the Loma Prieta aftershock sequence characteristics may reflect conditions local to the aftershock zone, while the forecast we seek is for earthquakes outside the zone. Therefore, use of a model based on this specific sequence may not be preferable to the use of a generic model. It is arguable that the mainshock stress pulse applied to the Bay Area faults, and not the aftershock pattern, per se, is relevant to the long range Bay Area forecast. Accordingly, I give below a long-range forecast for strong aftershocks analogous to the one above, but following a "generic $M = 7.1$ earthquake" assumed to have occured on October 17, 1989.

1-year interval: January 1, 1990 – Dec 31, 1990

$$P(M \geq 6.0) = 0.113$$
$$P(M \geq 7.0) = 0.015$$

2-year interval: January 1, 1990 – Dec 31, 1991

$$P(M \geq 6.0) = 0.145$$
$$P(M \geq 7.0) = 0.019$$


AFTERSHOCK MODEL – PROBABILITY FOR M≥7.0
EVENT FOLLOWING THE LOMA PRIETA QUAKE
IN A SLIDING 1-YEAR WINDOW
"BLUE BOOK" PROBABILITY FOR
PENINSULA SEGMENT S.A. FAULT 20% IN 30 YRS
0.67% PER YEAR
DAYS AFTER MAINSHOCK
(WINDOW BEGINS)
0
10
20
30
40
50
60
PERCENT PER YEAR
1
2
3
4
5
10

APPENDIX VI
Distribution List for Loma Prieta aftershock forecasts

California Office of Emergency Services - Ontario

California Office of Emergency Services - Sacramento

FEMA - Mt. View Disaster Field Office

US Army Corps of Engineers

Navy Geotechnical Department - San Bruno

US Navy, Santa Barbara

California Division of Mines and Geology

California Division of Safety and Dams

BAREPP - Oakland

Office of Emergency Services, City of Los Angeles

California Institute of Technology

UC Santa Cruz

EERI Headquarters

USGS - OEVE, Reston

USGS - Pasadena

USGS - Seattle

USGS - Deer Creek

USGS - Geologic Risk Assessment, Denver

USGS - Global Seismology, Denver

Japan Geological Survey

Stanford Linear Accelerator Center

Associated Press - San Francisco

Bay City News

UPI - San Francisco

Approximately 20 individual newspapers, radio and television stations.

EARTHQUAKE REPORT
for the San Francisco Bay Area
from the
UNITED STATES GEOLOGICAL SURVEY
Office of Earthquakes, Volcanoes, and Engineering
345 Middlefield Road, Menlo Park, CA 94025

APPENDIX VII -- Text of USGS Press Release on the Loma Prieta Earthquake and Aftershocks - 18 October to 30 November, 1989

18 OCTOBER, 1989 - 11:00 AM PDT

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 08:30 PDT Wednesday, October 18, sixty-two aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park. The largest aftershock, magnitude 5.9, occured 2 and one half minutes after the mainshock. The second largest aftershock was magnitude 5.2, occuring 37 minutes after the mainshock. In addition, 10 aftershocks of magnitude 4.0 and larger have occured, as of 08:30 PDT.

Modeling of the aftershock sequence based on the aftershocks recorded in the first 15 hours shows that this earthquake sequence generally follows the behavior usually seen in a California sequence. It appears to differ, however, from a typical sequence in that its aftershocks are decaying in time somewhat more rapidly than usual, and it has produced fewer than normal aftershocks. Given this behavior, a statistical model has provided a forecast of future strong aftershocks. As of Wednesday morning, there is a 3 percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. Seismologists will be monitoring the aftershock sequence and updating the forecast for future aftershocks throughout the day.

Attached is a list of aftershocks, magnitude 3.0 and larger, recorded in Menlo Park as of 8:30 am Wednesday.

EARTHQUAKE REPORT
for the San Francisco Bay Area
from the
UNITED STATES GEOLOGICAL SURVEY
Office of Earthquakes, Volcanoes, and Engineering
345 Middlefield Road, Menlo Park, CA 94025

FROM THE U.S. GEOLOGICAL SURVEY IN MENLO PARK, CALIFORNIA

WEDNESDAY, OCTOBER 18, 5:00 PM PDT

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 3:30 PM PDT Wednesday, October 18, sixty-five aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park. The largest aftershock, magnitude 5.9, occured 2 and one half minutes after the mainshock. The second largest aftershock was magnitude 5.2, occuring 37 minutes after the mainshock. In addition, 10 aftershocks of magnitude 4.0 and larger have occured, as of 3:30 PM PDT.

In the next few days seismologists advise that additional aftershocks are expected, some possibly strong enough to cause additional damage, especially to structures weakened in Tuesday's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

Most probably, additional earthquakes in the next few days will be smaller than Tuesday's $M = 7$ earthquake. As for the possibility of an earthquake comparable to or larger than Tuesday's quake, scientists characterize the chances for that as "very small", but not zero. In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. Such triggering, however, is considered unlikely. For example, no such triggering occured after the magnitude 6.5 earthquake believed to have occured on the same Santa Cruz segment of the San Andreas fault in 1865.

To assess the chances for smaller, but still damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. Modeling of the aftershock sequence based on the aftershocks recorded in the first 24 hours shows that this earthquake sequence generally follows the behavior usually seen in a California sequence. It appears to differ, however, from a typical sequence in that its aftershocks are decaying in time somewhat more rapidly than usual, and it has produced fewer than the normal number of aftershocks. Given this behavior, a statistical model has provided a forecast of future strong aftershocks. As of Wednesday at 5 PM PDT, there is only a 2 percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same period, the probability of a magnitude 5.0 or larger aftershock is 13 percent.

In this, as in all earthquake sequences, the probability for aftershocks decreases rapidly with time after the mainshock. The most likely period for strong aftershocks is immediately after the mainshock. At present, 1 day after the mainshock, the aftershock probabilities have already diminshed substantially. In the days to come, these probabilities will continue to decline. Seismologists will continue to monitor the aftershock sequence and update the forecast for future aftershocks as the sequence progresses.

Attached is a list of aftershocks, magnitude 3.0 and larger, recorded in Menlo Park as of 3:30 PM PDT Wednesday.

FROM THE U.S. GEOLOGICAL SURVEY IN MENLO PARK, CALIFORNIA

THURSDAY, OCTOBER 19, 9:00 AM PDT

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 9:00 AM PDT Thursday, October 19, seventy-eight aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park. The largest aftershock, magnitude 5.9, occured 2 and one half minutes after the mainshock. The second largest aftershock was magnitude 5.2, occuring 37 minutes after the mainshock. Most recently, a magnitude 5 aftershock occured Thursday at 3:14 AM PDT. In addition, a total of 12 aftershocks of magnitude 4.0 and larger have occured, as of 9:00 AM PDT.

In the next few days seismologists advise that additional aftershocks are expected, some possibly strong enough to cause additional damage, especially to structures weakened in Tuesday's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

Most probably, additional earthquakes in the next few days will be smaller than Tuesday's $M = 7$ earthquake. As for the possibility of an earthquake comparable to or larger than Tuesday's quake, scientists characterize the chances for that as "very small", but not zero. In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. Such triggering, however, is considered unlikely. For example, no such triggering occured after the magnitude 6.5 earthquake believed to have occured on the same Santa Cruz segment of the San Andreas fault in 1865.

To assess the chances for smaller, but still damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. Modeling of the aftershock sequence based on the aftershocks recorded in the first 24 hours shows that this earthquake sequence generally follows the behavior usually seen in a California sequence. It appears to differ, however, from a typical sequence in that its aftershocks are decaying in time somewhat more rapidly than usual, and it has produced somewhat fewer than the normal number of aftershocks. Given this behavior, a statistical model has provided a forecast of future strong aftershocks. As of Thursday at 9 AM PDT, there is only a 2 percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same period, the probability of a magnitude 5.0 or larger aftershock is 12 percent.

In this, as in all earthquake sequences, the probability for aftershocks decreases rapidly with time after the mainshock. The most likely period for strong aftershocks is immediately after the mainshock. At present, one and two-thirds days after the mainshock, the aftershock probabilities have already diminshed substantially. In the days to come, these probabilities will continue to decline. Seismologists will continue to monitor the aftershock sequence and update the forecast for future aftershocks as the sequence progresses.

SPECIAL EARTHQUAKE REPORT
for the San Francisco Bay Area
from the
UNITED STATES GEOLOGICAL SURVEY
Office of Earthquakes, Volcanoes, and Engineering
345 Middlefield Road, Menlo Park, CA 94025

FRIDAY, OCTOBER 20, 5:00 PM PDT

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 3:30 PM PDT Friday, October 20, 70 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest event, magnitude 5.0, occurred Thursday at 3:14 AM PDT. In addition, a total of 13 aftershocks of magnitude 4.0 and larger have occurred, as of 3:30 PM PDT, Friday. Fifty-one magnitude 3.0–3.9 aftershocks occurred during the first 24-hour period after the mainshock, and 16 occurred during the second 24-hour period. During the third day of the sequence, only three aftershocks with magnitude 3.0 and larger have occurred. During the fourth day – the 24-hour period beginning at 5:00 PM PDT Friday, October 20 – approximately four more aftershocks with magnitude 3.0 and greater are expected to occur.

In the next few days seismologists advise that additional aftershocks are expected, some possibly strong enough to cause additional damage, especially to structures weakened in Tuesday's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

Most probably, additional earthquakes in the next few days will be smaller than Tuesday's $M = 6.9$ earthquake. As for the possibility of an earthquake comparable to or larger than Tuesday's quake, scientists characterize the chances for that as "very small", but not zero. In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. Scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City, with some concern that Tuesday's earthquake may have increased the stress on that segment. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

To assess the chances for smaller, but still damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. Modeling of the aftershock sequence based on the aftershocks recorded so far shows that this earthquake sequence generally follows the behavior usually seen in a California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Friday, October 20, at 5:00 PM PDT, there is only a two percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same period, the probability of a magnitude 5.0 or larger aftershock is 11 percent.

In this, as in all earthquake sequences, the probability for aftershocks decreases rapidly with time after the mainshock. The most likely period for strong aftershocks is immediately after the mainshock. At present, three days after the mainshock, the aftershock probabilities have already diminished substantially. In the days to come, these probabilities will continue to decline. Seismologists will continue to monitor the aftershock sequence and update the forecast for future aftershocks as the sequence progresses.

Attached is a list of aftershocks with magnitude 3.0 and larger recorded in Menlo Park as of 3:30 PM PDT, Friday.

United States
Department of the Interior
Geological Survey, Western Region
Menlo Park, California 94025

Public Affairs Office (415) 329-4000

SATURDAY, OCTOBER 21, 7:00 AM PDT

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 6:30 AM PDT Saturday, October 21, 71 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest event, magnitude 5.0, occurred Thursday at 3:14 AM PDT. In addition, a total of 16 aftershocks of magnitude 4.0 and larger have occurred, as of 6:30 AM PDT, Saturday. Fifty-one magnitude 3.0–3.9 aftershocks occurred during the first 24-hour period after the mainshock, and 16 occurred during the second 24-hour period. During the third day of the sequence, only three aftershocks with magnitude 3.0 and larger occurred. During the fourth day – the 24-hour period beginning at 5:00 PM PDT Friday, October 20 – approximately four more aftershocks with magnitude 3.0 and greater are expected.

In the next few days seismologists advise that additional aftershocks are expected, some possibly strong enough to cause additional damage, especially to structures weakened in Tuesday's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Saturday, October 21, at 7:00 AM PDT, there is only a one percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same period, the probability of a magnitude 5.0 or larger aftershock is eight percent.

(more)

Most probably, additional earthquakes in the next few days will be smaller than Tuesday's $M = 6.9$ earthquake. As for the possibility of an earthquake comparable to or larger than Tuesday's quake, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City, with some concern that Tuesday's earthquake may have increased the stress on the southern end of that segment. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

In this, as in all earthquake sequences, the probability for aftershocks decreases rapidly with time after the mainshock. The most likely period for damaging aftershocks is immediately after the mainshock. At present, three and one half days after the mainshock, the probability for a damaging aftershock has already diminished substantially. In the days to come, these probabilities will continue to decline. Smaller aftershocks – some of which will be felt in the epicentral region – are expected to continue for several months. Seismologists will continue to monitor the aftershock sequence and update the forecast for future aftershocks as the sequence progresses.

Attachments:

1. List of $M \geq 4.0$ earthquakes as of 6:30 AM PDT, Saturday, October 21.

2. Graph showing the expected and observed numbers of aftershocks ($M \geq 3.0$) for each whole day of the sequence to date.

USGS

SATURDAY, OCTOBER 21, 5:00 PM PDT

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 4:30 PM PDT Saturday, October 21, 72 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest event, magnitude 5.0, occurred Thursday at 3:14 AM PDT. In addition, a total of 17 aftershocks of magnitude 4.0 and larger have occurred, as of 4:30 PM PDT, Saturday. Fifty-one magnitude 3.0–3.9 aftershocks occurred during the first 24-hour period after the mainshock, and 16 occurred during the second 24-hour period. During the third day of the sequence, only four aftershocks with magnitude 3.0 and larger occurred. The fourth day of the sequence produced only one aftershock, magnitude 4.6.

In the next few days seismologists advise that additional aftershocks are expected, some possibly strong enough to cause additional damage, especially to structures weakened in Tuesday's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Saturday, October 21, at 5:00 PM PDT, there is only a one percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same period, the probability of a magnitude 5.0 or larger aftershock is eight percent. The outlook for the long term underscores the enduring nature of aftershock sequences. Over the next two months the probability of a magnitude 6.0 or larger aftershock is 12 percent, while the probability of a magnitude 5.0 or larger event in the same period is 55 percent.

Most probably, additional earthquakes in the next few days will be smaller than Tuesday's $M = 6.9$ earthquake. As for the possibility of an earthquake comparable to or larger than Tuesday's quake, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City, with some concern that Tuesday's earthquake may have increased the stress on the southern end of that segment. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

In this, as in all earthquake sequences, the probability for aftershocks decreases rapidly with time after the mainshock. The most likely period for damaging aftershocks is immediately after the mainshock. At present, four days after the mainshock, the probability for a damaging aftershock has already diminished substantially. In the days to come, these probabilities will continue to decline. Smaller aftershocks - some of which will be felt in the epicentral region - are expected to continue for several months. Seismologists will continue to monitor the aftershock sequence and update the forecast for future aftershocks as the sequence progresses.

Attachments:

1. List of $M \geq 4.0$ earthquakes as of 4:30 PM PDT, Saturday, October 21.

SUNDAY, OCTOBER 22, 7:00 AM PDT

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 6:30 AM PDT Sunday, October 22, 73 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest event, magnitude 5.0, occurred Thursday at 3:14 AM PDT. In addition, a total of 17 aftershocks of magnitude 4.0 and larger have occurred, as of 4:30 PM PDT, Saturday. Fifty-one magnitude 3.0–3.9 aftershocks occurred during the first 24-hour period after the mainshock, and 16 occurred during the second 24-hour period. During the third day of the sequence, four aftershocks with magnitude 3.0 and larger occurred. The fourth day of the sequence produced only one aftershock, magnitude 4.6.

In the next few days seismologists advise that additional aftershocks are expected, some possibly strong enough to cause additional damage, especially to structures weakened in Tuesday's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

The probability for aftershocks decreases rapidly with time after the mainshock. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Sunday, October 22, at 7:00 AM PDT, there is only a one percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same period, the probability of a magnitude 5.0 or larger aftershock is six percent.

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is 12 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is 55 percent.

Most probably, additional earthquakes in the next few days will be smaller than Tuesday's $M = 6.9$ earthquake. As for the possibility of an earthquake comparable to or larger than Tuesday's quake, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City, with some concern that Tuesday's earthquake may have increased the stress on the southern end of that segment. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence and update the forecast for future aftershocks as the sequence progresses.

Attachments:

1. List of $M \geq 4.0$ earthquakes as of 6:30 AM PDT, Sunday, October 22.

MONDAY, OCTOBER 23, 7:00 AM PDT

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 6:45 AM PDT Monday, October 23, five and one-half days after Tuesday's earthquake, 74 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest event, magnitude 5.0, occurred Thursday at 3:14 AM PDT. In addition, a total of 17 aftershocks of magnitude 4.0 and larger have occurred, as of 6:45 AM PDT, Monday. Fifty-one magnitude 3.0–3.9 aftershocks occurred during the first 24-hour period after the mainshock, and 16 occurred during the second 24-hour period. During the third day of the sequence, four aftershocks with magnitude 3.0 and larger occurred.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in last Tuesday's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

24-HOUR FORECAST:

The probability for aftershocks decreases rapidly with time after the mainshock. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Monday, October 23, at 7:00 AM PDT, there is only a one percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same period, the probability of a magnitude 5.0 or larger aftershock is six percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is 11 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is 50 percent. Also, in the next two months, approximately three magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few days will be smaller than Tuesday's $M = 6.9$ earthquake. As for the possibility of an earthquake comparable to or larger than Tuesday's quake, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City, with some concern that Tuesday's earthquake may have increased the stress on the southern end of that segment. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence and update the forecast for future aftershocks as the sequence progresses.

Attachments:

1. List of $M \geq 4.0$ earthquakes as of 6:45 AM PDT, Monday, October 23.

MONDAY, OCTOBER 23, 5:00 PM PDT

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 4:45 PM PDT Monday, October 23, six days after Tuesday's earthquake, 74 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest event, magnitude 5.0, occurred Thursday at 3:14 AM PDT. In addition, a total of 17 aftershocks of magnitude 4.0 and larger have occurred, as of 6:45 AM PDT, Monday. Fifty-one magnitude 3.0–3.9 aftershocks occurred during the first 24-hour period after the mainshock, and 16 occurred during the second 24-hour period. During the third day of the sequence, four aftershocks with magnitude 3.0 and larger occurred. The most recent magnitude 3.0 or larger aftershock was a magnitude 3.8 event yesterday at 7:24 AM, PDT, which was felt throughout the San Francisco Bay area.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in last Tuesday's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

24-HOUR FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Monday, October 23, at 5:00 PM PDT, there is only a one percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same period, the probability of a magnitude 5.0 or larger aftershock is five percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is 10 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 50 percent. Also, in the next two months, approximately three magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few days will be smaller than Tuesday's $M = 6.9$ earthquake. As for the possibility of an earthquake comparable to or larger than Tuesday's quake, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City, with some concern that Tuesday's earthquake may have increased the stress on the southern end of that segment. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence and update the forecast for future aftershocks as the sequence progresses.

Attachments:

1. List of $M \geq 4.0$ earthquakes as of 5:00 PM PDT, Monday, October 23.

PLEASE NOTE:

Previous releases of the list of $M \geq 4.0$ earthquakes gave an early and inaccurate location and depth for the mainshock. The most recent and correct location and depth of the mainshock are given in the attached list. We apologize for the error.

TUESDAY, OCTOBER 24, 7:00 AM PDT

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 7:00 AM PDT Tuesday, October 24, six and one-half days after last Tuesday's earthquake, 75 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest event, magnitude 5.0, occurred Thursday at 3:14 AM PDT. In addition, a total of 17 aftershocks of magnitude 4.0 and larger have occurred so far. Fifty-one magnitude 3.0–3.9 aftershocks occurred during the first 24-hour period after the mainshock, and 16 occurred during the second 24-hour period. During the third day of the sequence, four aftershocks with magnitude 3.0 and larger occurred. The most recent magnitude 3.0 or larger aftershock was a magnitude 3.0 event last night at 9:48 PM, PDT.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in last Tuesday's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

24-HOUR FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Tuesday, October 24, at 7:00 AM PDT, there is only a one percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same period, the probability of a magnitude 5.0 or larger aftershock is five percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is 10 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 50 percent. Also, in the next two months, approximately three additional magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few days will be smaller than last Tuesday's $M = 6.9$ earthquake. As for the possibility of an earthquake comparable to or larger than Tuesday's quake, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that last Tuesday's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

Attachments:

1. List of $M \geq 4.0$ earthquakes as of 7:00 AM PDT, Monday, October 24.

CORRECTION:

Previous releases of the list of $M \geq 4.0$ earthquakes gave an early and inaccurate location and depth for the mainshock. The most recent and correct location and depth of the mainshock are given in the attached list.

TUESDAY, OCTOBER 24, 5:00 PM PDT

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 5:00 PM PDT Tuesday, October 24, exactly one week after last Tuesday's earthquake, 75 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest event, magnitude 5.0, occurred Thursday at 3:14 AM PDT. In addition, a total of 17 aftershocks of magnitude 4.0 and larger have occurred so far. Fifty-one magnitude 3.0–3.9 aftershocks occurred during the first 24-hour period after the mainshock, and 16 occurred during the second 24-hour period. During the third day of the sequence, four aftershocks with magnitude 3.0 and larger occurred. The most recent magnitude 3.0 or larger aftershock was a magnitude 3.0 event last night at 9:48 PM, PDT.

The magnitude of the earthquake was revised to 7.1 by the National Earthquake Information Service in Golden, Colorado, at 11:00 AM today. This revision is the result of additional data received from 18 seismographic stations around the world, and represents an average of the observations made at these stations.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in last Tuesday's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

24-HOUR FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Tuesday, October 24, at 5:00 PM PDT, there is only a one percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same period, the probability of a magnitude 5.0 or larger aftershock is five percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is 10 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 50 percent. Also, in the next two months, approximately three additional magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few days will be smaller than last Tuesday's $M = 6.9$ earthquake. As for the possibility of an earthquake comparable to or larger than Tuesday's quake, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that last Tuesday's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

Attachments:

1. List of $M \geq 4.0$ earthquakes as of 5:00 PM PDT, Tuesday, October 24.

CORRECTION:

Previous releases of the list of $M \geq 4.0$ earthquakes gave an early and inaccurate location and depth for the mainshock. The most recent and correct location and depth of the mainshock are given in the attached list.

WEDNESDAY, OCTOBER 25, 7:00 AM PDT

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 7:00 AM PDT Wednesday, October 25, seven and one-half days after last Tuesday's earthquake, 77 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest event, magnitude 5.0, occurred Thursday at 3:14 AM PDT. In addition, a total of 17 aftershocks of magnitude 4.0 and larger have occurred so far. Fifty-one magnitude 3.0–3.9 aftershocks occurred during the first 24-hour period after the mainshock, and 16 occurred during the second 24-hour period. During the third day of the sequence, four aftershocks with magnitude 3.0 and larger occurred. The most recent strong aftershock was a magnitude 4.5 event last night at 6:27 PM, PDT, felt throughout the San Francisco Bay area. This was the strongest aftershock since Saturday. A magnitude 3.7 aftershock, felt in the Santa Cruz area, occurred at 6:00 AM, PDT, today.

The magnitude of the earthquake was revised to 7.1 by the National Earthquake Information Service in Golden, Colorado, at 11:00 AM Tuesday, October 24. This revision is the result of additional data received from 18 seismographic stations around the world, and represents an average of the observations made at these stations. Such revisions in magnitude are normal and reflect the increasing number of observations coming in from seismographs around the world.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in last Tuesday's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

24-HOUR FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Wednesday, October 25, at 7:00 AM PDT, there is only a one percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same period, the probability of a magnitude 5.0 or larger aftershock is four percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is approximately 10 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 45 percent. Also, in the next two months, approximately three additional magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few days will be smaller than last Tuesday's $M = 7.1$ earthquake. As for the possibility of an earthquake comparable to or larger than Tuesday's quake, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that last Tuesday's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

United States
Department of the Interior
Geological Survey, Western Region
Menlo Park, California 94025

Public Affairs Office (415) 329-4000

WEDNESDAY, OCTOBER 25, 5:00 PM PDT

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 5:00 PM PDT Wednesday, October 25, eight days after last Tuesday's earthquake, 79 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest aftershock, magnitude 5.0, occurred Thursday at 3:14 AM PDT. In addition, a total of 20 aftershocks of magnitude 4.0 and larger have occurred so far. Fifty-one magnitude 3.0–3.9 aftershocks occurred during the first 24-hour period after the mainshock, and 16 occurred during the second 24-hour period. During the third day of the sequence, four aftershocks with magnitude 3.0 and larger occurred. The most recent widely felt aftershocks were two magnitude 3.7 events today at 6:01 AM and 3:02 PM, PDT.

The magnitude of the earthquake was revised to 7.1 by the National Earthquake Information Service in Golden, Colorado, at 11:00 AM Tuesday, October 24. This revision is the result of additional data received from 18 seismographic stations around the world, and represents an average of the observations made at these stations. Such revisions in magnitude are normal and reflect the increasing number of observations coming in from seismographs around the world.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in last Tuesday's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

24-HOUR FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Wednesday, October 25, at 5:00 PM PDT, there is less than a one percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same 24-hour period, the probability of a magnitude 5.0 or larger aftershock is four percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is approximately 9 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 43 percent. Also, in the next two months, approximately three additional magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few days will be smaller than last Tuesday's $M = 7.1$ earthquake. As for the possibility of an earthquake comparable to or larger than Tuesday's quake, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that last Tuesday's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

United States
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THURSDAY, OCTOBER 26, 5:00 PM PDT

THE LOMA PRIETA, CALIFORNIA. EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 5:00 PM PDT Thursday, October 26, nine days after last Tuesday's earthquake, 79 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest aftershock, magnitude 5.0, occurred Thursday at 3:14 AM PDT. In addition, a total of 20 aftershocks of magnitude 4.0 and larger have occurred so far. Fifty-one magnitude 3.0–3.9 aftershocks occurred during the first 24-hour period after the mainshock, and 16 occurred during the second 24-hour period. During the third day of the sequence, four aftershocks with magnitude 3.0 and larger occurred. The most recent magnitude three or larger event was a magnitude 3.4 aftershock this morning at 2:01 AM, PDT.

The magnitude of the earthquake was revised to 7.1 by the National Earthquake Information Service in Golden, Colorado, at 11:00 AM Tuesday, October 24. This revision is the result of additional data received from 18 seismographic stations around the world, and represents an average of the observations made at these stations. Such revisions in magnitude are normal and reflect the increasing number of observations coming in from seismographs around the world.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in last Tuesday's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

(more)

24-HOUR FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Thursday, October 26, at 5:00 PM PDT, there is less than a one percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same 24-hour period, the probability of a magnitude 5.0 or larger aftershock is three percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is approximately 9 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 42 percent. Also, in the next two months, approximately three additional magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few days will be smaller than last Tuesday's $M = 7.1$ earthquake. As for the possibility of an earthquake comparable to or larger than Tuesday's quake, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that last Tuesday's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

(more)

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FRIDAY, OCTOBER 27, 5:00 PM PDT

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 4:00 PM PDT Friday, October 27, ten days after last Tuesday's earthquake, 79 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest aftershock, magnitude 5.0, occurred Thursday at 3:14 AM PDT. In addition, a total of 20 aftershocks of magnitude 4.0 and larger have occurred so far. Fifty-one magnitude 3.0–3.9 aftershocks occurred during the first 24-hour period after the mainshock, and 16 occurred during the second 24-hour period. During the third day of the sequence, four aftershocks with magnitude 3.0 and larger occurred. The most recent magnitude three or larger event was a magnitude 3.4 aftershock yesterday morning at 2:01 AM, PDT.

The magnitude of the earthquake was revised to 7.1 by the National Earthquake Information Service in Golden, Colorado, at 11:00 AM Tuesday, October 24. This revision was the result of additional data received from 18 seismographic stations around the world, and represents an average of the observations made at these stations. Such revisions in magnitude are normal and reflect the increasing number of observations coming in from seismographs around the world.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in last Tuesday's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

(more)

24-HOUR FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Friday, October 27, at 5:00 PM PDT, there is less than a one percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same 24-hour period, the probability of a magnitude 5.0 or larger aftershock is three percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is approximately 8 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 40 percent. Also, in the next two months, approximately three additional magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few months will be smaller than last Tuesday's $M = 7.1$ earthquake. As for the possibility of an earthquake comparable to or larger than Tuesday's quake, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that last Tuesday's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

A recorded message summarizing the information in this Press Release may be heard by dialing the U.S. Geological Survey at (415)-329-4026.

(more)

SATURDAY, OCTOBER 28, 5:00 PM PDT

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 4:00 PM PDT Saturday, October 28, eleven days after last Tuesday's earthquake, 80 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest aftershock, magnitude 5.0, occurred Thursday at 3:14 AM PDT. In addition, a total of 20 aftershocks of magnitude 4.0 and larger have occurred so far. Fifty-one magnitude 3.0–3.9 aftershocks occurred during the first 24-hour period after the mainshock, and 16 occurred during the second 24-hour period. During the third day of the sequence, four aftershocks with magnitude 3.0 and larger occurred. The most recent magnitude three or larger event was a magnitude 3.1 aftershock today at 2:28 PM, PDT.

The magnitude of the earthquake was revised to 7.1 by the National Earthquake Information Service in Golden, Colorado, at 11:00 AM Tuesday, October 24. This revision was the result of additional data received from 18 seismographic stations around the world, and represents an average of the observations made at these stations. Such revisions in magnitude are normal and reflect the increasing number of observations coming in from seismographs around the world.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in last Tuesday's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

24-HOUR FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Saturday, October 28, at 5:00 PM PDT, there is less than a one percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same 24-hour period, the probability of a magnitude 5.0 or larger aftershock is two percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is approximately 7 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 37 percent. Also, in the next two months, approximately three additional magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few months will be smaller than last Tuesday's $M = 7.1$ earthquake. As for the possibility of an earthquake comparable to or larger than Tuesday's quake, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that last Tuesday's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

A recorded message summarizing the information in this Press Release may be heard by dialing the U.S. Geological Survey at (415)-329-4026.

SUNDAY, OCTOBER 29, 5:00 PM PST

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 4:00 PM PST Sunday, October 29, twelve days after the earthquake, 80 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest aftershock, magnitude 5.0, occurred Thursday at 3:14 AM PDT. In addition, a total of 20 aftershocks of magnitude 4.0 and larger have occurred so far. Fifty-one magnitude 3.0–3.9 aftershocks occurred during the first 24-hour period after the mainshock, and 16 occurred during the second 24-hour period. During the third day of the sequence, four aftershocks with magnitude 3.0 and larger occurred. The most recent magnitude three or larger event was a magnitude 3.1 aftershock yesterday at 2:28 PM, PDT.

The magnitude of the earthquake was revised to 7.1 by the National Earthquake Information Service in Golden, Colorado, at 11:00 AM Tuesday, October 24. This revision was the result of additional data received from 18 seismographic stations around the world, and represents an average of the observations made at these stations. Such revisions in magnitude are normal and reflect the increasing number of observations coming in from seismographs around the world.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in this month's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

24-HOUR FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Sunday, October 29, at 5:00 PM PST, there is less than a one percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same 24-hour period, the probability of a magnitude 5.0 or larger aftershock is two percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is approximately 7 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 35 percent. Also, in the next two months, approximately two additional magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few months will be smaller than this month's $M = 7.1$ earthquake. As for the possibility of an earthquake comparable to or larger than the quake of October 17th, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that this month's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

A recorded message summarizing the information in this Press Release may be heard by dialing the U.S. Geological Survey at (415)-329-4026.

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MONDAY, OCTOBER 30, 5:00 PM PST

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 4:30 PM PST Monday, October 30, thirteen days after the earthquake, 81 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest aftershock, magnitude 5.0, occurred Thursday at 3:14 AM PDT. In addition, a total of 20 aftershocks of magnitude 4.0 and larger have occurred so far. Fifty-one magnitude 3.0–3.9 aftershocks occurred during the first 24-hour period after the mainshock, and 16 occurred during the second 24-hour period. During the third day of the sequence, four aftershocks with magnitude 3.0 and larger occurred. The most recent magnitude three or larger event was a magnitude 3.5 aftershock today at 3:17 AM, PST.

The magnitude of the earthquake was revised to 7.1 by the National Earthquake Information Service in Golden, Colorado, at 11:00 AM Tuesday, October 24. This revision was the result of additional data received from 18 seismographic stations around the world, and represents an average of the observations made at these stations. Such revisions in magnitude are normal and reflect the increasing number of observations coming in from seismographs around the world.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in this month's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

(more)

24-HOUR FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Monday, October 30, at 5:00 PM PST, there is less than a one percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same 24-hour period, the probability of a magnitude 5.0 or larger aftershock is two percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is approximately 6 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 33 percent. Also, in the next two months, approximately two additional magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few months will be smaller than this month's $M = 7.1$ earthquake. As for the possibility of an earthquake comparable to or larger than the quake of October 17th, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that this month's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

A recorded message summarizing the information in this Press Release may be heard by dialing the U.S. Geological Survey at (415)-329-4026.

(more)

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TUESDAY, OCTOBER 31, 1989, 5:00 PM PST

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 4:30 PM PST Tuesday, October 31, fourteen days after the earthquake, 82 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park, California. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest aftershock, magnitude 5.0, occurred Thursday, October 19, at 3:14 AM PDT. In addition, a total of 20 aftershocks of magnitude 4.0 and larger have occurred so far. Fifty-one magnitude 3.0–3.9 aftershocks occurred during the first 24-hour period after the mainshock, and 16 occurred during the second 24-hour period. During the third day of the sequence, four aftershocks with magnitude 3.0 and larger occurred. The most recent magnitude three or larger event was a magnitude 3.1 aftershock today (October 31) at 12:34 AM, PST.

The magnitude of the earthquake was revised to 7.1 by the U.S.G.S. National Earthquake Information Service in Golden, Colorado, at 11:00 AM Tuesday, October 24. This revision was the result of additional data received from 18 seismographic stations around the world, and represents an average of the observations made at these stations. Such revisions in magnitude are normal and reflect the increasing number of observations coming in from seismographs around the world.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in this month's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

(more)

24-HOUR FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Tuesday, October 31, at 5:00 PM PST, there is less than a one percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same 24-hour period, the probability of a magnitude 5.0 or larger aftershock is two percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is approximately 6 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 31 percent. Also, in the next two months, approximately two additional magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few months will be smaller than this month's $M = 7.1$ earthquake. As for the possibility of an earthquake comparable to or larger than the quake of October 17th, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that this month's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

A recorded message summarizing the information in this press release may be heard by dialing the U.S. Geological Survey at (415)-329-4026.

(more)

WEDNESDAY, NOVEMBER 1, 1989, 5:00 PM PST

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 4:30 PM PST Wednesday, November 1, fifteen days after the earthquake, 83 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park, California. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest aftershock, magnitude 5.0, occurred Thursday, October 19, at 3:14 AM PDT. In addition, a total of 20 aftershocks of magnitude 4.0 and larger have occurred so far. Fifty-one magnitude 3.0–3.9 aftershocks occurred during the first 24-hour period after the mainshock, and 16 occurred during the second 24-hour period. During the third day of the sequence, four aftershocks with magnitude 3.0 and larger occurred. The most recent magnitude three or larger event was a magnitude 3.7 aftershock today (November 1) at 12:03 AM, PST.

The magnitude of the earthquake was revised to 7.1 by the U.S.G.S. National Earthquake Information Service in Golden, Colorado, at 11:00 AM Tuesday, October 24. This revision was the result of additional data received from 18 seismographic stations around the world, and represents an average of the observations made at these stations. Such revisions in magnitude are normal and reflect the increasing number of observations coming in from seismographs around the world.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in last month's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

24-HOUR FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Wednesday, November 1, at 5:00 PM PST, there is less than a one percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same 24-hour period, the probability of a magnitude 5.0 or larger aftershock is two percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is approximately 6 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 31 percent. Also, in the next two months, approximately two additional magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few months will be smaller than last month's $M = 7.1$ earthquake. As for the possibility of an earthquake comparable to or larger than the quake of October 17th, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that last month's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

THURSDAY, NOVEMBER 2, 1989, 5:00 PM PST

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 4:00 PM PST Thursday, November 2, sixteen days after the earthquake, 84 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park, California. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest aftershock, magnitude 5.0, occurred Thursday, October 19, at 3:14 AM PDT. In addition, a total of 21 aftershocks of magnitude 4.0 and larger have occurred so far. The most recent magnitude three or larger event was a magnitude 4.4 aftershock yesterday (November 1) at 9:50 PM, PST. This event, which was widely felt in the San Francisco Bay area, was the largest aftershock since October 24.

The magnitude of the earthquake was revised to 7.1 by the U.S.G.S. National Earthquake Information Service in Golden, Colorado, at 11:00 AM Tuesday, October 24. This revision was the result of additional data received from 18 seismographic stations around the world, and represents an average of the observations made at these stations. Such revisions in magnitude are normal and reflect the increasing number of observations coming in from seismographs around the world.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in last month's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

24-HOUR FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Thursday, November 2, at 5:00 PM PST, there is less than a one percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same 24-hour period, the probability of a magnitude 5.0 or larger aftershock is two percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is approximately 6 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 30 percent. Also, in the next two months, approximately two additional magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few months will be smaller than last month's $M = 7.1$ earthquake. As for the possibility of an earthquake comparable to or larger than the quake of October 17th, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that last month's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

FRIDAY, NOVEMBER 3, 1989, 5:00 PM PST

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 4:00 PM PST Friday, November 3, seventeen days after the earthquake, 84 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park, California. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest aftershock, magnitude 5.0, occurred Thursday, October 19, at 3:14 AM PDT. In addition, a total of 21 aftershocks of magnitude 4.0 and larger have occurred so far. The most recent magnitude three or larger event was a magnitude 4.4 aftershock Wednesday, November 1, at 9:50 PM, PST. This event, which was widely felt in the San Francisco Bay area, was the largest aftershock since October 24.

The magnitude of the earthquake was revised to 7.1 by the U.S.G.S. National Earthquake Information Service in Golden, Colorado, at 11:00 AM Tuesday, October 24. This revision was the result of additional data received from 18 seismographic stations around the world, and represents an average of the observations made at these stations. Such revisions in magnitude are normal and reflect the increasing number of observations coming in from seismographs around the world.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in last month's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

24-HOUR FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Friday, November 3, at 5:00 PM PST, there is less than a one percent chance of a magnitude 6.0 or larger aftershock in the next 24 hours. In the same 24-hour period, the probability of a magnitude 5.0 or larger aftershock is two percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is approximately 6 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 29 percent. Also, in the next two months, approximately two additional magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few months will be smaller than last month's $M = 7.1$ earthquake. As for the possibility of an earthquake comparable to or larger than the quake of October 17th, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that last month's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

A recording summarizing the information in this press release may be heard by dialing the U.S.G.S. at 415-329-4026.

MONDAY, NOVEMBER 6, 1989, 5:00 PM PST

THE LOMA PRIETA, CALIFORNIA, MAGNITUDE 7.1, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 4:00 PM PST Monday, November 6, twenty days after the earthquake, 87 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park, California. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest aftershock, magnitude 5.0, occurred Thursday, October 19, at 3:14 AM PDT. In addition, a total of 22 aftershocks of magnitude 4.0 and larger have occurred so far. The most recent magnitude three or larger event was a widely felt magnitude 4.0 aftershock Sunday, November 5, at 5:37 AM, PST.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in last month's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

ONE-WEEK FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Monday, November 6, at 5:00 PM PST, there is a one percent chance of a magnitude 6.0 or larger aftershock in the next 7 days. In the same 1-week period, the probability of a magnitude 5.0 or larger aftershock is eight percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is approximately 6 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 29 percent. Also, in the next two months, approximately two additional magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few months will be smaller than last month's $M = 7.1$ earthquake. As for the possibility of an earthquake comparable to or larger than the quake of October 17th, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that last month's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

OTHER BAY AREA EARTHQUAKES:

Two felt earthquakes have occured elsewhere in the Bay Area in the past few days. A magnitude 3.6 earthquake at 11:16 PM PST, November 3, on the Hayward fault near San Leandro was widely felt throughout the area. More recently, a magnitude 3.0 earthquake at 3:37 PM PST today (November 6) on the San Andreas fault under Daly City was felt locally. Earthquakes of these magnitudes are not unusual for these portions of the Hayward and San Andreas faults, and their occurrence this week does not change the long-term probability for strong earthquakes in the Bay Area. The probability of a strong (magnitude 7) earthquake in the Bay Area, occuring on either the Hayward or San Andreas faults, is 50 percent over the next 30 years.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

SCHEDULE CHANGE: Beginning today, unless there is new and unusual earthquake activity in the Bay Area, these press releases will be issued on Mondays and Thursdays only, at 5:00 PM PST.

THURSDAY, NOVEMBER 9, 1989, 5:00 PM PST

THE LOMA PRIETA, CALIFORNIA, MAGNITUDE 7.1, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 4:00 PM PST Thursday, November 9, 23 days after the earthquake, 88 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park, California. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest aftershock, magnitude 5.0, occurred Thursday, October 19, at 3:14 AM PDT. In addition, a total of 22 aftershocks of magnitude 4.0 and larger have occurred so far. The most recent magnitude three or larger event was a widely felt magnitude 4.0 aftershock Tuesday, November 7, at 3:42 PM, PST. This earthquake, located about 6 km southwest of Saratoga, was the most northerly strong aftershock to date.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in last month's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

ONE-WEEK FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Thursday, November 9, at 5:00 PM PST, there is a one percent chance of a magnitude 6.0 or larger aftershock in the next 7 days. In the same 1-week period, the probability of a magnitude 5.0 or larger aftershock is eight percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is approximately 6 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 29 percent. Also, in the next two months, approximately two additional magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few months will be smaller than last month's $M = 7.1$ earthquake. As for the possibility of an earthquake comparable to or larger than the quake of October 17th, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that last month's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

OTHER BAY AREA EARTHQUAKES:

Two felt earthquakes have occured elsewhere in the Bay Area in the past week. A magnitude 3.6 earthquake at 11:16 PM PST, November 3, on the Hayward fault near San Leandro was widely felt throughout the area. More recently, a magnitude 3.0 earthquake at 3:37 PM PST today (November 6) on the San Andreas fault under Daly City was felt locally. Earthquakes of these magnitudes are not unusual for these portions of the Hayward and San Andreas faults, and their occurrence this week does not change the long-term probability for strong earthquakes in the Bay Area. The probability of a strong (magnitude 7) earthquake in the Bay Area, occuring on either the Hayward or San Andreas faults, is 50 percent over the next 30 years.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

SCHEDULE CHANGE: You are reminded that Friday, November 10, is a Federal Holiday. The offices of the U.S. Geological Survey will be closed. The next scheduled press release on aftershocks will be Monday, November 13, at 5:00 PM, PST. A summary of the aftershock forecast can be heard by dialing the U.S.G.S. at 415-329-4026.

MONDAY, NOVEMBER 13, 1989, 5:00 PM PST

THE LOMA PRIETA, CALIFORNIA, MAGNITUDE 7.1, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 4:30 PM PST Monday, November 13, 27 days after the earthquake, 88 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park, California. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest aftershock, magnitude 5.0, occurred Thursday, October 19, at 3:14 AM PDT. In addition, a total of 22 aftershocks of magnitude 4.0 and larger have occurred so far. The most recent magnitude three or larger event was a widely felt magnitude 4.2 aftershock Tuesday, November 7, at 3:42 PM, PST. This earthquake, earlier misreported as magnitude 4.0, was located about 6 km southwest of Saratoga, and was the northernmost strong aftershock to date.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in last month's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures.

ONE-WEEK FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Monday, November 13, at 5:00 PM PST, there is a one percent chance of a magnitude 6.0 or larger aftershock in the next 7 days. In the same 1-week period, the probability of a magnitude 5.0 or larger aftershock is seven percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several weeks or months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is approximately 5 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 28 percent. Also, in the next two months, one or two additional magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few months will be smaller than last month's $M = 7.1$ earthquake. As for the possibility of an earthquake comparable to or larger than the quake of October 17th, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that last month's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

The next scheduled press release on aftershocks will be Thursday, November 16, at 5:00 PM, PST. A summary of the aftershock forecast can be heard by dialing the U.S.G.S. at 415-329-4026.

United States
Department of the Interior
Geological Survey, Western Region
Menlo Park, California 94025

Public Affairs Office Pat Jorgenson **(415) 329-4000**

THURSDAY, NOVEMBER 16, 1989, 5:00 PM PST

THE LOMA PRIETA, CALIFORNIA, MAGNITUDE 7.1, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 4:00 PM PST Thursday, November 16, 30 days after the earthquake, 90 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park, California. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest aftershock, magnitude 5.0, occurred Thursday, October 19, at 3:14 AM PDT. In addition, a total of 22 aftershocks of magnitude 4.0 and larger have occurred so far. A 7-day period without any magnitude 3.0 or larger aftershocks ended Tuesday, November 14, with a magnitude 3.1 aftershock at 1:17 PM, PST. It was followed Wednesday night at 8:59 PM, PST, by a magnitude 3.2 aftershock. This one-week interval without a felt aftershock is a normal fluctuation in the aftershock process. Such a pause does not signal an end to the aftershocks; felt aftershocks are expected in the epicentral region, at an ever-diminishing rate, for the next two years.

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in last month's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures, and in areas prone to land slides.

ONE-WEEK FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Thursday, November 16, at 5:00 PM PST, there is a one percent chance of a magnitude 6.0 or larger aftershock in the next 7 days. In the same 1-week period, the probability of a magnitude 5.0 or larger aftershock is six percent.

(more)

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is approximately 5 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 27 percent. Also, in the next two months, one or two additional magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few months will be smaller than last month's $M = 7.1$ earthquake. As for the possibility of an earthquake comparable to or larger than the quake of October 17th, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that last month's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

The next scheduled press release on aftershocks will be Monday, November 20, at 5:00 PM, PST. A summary of the aftershock forecast can be heard by dialing the U.S.G.S. at 415-329-4026.

* * * USGS * * *

MONDAY, NOVEMBER 20, 1989, 5:00 PM PST

THE LOMA PRIETA, CALIFORNIA, MAGNITUDE 7.1, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 4:00 PM PST Monday, November 20, 34 days after the earthquake, 90 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park, California. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest aftershock, magnitude 5.0, occurred Thursday, October 19, at 3:14 AM PDT. In addition, a total of 23 aftershocks of magnitude 4.0 and larger have occurred so far. The most recent magnitude 3.0 or larger event was a magnitude 3.0 aftershock last Wednesday night at 8:59 PM, PST. (This event was incorrectly reported earlier as having magnitude 3.2.)

Seismologists advise that additional aftershocks are expected in the next few weeks to months, some possibly strong enough to cause additional damage, especially to structures weakened in last month's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures, and in areas prone to land slides.

ONE-WEEK FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Monday, November 20, at 5:00 PM PST, there is less than a one percent chance of a magnitude 6.0 or larger aftershock in the next 7 days. In the same 1-week period, the probability of a magnitude 5.0 or larger aftershock is five percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is approximately 4 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 25 percent. Also, in the next two months, one or two additional magnitude 4.0 or larger aftershocks are expected.

Most probably, additional earthquakes in the next few months will be smaller than last month's $M = 7.1$ earthquake. As for the possibility of an earthquake comparable to or larger than the quake of October 17th, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that last month's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely. For example, no such triggering occurred after the magnitude 6.5 earthquake believed to have occurred on the same Santa Cruz segment of the San Andreas fault in 1865.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

The next scheduled press release on aftershocks will be Monday, November 27, at 5:00 PM, PST. A summary of the aftershock forecast can be heard by dialing the U.S.G.S. at 415-329-4026.

MONDAY, NOVEMBER 27, 1989, 4:00 PM PST

THE LOMA PRIETA, CALIFORNIA, MAGNITUDE 7.1, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK SEQUENCE OBSERVATIONS AND FORECAST

As of 4:00 PM PST Monday, November 27, 41 days after the earthquake, 91 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park, California. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest aftershock, magnitude 5.0, occurred Thursday, October 19, at 3:14 AM PDT. In addition, a total of 23 aftershocks of magnitude 4.0 and larger have occurred so far. The most recent magnitude 3.0 or larger event was a magnitude 3.0 aftershock Saturday, November 25, at 4:50 PM, PST.

Seismologists advise that additional aftershocks are expected in the next few months, some possibly strong enough to cause additional damage, especially to structures weakened in last month's quake. Because of this continuing hazard, scientists urge that earthquake preparedness measures continue to be taken, and that extreme caution be exercised in and around damaged structures, and in areas prone to land slides.

ONE-WEEK FORECAST:

The probability for aftershocks decreases with time most rapidly during the first week after the mainshock; then, the probability for aftershocks decreases more slowly in the later weeks and months of the earthquake sequence. To assess the chances for additional damaging aftershocks, scientists rely on the average behavior of past California sequences, and on observations of the current earthquake sequence. The aftershocks recorded so far generally follow the behavior of a typical California sequence. From these observations, a statistical model has provided a forecast of future strong aftershocks. As of Monday, November 27, at 4:00 PM PST, there is less than a one percent chance of a magnitude 6.0 or larger aftershock in the next 7 days. In the same 1-week period, the probability of a magnitude 5.0 or larger aftershock is three percent.

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is approximately 3 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 20 percent. Also, in the next two months, approximately one additional magnitude 4.0 or larger aftershock is expected.

Most probably, additional earthquakes in the next few months will be smaller than last month's $M = 7.1$ earthquake. As for the possibility of an earthquake comparable to or larger than the quake of October 17th, scientists characterize the chances for that as "very small, but not zero". In a small fraction of the cases observed in California, a large earthquake has triggered a comparable or larger earthquake on an adjacent segment of the same fault, or on a neighboring fault. In particular, scientists are focusing attention on the Peninsula segment of the San Andreas fault, from Los Gatos to Daly City. This segment of the San Andreas was previously identified as being capable of producing a magnitude 7 earthquake, and was given a 20 percent chance of doing so in the next 30 years. There is concern among scientists that last month's earthquake may have increased the stress on the southern end of that fault segment, thus increasing the chances for a strong earthquake on the San Francisco Peninsula over the next few years. Such triggering, however, is considered unlikely.

Seismologists will continue to monitor the aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and update the forecast for future aftershocks as the sequence progresses.

The next scheduled press release on aftershocks will be Thursday, November 30, at 4:00 PM, PST.

United States
Department of the Interior
Geological Survey, Western Region
Menlo Park, California 94025

Public Affairs Office Pat Jorgenson (415) 329-4000

THURSDAY, NOVEMBER 30, 1989, 4:00 PM PST

THE LOMA PRIETA, CALIFORNIA, MAGNITUDE 7.1, EARTHQUAKE OF OCTOBER 17, 1989

AFTERSHOCK OBSERVATIONS AND FORECAST

** LAST SCHEDULED STATEMENT **

As of 4:00 PM PST Thursday, November 30, 44 days after the earthquake, 91 aftershocks of magnitude 3.0 and larger were recorded by the U.S. Geological Survey in Menlo Park, California. The largest aftershock, magnitude 5.2, occurred 37 minutes after the mainshock. The second largest aftershock, magnitude 5.0, occurred Thursday, October 19, at 3:14 AM PDT. In addition, a total of 23 aftershocks of magnitude 4.0 and larger have occurred so far. The most recent magnitude 3.0 or larger event was a magnitude 3.0 aftershock Saturday, November 25, at 4:50 PM, PST.

NOTE:

Because the aftershocks are decreasing in frequency in a normal fashion, and because the probabilities for future strong aftershocks are similarly diminishing, this statement is the last scheduled assessment of the afterhsocks sequence.

*** SEE IMPORTANT NEW TEXT ON PAGE 2 ***

(more)

LONG TERM FORECAST:

The long term outlook underscores the enduring nature of aftershock sequences. It is not uncommon for a strong aftershock to occur several months after a mainshock. Over the next two months the probability of a magnitude 6.0 or larger aftershock is approximately 3 percent, while the probability of a magnitude 5.0 or larger event in the same two-month period is about 15 percent. In the next two months, approximately one additional magnitude 4.0 or larger aftershock is expected. In the next year, there is a 25 percent chance of a magnitude 5.0 or larger aftershock.

IMPORTANT NEW TEXT:

While the aftershocks are diminishing in rate, one should not be lulled into a false sense of security! Additional strong aftershocks are still quite possible. For example, in another recent earthquake sequence – 1983 Coalinga, California, magnitude 6.7 earthquake sequence – the strongest aftershock, with magnitude 6.0, occurred more than two months after the earthquake. If a such a late, strong aftershock to the Loma Prieta earthquake were to occur, additional dammage to structures weakened in the October 17 earthquake could result, and unstable slopes could produce dangerous land slides.

As we end our regular updates on aftershock activity, we leave you with this sobering message. Another earthquake with magnitude comparable to the October 17 earthquake, but located closer to the population centers in the San Francisco Bay Area, is expected to occur – with a probability of 50 percent over the next 30 years. When it occurs, the next strong Bay Area earthquake is expected to cause far greater dammage and loss of life than last month's earthquake. If the Loma Prieta earthquake taught us anything, it taught us that we must respect the power of the Earth. We can best express our respect not with fear, but with thoughtful preparations for the next earthquake. Now, not later, is the time to prepare.

Seismologists will continue to monitor the Loma Prieta aftershock sequence, as well as any unusual earthquake activity elsewhere in the San Francisco Bay area, and will issue additional unscheduled press releases when appropriate.

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