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The 2004 Parkfield Earthquake, the 1985 Prediction, and Characteristic Earthquakes: Lessons for the Future

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Abstract The 1985 prediction of a characteristic magnitude 6 Parkfield earthquake was unsuccessful, since no significant event occurred in the 95% time window (1985–1993) anywhere near Parkfield. The magnitude 6 earthquake near Parkfield in 2004 failed to satisfy the prediction not just because it was late; it also differed in character from the 1985 prediction and was expectable according to a simple null hypothesis. Furthermore, the prediction was too vague in several important respects to meet the accepted definition of an earthquake prediction. An event occurring by chance and meeting the general description of the predicted one was reasonably probable. The original characteristic earthquake model has failed in comprehensive tests, yet it is still widely used. Modified versions employed in recent official seismic hazard calculations allow for interactions between segments and uncertainties in the parameters. With more adjustable parameters, the modified versions are harder to falsify. The characteristic model as applied at Parkfield and elsewhere rests largely on selected data that may be biased because they were taken out of context. We discuss implications of the 2004 event for earthquake prediction, the characteristic earthquake hypothesis, and earthquake occurrence in general.

Introduction

In 1985 the National Earthquake Prediction Evaluation Council (NEPEC) issued a statement (Shearer, 1985) that an earthquake of about magnitude 6 would probably occur before 1993 on the San Andreas fault near Parkfield, California. That statement was largely based on the apparently quasi-periodic occurrence of characteristic earthquakes with similar magnitude in 1881, 1901, 1922, 1934, and 1966 (Bakun and Lindh, 1985). However, no such earthquake occurred till 28 September 2004, when one of magnitude 6.0 struck near Parkfield (Bakun *et al.*, 2005). The 1985 Parkfield prediction model, described in an article by Bakun and Lindh (1985), was based largely on the characteristic earthquake hypothesis (Schwartz and Coppersmith, 1984). This hypothesis, in its most basic form, assumes that faults are divided into segments, and that sequences of characteristic earthquakes, mostly contained within each segment, are responsible for most of the geologically observed slip there.

The Parkfield prediction was perhaps the most widely publicized application of the characteristic model, so whether the 2004 event was the predicted one and whether it was indeed characteristic, are important questions. Although the 1985 prediction clearly failed, some (e.g., Bakun *et al.*, 2005; Lindh, 2005) contend that except for time, most aspects of the prediction were satisfied. Because the prediction was based on the characteristic hypothesis, a partially successful prediction would appear to support that hypothesis. Here we examine the 2004 earthquake in the double context of the 1985 prediction and the characteristic earthquake model. We also develop a null hypothesis that Parkfield earthquakes are Poissonian in time with a tapered Gutenberg–Richter (G–R) magnitude distribution, and we compare Parkfield earthquakes with that hypothesis as well.

We first briefly discuss the model of characteristic quasi-periodic earthquakes and review the history of the Parkfield prediction. Then, using our analysis as well as results by other researchers, we show that the 2004 Parkfield event did not satisfy many of the prediction's conditions. We examine the earthquakes' magnitude distribution and present a noncharacteristic null hypothesis. The tectonic moment rate and its relationship to earthquake frequency is then considered, as well as the regularity of earthquake occurrence. We ask whether the results of Parkfield apply to other places. The most important part of the article shows that the method of the Parkfield prediction and its later developments violate accepted scientific rules of forming and testing hypotheses. In particular, we propose that any scientific model needs to be tested and discuss requirements for validation. We briefly consider development of the characteristic and seismic gap models and the controversies connected with testing these hypotheses. We also discuss recent applications of these models. Finally, we make recommendations to test the characteristic earthquake hypothesis critically and so improve seismic hazard evaluation using the results of such tests.

Characteristic Earthquakes and Seismic Gaps

Characteristic earthquakes are presumed to be so similar that they can be picked out of a large catalog of events with little ambiguity. The basic description above requires that they have similar rupture areas and magnitudes, but many other properties are sometimes associated with them. They are often assumed to have similar hypocenters, similar displacement distributions within the rupture area, similar source time functions (leading to similar seismograms), or quasi-periodic recurrence. All of these properties have been attributed to the Parkfield earthquakes of 1881, 1901, 1922, 1934, and 1966 (Bakun and Lindh, 1985). It is important to distinguish these properties because "characteristic" may to some imply all of these properties, and one of these properties might be taken to imply the others. If an earthquake is predicted by specifying many broadly defined requirements, almost any future event would satisfy some of them. It has become customary to call an anticipated earthquake at Parkfield and any member of the set of previous magnitude 6 events there "the Parkfield earthquake" without further elaboration. For example a 1993 review of the Parkfield project stated "Estimates of the probability of the Parkfield earthquake occurring in the near future have been generated by a number of scientists" (National Earthquake Prediction Evaluation Council Working Group, 1994, p. 1). Such a statement clearly raises the expectation that some future earthquake will be clearly recognized as "the" one, but there is no statement about which properties are to identify it.

The seismic gap model (McCann *et al.*, 1979; Nishenko, 1989, 1991) assumes that characteristic earthquakes are quasi-periodic with a characteristic recurrence time. According to the gap model, plate boundaries, like faults, are divided into segments, each with its own characteristic earthquake (Fedotov, 1968; McCann *et al.*, 1979; Nishenko, 1989, 1991).

The characteristic earthquakes are assumed large enough to dominate the seismic moment release and substantially reduce the average stress. The standard explanation for quasi-periodicity is that the stresses that cause earthquakes are slowly building up by plate movements after one event (Nishenko and McCann, 1981, p. 21); a new, strong earthquake is less probable until the stress or deformational energy reaches a critical value (Shimazaki and Nakata, 1980). A seismic gap, according to the model, is a fault or plate segment for which the time since the previous characteristic earthquake is close to or exceeds the characteristic recurrence time. In many applications, some past earthquakes are assumed characteristic, and the average time between them is assumed to be the characteristic recurrence interval. Parkfield is such a case, so it would have been a seismic gap before 2004.

The characteristic hypothesis, which implies a sequence of recognizably similar events, provides the logical basis for discussing recurrence. Recurrence intervals and their statistics are meaningless with no clear definition of the characteristic earthquake. While Reid (1910), Fedotov (1968), and McCann *et al.* (1979) all predated the first article to use the term "characteristic earthquake," they clearly had in mind a similar concept: one earthquake would begin a cycle by reducing stress and when stress recovered, a similar earthquake would follow.

The characteristic earthquake hypothesis, generally with the assumption of quasi-periodic events, has generated considerable controversy, as discussed later.

The Parkfield Prediction

History of the Parkfield Prediction

The Parkfield, California, prediction is often referred to as the only one reviewed and approved by the U.S. government. Here we summarize several descriptions of the predicted event and compare them with the generally accepted definition of earthquake prediction (see also Geller, 1997; pp. 438–440).

In 1976 a National Academy panel on earthquake prediction wrote, "An earthquake prediction must specify the expected magnitude range, the geographical area within which it will occur, and the time interval within which it will happen with sufficient precision so that the ultimate success or failure of the prediction can readily be judged" (National Academy of Sciences, 1976, p. 7).

The sequence of characteristic earthquakes at Parkfield was described by Bakun and McEvilly (1984). They referred to the "20- to 30-km long section of the fault." They estimated the local magnitude M_L of the 1934 and 1966 earthquakes to be 5.6 each.

The NEPEC met in November of 1984 to consider the implications of the apparent characteristic sequence at Parkfield (Shearer, 1985). The official prediction was expressed in a letter dated 4 April 1985 by Dallas Peck, Director of the U.S. Geological Survey, to William Medigovich, Director of the California Office of Emergency Services. Peck mentions "another magnitude 6 earthquake" on the "San Andreas fault near Parkfield" with a 95% chance of occurring in the 1985–1993 interval. He goes on to state that "an earthquake larger than magnitude 6 is possible in the Parkfield area, with the fault breaking up to 25 miles further south than it did in 1966."

Donovan Kelly, Public Affairs Officer of the U.S. Geological Survey (USGS), reported the prediction in a public announcement on 5 April 1985. Kelly's letter referred to "an earthquake of magnitude 5.5 to 6 . . . in the Parkfield, Calif., area within the next several years (1985–1993)."

Michael and Jones (1998, p. 125) define the Parkfield earthquake as a $M_w > 5.7$ event with the surface rupture "between 36 N and 35.75 N [degrees] and within 5 km of the mapped trace." The length of fault between the latitude limits above is 37 km. Their figure 1 shows several polygons surrounding the mainshock and aftershocks of the 1966 event. None is clearly identified as the box in which the next Parkfield earthquake was expected to occur, but from the context the "mainshock box" seems the best candidate.

From the previous statements, it appears that the Parkfield prediction could have been satisfied by a timely earthquake having a magnitude anywhere from 5.5 to 7.5, with any rupture length over 20 km. Not until the Michael and Jones (1998) article was the Parkfield area defined in terms of a polygon. Even that description was ambiguous, because the requirement of surface rupture could be read to mean (1) any surface rupture partly within the latitude limits; (2) a surface rupture entirely contained within the latitude limits, or (3) a surface rupture spanning the latitude limits. The distinction is important in terms of the presumed properties of the characteristic earthquake. Under (1), earthquakes satisfying the prediction could have quite different rupture areas and might rupture past the polygon boundaries. Interpretation (2) would be most appropriate if the margins of the polygon represent physical constraints on rupture. Interpretation (3) makes sense if the cause of the characteristic earthquakes and their quasi-periodicity is assumed to be accumulated moment that must be released. A. J. Michael (personal comm., 2005) wrote that (1) was the intended interpretation because (2) would violate their statement that "events that produce additional surface rupture outside this box or on other faults are also Parkfield mainshocks" and (3) would imply the clear contradiction that the M 6.0 event in 1966 is not a Parkfield mainshock because it had discontinuous surface rupture.

Clearly the 1985 prediction statement did not meet the requirements for specifying the magnitude and spatial limits expressed by the 1976 National Academy report. The specification was improved by Michael and Jones (1998), although the definition of the predicted event was not adequate for a scientific hypothesis test.

Despite the ambiguity of its definition, the Parkfield prediction carried some amazingly specific expectations. According to Bakun and McEvilly (1984), the next characteristic Parkfield earthquake should have several properties in common with the previous ones, including the "same epicenter, magnitude, seismic moment, rupture area, and southeast direction of rupture expansion." Bakun and Lindh (1985, p. 620) add that the "Characteristic Parkfield Earthquake" may have magnitude 5.1 foreshocks preceding each mainshock by 17 minutes, based on the quakes in 1934 and 1966. However, because these specific expectations were not contained in all of the various statements made about the predicted event, it is difficult to know what the actual hypothesis was and this situation makes testing this hypothesis problematic.

Prediction Scorecard

Rymer *et al.* (2006, their figures 1 and 2) show the rupture traces of the 2004 Parkfield earthquake and epicenters of 1966 and 2004 events; see also figure 1 by Bakun *et al.* (2005). Langbein *et al.* (2005) and Bakun *et al.* (2005) review the observations concerning the 2004 Parkfield event. Its magnitude (6.0) was certainly within the predicted range. The northern termination of the rupture zone was within a few kilometers of that of the 1966 earthquake, while the southern termination was about 5 km short (north) compared to that of the 1966 event. If we use interpretation (1) or (2) of the rupture zone criterion by Michael and Jones (1998) the 2004 Parkfield event met that part of the prediction. However, it came about 12 years too late, and it clearly missed the predictions concerning epicenter, rupture area, southeast propagation, and magnitude 5.1 foreshocks.

Magnitude Distribution of Parkfield Earthquakes

Since the great earthquake of 1857, there have been six earthquakes near Parkfield with M 6 (Bakun *et al.*, 2005). The great event had a magnitude of about 7.9, and it too may have ruptured the San Andreas fault at Parkfield (Sieh, 1978). Since then there have been no earthquakes with epicenters in the prediction zone with reported surface-wave magnitudes between 5.2 and 5.6, or greater than 6.3. This leaves a cluster of magnitudes around 6.0 generally taken as evidence for characteristic behavior at Parkfield (Bakun *et al.*, 2005, their supplement). They estimated the moment magnitudes of the last four to be 6.0, 6.0, 6.05, and 6.0, respectively. Allowing for reasonable uncertainties, we assumed that the characteristic magnitude included the range 5.7 to 6.3.

There are two significant problems with interpreting the sequence of magnitude 6 earthquakes as characteristic. First is that the data come from rather diverse sources. The magnitudes and locations of the 1857, 1881, and 1901 earthquakes were determined from qualitative comments by residents and travelers with little prior experience of earthquakes (Toppozada *et al.*, 2000, 2002). Given the sparse population and the lack of consistent standards to judge shaking, the estimated magnitudes and locations must have large uncertainties. Thus, we cannot be sure that those events have magnitude $6.3 \geq M \geq 5.7$ and are located within the Parkfield rupture zone.

The second, even more serious problem is data selection. The spatial, temporal, and magnitude limits employed in selecting those quakes were not set before the data were selected (Kagan, 1997). That the first six of the Parkfield characteristic events were selected from a much larger set of California earthquakes, and the boundaries drawn after looking at the data both invite selection bias. A feature that might be an expectable coincidence in a large set of data can appear quite nonrandom when the sample is narrowed to a small number of events. It is impossible in retrospect to know what in fact were the selection criteria unless they are specified before the data themselves are available for selection. For this reason we conclude that it is invalid to infer a magnitude distribution from the magnitudes of the presumed characteristic earthquakes at Parkfield.

A Simple Null Hypothesis

As an alternative to the quasi-periodic characteristic model, we propose a simpler one in which earthquakes (except aftershocks) are governed by a Poisson process and their magnitudes follow a tapered G–R distribution. This distribution (Kagan, 2002) has three parameters: α, a multiplicative constant proportional to the a-value of the standard G–R distribution: the b-value; and the corner magnitude M_c. The standard two-parameter G–R distribution is equivalent to a power-law distribution of seismic moments. The tapered G–R distribution includes an exponential rolloff of frequency for moments near and above the corner moment. The corner magnitude is the moment magnitude corresponding to that value. The taper assures that the total moment rate is finite, and the value of the total moment rate depends strongly on the corner magnitude. For magnitudes the tapered G–R relation can be written as

$$\log_{10} N(M) = \log_{10}(\alpha) - b(M - M_t) + \frac{1}{\log(10)}\left[10^{1.5(M_t - M_c)} - 10^{1.5(M - M_c)}\right], \quad (1)$$

where M is earthquake magnitude, M_t is the threshold magnitude, and $N(M)$ is the number of earthquakes with magnitude equal or greater than M. For the standard two-parameter G–R distribution the last two terms in the right-hand part of (1) are zero ($M_c \rightarrow \infty$).

Here we determine α and the b-value from the Parkfield earthquake catalog. We take the corner magnitude from the study of Bird and Kagan (2004), who estimated parameters by combining regions of similar tectonic character around the globe. In their classification, Parkfield is in a continental transform fault region, for which they found a corner magnitude $8.0^{+.47}_{-.21}$. With this large corner magnitude, the magnitude distribution for earthquakes near magnitude 6 is indistinguishable from the standard G–R distribution. Figure 1 shows the cumulative magnitude distribution for earthquakes within the mainshock zone defined by Michael and Jones (1998). We assume that this zone was defined solely by the rupture zone and the early aftershocks of the 1966 Parkfield earthquake, so that earthquakes after 1966 have no impact on zone boundaries. We considered earthquakes since 1967 greater than magnitude 3, safely above the completeness threshold.

Figure 1a shows the cumulative earthquake count for earthquakes in the mainshock zone from the beginning of 1967 through the end of 2003, before the recent (2004) earthquake. The straight line in the figure is the best-fit G–R distribution, determined using the maximum-likelihood method of Aki (1965). We use the parameters of that line to determine the α and b-value parameters of our null hypothesis. The best-fit α value corresponds to a frequency of magnitude 6 or larger events = 1/142 eq/yr. The best fit b-value is 0.87. The displayed 95% confidence limits are conditioned by the total number of earthquakes observed. To calculate properly the full uncertainty bounds, it would be necessary to convolve the b-errors with the event number distribution. We made the simple assumption that this distribution is Poisson. For the number N of samples in the Poisson distribution greater than 30, one can accurately approximate the Poisson distribution with a Gaussian one having variance equal to N. For this illustration we simply extended the Gaussian approximation down to $N = 1$. The approximation underestimates both the upper-bound and lower-bound frequencies, but this does not affect our conclusion: earthquakes from 1967 through 2003 were quite consistent with our null hypothesis.

That the 2004 earthquake had a magnitude of 6.0, close to the estimated characteristic magnitude, would seem to support the characteristic earthquake hypothesis. However, the magnitude of the 2004 event was quite consistent with the null hypothesis. Using the description given in Michael and Jones (1998), any earthquake over magnitude 5.7 with some rupture in the predicted zone might be counted as a successful prediction. For discussion we assume that a characteristic event is a shallow earthquake with its epicenter in the prediction zone and a magnitude in the range 5.7 to 6.3. Earthquakes smaller than 5.7 would be considered irrelevant, as were the five events of about magnitude 5 shown in Figure 1b. Events over magnitude 6.3 would probably violate the characteristic hypothesis by breaking past the presumed segment boundary. What is the chance that the next earthquake over 5.7 in the predicted zone after 1966 would have a magnitude in the characteristic range? It is just $(R - S)/R$, where R is the rate of magnitude 5.7 and above, and S is the rate of magnitude 6.3 and above, in the prediction zone. From the maximum-likelihood G–R line in Figure 1a, $R = 0.0128$/yr and $S = 0.0039$/yr. Thus, according to the null hypothesis, the probability that the next event would have a characteristic magnitude is 70%.

What is the probability that an earthquake of magnitude 5.7 or larger after 1967 would occur before the end of 2004? Assuming a Poisson process, that probability is $1 - \exp(-RT)$, where T is $2005 - 1967 = 38$ years. The probability is 38%. The corresponding probability for an earthquake with magnitude between 5.7 and 6.3 is 28%, and that for an earthquake of 6.0 or larger is 23%. Thus, neither the size nor the timing of the 2004 Parkfield event should surprise us, assuming a simple null hypothesis of Poissonian, G–R earthquakes at Parkfield.

Figure 1b shows the magnitude distribution when the recent (2004) earthquake and its aftershocks are included. The overall seismicity increases modestly, but the change in the b-value is negligible, and the earthquake count is within the 95% confidence limits for all magnitudes. Thus, if we use instrumental magnitudes and selection criteria independent of the catalog itself, objective evidence is consistent with the null hypothesis. For estimating future earthquake

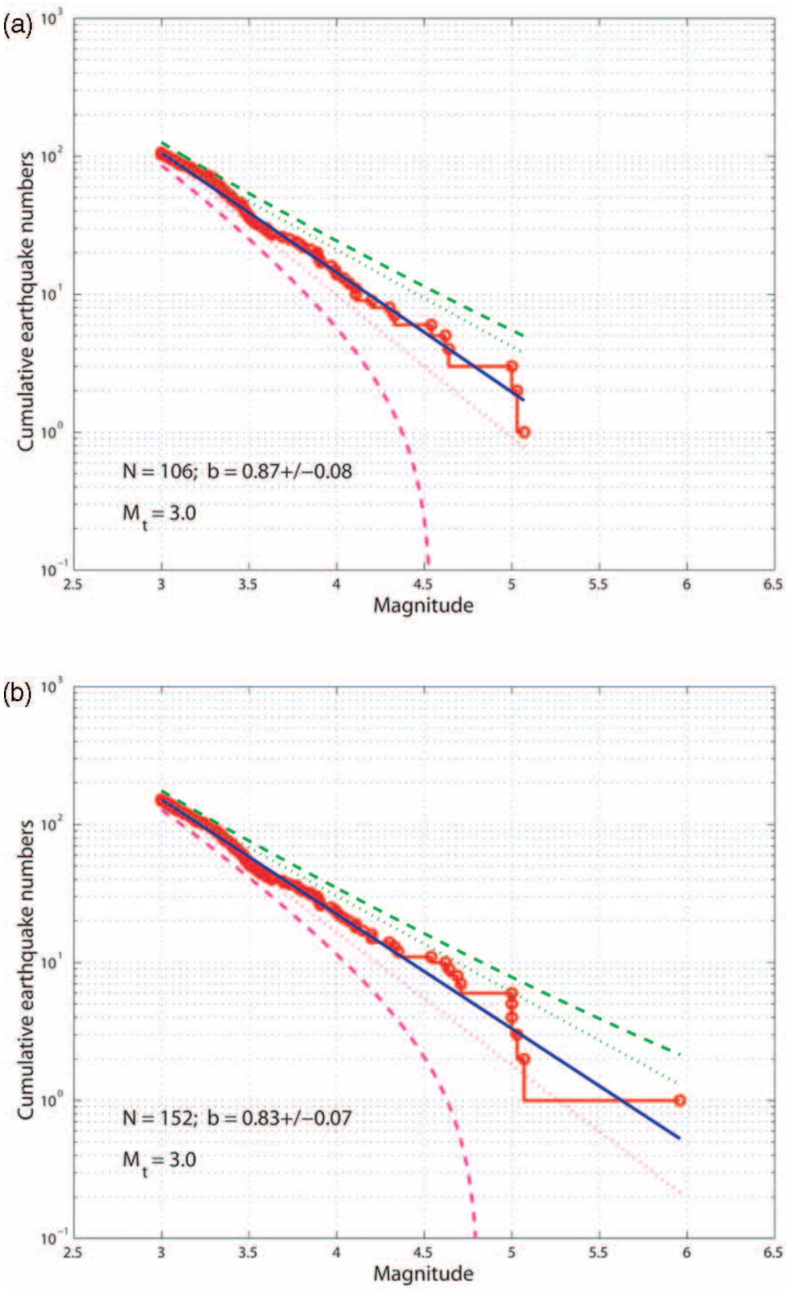

Figure 1. Magnitude–frequency relation for the Parkfield earthquakes. The Advanced National Seismic System (ANSS, 2006) catalog is used (http://quake.geo.berkeley.edu/anss/catalog-search.html). Earthquakes are selected in the Parkfield box proposed by Michael and Jones (1998); its corners are: 35.971° N, 120.598° W, 36.029° N, 120.512° W, 35.788° N, 120.262° W, 35.729° N, 120.347° W. Solid line is the G–R approximation. Dotted and dashed lines are 95% confidence limits; former are conditioned by the total number of earthquakes observed, and latter are estimates based on the Poisson assumption for earthquake occurrence. (a) Time period 1967–2003 (before the 2004 Parkfield earthquake); (b) time period 1967–2005 (including time after the 2004 Parkfield earthquake).

potential and seismic moment, we would use an updated null hypothesis with parameters determined from Figure 1b: α corresponds to 1/77 magnitude 6 events per year, and the b-value is 0.83.

If characteristic earthquakes explain most of the slip on a fault segment, then the frequency of larger earthquakes should be very small relative to that of characteristic earthquakes. Thus, the absence of any earthquakes larger than about 6.3 would seem to support the characteristic model. However, the absence of larger earthquakes is also consistent with our Poissonian G–R null hypothesis. It indicates a 34% chance that no earthquake larger than M 6.3 should occur on the Parkfield segment in the 148 years between 1857 and 2005.

Some of the Parkfield predictions (Bakun and Lindh, 1985) included a discussion of possible larger events. This extension of the characteristic earthquake hypothesis makes it even harder to differentiate it from the null hypothesis than a stricter characteristic hypothesis.

Moment Release at Parkfield

The tectonic moment rate and its release by Parkfield earthquakes have been discussed thoroughly in articles by

Kagan (1997), Murray and Segall (2002), Harris and Archuleta (1988), Murray *et al.* (2004), and Murray and Langbein (2006). All these authors point out that Parkfield earthquakes of the size and frequency observed so far are inadequate to explain the moment rate and/or the slip rate implied by long-term tectonic motion of the San Andreas fault. Those articles present detailed estimates of the spatial and temporal distribution of slip near Parkfield, and they offer various explanations. One explanation is that much of the Parkfield segment slips aseismically, so that characteristic earthquakes release stress only on asperities that cover part of the fault segment area. Another explanation is that a slip deficit, comparable to the slip released in the 1857 earthquake, has accumulated in the southeast part of the Parkfield section (Toké and Arrowsmith, 2006).

Because comparing seismic and tectonic moments is relevant to the characteristic earthquake model, we present a brief comparison here. Assuming that the rigidity is 3×10^{10} N/m^2, and that the Parkfield segment is 35 km long, has a 15-km-width measured down-dip, and slips at 35 mm/yr, the tectonic moment rate for the segment is 0.55×10^{18} N m/yr. In the 148 years since 1857, a tectonic moment of 82×10^{18} N m would have accumulated. A magnitude 6 earthquake releases about 10^{18} N m of seismic moment. Earthquakes smaller than magnitude 6 release only a small part of the total. Thus, the six Parkfield earthquakes since 1857 would have released about 6×10^{18} N m, leaving about 76×10^{18} N m unexplained. Any of the assumed parameters might be questioned, and evidently some fraction of the tectonic moment is released aseismically (Segall and Harris, 1986, 1987; Harris and Archuleta, 1988). However, the discrepancy between tectonic accumulation and seismic release is so large that reasonable adjustments won't resolve it. One of the primary features of the basic characteristic earthquake model is that the characteristic events cause most of the tectonic moment release. If the primary mechanism for moment relief were magnitude 6 earthquakes, they would need to occur about every two years on average.

The tectonic moment release is well explained by our null hypothesis. Using equation (7) in Kagan (2002), we calculate the moment rate $\dot{M}$, to be

$$\dot{M} = \frac{\alpha M_0^{\beta}\, M_x^{1-\beta}\, \Gamma(2 - \beta)\xi_{\mathrm{m}}}{1 - \beta}, \qquad (2)$$

where α is the frequency of M 3 earthquakes; β is the exponent for the moment-frequency relation ($\beta_1 = b/1.5 = 0.87/1.5 = 0.58$; $\beta_2 = 0.55$); $M_0 = 10^{13.5}$ N m is the moment of the earthquake for which α-value is calculated ($M3$); $M_x = 10^{21}$ N m is the corner moment for the $M8$ earthquake; Γ is a gamma function, $\Gamma(1.42) = 0.8864$, $\Gamma(1.44) = 0.8857$; and $\xi_{\mathrm{m}} = \exp(M_0/M_x)$ is the correction for the exponential tail (can be neglected for M 3 earthquake). We obtain the $\dot{M}$ value of about 0.27×10^{18} for the original null hypothesis (Fig. 1a) and 0.56×10^{18} for the updated null hypothesis (Fig. 1b). Thus, assuming the seismic coupling efficiency of 100% (Bird and Kagan, 2004), the tectonic moment rate can be satisfied with a tapered G–R magnitude distribution such that magnitude 3 or larger events occur with a yearly frequency of 2.9 or 4.0 (see Fig. 1a,b) and a corner magnitude of 8.0. This is astoundingly good agreement, given that the first estimate (0.55×10^{18}) is based on slip-rate data while the second is based on seismicity only.

The great 1857 earthquake, with magnitude about 7.9, fits into that picture nicely. Earthquakes between magnitude 6 and 8 most likely occur too, but their frequency would be such that absence of any during the period of instrumental seismology would not be surprising.

The parameters we selected for moment-balance calculations are in the middle range of published values (Bakun *et al.*, 2005). Of these parameters the depth is most arbitrary, but it is the integral of area and coupling efficiency that counts. Even if the fault area we considered is only 25% coupled, due to aseismic slip on different fault segments, there is still a serious problem accounting for the tectonic moment in the strict characteristic model. However, as we mentioned previously (the last paragraph of the previous section) inclusion of possible larger events in the characteristic model makes any comparison problematic.

Are Parkfield Earthquakes Periodic?

A major justification for both the Parkfield prediction and the quasi-periodic characteristic earthquake hypothesis was earthquake temporal statistics: the 22-year recurrence interval and 95% prediction (Bakun and Lindh, 1985) all result from the statistical analysis of seismicity. It is doubtful that the experiment would have been proposed if magnitude 6 earthquakes did not appear quasi-periodic.

Bakun *et al.* (2005, supplement) report that the six moderate Parkfield earthquakes since 1857 have occurred with statistically significant regularity in time. However, the spatial, temporal, and magnitude limits employed in selecting those quakes were not set before the data were selected. The freedom to draw boundaries after looking at the data invites selection bias (Kagan, 1997). While the 2004 Parkfield earthquake was not handpicked, the previous five were, so the time interval between the 1966 and 2004 events has little real effect on the inferred regularity of the sequence. Thus, it is invalid to infer a temporal distribution, quasi-periodic or otherwise, from preselected data.

Is Parkfield Special?

The part of the characteristic model best fit by the 2004 Parkfield event is that its rupture zone resembled that of earlier moderate events (Bakun *et al.*, 2005). This could have important implications for earthquakes elsewhere if the conditions that confined the rupture to the prediction zone also exist and can be recognized elsewhere. It would be especially convenient if those conditions were intrinsic rock properties or features of the fault geometry that would persist for geologic time periods and be recognizable with available technology. A less convenient but still useful condition would be that earthquakes in general are controlled by stress conditions or other extrinsic properties that nevertheless prevail for centuries or longer.

Earthquakes during the nineteenth century suggest that the general picture we have of the seismicity at Parkfield, and the creeping zone north of it that presumably prevents earthquakes from propagating further north, may not be permanent. Figure 2 shows the times and latitudes of the events within 20 km of the San Andreas fault, using data from Toppozada *et al.*'s (2000) statewide earthquake catalog. The creeping zone north of latitude 36 apparently experienced moderate earthquakes where today we see only small ones. As we mentioned previously, the magnitudes and locations of nineteenth century earthquakes are not very accurate. Even so, the rate of moderate earthquakes near Parkfield is apparently quite variable, and the predominance of magnitude 6 events may not be permanent.

Is Parkfield typical, or unusual? Such a judgment cannot be made by examining Parkfield in isolation. A program that might lead to success is to identify the specific conditions that make Parkfield earthquakes cluster in the magnitude and space domains, identify other places where similar conditions apply, and test for magnitude and temporal clustering there as well. In other words, Parkfield should be viewed as an experiment to develop a hypothesis for testing elsewhere.

Discussion: Lessons for the Future

Validation Requirements

The most fundamental characteristic of any scientific method is the falsifiability of its hypotheses and ability to modify a model depending of test results (Kuhn, 1965; Popper, 1980). For earthquake prediction and forecasting, this poses three general requirements. First, a meaningful hypothesis must be clearly stated (Jordan, 2006). The criteria for data selection must be prescribed, the possible outcomes that confirm or reject the hypothesis must be defined unambiguously, and the conditions under which the hypothesis is assumed to apply must be stated. Second, there should be a reasonable null hypothesis that states what to expect if the primary hypothesis were not true. Third, there must be a strong possibility that sufficient data will exist to test the hypothesis in a reasonable time interval. There must be more than enough data to resolve any free parameters and independent data for testing hypotheses. For hypotheses that involve modest probabilities, there must be enough data to distinguish between the primary and null hypotheses. Hy-

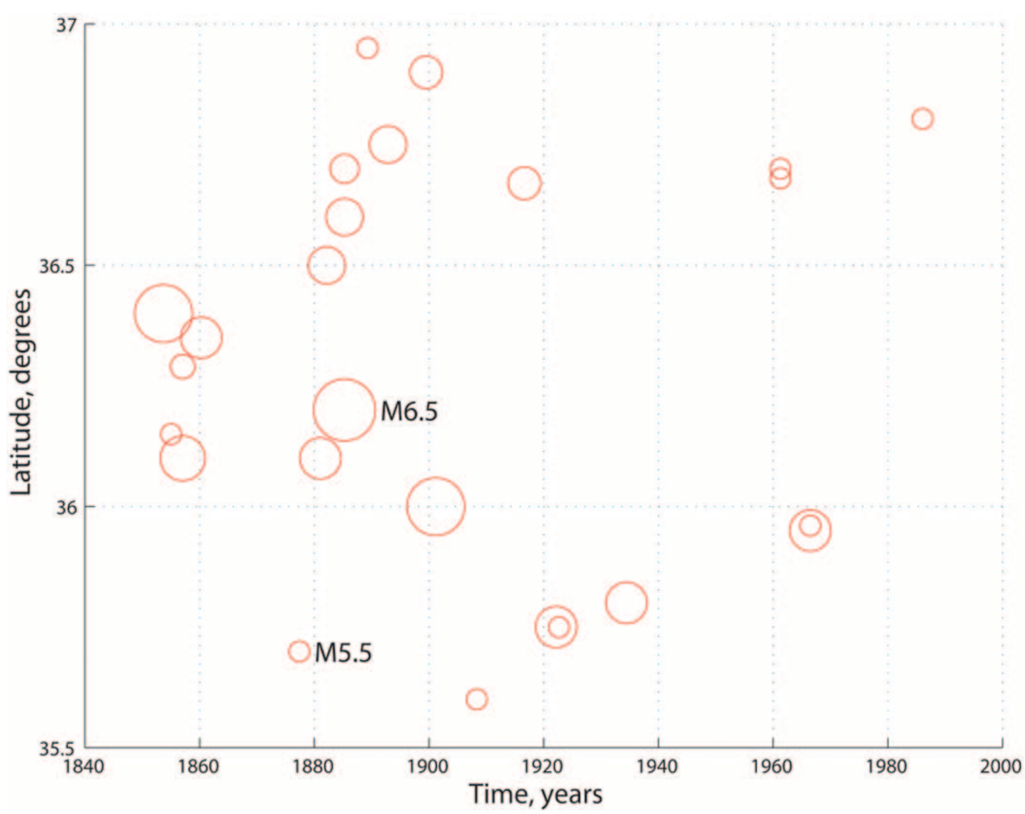

Figure 2. Temporal pattern for $M \geq 5.5$ earthquakes along the San Andreas fault trace. Diameter of circles is roughly proportional to earthquake magnitude.

potheses should evolve in response to new data, but they are not useful if they become obsolete before they can be tested.

Development of the Seismic Gap Model

The seismic gap hypothesis has enjoyed intuitive appeal since the early work of Reid (1910). He suggested that a large earthquake releases most of the stress on a given part of a fault and that further earthquakes could be expected when that stress has reaccumulated through tectonic motion. The acceptance of plate tectonics in the 1960s as a believable mechanism for resupplying stress added more intuitive arguments for the seismic gap hypothesis. Fedotov (1968) identified several plate boundary regions that had experienced large historical earthquakes and named several zones as likely to have earthquakes in the near future. McCann *et al.* (1979) adopted the gap model and produced a colored map of "earthquake potential" for nearly a hundred circum-Pacific zones. They assumed that seismic potential increases with the absolute time since the last large earthquake. Bakun and Lindh (1985) used the history of earthquakes at Parkfield to estimate a distribution of recurrence times and a probability for a repeat earthquake at Parkfield: this formed the basis of the Parkfield prediction. Nishenko (1989, 1991) for the first time refined the seismic gap model into one that could rigorously be tested. He specified the geographical boundaries, characteristic magnitudes, and recurrence times for each segment. He used a quasi-periodic recurrence model to estimate conditional earthquake probabilities for 125 plate boundary segments around the Pacific Rim. Nishenko's regions, including Parkfield, were defined by previous earthquake ruptures zones.

The seismic gap idea has been applied to make long-term forecasts for many faults and plate boundaries around the world. Rong *et al.* (2003) give a summary (see also Kagan and Jackson, 1991, 1995; Nishenko and Sykes, 1993, Jackson and Kagan, 1993; but there are too many to list here). So far, only the models by McCann *et al.* (1979) and Nishenko (1989, 1991) have been comprehensive enough to test using later earthquakes, and they both failed the test (Rong *et al.*, 2003) (see the following section).

How could such an obvious, intuitive model not be true? Consider the chain of simplifying assumptions behind it. First, the segmentation assumption is crucial. If successive earthquakes are not confined between the same segment boundaries, there is no reason to expect similar rupture lengths, magnitudes, and so forth. Second, we must assume that the average displacement is similar for successive events, else the magnitudes will not be similar. Third, we must assume that earthquake initiation and termination depend almost entirely on processes on that fault segment; stresses from earthquakes on other segments or other faults would likely ruin the similarity of successive quakes. If the assumption of identical events is maintained, it is possible to estimate how larger off-segment earthquakes affect the timing of characteristic events (Working Group on California Earthquake Probabilities, 1990; Cornell *et al.*, 1993), but the required assumption is questionable. Finally, to use this simplifying model, we must be able to recognize the size of the characteristic earthquake with little ambiguity. Should we be fooled by a sequence of earthquakes smaller than the characteristic magnitude and assume that they were characteristic, then we would seriously overestimate their frequency.

Controversy Regarding the Characteristic Model

The characteristic earthquake hypothesis and the seismic gap model have encountered many problems. Kagan and Jackson (1991) compared the model of McCann *et al.* (1979) against later earthquakes. They found that large earthquakes were more frequent in those zones where McCann *et al.* (1979) had estimated low seismic potential. Those zones proved to be ones with consistently high seismicity. The test required that definitions of the qualifying earthquakes and terms like "earthquake potential" be supplied in retrospect. Understandably, this led to strong debate (Jackson and Kagan, 1993; Nishenko and Sykes, 1993).

The validity of the characteristic hypothesis was vigorously contested in a *Nature* debate on earthquake prediction (Main, 1999). Stein and Newman (2004) and Stein *et al.* (2005, p. 432) suggested that evidence for characteristic earthquakes can result from three possible selection biases: (1) short instrumental earthquake history, (2) errors and biases in estimating the size or frequency of the largest earthquakes from paleoseismic records, and (3) selection of the spatial extent of the seismic zone considered. Kagan and Jackson (1995) found that earthquakes after 1989 did not support Nishenko's (1989, 1991) gap model. Rong *et al.* (2003) concurred. They found that the rate of earthquakes meeting the characteristic threshold was significantly less than the number predicted by Nishenko (1989, 1991): 19 were predicted but only 5 occurred for the period 1989–2001. Had the 2004 Parkfield event instead happened before the end of 2001, which would have been more favorable to the seismic gap model, there would be one more success. Even then the hypothesis would have failed at the 95% confidence level.

Figure 3 illustrates how selection bias caused Nishenko's forecast of 1989 to overpredict the rate of characteristic earthquakes. We compiled earthquake subcatalogs using the Preliminary Determination of Epicenters (PDE) earthquake reports (available at www.neic.cr.usgs.gov/neis/data_services/ftp_files.html) for each of the 125 zones, computed magnitudes relative to the estimated characteristic magnitude for each zone, and stacked all the data. If the earthquake magnitude distribution in each zone were compatible with the characteristic model, then the magnitude distribution should exhibit a strong concentration at zero (relative to the characteristic magnitude). The dashed curve in Figure 3 shows the expected concentration, based on a literal interpretation of the curve in figure 15 of Schwartz and Coppersmith (1984). The curve connecting circles shows the

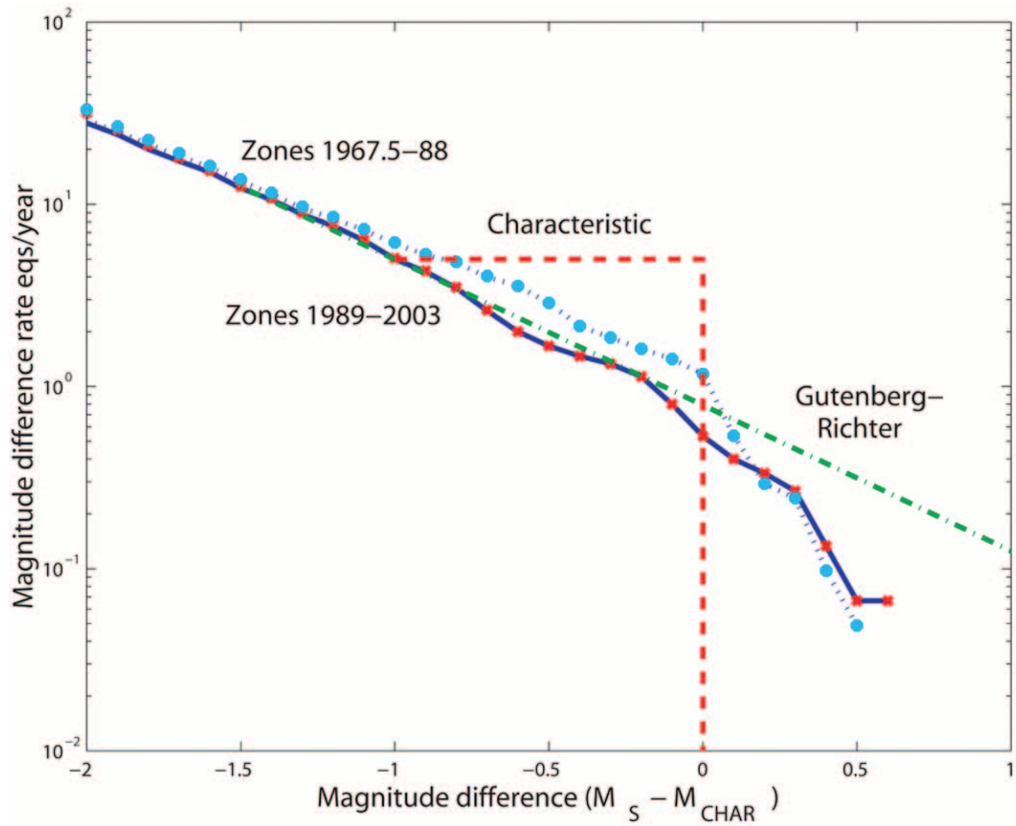

Figure 3. Distribution of PDE magnitude differences for two time periods: 1 July 1968–1 January 1989 and 1 January 1989–1 January 2003, calculated relative to the characteristic magnitude (Nishenko, 1991). Circles, 1 July 1968–1 January 1989; crosses, 1 January 1989–1 January 2003; dash-dot line, the G-R relation; dashed line, the predicted distribution of characteristic magnitudes.

stacked magnitude distribution in the Nishenko zones for earthquakes occurring before 1989. Earthquakes in that time interval were the ones used to set the zones, characteristic magnitudes, and frequencies used in the 1989–1991 articles. The curve shows a noticeable kink at about the characteristic magnitude, but not nearly as extreme as depicted in the Schwartz and Coppersmith (1984) article. The curve connecting x's shows the distribution of magnitudes after 1989. Earthquakes in that time period were independent of the forecast in the 1989–1991 articles. In that time interval, the magnitude distribution agrees well with the G–R distribution, and the rate of earthquakes at about the characteristic magnitude is lower by a factor of about 2 than it was before 1989. Why the difference? Earthquakes before 1989, and the zones around them, were specially selected, while later earthquakes in the zones were not subject to choice. Only those zones with two or more events before 1989 were included in Nishenko's (1989, 1991) study. Regions with more than their average number of large earthquakes before 1989 were thus preferentially included, while those with less were omitted. After 1989 the event rates were no longer preferentially higher than average, so the rate of events generally decreased (Kagan and Jackson, 1995).

The early history of the seismic gap hypothesis provides a good illustration of the constructive role of the scientific method. In its early manifestations (e.g., Reid, 1910, Fedotov, 1968; McCann *et al.*, 1979), the seismic gap proponents discussed recurrence without a clear definition of what exactly was to recur. The model was considerably refined by Nishenko (1989, 1991) and applied to enough zones in a prospective forecast that could be tested at a high confidence level. It was tested, and several problems were identified. We have identified retrospective data selection and assumption of an inconsistent magnitude distribution as problems. In the *Nature* debate (Main, 1999), Christopher Scholz suggested that inaccurate estimates of the characteristic magnitudes may have caused the failure of Nishenko's model, but he did not offer any ideas how these magnitudes can be evaluated.

Recent Applications of the Characteristic Model

Unfortunately, the problems with the characteristic hypothesis and seismic gap model have been largely ignored by those who use them. The characteristic hypothesis has been used in many recent estimates of U.S. earthquake probability and seismic hazard. Without doubt it influences earthquake hazard assessments in other countries as well. Modifications and complexities have been added, but the validity of the results still depends in large part on the validity of the characteristic model. Cao *et al.* (2003) adopted characteristic earthquakes in constructing a seismic hazard model for California. They assumed that all seismic moment was released by combinations (cascades) of characteristic earthquakes on the major faults, although they did assume Poissonian rather than quasi-periodic behavior. Frankel *et al.* (2002) adopted that model for the California part of the National Seismic Hazard Map. Cao *et al.* (2005) also extensively used the characteristic model in their analysis of the California seismic hazard maps. The Working Group on California Earthquake Probabilities (2003) estimated earthquake hazards for the San Francisco Bay area using weighted averages of several different models, of which the predominant one for many major faults was characteristic and quasi-periodic.

A search in the "ISI Web of Science" (isiknowledge.com/) under the topic "characteristic earthquake*" yields 15 publications for the year 2004 alone. They include applications of the characteristic earthquake model in the United States, Japan, France, Russia, New Zealand, India, Turkey, and other countries. These and earlier articles either assume that the characteristic earthquake model is correct or find that the model agrees with at least some aspect of the data. They do not test the model by examining whether all its predictions are confirmed. However, a successful scientific theory should not just explain phenomena; it should also be able to predict results that can be tested with independent data. None of the 2004 articles on characteristic earthquakes in the ISI search cited the articles on the controversy surrounding characteristic earthquakes (see the previous section and the debate in *Nature* [Main, 1999]). It would be acceptable to address these questions and explain why the characteristic earthquake model might be still appropriate. To ignore the problems is unacceptable, especially when using the model for the important task of seismic hazard mitigation.

As the seismic gap model has evolved to cover more regions and earthquakes, it has split into several versions and accumulated more unknown parameters. For example, segments are redefined, uncertainties are given for characteristic magnitudes and recurrence times, and so forth. Unfortunately, there is no hope that the data available for parameter estimation and model confirmation could grow in proportion. In spite of the modifications to the model, earthquakes continue to challenge the basic segmentation idea behind the characteristic hypothesis and the gap model. For example, the two recent Sumatra earthquakes with magnitudes 9.3 and 8.7 (Bilham, 2005; Lay *et al.*, 2005) broke through the boundaries of many segments proposed by McCann *et al.* (1979) on the basis of previous characteristic earthquake ruptures.

Some versions of the characteristic hypothesis treat such transgressions as cascades (e.g., Frankel *et al.*, 2002), or rupture of contiguous segments with some triggering probability. However, this concept can't be tested without data on many future earthquakes and a definitive procedure to estimate those probabilities. Furthermore, as the triggering probability increases, the cascade magnitude distribution begins to approach a G–R distribution, and the fundamental features of the characteristic model are lost. Unfortunately, despite the failure of the McCann *et al.* (1979) and Nishenko (1989, 1991) predictions (Rong *et al.*, 2003), no new tests of the characteristic model have been proposed, let alone carried out. There have been no serious attempts to frame the modified versions of the model in testable form.

The new characteristic hypothesis may differ from the G–R model only in a few less active fault segments. In these segments, the characteristic model would predict maximum earthquakes that are significantly different (smaller) from the G–R predictions. Thus, to falsify the characteristic model model one would need to show that the size distribution for future earthquakes in these zones is better described by the G–R law than by the characteristic model model.

One can estimate the time necessary to test the new characteristic model. Assuming the Poisson occurrence of earthquakes, we simulate an earthquake occurrence according to both hypotheses (characteristic model and G–R). Then we can use one of the standard statistical tests to estimate the forecast time necessary to reject one of the models with 95% confidence in 95% of the tests (Rong *et al.*, 2003). If the forecast time exceeds 5–10 years, the model should be considered as practically nonfalsifiable and consequently untestable.

If its predictions are indistinguishable from the G–R law, then the only distinctive feature left in the characteristic model model is its name. In that case, the principle of Occam's razor implies that the simpler G–R model should be preferred over more complex modified characteristic model.

The 2002 Working Group Report

A complicated form of the seismic gap model has been applied to estimate earthquakes probabilities in the San Francisco Bay region (Working Group on California Earthquake Probabilities, 2003 WG02). The WG02 has used weighted combinations of models, and a weighted combination of parameter estimates within each model, in a logic tree approach. Voting by human experts determined the weights. Models included characteristic earthquakes with various forms of quasi-periodic recurrence, cascades, characteristic earthquakes with Poisson behavior, and others. In the end, the earthquake probabilities for the major faults were dominated by the calculated rates of characteristic earthquakes. The WG02 concluded that "there is a 0.62 [0.38–0.85] probability of a major, damaging [$M \geq 6.7$] earthquake striking the greater San Francisco Bay Region over the next 30 years (2002–2031)" (ch. 6, p. 4).

The WG02 document mentions neither the circum-

Pacific predictions by McCann *et al.* (1979) and Nishenko (1989, 1991), nor the negative testing results for these predictions (Rong *et al.*, 2004, and references therein). The WG02 models are individually complicated and in combination difficult even to describe, let alone to test. If an earthquake with $M \geq 6.7$ occurs during the next 30 years it will not validate any one of the many theories employed because even a simple Poisson model suggests likely occurrence of such a quake. If no such earthquake occurs, the combination model could not be rejected because the model assigns that outcome a 38% probability.

Stark and Freedman (2003) argue that the probabilities so defined are meaningless because they cannot be validated. Referring specifically to the San Francisco Bay earthquake study, they advise that the reader "should largely ignore the USGS probability forecast." The WG02 was apparently unconcerned about verification. In a final chapter entitled "Reflections and Future Directions," there is no discussion of "testing," "verification," "validation," "falsification," or variants of these terms.

Parkfield Lessons

The Parkfield prediction experiment can have only limited value as a hypothesis test because the hypothesis was stated too broadly to distinguish it from an elementary null hypothesis and because it only predicted one event. With a more comprehensive forecast (e.g., Nishenko, 1989, 1991), one might find a subclass of events for which the hypothesis performs well, or identify conditions that might lead to failure. This could suggest a targeted follow-on experiment with a fresh chance to succeed, without introducing a whole new set of variables. For a single-event prediction, failure offers little opportunity for new understanding.

In reviewing the implications of the 2004 event, Bakun *et al.* (2005) proposed neither improvements to the characteristic model nor tests to verify the existing model. The original Parkfield prediction (Bakun and Lindh, 1985) can be justified as a project to gather information and build hypotheses for later testing. Unfortunately such testing never occurred, and we are back in the exploratory stage, still without a hypothesis specific enough to test. How could we let this happen, after 20 years of study at what is probably the most heavily instrumented natural laboratory for earthquake studies? The more important question is why there is still no strategy to rigorously test the characteristic quasi-periodic earthquake model?

One predicted feature that was approximately realized in the 2004 event was the geographical extent of the rupture. There were differences of several kilometers between the limits of the 2004 and earlier Parkfield events (Rymer *et al.*, 2006) and significant differences in the displacement patterns of the several events (Murray *et al.*, 2004; Murray and Langbein, 2006).

Nevertheless, the rupture areas were similar enough to suggest that rupture was limited by the same effect in all or most of the Parkfield events. If this feature is special to Parkfield, it may have limited value in earthquake studies elsewhere. If not, such an effect should be amenable to a convincing test.

Various features, such as fault offsets, fault bends, changes in lithology, and differences in displacement along previous ruptures, have been suggested as causes or markers of segment boundaries. However, previous publications generally propose that observed fault geometry or geology implies segment boundaries without direct relationship to observed earthquakes, or they examine earthquakes retrospectively to associate rupture termination with some fault feature. None to our knowledge has proposed a formal definition that could lead to a test. Black *et al.* (2004) have shown that southern California earthquakes commonly rupture beyond the previously mapped or mappable ends of faults, suggesting that even the ends of faults do not make impenetrable segmentation boundaries. One could specify a way to define the rupture limits of an earthquake (e.g., the first 24-hour aftershock zone); draw polygons on the map, as small as reasonable, containing the rupture limits of past earthquakes; do the same for future earthquakes; and compare past with future results. Suppose rupture termini actually denote physical barriers to rupture, as implied by the Parkfield characteristic model. Then future earthquakes should stop within the polygons drawn for past ones, and rupture should very rarely cut entirely through one of the polygons.

Conclusions

Before 2004 many claims were made about the nature of an earthquake predicted to occur at Parkfield (Ben-Zion *et al.*, 1993; Geller, 1997, pp. 438–440; Roeloffs, 2000). Some of those were too vague to be tested rigorously by the actual 2004 Parkfield event. Examples of such claims include the presumed similarity to the 1966 and earlier Parkfield earthquakes, and the predicted surface rupture. Other predictions such as the expected rupture length were given different values by different authors. As a result, there was not a clear, testable definition of the expected event before the 2004 earthquake (Savage, 1993).

The 2004 Parkfield event failed to satisfy most predictions specific enough to test. Examples included the time of the event, the location of the hypocenter, the direction of rupture propagation, and the presence of sizable foreshocks within minutes before the event. The 2004 Parkfield quake did have a magnitude within the range usually predicted, but this result is also a predicted feature of G–R seismicity: smaller events don't count, and larger ones are rare. The 2004 Parkfield event did rupture a part of the San Andreas fault that had been ruptured previously in 1966, probably in 1934, and perhaps in 1922. 1901, 1881, and/or 1857. This repeated rupture, stated very generally, was successfully predicted, and it may carry important information about what controls rupture initiation and termination at Parkfield.

The common claim that moderate Parkfield earthquakes are quasi-periodic is baseless. The first five earthquakes chosen for study were selected from a much larger sample, and their apparent periodicity may have been a factor in their choice (Kagan, 1997; Jackson and Kagan, 1998). When data are examined before defining the sample specification, subjective choice may invalidate any amount of statistics. If the magnitude threshold for inclusion were raised or lowered a modest amount, the sampled catalog would be much less periodic.

The 2004 Parkfield event adds little support to the characteristic earthquake hypothesis. Magnitude 6 earthquakes do not explain the moment accumulation on the fault segment, while a G–R distribution with corner magnitude 8 does. The magnitude distribution of Parkfield earthquakes resembles the G–R distribution more than a characteristic magnitude distribution, as it also does for many seismic gaps around the globe (Fig. 3).

Generally, there is an obvious failure to follow accepted scientific principles as applied to the quasi-periodic characteristic earthquake model. After the model was formulated in its present form 20 or 30 years ago (McCann *et al.*, 1979; Nishenko, 1989, 1991; Schwartz and Coppersmith, 1984) the model proponents have not attempted to verify its fundamental assumptions in a critical test, and the apparent failure of the predictions was not extensively analyzed and explained (see, for example, the debate in *Nature* [Main, 1999] and the discussion in Bakun *et al.* [2005]). Nevertheless, this questionable model continues to be used for seismic hazard assessment in the United States and many other countries.

Supporters of the characteristic earthquake model should define terms, demonstrate that characteristic events can be identified in many seismic regions, and prove that future quakes confirm the model. Such tests would show whether this model in its original or modified (WG02) form has any predictive power. Results from such tests would help us better understand earthquake occurrence and respond more appropriately to seismic risk.

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