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Pure and Applied Geophysics

Case 23
Nomination of Precursory Seismic Quiescence as a Significant Precursor

MAX WYSS[1]

Procedure for Handling Nomination of Precursory Seismic Quiescence

This nomination was submitted by the Chairman of the Sub-commission on Earthquake Prediction. As a matter of practice, whenever a Sub-commission member is involved in a nomination, that member plays no part whatever in the evaluation process. In this case the calling for reviews and convening of the panel was handled by me in collaboration with Chen Yong. Memorandum sent by the Chairman to members of the Sub-commission is reproduced below. Consequently, Chen Yong was unable to attend and chair the meeting of the panel, but stated an opinion in writing. G. Sobelev was also unable to attend, but delivered a verbal opinion. I reported both of these opinions to the meeting which was attended by seven panelists, including five members of the Sub-commission.

D. A. Rhoades, December 1991

Memorandum:
To: 8 Members, IASPEI Sub-commission on Earthquake Prediction
From: Max Wyss, Chairman
Date: January 16, 1991
Ref: My own nomination of a precursor for the IASPEI list

I wish to nominate seismic quiescence for the IASPEI List of Significant Precursors. As the evaluation process of these nominations is usually conducted by me it is important that we insure that in this case I have no part in the evaluation. Therefore I propose the following procedure: (1) I am sending with this memo the nomination package to all members of the Sub-commission and to the chairman of the IASPEI Commission on Earthquake Hazard and Prediction, G. Sobolev. (2) The evaluation should be handled jointly by the vice-chairman of the Sub-commission (Chen Yong) and the member of the Sub-commission most critical of proposed

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precursors, who, I believe, may be David Rhoades. (3) Because David Rhoades is a statistician, well acquainted with the problem of seismicity patterns, he should be in charge of selecting anonymous reviewers and to distribute these reviews to the panel members, excluding of course myself. (4) Chen Yong should chair the panel that reviews the mail-reviews together with the nomination and decides whether or not to accept the nomination with D. Rhoades as vice-chair of this panel, G. Sobolev and as many of the Sub-committee members as possible probably should serve on this panel. (5) The panel should meet during the IUGG-IASPEI meeting in Vienna.

Sub-committee members who will not attend the Vienna meeting and may send their comments on this matter to Chen Yong or D. Rhoades before the meeting. Usually we try to obtain 4 mail-reviews and about 7 reviews from panel members.

Documentation in Support of the Nomination Submitted by the Author

Summary. The purpose of this document is to nominate seismic quiescence for the IASPEI List of Significant Precursors. Precursory seismic quiescence is defined as a statistically significant decrease of the background seismicity rate restricted to a mainshock volume (and possibly its vicinity), that precedes this mainshock by months to years, and that occurs in all magnitude bands (or possibly in the larger magnitude bands only). The size of the mainshock can vary from 3.5 to 9.5, depending on the tectonic environment, but it must be a major event and it is usually followed by an aftershock sequence.

There have been at least two successful earthquake predictions based on quiescence. In three additional predictions there are questions whether the prediction may have been fulfilled by chance. In spite of these successes I do not view the method as fully matured and ready for application. Rather I see it as needing further development but matured enough to be placed on the List. More case histories, refinements of the detection method, and constraints for the physical explanation are still needed. The total number of quantitatively measured case histories of seismic quiescence that can be viewed as reliable is between 10 and 20. If false alarms are defined as instances of quiescence that are as significant or more than some precursory quiescences, then the false alarm rate may be approximately 50%. This rate of false alarms is tolerable. The rate of failures to predict is less well-known, but it may also be in the 50% range.

The greatest source of errors that interferes with correctly identifying precursory seismic quiescence is the heterogeneous reporting in earthquake catalogs. Many reductions in reporting rate can be traced to artificial sources. Without a careful study of the reporting hsitory of a catalog, and testing of proposed quiescences, false claims of precursors are possible.

After careful consideration of the current state of our understanding of quiescence, I feel that several very strong case histories exist as do several weaker ones. Thus I no longer doubt that the phenomenon of precursory quiescence actually occurs, although I feel that its characteristics are poorly known at the present.

Introduction

The first suggestion that seismic quiescence may precede large mainshocks came from MOGI (1969), who observed a doughnut pattern of earthquakes having $M \geq 6$. In and near the epicentral area the seismicity rate was reduced, while it was enhanced at farther distances. Since this discovery several authors have qualitatively discussed data with this seismicity pattern, or variations of it (e.g., KELLEHER and SAVINO, 1975). However, these early analyses will not be used here in support of quiescence, because they were not done quantitatively. Seventeen case histories that are fairly convincing and those for which the seismicity rate decrease was measured quantitatively, were summarized by WYSS and HABERMANN (1988a, attachment 1). Two new additional case histories and the five of the list by WYSS and HABERMANN, in which we have the most confidence, are briefly summarized in this nomination.

The conditions for a case to be included here in support of the quiescence hypothesis are: (1) that the seismicity rate decrease has been measured quantitatively, (2) that the significance of this rate decrease has been evaluated, (3) that the association of the anomaly with the mainshock, in space and time, has been plausibly demonstrated, and (4) that it was shown in a thorough analysis that the rate decrease was most likely not due to artificial reporting rate changes. It is necessary to impose this important last condition because the majority of significant seismicity rate changes that we have encountered were due to changes in the seismograph network and in the method by which the catalog was compiled (e.g., HABERMANN, 1982, 1983, 1986, 1987, 1988; HABERMANN and WYSS, 1984; PEREZ and SCHOLZ, 1984; WYSS and BURFORD, 1985; WYSS and HABERMANN, 1988b; HABERMANN and CRAIG, 1988; WYSS and FU, 1989; WYSS, 1991).

I believe that the rigor and amount of effort we have applied to test the probability that the quiescences are real, and not brought about artificially, are greater than for any other precursor discussed in the literature. For example, it has become standard procedure in our work to document in detail the noise level against which the significance of a potential precursory quiescence (target) has to be judged. We do this by comparing the z values (standard deviate z) of the rate change in the target sample (comparing the quiescence to its background rate) with the z values of several thousand other samples. These other samples are seismicity rates in randomly chosen volumes in the vicinity of the target volume during periods equal to the target duration. In these histograms we find that the target z

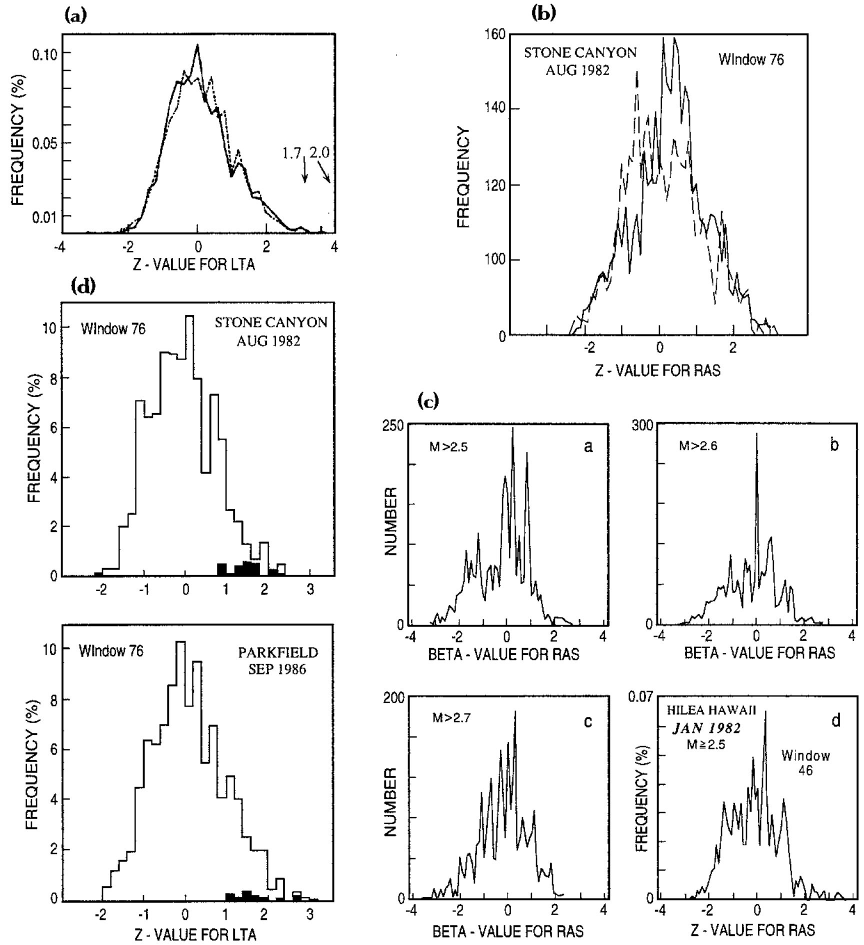


Figure 1

Histograms of z and β values comparing the rate in moving time windows within several fault segments to the long-term average (lta). The larger the z and β values, the more significant is the difference between a low rate in the window and lta. The distributions of z and β values that are observed along fault zones are centered, and peak, at 0 (no change), and they taper off to no occurrences around $z = 2.5$. The precursory anomalies I believe to be real rate in the range of $2.3 \leq z \leq 10.0$ (Table 1). This means that most precursor anomalies are unique, i.e., never surpassed in significance by other periods of low seismicity rate. (a) From WYSS and BURFORD (1987) 7,912 comparisons of the lta rate with the rates in 89-week windows in 5-km segments of the San Andreas fault. The solid and dotted lines are for $M_L \geq 1.7$ and $M_L \geq 2.0$, respectively. Arrows point to the z values ($z(1.7) = 3.1$ and $z(2.0) = 4.6$) for the target period in the volume for which the prediction was made. One standard deviation from the mean equals 1. (b) From WYSS and HABERMANN (1988b) all comparisons of the lta with the rate in 76-week windows. The solid and dashed lines are for $M \geq 1.7$ and M 2.0, respectively. The values for the target windows are $z(1.7) = 3.99$ and ($z(2.0) = 3.22$). These values are larger than any of the others. (c) From WYSS and FU (1989) histograms for the RAS-function (similar to lta) in 46-week time windows in several magnitude bands. The target sample had values of $z = 2.65$, $z = 2.88$ and $z = 2.36$, which makes this one of the weakest precursor anomalies accepted in this summary. (d) From WYSS *et al.* (1992) a comparison of the histograms at Stone Canyon and Parkfield for 76-week windows compared to the lta. In each case the target sample scores the highest z values (shaded), and is thus recognizable as a unique anomaly.

values are either the largest of all samples (which means that the significance of the anomaly is unique, never surpassed during the known history of the area in question) or the z values of one of three samples exceed that of the target (in this case one to three false alarms exist). Examples of histograms containing these comparisons are Figure 3 in WYSS and BURFORD (1987), Figure 10 in WYSS and HABERMANN (1988b), Figure 4 in WYSS *et al.* (1991), and Figure 6 in WYSS and FU (1989).

In our research of the phenomenon of precursory quiescence we devote approximately three quarters of the effort on analysis of heterogeneities of the earthquake catalogs (the chief noise source). As a consequence we now have a new understanding of the nature and the causes of artificial reporting rate changes, and we have substantial confidence in the top quality case histories of precursory quiescence which we will present below.

Material Submitted in Support of the Nomination

The important point concerning the strengths and weaknesses of seismic quiescence as a precursor have been made in articles published in press. Thus we summarize them only very briefly in this nomination and refer the reader to the articles attached. The following list of articles is ordered in the approximate sequence of importance for supporting the nomination and of quality of the data for case histories.

(1) WYSS, M., and HABERMANN, R. E. (1988a), *Precursory Quiescence*, Pure and Appl. Geophys. *126*, 319–332.

(2) HABERMANN, R. E. (1988), *Precursory Seismic Quiescence: Past, Present and Future*, Pure and Appl. Geophys. *126*, 279–318.

(3) WYSS, M., and HABERMANN, R. E. (1988b), *Precursory Quiescence Before the August 1982 Stone Canyon, San Andreas Fault, Earthquakes*, Pure and Appl. Geophys. *126*, 333–356.

(4) WYSS, M. (1986), *Seismic Quiescence Precursor to the 1983 Kaoiki ($M_s = 6.6$), Hawaii, Earthquake*, Bull. Seismol. Soc. Am. *76*, 785–800.

(5) WYSS, M., BODIN, P., and HABERMANN, R. E. (1990), *Seismic Quiescence at Parkfield: An Independent Indication of an Imminent Earthquake*, Nature *345*, 426–428.

(6) WYSS, M. (1991), *Reporting History of the Central Aleutians Seismograph Network and the Quiescence Preceding the 1986 Andreanof Island Earthquake*, Bull. Seismol. Soc. Am. *81*, 1231–1254.

(7) KISSLINGER, C. (1988), *An Experiment in Earthquake Prediction and the 7 May 1986 Andreanof Islands Earthquake*, Bull. Seismol. Soc. Am. *78*, 218–229.

(8) WYSS, M., and BURFORD, R. O. (1987), *A Predicted Earthquake on the San Andreas Fault, California*, Nature *329*, 323–325.

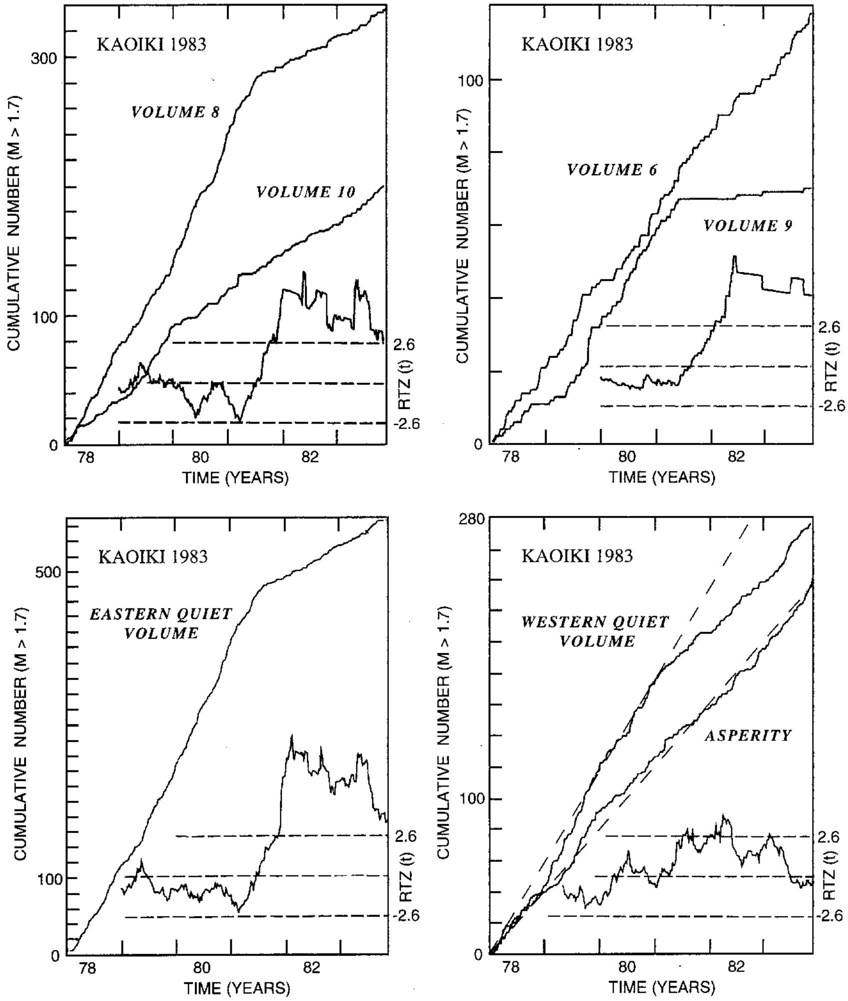


Figure 2

Cumulative number of earthquakes as a function of time in several parts of the source volume of the 1983, $M_S = 6.6$, Kaoiki earthquake which occurred at the time coinciding with the right edge of the figures (summarized from WYSS, 1986, his Figures 4, 5, 7, 8). The parts with constant seismicity rate (volumes 6 and 10) are interpreted as the main asperity. The function RTZ (real time z) presents the z value for a comparison of the average rate in the last half year of the data set with the average rate previous to it, moving the assumed end point of the data through time. The z values and confidence levels for this anomaly are the highest measured so far (Table 1).

(9) WYSS, M., and BUFFORD, R. O. (1985), *Current Episodes of Seismic Quiescence along the San Andreas Fault between San Juan Bautista and Stone Canyon, California: Possible Precursors to Local Moderate Mainshocks?*, U.S. Geol. Survey, Open File Report 85–745, 367–426.

(10) WYSS, M., HABERMANN, R. E., and BODIN, P. (1991), *Seismic Quiescence: A Test of the Hypothesis and a Precursor to the Next Parkfield, California, Earthquake*, Geophys. J. Int. *110*, 518–536.
(11) WYSS, M., *Examples of an artificial and a precursory seismic quiescence*. In *Earthquake Prediction: State-of-the-Art* (Council of Europe, Strasbourg, France 1991), pp. 157–166.
(12) WYSS, M., KLEIN, F. W., and JOHNSON, A. C. (1981), *Precursors to the Kalapana $M = 7.2$ Earthquake*, J. Geophys. Res. *86*, 3881–3900.
(13) WYSS, M., and FU, Z. X. (1989), *Precursory Seismic Quiescence before the January 1982 Hilea, Hawaii, Earthquakes*, Bull. Seismol. Soc. Am. *79*, 756–773.
(14) HABERMANN, R. E., and WYSS, M. (1984), *Background Seismicity Rates and Precursory Seismic Quiescence: Imperial Valley California*, Bull. Seismol. Soc. Am. *74*, 1743–1755.
(15) HABERMANN, R. E., and WYSS, M. (1987), *Reply*, J. Geophys. Res. *92*, 9446–9450.

The Strongest Case Histories

The strengths and weaknesses of some of the strongest case histories in my view are summarized below, using the attached support material for reference.

1. *Kaoiki, 16 November 1983*, $M = 6.6$. The seismic quiescence shown in Figures 4, 5 and 8 by WYSS (1986) are the most striking documentations of seismic quiescence known to me. Their statistical significance is very high as is the seismicity rate, which means that during the 2.5 year precursor time approximately 300 earthquakes that would have been expected based on the background rate did not occur. P. Reasenberg, M. Matthews and I reanalyzed this anomaly with the intent of eliminating it, if possible. However, the anomaly stood up to all tests we could design (REASENBERG *et al.*, 1988). It definitely exists. Reasenberg and I still disagree on the interpretation of the phenomenon: he suggested that one might interpret the rate during 1978 to 1981 (the background time according to my interpretation) as unusually high instead of that during 1981 to the mainshock as unusually low. The rate decrease from high to low, however, is not in question.

The lack of control volumes around the Kaoiki area may be viewed as a shortcoming because it is desirable to demonstrate constant reporting in neighboring parts of the area covered by the seismograph network. However, there are parts of the source volume which show constant seismicity rates throughout (Figures 4, 5, and 7 in WYSS, 1986). Thus it is very unlikely that the quiescence is artificial.

2. *Kalapana, 29 November 1975*, $M = 7.2$. The seismicity rate in the source volume of this earthquake is high such that the quiescence is well defined (Figures

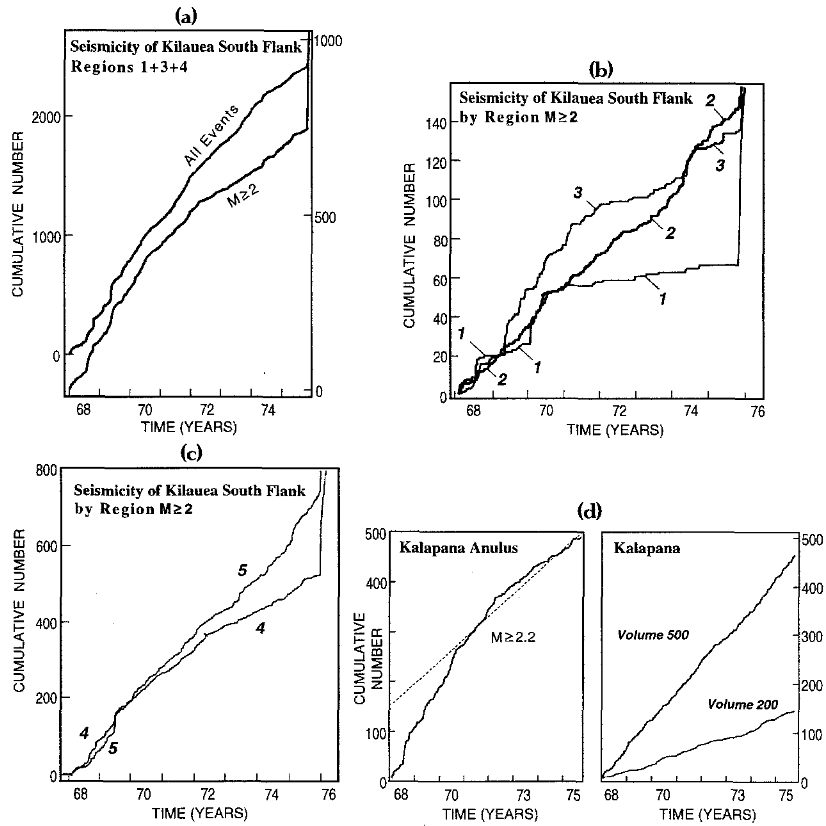


Figure 3
Cumulative numbers of earthquakes as a function of time in the source volume of the Kalapana, $M = 7.2$, earthquake of 29 November 1975. (a), (b) and (c) are from WYSS *et al.* (1981) showing the seismicity rate in different subcolumns of the source (volumes 1, 2, 3, 4 and 5). (d) is from WYSS (1992) where the rate decrease was found to be significant above the 99% level ($z = 7.5$) (subvolume "annulus" $\equiv 1 + 3 + 4$ of the first paper, $200 \equiv 2$ and $500 \equiv 5$). The occurrence time of the mainshock coincides with the right edge of the figure.

4, 5, and 6 of WYSS *et al.*, 1981). At the time of the original investigation we had not yet developed the quantitative techniques to evaluate the significance and possible artificial source of such an anomaly. For this reason this case was re-investigated. It was found that indeed the rate decrease is highly significant and cannot be explained by an artificial cause (Figures 5, and 7 in WYSS, 1992).

The shortcoming is that no neighboring control volumes are available. However, based on the detailed analysis of this anomaly by the magnitude signature technique I conclude that the anomaly is not caused artificially (Figure 5 in WYSS, 1992).

3. Andreanof Islands, 7 May 1986, M $= 7.9$. The seismic quiescence is outstanding to the eye in this case (Figure 3 in KISSLINGER, 1988; Figure 7 in WYSS, 1992). The main concern was that repairs to the seismograph network at the time of the

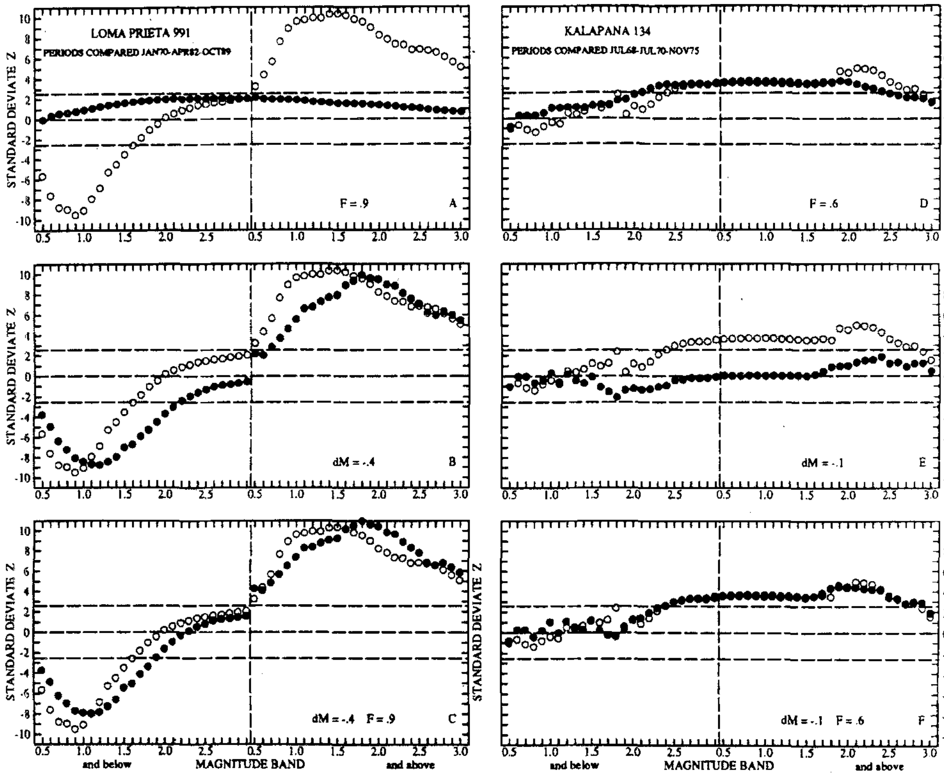


Figure 4

These examples of magnitude signatures from WYSS (1992) demonstrate a case of a rate decrease that is possibly natural (Kalapana, on the right), and a case that is most likely artificial (Loma Prieta, on the left). For each earthquake the observed magnitude signature (open circles) is compared to three synthetic signatures (solid dots). In the two top frames the signatures are modelled assuming a rate change only took place (the factor is 0.9 and 0.6 for the Loma Prieta and Kalapana cases, respectively). In the middle two frames the signatures are modelled assuming a magnitude shift only took place (the shift is -0.4 and -0.1 for Loma Prieta and Kalapana, respectively). In the bottom two signatures, the above factors and magnitude shifts were jointly applied. The models applying a magnitude shift as well as a factor yield the best fits to the observed signatures (C and F). However, in the Kalapana case a good approximation of the observations is achieved by assuming that a rate change only took place (D), while the assumption of a magnitude shift alone leads to an unsatisfactory fit (E). In the Loma Prieta case the opposite is true: assuming that a rate change only took place leads to an incorrect model (A), while the application of a magnitude shift yields a model that fits the observations quite well (B). These observations lead to the conclusion that the decrease in reporting rate before the Loma Prieta and Kalapana earthquakes was artificial and real, respectively.

anomaly onset may have in some way influenced the reporting rate negatively. However, this question was examined in detail (WYSS, 1991) and there is virtually no reasonable way in which this anomaly could have been created artificially. An independent data set also shows quiescence (Figures 8, 9, and 10 in WYSS, 1992). I conclude that this quiescence was real and that the prediction issued by KISSLINGER *et al.* (1988) was in essence fulfilled by this earthquake. The probabil-

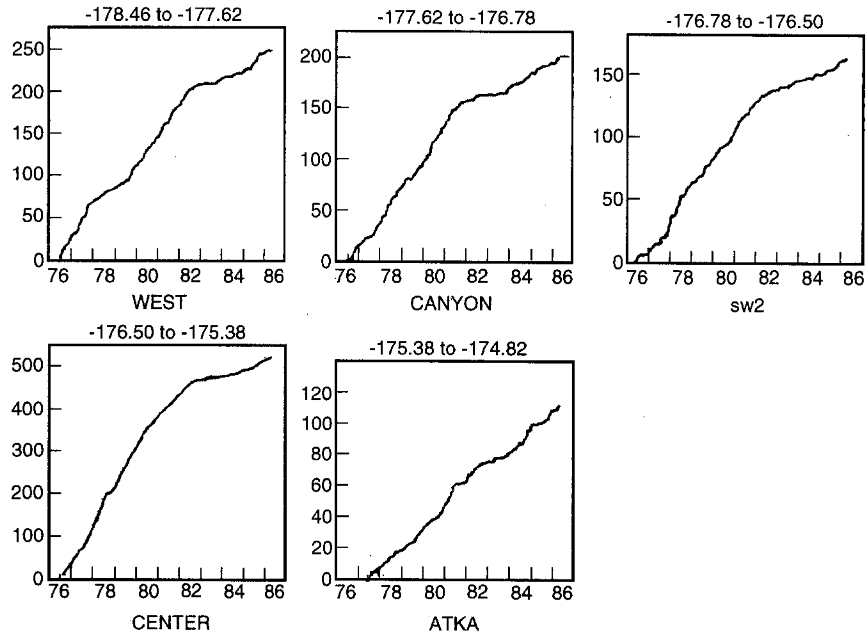


Figure 5
Cumulative number of earthquakes as a function of time in parts of the source volume of the Andreanof Islands earthquake, $M = 8.0$, 6 May 1986 (from KISSLINGER, 1988). The occurrence time of the mainshock coincides with the right edge of the figure. The expectation that a large earthquake should occur in the segment of the Aleutian island arc covered by the Adak network was based on this data set. The specific parameters of the expected earthquake were derived by KISSINGER *et al.* (1985) in part from other considerations, which turned out to have been incorrect.

ity of a very large earthquake occurring by chance in a short time interval and along a plate boundary segment that had ruptured rather recently (in 1957 in the great Rat Island earthquake) is very low indeed.

4. Stone Canyon, 31 May 1986, $M = 4.7$. The prediction of the size and location of this earthquake (WYSS and BURFORD, 1985) was fulfilled very accurately (Figure 1 in WYSS and BURFORD, 1987), and it occurred on the last day of the specified time window. The probability of success at random was estimated as less than 5% (WYSS and BURFORD, 1987). The anomaly was strong and unique for this part of the San Andreas fault (Figures 2, and 3 in WYSS and BURFORD, 1987; Figure 10 in WYSS and BURFORD, 1985).

A shortcoming is that the seismicity rate within the anomalous volume was perturbed by another precursory quiescence, that of the August 1982 earthquakes sequence studied by WYSS and HABERMANN (1988b). This prediction generated one false alarm. In the attached original document (WYSS and BURFORD, 1985) two false alarms were generated, one at San Juan Bautista and one at Cienega Winery. In a revised version of this work (not provided here) the Cienega Winery prediction was cancelled because the statistical significance was low.

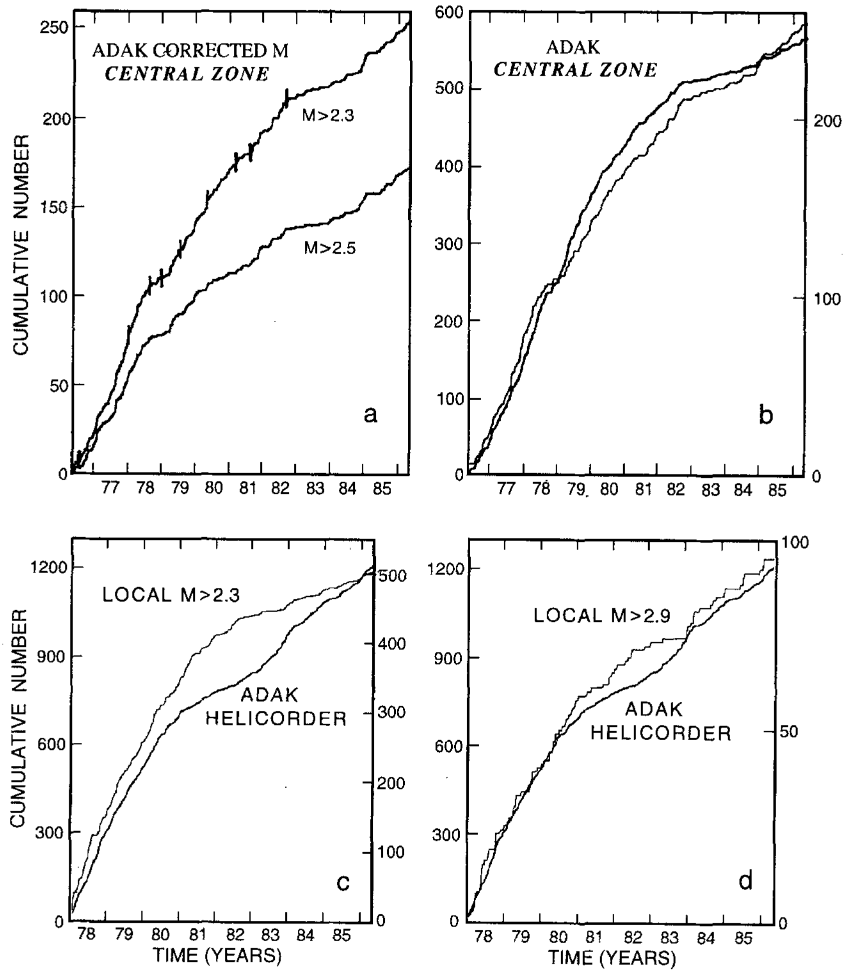


Figure 6

Cumulative number of earthquakes in crustal volumes near Adak as a function of time (from WYSS, 1991). The occurrence time of the mainshock ($M = 8$, 6 May 1986) coincides with the right edge of the figure. (a) The times of magnitude shifts in the catalog, which were corrected for, are marked by vertical lines. (b) The corrected catalog (bold line) shows the quiescence even more clearly then the original data. (c) and (d) An additional independent data set (helicorder), covering the seismicity in and near the western end of the 1986 mainshock rupture, is compared to the corrected Adak catalog data (local). The helicorder data also show the quiescence, although with a somewhat different time history. The conclusion is that the rate decrease in the Adak catalog before the 1986 mainshock is not likely due to artificial sources.

5. Stone Canyon, August 1982. Several mainshocks and numerous aftershocks added up to an equivalent magnitude of $M = 5$. The statistical significance of this anomaly is high enough to be unique (it generated no false alarm, Figure 10 in WYSS and HABERMANN, 1988b). A detailed and rigorous analysis of the catalog indicates that the anomaly is not likely to be artificial (WYSS and HABERMANN, 1988b).

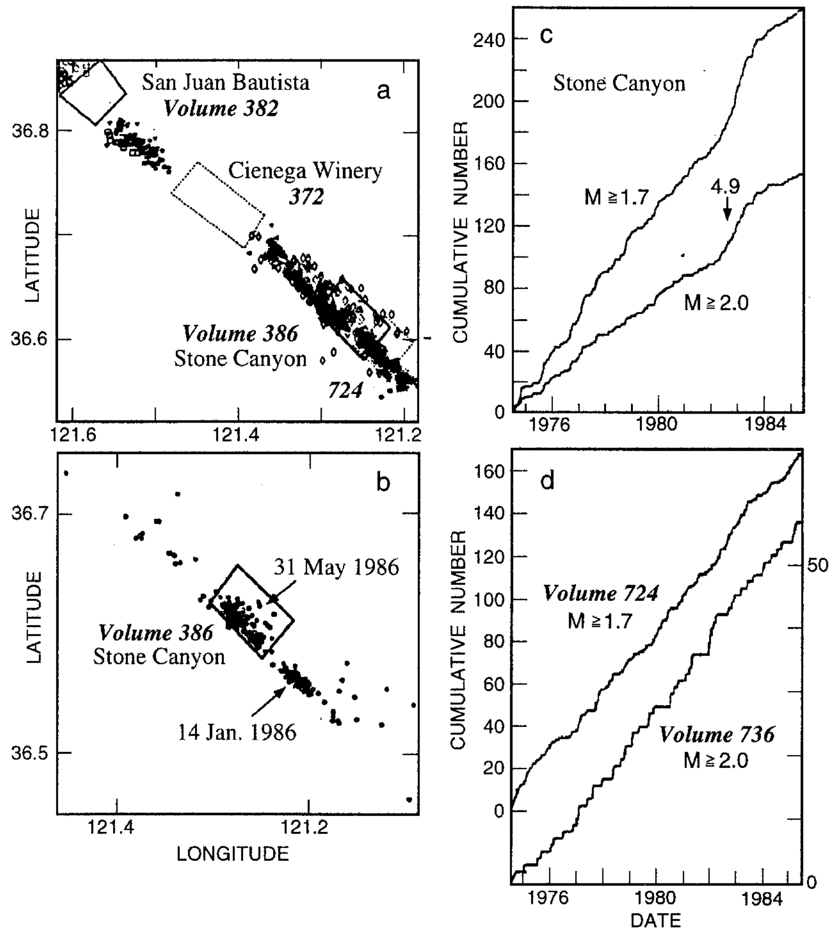


Figure 7

(a) Map of a section of the San Andreas Fault showing aftershocks (two weeks with different symbols for each case) for mainshocks between August 1974 and January 1985. Solid polygons define crustal volumes of depth 20 km in which mainshocks were predicted. Note that the absence of aftershock zones is defining a seismic gap near the Cienega Winery, however, precursory quiescence can occur on any segment of the fault, regardless of its background seismicity rate or aftershock activity. (b) Map of the aftershock areas of the predicted Stone Canyon earthquake of 31 May ($M_L = 4.6$), and the missed mainshock of 14 January 1986 ($M_L = 0.46$). Plotted are all events which occurred within 14 days of these mainshocks. The polygon number 386 defined the location of the predicted event a year before it occurred. (c) Cumulative number of earthquakes as a function of time for polygon 386 defined in *a*. The two curves are for events of $M_L \geq 1.7$ and $M_L \geq 2.0$. The occurrence time of the 1982 mainshocks ($M_L = 4.9$ is the equivalent magnitude of the cluster) is marked by the arrow. The slope of these curves equals the seismicity rate and is noticeably lower during the last two years of the data. A prediction of a mainshock was issued based on this data set. (d) Cumulative number of earthquakes that occurred within two randomly chosen volumes of length 5 km located on the San Andreas Fault near the target volume. In these volumes the seismicity rate is more nearly constant throughout. The location of volume 724 is given in (a) 736 is located at latitude 36.38°N (from WYSS and BURFORD, 1987).

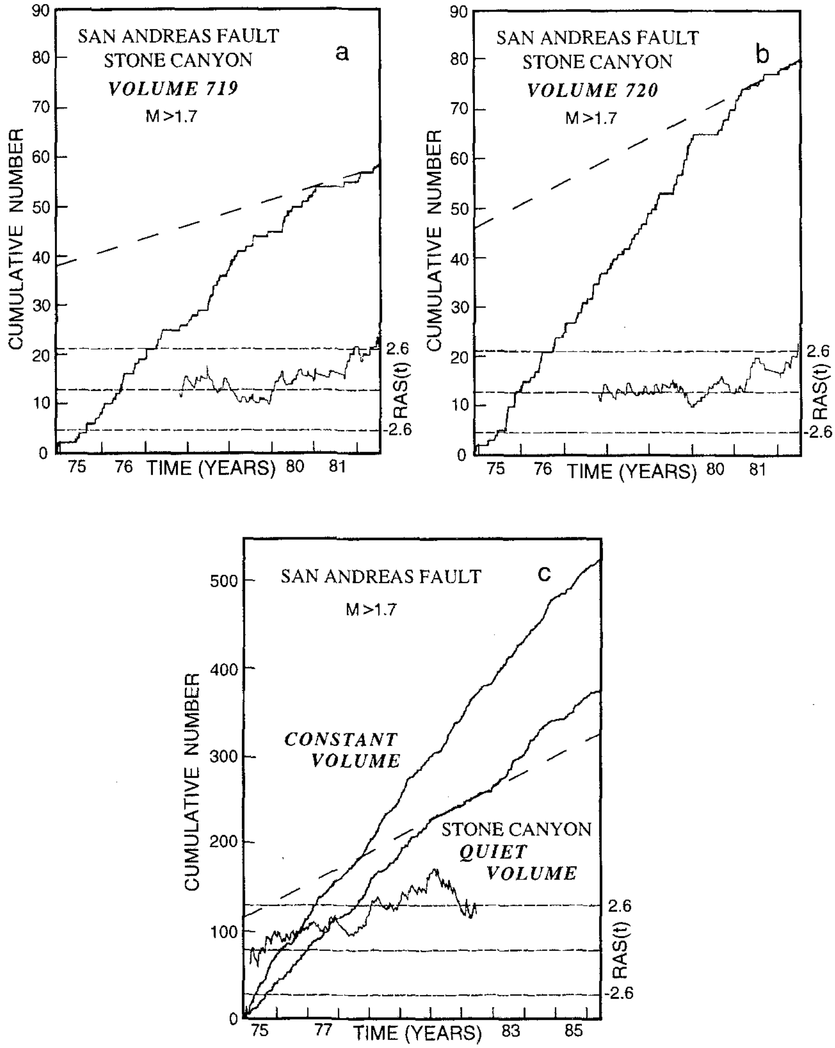


Figure 8
Cumulative numbers of earthquakes for several segments of the San Andreas Fault in the Stone Canyon area (from WYSS and HABERMANN, 1988b). (a) and (b) show that quiescence occurred in randomly chosen, overlapping segments before the mainshock sequence which happened in these segments and at the time terminating the graph at the right side. (c) shows that the Stone Canyon segment showed an unusually inactive period of 76 weeks before the August 1982 mainshocks in this segment. At no other time was the activity as low, in the Stone Canyon segment or in the rest of the study area, as during what we propose was the precursor time of 76 weeks in 1981/82.

6. Parkfield, 29 August 1986, $M = 3.6$. Although of small magnitude this earthquake was the second largest earthquake in the Parkfield segment of the San Andreas Fault for the last 24 years. The largest shock during this time span occurred before the catalog was of high enough quality for a seismicity pattern investigation.

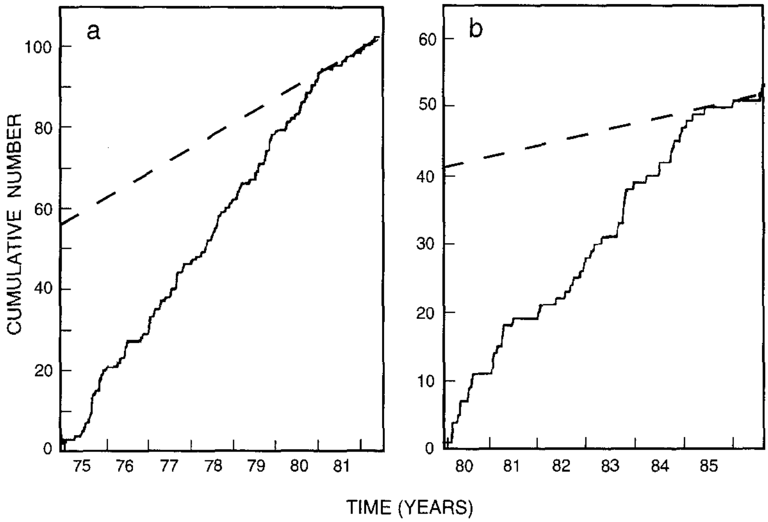


Figure 9

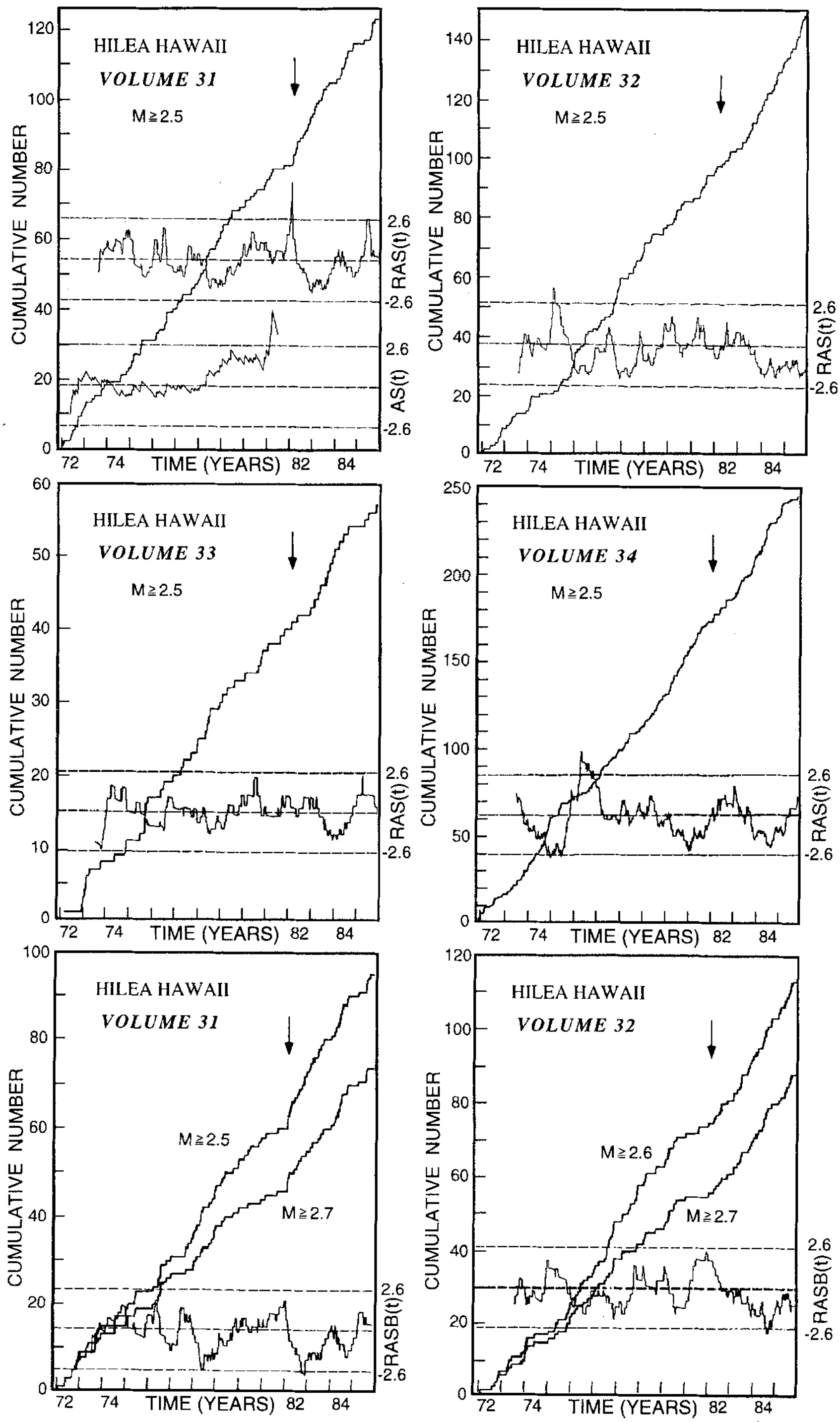
Applicability of the quiescence hypothesis to the Parkfield segment of the San Andreas Fault, tested by comparing the patterns of seismicity rate in the source volumes of mainshocks at (a) Stone Canyon and (b) Parkfield. The mainshocks of ($M = 3.6$ at Parkfield) occurred at the time of the right end of the plots of cumulative seismicity (all shocks $M > 1.8$ at Stone Canyon and $M > 0.9$ at Parkfield) and quiescence started 1.5 years before the mainshocks. The slope of these curves is the main seismicity rate. The dashed lines extrapolate the anomaly low precursory rate back in time for comparison with the observed background rate. The similarity of the pattern strongly suggests that the quiescence hypothesis should be as applicable at Parkfield as at Stone Canyon, where a successful prediction was made (from WYSS *et al.*, 1990).

The shortcoming is that only about 50 earthquakes were available for definition of the anomaly, however it is a quite significant anomaly (Figure 1 in WYSS *et al.*, 1990). This result was not available yet when the summary Table 1 of WYSS and HABERMANN (1988a) was published.

7. Hilea, 21 January 1982, $M = 5.4$. This anomaly is somewhat marginal (Figures 3 and 5 in WYSS and FU, 1989) possibly because of the relatively low seismicity rate. This case is mentioned here because it was published after the summary of WYSS and HABERMANN (1988a) and because it is an example of a possible anomaly just barely resolvable at the edge of the noise level, even with a strong effort at solving catalog problems (Appendix in WYSS and FU, 1989). A small number of false alarms exists in the data set (Table 2 in WYSS and FU, 1989).

Additional Cases Analyzed Quantitatively

Additional cases, which we have fairly high confidence represent real rate changes, are listed in Table 1 of WYSS and HABERMANN (1988a). The Oaxaca cases in this list are now in question because of problems with heterogeneous reporting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(HABERMANN and WHITESIDE, 1990). The remaining cases listed are still acceptable. They are not summarized here because the quantitative work was done some years ago with less rigorous investigations of catalog problems than we conduct currently. Thus I would rank them after the most convincing cases 1 through 5 listed above, and about equal to cases 6 and 7 above.

Successful Predictions

The occurrence of an earthquake with the parameters specified beforehand does not necessarily validate the prediction or the method used because the earthquake may have happened by chance. The Oaxaca earthquake of 29 November 1978 ($M = 7.8$) appeared to be a successfully predicted event (OHTAKE *et al.*, 1977; 1981) until WHITESIDE and HABERMANN (1989) showed that the observed rate decrease may have been brought about artificially.

There are two successful predictions of which I have confidence were not fulfilled by chance. These are the aforementioned strong cases (3) and (4). In these cases all aspects of the data have been investigated in great detail.

Two additional predictions that may have been successful are discussed by HABERMANN (1988, page 311). However, these were based on investigations published about 10 years ago, at a time when the detail and rigor of seismicity pattern research were below the standards we now demand.

False Alarms and Failures to Predict

False alarms exist, but as long as their percentage is not too large they do not invalidate the quiescence method employed to predict earthquakes. I am aware of three false alarms. These are summarized by HABERMANN (1988, pages 312 and 313).

We define "failures to predict" as those mainshocks before which the background rate was measurable but did not decrease. Mainshocks which occur in areas where the seismicity rate is too low to be measured reliably are not predictable by the quiescence method, but they are not counted as failures of the hypothesis that quiescence precedes mainshocks.

Figure 10

Cumulative numbers and RAS functions for several volumes in and near the source volume of the Hilea mainshock, $M = 5.5$, 21 January 1982 (from WYSS and FU, 1989). A quiescence appears fairly clear to the eye in the data sets covering the volume of the aftershocks and their immediate vicinity (volumes 31 and 32), while it is not present in the control volumes (33 and 34) which are farther removed. Nevertheless, we consider this anomaly marginal, because it scores low (75% and 49% significance level) on the z and β tests, respectively.

Table 1

Precursory quiescence (updated from WYSS *and* HABERMANN*, 1988a)*

Event No.	Date D	M	Y	Location	Magnitude $M_S(M_L)$	Quiescence duration (months)	Rate decrease %	z value	Confidence level %	Reference
1	07	05	86	Aleutians	8.0	42	83	8.8	99	K 85, 88, W 91
2	14	01	76	Kermadec	8.0	63	85	4.1	99	W *et al.* 84
3	16	05	68	Tokachi-Oki	7.9	75	64	4.4	99	M 69; H 81b
4	10	10	74	Lima	7.5	27	90	3.6	97	H 81a
5	30	01	73	Colima	7.4	21–24	80	4.3	99	H 81b; McN 81
6	22	06	77	Tonga	7.2	25	70	4.5	99	W *et al.* 84
7	29	11	75	Hawaii	7.2	64	45	7.5	99	W *et al.* 81, W 92
8	24	05	78	Aleutians	6.6	38	69	3.5	97	H 81a
9	16	11	83	Hawaii	6.6	29	70	10.0	99	W 86
10	22	02	75	Aleutians	6.5	15	68	2.3	<95	H 81a
11	28	07	74	Kuriles	6.3	27		2.7	<95	H 81b
12	23	04	84	Morgan Hill	6.1	23	56	3.5	97	H&W 84b
13	06	08	79	Coyote Lake	5.9	22	78	5.1	99	W&H 84b
14	21	01	82	Hawaii	5.6	11	87	4.9	< 76	W&F 89
15	10	08	82	San Andreas	5.0	18	60	4.0	99	W&H 88
16	31	05	86	San Andreas	4.7	35	70	3.8	98	W&B 85, 87
17	09	12	88	North Anatolia	4.3	12	80	4.3	79	W *et al.* 92b
18	29	08	86	San Andreas	3.6	18	60	2.6	90	W *et al.* 92a

One failure is documented by WYSS (1992), another is mentioned by WYSS and FU (1989). I believe that the claim by REASENBERG and MATTHEWS (1988) of having found several failures is incorrect, because these authors have not tested the hypothesis that quiescence is expected in the source volumes of the mainshocks. Only a fraction of the crustal volumes examined by these authors for quiescence covered the mainshock source volumes, the rest was surrounding crust. According to many authors (e.g., MOGI, 1969) a seismicity rate increase is expected in the surrounding crust. Thus the analysis of REASENBERG and MATTHEWS (1988) did not address the hypothesis as proposed by us.

At the present the rate of failures to predict is poorly known. In my estimation it may be about 50%. However, it is not crucial to know this rate for assessing the validity of the quiescence method. If we can show convincingly that quiescence occurs before at least some mainshocks, then we have a valid, although not failure proof, method to predict earthquakes.

The Achilles Heel of the Quiescence Method

The heterogeneity of reporting present in most earthquake catalogs is the greatest source of problems, and it can lead to false claims of precursors, unless great care is used in analyzing the reporting history of the catalog. An example of a quiescence that might have been misinterpreted as a precursor is discussed by WYSS (1992). Other authors who discuss in detail the problem of catalog heterogeneity are HABERMANN (1982, 1983, 1986, 1987, 1988), HABERMANN and WYSS (1984), PEREZ and SCHOLZ (1984), WYSS and BURFORD (1985), WYSS and HABERMANN (1988b), HABERMANN and CRAIG (1988), WYSS and FU (1989), WYSS (1991, 1992).

Although heterogeneous reporting adds undesirable noise to the parameter we wish to monitor, the seismicity rate, the problems created by this are not insurmountable. We simply have to use methods which allow us to measure a signal in the presence of noise. This is a common problem in all of science, and we have made progress in developing methods to recognize artificial rate decreases (see any of the references given in the previous paragraph, especially the more recent ones).

The Cause of Quiescence

There are not enough constraints available to identify the physical process responsible for quiescence. Most of our work has concentrated on dealing with noise sources and establishing that precursory quiescence really exists, before speculating about its cause. Nevertheless, I can think of several mechanisms that might be at work. The observation that quiescence may be correlated with a reduction in creep rate along the San Andreas Fault (WYSS and BURFORD, 1985; 1987) and reduction in deformation rate (WYSS *et al.*, 1990a,b) suggests that the fault segment in question may become clamped by a redistribution of stresses due to other tectonic events in the area, or that the strain accumulation rate may have been reduced (STUART, 1991), or that dilatancy hardening (SCHOLZ *et al.*, 1973) in the fault zone may reduce its mobility. Any of these three mechanisms could explain the observed quiescence within a fault zone, such as in the aforementioned strong cases numbers 4, 5 and 6. However, it is not clear which of these would be most plausible in terms of being an integral part of the unknown process that could be described as the earthquake failure preparation process.

Yet another mechanism can be proposed for cases in which the quiescence is observed in a volume surrounding a fault, but not necessarily concentrated on a fault surface. These cases are earthquakes located in subduction zones (example 3 of aforementioned strong case histories) and in Hawaii (examples 1 and 2), where the quiescence is probably due to reduction of the rate of shallow earthquakes distributed throughout the entire depth range of the crust above the near horizontal fault plane. In these cases the most attractive explanation may be precursory slip softening along the fault plane (e.g., STUART, 1979).

It is easy to think of reasonable mechanisms which can explain quiescence. Thus the phenomenon cannot be rejected as impossible. However, it is clear that we need more detailed case histories and constraints by additional parameters to select a compelling physical model to explain quiescence.

Conclusions

Several cases of extremely strong quiescences have been investigated in great detail, and it was found that they are statistically highly significant and that they cannot be reasonably explained by catalog heterogeneity. Several additional cases of quantitatively measured quiescence have been documented. The method of measuring quiescence has progressed from using visual means to using a quantitative approach, and the understanding of the noise sources has significantly advanced during the last few years. Therefore I feel that quiescence is a real phenomenon and the method to detect it has matured to a point that is acceptable for the List of Significant Precursors, although considerably more work needs to be done to understand this parameter and its role in the earthquake generation process.

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Precursory Seismic Quiescence

Max Wyss and R. E. Habermann

Pure and Appl. Geophys. *126*, 319–332, 1988

Abstract—Seventeen cases of precursory seismic quiescence to mainshocks with magnitudes from $M_L = 4.7$ to $M_S = 8.0$ are summarized. The amount of rate decrease ranges from 45% to 90%. The significance of these changes varies between 90% and 99.99%. The assumption that the background rate is approximately constant is fulfilled in most crustal volumes studied. All quiescence anomalies seem to have abrupt beginnings, and the rate during the anomalous period is fairly constant. The duration of the precursors ranges from 15 to 75 months, and it is not clear what factors determine that time. At least three successful predictions have been based on seismic quiescence. These cases have shown that mainshocks can be predicted based on quiescence, but they have also shown that the interpretation of the data in real time is difficult and nonunique. If a false alarm is defined as a period of quiescence with a significance level larger than a precursory quiescence in the same tectonic area, then we estimate, based on searches in four areas, that the false alarm rate may be on the order of 50%. Failure to predict may be expected in perhaps 50% of mainshocks, even in carefully monitored areas. Quiescence cannot be used as a precursor in tectonic environments with low seismic activity. Most

characteristics of the phenomenon are still poorly defined, but data exist which probably permit at least a doubling of the presently available data on case histories.

Precorsory Seismic Quiescence: Past, Present, and Future

R. E. Habermann

Pure and Appl. Geophys. *126*, 279–318, 1988

Abstract—Precursory seismic quiescence has played a major role in most of the successful earthquake predictions made to date. In addition to these successes, the number of detailed post-mainshock documentations of precursory quiescence is steadily growing. These facts suggest that precursory quiescence will play an important role in earthquake prediction programs of the future. For this reason it is important to critically evaluate the present state of knowledge concerning this phenomenon. The history of observations of precursory seismic quiescence includes work on seismic gaps and 'seismic preconditions' as well as actual studies of temporal quiescence. These papers demonstrated the importance of quantitative evaluation of seismicity rates and the benefits of systematic analysis. During the early 1980s the impact of man-made effects on seismicity rates was demonstrated for the first time. Despite progress in catalog understanding, the identification and correction of man-made seismicity changes remains as the major barrier to earthquake prediction using these data. Effects of man-made changes are apparent in many past studies of seismicity patterns, making the results difficult to evaluate. Recent experience with real-time anomalies has demonstrated the necessity of determining the false alarm rates associated with quiescence precursors. Determination of false alarm rates depends on quantitative definitions of anomalies and statistical evaluations of their significance. A number of successful predictions, which have been made on the basis of seismic quiescence, provide important lessons for present and future work. There are many presently unanswered questions regarding seismic quiescence which must be answered before we can determine the reliability of this phenomenon as a precursor.

Precursory Quiescence Before the August 1982 Stone Canyon, San Andreas Fault, Earthquakes

Max Wyss and R. E. Habermann

Pure and Appl. Geophys. *126*, 333–356, 1988

Abstract—The Stone Canyon earthquake sequence started during August 1982 and lasted for about four months. It contained four mainshocks with $M_L \geq 4$, each

with an aftershock zone about 4 km long. These mainshocks, progressing from southeast to northwest, ruptured a segment of the fault approximately 20 km long leaving two gaps, which were later filled by the $M_L = 4.6$ mainshocks of January 14, and May 31, 1986. The equivalent magnitude of the sequence is $M_L = 5.0$.

Precursory seismic quiescence could be identified in: (1) the northernmost 10 km of the aftershock zone which contained three of the mainshocks; and (2) the southern gap in the aftershock zone. The fault segment containing the first mainshock and its aftershocks did not show quiescence. This pattern of precursory quiescence is very similar to two cases in Hawaii where the rupture initiation points of the mainshocks ($M_S = 7.2$ and 6.6, respectively) were located in volumes without pronounced precursory quiescence.

The precursory quiescence before the August 1982 Stone Canyon earthquakes lasted for 76 weeks, amounted to a reduction in rate of about 60%, and could be recognized without any false alarms. That is, the anomaly was unique within the 60 km study segment of the fault and in the years 1975 through August 1982. Eighteen foreshocks occurred between July 27 and August 7, 1982. We conclude that the August 1982 mainshocks could have been predicted, based on seismic quiescence and foreshocks.

Seismic Quiescence Precursor to the 1983 Kaoiki ($M_S = 6.6$), Hawaii, Earthquake

Max Wyss

Bull. Seismol. Soc. Am. *76*, 785–800, 1986

Abstract—A remarkable seismicity rate decrease of 65 percent occurred in most of the aftershock volume 2.4 yr before the 1983 Kaoiki $M_S = 6.5$ mainshock. If the background seismicity rate (1978 to mid-1981) is extrapolated to the time of the mainshock, more than 300 earthquakes of $M_L \geq 1.8$ are missing because of the quiescence. Subvolumes measuring 5.5 km on a side, and located within the aftershock zone, showed seismicity rate decreases ranging from 0 to 90 percent. The volume of no change had dimensions of approximately 10×3 km. It contained the mainshock hypocenter, and was located near the center of the 10 km radius aftershock area. The seismic quiescence in different subvolumes of the aftershock volume surrounding this central nonquiet zone varied somewhat in starting time, amount of rate decrease, and statistical significance. According to the standard deviate z test, the reported rate decrease is the most pronounced example of precursory quiescence defined to date. The seismicity pattern before the 1983 Kaoiki shock conformed to the quiescence hypothesis proposed on the basis of the precursors to the 1975 Hawaii mainshock: no quiescence was observed within

the immediate surrounding of the hypocenter, while strong rate decreases occurred in most of the rest of the mainshock source volume. It is thus hypothesized that major asperities which contain high stress levels, and from which main ruptures can emanate, may be recognizable as volumes of contant seismicity rate within surrounding volumes of quiescence, provided that decreases of seismicity rate as a function of time can be defined quantitatively.

Seismic Quiescence at Parkfield: An Independent Indication of an Imminent Earthquake

Max Wyss, P. Bodin, and R. E. Habermann

Nature *345*, 426–428, 1990

Abstract—The Parkfield segment of the San Andreas Fault midway between San Francisco and Los Angeles has experienced six moderate-sized earthquakes since 1850, with an average recurrence time of about 22 years. Based on this regular behavior, and the occurrence of the most recent earthquake in 1966, a shock of local magnitude $M_L = 5.7$ is expected to occur by 1993. Here we suggest that a current lack of small earthquakes on this segment could be a precursory anomaly to the next characteristic Parkfield earthquake. Only four earthquakes of $M \geq 2.5$ have occurred on the segment since January 1986, whereas twenty would have been expected, extrapolating from the mean background rate. Comparison with other cases of precursory quiescence suggests that the $M = 5.7$ earthquake should occur in the next two years, rupturing the same 35-km fault segment that ruptured in 1966.

Reporting History of the Central Aleutians Seismograph Network and the Quiescence Preceding the 1986 Andreanof Island Earthquake

Max Wyss

Bull. Seismol. Soc. Am. *81*, 2320–2334, 1991

Abstract—The earthquake catalog of the Central Aleutian Seismic Network (CASN) was searched systematically for significant rate changes in the period from 1976 through 1985. The magnitude signatures for the nine changes were modeled by synthetic signatures. By this method, six of the rate changes could be identified as artificial, based on the criteria that the rate change was confined to small magnitude events and that magnitude shifts were present. For each of these changes an artificial

cause existed that affected the network within one to two months of the time of change as estimated from the catalog analysis. One of these cases was a rate decrease by a factor of 2 associated with a storm that had put out of operation two thirds of the network. Another change coincided with the introduction of digital data processing. The four remaining cases were artificial reporting rate increases due to installation of several new stations or to repair of several stations that failed. The three rate changes that could not be identified unambiguously as artificial or natural on the basis of magnitude signatures were all rate decreases by factors of approximately 2. Two of these were clearly due to disasters that had put out of operation more than half of the network. The third was the proposed precursory quiescence to the 1986 Andreanof Island ($M = 7.9$) earthquake. From this we conclude that, without knowledge of the network history, many of the artificial reporting rate changes in earthquake catalogs can be identified as artificial and that their onset time can be estimated to within one to two months.

An earthquake count, independent from the Adak catalog, was obtained from the Helicorder records of the station Adak for the years 1978 through 1985 for the vicinity of Adak Island. Of a total of 1831 events, 335 were not in the Adak catalog and 981 were located within the 1986 aftershock area. The Helicorder earthquake count showed a pronounced decrease by about 50 percent, similar in amount to that in the Adak catalog. However, the decrease started in 1980, at a time when in the central subregion covered by the Adak catalog only $M \geqq 2.9$ events decreased, while the smaller magnitude bands show a maximum decrease in 1982. We conclude that the possibility could not be ruled out that electronics changes contributed to the reporting rate decrease starting in the years 1980 to 1982. However, it seems very unlikely that a network that was at its healthiest during the precursor time would be reduced by an improvement in the electronics to a detection level approximately equal to that in two short periods when only one third of the stations were operating. Therefore, the seismic quiescence reported and interpreted as a precursor by KISSLINGER *et al.* (1985) was most likely a natural phenomenon.

An Experiment in Earthquake Prediction and the 7 May 1986 Andreanof Islands Earthquake

Carl Kisslinger

Bull. Seismol. Soc. Am. *78*, 218–229, 1988

Abstract—The occurrence of the 7 May 1986 Andreanof Islands earthquake provides the opportunity to evaluate the earthquake forecast and specific prediction that had been formulated and promulgated, starting more than 2 yrs before. The prediction experiment was based on the observation of seismic quiescence in the

part of the Aleutian subduction zone monitored by the Central Aleutians (Adak) Seismic Network. The magnitude estimate (M_S 7 to 7.5) was based on the size of the quiescent zone and the seismic history of the Adak region since 1990. The time of occurrence was predicted as a test of the discovery by Habermann of a quiescence lasting about 3 yrs prior to the 2 May 1971 Adak Canyon event, and the hypothesis that a characteristic precursor time is a valid concept. The place was originally forecast as "near Adak Island," then specified with epicenter at the eastern margin of Adak Canyon, rupturing to the west under the canyon. The 7 May 1986 earthquake had magnitude M_S 7.7 (M_W 8.0), with epicenter 140 km east of the predicted place, rupturing east of Adak Canyon and stopping in the area predicted as the nucleation point. The time of this event was 6 months later than predicted. Thus, the specifically predicted event has not happened. The largest part of the rupture did go through the segment that had been most active before the onset of quiescence and which experienced the sharpest and most persistent quiescence. A cause-and-effect relation between preparation for this earthquake and the quiescence is still to be firmly established, but the distribution of the pattern of quiescence relative to the epicentral location and the site of the greatest moment release suggest a physical connection between earthquake and seismicity patterns. The predictions of location and time were acknowledged throughout as highly speculative. No firm basis exists for quantitative estimation of the uncertainties to be assigned to the elements of an intermediate-term prediction.

This experiment lends support to the validity of quiescence as a precursor, at least for some earthquakes, and demonstrates the need for local network data to provide the high resolution of seismicity required for prediction efforts based on seismicity patterns.

Occurrence of a Predicted Earthquake on the San Andreas Fault

Max Wyss and R. O. Burford

Nature *329*, 323–325, 1987

Abstract—In May 1985 we predicted that an earthquake would occur on the San Andreas Fault near Stone Canyon, California within a year. The prediction was based on the observation of seismic quiescence—defined as a significant decrease in the average occurrence rate of earthquakes within the source volume of the future mainshock. A mainshock of magnitude $M_L = 4.6$ occurred on 31 May 1986, rupturing exactly the specified segment of the fault. This is the first successful prediction of an earthquake along the San Andreas Fault, and the probability to have come true by chance is $<5\%$. Although the prediction addressed only a small mainshock, its success was significant because the location, size and occurrence time

were correctly specified for an earthquake in a populated area. Larger earthquakes will undoubtedly be successfully predicted by the same method in the future, but the major segments of the San Andreas fault near San Francisco and Los Angeles have such a low-background seismicity rate that the method will probably not be applicable there.

Current Episodes of Seismic Quiescence Along the San Andreas Fault Between San Juan Bautista and Stone Canyon, California: Possible Precursors to Local Moderate Mainshocks?

Max Wyss and Robert O. Burford

U.S. Geological Survey, Open File Report 85–754, 367–425, 1985

Abstract—A quantitative evaluation of the seismicity rates along a 100-km segment (36.36° to 37.0°N) of the San Andreas Fault for the period August 1973 through December 1984 has established that three separate subsegments of the fault are quiescent at the present. For earthquakes of $M_L \geq 1.7$ and $M_L \geq 2.0$ seismicity rates show highly significant average decreases of 66%, 65%, and 71% below the background rate in the Cienega Winery seismic gap, the San Juan Bautista seismic gap, and the Stone Canyon section, respectively. These anomalies began in June 1982, February 1983, and June 1983. Athough these anomalously quiet fault segments are separated by approximately 10-km long segments where the current seismicity rates are normal, there is a possibility that all three are related to a common mechanism. All three anomalies are unique in the data set, by far surpassing in significance any other rate changes, with z values calculated by $AS(t)$ of 4.9 and 7.7 (San Juan and Stone Canyon, respectively for $M_L \geq 2.0$). In addition, two precursory quiescence anomalies were discovered for past mainshocks in the study area: the $M_L = 4.0$ (2 August 1979) and $M_L = 4.2$ (11 August 1982) mainshocks were preceded by decreases in seismicity rates of 80% and 60% respectively, with the anomalies starting 15 and 19 months before the respective mainshocks. Based on these observations, it is proposed that the present-day quiescence anomalies are probably precursors to one or several future earthquakes. The interpretation that the present quiescences might have been caused artificially by a change of data acquisition or analysis procedures is made unlikely by the observation that six 10-km fault segments in the area show no significant seismicity-rate changes in the last 5 to 11 years. The lengths of the anomalous segments are small, 5 to 10 km, suggesting that the expected mainshocks should be in the range $4 \leq M_L \leq 5$. However, the anomaly durations range from 2.8 to 1.9 years, suggesting that these magnitude estimates may be too low by approximately one unit. This invites the interpretation that the three

quiescence anomalies jointly outline the rupture length of one mainshock of $M_S = 6.2 \pm 0.3$ centered near 36.75°N and 121.4°W. All magnitude estimates presented are based on the assumption that the expected rupture(s) will occur within the next 12 months. If the quiescence anomalies persist without mainshocks for another year the magnitude estimate should be increased. The probability for an individual quiescence to be a false alarm (no mainshock follows) is estimated from observations in other areas to be approximately 30%.

Examples of An Artificial and A Precursory Seismic Quiescence

Max Wyss

Conference on Earthquake Prediction, State-of-the-Art, Council of Europe, Strasbourg, France, 157–166, 1992

Abstract—It is often difficult to identify artificial seismicity rate decreases, and many authors do not attempt to identify them. However, for claiming that precursory quiescence existed it is not enough to require that it coincide approximately in space and time with a mainshock, because a more detailed analysis may show that the quiescence may be explained by a magnitude shift. This is the case for the fault segment at the southernmost end of the Loma Prieta 1989 aftershock sequence, which shows a spectacular rate decrease during many years before this mainshock ($M = 7.0$). However, it was found that this decrease could be modeled as due to an inadvertent change of the magnitude scale by about -0.4 units. After the catalog was corrected for several magnitude shifts, the Loma Prieta aftershock volume did not show a significant precursory quiescence. Nevertheless seismic quiescence seems to be a real precursor to some mainshocks. A quantitative analysis shows that a highly significant rate decrease in all magnitude bands, not explicable by a magnitude shift, took place during 5.3 years before the 1975 Kalapana earthquake ($M = 7.2$).

Precursors to the Kalapana $M = 7.2$ Earthquake

Max Wyss, F. W. Klein, and A. C. Johnson

J. Geophys. Res. 86, *3881–3900, 1981*

Abstract—The Kalapana, Hawaii earthquake of November 1975 had a rupture length of 40 to 50 km and was located on the south flank of the active volcano Kilauea. The source mechanism was dip slip normal faulting on a plane dipping

$\sim$20 degrees to the SE, with the greatest principal stress oriented in that direction and accumulated by volcanic intrusions into Kilauea's rifts. The source area of the 1975 earthquake was subject to intensive geological and geophysical research for many years before this earthquake because of its proximity to the volcano. We studied the distribution of epicenters for small earthquakes from 1962 to 1975. Seven seismographs located within 3 km of the aftershock area had been in operation for 3 to 10 years before the mainshock, and geodetic triangulations and trilaterations in the source area had been carried out repeatedly since 1914. We found that precursory changes occurred throughout most of the rupture area but in two distinctly different patterns. In the larger outer anomalous area the seismicity rate was decreased by 50% during the 3.8 years before the mainshock; in addition, several geodetic lines indicated anomalous strain release during this time. Within two inner areas the seismicity remained high, then increased shortly before the mainshock. In one of the inner areas a P-wave travel time delay of 0.2 s could be detected, which began about 3.5 years before the mainshock. Within the other inner anomalous area geodetic strain was accumulating until the first half of 1975 when 3.5×10^{-4} strain (35 bars), was released aseismically. By contrast, the outer anomalous volume was experiencing strain softening from 1970/1971 on. We interpret these observations as indicating that strain softening by fault creep in the outer anomalous area transferred stress into two major asperities (locked portions of the fault). A velocity decrease and foreshocks were observed in one asperity and high stress accumulation in the other, implying that dilatancy of the crust probably occurred. Our model is qualitatively supported by the independent evidence of strong motion records which show that the Kalapana earthquake was a complex multiple rupture. We conclude that the Kalapana earthquake was preceded by a preparatory process which lasted 3.8 ± 0.3 years and which had dimensions of 45×10 km covering approximately the aftershock area.

Precursory Seismic Quiescence Before the January 1982 Hilea, Hawaii, Earthquakes

Max Wyss and Zhengxiang Fu

Bull. Seismol. Soc. Am. *79*, 756–773, 1989

Abstract—Two earthquakes of $M_L = 5.4$ occurred within half an hour of each other within the Hilea area of Southern Hawaii on 21 January 1982. The aftershock distribution suggests that together they ruptured an area of approximately 5-km radius, and their joint equivalent magnitude was 5.6. The first motions indicate faulting on a near horizontal plane at 10 km depth, with the crust slipping to the southeast.

The seismicity rate in the source area was studied using the earthquake catalog of the Hawaiian Volcano Observatory. This catalog contains some reporting rate

changes that affect the count of smaller earthquakes strongly, with a period of low reporting during 1974 to 1977. Although we have used 2.5 as the minimum magnitude of homogeneous reporting after 1971, some of the artificial rate changes are still present in the data. The catalog was declustered using Reasenberg's algorithm, and a magnitude correction of -0.1 was applied to the data between 1974 and 1984.

The seismicity rate for the period of November 1971 through 1985 was examined in four adjacent regions; one of these contained the aftershocks. The aftershock volume and the 3-km annulus around it showed a period of 46 weeks of low seismicity rate immediately before January 1982, during which the rate was decreased by 87 percent. The seismicity rate in the other three volumes was normal during this time. We conclude that this low reporting rate was not likely due to artificial changes in the catalog. The fact that the quiescence anomaly coincided in space with the 1982 aftershock volume and that its termination coincided with the 1982 mainshocks suggests that the quiescence was a precursor.

Comparing the seismicity rate within all possible 46-week windows to the background rate, we found that the precursory rate decrease was more significant than any other rate decrease in all volumes studied except artificial low rate periods. Thus, this quiescence precursor could be recognized without false alarms. However, the statistical significance estimated by the z and β tests was low, $\leqq 75$ percent and $\leqq 49$ percent, respectively. More case histories are needed to determine empirically the thresholds of these tests for accepting precursory anomalies without too many false alarms.

The $M = 6.6$ Kaoiki earthquake that was located about 25 km north of the 1982 source area was preceded by 125 weeks of quiescence, while the $M = 7.2$ Kalapana earthquake quiescence precursor lasted about 200 weeks. These observations suggest that in Hawaii quiescence precursor times may be a function of magnitude.

Background Seismicity Rates and Precursory Seismic Quiescence: Imperial Valley, California

R. E. Habermann and M. Wyss

Bull. Seismol. Soc. Am. *74*, 1743–1755, 1984

Abstract—The problem of recognizing precursory seismicity rate changes consists of two steps. First, a background or normal rate must be determined and, second, anomalous rates must be recognized. In this paper, we address the first of these steps, determining a background seismicity rate. Two problems must be dealt with, if a meaningful background rate is to be determined. First, dependent events must be recognized and removed from consideration and, second, detection or

reporting changes must be accounted for. A number of techniques are available for recognizing dependent events. We used the one developed by McNally (1976) in this work. The technique we used for recognizing detection and reporting changes was developed by Habermann (1983). We demonstrate these techniques on seismicity from the Imperial Valley region of California. After a reasonable background rate is determined, we examine seismicity rates in this region prior to the Imperial Valley earthquake of 15 October 1979. The source area of the earthquake shows a possible precursory quiescence which started during July 1979. The time of this rate decrease is close to the time of a change in the seismic instrumentation in the Imperial Valley which makes it difficult to determine whether the decrease is real or related to detection. Several other seismicity rate changes observed in the Imperial Valley appear to be related to changes in the operation of the network there. These include quiescent periods which occur only if magnitude cutoffs are applied to the data and periods of low reporting of events with $M \geqq 2.5$. These observations suggest that magnitudes were not reported for some events during several time periods. All of these observations indicate that determination of detection histories is crucial for meaningful seismicity studies.

Reply

R. E. Habermann and Max Wyss

J. Geophys. Res. *92*, 9446–9450, 1987

Introduction. The importance of seismicity data for earthquake prediction has been demonstrated in a number of studies during the last decade. The most successful earthquake predictions yet accomplished, as well as several presently open predictions, have been based chiefly on seismicity analysis (Geological Sinica, 1976; Ohtake *et al.* 1977a,b; Van Wormer and Ryall, 1980; Bakun and McEvilly, 1984; Wyss and Burford, 1985; Kisslinger, 1985). The primary advantage of seismicity data is that they are available for all seismically active regions of the world, allowing the development of a number of case studies of possible precursory patterns. Precursory seismic quiescence (decreased seismicity rate) has been well documented in a number of cases and used successfully for actual predictions in four of the cases mentioned above. For this reason, changes in seismicity rate seem, at present, to provide the most promising means for recognizing possible precursory patterns.

During the last several years we have developed an approach to the problem of studying seismicity rate variations (Habermann, 1981a,b, 1982, 1983; Habermann and Wyss, 1984). Quantitative description and evaluation of rate changes have been an important part of our approach, and the use of quantitative techniques is a primary difference between our work and most other seismicity studies related to earthquake prediction. We believe that a systematic and quantitative approach to anomaly recognition and evaluation is crucial if the potential of seismicity data for earthquake prediction is to be realized. The system of analysis that we have developed has led to recognition of a number of precursors to past earthquakes as well as to recognition of presently occurring precursors and successful predictions. In addition, we have successfully recognized the times of detection and reported related changes in seismicity rates with remarkable accuracy. The man-made changes were recognized without prior knowledge of their existence, thus constituting a blind test of our approach.

MATTHEWS and REASENBERG [this issue] (herein referred to as MR) claim that the statistical test that we have used for recognizing seismicity rate changes overestimates the significance of those changes and thus finds many false alarms. In addition, they propose that the arbitrary bin size that we impose on the problem strongly effects our results. We show that their conclusions about the effect of bin size on our results cannot be supported by observations. We then show that our significance estimates can be improved using simulations as MR point out. We conclude that the 99% critical level for long runs and minimum window lengths longer than 50 samples is close to $z = 3.6$ rather than 2.6.

Comments by the Panel

1. The panel makes no decision on the nomination of seismic quiescence at this time. Quiescence may well be a real precursory phenomenon, but methodological shortcomings in the present nomination mean that it cannot yet be placed on the list of significant precursors.
2. We are impressed by the careful work that has gone into recognizing inhomogeneity in earthquake catalogs. The methods developed have prepared the way for a more systematic study of quiescence as a precursor than has so far been undertaken. This study should include a systematic accounting for false alarms and failures to predict. At present there are deficiencies in this area. For example, the present method for recognizing false alarms depends on the significance level of an already recognized success in an adjacent area, and on the size of the source region of the related mainshock. This is not satisfactory. No serious attempt seems to have been made to recognize failures to predict.
3. We have concerns about removing dependent events and establishing the background level of seismicity. The methods used are not fully explained. We wonder whether they would bear close scrutiny, and whether a consistent approach has been adopted.
4. The plots presented of the cumulative number of earthquakes always begin during a period of supposedly normal seismicity and end at the time of the

mainshock. We would like to see plots covering a much longer period, before and after. This would help to dispel doubts concerning what the normal level of seismicity is.

5. Most of the examples presented are *ex post facto* case histories and are drawn from a wide range of catalogs. The real-time predictions are three (later reduced to two) on the San Andreas Fault, one at Andreanof Island and two at Parkfield (one of which is still current). In one of the San Andreas examples (Stone Canyon) it is fair to say that the predicted event occurred, despite some "hedging of bets" about the windows for time, space and magnitude. As noted by the reviewers, the Adreanof Island event was an unsuccessful prediction. Also the time-window specified in the original Parkfield prediction has now elapsed. The valid alarm rate for PSQ may thus be about 1/5 to 1/4 in real-time prediction. This may be high enough to make it a useful precursor.
6. The reviewers comments about vagueness in the definition of PSQ must be taken seriously. We think that the definition of quiescence needs to be firmed up. An objective historical study of successes, false alarms and failures should then be undertaken in an extended region, over as long a period of time as homogeneity of data permits. Such a study could be extended to a validation of the method in real-time prediction in the same extended region.

Reviews

Review 23.1

A satisfactory earthquake prediction method should contain the following elements.

1. A clear definition of the event or events being predicted, including time window, space volume, magnitude window, and any special conditions such as mechanism etc., that might apply.

2. A clear definition of the conditions leading to the prediction.

3. A statement of the frequency of occurrence of the "alarm" conditions.

4. A statement of the background probability (unconditional) that an event satisfying (1) would occur, and

5. a statement of the conditional probability, or the probability gain, or equivalent.

Items (1) and (2) should be unequivocal, but of course items (3), (4) and (5) must be approximate in practice.

The record for the seismic quiescence precursor does not satisfy these criteria at present. Most of the cases discussed in the summary are examples of *ex post facto* predictions, where the predicted events, and the quiescence preceding them are defined by example. Exceptions are the case of Stone Canyon (event 4, 1986) and

Andreanof Island (1987, event 3). In the latter case the predicted event was in fact carefully described, but the prediction was not satisfied. In general, quiescence is described by example rather than by an objective criterion. To be useful as a prediction tool, quiescence needs a formal definition.

Beginning with the Parkfield prediction, Wyss has begun to be far more specific about the predicted event. This is laudable. The Parkfield prediction is still pending.

Evaluating the track record of quiescence is problematical for a few reasons. One is the ambiguous definition discussed above. Another is the data selection procedure: the case histories are very few in number, and they include only cases in which a significant earthquake did occur. From a prediction standpoint, a false alarm must include any case for which the condition (apparent quiescence) occurred but *no* predicted event occurred. Thus it seems that the selection method advocated by Wyss is inappropriate.

The method deserves further study. Certainly criteria for recognizing quiescence before a major earthquake should be developed, and tested objectively. A list of a few successes is not sufficient. I thought the work of Matthews and Reasenberg was a good approach to an objective evaluation. Wyss questions their selection procedure, without giving a full explanation. But Wyss's demand that selection be "restricted to a mainshock volume" (paragraph 1 of Wyss nomination) requires the mainshock to be known in advance; this cannot be applied in true prediction. Thus some workable selection criteria are still needed.

Review 23.2

This proposal is difficult to review because of the lack of definiteness, the frequent recourse to subjective statements, and internal inconsistencies.

The definition of precursory seismic quiescence (Summary, paragraph 1) contains only two definite requirements: that the decrease precedes the mainshock by months to years, and that the mainshock must be a major event. Even so, the "background seismicity rate," which has to decrease, is not defined. (For example, should it include or exclude aftershocks and swarms?) Also, the decrease has to be "statistically significant," but the level of significance is not specified. Nor is "major event" defined. Definiteness is also lacking in such statements as "the false alarm rate may be approximately 50%;" "the rate of failure . . . may also be in the 50% range;" "it is very unlikely that . . .;" etc.

The use of subjective statements puts the reader in the unsatisfactory position of being asked to accept the author's say-so. These statements include such usages as: I do not view . . . ; rather I see it . . . ; the total number . . . that can be viewed as reliable . . . ; this rate . . . is tolerable; . . . I feel that . . . ; . . . I no longer doubt that . . . ; . . . in which we have most confidence . . . ; I believe that . . . ; . . . we now have a new understanding . . . ; . . . we have a great deal of confidence . . . ; etc.

The argument for precursory quiescence is undermined by the author's statement (p. 5): "... it is not crucial to know ... [the failure] rate for assessing the validity of the quiescence method. If we can show convincingly that quiescence occurs before at least some mainshocks, then we have a valid, although not failure proof, method to predict earthquakes." This is a very weak criterion; a sufficiently large failure rate will surely render the method ineffective.

The citing of the Andreanof Islands as one of at least two successful earthquake predictions based on quiescence is inconsistent with the author's third condition for a case to be included in support of the quiescence hypothesis (p. 2, paragraph 2).: "that the association of the anomaly with the mainshock, in space and time, has been plausibly demonstrated." Carl Kisslinger states of his own prediction: ... "the specifically predicted event has not happened;" and again, with regard to location; "The predicted earthquake has not happened." (BSSA *78*, 1988, pp. 218, 220).

These difficulties are sufficient to indicate to the present reviewer that a strong case has not been made in favor of precursory seismic quiescence.