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# Precursory Seismic Quiescence

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*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.

**Key words:** Earthquake prediction, seismicity patterns, seismic quiescence.

## *Introduction*

Seismic quiescence may be the most promising intermediate-term precursor. For this reason we assess our present understanding of this phenomenon, although far-reaching conclusions cannot be drawn from the small number of high quality examples available. During the last few years we have become aware of a number of problems which must be addressed if seismic quiescence is to be unambiguously identified (HABERMANN, 1988). Below we propose a set of criteria for evaluating studies of quiescence, and we use these criteria to select the most well-documented cases. As we are in the process of forming an opinion on the nature of seismic quiescence, we think it is better to form this opinion on the basis of a small but high quality data set, rather than on one diluted by possibly invalid data points. As a consequence we may have omitted some data which are in fact valid, and just appear

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to be lacking in our judgment. Perhaps such data points could be added in the future.

*Definition of seismic quiescence*

Seismic quiescence is a decrease of mean seismicity rate as compared to the preceding background rate in the same crustal volume, judged significant by some clearly defined standard. The rate decrease takes place within part, or all, of the source volume of the subsequent mainshock, and it extends up to the time of the mainshock, or may be separated from it by a relatively short period of increased seismicity rate. Usually the rate decrease is larger than 40%, and takes place in all magnitude bands.

*Criteria for evaluating studies of seismic quiescence*

We propose that studies of seismic quiescence should contain the following elements: (1) An evaluation of man-made changes in the earthquake catalog used. (2) Demonstration of the minimum magnitude of homogeneous reporting. (3) Removal of dependent events. (4) A quantitative measure of the amount and significance of the anomaly. (5) A quantitative determination of the beginning of the anomaly. (6) An estimate of the dimensions of the anomaly. (7) Evaluation of the significance of the anomaly as a function of magnitude band. (8) An evaluation of the false alarm rate. (9) A design of the experiment which makes sense in the tectonic framework and which is appropriate for testing the quiescence hypothesis. (10) Independent evidence that precursory processes may have been occurring prior to the mainshock in question.

No report of precursory quiescence has yet satisfied all of these criteria, but we nevertheless propose them as an ideal. Although the cases we include in the summary fall short of fulfilling all of the criteria we list above, all of them fulfill some of the more crucial ones. Most of the cases on the list are ones that we have developed. This reflects the fact that many investigators have not evaluated the heterogeneity of the catalogs they used or have not quantitatively evaluated precursory quiescence anomalies.

The pioneering work of Mogi (1969) first brought attention to the possibility that reduced seismicity rates may exist in the source volume before some mainshocks. However, in this summary, we included only one of these examples, because most of the conditions we now require (above) were not fulfilled in this early work and because earthquakes with magnitude 6 and larger usually do not provide constant background rates against which quiescence can be measured reliably. No results are included from the study of Reasenberg and Matthews (this volume) because it violates conditions 1, 2, 6, 7, 8, 9 and 10. The most serious flaw is the experimental design of Reasenberg and Matthews, in which they did not separate the source volume from surrounding volumes of the crust. Hence they did not test the hypothesis that quiescence may exist in the source volume. We also do not include any of the cases from the review by KANAMORI (1981) because it contains no quantitative evaluation of the significance, and of the onset of the anomalies, and it does not consider the effects of the severe catalog heterogeneities.

*Successful predictions based on seismic quiescence*

There are three cases which can be considered successful predictions in the sense that a quiescence anomaly was recognized and interpreted as a precursor prior to the occurrence of the mainshock. All of these cases had shortcomings, but they provide important lessons which can only be learned in a real prediction experiment.

In the Oaxaca case (OHTAKE *et al.*, 1977; 1981) the data base was limited because of the lack of a regional network, and the catalog contains strong artificial rate decreases (HABERMANN, 1981b). Therefore quiescence cannot be defined with as high a confidence level as desirable or possible in other cases (GARZA and LOMNITZ, 1979; HABERMANN, 1981b; Table 1). This means that false alarms are more likely to be generated if the alarm level is lowered to the significance of quiescence observed for this case. The prediction of KISSLINGER *et al.* (1985) contained some details which did not come true, and the location was not anticipated in an optimal way. Nevertheless, the signal of seismic quiescence was strong (high relative significance, Table 1), and it was recognized and correctly interpreted as a precursor. The same two problems as in the above predictions arose in the Stone Canyon case: the question of statistical significance required for an alarm and that of the correct detailed interpretation of observed facts. WYSS and BURFORD (1985) first identified three fault segments as quiet, subsequently raised the alarm level and retained only two segments for their final prediction (WYSS and BURFORD, 1986; unpublished report in WYSS, 1987) in response to criticism (BAKUN, 1985; LINDH, 1985; MATTHEWS, 1985; SAVAGE, 1985). Also, WYSS and BURFORD (1985) offered two scenarios. In one of these, individual mainshocks were to rupture the anomalous fault segments separately, in the other a larger quake was to rupture all of them.

The problems which qualified these successes point out that the heterogeneity of the catalogs can pose obstacles, that the optimal alarm level still awaits to be established empirically, and that the interpretation of precursors is not unique.

It would be desirable for the reader to find documentation of all cases of quiescence in figures in this summary. However, we have not done this because, even though the older cases may be adequately analyzed, they do not conform to our present higher standards for detailed investigations. Below we will refer the interested reader to the exact figure in the original publications where the relevant data were presented.

Table 1

*Precursory quiescence*

| Event No. | Date D | M | Y | Location | Magnitude $M_S(M_L)$ | Quiescence duration (months) | Rate decrease % | $z$-value | Confidence level % | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 14 | 01 | 76 | Kermadec | 8.0 | 63 | 85 | 4.1 | 99 | W *et al.* 84 |
| 2 | 16 | 05 | 68 | Tokachi-Oki | 7.9 | 75 | 64 | 4.4 | 99 | M 69; H 81b |
| 3 | 29 | 11 | 78 | Oaxaca | 7.7 | 43–66 | 70 | 2.5 | <95 | O 77; McN 81; H 81b |
| 4 | 07 | 05 | 86 | Aleutians | 7.7 | 42 | 83 | 8.8 | 99 | K 85, 87 |
| 5 | 10 | 10 | 74 | Lima | 7.5 | 27 | 90 | 3.6 | 97 | H 81a |
| 6 | 02 | 08 | 68 | Oaxaca | 7.5 | 32 | | | | O *et al.* 77 |
| 7 | 30 | 01 | 73 | Colima | 7.4 | 21–24 | 80 | 4.3 | 99 | H 81b; McN 81 |
| 8 | 22 | 06 | 77 | Tonga | 7.2 | 25 | 70 | 4.5 | 99 | W *et al.* 84 |
| 9 | 29 | 11 | 75 | Hawaii | 7.2 | 46 | 45 | | | W *et al.* 81 |
| 10 | 24 | 05 | 78 | Aleutians | 6.6 | 38 | 69 | 3.5 | 97 | H 81a |
| 11 | 16 | 11 | 83 | Hawaii | 6.6 | 29 | 70 | 10.0 | 99 | W 86 |
| 12 | 22 | 02 | 75 | Aleutians | 6.5 | 15 | 68 | 2.3 | <95 | H 81a |
| 13 | 28 | 07 | 74 | Kuriles | 6.3 | 27 | | 2.7 | <95 | H 81b |
| 14 | 23 | 04 | 84 | Morgan Hill | 6.1 | 23 | 56 | 3.5 | 97 | H&W 84b |
| 15 | 06 | 08 | 79 | Coyote Lake | 5.9 | 22 | 78 | 5.1 | 99 | W&H 84b |
| 16 | 10 | 08 | 82 | San Andreas | 5.0 | 18 | 60 | 4.0 | 99 | W&H 88 |
| 17 | 31 | 05 | 86 | San Andreas | 4.7 | 35 | 70 | 3.8 | 98 | W&B 85, 87 |

*The Method of Detecting Seismic Quiescence*

A short discussion of the method for identification of quiescence is necessary because it influenced our selection of high quality data. The criteria we listed above contain the steps we feel are necessary for building an unambiguous case of precursory quiescence. These steps fall into two broad categories: catalog preparation and anomaly identification and evaluation. The catalog preparation category includes criteria 1, 2 and 3. The anomaly identification and evaluation category includes criteria 4 through 8. In this section we discuss justification for these criteria, and some of the techniques we have used to satisfy them.

Anomalous seismicity rates cannot be recognized unless the background or normal rate is well defined. HABERMANN and WYSS (1984a) discuss two major problems involved in determining a background rate: (1) correction for man-made changes in the catalogs, and (2) removal of dependent events. Since that time two additional problems have been demonstrated. (3) Strong spatial variations in seismicity rate occur along strike of many seismic zones (e.g., Figure 8 in WYSS *et al.*, 1984; Figures 1 through 6 in HABERMANN *et al.*, 1986). These spatial variations make it difficult to compare rates between neighboring volumes in many cases. (4) Magnitude estimates in most catalogs show systematic temporal variations which cause changes in apparent seismicity rates when magnitude cutoffs are applied (HABERMANN and WYSS, 1984a; PEREZ and SCHOLZ, 1984; WYSS and BURFORD, 1985; HABERMANN, 1986, 1987, 1988; WYSS and HABERMANN, 1988). A complete study of precursory quiescence must, therefore, address all four of these problems before background rates can be adequately determined.

Numerous examples of artificial rate changes in catalogs have now been identified and documented (e.g., Figure 6 in HABERMANN, 1981b; Figure 1 in HABERMANN, 1982a; HABERMANN, 1983, 1987; Figure 1 in WYSS *et al.*, 1984; Figures 6 and 7 in HABERMANN and WYSS, 1984a; Figure 3 in HABERMANN, 1986). The reporting of large events is complete in modern catalogs, but for small ones it fluctuates. Therefore a lower magnitude cutoff ($M_{\min}$) must be used to eliminate events which are not homogeneously reported. It is desirable to choose $M_{\min}$ as low as possible, because quiescence can be better defined with more data. In addition to determining $M_{\min}$ one must insure that the magnitude estimates in the catalog being examined are temporally consistent (HABERMANN and WYSS, 1984a; HABERMANN, 1986, 1987). HABERMANN (1988) discusses several cases where catalog detection problems and magnitude instability have interfered with seismicity rate studies.

We have found that remarkably constant background seismicity rates exist in most of the regions we have examined, if magnitude corrections have been made and dependent events removed (e.g., Figures 4 and 5 in WYSS, 1986; Figures 6 and 8 in WYSS and HABERMANN, 1988). Identifying dependent events is relatively easy in teleseismic catalogs, but can be difficult in local ones. In some regions large mainshocks occur, but the background rates are so low that seismic quiescence cannot be used as an earthquake prediction tool.

Once reasonable background rates can be established, one can identify and evaluate anomalous rates. Rate changes must be quantitatively described in order to do this. Several authors have proposed statistical tools for evaluating the significance of rate changes (HABERMANN, 1981a,b; OHTAKE *et al.*, 1981; MCNALLY, 1981; VENEZIANO and VAN DYCK, 1985; MATTHEWS and REASENBERG, 1988). We have relied on the $z$-test for a difference between two means for this evaluation. One must be careful when using this or any other test to search data sets for anomalies, because the significance levels associated with a given statistic are affected by the process of searching (MATTHEWS and REASENBERG, 1987). Recent work using simulated data has improved our estimates of the significance of observed $z$-values (HABERMANN and WYSS, 1987). In light of this we have re-evaluated the significance of all cases in Table 1, where sufficient data are available. This work indicates that the significance of about half of the cases was originally overestimated by about 2 to 5% (Table 1).

It is important to realize that the confidence level gives only a relative measure to judge an anomaly's significance. The physics of the earthquake preparation process may lead to different levels of significance for real precursors in different tectonic areas. In addition, the significance level used for issuing alarms will depend on the data quality and the consumer's needs. For these reasons we have not proposed a specific significance level as alarm threshold. Instead, we have used the criterion of uniqueness to define an alarm (HABERMANN, 1981a,b; WYSS and BURFORD, 1987; WYSS and HABERMANN, 1988). The empirical determination of the significance level at which alarms should be issued remains as one of the important tasks in developing the quiescence method as an earthquake prediction tool.

To evaluate the false alarm rate, we have searched systematically for periods of quiescence with $z$-values exceeding the target $z$-value (e.g., HABERMANN, 1981a,b; WYSS *et al.*, 1984; WYSS and BURFORD, 1985; WYSS and HABERMANN, 1988). The search was usually conducted in a seismic zone about ten times longer than the target volume (the source volume of the mainshock). The searched zone was divided into abutting volumes equal in dimensions to the target volume, and originating at random coordinates. In addition, a second set of volumes of the same size, but overlapping 50% of adjacent volumes of the first set, was searched. In all of these volumes the mean rate within a moving time window of the anomaly length was compared to the background rate by the $z$-test. The resulting $z$-values can then be compared to the target $z$-value (e.g., WYSS and BURFORD, 1987; WYSS and HABERMANN, 1988). If the target $z$-value is larger than all others, then the anomaly can be recognized without generating false alarms. If the $z$-values in one window, or in a group of consecutive windows in one volume, exceeds the target $z$-value, then we have found one false alarm.

We have not yet defined false alarms as a function of threshold. In the method we used to search systematically for false alarms we defined the threshold as the $z$-value of the suspected precursory anomaly. That is, we had a particular precursory quiescence at hand and wished to know whether the significance of this precursor was topped by other quiescences not followed by mainshocks. If this was not the case, we concluded that the precursor can be recognized without generating a false alarm.

The areas in which we have searched for false alarms included the Aleutians (HABERMANN, 1981a), the Tonga-Kermadec (WYSS *et al.*, 1984), the central San Andreas fault (WYSS and BURFORD, 1985; WYSS and HABERMANN, 1988), the Kaoiki-Hilea area (WYSS, 1986), and the Calaveras fault (HABERMANN and WYSS, 1984b). In these areas we did not find any false alarms, except for the Aleutians, where we found three, and for the central San Andreas fault where WYSS and BURFORD (1985) generated one false alarm (WYSS and BURFORD, 1987). Based on this limited experience we have found more precursory quiescences in the areas investigated (Table 1) than false alarms. Nevertheless, we propose that one should expect a false alarm rate of about 50% with the definition we used.

## *Characteristics of Seismic Quiescence*

The cases of precursory quiescence which we selected, based on our criteria outlined above, are summarized in Table 1. Their characteristics are discussed below.

*The amount of rate decrease* is larger than 40% and can reach 90% (Table 1). Therefore periods of seismic quiescence are often very obvious and resilient to different approaches, or even errors in analysis. In four cases, enough events were reported so that it was possible to measure rate changes separately in subregions of the rupture volumes (cases no. 4, 9, 11, 16 in Table 1). Strong spatial variations in the amount of rate decrease occurred in all of these cases. In three of them the rupture initiation points were located in volumes of little or no change, surrounded by volumes of substantial rate decreases (WYSS *et al.*, 1981a; Figure 9 in WYSS, 1986; WYSS and HABERMANN, 1988). We have interpreted this observation as indicating heterogeneous stress (strength) distribution in the source volume, with major asperities in which the mainshocks nucleate showing no quiescence (WYSS *et al.*, 1981b).

*The variance of the mean rate* during the anomalous time is remarkably low in most cases. This is especially clear in those examples with large numbers of earthquakes (e.g., Figures 4 and 8 in WYSS, 1986; Figures 2 and 4 in KISSLINGER, 1988). This constant rate of earthquake generation during the precursor time supports our interpretation that the anomalies reflect a change of process in the rupture zone. First, some process produces events at a constant background rate, then a change takes place and events are produced again at a constant but reduced rate.

*The spatial extent* of the quiescence anomalies is usually not well defined. In teleseismic data the earthquake density per volume is too low to allow sharp definition of the edges. In some of the local data sets not enough earthquakes occur beyond the end of the main rupture. In most data sets the anomaly extent seems to approximately equal the source volume. In few cases, it appears that the quiescence volume may be larger than the source volume (e.g., nos. 3 and 8 in Table 1; Figure 2 in OHTAKE *et al.*, 1981; and Figure 5 in WYSS *et al.*, 1984, respectively). In cases where the seismicity rate was high enough to allow separate analysis of subvolumes of the source, the volume of quiescence was found to be smaller than the total source volume (WYSS *et al.*, 1981b; WYSS, 1986; WYSS and HABERMANN, 1988). Thus, if a quiescence anomaly is defined in real time and an alarm is issued, one has no reasonable alternative but to assume that the future rupture length will equal approximately the length of the quiescence. WYSS and BURFORD (1985, 1987) were successful with this assumption, and KISSLINGER *et al.* (1985) would have come closer to estimating the magnitude and source area of the May 7, 1986 Andreanof islands earthquake correctly if they had made the same assumption.

*The onset time* of quiescence is defined sharply in most cases. The data sets with the most numerous earthquakes again demonstrate this most clearly (e.g., Figures 4, 5 and 8 in WYSS (1986); Figures 2 and 4 in KISSLINGER (1987); Figures 6 and 10 in WYSS and BURFORD (1985); Figure 5a in WYSS and HABERMANN (1988)). In some of the cases, where subvolumes of the source were analyzed separately, it seems that quiescence appears at somewhat different times in the different subvolumes (WYSS, 1986; KISSLINGER, 1987). However, with so few examples available, one cannot discern a pattern yet for the spatial distribution of onset time.

*The duration of quiescence* is well defined because the onset time is sharp. In those cases where the quiet period is separated from the mainshock by renewed activity, we will use the entire precursor time, from onset of quiescence to mainshock, in the following discussion. The durations of quiescence reported (Table 1) range from slightly over one to 6.3 years. These limits may be imposed artificially by the data. Because high quality catalogs cover 10 to 20 years only, it may not be possible to define quiescence anomalies of 10 years, even if they existed. The short duration cutoff for anomalies is a function of the reporting rate and the variance from the mean rate. If the reporting rate is very high and has a low variance, then short periods of anomalous rate may be defined. In our experience, the shortest periods for which quiescence can be defined by the data we have used, without generating false alarms, is approximately one year (e.g. WYSS and HABERMANN, 1988).

*The magnitude band* in which the quiescence occurs seems to include all magnitudes. When only larger background events are used, the rate decrease tends to be less significant, according to statistical tests. This is because fewer events are available to define the rate, and hence the variance is large. When all events above $M_{\min}$ are included, we find that the significance of the anomaly is stronger, because the variance of the background is smaller.

*The false alarm rate* is not a simple constant, but it depends on the threshold set to call alarms, and this threshold, in turn, depends on the consumer (KAGAN and KNOPOFF, 1987). Scientists who wish to test a hypothesis in real time may be able to tolerate a relatively high rate of false alarms compared to government officials, or the public. For this reason we should define the false alarm rate as a function of the alarm threshold. The consumer could then make his own choice of threshold acceptable for the purpose at hand. Clearly the threshold for deciding that an observed seismicity rate decrease should be interpreted as a precursor (alarm) is to be determined empirically. The significance of a rate decrease has to be measured by a well-defined statistical scheme. The level at which to declare the alarm, however, will not follow from statistical considerations, instead it will be determined by the earthquake generating process in the study area, and by the consumers ability to tolerate false alarms. With our definition we find less than 50% false alarms (see discussion above).

*Failures to predict* are defined as occurrences of mainshocks without precursory quiescence. A few such cases have been found in the same areas where successes were also reported (HABERMANN, 1981b; WYSS *et al.*, 1984; WYSS, 1986; WYSS and BURFORD, 1987). Dividing the number of failures by that of successes in the same areas one arrives at approximately 50% as the average failure rate. Again, this value is likely to change as more information becomes available, and it may also be a function of tectonic setting.

## *Mechanism of Quiescence*

There is not enough evidence available to discriminate between possible mechanisms which may cause quiescence. As it is most important at this point to learn more about the phenomenon, we have de-emphasized speculations about the mechanism. Below we will briefly outline three obvious possibilities which may cause quiescence in different tectonic environments.

*Slip softening* may lead to a lowering of the ambient stress in the source volume, and hence every asperity which was near rupture stress, and which would have ruptured in the next unit of time, has a lower probability of rupture after the volume has passed through peak stress. Geodetic observations from the south coast of Hawaii support this model. In the epicentral area of the Kalapana earthquake ($M_S$ = 7.2, Nov. 1975, depth = 8 km) the lengths of lines between 3 and 8 km long had been measured since the beginning of this century, and it was found that compressive strain of about $4.10^{-4}$ had accumulated by 1973. Because of this, SWANSON *et al.* (1976) suggested that a mainshock may occur in this area. During one to several years before this mainshock at least one, and probably three, of the geodetic lines lengthened (Figures 16 and 17 in WYSS *et al.*, 1981a; Figure 22 in LIPMANN *et al.*, 1985). The measured strain-drop on the longest of these line was $3.10^{-5}$ corresponding to a stress-drop of at least 20 bar.

Based on this observation, WYSS *et al.* (1981a,b) proposed that precursory creep on the near horizontal subsequent mainshock fault plain lowered the ambient stress in the crustal volume above the fault plane. The parts of the source volume in which quiescence did not occur were assumed to be asperities where fault creep did not take place. This model assumes that the earthquake population which showed quiescence is distributed in the crustal volume above the fault plane. This is likely to be the case, because most earthquakes in this area have hypocenters between 5 and 8 km depth.

*The locked fault model* may be more attractive as an explanation for the precursory quiescences observed in the creeping segment of the San Andreas fault, because creep-retardation was observed at the Lewis Ranch creep-meter (Figure 2a in BURFORD and SCHULZ, 1985). The onset of the creep-retardation and the quiescence coincided approximately, and the creep-meter was located at the northern edge of the fault-segment along which quiescence was observed before the 31 May 1986 mainshock (Figures 1 and 2 in WYSS and BURFORD, 1987). In this model we propose that by some unknown means (slip on a nearby fault could have this effect) a segment of the creeping fault is locked partially. As a consequence, the creep-rate and the seismicity rate are reduced. This model assumed that the counted earthquakes are located in a narrow fault zone, not in the crust surrounding it.

*Dilatancy hardening* is also proposed as a mechanism for quiescence (SCHOLZ, 1988). Although this could provide a means to arrest fault slip and cause quiescence as observed in Stone Canyon (WYSS and BURFORD, 1985), this mechanism is difficult to reconcile with the observation that the immediate hypocentral volume shows no quiescence tendency (WYSS *et al.*, 1981a,b; WYSS, 1986; WYSS and HABERMANN, 1988).

It is not attractive to explain the same phenomenon by different mechanisms (strain softening and locked fault model) in different locations. One would prefer a unifying explanation. However, the presently available data do suggest that different mechanisms may produce quiescence in tectonic settings where the background activity is distributed through a crustal volume, and settings where it is located in a narrow fault zone. The ideas proposed here should be refined by quantitative and specific models for case histories. The detailed comparisons of crustal deformation with seismicity data are very important, but difficult to make, because too few geodetic lines and creep meters exist.

## *Discussion and Conclusions*

Progress in learning the facts about precursory quiescence has been rather slow since its discovery almost 20 years ago (MOGI, 1969). However, recent quantitative analysis of the phenomenon (Table 1), and recent partially successful predictions based on quiescence strongly suggest that precursory quiescence has occurred and will be useful for predictions. The main task now is to establish the characteristics of this precursor, and to further refine methods by which correct predictions with a tolerable false alarm rate can be made.

The number of high quality quiescence cases is still small (Table 1), too small for instance to answer the important question of what the precursor time depends on.

The idea that precursor times may be a function of the mainshock magnitude is linked to the dilatancy diffusion model (e.g., SCHOLZ *et al.*, 1973; RIKITAKE, 1975). At the moment there is no compelling reason for which one can accept or reject that idea. The quiescence data in Table 1 come from a variety of tectonic settings, which may influence the precursor time. Plotting these data versus magnitude one finds a weak correlation (Figure 1). The two data points from the creeping segment of the San Andreas fault do not fit the trend of the other data. Their quiescence times are longer than expected for such small mainshocks. If one omits these two points, one can find the following least squares fit (minimizing $T_Q$ and units in months)

$$\log T_Q = 0.0 + 0.21\, M \tag{1}$$

with a correlation coefficient of 0.7 (dashed line in Figure 1). This relationship is close to the one proposed by SCHOLZ *et al.* (1973) for $M = 6$, but it is a factor of 6 below that relation (dotted line in Figure 1) for $M = 8$. The relationship of RIKITAKE (1975) overestimates the quiescence precursor time by an order of magnitude for $M = 8$ events. In our opinion the existing data are not sufficient to allow a decision, whether a quiescence-time versus magnitude relationship as in (1) is valid or not, and whether differences between tectonic settings exist.

Given these uncertainties, the occurrence time of a future mainshock is difficult to estimate, based on quiescence alone. We propose that the magnitude should be

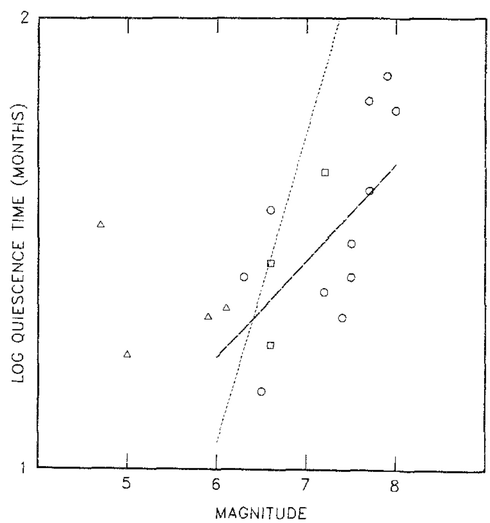


Figure 1
Logarithm of seismic quiescence duration as a function of magnitude (data from Table 1). Circles mark earthquakes from subduction zones, squares indicate intra-plate events, and triangles are data from the San Andreas fault system. The dashed line is a least squares fit through the data without the values for the two smallest events. The dotted line is the relationship proposed by SCHOLZ *et al.* (1973).

estimated from the anomaly dimensions, and the precursor duration should be estimated as the average of known quiescence precursor times in the same seismic zone, or in tectonically similar seismic zones.

The false alarm rate and the failure rate are also poorly established at this time. And more fundamentally, questions concerning the homogeneity of the most important earthquake catalogs are not answered, and probably will not be answered for some time.

Thus we find ourselves in a situation where precursory quiescence seems to be the most successful parameter for prediction of mainshocks, but the adequacy of the fundamental data sets are in question. In addition, the most important areas of earthquake hazard in the U.S., California and Alaska, have not been searched systematically for precursors, false alarms and failures. And the existing data set is so small that we cannot say what the precursor time depends on. Nevertheless, in May of 1986 two earthquakes occurred which were predicted, based on quiescence. However, the surface has hardly been scratched in the search for precursors to past mainshocks. The data base which we now have (Table 1) could probably be doubled or tripled, using existing seismic catalogs.

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