SOME CHARACTERISTICS OF FORESHOCKS AND THEIR POSSIBLE RELATIONSHIP TO EARTHQUAKE PREDICTION AND PREMONITORY SLIP ON FAULTS

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Abstract. Foreshocks occur before a large fraction of the world's major ($M \geq 7.0$) earthquakes. Teleseismically located events before major earthquakes from 1914 to 1973 were considered together to examine possible average temporal and spatial patterns of foreshock occurrence. Several days before the main shocks and apparently near the epicenters of them ($\Delta \lesssim 30$ km) the activity begins to increase, culminating in a final rapid acceleration of activity in the last day. The acceleration continues up to the time of the main shocks, except for a possible temporary decrease about 6 hours before them. The seismicity increases approximately as the inverse of time before main shock. This relationship is essentially unrelated to the magnitude of the main shock. The magnitude of the largest foreshock is also unrelated to the magnitude of the main shock. In addition, pairs of major events are common. Ten percent of the world's major events are preceded by other major events within 100 km and 3 months. For foreshocks within each of three sequences studied, the ratio of the amplitudes of the P and S waves were approximately the same, suggesting that the faulting mechanisms are the same for events in each sequence. By assuming an inhomogeneous fault plane on which asperities fail by static fatigue, we derived an equation for accelerating premonitory slip as a function of time, which agrees with the observed time dependence of foreshocks.

Introduction

When present, foreshocks are the most obvious premonitory phenomenon preceding major earthquakes. If they could be recognized as such before a main event, they would be a very useful tool in earthquake prediction because they accurately pinpoint the time and location of the forthcoming earthquake. This was demonstrated by the successful prediction of the February 4, 1975, Haicheng earthquake, wherein foreshocks played a crucial role [Raleigh et al., 1977; Wu et al., 1976; Zhu, 1976]. But even beyond their use in earthquake prediction, foreshocks are the most convincing evidence that we have of deformation of the earth before major earthquakes. Therefore an improved understanding of foreshocks may provide important information about precursory deformation. Motivated both by the possibility of using foreshocks as a short-term predictor and by the need to better understand the mechanical behavior of the nearby rocks immediately preceding major earthquakes, we studied some characteristics of foreshocks that occur in the few hours, days, and weeks before large events.

In presenting the results we first discuss the temporal and spatial distribution of seismicity prior to main shocks to define temporal patterns of short-term foreshock activity and to determine how common foreshocks are. As part of this analysis we consider the possible effects of various characteristics of the main shocks (magnitude, tectonic setting, geographical position, etc.) on these patterns. We then examine the relative magnitudes of foreshocks and main shocks and the radiation patterns of three foreshock sequences for possibly recognizable characteristics. Finally, we compare the data with a simple mathematical expression derived for accelerating premonitory fault slip.

Data

We considered foreshocks before three groups of main shocks. The first is all major ($M \geq 7.0$) shallow (depth <100 km) earthquakes in the world from 1914 to 1949 (511 events), listed by Duda [1965]. We searched for foreshocks in the Bulletins of the International Seismological Summary (ISS). The second group is all major shallow earthquakes in the world from 1950 to 1964 [Duda, 1965] and from 1965 to 1973 (250 events) [U.S. Government Printing Office, 1965-1973]. For this group, earthquakes were taken from the catalogue of world events prepared by the National Oceanic and Atmospheric Administration (NOAA) and Bulletins of the International Seismological Center (ISC). All of the locations had been computed from teleseismic data. Because of the location capability of worldwide networks, the magnitudes of essentially all of these earthquakes are greater than 4 and usually greater than 4 1/2 [Evernden, 1970, 1971]. The appendix table lists the main shocks and foreshocks from these two data sets used in the following analysis.[1]

We also searched the literature for field reports of foreshock activity before individual main shocks. Such foreshocks are also listed in the appendix, but were not used in most of

[1] Appendix table is available with entire article on microfiche. Order from American Geophysical Union, 1909 K Street, N.W., Washington, DC 20006. Document J79-005; $1.00 Payment must accompany order.

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the analysis. For some of the analysis, however, we did use a third group of main shocks, earthquakes occurring near Greece, with $M \geq 5.6$ for events between 1911 and 1965 and $M \geq 5.1$ between 1966 and 1973. Many of these events were preceded by foreshock sequences, which are listed by Papazachos et al. [1967; Papazachos, 1975a].

In some situations, two or more major earthquakes occurred very close to each other in time and space. In such cases it did not seem reasonable to call these events separate main shocks. When the events occurred within 3 months and 100 km of each other (within the most extreme limit of foreshock activity discussed below), we considered the series of events to be only one sequence. These multiple major events occurred quite frequently. Of 939 major sequences recorded since 1897, 92 included two or more events with magnitudes greater than 7.0 and occurring within 3 months of each other. Of these 92 sequences, 67 were not clear main shock-aftershock sequences in the sense that the first event was either smaller than, or no more than 0.4 units of magnitude greater than, a later event.

If the first of the large events had the largest magnitude, its origin time was naturally used as that of the main shock. If the magnitude of the first event was no more than 0.2 units of magnitude less than the later events, the series was considered to be a double event, and again the origin time of the first event was used. Only if the second event had a magnitude more than 0.2 units greater than the magnitude of the first event was the first event considered to be a foreshock. In general, the smaller events occurring between the two large events were not considered to be foreshocks, because they appeared to be aftershocks of the large foreshock. Only when we could distinguish which of the events occurring between the two large earthquakes were the aftershocks of the large foreshock and which were foreshocks of the second event were the latter used. For instance, an event with $M \sim 6.0$ occurred on March 7, 1966, 15 days before the March 22, 1966, Hsing-tai earthquake. In the day following the first earthquake there were six events listed in the NOAA catalogue, which we assume were aftershocks. Then two events occurred on March 11, one on March 19, and two more on March 22. Among these we assumed that only the main event of March 7 and those on March 19 and March 22 were foreshocks.

None of the sequences that included main events with $M \geq 7.0$ resembled swarms, as defined by Mogi [1963] and Sykes [1970]. In general, two, or at most three, events clearly were the largest, and the first of these was never preceded by the gradual increase in either frequency of occurrence or magnitude of earthquakes that characterizes swarms. Therefore of the three types of sequences described by Mogi [1963] - main shocks with foreshocks, main shocks without foreshocks, and swarms - only the first two categories seem to be represented by major earthquakes. Swarms appear to be a property only of earthquakes with magnitudes smaller than 7.

Temporal and Spatial Distribution of Foreshocks

In studying the temporal variation in foreshock occurrence a definition of foreshocks that distinguishes them from background seismicity is necessary. To obtain a crude impression of the frequency of occurrence, we first considered any earthquake a foreshock if its computed location was within 100 km and it occurred within 40 days of the main event [see Jones and Molnar, 1976]. This definition is only a starting point for the discussion, and criteria for distinguishing foreshocks from background seismicity are discussed below. One hundred kilometers was chosen because it allows inclusion of essentially all events that occurred within the rupture area of main shocks with $M \sim 7$, given the errors in the locations. All locations were taken from the sources cited above. Forty days was arbitrarily chosen because it seemed to correspond to the common usage of the term foreshock in the literature. By these criteria the percentage of main shocks preceded by foreshocks increases steadily until the present (Figure 1). This observation is almost surely a result of poorer recording capability earlier in the century. Notice also that the percentage of earthquakes with such foreshocks reported becomes nearly constant in 1950. For that reason we rely primarily on the second data set to draw inferences about foreshock activity.

In search of temporal patterns of foreshock activity, we examined the seismicity for a year before each of the main shocks that occurred after 1950 with more than two aftershocks listed in the NOAA catalogue. We assumed that if only two aftershocks were located by teleseismic data, the location capability of the network was poor. Indeed, the number of major events with only two or fewer aftershocks located teleseismically and preceded by foreshocks (as defined above) was considerably less than those with three or more aftershocks (Fig. 1). Because of the poor location capability of the network before 1950, we did not examine the entire year before the main shocks during this interval. Nor did we use the events near Greece for this analysis, because Papazachos [1975a] did not list locations of events and did not describe the seismicity for the entire year before these main shocks. Examining 1 year is obviously insufficient to determine long-term trends in seismicity, but our purpose here is to analyze only the activity a few weeks before the main shocks, not years. For this situation a year of data is enough to define a background level and to allow recognition of short-term changes in earthquake occurrence.

The events occurring during the year before the main shocks were separated into three groups by the distance between their computed locations and those of the main shocks, 30, 60, and 100 km. Since no individual sequence contained enough recorded events to define temporal and spatial patterns of occurrence, all of the sequences were combined into a single sequence. This was done by putting all of the sequences onto the same axis where the origin is the time of occurrence of each main shock. A histogram was made by plotting the total number of foreshocks occurring in each 24-hour period before the mainshocks (Figure 2).

Possible Phases of Foreshock Activity

There is a suggestion of three changes in level of seismic activity preceding major earthquakes. Close to the epicenters of the main shocks, there are a very large number of events that occur in the day immediately preceding the mainshocks. This large number of events appears to be the culmination of an increasing frequency of occurrence near the main shocks beginning several days earlier. Farther from the main shocks, there is also a suggestion of an increase in activity that starts about 3 months before the main shocks.

It is necessary to determine how representative these patterns are of all foreshock sequences. Below we consider a number of possible factors that could affect the temporal pattern of foreshock activity in Figure 2. Among these factors are various ways that background seismicity could distort the patterns and dependencies of foreshock activity on magnitudes of main shocks and on their tectonic or regional setting. We find that only the two increases in activity close to the main shocks in time and space seem to be representative of premonitory seismic activity.

Background Seismicity

Mislocation of earthquakes could contaminate the data by introducing background seismicity into the plot in Figure 2. A systematic relocation of seismicity will probably sharpen the temporal and spatial relationships to main shocks (and is in progress). A crude test of whether mislocations are introducing

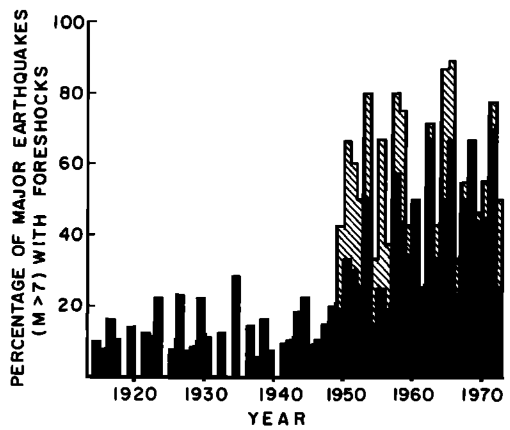

Fig. 1. Percentage of major earthquakes ($M \geq 7$) in each year from 1914 to 1973 that were preceded by recorded foreshocks. For 1950 to 1973 the hatched area is the percentage of earthquakes that had at least two aftershocks recorded by NOAA and that were preceded by foreshocks.

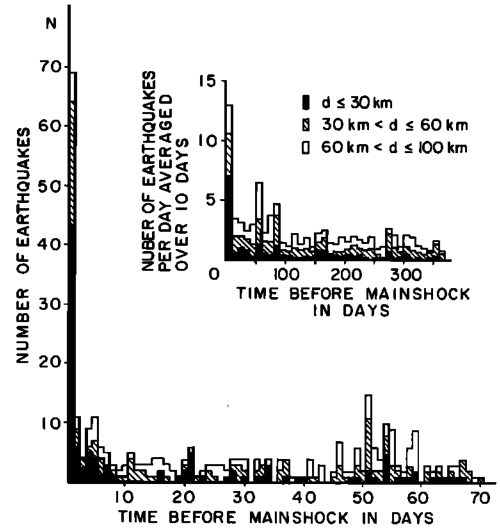

Fig. 2. Foreshock activity as a function of time before main shocks occurring between 1950 and 1973. The number of foreshocks are given separately for three different ranges of distance between the computed foreshock and main shock epicenters. Inset shows the number of foreshocks averaged over 10-day periods for a 1-year period preceding the main shocks.

spurious temporal patterns can be made by plotting a subset of the data, those earthquakes occurring after 1964, which are the more reliably located (Figure 3). The similarity between Figures 2 and 3 suggests that either poor locations do not contaminate the data or that a careful relocation of hypocenters is required to reveal a contaminating effect.

A large number of foreshocks from a few main shocks could be dominating the plots in Figures 2 and 3 so that they are not representative of average foreshock sequences. To test for this possibility, separate histograms were made for main shocks from the second data set with only one, two or three, four or five, and more than five events within 40 days of the mainshocks (Figure 4). The peak on the last day exists for all cases and clearly does not depend upon how many foreshocks occurred before any event. Although the increase in activity a few days before the main shocks is less well-defined (perhaps due in part to the smaller data base involved), it does occur before main shocks with more than one foreshock. Therefore we conclude that neither the increase in activity beginning a few days before the main shocks nor the peak in activity on the last day is due to abundant seismicity before a small number of main shocks.

The increase in activity beginning about 90 days before the main shocks, however, does seem to be due to events preceding a few main shocks. Almost half of the events occurring in the 50 to 90 day period occurred before three main shocks, two in the New Hebrides (January 23, 1972 and November 2, 1972) and one in the Aleutians (May 2, 1971). To illustrate this, Figure 5 separates the data in Figure 2 into plots of seismicity preceding main shocks in the New Hebrides and the Solomon Islands alone

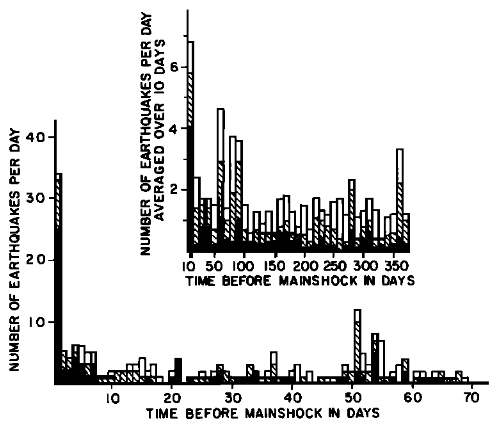

Fig. 3. Foreshock activity as a function of time before main shocks between 1964 and 1973 (procedure as in Figure 2).

and of seismicity from the rest of the world exclusive of these regions. Notice that the increase beginning about 90 days before the main shocks in Figures 2 and 3 is barely discernible when data from the New Hebrides and the Solomon Islands are excluded. Thus we conclude that the apparent increase 90 days before the main shocks is probably not a common feature of foreshock sequences.

The absence of any pronounced foreshock activity in the last few days before main shocks in the Solomon Islands (Figure 5) suggests that inclusion of the seismicity preceding these events in Figures 2 and 3 merely increases the background level of activity without clarifying the relationships between main shocks and the seismicity that precedes them. To investigate the background seismicity further, we determined how many events were preceded by earthquakes in three arbitrary 10 and 40 day periods well before the times of the main shocks (Table 1). For this we used the 161 major earthquakes occurring between 1950 and 1973 with more than two reported aftershocks. Seismicity occurred within 100 km of about 25% of the main shocks in the 40-day intervals, but it occurred within 30 km of only about 6% of them. For 10-day periods the percentages were closer to 2%. Therefore the increase in activity in the several days before the main shocks is clearly not strongly influenced by background activity.

Perhaps more important for this analysis was the recognition that the background seismicity was much higher in active subduction zones than elsewhere (Table 1). To illustrate this, Figure 6 shows a plot like those in Figures 2 and 3 but for earthquakes in nonsubduction zones. Of the 41 events in nonsubduction zones, 21 were preceded by seismicity in the 40 days preceding them, and 20 were preceded by foreshocks within 30 km of the mainshocks in the last 10 days. (These numbers, but not the data in Figure 6, include foreshocks reported in the literature but not located teleseismically.) Note that the background activity preceding mainshocks in nonsubduction zone regions is low and the increase in activity within 30 km of the main shocks begins several days before them.

This approximately 10 day initiation of foreshock activity may also occur for subduction zones, despite the contamination by background seismicity. As described above, the activity in the New Hebrides seemed to contribute to a spurious apparent increase about 90 days before the main shock. The plot of all the data, except for events from the New Hebrides and from the Solomon Islands, for which there does not seem to have been foreshock activity (Figure 5c), reveals an increase in activity relatively close to them (computed location, less than 30 km), beginning about 10 days before the main shock. For this distance range the activity in the last 10 days is clearly more pronounced than that in preceding periods of the same duration. Better locations can probably enhance this pattern.

Effects of Tectonic and Regional Setting

We were unable to detect any clear dependence of the temporal pattern of foreshock activity on the tectonic setting of the main shocks. At the same time our limited data set might be inadequate to reveal such a dependence. The greater percentage of events in nonsubduction zones with seismicity 10 days before them than for those in subduction zones may indicate that the occurrence of foreshock activity is dependent upon the tectonic setting. The data at present, however, are probably insufficient to explore this possibility further.

Similarly, the data are probably inadequate to reveal a regional difference in the temporal patterns of foreshock activity. Although the increase beginning several days before main shocks is absent in the New Hebrides and the sharp increase on the last day is absent in the Solomon Islands (Figure 5), we do not think that these data are sufficient to show that

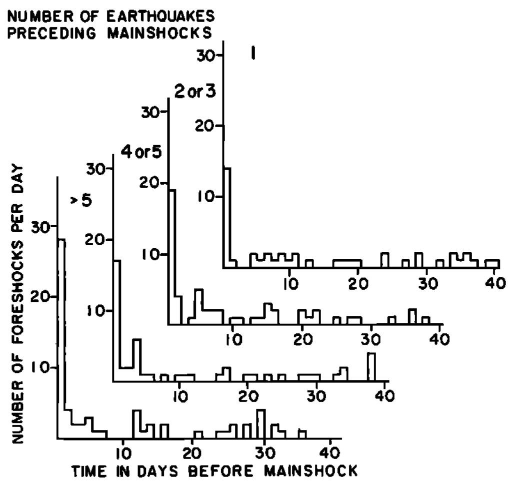

Fig. 4. Number of foreshocks per day as a function of number of the foreshocks recorded for different earthquakes. Separate plots are shown for foreshock sequences consisting of only 1 event, 2 or 3, 3 or 4, or greater than 5 events. Note that the increase about 5 days before the main shocks and the peak on the last day do not depend upon how many foreshocks preceded each event.

regional differences in the temporal patterns exist. There may be regional differences in the frequency of occurrence of foreshocks. The apparent absence of foreshocks in the Solomon Islands may be one example. Moreover, foreshocks seem to be common in several regions and not in others [see Jones and Molnar, 1976, Figure 2], but once again we do not think that these data are sufficient to demonstrate regional variations in the frequency of occurrence.

Dependence on Magnitude of the Main Shock

A dependence of foreshock activity on magnitude also might affect the reliability of the patterns in Figure 2. To examine this possibility, sequences were plotted separately for main shocks with M < 7.0 (Greek events only), 7.0 ≤ M < 7.8, and M ≥ 7.8 (Figures 7a-7c). The time dependences of these three sequences are very similar to each other and also to that of the combined sequence (Figure 7d). All of the sequences show the same pattern of seismicity - an increase in activity a few days before the main events, culminating in a prominent maximum on the day before the main shocks.

The data in Figure 7 were fitted to both exponential and power law functions by linear regression. Unlike the data of Pho et al. [1976], exponential functions fit poorly and are probably not a good representation of the physical processes involved. The data fit much better to power law equations. The combined data showed that foreshock activity is proportional to time raised to the minus one power, which agrees with the findings of Kagan and Knopoff [1978] and Papazachos [1974a,b, 1975b]. Although the calculated exponent is more negative for main shocks with larger magnitudes, the difference is slight and probably negligible.

In reference to very short term premonitory seismicity a plot by hour of foreshock activity in the last few days shows that the frequency of occurrence continues to increase toward the time of the mainshocks (Figure 8). This average pattern continues except for a lull in activity 5-8 hours before the main shocks. This peak is defined by foreshocks before 18 events, not by just a few main shocks. This peak followed by a lull is of interest because Chinese seismologists reported a drop in foreshock activity 4-8 hours before both the 1973 Haicheng and the 1966 Hsing-tai earthquakes [Wu et al., 1976].

Summary of Time Dependences of Foreshock Activity and Frequency of Occurrence of Foreshocks

The data presented in Figures 2-8 suggest several different possible definitions of foreshocks. The data in Figure 2 suggest three possible phases in activity beginning about 90 days, a few days (5-10), and on the last day before the main shocks. Although many main shocks are preceded by seismicity 90 days or less before them (Table 2), the apparent abrupt increase at that time appears to be due to swarms of events preceding three main shocks and possibly not related to them (Figure 5). Therefore we do not think that the increase at 90 days is representative of foreshock sequences. The increase a few days

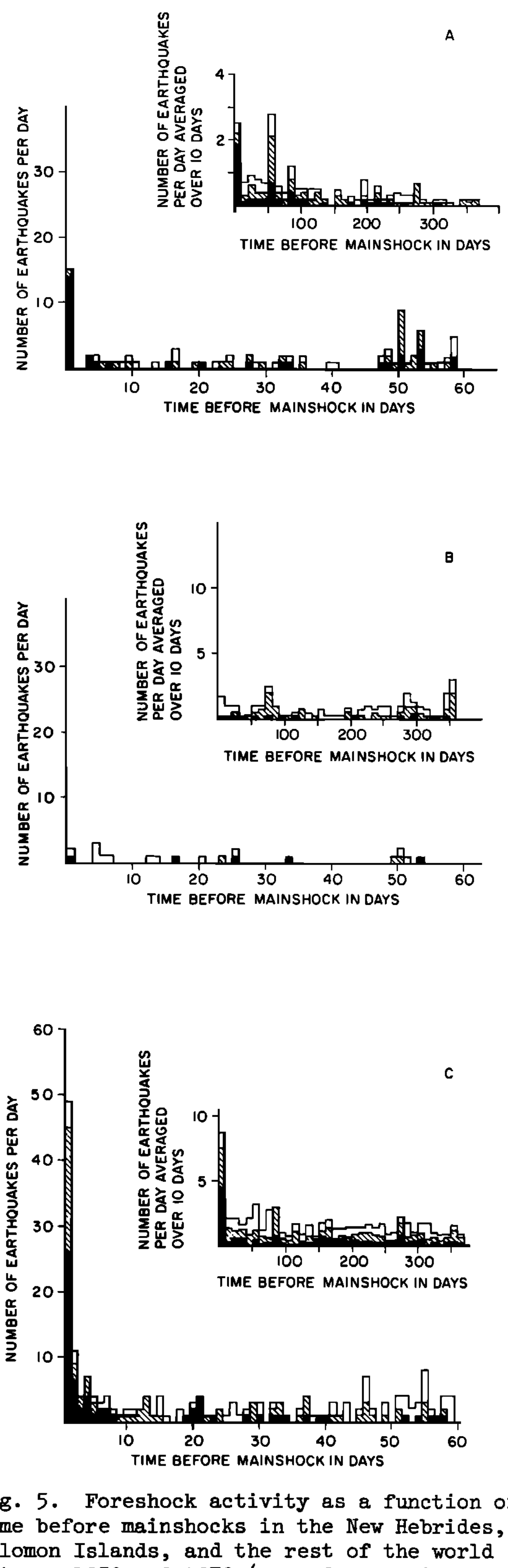

Fig. 5. Foreshock activity as a function of time before mainshocks in the New Hebrides, Solomon Islands, and the rest of the world between 1950 and 1973 (procedure as in Figure 2).

TABLE 1. Background Seismicity

Distance	Time Interval, days	Main Shocks					
		All	Nonsubduction	Subduction			
				All	Without New Hebrides and Solomon Islands*	New Hebrides	Solomon Islands
			40-Day Periods				
30km	101-140†	6	0	9	7	17	11
	118-220	7	0	10	10	11	11
	281-320	5	0	7	5	6	22
	average	6	0	8	7	11	15
60km	101-140	16	2	20	15	44	22
	181-220	16	2	21	21	22	22
	281-320	16	0	21	17	28	44
	average	16	2	21	18	31	30
100km	101-140	24	7	29	23	61	33
	181-220	27	5	34	33	44	33
	281-320	28	5	36	33	44	56
	average	26	6	33	29	50	41
			10-Day Periods				
30km	111-120	1	0	2	1	0	11
	201-210	2	0	3	3	0	11
	291-300	2	0	3	3	0	11
	average	2	0	3	3	0	11
60km	111-120	6	2	7	4	17	22
	201-210	6	2	7	7	6	11
	291-300	5	0	7	7	0	22
	average	6	2	7	6	7	19
100km	111-120	9	5	11	4	39	22
	201-110	8	2	10	10	11	11
	291-300	9	0	12	12	6	22
	average	9	2	11	9	19	19

Values are percentages of main-shocks with more than two aftershocks occurring between 1950 and 1973 preceded by earthquakes in arbitrary time intervals before the main-shocks and at different calculated distances from them.

*Main-shocks occurring on subduction zones except those in New Hebrides or the Solomon Islands.

†For example, 101-140 days before the main-shocks.

before the main shocks is more distinct and is especially clear for main shocks in non-subduction zones (Figure 6). There is no apparent dependence of these temporal patterns on the magnitudes of the main shocks or on the regional or tectonic settings of them.

Table 2 summarizes the frequency of occurrence of seismicity preceding mainshocks in different time intervals and at different computed distances from them. It is intended to summarize the range of possible definitions of foreshocks and background seismicity. Regardless of the definition, foreshocks are not a rare occurrence. Moreover, many events are preceded by foreshocks that are not located teleseismically and therefore not included in Figures 1-8. The 1966 Congo [Lahr and Pomeroy, 1970], the 1915 Pleasant Valley (R. E. Wallace, personal communication, 1978), the 1952 Kern County and the 1954 Dixie Valley - Fairview Peak earthquakes [Richter, 1958] were all preceded by foreshocks not located with teleseismic data. There probably are many other major events with foreshocks too small to be located. It is noteworthy that none of the more than 500 foreshocks of the 1975 Haicheng earthquake [Wu et al., 1976] were located teleseismically. It is almost certain that there have been other foreshocks about which we could not find any information.

Relative Magnitudes of Foreshocks and Main Shocks

The time dependence of foreshock activity does not appear to be sensitive to the magnitude

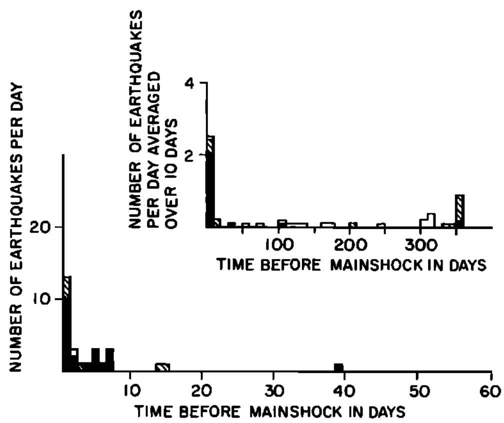

Fig. 6. Foreshock activity as a function of time before main shocks in nonsubduction zone regions between 1950-1975 (procedure as in Figure 2).

of the main shocks (Figure 7). If foreshocks are to be used for earthquake prediction, some other characteristic must be used to estimate the magnitude of the main shock. Papazachos [1974a, 1975b] and Wu et al., [1976] suggested that in spite of a great deal of scatter there is a linear relationship between the magnitudes of main shocks and those of their largest foreshocks. Figure 9 explores this possibility using all of the data available to us. Even allowing for an error of 0.5 units in magnitude, we can see no relationship between the magnitudes of main shock and largest foreshock. The only limits on the distribution of the magnitudes of the largest foreshocks appear to be that a foreshock be smaller than its main shock and large enough to be located. We suspect that the crude relations in the data of Papazachos and Wu et al. are the result only of the limited magnitude range of their data. We thus conclude that foreshocks cannot be used to predict reliably the magnitude of an

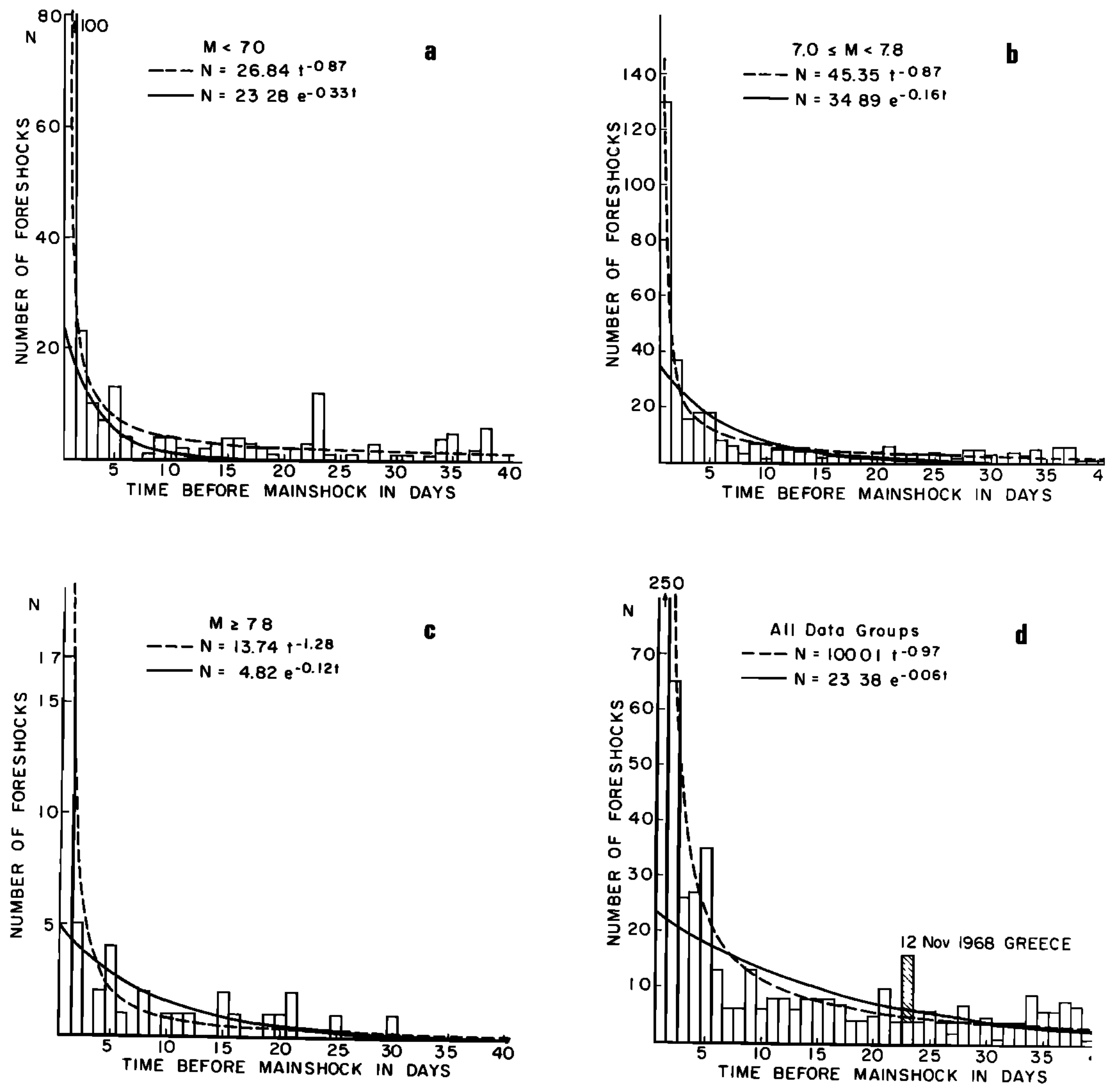

Fig. 7. Foreshock activity (a-c) as a function of time before main shocks of different magnitudes and (d) for all main shocks from all three data sets. Also shown are the exponential (solid line) and power law (dotted line) equations that best fit these data. Note that the temporal variation does not depend upon the magnitude of the main shock.

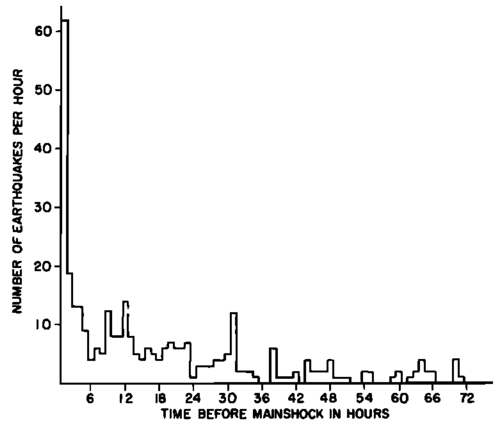

Fig. 8. Foreshock activity as a function of time before main shocks for the 3 days before the main shocks.

impending earthquake. This lack of correlation can be interpreted to mean that neither the area that slips nor the amount of slip during foreshocks is a constant fraction of the fault area or displacement caused by the main shock.

Amplitude Ratios of P and S Waves

From Foreshocks

Jin et al. [1976] suggested that the fault plane solutions of foreshocks are similar and that this aspect would be diagnostic of them. Because most foreshocks are too small for determination of a fault plane solution, they suggested that the similarity could be examined by comparing the amplitudes of P and S waves recorded at one station. The ratio of these amplitudes depends upon three factors - the propagation path, the fault plane solution, and the position of the station with respect to the fault plane. If the amplitudes are measured at only one station and the foreshock hypocenters are very close to each other, the amplitude ratios will depend only on the fault plane solution. Jin et al. [1976] found that the foreshocks of the 1975 Haicheng earthquake did have very similar amplitude ratios. Lindh et al. [1978] observed essentially the same pattern for three foreshock sequences that they studied (see also Bolt et al. [1977]), but Engdahl and Kisslinger [1977] did not for foreshocks preceding an Aleutian event by a few weeks.

We studied three main shocks with many foreshocks, the only ones that have occurred since the World Wide Standardized Seismograph Network (WWSSN) was installed and that occurred sufficiently close to a WWSSN station to be well recorded. Records from the station at Baguio (BAG) were used for the August 1, 1968, earthquake in the Philippines [Su, 1969], and records from the station at Athens University (ATU) were used for the December 5, 1968, earthquake near Greece and the March 28, 1969, earthquake in western Turkey [Papazachos, 1975a]. In all cases the events preceding the main shocks are too small to be located reliably. They are brought to be foreshocks from their approximate locations determined from recordings at a single station. Their times of occurrence and P and S wave amplitudes are listed in Table 3. The maximum amplitudes of the P and S waves, plotted versus one another for the three sequences in Figures 10,

TABLE 2. Foreshock Activity

			1950–1973						
				Aftershocks > Magnitude 2					
						Subduction			
Distance From Main Shock, km	Time Before Main Shock, days	1914–1949 (511)	All (250)	All (161)	Non Subduction (41)	All (120)	Without New Hebrides and Solomon Islands (93)	New Hebrides (18)	Solomon Islands (9)
100	40	11.3	42.2	50.3	36.6	55.0	48.4	77.8	77.8
60	15	9.6	21.2	29.9	34.1	26.7	24.7	44.4	11.1
30*	10	9.4	15.6	24.8	29.3	20.0	17.2	38.9	11.1
30†	10†			28.6	48.3	21.7	19.4	38.9	11.1

Values are percentages of main shocks in different regions preceded by premonitory seismicity within different time intervals and calculated distances of the main shocks. Numbers in parentheses after the headings are the number of main shocks.

*There are also two main shocks not appearing in these percentages that occurred before 1964 in non subduction regions and three others in subduction zones that are preceded by events occurring within 10 days of the main shocks but located between 30 and 60 km from them. As these earthquakes are in remote regions (such as Tibet and the South Pacific), it is likely that they are mislocated and are actually closer to their main shocks.

†Including written reports.

11, and 12, define straight lines passing through the origin. In fact, not only are the amplitude ratios the same, but in general the shapes of the signals are remarkably similar. The only points that deviate from the lines in Figures 10, 11, and 12 are those for a few foreshocks occurring more than 3 weeks before the earthquake in Greece. All of the other foreshocks occur within 4 days of the main shocks.

Although not proof, these data are consistent with identical fault plane solutions for the foreshocks occurring within about 4 days of their main shocks. The different amplitude ratios of the earlier foreshocks of the event in Greece could be due either to differing fault plane solutions or different locations, as Engdahl and Kisslinger [1977] report for the Aleutian event.

Discussion

One purpose of this study is to consider possible implications of foreshock activity for precursory deformation. We think that characteristics of foreshocks mentioned here are suggestive of accelerating precursory fault slip. Foreshocks, being earthquakes, definitely represent slip somewhere; the close proximity of the events to one another and identical amplitude ratios (for the few events that we could study) suggest that in general, the slip takes place on the same plane for each. We presume that this plane is the one that ruptures during the main shock, although the data of Bolt et al. [1977] and Engdahl and Kisslinger [1977] suggest that this may not always be the case. The temporal distribution implies that wherever the slip is, it is accelerating. The lack of a correlation between the magnitudes of the main shock and foreshocks suggests that the area that slips during the foreshocks is not a constant fraction of the rupture area of the main shock. The foreshocks probably involve slip only in the vicinity of the main shock hypocenters, where the main shocks are triggered. To illustrate how accelerating premonitory fault slip can explain these properties of foreshocks, we derive a simple expression for the development of an instability to compare with these data. Although the particular instability that we discuss was motivated by the observed characteristics of foreshocks, we do not claim that the data prove that it is an accurate description of what actually occurs.

Assume that the fault plane is held in place at a number of asperities. This could also represent a plane of inhomogeneous stress where the points of highest stress are modeled by asperities. During the short time period involved (a few months or less) the tectonic stress acting on the whole fault plane can be assumed to be constant. If A_0 is the rupture area, A_u is the portion of A_0 that has not yet slipped, σ_0 is the tectonic shear stress, and σ is the average shear stress acting on the unslipped portion, these assumptions can be expressed as

$$A_0\sigma_0 = A_u\sigma \tag{1}$$

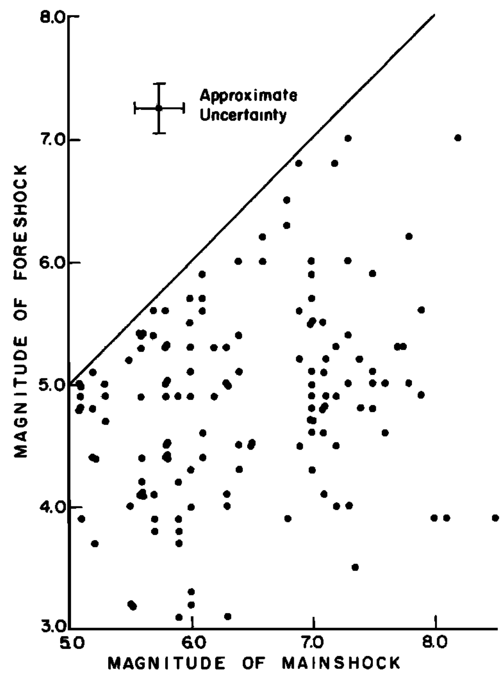

Fig. 9. The magnitudes of the largest foreshocks as a function of the magnitude of their main shocks. No pattern is obviously discernible. This is the only figure in which data from written reports of foreshock activity are used.

The number of asperities, N, can be related to A_u by

$$A_u = N\bar{A} \tag{2}$$

where $\bar{A}$ is the average area of an asperity. As slip occurs on some segments of the fault (rupture of some asperities), the stress on the remaining unslipped segments will increase, and the increased stress will increase the probability of further slip on the remaining asperities. Eventually, the rate of failure of asperities increases rapidly, causing an instability. With some additional, simple assumptions we can derive a differential equation relating the change in unslipped area to time.

Presumably, the lifetime of an asperity depends upon the stress acting on it. For instance, in the static fatigue of quartz in uniaxial compression, Scholz [1972] showed that such a dependence could be expressed in terms of the mean time before failure

$$\langle t \rangle = T \exp(-k\sigma) \tag{3}$$

where σ is the differential stress and T and k are constants that can be determined experimentally [see Scholz and Martin, 1971]. T is a time constant that depends upon the fluid pressure in the rock. Scholz [1972] did not evaluate T, and it is difficult to calculate it for conditions in the earth. Scholz did evaluate k, which is a measure of the rock strength. We assume that the lifetime of asperities on a fault obeys an equation like (3).

TABLE 3. Maximum Amplitudes of Events Preceding Major Earthquakes

Date	Time, UT	Vertical P	Vertical S	North P	North S	East P	East S
			Earthquakes Preceding the August 1, 1968, Event in the Philippines				
Aug. 1, 1968	2013	18	(70)	15	(70)	...	...
	2008	3	18	3	15	5	17
	2000	8	38	6	33	9	...
	1858	5	30	4.5	28	6	...
	1823	(25)	(70)	24	...	...	...
	1716	2	13	2	10	3	(15)
	1638	3	18	3	15	4	35
	1117	5	30	10	55	...	...
			Earthquakes Preceding the December 5, 1968, Event in Greece				
Dec. 4, 1968	2048	2.5	6	2	7	2.5	6
	2030	6	24	6	22	7.5	18
	2011	5	16	5	20	6	15
	1937	40	(75)	(24)	(100)	(40)	(86)
	1852	20	(48)	(14)	(60)	20	50
	1842	7	22	6	25	10	22
Nov. 26, 1968	0430	15	(120)	13	...	21	53
Nov. 13, 1968	1748	12	40	10	38	20	70
Nov. 12, 1968	2309	(2)	15	2	10	5	10
	0652	(3)	30	(4)	36	28	52
	0609	(52)	(100)	(30)	(84)	(30)	(76)
	0401	8	50	8	(30)	10	38
	0342	15	42	9	(40)	19	(60)
	0120	2	11	2	8	4	9
	0117	2	20	2	16	3	18
Nov. 3, 1968	1408	4	20	2	10	3	10
			Earthquakes Preceding the March 28, 1969, Event in Turkey				
March 27, 1969	1807	4	6			3	6
March 26, 1969	0900	2	3			2	4
	0331	7	12			7	14
March 25, 1969	1613	10	25			15	31
	1440	4	10			5	14
	1419	16	30			16	37
March 24, 1969	1213	6	13			7	16
	1135	6	24			6	14
	0813	9	21			8	20
	0259	3	6			3	7
March 23, 1969	0351	5	8			4	9
	0016	5	9			4	9

Amplitude recorded on short-period instruments are given in millimeters (accuracy, ±10%). Parentheses around a number indicate that the wave trace was too faint to allow accurate readings.

If static fatigue is a random process, then for a given stress we might expect that the number of asperities that break per unit time will be proportional to the number of unbroken asperities. Therefore

$$\frac{dN}{dt} = -\frac{N}{t_o}$$

where t_o is the average lifetime of an asperity. If t_o = <t> defined in (3), then

$$\frac{dN}{dt} = -\frac{N}{T\exp(-k\sigma)}$$

Combining this equation with (2) to express this failure rate in terms of area, we have

$$\frac{dA_u}{dt} = -\frac{1}{T} A_u \exp(k\sigma) \tag{4}$$

Using (1) and introducing a dimensionless variable

$$x = \frac{A_o}{A_u} = \frac{\sigma}{\sigma_o}$$

(4) becomes

$$\frac{dx}{dt} = \frac{1}{T}\exp(k\sigma_o x),$$

which can be integrated to give

$$\frac{t}{T} = \ell n(k\sigma_o x) + \sum_{n=1}^{\infty} \frac{(-k\sigma_o x)^n}{n.n!} - \frac{C}{T} \qquad (5)$$

While the tectonic stress on the fault plane remains constant, as slip occurs on some asperities, the actual stress on the locked sections of the fault increases as shown in Figure 13.

This equation can also be expressed in terms of area. In Figure 14 a nondimensional area variable, $(\frac{1}{k\sigma_o x})$ is plotted as a function of a nondimensional time, $\frac{(t+C)}{T}$. The former is related to the unslipped area A_u by

$$\frac{1}{k\sigma_o x} = \frac{1}{k\sigma_o}\frac{A_u}{A_o}$$

and to the area that has slipped, $A_s = A_o - A_u$, by $\frac{1}{k\sigma_o x} = 1 - \frac{A_s}{A_o}$

The curve in Figure 14 is applicable only for a range of values of x: $1 \leq x < \infty$, corresponding to $A_o \geq A_u \geq 0$. Notice that

$$\lim_{k\sigma_o} \quad x\to\infty \quad \frac{\ell n(k\sigma_o x)}{\sum_{n=1}^{\infty} \frac{(-k\sigma_o x)^n}{n.n!}} = -1 \qquad (6)$$

Therefore as x approaches ∞ and A_u approaches zero, t approaches -C. The choice of C arbitrarily sets the origin, or completion time of the process. The instability begins when $A_u = A_o$, or x = 1, for which

$$\frac{t}{T} = \ell n(k\sigma_o) + \sum_{n=1}^{\infty} \frac{(-k\sigma_o)^n}{n.n!} - \frac{C}{T} \qquad (7)$$

Below we set t = 0 in (5) to correspond to the time of the main shocks, so that the absolute value of t in (7) gives the duration of the instability. Because the first and second terms in (5) approach one another in magnitude as $k\sigma_o x$ approaches infinity but differ in sign, the duration of the instability is less

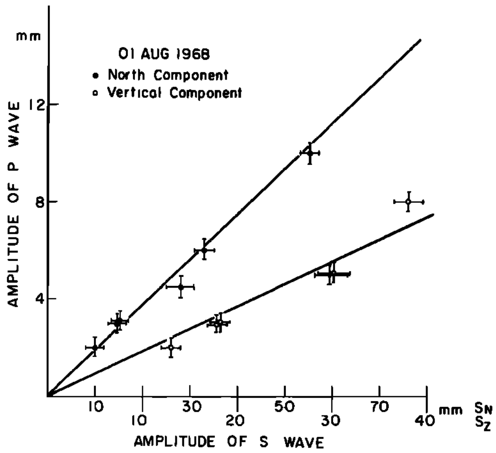

Fig. 10. The maximum amplitude of the P wave versus the maximum amplitude of the S wave of both the vertical and north-south records of the August 1, 1968, earthquake in the Philippines recorded at Baguio (BAG).

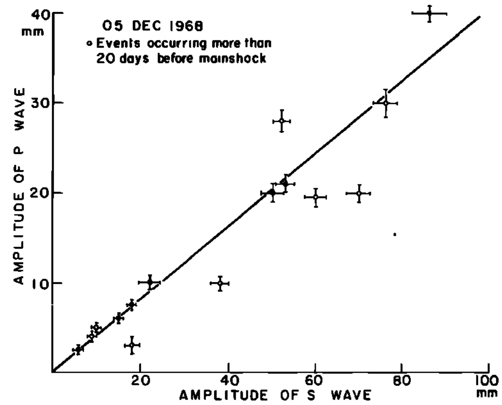

Fig. 11. The maximum amplitude of the P wave versus the maximum amplitude of the S wave of the December 5, 1968, earthquake near Greece recorded at Athens University (ATU). The solid circles are foreshocks that occurred within 4 days of the main shock, while the open circles are foreshocks occurring more than 20 days before it.

for larger values of σ_o or k (higher tectonic stress or weaker asperities) than for smaller values.

If foreshocks are a manifestation of premonitory slip and the dependence on time of premonitory slip is approximately that of foreshock activity, then the time dependence of A_s/A_o should match the cumulative plot of foreshock activity with time (Figure 14). These two curves are remarkably similar. Expressing the time scale in terms of days allows values of T = 3000 days and the constant of integration, C = 1732 days, to be assigned. This value of C corresponds with setting the time of the main shock at t = 0. Because of the dependence of T on fluid pressure, temperature, and pressure, it is probably futile to attempt to compare this estimate of T with estimates calculable from laboratory data.

One feature of the fit of (5) to the data in Figure 14 is that the main shock does not occur until almost 100% of the area has slipped. This need not mean that almost 100% of the total rupture area slips before the main shock. It appears that in a few days before the mainshock, foreshocks occur very close to the epicenter of the mainshock (Figures 2 and 7) [e.g., Kelleher and Savino, 1975; Wesson and Ellsworth, 1973; Wu et al., 1976]. Perhaps premonitory slip occurs only over a small fraction of the total area, which could be termed a triggering area. A rupture of the triggering area then propagates through to the rest of the fault plane [e.g., Brune, 1978].

The duration of the instability is related to the tectonic stress and the strength of the asperities. Using the fit of (5) to the foreshock data (Figure 14) for $k\sigma_o = 4$, the instability would begin to develop 10 days before the mainshock, but for $k\sigma_o = 1$ or 0.2 the instability would begin to develop 330 days or 2576 days (~7 years) before it. Scholz [1972] obtained a value of k = 3.7 $kbar^{-1}$ for the a axis of uniaxiality loaded single quartz

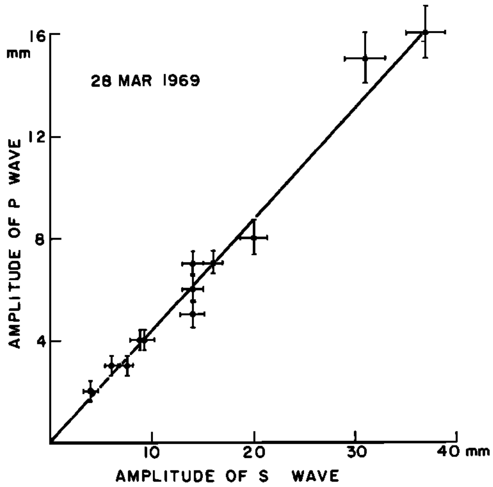

Fig. 12. The maximum amplitude of the P wave versus the maximum amplitude of the S wave of the March 28, 1969, earthquake in western Turkey recorded at Athens University (ATU).

crystals. This value of k is for the case where σ is differential stress: if σ represents shear stress as in (5), then the value of k should be doubled. Using $k = 7.4\ \mathrm{kbar}^{-1}$ in (5), we obtain estimates of the tectonic stress of 1081, 270, and 54 bars for $k\sigma_0$ = 4, 2, and 1, respectively. If the asperities were weaker than Scholz's single quartz crystals, such estimates of the tectonic stress would be lower.

Figure 14 and (5) describe a simplistic model strictly valid only for a static situation. If this sort of instability takes place, the assumptions of static fatigue and of setting $t_o = \langle t \rangle$ in (3) are probably invalid as the ruptured area grows rapidly near the time of the main shock. Nevertheless, the remarkably good fit encourages us to pursue it further.

Conclusions

Although long sequences of foreshocks are not common, small numbers of foreshocks occur before a large fraction of major earthquakes (see Table 2). We combined these short sequences, often with only one event, into one average sequence by plotting all data as a function of the time before their corresponding main shocks. Activity increases only slightly until about 5-10 days before the main shocks, when it begins to increase rapidly, apparently near the main shock epicenters. This increase culminates with a peak in activity on the last day. On the last day the activity continues to increase until the time of the main event, except for a possible slight and apparently temporary drop in activity a few hours before it. Neither the magnitudes of foreshocks nor the time dependence of foreshock activity seem to depend significantly on the magnitudes of the mainshocks. The magnitude of the largest foreshock can range from being too small to locate to nearly the magnitude of the mainshock (20% of the world's major earthquakes occur in series with at least one other major event).

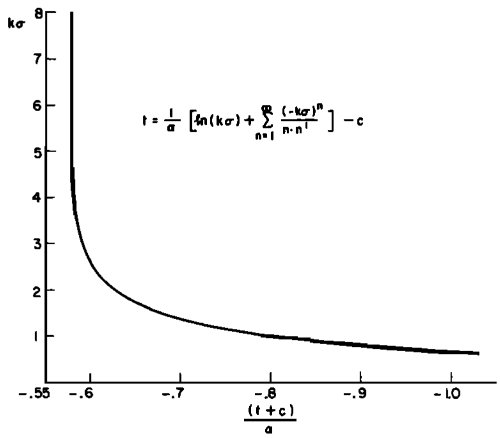

Fig. 13. A plot of (5) in terms of the nondimensional variables $k\sigma (= k\sigma_0 x)$ and $(t+C)/T$. This shows the increase of stress on the remaining area with unbroken asperities with increasing time to the left.

Judging by a few sequences studied, it seems likely that faulting mechanisms are usually the same for foreshocks within one sequence.

These findings suggest that foreshocks alone are insufficient for earthquake prediction. In many cases they will not occur at all. When they do occur, they might be recognized by their temporal distribution or, in some cases, by the similarity of their radiation patterns. Therefore they will in some cases be of use in predicting the location and time of the impending main shock, but they will not provide much information about the magnitude of the main shock.

The frequency of foreshock occurrence shows that precursory deformation does occur before many major earthquakes. Many characteristics of foreshock activity could be explained if the deformation occurs by accelerating premonitory fault slip.

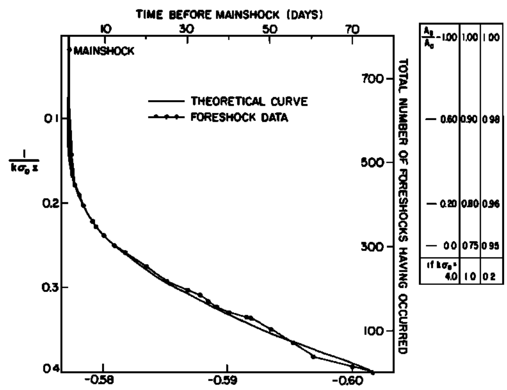

Fig. 14. A plot of (5) in terms of the nondimensional variables $1/k\sigma_0 x$ and $(t+C)/T$. Smooth curve shows the decrease of unslipped area with time. The fraction of this area that has slipped is shown at the right for three values of $k\sigma_0$. Dots connected by line segments show the total integrated number of foreshocks that have occurred up to the given time (in days) before the main shock.

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