SEISMIC GAPS : A DISCUSSION

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1. INTRODUCTION

Most large earthquakes are preceded by lulls in seismic activity which can be identified (a posteriori, at least) as seismic gaps (Kelleher, et al., 1973; McCann et al., 1979). The question as to whether these gaps are of predictive value is of some theoretical and practical interest.

The logic according to which research on seismic gaps should be conducted is still unclear. No generally accepted conceptual model has been brought to bear on the problem of earthquake prediction in general, or of seismic gaps in particular. Sir Harold Jeffreys once aptly remarked that if some precursor were strong enough to be of predictive value, "no statistics should be required to bring it out". The following discussion is presented in the same tradition of thought.

2. HISTORICAL BACKGROUND

In 1950 Benioff predicted an earthquake of magnitude 7.5 on the Indian Ocean Ridge, by extrapolating the cumultative plot of the square roots of the energy release of earthquakes in this region. The predicted earthquake occured on December 8, 1951 (Fig. 1). It led Benioff to state that "this sequence provides convincing evidence that in a given region the accumulating strain may be relieved either by a large number of small shocks or by a small number of large shocks" (Benioff, 1955). Yet no further successful predictions of this kind were documented.

Benioff had noticed that plotting the energy directly (rather than its square root) tended to exaggerate the contribution of large events at the expense of the smaller ones. The seismic moment M_0 being numerically of the same order as the energy, cumulative plots of M_0 would entail the same effect, thus oversimplifying the history of seismic strain accumulation by reducing it to a very few, very large events. Unfortunately the error in the determination

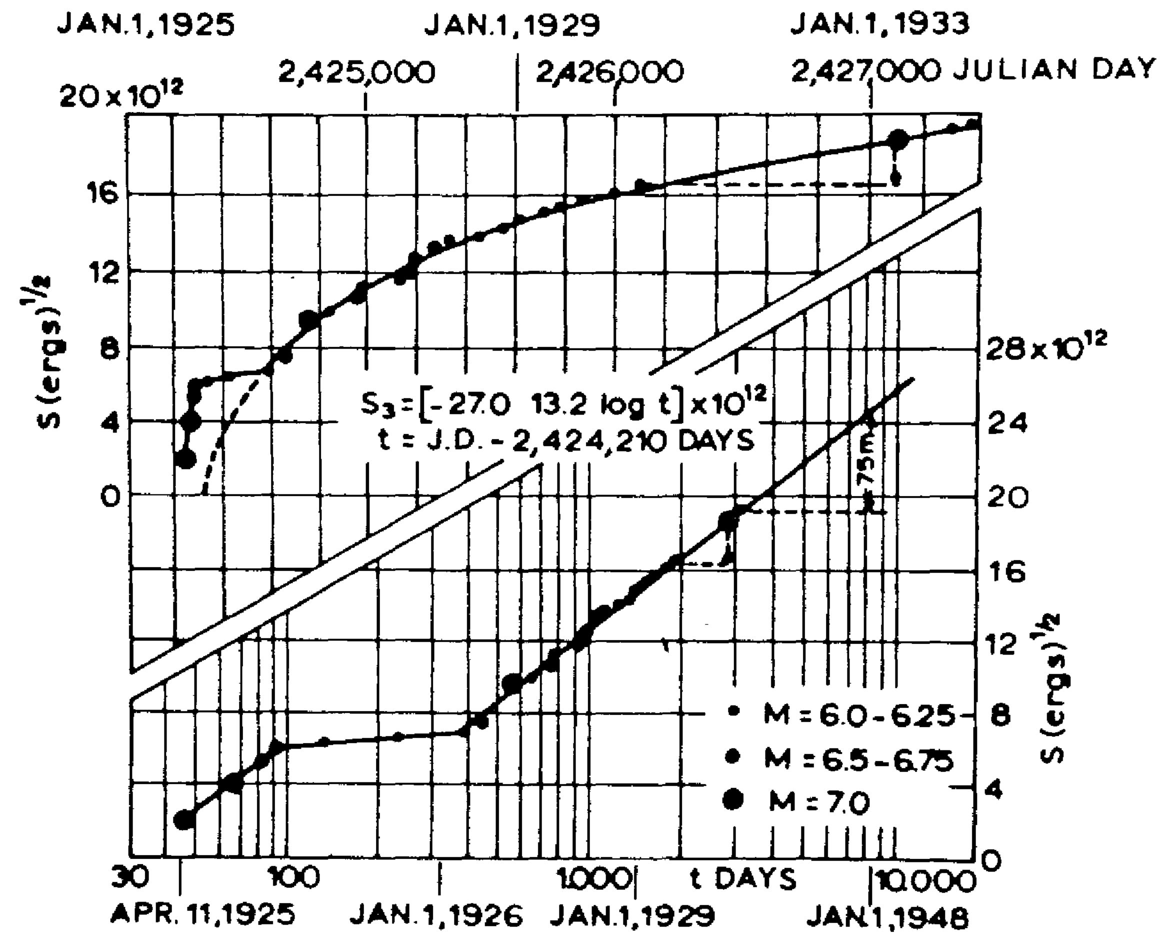


Fig. 1

Cumulative strain release for the region about 34°S, 58°E in the Indian Ocean, showing the predicted earthquake of magnitude 7.5 (after Benioff, 1951).

of M_o is also quite large, so that the extrapolation of such graphs appears to be of limited practical significance.

Benioff eventually recognized that the linear trend of cumulative plots of earthquake size (whether magnitude, energy, or square root of energy) merely indicated that the rate of energy release is roughly stationary in time. Extrapolating the mean of a process is one form of prediction ; however, Benioff's hope had been to predict the <u>times of occurence</u> of large events and this of course, proved impracticable.

With the advent of plate tectonics a further rationale for the stationarity of earthquake sequences was introduced. If the rate of plate motions stays constant over long periods of geological time, it follows that the rate of seismic strain accumulation and release at plate boundaries is also stationary. Benioff's approach has now been revived in connection with earthquake prediction (Shimazaka and Nataka, 1980).

This "new" approach to earthquake prediction is a throwback to a time when seismologists held an earthquake to be "nothing but" the result of regional strain levels reaching a deterministic threshold value (Andrew Lawson, quoted in Lomnitz, 1974, p. 45). The known complexities of the process are swept under the carpet. The prediction by Brady and Spence of a series of large earthquakes in Peru in 1981 is a typical application of this reductionist approach.

3. DEFINITION OF SEISMIC GAPS

A seismic gap is a lull in regional seismic activity which lasts over a period of months or years. Seismic gaps and large earthquakes are mutually exclusive events; hence a connection between seismic gaps and large earthquakes is implicit in the definition itself.

The question about seismic gaps and <u>small</u> earthquakes remains unresolved, however. The original definition of seismic gaps was intended to disregard minor seismicity altogether (Nishenko and McCann, 1981); in this sense, the claim of a prediction of the 1978 Oaxaca earthquake by seismic gap techniques (Ohtake, et al., 1981) is invalid, though this claim is regularly cited as a success of the seismic gap hypothesis. Any lull in minor seismic activity may be taken as relevant or irrelevant to prediction, depending on whether or not it is followed by a large shock.

In some statistically measurable sense any interval between two events can be described as a seismic gap. This tautological definition cannot have any predictive value, of course. An explicit statement of the magnitude threshold of the data must become part of the gap concept; otherwise it remains meaningless. But the magnitude is a continuous parameter : no boundary between "large" and "small" seismicity can be defined a priori. If an earthquake to be predicted is of magnitude 7.5 (as in the Oaxaca case), most seismologists will agree that shocks in the magnitude range of 4 to 5 represent "minor" seismicity. But if the 1978 Oaxaca event had been of magnitude 6 it would still have been claimed as a favorable outcome of the prediction, and in this case the activity in the range $4.0 < M < 5.0$ might no longer qualify as "minor".

4. A NULL HYPOTHESIS

A sequence of earthquakes may be represented as the realization of a point process in time. The prototype of point processes is the Poisson process, which is characterized by the fact that the intervals T between events are exponentially distributed :

$$f(T) = \lambda e^{-\lambda T} \qquad (1)$$

where λ is the rate of occurence of events per unit time.

Exponentially distributed time intervals are not equally spaced. Short intervals occur more frequently than long ones. In other words, clusters of events occur, followed by rare, long intervals. Thus some kind of gaps can already be seen in Poisson sequences. Yet the Poisson process implies perfect independence between events : the length of any interval is irrelevant in terms of predicting the time of the next event.

In every natural process which produces rare discrete events, such as the earthquake process, the Poisson model provides a reasonable first approximation to the description of the process. This is so because the interaction between widely spaced events is weak, so that the assumption of independence is reasonably well verified. True independence cannot occur in nature : it is a statistical artifact.

Deviations from the classical Poisson process occur in earthquake sequences. It appears, however, that these deviations concern chiefly the assumption of stationarity rather than the assumption of independence. In other words, the rate of occurence λ becomes nonstationary after large events. This phenomenon is known as an aftershock sequence. It we introduce a change in the time variable :

$$\tau = 1 - \frac{P}{q+(t-t_o)} \quad , \; t>t_o \tag{2}$$

where t_o is the time of occurence of the large shocks, the transformed process will again fit a simple Poisson model. (Lomnitz and Hax, 1966). Nonstationary Poisson processes are not difficult to analyse; the rate λ in eq (1) merely becomes a function of the time of occurence and the magnitude of past events. This does not improve the predictability of future events.

Thus, immediately after a major shock in a region one can predict that many more earthquakes will follow: but this prediction is regarded as trivial by seismologists. With time the rate λ slows down and approaches a quasi-stationary value; in other words, the dependence on t_o weakens to the point where the assumption of independence regains practical validity. The larger the main event the greater is the subsequent increase in λ. This accentuates the impression that "gaps" occur before major events.

If the usefulness of a predictor is related to the "degree of astonishment" at its occurence, seismic gaps are among the least promising of predictors. Elementary statistical considerations suggest that gaps should occur before every major shock, simply because the rate of occurence normally increases after major shocks. The illusion of a forward dependence between gaps and large events is a result of faulty logic in at least one simple case (Lomnitz, 1982). The question of whether seismic gaps have any predictive value cannot be decided in the abstract, however. In this paper we propose a null hypothesis against which real earthquake data can be tested.

This null hypothesis may be described as a nonstationary Poisson process with hyperbolic decay rate. The basic equations of the process have already been defined (cf. eq. 1 and 2). More specifically, the probability of occurence of an earthquake in the time interval $(t, \quad t + \Delta t)$ is given by

$$P(t, \Delta t) = \lambda + \sum_i \frac{A \exp(M_i - M_o)}{B + t - t_i} \qquad (3)$$

where t_i is the time of occurence of the i-th earthquake and M_i is the corresponding magnitude. The parameter λ is a small base probability which prevents the process from dying out.

Computer simulation of the process defined by (3) offers no special difficulties. For choices of parameters which correspond to actual earthquake data it is found that earthquakes with magnitude $M_i \quad M_o$ generate no significant aftershock sequences. Thus the sum in (3) can be practically reduced to a few significant terms. In the program which we used in the following discussion, only the events which provided the ten largest contributions to the sum in (3) were preserved for every time, t. As we shall see, the gaps generated by this process bear a significant resemblance to seismic gaps found in real data.

5. THE CASE OF THE 1978 OAXACA EARTHQUAKE

The Oaxaca earthquake of 29 November 1978 (M_s= 7.7) has been claimed as the realization of a prediction based on seismic gap techniques (Ohtake et al., 1980). A segment of the Middle America subduction zone of 270 km in length had remained quiescent from June 1973 though January, 1978. The seismic activity which resumed in the region between January and November 1978 was undistinguishable from the activity prior to 1973.

The history and social effects of a coincidental prediction on the coast of Oaxaca, made by an independent group, has been described elsewhere (Garza and Lomnitz, 1978). The actual earthquake caused no significant damage.

On the other hand, a damaging earthquake of about the same magnitude occured four months later (14 March 1979) off the Coast of Guerrero. While the area had once been identified as a seismic gap (Kelleher et al., 1973) it did not show any significant decrease of seismicity in the months or years preceding the earthquake. Figure 2, taken from Ohtake et al. (1980), documents the variations of seismicity along the Guerrero-Oaxaca coastal area.

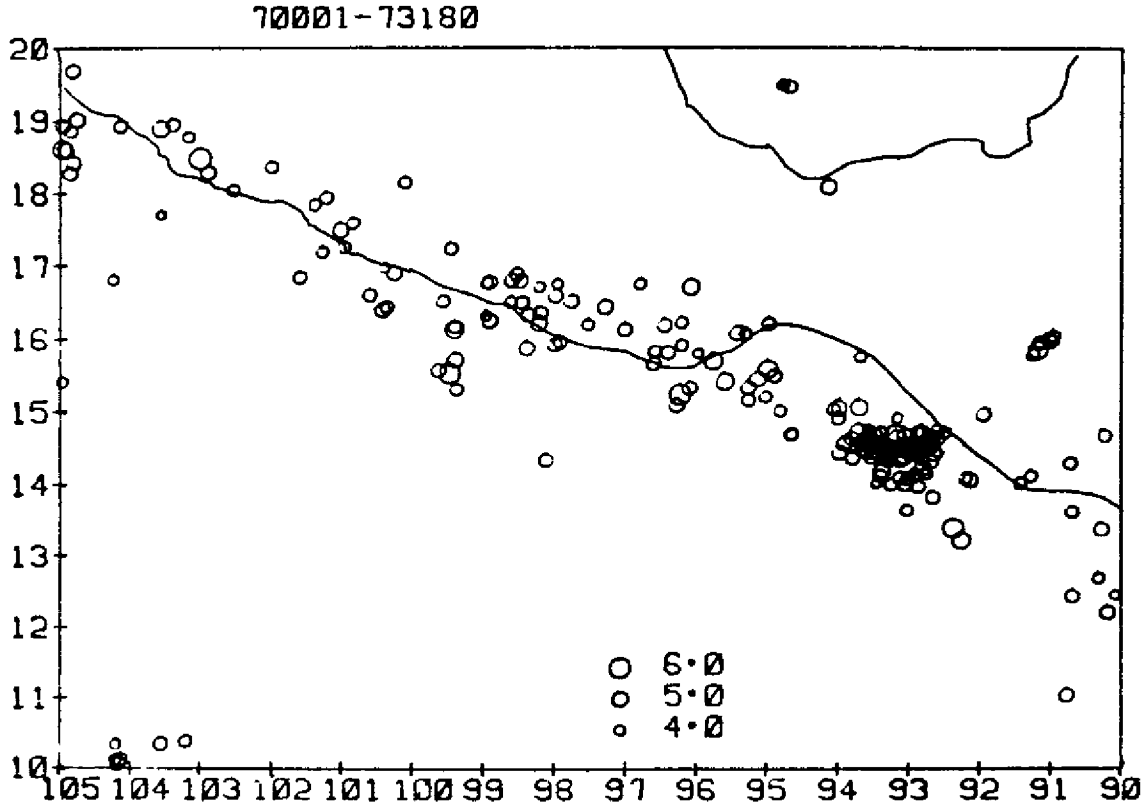


FIG. 2a: Epicentral distribution of shallow earthquakes along the coast of Mexico from January 1970 through June 1973. Data are from computer printouts by T. Matumoto. The epicentres of the 1978 and 1979 earthquakes are also shown.

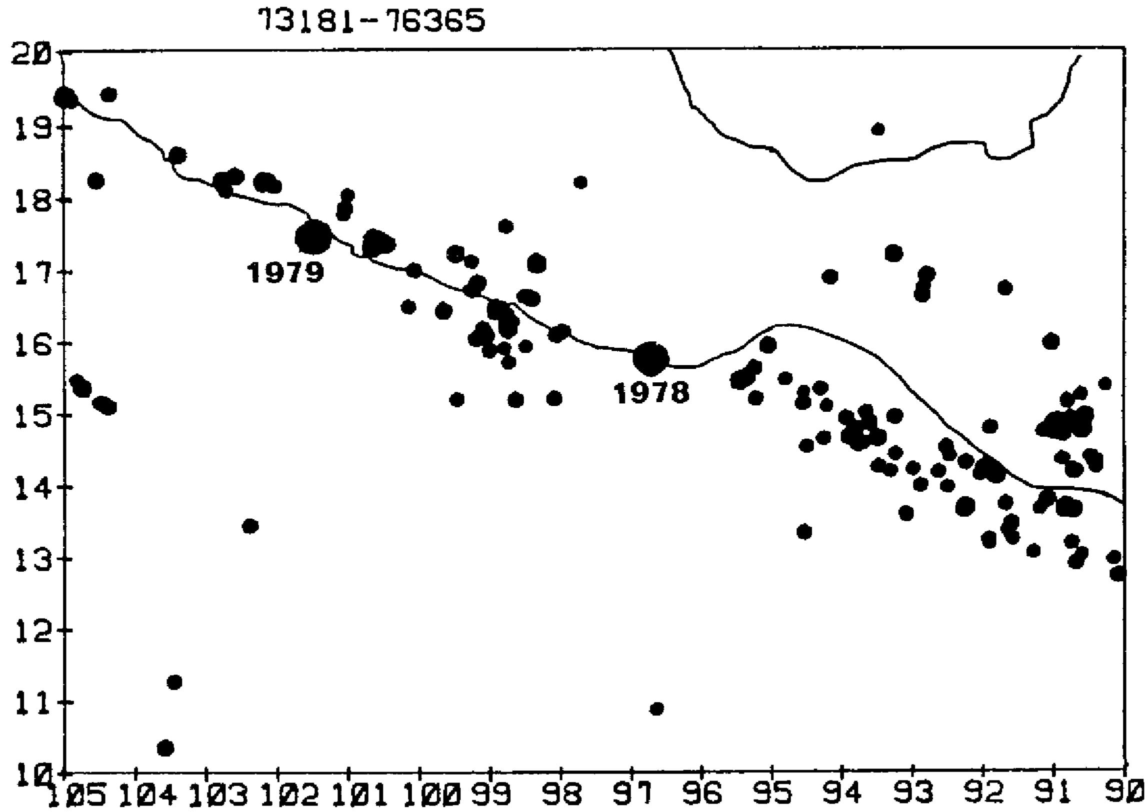


Fig.2: Epicentral distribution of shallow earthquakes along the coast of Mexico from July 1973 through December 1976. Data are from computer printouts by T. Matumoto. The epicentres of the 1978 and 1979 earthquakes are also shown.

Habermann (1980) has even suggested that the quiescence could not be used as a reliable 1978 earthquake was unique. If so, quiescence could not be used as a reliable precursor. Ohtake et al. (1980) claim that five major shocks between 1964-1974 were preceded by similar periods of quiescence; but there are gaps of equal prominence in the same period which were not followed by major earthquakes. Indeed, the only clear instance of a quiescence occured before the 2 August 1968 earthquake; and this quiescence was shorter than the period of resumed seismic activity before the 1978 earthquake.

This discussion is intended to demonstrate the logical flaw in earthquake prediction based on gaps or quiescence. All earthquakes are preceded by fluctuations in seismicity. In at least one region (the southern coast of Oaxaca) minor seismicity is also absent for variable periods of time. Now if a large event occurs it will always be preceded by such a gap, or by a period of resumed activity, or both. Figure 2 shows the actual situation. In most cases there is no real quiescence before the earthquake; the major period of quiescence occurs only once. Now if the earthquake had occured one or two years later it would simply have meant a longer period of resumed activity (the so-called β -activity would have been longer). Since five major events occured in the decade 1964-1974, and no large earthquake had occured since 1973, the fact that a large shock did occur is not remarkable. Indeed the long period of quiescence was more unusual than the earthquake itself.

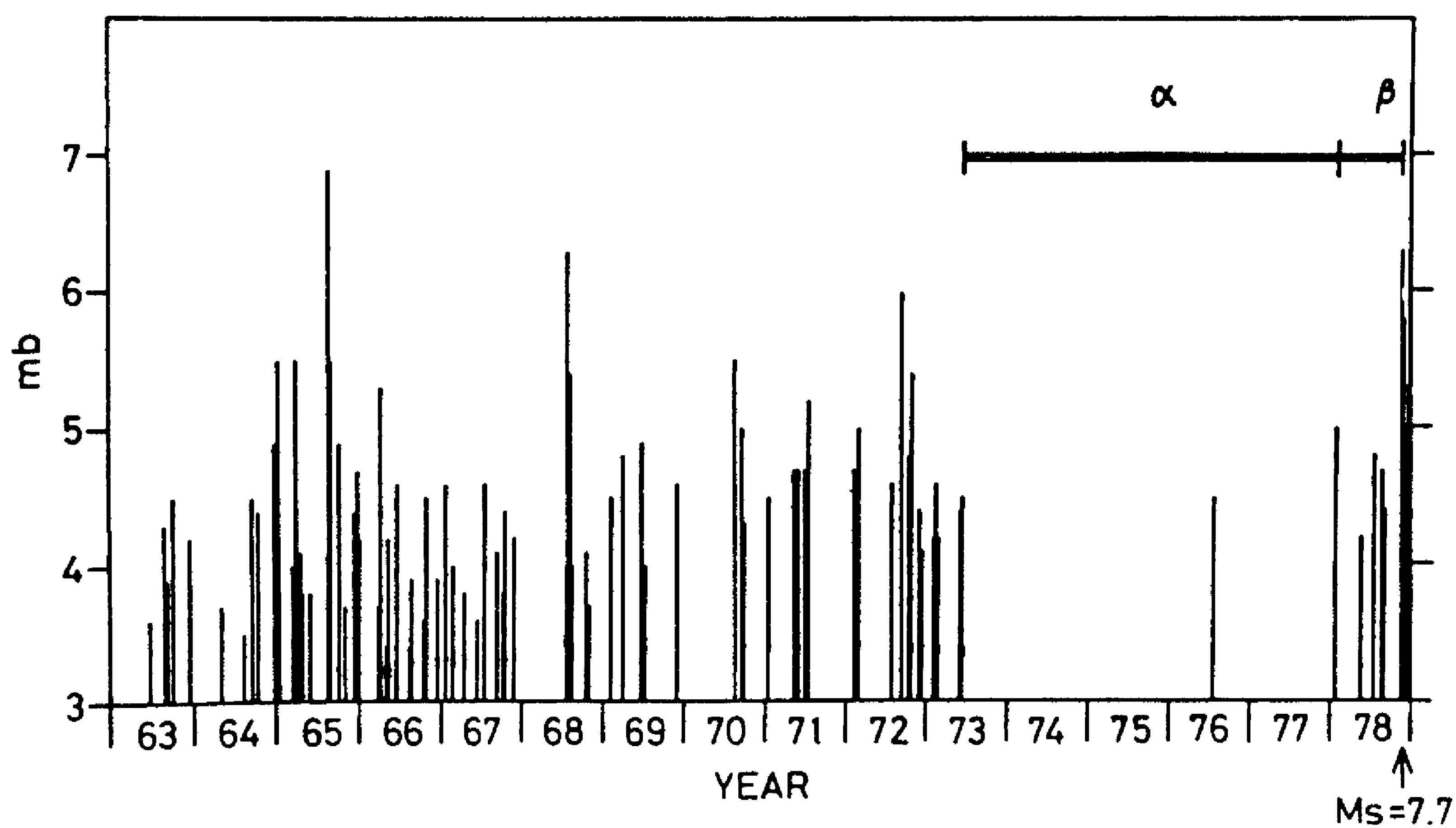
Suppose we have two types of events, A and B, and consider the hypothesis that B is a predictor of A. If B occurs quite regularly before A there is at least the possibility of a correlation, which may or may not be unique. But if A occurs quite often and B occurs very rarely the likelihood of predicting A from B is remote. It is true that an event A will occur after every B; but events A are frequent and will occur anyway, whether B occurs or not. This is true in any case, independently of whether A and B are causally related.

In conclusion, the claim that quiescence preceding the 1978 Oaxaca earthquake was a predictor is at least premature. In the available data run, the 1973-1978 quiet period is unique; but earthquakes are not unique.

Because of the aftershock process, seismicity will tend to be lower than average before every large earthquake. Gaps and quiescent periods are therefore to be expected. They can be found on computer runs of simulated earthquake sequences (Fig. 3).

Fig.3

Magnitude of shallow earthquakes in the Oaxaca Gap since 1963. The a and b stages of the gap are shown from Ohtake et al., 1981.



Large seismic gaps may persist over periods of over 100 years, as in the case of the North Chile gap, without being filled by a major shock. There is no question but that an earthquake will elventually occur; in this case, some claims about the predictive significance of the preceding gap will undoubtedly be made. But we know from seismic history that large events in this area were not generally preceded by such long gaps.

6. CONCLUSION

Seismic gaps and quiescent periods are of questionable significance in terms of earthquake prediction.

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DISCUSSION

In response to questions and expanding on his paper, Prof. Lomnitz concluded that there may be two types of seismicity: (1) ordinary (or random) seismicity, related to low-level events and (2) cyclical seismicity resulting in catastrophic events.

In reply to a question from Dr. Zhu Chuanzhen about what the catastrophic mechanism might be, Prof. Lomnitz suggested that the theoretical concept of asperities proposed by Dr. Kanamori of Caltech might be one mechanism.

Prof. Nersesov suggested that Prof. Lomnitz should examine the significance of events of different magnitude ranges when evaluating the seismic gap theory as it related to the western coast of Mexico. Prof. Lomnitz, however, remained somewhat doubtful about the predictive value of the seismic gap theory because a gap should naturally occur prior to a major earthquake as a result of the decrease of aftershocks as time elapsed after the preceding large earthquake. Dr. Nersesov asserted that because different geological areas have different seismic patterns, seismic gaps may be useful in locating where an earthquake may occur even though the time of occurrence could not be determined.

Dr. Tazieff, who was not present at the discussion of this paper, sent the following written comment on the draft proceedings circulated to participants: "I have read with interest the paper delivered by Dr. Lomnitz and I was really glad to discover he professes the same attitude I do as regards earthquake prediction, and especially about the gap theory".