Geophys. J. Int. (2003) **155,** F1–F5

FAST TRACK PAPER

Accelerating seismicity of moderate-size earthquakes before the 1999 Chi-Chi, Taiwan, earthquake: Testing time-prediction of the self-organizing spinodal model of earthquakes

Chien-chih Chen

Institute of Geophysics, National Central University, Chungli, Taiwan 320. *E-mail: s123@sal.gep.ncu.edu.tw*

Accepted 2003 July 2. Received 2003 June 24; in original form 2003 January 6

SUMMARY

Seismic activation of moderate-size earthquakes for the 1999 Chi-Chi, Taiwan, earthquake has been found. A self-organizing spinodal (SOS) model can explain some observations concerning seismic activation, but the equal time durations of the mid and precursory periods during an earthquake cycle conjectured in the original, published, SOS model have not been supported in this case. The Chi-Chi test presented here shows unequal time durations of the mid and precursory periods of an earthquake cycle. This, in turn, makes the possibility of time prediction of a characteristic earthquake impossible in the context of the SOS model. In addition, comparisons with numerical simulations of the sliding-block model suggest the change in the system's stiffness is a potential mechanism of seismic activation.

Key words: Chi-Chi earthquake, seismic activation, self-organizing spinodal model.

1 INTRODUCTION

There is growing understanding of earthquakes coming from various conceptual models in statistical physics. The scaling properties of earthquake populations, for instance, show remarkable similarities to those observed among the critical phenomena of magnetic or other composite systems in statistical physics. In the course of analyzing seismicity as a critical phenomenon there has been an accumulation of evidence to favour the concept of the critical earthquake. The evidence includes some great earthquakes being preceded by a period of accelerating seismicity of moderate-size earthquakes (e.g. Sykes & Jaume 1990; Bowman *et al.* 1998). These precursory earthquakes with intermediate magnitude occurred in the several years to decades prior to the occurrence of the subsequent major event, and also over a region much larger than its rupture zones. Thus, many investigators have attempted to model the earthquake process by analogy with the statistical mechanics of phase transitions, culminating in a characteristic event that is analogous to a kind of critical point (e.g. Sornette & Sornette 1990; Knopoff *et al.* 1996; Jaume & Sykes 1999; Rundle *et al.* 2000).

Precursory seismic activation over a region with a characteristic length much larger than the rupture length of the main shock cannot be explained by the classical theory of fracture, which would restrict the activation region to a length scale approximating its rupture length. It is this very point that has led to the suggestion of a self-organizing spinodal (SOS) model for earthquakes (Fig. 1) proposed by Rundle *et al.* (2000). Following the standard theory of spinodal nucleation for phase transition, Rundle *et al.* (1997) obtained a spinodal equation of earthquakes. Two important aspects of the aforementioned observation on seismic activation are further derived in Rundle *et al.* (2000) from their spinodal equation. First, the correlation length for seismic activation, as observed in Bowman *et al.* (1998), is proportional to the square root of the rupture area of the characteristic event. This results from a plausible assumption that the fluctuation of the slip deficit on the fault system is proportional to the mean slip on individual faults and the inverse of the mean of their activated volumes (Rundle *et al.* 2000, eq. 25). Second, the power-law exponent to fit the cumulative Benioff strain as a function of time can be calculated theoretically as 0.25 from the SOS model (Rundle *et al.* 2000, eq. 31), which is in excellent agreement with the actual earthquake data in Bowman *et al.* (1998).

Time scales appear to be relevant. Rundle *et al.* (2000), as illustrated in Fig. 1, have divided a complete earthquake cycle into three time periods distinctly while other research groups (e.g. Bowman *et al.* 1998; Jaume & Sykes 1999) have mostly focused on spatial scales. In the SOS model (Rundle *et al.* 2000) small earthquakes occur uniformly at all times in the earthquake cycle. The length of a complete earthquake cycle, t_0, is defined as the time interval between two successive characteristic earthquakes. Then, Δt $(=1 - t/t_0)$ counts the non-dimensional time remaining until the next characteristic earthquake, where t is the time measured forward from the previous characteristic earthquake. There is a systematic lack in number of moderate-size events during the time period $1.0 > \Delta t > 0.2$ and then an increase in the next time period $0.2 > \Delta t > 0.1$. Seismic activation and a further increase in the numbers of the intermediate-sized events occurs in the precursory time period

© 2003 RAS

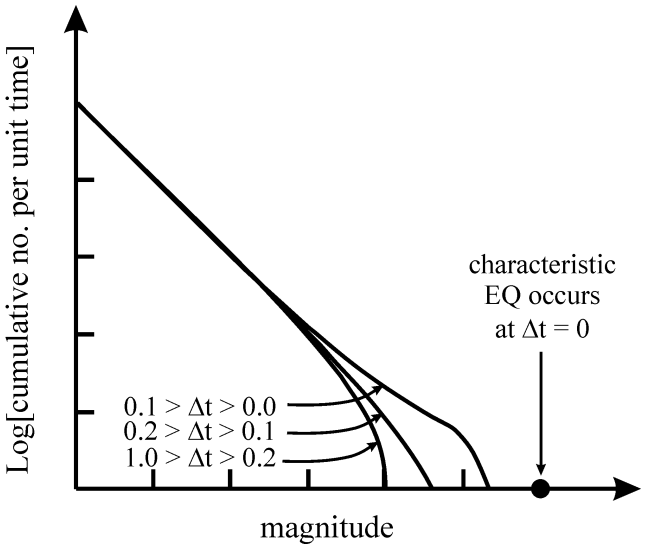

Figure 1. The cumulative frequency-magnitude distribution of earthquakes in three time periods during the earthquake cycle for the self-organizing spinodal (SOS) model (after Rundle *et al.* 2000). Small earthquakes occur at a constant rate but there is an activation of moderate-size earthquakes prior to the occurrence of the characteristic earthquake at $\Delta t = 0$.

$0.1 > \Delta t > 0.0$. These three time periods are here called the earlier term, the mid term and the precursory term, respectively. The characteristic earthquake eventually arrives at the SOS critical point, $\Delta t = 0$.

The abovementioned time division, however, for the earthquake cycle in Rundle *et al.* (2000) seems arbitrary and without any theoretical derivation. This is because there is no explicit expression for the time evolution of the cumulative frequency-magnitude distribution of earthquakes in the SOS model. From the practical viewpoint of seismic hazard prevention (e.g. Karakaisis *et al.* 2002), if the time division of the earthquake cycle in Rundle *et al.* (2000) could be verified, time prediction of the characteristic earthquake by monitoring the seismic activation of moderate-size event could become possible. The testing result will be provided for the case of 1999 Chi-Chi, Taiwan, earthquake in this paper. Also, the possible mechanism for seismic activation is proposed in the end of this study.

2 TESTING THE SELF-ORGANIZING SPINODAL BEHAVIOUR OF CHI-CHI EARTHQUAKE

An earthquake with local magnitude 7.3 took place in central Taiwan on 1999 September 21 (or at UTC 17:47 20 September) and the epicentre was located near the small town of Chi-Chi (Fig. 2). The Chi-Chi earthquake ruptured an approximately 100 km segment of the Chelungpu fault, which represents a geological boundary separating the foothills from the plain areas in the central western Taiwan. The Chi-Chi event also inflicted severe damage in central Taiwan and in the Taipei basin, as far as 150 km away from the epicentre. This earthquake is believed to be the largest earthquake to occur on the island over the past hundred years (Shin 2000; Shin & Teng 2001) and it is fair to consider the Chi-Chi earthquake as a characteristic earthquake for the SOS model, although a quantitative definition for the characteristic earthquake is still missing (Rundle *et al.* 2000). Its qualitative definition is the earthquake occurring as the consequence of the fault reaching its limit of stability, although such a definition does little to facilitate the practical assignment of a characteristic earthquake. This has led Rundle *et al.* (2000) to argue that even the Landers and Northridge earthquakes might represent only precursory activation of the next characteristic earthquake on the San Andreas Fault in California (Rundle *et al.* 2000). Nonetheless, the Chi-Chi earthquake is regarded as a characteristic event in this study.

The earthquake catalogue used in this study is released from the Central Weather Bureau (CWB) of Taiwan (Shin & Teng 2001) and includes data on earthquakes occurring in the Taiwan area from 1991 to 2000. The CWB began to install a new local seismic network, CWBSN, at the beginning of 1990s. For high performance seismic monitoring, digitally telemetered and recorded three-component short-period velocity sensors and then three-component high-quality force balanced accelerometers were installed at all 73 stations. The catalogue released in Shin & Teng (2001) is the most definitive record produced by modern seismic monitoring work in Taiwan. Thus the earlier earthquake data before the 1990s has been disregarded. Besides, for testing the SOS model, such data selection beginning from 1991 will not distort the analysis of seismic activation provided that those two division points of time scales are both located within the spanning range of the earthquake catalogue. The spatial extent around the Chi-Chi focus of the events appearing in the CWB catalogue is less than 600 km. The rupture area of the Chi-Chi earthquake is about 4000 km^2 (Zeng & Chen 2001), and gives a correlation length of about 600 km (Rundle *et al.* 2000). It thus is reasonable to consider all events in that catalogue.

Shown in Fig. 3 are the results of the seismic activation analysis for the Chi-Chi earthquake. No attempt was made to split the whole earthquake catalogue into three different periods *a priori* (e.g. Jaume & Sykes 1999; Karakaisis *et al.* 2002). Instead, described here is an algorithm used to search for the time breaks in the SOS model. Recall the cumulative frequency-magnitude distribution for different periods in the SOS model (Fig. 1). When plotting the distribution diagram only for the earlier term, a sharp crossover magnitude, for example magnitude 5.0 in Fig. 3(a), could be found. The distribution should be able to fulfill the power law distribution very well for smaller events than the crossover magnitude. Beyond the crossover magnitude a fall-off in the cumulative frequency appears. When one involves more and more data gradually passing through the time break between the earlier and mid terms, the fall-off becomes smeared. A sharp crossover magnitude and a systematic lack of moderate events could be found in the CWB earthquake catalogue from 1991 to 1993 indeed, but disappeared when the earthquake data from 1994 was involved. A similar algorithm could be also used to figure out the break time between the precursory and mid terms, but the data analysed started initially from 1999 and went back to involve the earthquake data before. As shown in Fig. 3(c), the CWB data before the Chi-Chi earthquake does exhibit seismic activation of moderate-size events with magnitude greater than 5.0 after 1998 and seismic activation becomes smeared for the subset from 1997 to 1999.

To improve the time resolution of the above analysis of seismic activation and to quantitatively determine the time break between the early/mid or mid/precursory terms in the SOS model, I further divided the whole catalogue into many timely consecutive segments with the duration of two months. A statistical correlation coefficient then was calculated as an initial rough measure of linear correlation between the cumulative frequency-magnitude distributions of two consecutive segments. It is reasonable that two segments extracted from the same one period of the SOS model would have a significantly rectilinear trend with a high value of correlation coefficient

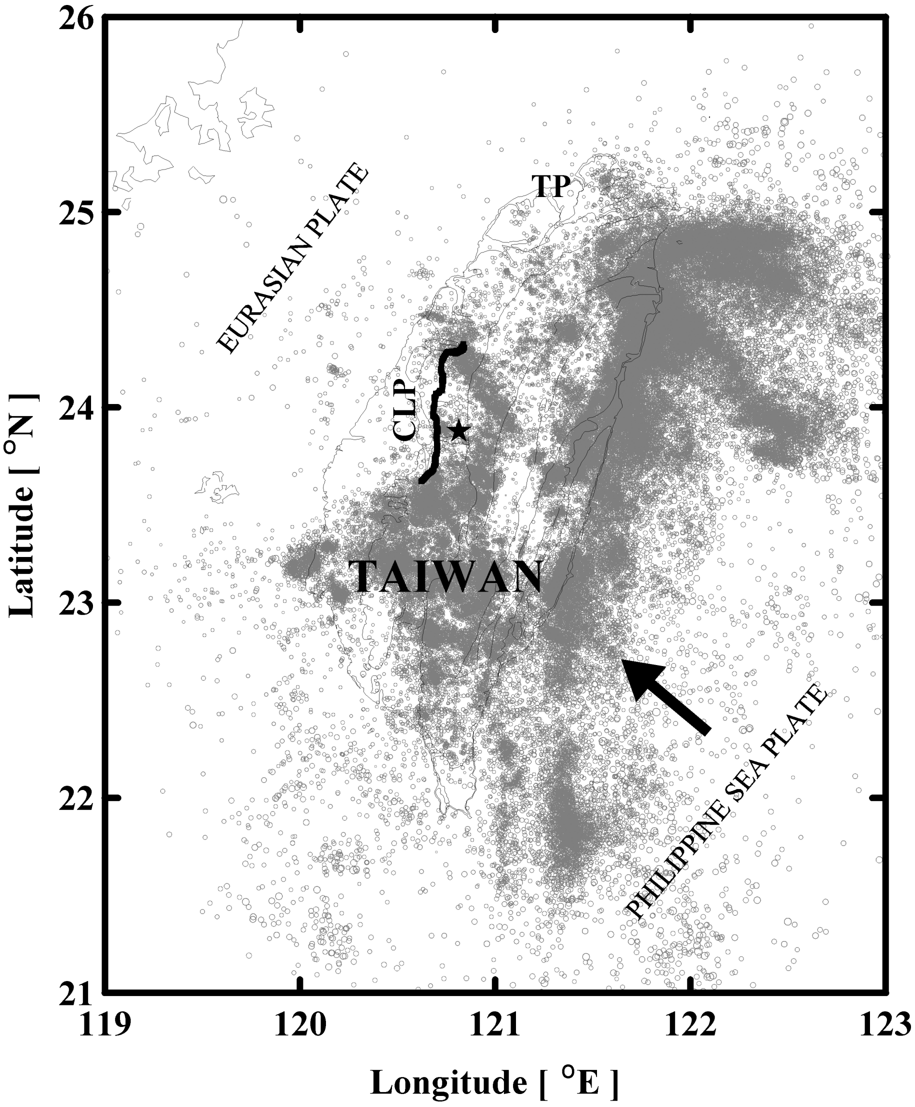

Figure 2. Map showing the epicentres of earthquakes used in this study (open circles) and the Chi-Chi main shock (star). CLP = the Chelungpu fault; TP = the Taipei basin. Thick arrow indicates the direction of relative motion between the Eurasian Plate and the Philippine Sea Plate.

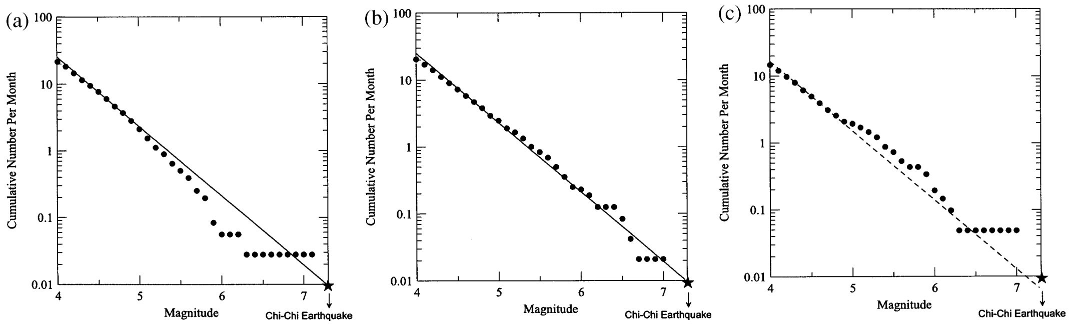

Figure 3. The cumulative frequency-magnitude distribution of the CWB catalog before the Chi-Chi earthquake for (a) the earlier term from 1991 to 1993, (b) the mid term from 1994 to 1997 and (c) the precursory term from 1998 to 1999 September 20. The solid lines in (a) and (b) are the best fitting line for the earthquake data of the mid terms. The dash line in (c) is the same as the solid one, but has been shifted downward to fit the distribution of small earthquakes. Note that the durations of the mid and precursory terms for the Chi-Chi case are not equal to each other while they do in the original SOS model (Fig. 1).

when drawing the scatter plot of two distributions. Conversely, different types of distribution patterns from different periods in the SOS model would produce a smaller degree of linear correlation. Thus a low correlation coefficient between two distributions of earthquake segments may indicate that such two segments were separately extracted from two different periods. Fig. 4 shows the variations in the correlation coefficients calculated from several pairs of two timely consecutive segments across the potential time breaks in the SOS

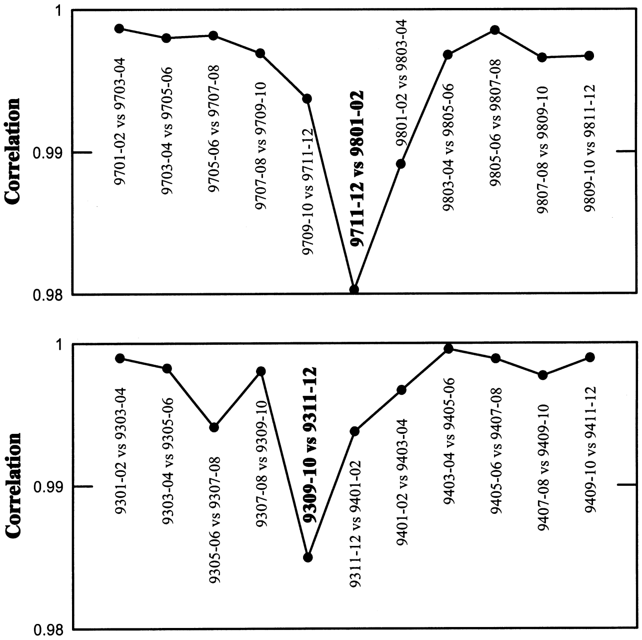

Figure 4. Variations in the correlation coefficients of several pairs of two timely successive segments across the potential time breaks between the mid/precursory terms (upper panel) and the earlier/mid terms (lower panel). The code of 9301-02 represents the subset of events occurring from January to February 1993, and so on. Each correlation coefficient was calculated from two timely consecutive subsets of earthquakes.

model. The frequency-magnitude distribution of events occurring from September to October 1993 is highly correlated to the distribution of events from July to August 1993, but less correlated with its next segment of November–December 1993. This indicates that the time break between the earlier/mid terms is around November 1993. The anomalously low correlation appearing in the pair of segments of November–December 1997 and January–February 1998 suggests that the break between the mid/precursory terms is around January 1998. It is also noted that many pairs consisting of two segments extracted from the same period in the SOS model are highly correlated indeed (Fig. 4).

Thus the CWB earthquake catalogue could be divided into three consecutive subsets corresponding to three different time periods in the SOS model. While the earlier term terminated around the end of 1993, the mid term began around 1994 and ended in 1997. The precursory term began in 1998 and culminated in the characteristic Chi-Chi earthquake on 1999 September 21. The shapes of the cumulative frequency-magnitude distribution of earthquakes (Fig. 3) for these three time periods are almost identical to those shown in Fig. 1 of the original SOS model proposed by Rundle *et al.* (2000). No attempt was made to de-cluster the earthquake catalogue to remove aftershocks in this study. Such de-clustering preferentially removes smaller events in the frequency-magnitude distribution and thus I would not expect de-clustering to make a significant difference for the results of the seismic activation analysis.

3 DISCUSSION AND CONCLUSION

Some researchers have tried to investigate seismic activation preceding a large earthquake with the Burridge-Knopoff block slider model. Shaw *et al.* (1992), for example, found that the seismic activity accelerates dramatically prior to a large event in their slider-block model and is usually a maximum in the neighbourhood of the future epicentre.

Most specifically, numerical simulations in Wang *et al.* (1995) and Wang (1997) clearly demonstrated the different distributions in the frequency versus rupture length of earthquakes for various stiffness ratios in the Burridge-Knopoff model. Wang's simulations (e.g. Figs 8 and 9 in Wang 1997) almost reproduce the SOS behaviour of a complete earthquake cycle. The earlier term of the cycle corresponds to the case of small stiffness ratio and the precursory term for the large one. This raises an interesting implication that a complete earthquake cycle in the SOS model strongly represents a process of gradual development in the intrinsic stiffness coupling of the spring-slider system. This is deeply connected to the following statement made in Rundle *et al.* (2000): *The stress on the rock is analogous to the temperature in the Ising model*. It has been also noticed that the derivation in Rundle *et al.* (2000) began exactly with an approximation to their spinodal equation using a system with large stiffness ratio. Thus, the change in the stiffness of the spring-slider system probably provides a candidate mechanism for seismic activation.

A competing approach also describing the time evolution of precursory seismic activation, which invokes an epidemic-type aftershock (ETAS) model introduced earlier in Kagan & Knopoff (1981), has been proposed by Helmstetter *et al.* (2003). They argued that the well documented modification of the magnitude distribution of foreshocks results from an additive power-law contribution with an amplitude growing exponentially upon the approach to the main shock. Such a modification, according to the ETAS model, is independent of the main shock magnitude also. Because the modification of the magnitude distribution prior to the main shock is a statistical property (Helmstetter *et al.* 2003), which yields an unambiguous signal only when stacking many foreshock sequences, it is difficult to distinguish the SOS and ETAS models using the Chi-Chi case alone. Indeed, after a preliminary test of the ETAS model on the CWB earthquake catalogue, the length of time window when dividing the limited foreshock sequence of the Chi-Chi case into many groups largely controls the amplitude of seismic activation. Conversely, it is noted that the systematic lack of intermediate-sized earthquakes as shown in the earlier term of Fig. 3 seems crucial to verify the ETAS model. The additional power law proposed by Helmstetter *et al.* (2003) cannot efficiently explain such a lack of moderate events. Of course, it is possible this apparent lack is due to the complex superposition of different space-time-magnitude windows during the catalogue duration. Much more work, thus, needs to be done to resolve this issue more fully.

In summary, while the SOS model of Rundle *et al.* (2000) appears to capture some phenomena concerning the earthquake process, one thing obtained in the present seismic activation analysis of the Chi-Chi earthquake is mainly different from their model, that is the durations of those three time periods in an earthquake cycle. This is relevant to the vital topic of earthquake prediction. From the original SOS model (Fig. 1) one may suggest that the complete earthquake cycle will take about ten times the duration of the precursory term, or the mid term. If the durations of the mid and precursory terms are equal and their total length occupies the fifth of the earthquake cycle, time prediction of the characteristic event will be realizable. Unfortunately, based on the case study of the Chi-Chi earthquake in this paper (Fig. 3), I have shown that the relation to the durations of the earlier, mid and precursory terms seems not as simple as the conjecture made in Rundle *et al.* (2000). An extended study on the durations of the individual terms and their roles in the SOS model may shed light on time prediction of the characteristic earthquake.

ACKNOWLEDGMENTS

The author is very grateful to anonymous referees and the editor of GJI for helpful suggestions, particularly for the information of the newly published papers on the ETAS model. This work was supported by College of Earth Sciences and Institute of Geophysics, NCU, and the research grant from National Sciences Council, ROC, as well.

REFERENCES

Bowman, D.D., Ouillon, G., Sammis, G., Sornette, A. & Sornette, D., 1998. An observational test of the critical earthquake concept, *J. geophys. Res.,* **103,** 24 359–24 372.

Helmstetter, A., Sornette, D. & Grasso, J.R., 2003. main shocks are aftershocks of conditional foreshocks: How do foreshock statistical properties emerge from aftershock laws, *J. geophys. Res.,* 108(B1), 10.1029/2002JB001991.

Jaume, S.C. & Sykes, L.R., 1999. Evolving towards a critical point: A review of accelerating seismic moment/energy release prior to large and great earthquakes, *Pure appl. Geophys.,* **155,** 279–306.

Kagan, Y.Y. & Knopoff, L., 1981. Stochastic synthesis of earthquake catalogs, *J. geophys. Res.,* **86,** 2853–2862.

Karakaisis, G.F., Papazachos, C.B., Savvaidis, A.S. & Papazachos, B.C., 2002. Accelerating seismic crustal deformation in the North Aegean Trough, Greece, *Geophys. J. Int.,* **148,** 193–200.

Knopoff, L., Levshina, T., Keilis-Borok, V.I. & Mattoni, C., 1996. Increased long-range intermediate-magnitude earthquake activity prior to strong earthquakes in California, *J. geophys. Res.,* **101,** 5779–5796.

Rundle, J.B., Klein, W., Gross, S. & Ferguson, C.D., 1997. Traveling density wave models for earthquakes and driven threshold systems, *Phys. Rev. E,* **56,** 293–307.

Rundle, J.B., Klein, W., Turcotte, D.L. & Malamud, B.D., 2000. Precursory seismic activation and critical-point phenomena, *Pure appl. Geophys.,* **157,** 2165–2182.

Shaw, B.E., Carlson, J.M & Langer, J.S., 1992. Patterns of seismic activity preceding large earthquakes, *J. geophys. Res.,* **97,** 479–488.

Shin, T.C., 2000. Some seismological aspects of the 1999 Chi-Chi earthquake in Taiwan, *TAO,* **11,** 555–566.

Shin, T.C. & Teng, T.L., 2001. An overview of the 1999 Chi-Chi, Taiwan, earthquake, *Bull. seismol. Soc. Am.,* **91,** 895–913.

Sornette, A. & Sornette, D., 1990. Earthquake rupture as a critical point: Consequences for telluric precursors, *Tectonophysics,* **179,** 327–334.

Sykes, L.R. & Jaume, S.C., 1990. Seismic activity on neighboring faults as a long-term precursor to large earthquakes in the San Francisco Bay area, *Nature,* **348,** 595–599.

Wang, J.H., 1997. On the frequency distribution of rupture lengths of earthquakes synthesized from a one-dimensional dynamical lattice model, *J. Phys. Earth,* **45,** 363–381.

Wang, J.H., Matsuzaki, M. & Koyama, J., 1995. Dynamical modeling of earthquake occurrences, in *Advance in Mathematical Seismology,* pp. 148–164, eds Koyama, J. & Feng, D., Seismological Press, Beijing.

Zeng, Y. & Chen, C.H., 2001. Fault rupture process of the 20 September 1999 Chi-Chi, Taiwan, earthquake, *Bull. seismol. Soc. Am.,* **91,** 1088–1098.