ANNALI DI GEOFISICA, VOL. 44, N. 1, February 2001

Model of long-term seismogenesis

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Abstract
A three-stage faulting model explains the observed quantitative relations between long-term precursory seismicity, mainshocks and aftershocks. Seismogenesis starts with the formation of a major crack, culminates in the corresponding major fracture and earthquake, and ends with healing. Crack formation is a self-organised critical phenomenon, and shear fracture is a delayed sequel to crack formation. It is postulated that the major crack generates a set of minor cracks, just as, later, the major fracture generates a set of minor fractures. Fracturing of the minor cracks raises the average seismicity level. By Mogi's uniformity criterion, the major earthquake is delayed until the minor fractures have healed and the stress-field has regained relative uniformity. In accord with the scaling principle, the model applies at all magnitude levels. The size of any given initial crack determines the scale of the ensuing seismogenic process. A graphical technique of cumulative magnitude analysis gives a quantitative representation of the seismicity aspects of the model. Examples are given for large earthquakes in a region of continental collision and a subduction region. The principle of hierarchy is exemplified by the seismogenesis of a M 5.9 mainshock occurring entirely within the precursory stage of a M 7.0 mainshock. The model is capable of accommodating a variety of proposed shorter-term precursory phenomena.

Key words *seismogenesis - faulting - precursory seismicity - scaling*

1. Introduction

Recent interest in seismogenesis has been concerned with three distinct time-scales. At one extreme is the class of hypothesis that considers the occurrence of a large earthquake to depend on preceding earthquakes of comparable magnitude on the same fault; the repeating seismogenic process is referred to as the «seismic cycle», and the time-scale as the «recurrence time». At the other extreme is the study of nucleation, *i.e.* the immediate initiation process of an earthquake. Precursory phenomena, as usually understood, occur on an intermediate time-scale. In the model discussed below, the time between the onset of seismogenesis and the earthquake is a fraction of the «recurrence time», but is long enough to encompass the range of precursor times that have been reported in the literature.

The model has been developed from a seismogenic process outlined earlier (Evison and Rhoades, 1998). The model relies more thoroughly on the proposition that the lithosphere is in a state of self-organized criticality. Accordingly, the main physical principles behind the model are an extreme sensitivity to initial conditions, and the scaling principle. As will be discussed below, these principles account for the sudden onset of seismogenesis, and for the observed quantitative relations between precursory seismicity, mainshock, and aftershocks.

In the model, the precursory earthquakes can occur in any order within the precursory period. In certain circumstances many of them, including the largest, are observed to occur in a particular grouping known as swarms. Since swarms

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are easily recognized, most of the empirical work has been concentrated on regions that favour swarm occurrence, especially shallow subduction regions. In the seismogenic process proposed earlier, however, it was already implied that swarms were a special case, with the inference that lesser concentrations in time should be found in other types of region. Subsequent observation confirmed this inference. Thus the model makes no mention of swarms nor of the conditions in which they occur. It is nevertheless convenient to summarise the earlier work by way of introduction to the model.

2. Long-term seismogenic process

The study of long-term precursory seismicity has advanced beyond the anecdotal stage through a systematic analysis of earthquake catalogues in Japan, Greece and New Zealand. This has been facilitated by the prominence of swarms in the precursory seismicity of shallow subduction regions. In all, 28 sequences of precursory seismicity, major earthquakes, and aftershocks have been identified. With clustering, these sequences include 42 major earthquakes (Evison and Rhoades, 2000). Correlation of these sequences enables the location, time and magnitude of major earthquakes to be estimated from the like parameters of the precursory seismicity. On this basis, the precursory seismicity, major earthquake, and aftershocks have been interpreted as stages in a long-term seismogenic process (Evison and Rhoades, 1998).

Inter-stage conditions in the process satisfy the Mogi (1963) criteria, which require the medium and stress-field to be non-uniform for the occurrence of swarm-like events, and uniform for the occurrence of mainshocks. Aftershock sequences, considered separately from mainshocks, can also be regarded as swarm-like events in the Mogi sense. Thus the seismogenic process is required to change the condition of the medium and stress-field from uniform to non-uniform, and *vice versa*, according to the type of seismicity that is about to occur. These changes are provided for by postulating that the three stages of the faulting phenomenon – crack formation, fracture and healing – can be separated in time. Cracks and fractures are then taken to constitute non-uniformity, while post-earthquake healing restores uniformity. Some form of stress evolution is prominent in most discussions of earthquake occurrence. Evolution away from or towards stress uniformity, on the appropriate scales, is crucial at successive stages in the present model.

A state of deterministic chaos is assumed to exist before the start and after the finish of the seismogenic process, and also, on a higher scale, during the swarm and aftershock stages. In the model, this state is identified with self-organised criticality, as will be discussed in some detail below. In conformity with the principle of scaling, the process is invariant with respect to magnitude, except where modified by large-scale boundaries in the medium.

Thus constructed, the seismogenic process accounts for the predictive relations without needing to include such matters as the mechanism by which swarms might be triggered. This is in accord with the algorithm for predicting mainshock events (Rhoades and Evison, 1993): the precursory seismicity is treated simply as an assemblage of individual earthquakes. In particular, the precursor location is taken as the magnitude-weighted mean of the individual epicentres, while the time is taken as the magnitude-weighted mean of the individual occurrence times, and the magnitude is taken simply as the average of the three largest individual magnitudes.

3. Long-term seismicity precursor, mainshocks and aftershocks

The observed relations between the long-term seismicity anomaly and subsequent events, irrespective of the internal structure of the anomaly, are as follows (Rhoades and Evison, 1993; Evison and Rhoades, 1998):

i) The long-term anomaly is followed by mainshock/aftershock events.

ii) The mainshock/aftershock events occur in the same vicinity as the long-term anomaly.

iii) The long-term anomaly is a predictor of the mainshock/aftershock events in respect of magnitude and time, as well as location.

iv) The long-term anomaly is similar to the aftershocks in respect of magnitude and fractality (but not temporal distribution).

v) The predictive relations have the property of scaling.

Relation (i) indicates that wherever the long-term seismicity anomaly occurs one can also expect to find the aftershock phenomenon. In relation (ii), the future mainshock epicentre is estimated from the precursor epicentres (assuming a bivariate normal distribution), and the precursor occupies an area comparable to that of the future aftershocks. This is a much smaller area than that occupied by some suggested shorter-term precursors, such as *M* 8 and accelerated moment release. Relation (iii) indicates that the long-term seismicity anomaly is an integral part of the seismogenesis of mainshock/aftershock events.

The key to the seismogenic model is provided by relations (ii) and (iv). The set of long-term precursory earthquakes is much as one would expect (apart from the internal time distribution) if it were preceded by the mainshock, instead of *vice versa*. And since there is no preceding mainshock, the internal time distribution is not described by Omori's law. But the model evidently needs to include some surrogate mainshock event which precedes the precursory earthquakes, and in some material sense resembles the future mainshock.

Scaling (relation v) is displayed by the empirical predictive relations over a range of mainshock magnitudes from 5.8 to 8.2. This, considered together with the fractality of both precursory anomaly and aftershocks (Evison and Rhoades, 1998), is supporting evidence for the proposition that seismogenesis takes place against a background of self-organised criticality.

4. Crack formation, fracture and healing

The required surrogate mainshock event which gives rise to the precursory earthquakes, and ensures their similarity to the subsequent aftershocks, is provided by the three-stage faulting phenomenon, assuming that the stages – crack formation, fracture and healing – can be widely separated in time. In these terms, the succession of events to be modelled is as follows:

a) A major crack is formed.

b) This produces a set of minor cracks.

c) The minor cracks fracture over time, producing the corresponding set of minor earthquakes. This is the precursory anomaly.

d) The minor fractures heal over time.

e) The major crack fractures, producing the mainshock.

f) This produces a set of minor cracks, and the corresponding set of minor fractures and earthquakes (aftershocks).

g) The minor fractures heal over time, restoring the medium to its original condition.

Here, the major crack is the surrogate: first it generates the precursory earthquakes (item (c)), and later it fractures, producing the mainshock, and thus generating the aftershocks (item (f)). The effect of a mainshock in generating aftershocks is commonly explained as due to a stress redistribution associated with the main fracture (*e.g.*, Marcellini, 1995). A similar mechanism is here proposed for the production of minor cracking by the major crack. But with the mainshock the redistributed stress is at a comparatively high level, so that the cracking is followed immediately by fracturing and intense aftershock activity. With the major crack, on the other hand, the level of stress change and redistribution is comparatively low, and the effect is limited to the production of minor cracks, which fracture over time. As discussed above, Mogi's (1963) criteria are satisfied throughout by the postulate that cracks and fractures constitute non-uniformity, and that healing restores the medium to a uniform condition.

The major crack that initiates the sequence of events may occur, though not necessarily, on a pre-existing fault, *i.e.* a fault that has been subject to previous cracking, fracturing and healing. The occurrence of the initiating crack is sufficiently accounted for by the medium being in a state of self-organised criticality.

5. Self-organised criticality and predictability

The model adopts the widely-held view that earthquakes are among those natural phenomena that occur under conditions of self-organised criticality (Bak and Tang, 1989). This is a high-order form of deterministic chaos (Main, 1995; Turcotte, 1997), and has been called the normal condition of the lithosphere (Scholz, 1991). Classical models of self-organised criticality are the sand-pile, the cellular automaton and the multi-unit spring-block system. Such models simulate the fractal nature of earthquake populations, but not the detailed process of seismogenesis. Moreover, the unpredictability that is a feature of chaotic systems seems at first sight incompatible with the observed relations between long-term seismicity precursors, mainshocks and aftershocks. The apparent paradox is resolved by the principle of scaling.

For any set of earthquakes that displays the property of self-similarity, as indicated by the Gutenberg-Richter relation, this property is taken here to imply unpredictability. This is in accord with the common view, which Kagan (1997) has stated thus: «The most probable consequence of earthquake self-similarity is a lack of earthquake predictability as popularly defined, that is a forecast of a specific individual earthquake». Within an aftershock sequence, for example, it is accepted that one cannot forecast the location, time and magnitude of an individual earthquake (Reasenberg and Jones, 1989). Yet by a modest extension of this concept of predictability, one can say that the set of aftershocks, as a whole, can be predicted from the mainshock by means of the following well-known relations (Evison, 1999): with respect to magnitude by the Gutenberg-Richter relation and Båth's law; with respect to time by Omori's law; and with respect to location by the mainshock hypocentre and Utsu's areal relation. Conversely, the mainshock parameters can be estimated from the set of aftershocks. This predictability is compatible with the self-similarity principle, since the mainshock is not a member of the self-similar set of aftershocks: the scale of the mainshock, as Båth's law indicates for magnitude, is much larger than that of the largest aftershocks.

A parallel explanation applies to the relation between precursory seismicity and mainshock. In view of the self-similar nature of a set of precursory earthquakes, as already mentioned, one would not expect to be able to forecast the location, time and magnitude of an individual precursory earthquake, but estimation of the mainshock parameters from the set of precursory earthquakes is not precluded. In both cases the principle of scaling and the related concept of hierarchy need to be taken into account. As Utsu (1970) pointed out, a small-scale mainshock-aftershock event can be nested within a large-scale set of aftershocks; similarly, a small-scale sequence of precursory earthquakes and mainshock-aftershock event can be nested within a larger-scale precursory episode, as will be illustrated below. In general, earthquakes differ mainly in their relations with other earthquakes, and a given earthquake can have one type of relation on one scale, and a different type on another scale.

The model thus adopts self-organised criticality as the ambient (*i.e.* both initial and final) condition under which long-term seismogenesis occurs. The condition also applies during stages of the model at which sets of minor cracks or fractures are present. Initiation of seismogenesis under self-organized criticality is extremely sensitive to initial conditions. An analogy can be drawn between the formation of a major crack and the formation of a tropical depression in meteorology. The «butterfly effect» which leads to the tropical depression is analogous to a «microtremor effect» leading to the major crack. Then, just as the tropical depression develops into the future tropical cyclone, so the major crack develops into the future major earthquake. Since scaling in seismology applies over a wide range of magnitudes, self-organized criticality as the initial state implies that the major crack may have any absolute size: it is major only on the scale of the particular seismogenic process that it initiates.

In short, the unpredictability that is a feature of self-organized critical systems is here attached to the initial stage of seismogenesis: crack formation. Modelling (or predicting) the occurrence of any individual crack is excluded. But once the crack has formed, the precursory anomaly and the eventual earthquake follow in the manner indicated by the observations.

6. The model

The scheme in fig. 1 represents stages in the seismogenic process (column 1), associated states of the stress-field (column 2), and phenomena that are or may be related to the process (column 3). Let the process occupy space *S* and time *T*, where *T* scales with *S*. Before the start of *T*, space *S* is an undifferentiated part of the greater seismic region. *S* becomes identified as seismogenic on its own scale by the formation of the major crack, which provides the first model stage. The successive stages display a simple structure: the five stages bracketed «a» closely resemble those bracketed «b», while the sequence of crack formation, fracture and healing appears three times. The major crack generates the minor cracks in bracket «a», on a scale about one order smaller than itself, and then, at the beginning of bracket «b», it defines the major fracture. These consequences of the major crack formation are the key to the predictability of the major earthquake.

The contrasting states of uniformity of the medium and stress-field within space *S*, as required by Mogi's (1963) extended criteria, are indicated in the second column of fig. 1: uniformity before the major crack and mainshock, and non-uniformity both before the precursory earthquakes and the aftershocks. On the scale of any particular example that the model might represent, the initial and final conditions are both characterised by uniformity, and the seismogenesis does not depend on external earthquake occurrences. Indeed, Mogi's criteria can be recognised as an expression of scaling: any earthquake occurrence is facilitated if the medium is in a sufficiently uniform state at the proper scale.

Phenomena that may be identified with various stages of the model are indicated in the right-hand column of fig. 1. The three essential phenomena are shown in bold type. Since research on many proposed earthquake precursors is still in the anecdotal stage (Evison, 1999), a seismogenic model that is well-grounded on a particular precursor may be a useful guide to the study of others. For example, the formation of minor cracks in bracket «a» may leave the medium in a state somewhat comparable to dilatancy (Scholz *et al.*, 1973). Precursory anomalies in seismic velocity and coda Q^{-1} have been attributed to this state (Jin and Aki, 1989), which may also provide the anisotropy that is observed as shear-wave splitting (Li and Crampin, 1991). Dilatancy, however, is usually visualised as a pervasive microcracking, while the minor cracks in the model have a fractal distribution, corresponding to that of the resultant precursory earthquakes. Such a distribution may, nevertheless, result from the propagation and coalescence of microcracks. A further phenomenon which is prominent in laboratory experiments on rock, and has been closely correlated with cracking, is acoustic emission (Scholz, 1990). In the present model, the expected time of occurrence of anomalies associated with crack formation is near the onset of seismogenesis and not, as much of the literature has envisaged, at the time of possible short- or medium-term precursors. A search for long-term precursors associated with the formation and presence of cracks could provide a test of the earlier stages of the model. Such precursors may include electrical and electromagnetic effects, and gas emission.

The durations of the various stages in a given example, and the intervals between them, differ widely. The stage of minor fractures in bracket «a», *i.e.* the stage of precursory seismicity, may begin with the onset of the seismogenesis and continue until its culmination in the mainshock. On the other hand, the formation of minor cracks in bracket «b» is started immediately by the mainshock and completed before the respective aftershocks. As presented, the model deals with the case of a single major earthquake; to allow for clustering would add complexity without requiring additional stages to be included.

The model does not depend on the detailed physics of faulting, which is complex and still incompletely understood. There is evidence (Scholz, 1990) that crack formation preparatory to fracture occurs as an assemblage of microcracks, each of which is oriented parallel to the greatest principal stress, while the assemblage as a whole is oriented appropriately for shear fracture. A kinetic, hierarchical model of cracking and fracturing has been proposed (Kuksenko *et al.*, 1996) which is suggestive of the time delays and scaling relations inherent in

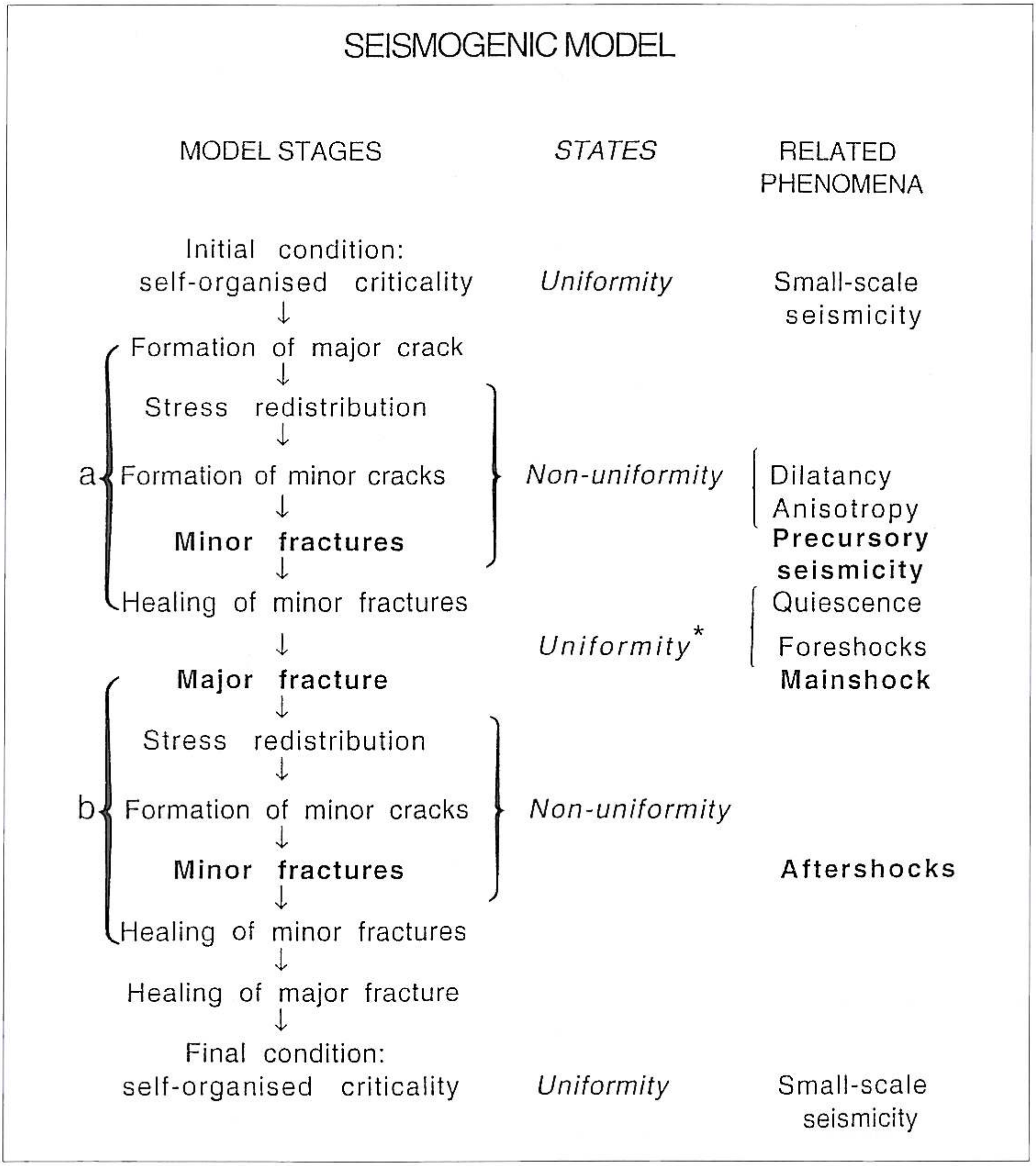

Fig. 1. Stages, states of the stress-field, and related phenomena in the seismogenic model. The time sequence of model stages is indicated by arrows. The middle column indicates the relative state of uniformity of the local medium and stress-field; the uniform state marked with an asterisk is similar to those of the initial and final conditions, except for the presence of the major crack. The right-hand column indicates phenomena which are positively identified (bold type), or potentially identified, with various stages of the model. The model is driven by tectonic plate motion, which maintains the lithosphere in a state of self-organised criticality. The size of the initiating major crack determines the scale of all succeeding stages.

seismogenesis as modelled here. Again, the duration of the healing process has been related to source dimension, stress drop and other factors (Marone *et al.*, 1995; Marone, 1998), but discrepancies remain between experimental and seismological results.

The reported variation of healing-time with the rate of loading (Marone, 1998) may be supported by studies of the long-term seismicity precursor. The healing of minor fractures (see fig. 1, bracket «a») occurs during the precursor time. In the combined data for Greece, Japan and New Zealand (Evison and Rhoades, 2000, fig. 4), the precursor time increases with magnitude, but less rapidly than simple scaling would suggest. Since the large magnitudes are all from Japan, the shortfall may be due to the greater loading rate in Japan. The precursory phenomena of seismic quiescence (Wyss and Habermann, 1988) and foreshocks (Ogata *et al.*, 1995) may be associated with the same healing stage. As a matter of simple contrast, this stage is quiescent relative to the frequently observed bursts of precursory seismicity on the one hand, and the mainshock/aftershock stages on the other. Again, the earthquakes that occur during the precursory period may leave a few of the available cracks untriggered, and these may fracture some time later, possibly as foreshocks which trigger the major fracture.

In accord with the principle of scaling, as discussed above, the model applies at any magnitude level. It is the initiating crack formation, which can be of any size, that determines the sizes of space S and time T. Thus the terms «major» and «minor» in fig. 1, and in the accompanying text, are to be understood in a purely relative sense. Furthermore, what is major on one scale may at the same time be minor on another. In practice, the scale of the mainshock is estimated from the magnitude level of the set of precursory earthquakes.

7. Precursory seismicity

Only those stages of the model that specify fracturing are represented by earthquake activity. These are highlighted in the first column of fig. 1, and the related earthquake phenomena are highlighted in the third column. The earthquake phenomena – precursory seismicity, mainshock and aftershocks – are the observational basis for the entire model. Any special form that the precursory seismicity might take (such as swarms) does not feature in the model, which only requires that the precursory minor cracks, fractures and earthquakes form similar fractal sets, and that the magnitude level of the earthquakes is similar to that of the subsequent aftershocks.

The nature of precursory seismicity can be illustrated by reference to the two most recent large earthquakes to have occurred in New Zealand: the Arthur's Pass earthquake (M_L 6.7) of 18 June 1994 (fig. 2), and the East Cape earthquake (M_L 7.0) of 5 February 1995 (fig. 3). The former occurred in a continental collision region, and the latter in a subduction region. The fine structure of the precursory seismicity is different in the two cases, while the overall patterns are similar. These examples are not merely anecdotal. They occurred during the lengthy series of formal hypothesis tests that are being conducted in New Zealand, Japan and, more recently, Greece. The East Cape precursor included swarms while the Arthur's Pass precursor did not.

The seismicity of the area containing the Arthur's Pass precursor, mainshock and aftershocks is shown in fig. 2. Figure 2A shows the epicentral relations. The upper plot in fig. 2B shows, for the same area, the magnitudes *versus* time, including a period extending back some 11 years before the onset of seismogenesis. The lower plot shows the same data in a form that better reveals the features relevant to the present model. Here the quantity plotted against time is the cumulative magnitude anomaly (cumag), $C(t)$, which is a type of cusum designed to show up temporal changes in the level of seismicity, having regard for magnitude. It is defined by

$$C(t) = \Sigma_{ts \le ti \le t} (M_i - M_c + 0.1) - k(t - t_s) \quad (7.1)$$

$$k = \Sigma_{ts \le ti \le tf} (M_i - M_c + 0.1)/(t_f - t_s) \quad (7.2)$$

where M_i is the magnitude and t_i the time of the ith earthquake, M_c is the threshold magnitude,

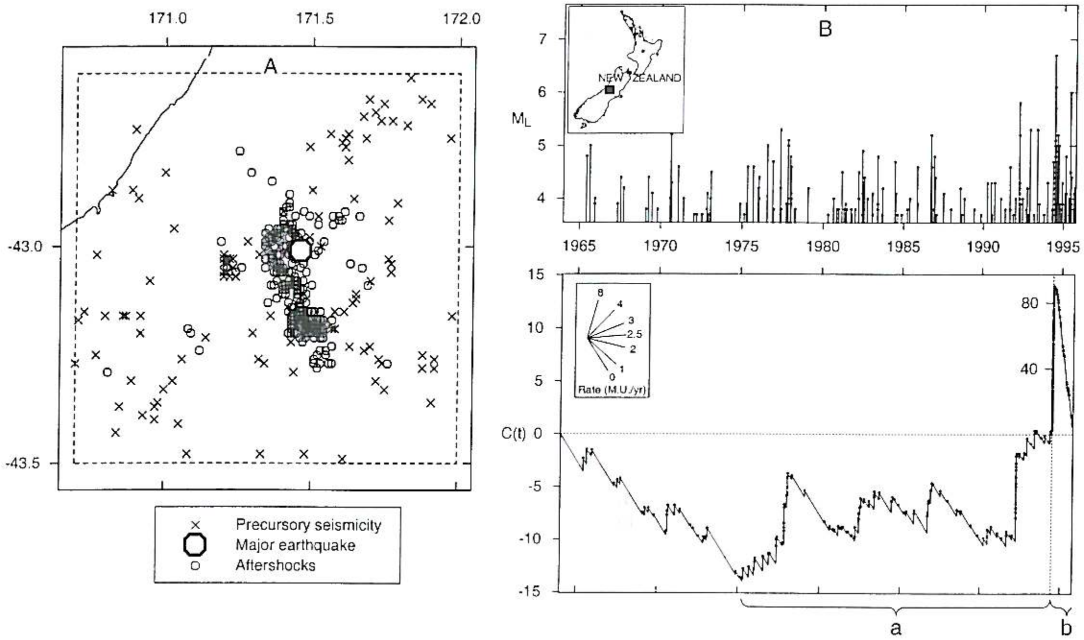

Fig. 2. Seismicity aspects of the model for a continental collision earthquake: the Arthur's Pass (New Zealand) earthquake, M_L 6.7, 18 June 1994. A: Epicentres of earthquakes in the seismogenic process. B: Magnitudes *versus* time for earthquakes in the seismogenic process and earlier period. The upper graph shows the magnitude and time of each earthquake: the lower graph shows the cumulative magnitude anomaly $C(t)$, given by eqs. (7.1) and (7.2). The scale of $C(t)$ is given on the left for the pre-mainshock period, and on the right for the mainshock-aftershock period. The gradient of the line between any two points on $C(t)$ is a measure of the average seismicity rate during the corresponding time interval. For the pre-mainshock period this is indicated by the protractor; rate is measured in magnitude units per year (M.U./yr), where magnitude is reckoned from the baseline value. Bracket «a» marks the precursory period (see fig. 1).

and k is the average rate of magnitude accumulation between the starting time t_s and the finishing time t_f. Accordingly, each earthquake is represented by an upward jump equal to the amount by which the magnitude exceeds the baseline value, which is 0.1 below the threshold magnitude. The downward slope between successive earthquakes is equal and opposite to the sum of all the upward jumps divided by the total time; thus the plot begins and ends at the value zero. It follows that the gradient of the line between any two points on the $C(t)$ curve is a measure of the average rate of earthquake activity during the corresponding time period. Many examples of cumag plots for Greece have been given by Evison and Rhoades (2000).

The periods marked «a» and «b» in the lower plot in fig. 2B correspond to those similarly labelled in fig. 1. The stage of «minor fractures» in the model (fig. 1, bracket «a») includes all the precursory earthquakes, which in fig. 2 are distributed over about 15 years. In the model, the onset of long-term seismogenesis is identified with the formation of the major crack. This is immediately followed by stress redistribution and minor crack formation. The minor fractures can begin to occur virtually at the onset. The essential signature of the precursory seismicity is a jump in the slope of the cumag. Accordingly, the change in the average rate of seismicity at the start of the bracket «a» period in fig. 2B, in early 1975, is taken as marking the onset of seismogenesis. As can be estimated by reference to the protractor, the average rate before the onset was 1.24 M.U./yr, while the average for period «a» was 3.21 M.U./yr, representing an increase by a factor of 2.6. From the upper plot in fig. 2B it can be seen that this change was first established by an unprecedented group of nine earthquakes of magnitude $M \geq 4.6$ over a three-year period. A count shows that the average annual number of earthquakes (with $M \geq 3.7$) increased by a factor of 2.5 over the precursory period compared with the earlier period.

Early 1975 is thus recognised, from the change of seismicity level in fig. 2, as approximately the time of formation of the major crack (fig. 1). According to the model, the major crack, by its time of formation, location and size, indicates the beginning and scale of time T, the location and scale of area S, and the magnitude level of the precursory seismicity. Fracture of the major crack occurred some 19 years later, launching the Arthur's Pass earthquake.

A similar pattern is shown in fig. 3 for the East Cape earthquake. In this case, the precursory seismicity included a cluster of six swarms, the first five of which were published, along with the prediction algorithm, by Evison and Rhoades (1993). The mainshock was the largest in the New Zealand region for 50 years past. According to the test prediction, the East Cape earthquake was more likely under the precursory swarm hypothesis than under the stationary Poisson model, by a factor of 114 (Evison and Rhoades, 1997).

The change in the slope of the cumag in fig. 3B (lower), marking the onset of seismogenesis for the East Cape earthquake, occurred in mid-1977. The average rate before the onset was 1.8 M.U./yr, while the average for period «a» was 6.0 M.U./yr, representing an increase by a factor of 3.4. This change resulted from an

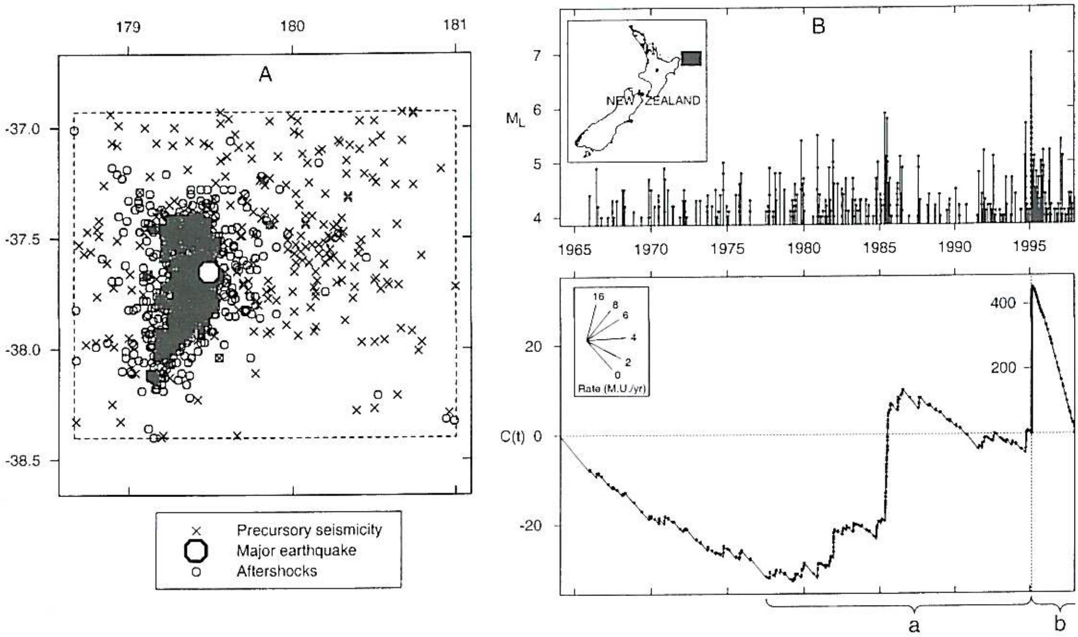

Fig. 3. Seismicity aspects of the model for a subduction region earthquake: the East Cape (New Zealand) earthquake, M_L 7.0, 5 February 1995. Details as for fig. 2. (Note that the seismicity rate depends on baseline magnitude and area, so rates are not to be compared from one example to another).

increase in the magnitudes of the larger earthquakes and a corresponding increase in the number of earthquakes with $M \geq 4.0$. (A count shows that the average annual number increased by a factor of 3.0). The largest swarm produced a prominent fluctuation in 1985.

It is proposed here that the fractal property, which is a feature of both aftershocks and precursory seismicity (Evison and Rhoades, 1998), is conducive to near-neighbour triggering. In other words, the space pertaining to a given major crack or fracture is sufficiently filled by the associated fractal set of minor cracks or fractures for the triggering of one event by another to be facilitated. It has already been suggested that, since precursory earthquakes are a fractal set on about the same scale as the associated aftershocks, the triggering of precursory swarms, when other conditions are favourable, is aided by fractality (Evison and Rhoades, 1998). Even without swarms, the precursory seismicity is found to include noticeable bursts of activity (Evison and Rhoades, 1999a); examples may be seen in fig. 2B. This triggering effect will diminish with the passage of time. The precursory seismicity at East Cape concluded with an earthquake of magnitude M 4.3 occurring 1.3 days before the mainshock, and located within the aftershock area, though at an epicentral distance of 55 km. This earthquake could be considered a foreshock; it may have triggered the mainshock, either directly or by finally rendering the stress-field uniform. The foreshock/mainshock phenomenon in general indicates that one or more smaller earthquakes may trigger a larger one when the distance between them is sufficiently small.

At East Cape, epoch 1977.5 is recognised, from the change of seismicity level in fig. 3, as approximately the time of formation of the major crack. The prediction of this earthquake, mentioned above, was based on the cluster of six

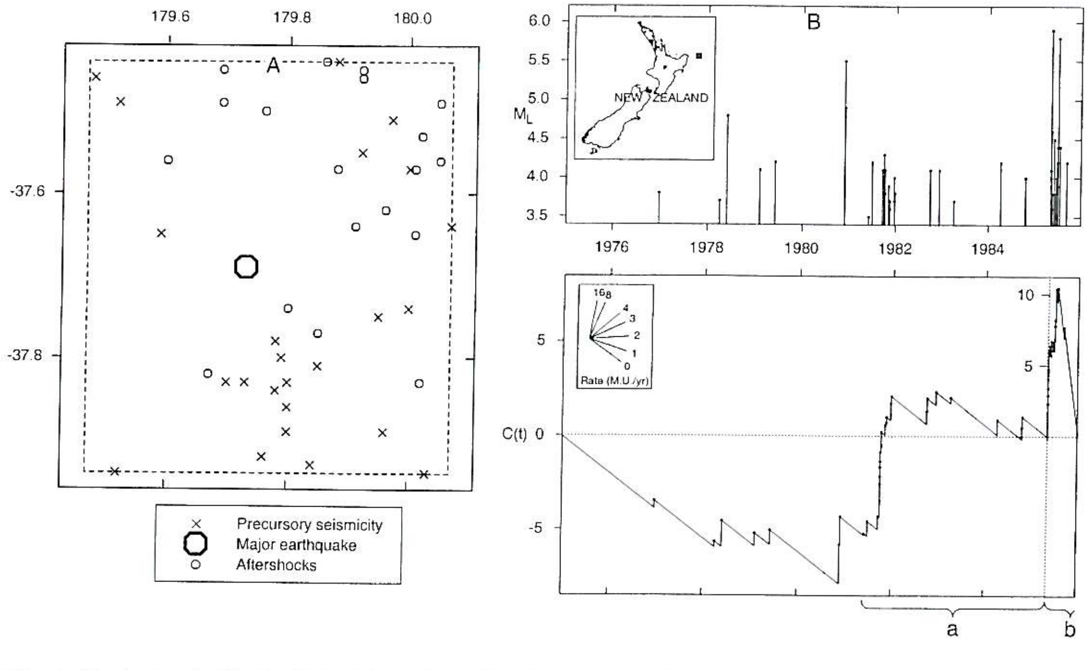

Fig. 4. Illustrating (with fig. 3) the hierarchy and scaling aspects of the model: the East Cape (New Zealand) earthquake, M_L 5.9, 6 May 1985. Details as for fig. 2. This example of long-term seismogenesis was nested within the precursory seismicity in fig. 3.

swarms, each of which was easily recognisable in the catalogue. According to the model, however, the essential precursory feature is the increased level of seismicity, which would be the same irrespective of whether it included swarms or any other type of fluctuation.

Self-organised criticality in the model is evidenced not only as a background for crack formation and by fractality, but also by hierarchy. This aspect of the model is illustrated by the nesting of a low magnitude seismogenic process within the East Cape sequence. The relevant seismicity is shown in fig. 4, which is a detail taken from fig. 3; the scale is about one order smaller. The mainshock in fig. 4 is the largest of the precursory earthquakes in fig. 3; it has magnitude M_L 5.9, compared with M_L 7.0 for the mainshock in fig. 3. The area occupied in fig. 4 is smaller than in fig. 3 by a factor of 11.4. This scaling factor can be compared with the value 12.6 given by Utsu's (1970) formula for the area occupied by aftershocks as a function of mainshock magnitude. The magnitude threshold in fig. 4 is taken as $M_c = 3.5$.

The broad similarity between fig. 2, fig. 3 and fig. 4 is striking. In fig. 4 the average rate before the onset was 1.0 M.U./yr, while the average for period «a» was 3.2 M.U./yr, representing an increase by a factor of 3.2. The corresponding factors in fig. 2 and fig. 3 were 2.6 and 3.4 respectively, as mentioned above. Values obtained in Greece range from 1.9 to 7.7 (Evison and Rhoades, 2000).

The relations between precursory seismicity and mainshock in fig. 4 are in good accord with the published predictive regressions for swarms (*e.g.*, Evison and Rhoades, 2000). These are

$$M_m = 3.1 + 0.67 M_p \qquad (7.3)$$

$$\log_{10} T_p = 1.3 + 0.40 M_p \qquad (7.4)$$

where M_p is the swarm magnitude, M_m is the mainshock magnitude, and T_p is precursor time; the values for the sequence in fig. 4 are $M_p = 4.2$, $M_m = 5.9$, and $\log_{10} T_p = 3.1$. The swarm occurred late in 1981, and is easy to recognize in fig. 4B. (The large East Cape sequence in fig. 3 is already included in the regression data). Thus the seismogenic model applies equally to the large East Cape earthquake sequence and the small sequence nested within it. And while, on the larger scale, self-organised criticality is the accepted condition during the precursory period (fig. 3, bracket «a»), the same time-interval, considered on the space-time scale of fig. 4, includes an entire seismogenic process, with predictability of the small mainshock.

Recognizing in practice that a particular mainshock is in preparation depends on searching the catalogue on the appropriate scale. In other words, one needs to search an area of appropriate size, for earthquakes of appropriate magnitude, over a time-period of appropriate duration. As in figs. 2, 3, and 4, the seismogenic process will then be revealed by a cumulative magnitude analysis. That so simple a precursor as an increase in seismicity has not hitherto been widely observed is accounted for by the need to scale, in unison, the area, magnitude and time. Further, the duration of the precursory anomaly is much longer than what has usually been supposed: for the Arthur's Pass and East Cape earthquakes it was nearly 20 years.

8. Conclusions

The model of seismogenesis described here displays some features that have been obtained by other types of modelling. Numerical modelling by Mikumo and Miyatake (1983) illustrates in detail how the degree of uniformity of the medium affects the type of earthquake event that occurs with increasing stress. A simulation model devised by Yamashita and Knopoff (1992) starts with a three-dimensional fractal assemblage of cracks, in a non-linear rheology, and reproduces the phenomena of precursory seismicity, quiescence, foreshocks, and mainshock. In the present model, this corresponds approximately to the stages of minor fractures, healing of minor fractures, and major fracture (fig. 1). Without explicitly invoking the Mogi criteria, Yamashita and Knopoff (1992) found that cracks and fractures constituted non-uniformity in the medium, and that a crack would «cast a stress shadow» on the adjacent medium.

The present model does not apply to intermediate or deep earthquakes, since precursory seismicity and aftershocks are usually observed only at shallow levels. In the model, these minor-earthquake phenomena which accompany major earthquakes are dependent on the occurrence of cracking and healing. It is inferred that at depth the faulting phenomenon may not include these stages, but consist solely in fracture.

The model implies that the major earthquake would be most effectively predicted if one could observe the formation of the major crack. This should give the most direct determination of the earthquake parameters. Such an approach may be not unreasonable in view of recent advances in seismic tomography. In the meantime, good estimates are obtainable from the seismicity changes which the model indicates, and observation supports, as a consequence of the major crack formation; the location, scale and timing of the seismogenesis all depend on the major crack, and are quantified in the precursory seismicity.

Finally, the model is capable of being tested in a variety of ways. Formal tests based on the swarm as representative of the precursory seismicity are in progress in New Zealand (Evison and Rhoades, 1993, 1997), Japan (Evison and Rhoades, 1999b), and Greece (Evison and Rhoades, 2000). Similar tests can be set up in other regions where the catalogues are adequate. Referring more specifically to the model, the postulated three stages of faulting imply changes to the medium, and these may be detectable as variations of anisotropy, scattering or absorption.

Acknowledgements

The authors thank E.G.C. Smith, R. Robinson and two anonymous reviewers for helpful comments. This work was supported by the N.Z. Foundation for Research, Science and Technology under Contract No. CO5X0006.

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(received August 9, 2000;
accepted December 20, 2000)