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Precursory small earthquake migration patterns

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ABSTRACT

Seismic precursors revealed by statistical physics methods are important for earthquake forecasting and helpful for understanding fault behaviour. One of the precursors, earthquake migration, has been observed in simulated models and rock experiments, as well as anecdotal observations for large earthquakes along major fault zones. However, there has been no systematic methodology for investigating earthquake migration in nature, and only a small number of studies have observed earthquake migration at large scales. In this work, we show that migration of small earthquakes towards the epicentre before large earthquakes can be visualized. We present a method for detecting small earthquake migration in the spatiotemporal domain, and retrospectively apply it to two recent examples of major earthquakes in Taiwan. We observe that anomalous seismicity occurs increasingly close to the epicentre as the occurrence time is approached. At that point, the bulk of the seismicity concentrates on the epicentre, accumulating stress on the rupture zone and leading to the full rupture. Our findings imply a new type of large-scale pre-seismic earthquake migration pattern that is complementary to the well-studied patterns of source-region activation and quiescence.

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Introduction

To gain insight into earthquake physics, statistical physics methods are applied to the study of seismicity and to the anomalous seismic activity seen before large earthquakes, such as quiescence, activation and migration (Shaw *et al*., 1992; Bowman *et al*., 1998; Jaumé and Sykes, 1999; Hainzl *et al*., 2000; Zoller and Hainzl, 2002; Zoller *et al*., 2002; Chen, 2003; Chen and Wu, 2006). These 'observed' seismic activities are examined because earthquake fault systems evolve via stress changes representing complex unobservable dynamics. Although it is hard to understand earthquake behaviour without knowledge of the unobservable underlying dynamics, a pattern dynamics can be constructed from observed seismicity (Rundle *et al*., 2000a,b; Tiampo *et al*., 2002a). To study how this anomalous seismic activity and large earthquakes are related, Rundle *et al*. (2000a,b) used the pattern informatics (PI) method, in which earthquake count represents one of the important state variables in a pattern dynamical system to identify changes in that system. Investigating the anomalous seismicity caused by the preparation process through statistical methods helps us understand how large earthquakes are generated and leads us towards the possible ways of earthquake prediction.

In our previous works (Wu *et al*., 2008a,b), we observed in a temporal scale the anomalous migration activity induced by small earthquakes, using a dynamic version of the PI method. This kind of migration behaviour, which has also been observed in simulated models and rock experiments (Ohnaka and Kuwahara, 1990; Rice, 1992; Lapusta and Rice, 2003), highly attracted our attention. As there had been no systematic methodology for investigating the spatiotemporal behaviour of seismicity migration patterns before, only few studies had found the migration activity at such a large scale as the Nature. To construct a methodology for spatiotemporally understanding such migration activity, here in this article, we have further improved the PI method to visualize the migration pattern based on a two-dimensional (2D) map. This new invention is retrospectively applied to reveal spatiotemporal migration activities preceding the 1999 Chi-Chi and the 2006 Pingtung earthquakes, two of the major events to strike Taiwan during the last 50 years. An important result of this work is the retrospective observation that anomalous seismicity associated with small earthquakes approaches the epicentre before the main shock.

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PI method and its new modification

The PI approach can be used to identify anomalous areas with high seismicity fluctuations for revealing the likely epicentral locations of future large earthquakes (Rundle *et al*., 2000a; Tiampo *et al*., 2002a,b; Chen *et al*., 2005; Holliday *et al*., 2007; Wu *et al*., 2008a). In the PI calculation, we consider the seismicity rate as the state vector in the earthquake dynamical system to investigate the system fluctuation in a change interval from t_1 through t_2. Firstly, the study region is divided into grid boxes with $0.1^\circ \times 0.1^\circ$ and the time parameters including the beginning of earthquake data t_0 and the change interval (t_1, t_2) are chose. As the original PI method is intended to be a promising candidate for earthquake forecasting method, the parameter of t_2 is usually supposed to be the current time. However, for the retrospective purpose here, t_2 is presumed to be the time just before two large Taiwanese earthquakes studied. In our earlier studies (Chen *et al*., 2005; Wu *et al*., 2008a), the determination of t_1 was mainly based on the frequency–magnitude analysis which reveals the self-organized spinodal-like behaviour of seismicity (Rundle *et al*., 2000c). Taking the method a step further, we very recently proposed the *dynamic* PI method, using a set of t_1 (Wu *et al*., 2008b), to measure the spatiotemporal variation in the locations of seismicity anomalies.

We define the seismic intensity $I(x_i, t_b, t)$ as the number of earthquakes with magnitudes larger than the cut-off magnitude M_c that occurred in a grid box x_i and its eight neighbouring boxes (the Moore neighbours) during the span from t_b through t. The seismicity intensity change between t_1 and t_2 is thus defined as $\Delta I(x_i, t_b, t_1, t_2) = I(x_i, t_b, t_1) - I(x_i, t_b, t_2)$ and briefly denoted as $\Delta I(x_i, t_b)$, where t_b is a reference sampling time and is shifted from t_0 to t_1 for eliminating the random fluctuation in seismicity intensity. We further remove the background value of seismicity intensity change by subtracting the temporal and spatial means and then dividing by their standard deviation. Seismic anomalies such as activation and quiescence would be then indicated by large positive and negative values of *normalized* intensity change. To include both of the seismic anomalies, we can take the absolute value and then its temporal average. Finally, the occurrence probability (i.e. the PI value) of threshold events is indicated by the mean-squared change. For details of the PI calculation used in this study, we refer the readers to the papers of Chen *et al.* (2006) and Wu *et al.* (2008a).

The grid boxes with the occurrence probability larger than some threshold value are then colour coded to show *hotspots* on a map. As the number of PI hotspots is dependent on the decision threshold for the probability, the higher the decision threshold is the less the hotspot number is. The area A_H covered by hotspots would then give a fraction $f = A_H/A$ of the map whereas the total area of the map is A. The less the hotspot number is the smaller the fraction f is. That is, a higher fraction f of the map indicates a lower decision threshold for the PI value. We have found before that the anomalous seismic activity shown by PI hotspots migrates with time (Wu *et al.*, 2008a,b). To study the temporal migration of PI hotspots around a specific grid site, we define the nearest distance from PI hotspots to that grid site as the error distance (Wu *et al.*, 2008b). As the error distances grow in general with a decreasing fraction f, we integrate from $f = 0$ to $f = 1$ the curve of the error distances vs. f to obtain an *integrated* error distance.

We then investigate the change of integrated error distances with time. The migration of the anomalous seismic activity with regard to a specific grid site could be observed by calculating the integrated error distances using a set of t_1 shifted every 3 months. The hotspot migration could be further quantified by fitting the curve of the integrated error distance vs. slid t_1. In our previous study (Wu *et al.*, 2008b), we arrived at the conclusion that PI hotspots leaving a site would produce a curve of integrated error distance vs. time with an increasing trend and a positive slope if the curve were fit linearly. In contrast, integrated error distances decrease overall and have a negative slope when PI hotspots approach a site. Locations without significant anomalous seismicity change, that is, with no PI hotspots, would have flat trends and slopes close to zero. To observe the migration pattern over the entire study region, we calculate the slope of the curve of integrated error distances vs. time for every grid site. We then image it on a 2D map to visualize the migration of PI hotspots and obtain a 2D PI migration map.

Results

We retrospectively apply our method abovementioned to the 21 September 1999 M7.6 Chi-Chi, Taiwan earthquake, and the 26 December 2006 M6.7 and M6.4 Pingtung offshore doublet earthquakes. These earthquakes were the most destructive earthquakes in the last 50 years and were examined in this study. We used the earthquake catalogue maintained by the Taiwan Central Weather Bureau (CWB). Events with magnitudes greater than 3.7 and 3.2 and depths ranging from 0 to 20 km and from 30 to 100 km, respectively, were used for these two cases. For the selection criteria of earthquakes in the analysis, we refer the readers to

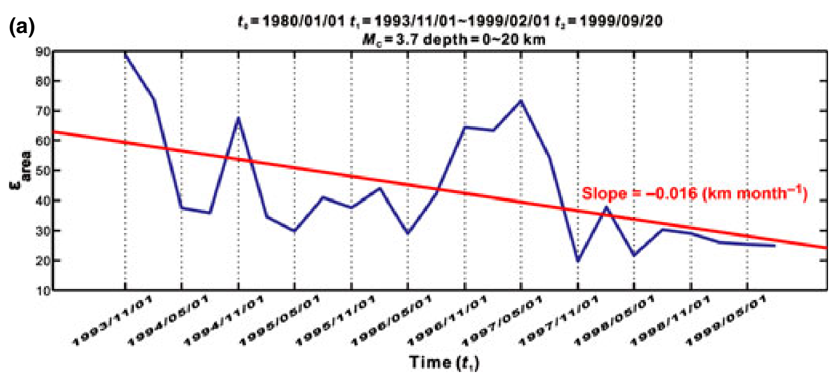

Fig. 1 (a) The blue curve shows the change of the integrated error distances (labelled as ε_{area}) of the Chi-Chi earthquake, and the linear fit is shown in red. The slope of −0.016 (±0.006) corresponds to a decreasing trend. Here, time moves from 1993/11/01 to 1999/02/01, constrained by the time period running from Stage 2 to Stage 3 in the SOS model. (b) The results for the Pingtung earthquake also show a decreasing trend; the slope is −0.024 (±0.007). The time period used here is 2002/03/01 to 2006/06/01 for the same reason as given above. For interpretation of color references in figure legend, please refer to the Web version of article.

our early papers of Chen *et al.* (2005) and Wu *et al.* (2008a,b).

In addition to verification of the existence of migration, we were most interested in the duration of the migration, which is part of the evolution of the earthquake fault system. The self-organized spinodal (SOS) model (Rundle *et al.*, 2000c; Chen, 2003), which illustrates that the earthquake cycle from one characteristic earthquake to another can be divided into three periods, is helpful to construct the timetable of earthquake evolution. According to the SOS model, a large earthquake evolves from Stage 1 to Stage 3 and matures at the spinodal point. The number of moderate events is systematically low in Stage 1, followed by an increase in Stage 2, and a further increase in the last stage, implying activation of moderate earthquakes. As shown from the Gutenberg–Richter relation (Chen, 2003), Stage 2 of the SOS model for the Chi-Chi earthquake occurred between November 1993 and January 1998, and Stage 3 occurred from that point until the occurrence of the Chi-Chi earthquake. The same mode of seismicity can be also observed for the Pingtung earthquake (Wu *et al.*, 2008a). An increase in moderate earthquakes appeared from March 2002 to March 2004, and a further increase occurred thereafter. As shown in Fig. 1, we shifted t_1 and calculated the integrated error distances every 3 months starting from Stage 2 of both events. The expected decreasing trends exist in the curves of the integrated error distances with time. Slopes of -0.016 (± 0.006) and -0.024 (± 0.007), respectively, obtained from fitting linearly the curves demonstrate that anomalous seismic activities migrated towards the epicentres of the Chi-Chi and Pingtung earthquakes.

Now, considering the migration in space, we can visualize the spatial pattern of seismicity migration on a 2D map by making the temporal migration curve (i.e. the curve of integrated error distance vs. time) and calculating its slope for each grid site over the studied region. As shown in Fig. 2a, the negative slopes (shown in blue) concentrate in the epicentral area of the Chi-Chi earthquake (indicated by a red star) for the span of Stage 2 of the SOS model. Slopes with positive values (shown in red) and values close to 0 (no colour) form a toroidal pattern ('Mogi donut') around the epicentral area, showing that PI hotspots (anomalous seismic activity) migrated towards the epicentre of the Chi-Chi earthquake. The result becomes featureless (i.e. a purely white map), with all slope values close to 0, after randomizing the catalogue in time and space. The same behaviour (Fig. 2b) exists in the case of the Pingtung earthquake. Two stars in Fig. 2b indicate the epicentres of the Pingtung doublets. Near the epicentres, a toroidal migration pattern is again observed, which indicates that anomalous seismic activity migrated towards the epicentral area of the Pingtung doublets. To demonstrate that the migration pattern is induced by the spatiotemporal process of real seismicity, we also made a null hypothesis that is the same migration pattern can be also observed in a random dataset by using the same PI method. We randomly shuffled the occurrence times and locations of the

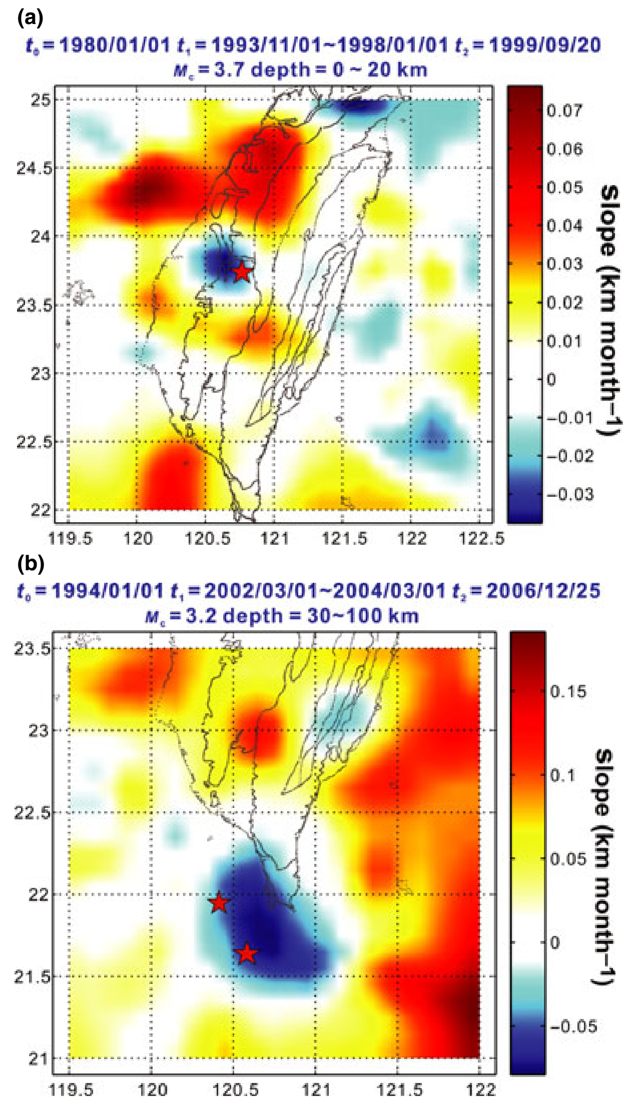

Fig. 2 (a) The Colour bar and colour scale were obtained by calculating the slope of the integrated error distance curve on every grid; sites with a negative or positive slope are coloured blue or red, respectively, except for sites with slopes close to 0. The red star corresponds to the epicentre of the Chi-Chi earthquake. Around the epicentre, the migration presents a toroidal pattern. (b) The red stars indicate the Pingtung doublets; a toroidal migration pattern was also observed near the epicentre. For interpretation of color references in figure legend, please refer to the Web version of article.

events, this random shuffling process is supposed to generate many surrogate catalogues having the same aggregate statistics as real seismicity, for example, the Gutenberg–Richter frequency–magnitude distribution, but totally different spatiotemporal processes. The perturbed seismicity shows the results against the null hypothesis. The result becomes featureless (i.e. a purely white map), with all slope values close to 0 for both of the Chi-Chi and Pingtung earthquakes, after randomizing the catalogue in time and space. From this null hypothesis test for both cases, we are able to show significantly that the migration was caused by precursory small earthquakes associated with the plausible preparation process of the main shock.

Note that shown in Fig. 2 is basically the migration behaviour for the span of Stage 2 of the SOS model only. A slightly different pattern is obtained by using the different time period combining Stages 2 and 3 of the SOS model, as shown in Fig. 3 for the cases of the Chi-Chi and Pingtung earthquakes. Weaker migration patterns before the Chi-Chi and Pingtung earthquakes, that is, weaker toroidal patterns compared with Fig. 2, were generated when both anomalous seismic activities during Stage 2 and Stage 3 of the SOS model were considered together.

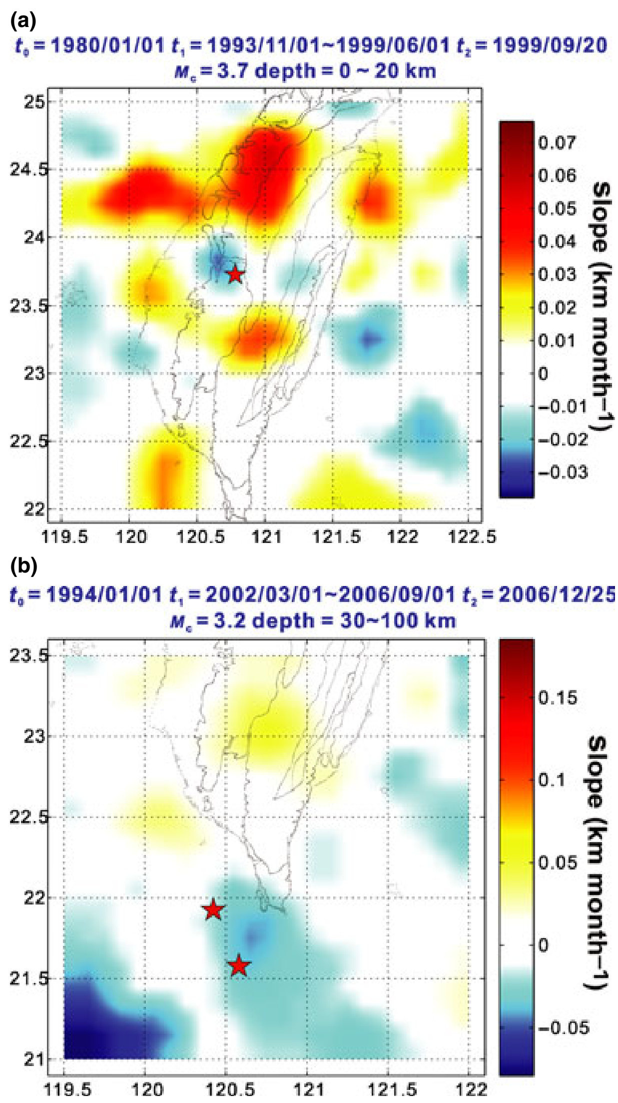

Fig. 3 (a) Same as Fig. 2a but with a span of covering Stages 2 and 3, as shown in the headline, for the Chi-Chi case. (b) The result for the Pingtung case when using the span of covering Stages 2 and 3.

Discussion and conclusion

The PI method (Rundle *et al*., 2000a; Tiampo *et al*., 2002a,b; Chen *et al*., 2005; Holliday *et al*., 2007; Wu *et al*., 2008a) has been used to examine anomalous seismic activity, including activation and quiescence before large earthquakes, for a specific space–time window. However, seismic activity does not occur at the specific location in a constant rate. Therefore, it is the space–time flow of small earthquake activity that we must examine to illuminate the source process of a forthcoming major earthquake. We have modified the PI method to investigate the time- and space-varying patterns calculated from seismicity change in a progressive series of time intervals (Wu *et al*., 2008b). Using this modification, we observe a decreasing trend in the distance between PI hotspots and epicentres of large forthcoming earthquakes and obtain the slope by fitting the trend. In this study, we further expand such a technique to a whole-studied region, calculating and imaging the slope at every site. A striking donut-like pattern shows that the PI hotspots migrate towards the epicentres of large forthcoming earthquakes not only in time but also in space domains. This observation offers a plausible evidence that cracks nucleate around the epicentre and accumulate stress until the whole fault ruptures. This study therefore represents a novel approach to the understanding of the process of anomalous seismicity migration associated with a large forthcoming event.

Our results suggest a preparation process before large earthquakes as following. We learned by examining many time sets that the migration is concentrated in Stage 2 of the SOS model. The variation of the integrated error distances in time (Fig. 1) also revealed similar information: it stopped decreasing after Stage 3 began. However, the PI maps (Wu *et al*., 2008b) tell us that the hotspots, which represent the anomalous earthquake activities, still acted on the epicentral area. In other words, anomalous seismicity merged into the epicentral region after the number of moderate events began to increase. Activation was maintained inside the region because additional moderate events occurred until the large earthquake struck. The activation performed by accelerating seismicity in Stage 3 seemed to trigger a large earthquake. Many previous investigators (Mogi, 1969; Raleigh *et al.*, 1982; Sykes and Jaumé, 1990; Knopoff *et al.*, 1996; Bowman *et al.*, 1998; Bowman and King, 2001) have explored the problem of accelerating seismicity and have attempted to predict the time of the upcoming main shock. One reasonable explanation for the different developments of anomalous seismicity in Stage 2 and Stage 3 of the SOS model is that the process of migration in Stage 2 may be associated with crack nucleation. This assumption implies that seismicity will tend to migrate towards the direction of fault growth (Scholz, 2002) and that stress accumulates on the asperity that is near to or surrounded by the cracks.

As a final remark, we suggest that the proposed PI migration map could be extended to be a potential tool of earthquake prediction. Precursory phenomena associated with large earthquakes are without question complicated, so that an operational algorithm for earthquake prediction is absolutely far beyond the scope of this study. Our retrospective analyses presented here have been, however, demonstrated two examples with the distinct donut-like migration patterns before large forthcoming earthquakes. Following the strategy described in PI method and its new modification, for the purpose of real-time prediction, it is possible to make the PI migration map, for example, every half years regularly to observe if the toroidal migration pattern appears and develops around some area. Yet, for verifying if the precursory migration pattern is crucial to the generation of large earthquake, an alternative way is to make the migration maps for large events worldwide occurred in the last two decades. We can then place the proposed method to a testable statistical playground for understanding the nucleation and migration hypothesis of great earthquake, which we will postpone to the future works.

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