

Forecasting the epicenter of a future major earthquake

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Although earthquake forecasting is a highly controversial issue, scientists are continuing to find valuable precursors of earthquakes (EQs). Among various precursors, seismicity changes play an important role in intermediate-term forecast study and have been tested for a long period (1, 2). Despite the debates (3) on short-term precursors, such as seismic electric signals [SES, low frequency (≤ 1 Hz) transient changes of the Earth's electric field], the knowledge accumulated during the long-term observations of SES data have led to the conclusion that the average lead time of SES activities is a few months (Fig. 1) (4, 5). Such a conclusion reflects that there exists a crucial time scale (e.g., a few months) at which the system enters the critical stage before a major EQ (6). Inspired by this conclusion, natural time analysis, which uncovers

hidden properties in complex time series (7), has revealed that the fluctuations of the order parameter of seismicity exhibit a minimum of a few months before major EQs (Fig. 1) (8). In PNAS, Sarlis et al. (9) present a novel approach to forecasting the epicenter of a future major EQ from natural time analysis of seismicity.

Forecasting a future epicenter plays a key role in seismic risk mitigation. There are many approaches concerning this issue from the seismicity analyses of conventional statistical seismology: for example, the b -values (relative size distributions) of seismicity data (10), the spatial forecast methods based on rates of seismicity and pattern informatics method (1, 11), the spatiotemporal variations of seismic quiescence (quantified by the Q -parameter taking into account the

occurrence time, epicenter, and magnitude of EQs) (12, 13), and so forth. However, almost all of these attempts focus on the long-term or intermediate-term, rather than the short-term (which receives more attention in both the science and social community because of its imminent impact on EQ hazards).

Different from the above seismicity analyses, SES data accumulated since 1981 in Greece show interesting results for short-term forecasting. The epicenter of a forthcoming EQ can be determined on the basis of SES data with an accuracy of 100 km using the selectivity map (4) of the station that recorded the SES. The initiation of an SES activity marks the time at which the system enters the critical stage, with a lead time of a few months from the occurrence of the forthcoming major EQ (Fig. 1). However, such an approach cannot determine more precisely when the system will approach the critical point (main shock occurrence).

Taking advantage of natural time analysis (e.g., an order parameter exists in natural time by which one can identify the approach of a dynamical system to the critical point, which is hard to identify in conventional time), Varotsos et al. (14) analyzed the Japan Meteorological Agency (JMA) EQ catalog in natural time and found that there exists a direct interconnection of SES and seismicity. In particular, the fluctuations of the order parameter of seismicity exhibited a minimum at the time of the initiation of a pronounced SES activity (5, 15) and a geomagnetic variation (5, 16) recorded about 2 mo before the Izu volcanic-seismic swarm activity in 2000. These two phenomena were found to be linked also in space (14). Further analyses of the JMA catalog from January 1, 1984 to March 11, 2011 (the day of the $M_w 9.0$ Tohoku EQ) in natural time indicated that the fluctuations of seismicity in the entire Japanese region exhibited distinct minima a few months before all of

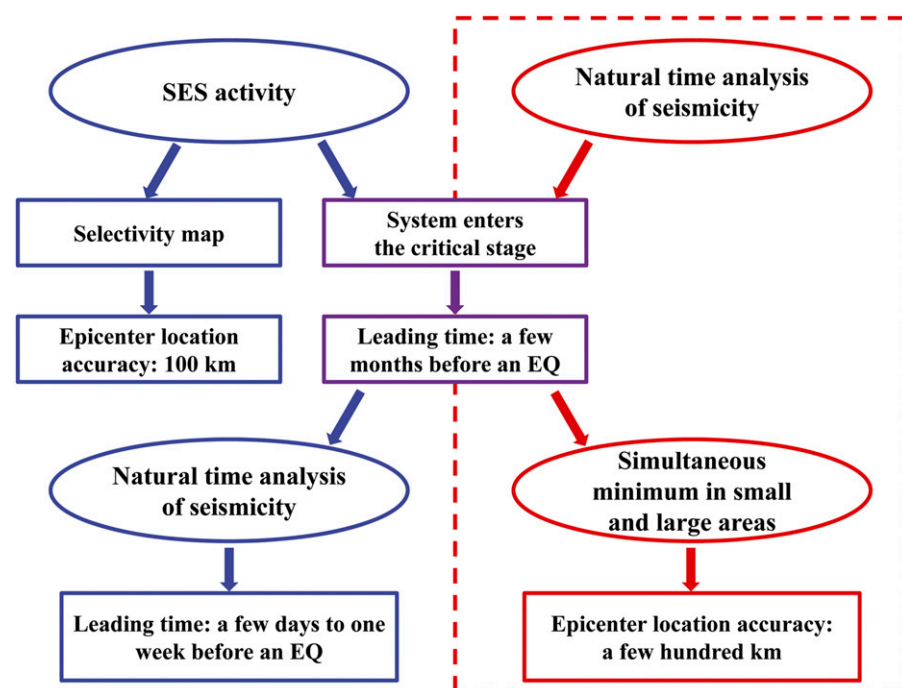


Fig. 1. Research procedures of SES and seismicity data. The red dashed rectangle indicates the main contributions of Sarlis et al. (8). After identifying the initiation of critical stage by analyzing seismicity in natural time in the large area, the authors propose an epicenter forecasting method by searching for the simultaneous characteristic change in small and large areas.

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the $M \geq 7.6$ shallow EQs (8). The deepest minimum was observed before the $M_w 9.0$ Tohoku EQ on January 5, 2011, which remarkably almost coincides with the initiation of anomalous geomagnetic variations observed 135 km from the epicenter (17).

It should be mentioned that if SES data are available, it would be possible to further enhance the forecasting capability in time (e.g., to narrow the lead time within a few days to 1 wk) (Fig. 1) by combining SES data with natural time analysis of the subsequent seismicity (7).

Taking into account that seismicity data are available everywhere but SES data are not, it is important to develop an approach to forecasting the epicenter of a future major EQ solely from seismicity data. Natural time analysis of the JMA catalog identified a characteristic change (i.e., exhibiting minimum of the fluctuations of the order parameter) of seismicity in the entire Japanese region a few months before each major EQ with $M \geq 7.6$ (including the 2011 $M_w 9.0$ Tohoku EQ). By dividing the entire investigated region (hereafter large area) into small areas and investigating the characteristic change of seismicity in a natural time domain between the sliding small areas and the large area, Sarlis et al. (9) found that a few months before each major EQ, some small areas show the characteristic change almost simultaneously with the large area and such small areas are clustered within a few hundred kilometers from the actual epicenter. Their report proposes a general method of forecasting the epicenter of a future major EQ from seismicity analysis in a natural time domain (see the procedure

given in the red dashed rectangle in Fig. 1). This new procedure can be applied to other EQ-prone areas and, hence, advances our knowledge on short-term earthquake forecasting. Of course, many intriguing questions toward a practical EQ forecast [the advance warning of potential EQ with enough accuracy in time, space, and magnitude to warrant actions that may prepare communities for a potential disaster (18)] remain and deserve further study. How do we ensure the reliability of the revealed precursors? What's the relationship between the characteristic change of seismicity order parameter and the stress evolution of the forthcoming major EQ? Is it a general phenomenon that multi-

physical quantities (e.g., seismicity, electric field, magnetic field, deformation, and so forth) exhibit consistent changes before major EQs and what's the inside physics of this phenomenon? Answers to these challenging questions would enrich our understanding of major EQs and provide a road map for EQ forecasting through interdisciplinary, physics-based investigations of EQ systems across a wide range of spatial and temporal scales.

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