COMMENTARY

Forecasting the epicenter of a future major earthquake

Qinghua Huang[1]
Department of Geophysics, School of Earth and Space Sciences, Peking University, Beijing 100871, China

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_w9.0 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

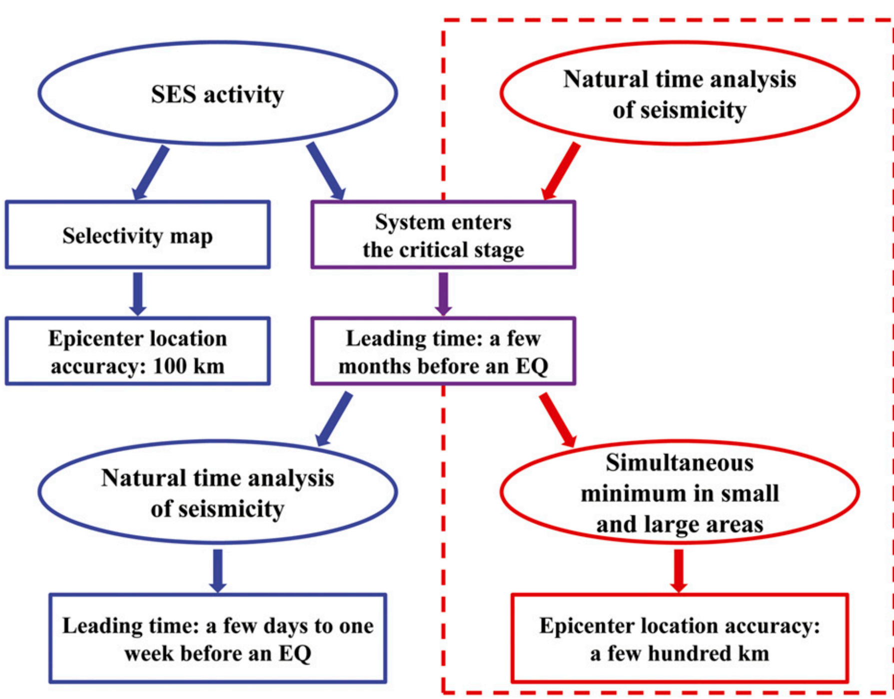

Fig. 1. Research procedures of SES and seismicity data. The red dashed rectangle indicates the main contributions of Sarlis et al. (8). After identifying the initiation of critical stage by analyzing seismicity in natural time in the large area, the authors propose an epicenter forecasting method by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

Author contributions: Q.H. wrote the paper.

The author declares no conflict of interest.

See companion article on page 986.

[1]Email: huangq@pku.edu.cn.

www.pnas.org/cgi/doi/10.1073/pnas.1423684112

the $M \geq 7.6$ shallow EQs (8). The deepest minimum was observed before the M_w9.0 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_w9.0 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.

ACKNOWLEDGMENTS. This work is supported in part by the National Science Fund for Distinguished Young Scholars (41025014), the National Special Research Fund for Earthquakes (200808069), and the Research Fund for the Doctoral Program of Higher Education, Ministry of Education, China (20120001110073).

1 Tiampo KF, Shcherbakov R (2012) Seismicity-based earthquake forecasting techniques: Ten years of progress. *Tectonophysics* 522:89–121.
2 Huang QH (2008) Seismicity changes prior to the Ms8.0 Wenchuan earthquake in Sichuan, China. *Geophys Res Lett* 35(23):L23308.
3 Geller R (1996) Debate on VAN. *Geophys Res Lett* 23(11):1291–1452.
4 Varotsos P (2005) *The Physics of Seismic Electric Signals* (Terrapub, Tokyo).
5 Uyeda S, et al. (2002) Electric and magnetic phenomena observed before the volcano-seismic activity in 2000 in the Izu Island Region, Japan. *Proc Natl Acad Sci USA* 99(11):7352–7355.
6 Varotsos P, et al. (2011) Scale-specific order parameter fluctuations of seismicity in natural time before mainshocks. *EPL* 96(5):59002.
7 Varotsos P, Sarlis NV, Skordas ES, Uyeda S, Kamogawa M (2011) Natural time analysis of critical phenomena. *Proc Natl Acad Sci USA* 108(28):11361–11364.
8 Sarlis NV, et al. (2013) Minimum of the order parameter fluctuations of seismicity before major earthquakes in Japan. *Proc Natl Acad Sci USA* 110(34):13734–13738.
9 Sarlis NV, et al. (2015) Spatiotemporal variations of seismicity before major earthquakes in the Japanese area and their relation with the epicentral locations. *Proc Natl Acad Sci USA* 112:986–989.
10 Schorlemmer D, Wiemer S (2005) Microseismicity data forecast rupture area. *Nature* 434(7037):1086.
11 Kafka AL, Ebel JE (2011) Proximity to past earthquakes as a least-astonishing hypothesis for forecasting locations of future earthquakes. *Bull Seismol Soc Am* 101(4):1618–1629.
12 Huang Q, Öncel AO, Sobolev GA (2002) Precursory seismicity changes associated with the $M_w = 7.4$ 1999 August 17 Izmit (Turkey) earthquake. *Geophys J Int* 151(1):235–242.
13 Huang QH, Ding X (2012) Spatiotemporal variations of seismic quiescence prior to the 2011 M 9.0 Tohoku earthquake revealed by an improved Region-Time-Length algorithm. *Bull Seismol Soc Am* 102(4):1878–1883.
14 Varotsos P, et al. (2013) Seismic electric signals: An additional fact showing their physical interconnection with seismicity. *Tectonophysics* 589:116–125.
15 Uyeda S, Kamogawa M, Tanaka H (2009) Analysis of electrical activity and seismicity in the natural time domain for the volcanic-seismic swarm activity in 2000 in the Izu Island region, Japan. *J Geophys Res* 114(B2):B02310.
16 Huang QH (2011) Rethinking earthquake-related DC-ULF electromagnetic phenomena: Towards a physics-based approach. *Nat Hazards Earth Syst Sci* 11(11):2941–2949.
17 Xu GJ, et al. (2013) Anomalous behaviors of geomagnetic diurnal variations prior to the 2011 off the Pacific coast of Tohoku earthquake (M_w9.0). *J Asian Earth Sci* 77:59–65.
18 Jordan TH (2006) Earthquake predictability, brick by brick. *Seismol Res Lett* 77(1):3–6.