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Why is the South Korean peninsula largely aseismic? Geodetic evidences

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Northeast Asia, including Korea, North China, Philippines and Japan, is one of the most seismically active regions in the world, with some of the most catastrophic earthquakes in human history. However, the South Korean peninsula has remained largely aseismic with respect to the surrounding highly-seismic areas. In this communication, we present geodetic evidence in support of the largely aseismic nature of South Korea by analysing the crustal strain and energy density rates derived from recent dense geodetic observations. The dilation rates show that Northeast Asia is under high WNW–ENE oriented compressional strain regime, but the rates are lower in South Korea. In addition, the scalar strain rates and strain energy density rates further imply that the South Korean peninsula is a stable block with low rates. High rates are mainly inferred in North China, southwest Japan and the western boundary of the Philippine Sea plate, consistent with high seismicity in these areas. Furthermore, we speculate that the low seismicity in South Korea may continue in the future.

Keywords: Earthquake, geodetic evidences, South Korean peninsula, strain energy density.

SUBDUCTION of the Philippine Sea and Pacific plates and expulsion of the Eurasian plate with the Indian plate collision[1–5] make Northeast Asia one of the most active seismic regions (Figure 1). The Korean peninsula is located in the northeastern Asia margin, between the Chinese continent and the Japanese Island Arc. However, it has never experienced a catastrophic earthquake in the past 2000 years[6]. In contrast, the neighbouring regions such as North China, Philippines and Japan are seismically active. In addition, some researchers consider the Korean Peninsula as part of the Archean Sino-Korean craton[7] (Figure 1). If so, it is surprising that the Korean peninsula has been largely

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aseismic in the Sino-Korean craton, while North China is relatively seismically active. For instance, there was the most devastating earthquake in human history, the 1976 Tangshan earthquake ($M = 7.5$) in North China that killed >250,000 people and completely destroyed the industrial city.

Accurate measurements of crustal strain accumulated energy rates help understand tectonic features and to evaluate the earthquake potential. Now the high precision space geodesy techniques, especially the low-cost and all-weather GPS, play a key role in monitoring the crustal strain state and accumulated energy variation. Although there are several investigations in Northeast Asia using GPS observations[3–5], a joint study on the Northeast Asia kinematics has never been performed well with dense GPS observations (including China, Japan and Korea). In addition, the present-day kinematics of the tectonic deformation in the South Korean peninsula is still largely unknown due to lack of observational data. In this study, we have collected all available GPS data and new Korean GPS Network (KGN) measurements in Northeast Asia and processed the dense GPS data in the uniform reference frame, ITRF2000. The derived velocity field is used to estimate the strain rates and strain energy density rates, in an attempt to verify the aseismic behaviour of South Korea and to assess the future earthquake risk potential.

In Northeast Asia, there are some larger GPS networks such as the Crustal Motion Monitoring Network in China (CMMN) established in 1991, the Crustal Motion Observation Network of China (CMONOC) established in 1988 by the State Seismological Bureau of China and GPS Earth Observation Network (GEONET), established in 1996 by the Geographical Survey Institute of Japan. Combining the recently established permanent Korean GPS network (KGN)[8], there are more than 2000 GPS sites distributed throughout Northeast Asia. Here we collect all available GPS data (January 1999 to December 2004) in and around South Korea and process them in the ITRF2000 reference frame[9] using GAMIT software[10] with IGS precise orbits and IGS earth rotation parameters. The site velocities are estimated by least square linear fitting to time variation of the daily coordinates for each station. All station velocities are referred to the stable Eurasian plate[11] and are shown in Figure 2. It is seen that the China and South Korea blocks are moving southeastward at about 5–9 mm/yr with respect to the Eurasian plate and converging with the southwest Japan block. In addition, the velocities of all GPS sites in the South Korea and China blocks are almost consistent, indicating that they are almost rigid blocks. However, South Korea is seismically quiet compared to the high seicmicity zone in North China.

Monitoring the pattern of crustal strain and comprehensive understanding of strain accumulation intensity are beneficial to reveal the physical process of crustal tectonic activities and to evaluate earthquake risk. As the first step in earthquake risk potential evaluation in Northeast Asia, the strain parameters were derived from the estimated GPS displacement rate field. In order to reduce the effects of abnormal site motions, the subnetwork with four GPS sites was used to estimate the strain parameters. The crustal strain rates in South Korea was derived from GPS horizontal deformation velocities[12]:

$$v_{ei} = \frac{\partial v_{ei}}{\partial x_{ei}} x_{ei} + \frac{\partial v_{ei}}{\partial x_{ni}} x_{ni}, \qquad v_{ni} = \frac{\partial v_{ni}}{\partial x_{ei}} x_{ei} + \frac{\partial v_{ni}}{\partial x_{ni}} x_{ni}, \qquad (1)$$

where v_{ei} and v_{ni} are the east and north component velocities at the site i located at (x_{ei}, x_{ni}). Strain components $\dot{\varepsilon}_{ee}$, $\dot{\varepsilon}_{nn}$ and $\dot{\varepsilon}_{en}$ are expressed as $\partial v_e/\partial x_e$, $\partial v_n/\partial x_n$ and $\frac{1}{2}((\partial v_e/\partial x_n) + (\partial v_n/\partial x_e))$ respectively. The dilation rates (Figure 3) show that Northeast Asia is under compressional strain regime at WNW–ENE, consistent with the focal mechanism of earthquakes in Northeast Asia (Figure 1). The high dilation rates appear in North China, south-

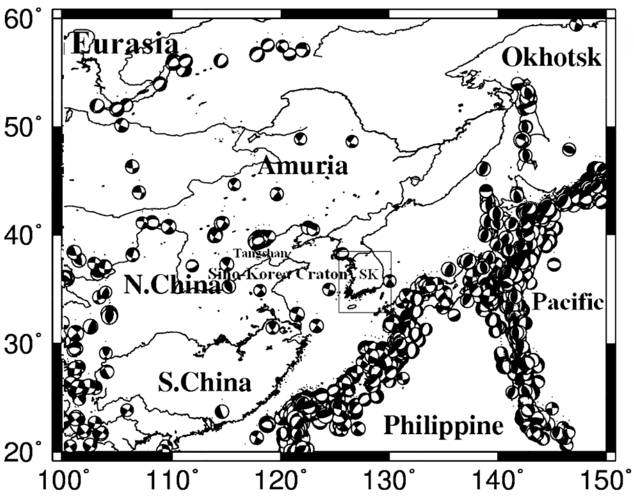

Figure 1. Earthquake epicentre distribution in Northeast Asia with $Mw > 5.0$ from 1976 to 2005. Solid and open quadrants in the beach balls denote extension and compression respectively. South Korea (SK) is represented by a rectangle.

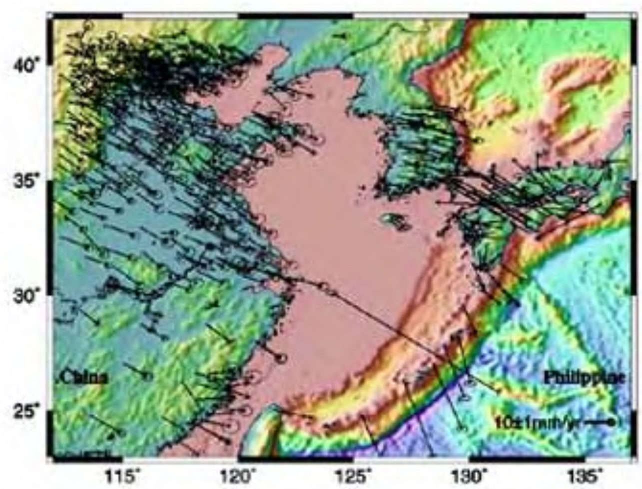

Figure 2. Crustal deformation rates in the Eurasia plate fixed reference frame. Error ellipses are 95% confidence limits.

west Japan and at the western boundary of the Philippine Sea plate. The strong compression rates are probably caused by the extrusion force due to the subduction of the Philippine Sea and Pacific plates, and the expulsion of the Eurasian plate with the Indian plate collision, causing frequent earthquakes in these regions. Inversely, the South Korean peninsula block has relatively lower dilation rates, indicating a lower indirect effect of push and subduction forces or as if such forces are transmitted through the South Korean peninsula without causing any deformation/strain. This may be attributed to the strong rheology and/or absence of relatively weak zones in the region.

In addition, we estimate the scalar strain rate, defined as

$$\dot{\varepsilon} = \sqrt{\dot{\varepsilon}_{ee}^2 + \dot{\varepsilon}_{nn}^2 + 2\dot{\varepsilon}_{en}^2}\ , \quad (2)$$

where e and n are the east and north directions respectively. Figure 4 shows the contour map of scalar strain rates in Northeast Asia, implying that the South Korean peninsula and South China are stable blocks with low strain rates. It once again highlights that high strain rates concentrate in North China, southwest Japan and the western boundary of the Philippine Sea plate, consistent with the high seismicity in these areas (Figure 1).

The accumulated strain energy is generally released through earthquakes until the adjacent fault blocks or plates reach a new state of equilibrium[13,14]. Therefore, release of tectonic strain energy stored within the crustal rock is the cause of major earthquakes. The strain energy per unit volume (i.e. the strain energy density) is an important index reflecting the intensity of crustal activities, and its variation rate indicates the long-term trend of accumulated energy within the crust. Larger the variation rate of strain energy density, higher is the energy accumulated in the crust, which would more probably result in earthquakes. Therefore, for earthquake risk evaluation and prediction, it is important to estimate the strain energy density from surface displacement observations and determine the state of strain energy density within the crust and its temporal variations.

For an elastic body, the strain energy equals the work done by external forces and its density is the strain energy per unit volume. The general tensor form for strain energy density can be expressed in terms of strain and stress using Hooke's Law:

$$U = \frac{1}{2}\sigma_{ij}\varepsilon_{ij}, \quad (3)$$

where U is the strain energy density (J m^{-3}), and σ_{ij} and ε_{ij} are the stress and strain respectively. The variation rate of strain energy density can be further derived from eq. (3) as

$$\dot{U} = \frac{1}{2}(\dot{\sigma}_{ij}\varepsilon_{ij} + \sigma_{ij}\dot{\varepsilon}_{ij}), \quad (4)$$

where $\dot{U}$ is the variation rate of the strain energy density (J m^{-3}/yr), and $\dot{\sigma}_{ij}$ and $\dot{\varepsilon}_{ij}$ are the stress rate and strain rate respectively. The stress and stress rates are obtained using the laws of elasticity theory as follows[15,16]:

$$\sigma_{ij} = 2\mu\varepsilon_{ij} + \delta_{ij}\lambda\Delta\,, \quad (5)$$

$$\dot{\sigma}_{ij} = 2\mu\dot{\varepsilon}_{ij} + \delta_{ij}\lambda\dot{\Delta}\,, \quad (6)$$

where μ is the modulus of rigidity, λ the Lame parameter, δ_{ij} Kronecker delta and Δ and $\dot{\Delta}$ are the 2D surface dilation ($\sum_{i=1}^{2}\varepsilon_{ii}$) and dilation rate ($\sum_{i=1}^{2}\dot{\varepsilon}_{ii}$) respectively. For Poisson's ratio $\nu = 0.25$, $\lambda = \mu$, modulus of rigidity is assumed to be the standard value of 3×10^{10} Pa (ref. 17). The stress (σ_{ij}), strain (ε_{ij}) and their rates can be derived from GPS displacements (1999–2004) and velocities respectively. Using eq. (4), the strain energy density variation rate in Northeast Asia can be obtained using the derived strain, stress and their rates, which are shown in Figure 5.

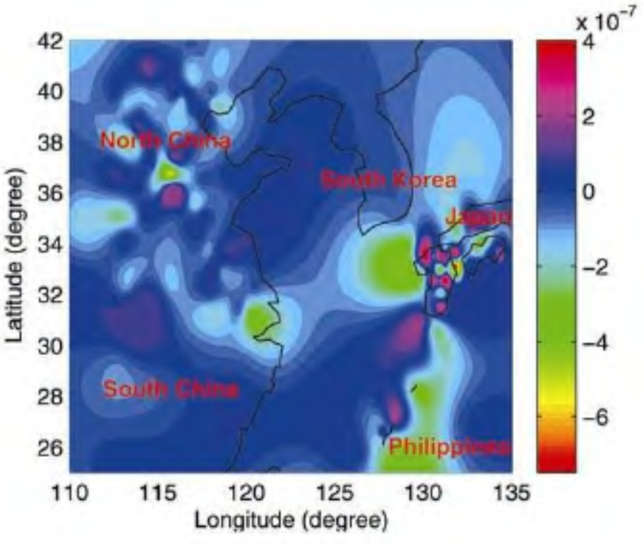

Figure 3. Dilation rate contour map in Northeast Asia.

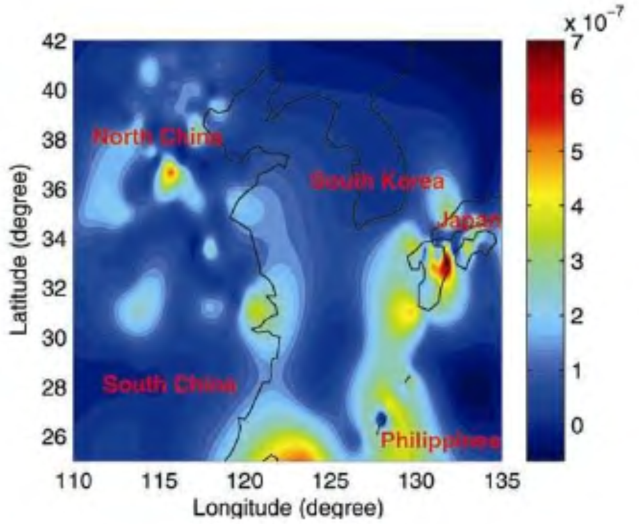

Figure 4. Contour map of scalar strain rates in Northeast Asia. Note: Very low strain rate in South Korea.

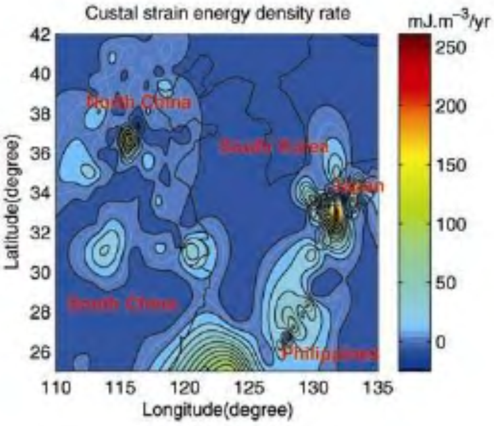

Figure 5. Variation rate of crustal strain energy density in Northeast Asia.

The distribution of strain energy density variation rates (Figure 5) shows that the most active areas are in North China, southwest Japan and the west margin of Philippine Sea plate respectively, again consistent with high seismic activity zones. As the GPS measurements are most made after the large historic earthquakes, the strain energy density rates derived from GPS displacement rates may include contributions from postseismic relaxation. These regions with anomalous large strain energy density rates probably indicate a high earthquake risk in the future, and the lower strain energy density rates in the South Korean peninsula imply that low seismicity may continue in the future.

The strain and energy density rates in Northeast Asia are investigated with GPS observations (January 1999 to December 2004). The dilation rates show that Northeast Asia is under the WNW–ENE-oriented compressional strain regime, consistent with the focal mechanism of earthquakes in the region. High dilation rates appear in North China, southwest Japan and the western boundary of Philippine Sea plate, probably caused by the compression force due to subduction of the Philippine Sea and Pacific plates and the expulsion of the Eurasian plate with the Indian plate collision. In contrast, the South Korean peninsula block has relatively lower dilation rates, indicating a possible lower effect of push and subduction forces or that such forces are transmitted through the South Korean peninsula without causing any deformation/strain. This may be attributed to the strong rheology and/or absence of weak zones in the region, which leads to fewer earthquakes. Moreover, the scalar strain rates and strain energy density rates imply that the South Korean peninsula is a stable block with low rates, and high rates mainly concentrate in North China, southwest Japan and the western boundary of Philippine Sea plate, consistent with highly seismic occurrences in these areas.

In addition, the strain energy density rate reflects a long-term trend of strain energy accumulation and release. Therefore, North China, southwest Japan and the western boundary of Philippine Sea plate with high strain energy density rates are still highly seismic and the low seismicity in South Korea with lower strain energy density rates may continue in the future.

Due to fewer GPS sites in the Philippine Sea plate and its western boundary as well as the Yellow Sea between China and Korea, the strain energy density rates and speculations need to be further investigated using more data with dense and long-time observations in the future. Moreover, the heterogeneous crust should be considered in different lithospheres of Northeast Asia.

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