Tectonic activities and deformation in South Korea constrained by GPS observations

Shuanggen Jin and Pil-Ho Park

Abstract—High precision GPS observations provide crucial insights into understanding the pattern and physical process of tectonic activities. In this paper, GPS data for the period from March 2000 to February 2004 were analyzed to quantitatively investigate the crustal deformation patterns and distributions in the southern Korean Peninsula. The high maximum shear strain rates are concentrated in the middle part of South Korea, which remarkably agrees with the shear trends in the Okcheon Belt and the Honam Shear Zone (HSZ) with a direction NE-SW. In addition, South Korea is dominated by both ENE-WSW compression and NNW-SSE extension, which is nearly consistent with earthquake focal mechanism solution ($M_w \geq 4.0$, 1936-2004), indicating that the seismicity can be used to improve GPS-derived deformation style and orientation. Furthermore, it reflects that the occurrence of shallow earthquakes in South Korea is closely related with the horizontal strain.

Key-Words—Tectonic activity, Fault, Earthquake, GPS, South Korea

I. INTRODUCTION

The southern Korean Peninsula is located in the northeastern Asia margin, which is characterized by the subduction of the Philippine Sea plate and the Southeastward expulsion of the Eurasian plate (Molnar and Tapponnier, 1975; Kogan et al., 2000; Jin et al. 2007). South Korea is composed of three Precambrian massif, Nangrim, Kyeonggi (KM) and Yeongnam (YM) massifs; and two Paleozoic basins, Pyeongnam (PB) and Okcheon (OB) sedimentary basins (Fig. 1) (Ernst et al., 1988; Kim and Lee, 2000). The earthquake activities in the southern Korean Peninsula are relatively low with about twenty events per year ranging from 2.0 to 5.5 on Richter scale. These earthquakes are shallow, ranging from 15 to 20 km in focal depths, which reflects that the intra-plate earthquakes are dominant in the southern Korean Peninsula (Jun, 1993). Fig. 2 shows the epicentral distribution (solid circles) and fault plane solutions (lower-hemisphere equal-area projection) of main 27 events with

$M_w \geq 4.0$ in and around the southern Korean Peninsula from 1936 to 2004. Solid and open quadrants respectively correspond to compression and dilatation; small solid circles in open quadrants and open circles in solid quadrants are the position of P- and T-axes, respectively.

The physical process caused by tectonic activities is quite complex. Accurate measurements of deformation pattern in the southern Korean Peninsula will contribute to understand tectonic features and evolution of the deformation belts in northeastern Asia. Now the permanent Korean GPS Network (KGN), with an average 50 km spatial interval of GPS sites, gives us the ability to obtain precise geodetic measurements with dense spatial sampling. In this paper, we are to quantitatively investigate the crustal deformation pattern and distribution of strain rates in South Korea using 4-year continuous GPS observations (2000-2004), and attempt to evaluate the earthquake risk and to determine whether there are regions with anomalous strain rates within South Korea corresponding to active tectonic areas.
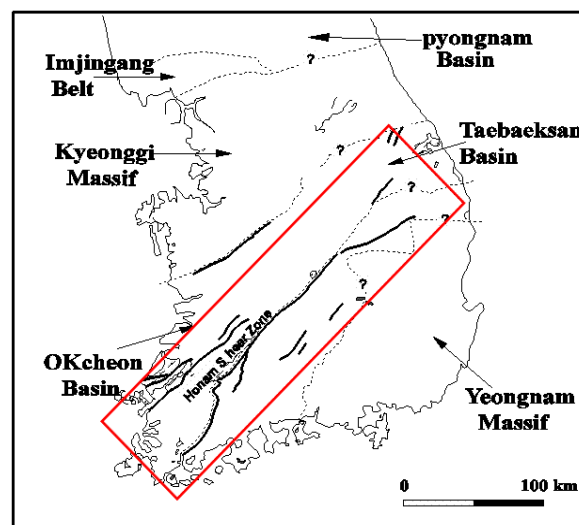

Fig.1 Tectonic setting in South Korea with the Honam Shear Zone, belts and basins.

II. GPS DATA AND PROCESSING

The Korean GPS Network (KGN) with more than 50 permanent GPS sites has been established since 2000 by the Korea Astronomy and Space Science Institute (KASI), the Ministry Of Governmental Administration and Home Affairs

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(MOGAHA), and the National Geographic Information Institute (NGI), etc. The KGN provides real observation data to monitor present-day crustal deformation in South Korea. We analyzed all available good data for the period from March 2000 to February 2004 using scientific GAMIT software (King and Bock, 1999) with IGS precise orbits and IGS Earth Rotation Parameters. All loosely constrained solutions for each day are then combined using the GLOBK, and the reference frame is applied to the solution by performing a seven-parameter transformation to align it to ITRF2000 with global 54 core stations (Altamimi et al. 2002). The site velocities are estimated by least square linear fitting to time variation of the daily coordinates for each station. Fig. 3 shows the GPS velocity fields in the Eurasian plate fixed reference frame (Jin et al., 2007).
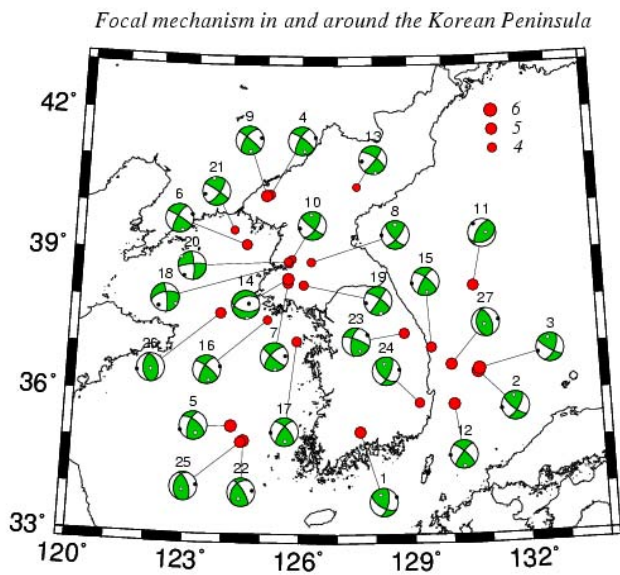

Fig. 2. Epicentral distribution (solid circles) and fault plane solutions (lower-hemisphere equal-area projection) for main 27 events with $M_w \geq 4.0$ in and around the Korean Peninsula from 1936 - 2004. Solid and open quadrants respectively correspond to compression and dilatation; small solid circles in open quadrants and open circles in solid quadrants show the position of P- and T-axes, respectively.

III. RESULTS AND DISCUSSION

Monitoring the variation of the crustal strain is a key issue to understand the deformation pattern and physic process within the southern Korean crust. The dense array of the continuous KGN provides an important kinematic velocity field to determine the crustal strain in the South Korean peninsula. Under the hypothesis that the velocity field v varies linearly inside each small sub-network covering the GPS sites, we can calculate the average horizontal velocity gradient $g = grad(v)$ over each subnetwork as (Malvern, 1969)
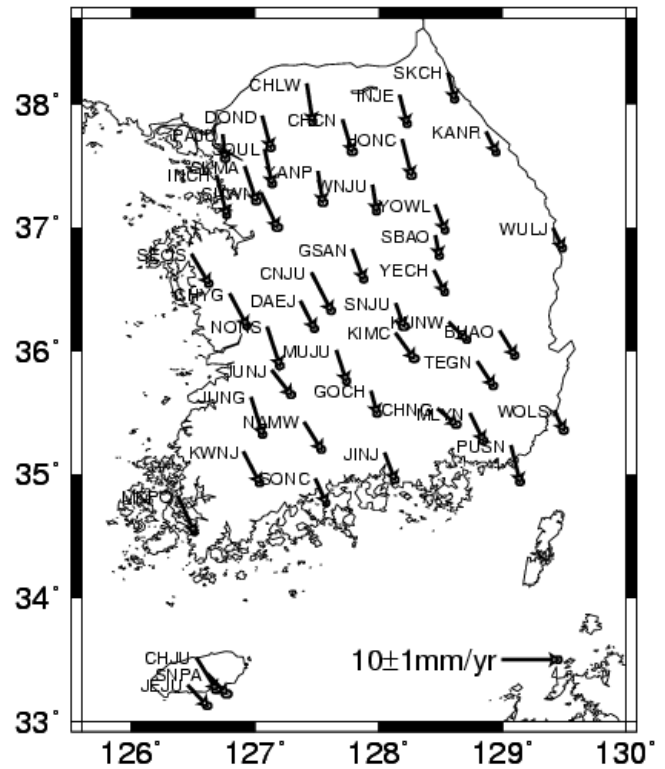

Fig. 3. The velocity field derived from 4-year GPS observations in the Eurasian plate (EU) fixed reference frame. Error ellipses are 95% confidence limits.

$$v_{ei} = \frac{\partial v_{ei}}{\partial x_{ei}} x_{ei} + \frac{\partial v_{ei}}{\partial x_{ni}} x_{ni}$$

$$v_{ni} = \frac{\partial v_{ni}}{\partial x_{ei}} x_{ei} + \frac{\partial v_{ni}}{\partial x_{ni}} x_{ni}$$

(1) where v_{ei} and

v_{ni} are the east and north component velocity 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 $\frac{\partial v_e}{\partial x_e}, \frac{\partial v_n}{\partial x_n}$ and $\frac{1}{2}(\frac{\partial v_e}{\partial x_n} + \frac{\partial v_n}{\partial x_e})$, respectively.

The maximum principal strain $\dot{\varepsilon}_1$ and the minimum principal strain $\dot{\varepsilon}_2$ are given by:

$$\dot{\varepsilon}_1, \dot{\varepsilon}_2 = \frac{1}{2}(\dot{\varepsilon}_{ee} + \dot{\varepsilon}_{nn}) \pm \sqrt{\frac{1}{4}(\dot{\varepsilon}_{ee} - \dot{\varepsilon}_{nn})^2 + (\dot{\varepsilon}_{en})^2} \quad (2)$$

with directions θ and $\theta + (\pi/2)$, with θ given by:

$$\tan(2\theta) = \frac{2\dot{\varepsilon}_{en}}{\dot{\varepsilon}_{ee} - \dot{\varepsilon}_{nn}} \quad (3)$$

Thus, using the GPS velocity field in Fig. 3, the principal strain rate of South Korea can be obtained through the weighted least squares algorithm. The magnitude and distribution variation of strain rates are wholly small with an

order of 10^{-8}/yr, which is one order of magnitude smaller when compared with the strain rates of about 10^{-7}/yr in areas of high crustal activity in Japan (Kato et al., 1998), according with lower and less earthquake activities within recent one century in South Korea (Kim and Lee, 2000). The maximum shear strain rates are shown in Fig. 4. We find that a remarkable shear trend with high strain rates focuses on the mid part of the southern Korean Peninsula with a direction NE-SW coinciding with the Honam Shear Zone (HSZ) running in the middle part of South Korea between Kyeonggi Massif and Yeongnam Massif. It indicates that our geodetic result is almost consistent with the geological evidence.
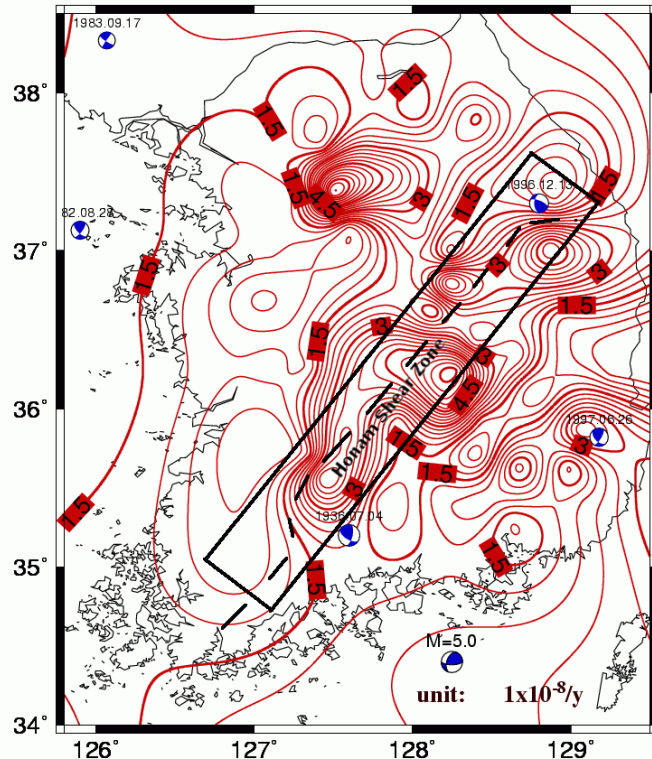

Fig. 4. Contour of the maximum shear strain rates and Honam Shear Zone in swath box.

The GPS principal axis of extension is NNW-SSE and the principal axis of compression is WSW-ENE (Fig. 5), which shows that South Korea is under both compression in WSW-ENE and extension in NNW-SSE, coinciding with the fault plane solutions (lower-hemisphere equal-area projection) for major 27 events with $M_w \geq 4.0$ in and around the Korean Peninsula from 1936 - 2004 (seeing Fig. 6, where the P- and T- axes were ENE-WSW compression and NNW-SSE extension, respectively). The compression rates in the W-E direction are maybe caused by the eastward expulsion due to the collision of India with the Eurasia and the western extrusion with the SW Japanese Island Arc, and thus, the W-E extrusion maybe leads to extension of the southern Korean Peninsula in the N-S direction. This speculation should be further investigated and testified in the future with more evidences. Compared to the principal seismicity strain rate (Fig. 5) shows that GPS strain rates are nearly consistent in

the principal strain rate orientation, but the GPS strain rate is two orders of magnitude higher than seismicity one. This is due to using available and limited historic earthquake data in recently recorded events. In fact, the amplitude of the seismic strain rate strongly depends on the number and the interval of events in the historic earthquake catalogue.
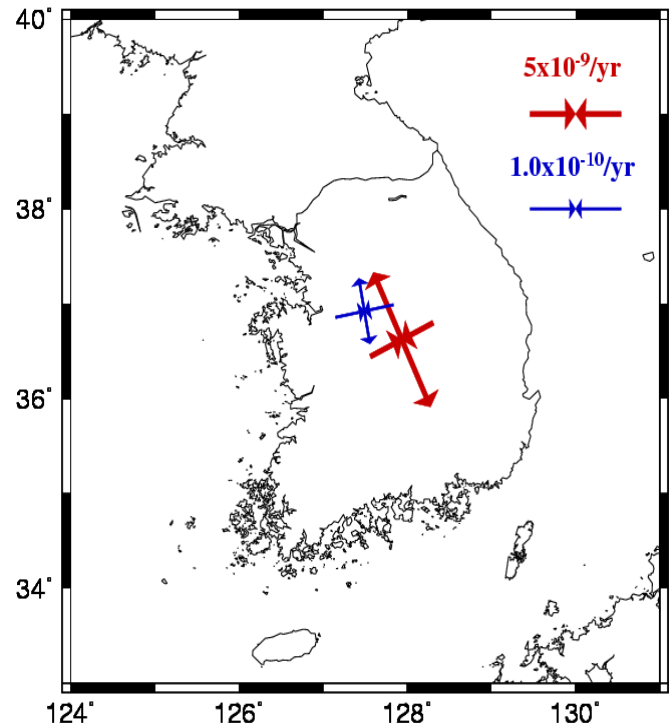

Fig. 5. The principal horizontal axes of the strain rate tensors in South Korea. The red arrows (thick lines) are the GPS-derived strain rates and the blue arrows (thin lines) are the seismicity-derived strain rates.
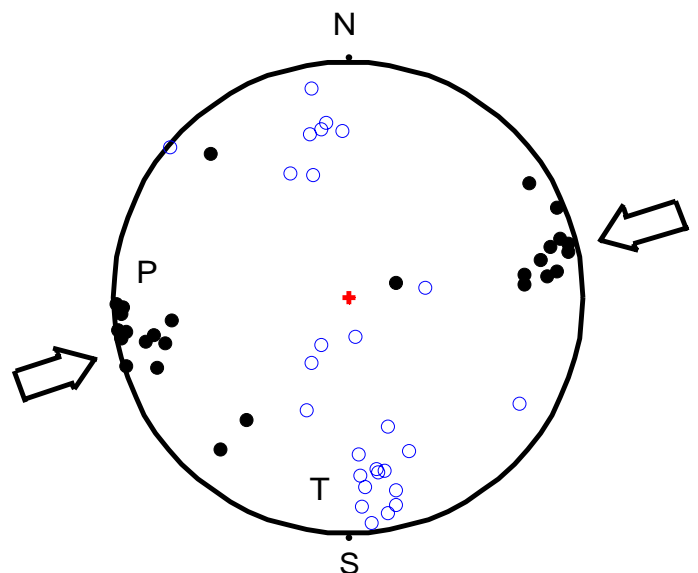

Fig. 6. Lower-hemisphere equal-area projection of the P (solid circle) and T (open circle) axes for 27 events for 1936-2004.

In addition, the accumulated strain energy within the crust is generally released through earthquakes until adjacent fault blocks or plates reach a new state of equilibrium. The release of tectonic strain energy stored within the crustal rock is the cause of major earthquakes. Strain energy per unit (i.e. the strain energy density) is an important index reflecting the intensity of crustal activity; and its variation rate indicates the trend of accumulated energy within the crust. The larger the variation rate of strain energy density, the higher the energy accumulated in the crust which will more probably result in earthquakes. Therefore, for earthquake prediction, it is important to rapidly estimate the strain energy density from surface displacement observations, and then determine the state of strain energy density within the crust, and how it changes with time. 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 Hooker's Law:

$$U = \frac{1}{2}\sigma_{ij}\varepsilon_{ij} \qquad (4)$$

where U is the strain energy density (Unit: $J.m^{-3}$), and σ_{ij} and ε_{ij} are the stress and strain, respectively. The strains (ε_{ij}) can be directly derived from GPS displacements (2000-2004), and the stresses (σ_{ij}) are obtained through the laws of elasticity theory as follows (Straub, 1996):

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

where μ is the modulus of rigidity, λ is the Lame parameter, δ_{ij} is Kroneckerdelta, Δ is the 2-D surface dilation ($\sum_{i=1}^{2}\varepsilon_{ii}$). For Poisson's ratio $\nu =0.25$, $\lambda =\mu$, module of rigidity is assumed as standard value of 3×10^{10} Pa (Hanks and Kanamori, 1979). The variation rate of strain energy density ($\dot{U}$) can be further derived from Eq. (4) (Unit: $J.m^{-3} / yr$). The Fig. 6 shows the strain energy density variation rate in South Korea. The distribution of strain energy density variation rates reveals that the most active areas are in the mid part, and northern and northeastern edges of the southern Korean Peninsula. These results almost locate at the main geological faults and highly seismically active zones in South Korea. As the GPS measurements are all almost made after the historically large earthquakes in South Korea, the strain energy density rates derived from the GPS displacements and rates are partly a consequence of postseismic relaxation, and further release by earthquakes is possible. Therefore, these regions with an anomalous large strain energy density rate probably indicate high earthquake
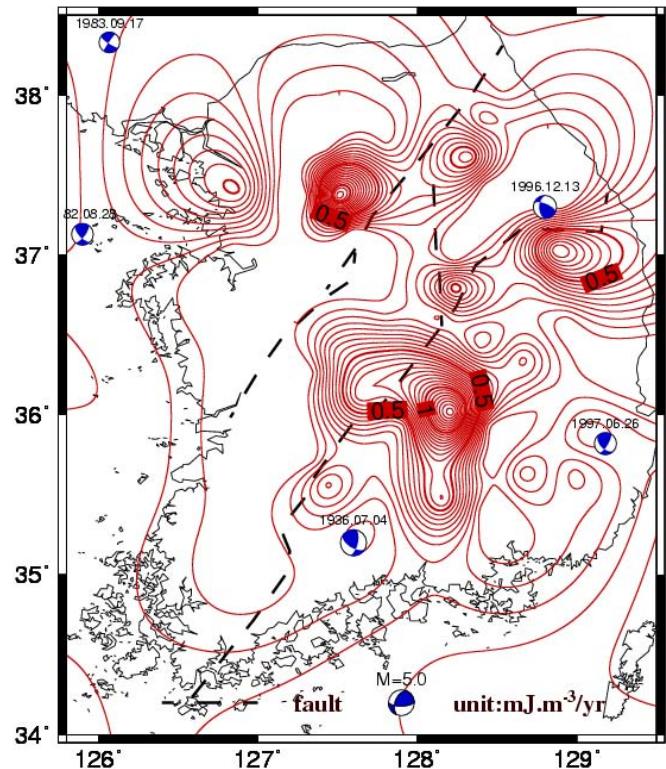
risk in the future.

Fig. 6. Variation rate of crustal strain energy density, fault lines and seismicities that occurred in the period from 1936 to the end of 2004 with $M_w \geq 4.0$ in and around South Korea.

IV. CONCLUSION

The tectonic activities and deformation in South Korea are analyzed based on four years of continuous GPS observations (2000-2004) and recently recorded seismicity data with $M_w \geq 4.0$ (1936-2004). The strain rates show that South Korea is dominated by both ENE-WSW compression and NWN-SES extension, which are consistent with focal mechanism solutions. The axes of the seismic strain rate tensors have a consistent orientation and style with those derived from the GPS velocity field in South Korea, indicating that the seismicity data improve to accurately define the deformation style and pattern in South Korea. In addition, the consistent principal horizontal axes of both GPS and seismicity strain rate tensors reflect that the occurrence of shallow earthquakes in South Korea is closely related with the horizontal strain. The maximum shear strain rates located in the mid part of South Korea and are almost consistent with geologically defined shear zones and high seismic activity zones. In addition, the distribution of strain energy density variation rates shows that the most crustal active areas are in the mid part, and northern and northeastern edges of the southern Korean Peninsula, indicating high earthquake risk in these areas in the future.

As some anomalous GPS station observations, such as the landslide, environment variations, etc. may directly affect the strain rate calculation, the results and speculations need to be further investigated with closer analysis using more available data with dense and long-term observations and consideration given to the heterogeneous crust of the southern Korean Peninsula.

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