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Vertical velocity from the Korean GPS Network (2000–2003) and its role in the South Korean neo-tectonics

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In the absence of adequate leveling observations in South Korea, the vertical deformation has been investigated using the Korean Global Positioning System (GPS) Network data (2000–2003). Although the vertical components of the GPS velocities have been rarely used in crustal deformation studies because of their high noise level, the processing strategy employed here enhances the data quality and eliminates the seasonal effect. The obtained vertical velocity field shows that the maximum vertical velocity in the ITRF 97 reference frame is 3.3 mm/year (subsidence), which reflects a relatively low level of seismic activity in South Korea. Two deformation patterns were recognized; subsidence in the Okchun Basin, and uplift in its adjacent areas. This subsidence is due to the collision of Kyonggi Massif and Okchun Basin (part of the South China block) against the Yongnam Massif and Taebaeksan Basin (part of the North China block).
Key words: KGN, GPS, vertical deformation, Okchun, Korea.

1. Introduction

The Korean Peninsula is located between the North and South China Blocks and the Japanese Island Arc as a part of the Eurasian or the Amurian Plate. The Korean Peninsula is standardly categorized into three main blocks of the Archaean and Proterozoic ages (Hurley *et al.*, 1973; Reedman and Um, 1975; Ernst *et al.*, 1988); these are, from north to south, the Nangrim-Pyongnam Massif (PM) and the Kyonggi Massif (KM), separated by the Imjingang Belt (IB) along the western part of the North Korea-South Korea border line, and the Yeongnam Massif (YM), separated from the Kyonggi Massif by the Okchun Belt (OB) (Fig. 1). A number of investigators have suggested that there was a continent-continent collision between the Kyonggi Massif (South China Block) and the Yongnam Massif (North China Block) from the late Permian to the early Triassic (Cluzel *et al.*, 1990, 1991a, b; Cluzel, 1992). Moreover, Chough *et al.* (2000) has proposed that the Kyonggi Massif (and the Okchun Belt) began to accrete to the Yongnam Massif (and the Taebaeksan Basin), which was located east of the Pyongnam Basin.

The recent tectonic evolution of the Korean Peninsula has been studied by several authors using different geophysical approaches (see Kyung, 1993; Choi *et al.*, 1999; Kim and Lee, 2000). In general, the recent tectonic environment in South Korea (Fig. 1) can be understood by considering two massifs—the Kyonggi Massif and the Yeongnam Massif—and two basins–the Okchun Basin and the Taebaeksan Basin (TB)–separated by five major faults–Bongwhajae, New-Okchun1, New-Okchun2, Taebkseogchun, and Yangsan.

A program for monitoring the crustal deformation in and around the Korean Peninsula has been designed combining geodetic data, geological structure, seismicity, and tectonic settings (Hamdy and Jo, 2002). In order to carry out the vertical deformation phase of this program, the available geodetic data, those of leveling and GPS, have been studied, since both repeated precise leveling survey data and GPS data provide estimates for the vertical deformation with high precision.

The leveling network in Korea was initially established between 1910 and1915, but all the existing stations in South Korea were virtually destroyed during the Korean War. The Korean National Geographic Information Institute (NGII) reconstructed the Korean first-order leveling network between 1960 and 1986). This network consists of 16 loops and 38 routes with a total length of 3,400 km and 2,030 benchmarks spaced at intervals of 2–4 km (Cho, 1999). On the other hand, the Korean GPS Network (KGN), which consists of 50 permanent GPS stations constructed on geologically stable marks (pillars), only became fully operational in 2000. However, since this time, our knowledge on the crustal deformation in the Korean peninsula and its adjacent areas has been improved (Park *et al.*, 2001; Hamdy *et al.*, 2004a, b; 2005).

Mäkinen *et al.* (2003) claimed that two leveling surveys taken at a 40-year interval would provide accurate vertical velocities of 0.3 mm/year (by assuming white noise, a precision$\geq$0.8 mm/$\sqrt{\text{km}}$, and a distance of 100 km). They also claimed that 3 years of scattered GPS weekly solutions over the same distance (100 km) would give similar accuracies. Therefore, in the absence of adequate leveling obser-

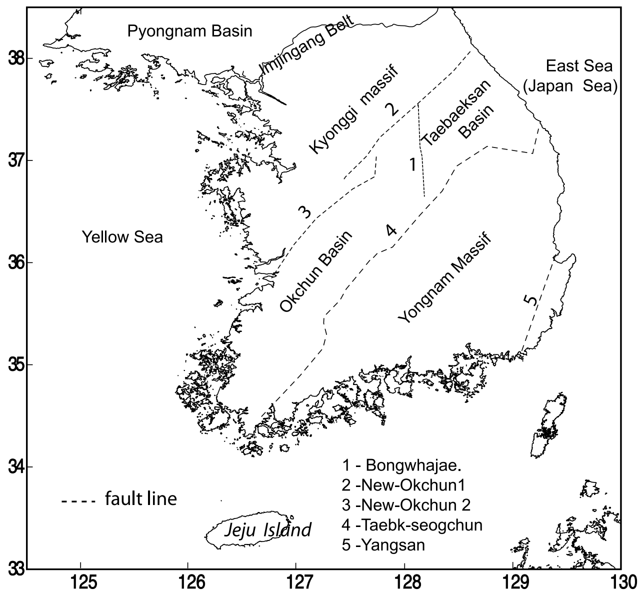

Fig. 1. Map of recent tectonic blocks in South Korea.

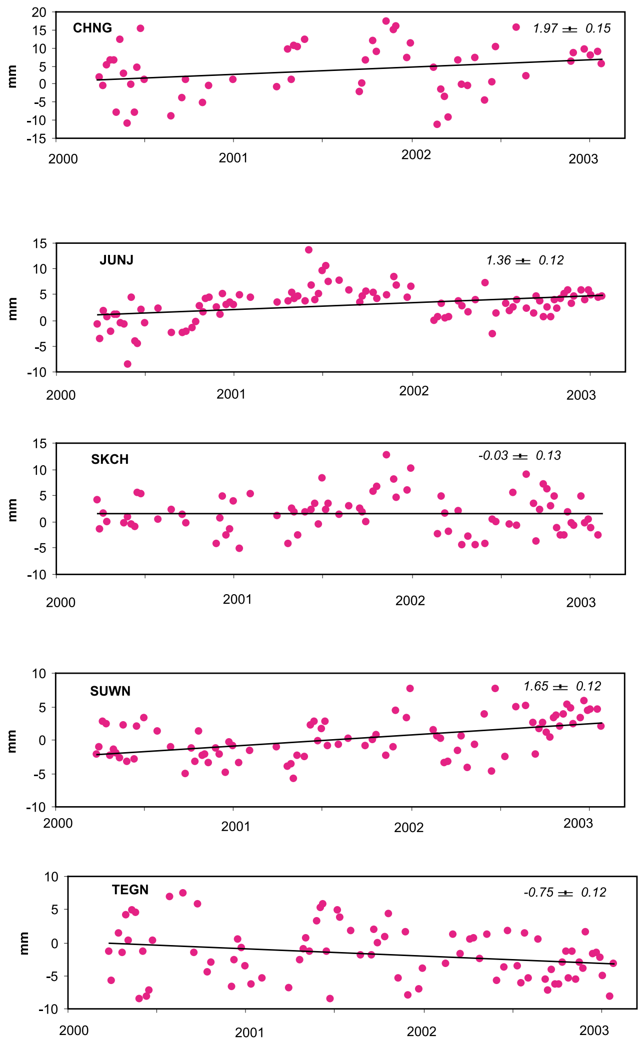

Fig. 2. Time series of the vertical component for selected GPS sites with respect to the DAEJ station. Solid lines are the best fit lines for temporal changes of the vertical component.

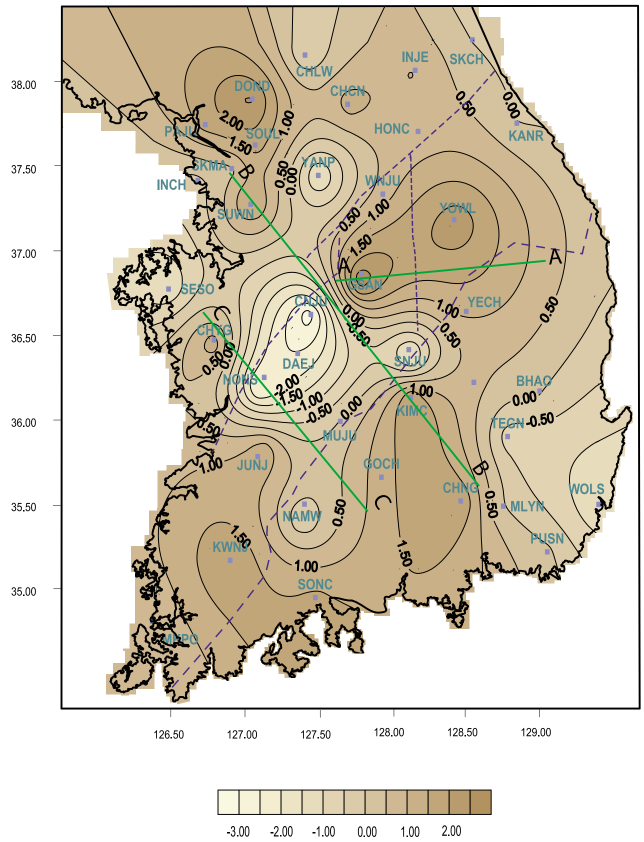

Fig. 3. Contour map with an interval of 0.5 mm/year representing the vertical movements in South Korea. Dashed lines represent the fault lines, solid lines represent the cross sections shown in Fig. 4.

vations in South Korea, we use the GPS vertical velocities, obtained from the KGN, to investigate vertical movements in the Korean peninsula and their role in the South Korean neo-tectonics.

2. Data Processing

The KGN data from April 2000 to March 2003 were processed with the Bernese GPS Software Version 4.2 (Beutler *et al.*, 2001). The International GNSS Service (IGS) final orbits, the satellite clock offsets, the Earth orientation parameters, and the antenna phase center correction models were implemented. Furthermore, the tropospheric delays were estimated using the GPSEST program, and the QIF strategy was employed in the ambiguity resolution. For the daily solutions, the DAEJ station was fixed to the International Terrestrial Reference Frame (ITRF) 97 reference frame, and weekly solutions were generated by combining daily normal equations. Examples of the vertical component time series are presented in Fig. 2.

The seasonal components in the obtained time series (Fig. 2) were eliminated by adopting the following processing strategy: (1) the polar motion, solid earth tide, and ocean tide models were evaluated, and these contributions amounted to up to 66% of the seasonal effect (Dong *et al.*, 2002); (2) the indirect sources coming from mixed receiver types were eliminated since all the KGN stations use the same type of receiver, Trimble 4000SSi; (3) the used ad-

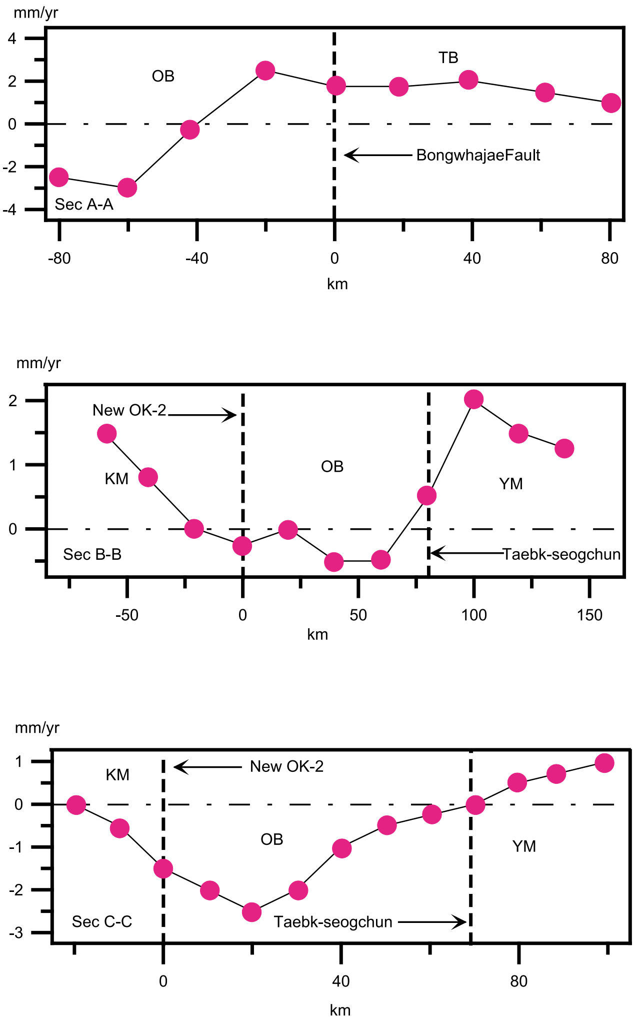

Fig. 4. Vertical velocities along the cross sections shown in Fig. 3. Vertical dashed lines represent the locations of the faults.

justment strategy (fixed network adjustment), together with the small size of the KGN (400 km long and 200 km wide) eliminate other sources of seasonal effect.

It is noteworthy that there is no evidence of shifts in levels, changes in the trends, and/or jumps in the given time series since none of the KGN stations antennas were replaced during the operational period. Finally, eight stations have been excluded from this study either for not covering the considered period or for showing abnormally large error ellipses in the station position

3. Results and Discussion

The estimated vertical velocity field in South Korea shows that the maximum subsidence (−3.3 mm/year) is at the CNJU station, while the maximum uplift (2.9 mm/year) is at the GSAN station (Table 1). The vertical velocities in Korea are much less than those in the Japanese Islands, where the largest velocity amounts to 8 mm/year (Aoki and Scholz, 2003). This difference reflects the lower level of seismic activity in South Korea and its higher tectonic stability.

Using the GPS vertical velocity results (Table 1), we have drawn up a contour map with an interval of 0.5 mm/year

Table 1. Vertical velocities (normal to ITRF97 surface) in the KGN stations from April 2000 to March 2003 with respect to the DAEJ station and their RMS.

Station	E	N	Vertical	RMS
BHAO	128.98	36.16	0.08	0.21
CHCN	127.71	37.87	1.23	0.14
CHLW	127.42	38.16	−0.49	0.14
CHNG	128.48	35.53	1.97	0.15
CHYG	126.8	36.46	1.34	0.14
CNJU	127.46	36.63	−3.30	0.18
DAEJ		Fixed Station		
DOND	127.06	37.9	2.62	0.14
GOCH	127.94	35.67	1.27	0.14
GSAN	127.79	36.82	2.9	0.13
HONC	128.19	37.71	0.67	0.14
INCH	126.69	37.42	−0.14	0.14
INJE	128.17	38.07	1.03	0.14
JUNJ	127.14	35.84	1.36	0.12
KANR	128.87	37.77	−0.02	0.17
KIMC	128.14	36.14	2	0.23
KUNW	128.57	36.23	0.67	0.14
KWNJ	126.91	35.18	2.01	0.2
MKPO	126.38	34.82	0.45	0.16
MLYN	128.74	35.49	0.12	0.28
MUJU	127.66	36	0.03	0.16
NAMW	127.4	35.42	−0.44	0.15
NONS	127.1	36.19	−2.61	0.16
PAJU	126.74	37.75	1.71	0.15
PUSN	129.07	35.23	0.12	0.14
SESO	126.49	36.78	−1.47	0.16
SKCH	128.56	38.25	−0.03	0.13
SKMA	126.92	37.49	0.35	0.23
SNJU	128.14	36.38	−1.75	0.2
SONC	127.49	34.96	1.63	0.2
SOUL	127.08	37.63	1.78	0.11
SUWN	127.05	37.28	1.65	0.12
TEGN	128.8	35.91	−0.75	0.12
WNJU	127.95	37.34	0.74	0.14
WOLS	129.42	35.51	−1.44	0.15
YANP	127.51	37.45	−1.58	0.16
YECH	128.45	36.65	1.09	1.2
YOWL	128.46	37.18	2.33	0.17

(Fig. 3). Apart from the edge effect, the contour map shows two primary deformation patterns: subsidence in the center of OB and an uplift of the surrounding region. Several cross sections (Fig. 4) in the contact area between the two juxtaposed blocks (KM-OB and YM-TB) were investigated. The first cross section (section A-A in Fig. 4) is perpendicular to the Bongwhajae fault line and shows that the TB stations were uplifted while those of OB subsided. This deformation pattern can be explained by considering the horizontal strain tensor observed during the same period 2000–2003, in OB where the predominant strain was compression and the basin translates toward SW (Hamdy *et al.*, 2005).

The second cross section along the northern part of OB (section B-B in Fig. 4) demonstrated that the KM and YM stations uplifted while those in OB mostly subsided. Taking account of the hypothesis of continent-continent collision (Cluzel *et al.*, 1990, 1991a, b ; Cluzel, 1992; Chough *et al.*, 2000) and the horizontal deformation tensors presented

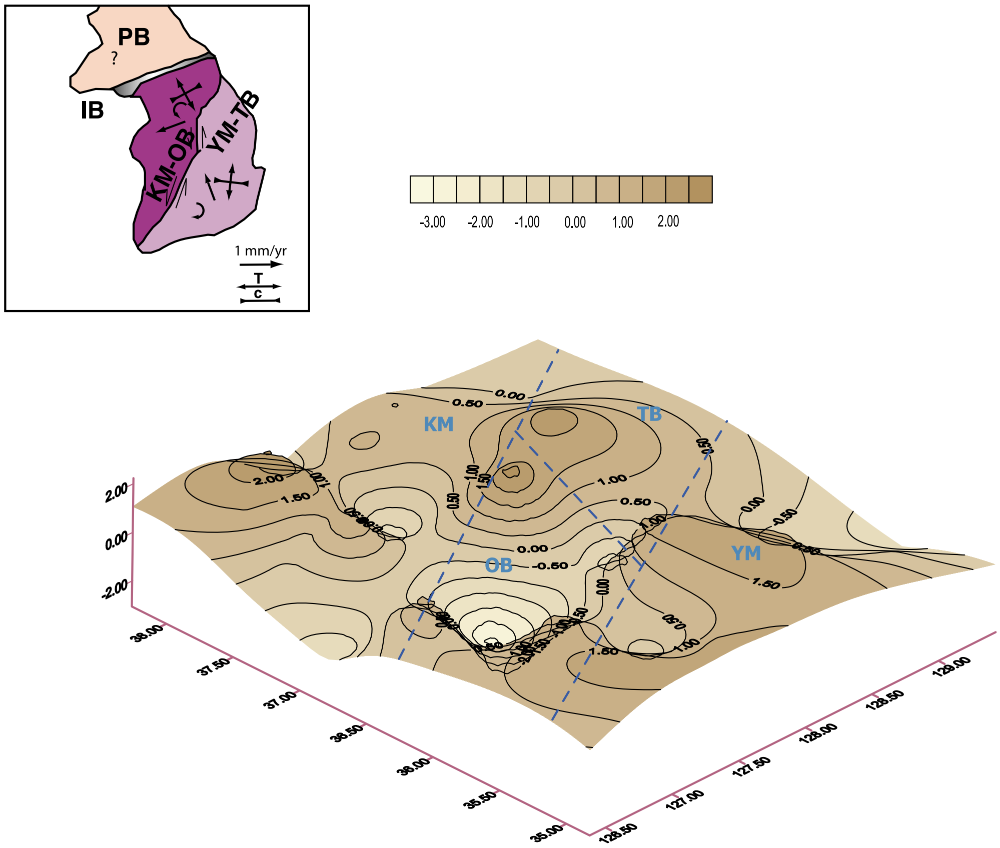

Fig. 5. Surface map showing the vertical velocities in South Korea. Dashed lines represent the fault lines. The inset map shows the horizontal deformation tensors after Hamdy *et al*. (2005).

by Hamdy *et al*. (2005), where YM-TB translates toward the NWN with clockwise rotation and KM-OB translates toward WSW with anticlockwise rotation, the combination of these strain tensors is considered to result in compression in the contact zone and its surroundings and the subsidence pattern of OB.

The third cross section (section C-C in Fig. 4) is located in the central part of OB and is almost parallel to the section B-B. This section, as well as the previous two sections, suggests the presence of a subsidence pattern in OB. In addition, it shows that the subsidence in the central part of OB is larger than that in the northern part.

In general, a combination of subsidence (this study) and contraction (Hamdy *et al*., 2005) are clearly found in OB (Fig. 5). The subsidence of OB can be explained as the downwarping of the basement due to the horizontal stress regime surrounding it, due to the collision of KM-OB (part of the South China block) against YM-TB (part of the North China block). This proposal may be justified by considering the negative gravity anomaly found to the south of Taejon (Choi *et al*., 1999), possibly caused by the downwarping of the basement and consequent crustal thickening. Moreover, it is worth pointing out that the observed subsidence in OB is composed of two main parts—the sediment compaction and the actual subsidence. In order to distinguish the actual subsidence, we need to have better information on the geological structure of OB that helps us determine the compaction part and then obtain the accurate subsidence movement.

4. Conclusion

We derived the distribution of the vertical deformation field in South Korea from continuous GPS data during the period 2000–2003. The maximum velocity was 3.3 mm/year (subsidence), and this result reflects the stability of South Korea and the lower level of seismic activity there. Two primary deformation patterns were found in South Korea: fast subsidence in the central part of the Okchun Basin and uplift of the surrounding area. The horizontal strain tensors and the subsidence of the Okchun Basin are due to the collision of the Kyonggi Massif and the Okchun Basin against the Yongnam Massif and the Taebaeksan Basin. More comprehensive results would be achieved using a larger GPS data set (longer time span and more stations along the eastern coast), and detailed studies of structural geology in South Korea (the Okchun Basin) would be beneficial.

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