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GEOGRAPHICAL SURVEY INSTITUTE
MINISTRY OF LAND, INFRASTRUCTURE
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JAPAN
CONTENTS

Tectonics in the Eastern Asia inferred from GPS observations

Shin’ichi MIYAZAKI, Shigeru MATSUZAKI, Kosuke HEKI, Masaru KAITZU, Yuki KUROISHI, Masaki MURAKAMI, Tetsuro IMAKIHE, Takashi TADA, Koh NITTA, Hiroyuki NAKAGAWA, Akifusa ITABASHI, Masao KARASAWA, Osamu OOTAKI, Norihiko ISHIKAWA, Masayoshi ISHIKOTO, Hiroaki TAKAHASHI, Minoru KASAHARA, and Ki-Dok An

1

Toward the Next Stage of the Global Mapping Project

- Successful Completion of Phase 1 with Release of Global Map Version 1.0 -

Hiroshi UNE

13

Development of Prototype Systems for Managing Spatio-temporal Information

Hidekazu HOSHINO, Norishige KUBO, Takeshi IIMURA, Akihiro IKEDA and Gousuke IITA

21

Slope Gradation Maps as a Useful Tool for Detecting Landform Features

Izumi KAMIYA and Hiroshi P. SATO

29

Current Status of Land Subsidence in Japan

Hiroshi P. SATO

35

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Tectonics in the Eastern Asia inferred from GPS observations

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Abstract

The crustal velocity field in Eastern Asia is investigated. We first analyze continuous GPS data for Korea, Far East Russia, China, and southwest Japan. Velocities are found to have an apparent eastward component relative to the stable interior of the Eurasian plate, and this eastward motion is fairly rigid in the region that includes Suwon, and Taejon (Korea), Xian (China), and Vladivostok and Yuchno-Sakhalinsk (Russia). This area corresponds to the Amurian plate and its Euler vector with respect to the Eurasian plate is estimated to be (21.7°, 108.0°, -0.092°/Ma). This result predicts that the convergence rate at the eastern margin of the Sea of Japan is about 16-18 mm/yr as the Amurian - North American relative plate motion. The result also implies that the convergence rate at the Nankai Trough is 60-65 mm/yr and the resultant deformation by this plate interaction reaches the northernmost part of the Chugoku district. The crustal velocity field of southwest Japan relative to the Amurian plate gives its intraplate deformation. We show that the obtained velocity field could be decomposed into an elastic loading by subduction and a collision-related deformation.

1 Introduction

Spreading rates at mid-oceanic ridges, strikes of transform faults, and slip vectors of interplate earthquakes have been used to model the movements of tectonic plates in terms of Euler vectors [e.g., DeMets et al., 1990]. However, all these data are derived along plate boundaries, so it is important that we know the exact plate boundaries in advance. When we study the movement of a plate with diffuse boundaries, velocities of space geodetic stations obtained by repeated site occupations are more suitable, that is, all we need to know is that the sites reside on the stable interior of the plate in concern.

Recent global space geodetic measurements have demonstrated that the velocities of tectonic plates originally modeled for the last few millions of years also hold for time scales as short as a decade. Heki [1996] established a three-dimensional Very Long Baseline Interferometry (VLBI) kinematic reference frame by minimizing the difference between the velocities of stable plate interior stations and those predicted by nrr-NUVEL1a [Argus and Gordon, 1991, DeMets et al., 1994]. He also estimated the velocities of sites close to plate boundaries relative to the plates on which the sites are supposed to reside. In Japan, the velocity of Tsukuba relative to the Eurasian plate (EU) appears to be about 20.5 mm/yr toward the west and 2.7 mm/yr toward the north. These values have been used as the reference velocities to relate local and regional velocity fields in and around Japan to a global plate tectonic framework.

Further, the recent expansion of IGS network allows us to extract plate motions in more detail. Several organizations routinely produce GPS site velocity fields in ITRF reference frames for all of IGS sites, the number of which has now surpassed 100. Among the products, data from JPL is available on the world wide web [Heflin, 1998]. Figure 1 shows some JPL products which we transformed into ones relative to the Eurasian plate, supposing that the kinematic part of ITRF coincides with nrr-NUVEL1a. Once site velocities are obtained relative to the stable interior of a certain plate, we can estimate the Euler vector for relative plate motions or absolute motions.
The Amurian plate and its motion

Zonenshain and Savostin [1981] hypothesized the existence of the Amurian plate (AM) covering eastern Mongolia, northeastern China, southeastern Siberia and the Korean peninsula (Figure 2). It is supposed to move eastward as one of the consequences of the lateral expulsion of crustal blocks caused by the Indian collision into Eurasia [Molnar and Tappin, 1975]. Recently Ishibashi [1995] suggested that this eastward motion generates the east-west compression of the inner arc of the southwest Japan arc as manifested by the 17 Jan 1995 Hyogoken Nanbu earthquake [Hashimoto et al., 1996]. It is therefore important to determine the plate motion of the Amurian plate for long-term hazard assessment in Japan as well as for tectonics studies.

Zonenshain and Savostin [1981] suggested that the northern and eastern boundaries of the Amurian plate run from the Baikal Rift to northern Sakhalin through the Stanovoi Range. Its southern boundary, however, remains ambiguous; it could lie along the Nankai Trough [Wei and Seno, 1998] or the Median Tectonic Line [Tamaki and Honza, 1985]. Wei and Seno [1998] estimated the Euler vector of AM relative to EU using earthquake slip vectors by assuming their southern boundary as the Nankai Trough. They employed a six-plate model, which consists of AM, EU, the Okhotsk (OK), the Philippine Sea (PH), the Pacific (PA), and the North American (NA) plate, and examined the focal mechanisms of earthquakes occurring between 1977 and 1995, to obtain 5 transform fault azimuths and 13 slip vectors in the Lake Baikal and Stanovoi Range regions relating to the AM-EU boundary, in addition to 364 slip vectors for other regions. Combining these data with 25 spreading rates, they computed all the closure-enforced Euler vectors simultaneously using the Monte-Carlo box method. They estimated the Euler vector for AM-EU as (60.42°N, 123.25°E, 0.025°/m.y.), which implies an extension rate along the Baikal Rift of 0.4 ~ 0.7 mm/yr. According to their AM-OK Euler vector, the convergence rate along the eastern margin of the Sea of Japan amounts to 6 to 15 mm/yr.

Miyazaki et al. [1996] also estimated AM-EU Euler vector using the GPS site velocities of Suwon in South Korea and several GEONET sites located in the northernmost part of the Japanese island of Chugoku. All of the sites are situated within AM, though we do not exactly know where its southern boundary is. However,
GPS sites are located in a small area in comparison with the whole Amurian plate. To improve this spatially biased distribution of GPS sites, they made use of the slip vectors of 13 earthquakes that had occurred along the northwestern boundary of the plate given by Wei and Seno [1998]. Euler vector estimated by Miyazaki et al. [1996] is (65.5°N, 131.4°E, 0.427°/m.y.), which gives a larger convergence rate of 2cm/yr along the eastern margin of the Sea of Japan than predicted from the relative motion of AM-NA by Wei and Seno [1998]. They further suggested from their analysis that OK was not necessary to introduce. After the study of Miyazaki et al. [1996] several GPS sites were installed in South Korea, China, and Russia. Takahashi et al. [1999] chose Taejon (TAEJ) of South Korea from IGS stations, Vladivostok (VLAD) of Russia from the Western Pacific Integrated Network of GPS (WING) [Kato et al., 1998b], and their own sites at Yuzhno-Sakhalinsk (YUZH) and Khabarovsk (KHAB) in Russia. They analyzed the data with Bernese software to estimate the Euler vector of AM-EU at (71.6°N, 153.4°E, 0.147°/m.y.) (Figure 3). However, it is difficult to confirm from their results the existence of AM because the residuals of site velocities at KHAB and VLAD were in the order of 5.0 to 10.0 mm/yr.

In order to demonstrate the existence of AM, it is necessary to show that the plate moves as a rigid body. In this paper, we reprocess the GPS data of several sites that are considered to be on AM together with those of surrounding sites in China and Japan.

3 Data and analysis

Data from several GPS points in Eastern Asia were used, as shown in Figure 4. In Korea, the National Geographical Institute has been operating a GPS station at Suwon. The station was registered as an IGS station on November 30, 1997. We also use the GPS data of four IGS stations, XIAN, SHAO, WUHN in China, and TAEJ in Korea. In Russia, in addition to IGS points such as Irkutsk (IRKT), GPS data are available for VLAD [Kato et al., 1998b] as well as for Okha (OXA) and YUZH, Sakhalin, operated by Hokkaido University and the Institute of Marine Geology of the Russian Academy of Science [Takahashi et al., 1999]. We further make use of the data of five GEONET stations in northern Kyushu and the Chugoku district, Southwest Japan. Data from the Tsukuba IGS station (TSKB) are also analyzed in order to compare the GPS results with VLBI results.

Among these stations, SUWN, TAEJ, and VLAD are considered to be on the stable interior of AM. IRKT is located on the western flank of the Baikal Rift, just beyond the boundary with EU. SHAO and WUHN are located in the South China block being extruded eastward slightly faster than 1cm/yr [Holt et al., 1995; Peltzer and
the GPS data for the effect of atmospheric gradient to reduce the scatter and error of site coordinates and of site velocities.

Figure 5 shows the time series of horizontal position of TAEJ. From such time series as given in the figure, we estimate site velocities in ITRF96.

Since the kinematic part of ITRF96 is adjusted to that of the nrr-NUVEL1a plate motion model [Argus and Gordon, 1991; DeMets et al., 1994], the site velocities obtained in ITRF96 can be converted to those relative to the stable part of EU by subtracting the absolute motion of EU. In other words, if a site is located just on the stable Eurasian plate, its site velocity relative to EU should be zero. The site velocities of TSKB and SHAO estimated from GPS data are compared with the velocities of corresponding Tsukuba and Shanghai VLBI points obtained by Heki [1996]. The GPS velocities coincide well with the VLBI velocities within the uncertainty of $\sigma$ (Figure 4). The obtained velocities are listed in Table 1.

4 Observation equation

The GPS site velocities listed in Table 1 show that VLAD, SUWN, TAEJ, which are considered to belong to

<table>
<thead>
<tr>
<th>Name</th>
<th>Station</th>
<th>Period</th>
<th>Velocity (mm/yr)</th>
<th>Error (mm/yr)</th>
<th>Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>North</td>
<td>East</td>
<td>North</td>
</tr>
<tr>
<td>SUWN</td>
<td>37.3</td>
<td>127.1</td>
<td>95 Apr 30</td>
<td>98 Jun 09</td>
<td>-2.7</td>
</tr>
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<td>TAEJ</td>
<td>36.4</td>
<td>127.4</td>
<td>95 Apr 30</td>
<td>98 Jun 09</td>
<td>-3.2</td>
</tr>
<tr>
<td>VLAD</td>
<td>43.2</td>
<td>131.9</td>
<td>96 Feb 09</td>
<td>97 Oct 02</td>
<td>-4.4</td>
</tr>
<tr>
<td>XIAN</td>
<td>34.4</td>
<td>109.2</td>
<td>96 Jul 11</td>
<td>98 Apr 21</td>
<td>-0.5</td>
</tr>
<tr>
<td>YUZH</td>
<td>47.9</td>
<td>142.7</td>
<td>195 Jul 28</td>
<td>97 Jul 30</td>
<td>-6.0</td>
</tr>
<tr>
<td>0073</td>
<td>35.5</td>
<td>133.7</td>
<td>95 Jul 17</td>
<td>98 Jun 09</td>
<td>0.0</td>
</tr>
<tr>
<td>0074</td>
<td>35.4</td>
<td>133.1</td>
<td>95 Jul 17</td>
<td>98 Jun 09</td>
<td>0.0</td>
</tr>
<tr>
<td>0075</td>
<td>35.0</td>
<td>132.2</td>
<td>95 Jul 17</td>
<td>98 Jun 09</td>
<td>0.8</td>
</tr>
<tr>
<td>0087</td>
<td>33.7</td>
<td>130.5</td>
<td>95 Jul 17</td>
<td>98 Jun 09</td>
<td>-3.5</td>
</tr>
<tr>
<td>0091</td>
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<td>129.9</td>
<td>95 Jul 17</td>
<td>98 Jun 09</td>
<td>-3.6</td>
</tr>
<tr>
<td>IRKT</td>
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<td>104.3</td>
<td>950 Oct 13</td>
<td>98 Jun 09</td>
<td>-0.8</td>
</tr>
<tr>
<td>OXA</td>
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<td>142.9</td>
<td>95 Jul 25</td>
<td>97 Aug 15</td>
<td>-1.5</td>
</tr>
<tr>
<td>SHAO</td>
<td>31.1</td>
<td>121.2</td>
<td>95 Apr 30</td>
<td>98 Jun 09</td>
<td>-7.3</td>
</tr>
<tr>
<td>TSKB</td>
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<td>140.1</td>
<td>95 Apr 30</td>
<td>98 Jun 09</td>
<td>2.2</td>
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<td>WUHN</td>
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<td>96 Jan 25</td>
<td>98 Jun 09</td>
<td>-5.2</td>
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<td>KSTU</td>
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<td>92.8</td>
<td>-</td>
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<tr>
<td>TAIW</td>
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<td>121.5</td>
<td>-</td>
<td>-</td>
<td>-3.8</td>
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<tr>
<td>Seshan</td>
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<td>121.2</td>
<td>-</td>
<td>-</td>
<td>-4.2</td>
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<tr>
<td>Tsukuba</td>
<td>35.9</td>
<td>140.1</td>
<td>-</td>
<td>-</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Table 1. Velocities of GPS sites relative to the Eurasian plate.

*1 GEONET station, *2 results of Heflin [1998], *3 VLBI station, *4 Plate to which the station belongs is unknown.
AM, move coherently in an E to ESE direction without showing any appreciable relative velocity to one another. We treat these three sites as core sites for the least-squares estimation of the AM-EU Euler vector. However, these core sites are located in a smaller area than the whole Amurian plate. Since the plate boundary of AM is not well defined, we can consider three cases for the Euler pole estimation. XIAN and YUZH have negligibly small velocities relative to the core sites, which suggests that these sites are involved in AM. In the first case (1), therefore, we combine the core site velocities with these two site velocities. This strategy may be called space geodetic strategy. XIAN is in the Weihe graben at the southern tip of the so-called Ordos block, and we do not know if this block is a part of AM. Moreover, XIAN is only a few tens of kilometers north of the Qinling fault, the northern boundary of the South China block [Zhang et al., 1995], and it is doubtful that XIAN velocity is free from the buildup of elastic strains between the two blocks. YUZH is considered to be the east of the AM-NA boundary, though no geological or seismological studies have ever allowed us to draw a clear boundary there.

In the second case (2), therefore, we exclude the data of XIAN and YUZH from the least squares estimation. On the other hand, it is physically reasonable to include, in addition to the core site velocity data, the velocity direction of IRKT by regarding it as representative of the plate interaction of AM-EU.

In the third case (3), we make use of the data of earthquake slip vectors in addition to the IRKT velocity direction. We include 13 slip vectors of earthquakes that occurred along the northwestern boundary of the plate [Wei and Seno, 1998].

In general, site velocity \( v \) for site \( s \) is expressed by an Euler vector \( \omega \) as

\[
v_s = \omega \times r_s
\]  

where \( r_s \) is the position vector of site \( s \). This can be rewritten as

\[
r_s = (\omega_1 r_3 - \omega_3 r_1) e_1 + (\omega_2 r_3 - \omega_3 r_2) e_2 + (\omega_3 r_1 - \omega_1 r_3) e_3 \\
= (r_s e_3 - r_3 e_s) \omega_1 + (r_s e_1 - r_1 e_s) \omega_2 + (r_s e_2 - r_2 e_s) \omega_3
\]

where \( e_1, e_2, e_3 \) are the basic vectors of Earth-centered and Earth-fixed Cartesian coordinates. We hereafter omit the suffix \( s \). We suppose that the shape of the earth is spherical, and introduce the polar coordinates \( e_r, e_{\theta}, e_{\phi} \) through the relations

\[
\begin{pmatrix}
e_1 \\
e_2 \\
e_3
\end{pmatrix}
= \begin{pmatrix}
cos \theta \cos \phi & -\sin \theta \cos \phi & -\sin \phi \\
cos \theta \sin \phi & -\sin \theta \sin \phi & \cos \phi \\
\sin \theta & \cos \theta & 0
\end{pmatrix}
\begin{pmatrix}
e_r \\
e_{\theta} \\
e_{\phi}
\end{pmatrix}
\]  

(3)

In the polar coordinates, \( v \) can be written as

\[
v = v_{\phi} e_{\phi} + v_{\theta} e_{\theta}
\]  

(4)

or, equivalently,

\[
v_{\phi} = (r_\phi \cos \theta + r_\phi \sin \theta \sin \phi) \omega_1 + (-r_\phi \sin \theta \cos \phi - r_\phi \cos \phi) \omega_2 + \phi(\cos \theta \sin \phi + \phi \sin \theta \cos \phi) \omega_3
\]

\[v_{\theta} = (-r_\phi \cos \theta) \omega_1 + (-r_\phi \sin \phi) \omega_2 + (r_\phi \cos \phi + r_\phi \sin \phi) \omega_3
\]

(5)

Note that the radial component is ignored because the vertical motion is out of our interest. Rewriting equation (2) by making use of (3), we have observation equations for linear inversion:

\[
\begin{pmatrix}
v_{\phi} \\
v_{\theta}
\end{pmatrix}
= \begin{pmatrix}
\frac{r_\phi \cos \theta + r_\phi \sin \theta \sin \phi}{\sqrt{r_1^2 + r_2^2}} & \frac{r_\phi \sin \theta \cos \phi - r_\phi \cos \phi}{\sqrt{r_1^2 + r_2^2}} & 0 \\
\frac{r_\phi \sin \theta}{\sqrt{r_1^2 + r_2^2}} & -\frac{r_\phi \cos \theta}{\sqrt{r_1^2 + r_2^2}} & \sqrt{r_1^2 + r_2^2}
\end{pmatrix}
\begin{pmatrix}
\omega_1 \\
\omega_2 \\
\omega_3
\end{pmatrix}
\]  

(6)

For the direction data of velocity and slip vectors, the observation equation is

\[
\Theta v = \tan^{-1} \left( \frac{v_{\phi}}{v_{\theta}} \right)
\]  

(7)

Substituting (5) into the above equation, we get

\[
\Theta v = \tan^{-1} \left( \frac{(r_\phi \cos \theta + r_\phi \sin \theta \sin \phi) \omega_1 + \phi(\cos \theta \sin \phi + \phi \sin \theta \cos \phi) \omega_3}{-r_\phi \sin \theta \omega_1 + (-r_\phi \sin \phi) \omega_2 + (r_\phi \cos \phi + r_\phi \sin \phi) \omega_3} \right)
\]

(8)
We calculate the partial derivatives of $\theta_v$ with respect to $\omega$, and perform an iterative nonlinear least-squares method to estimate the AM-EU Euler vector in the cases of (2) and (3).

For the nonlinear cases of (2) and (3), we used the Euler vectors obtained for the linear case of (1) as the initial value of the nonlinear least-squares method. Based on the variance of data around the solution, the standard deviations of GPS site velocities can be estimated.

On the other hand, no standard deviations have generally been given for the slip directions of earthquakes. Wei and Seno [1998] assigned 15 or 20 degrees to the standard deviations of slip directions depending on the results of a certain kind of quality test for the moment tensor solutions. In the present study, we adopted the standard deviations of slip vectors used by Wei and Seno [1998].

5 Results

5.1 Euler vector for the Amurian plate

The results are summarized in Table 2 and in Figure 6. Unlike the results of previous studies described in the preceding section, the pole position was estimated for all cases (1) – (3) on the southern hemisphere, which predicts a larger eastward velocity along the northern tip of AM than its southern part. In the case of (1), the Euler vector is estimated as (21.7°S, 108.0°E, -0.092'/m.y.) with the Euler pole displayed in Figure 6. The weighted root mean square (wrms) estimated for the observation of site velocities is as small as 0.33mm/yr, which suggests that the area that is presumed to be AM moves as a rigid body, and that the pole position is well constrained (case (1) in Figure 6).

For case (2), the estimated Euler vector is (50.2°S, 95.0°E, -0.081'/m.y.), the wrms of the postfit velocity residuals is 0.31mm/yr, and the direction residual of IRKT is 0.9°. The pole position is considered to be well constrained (case (2) in Figure 6).

Finally in case (3), the estimated Euler vector is (73.5°S, 40.4°E, -0.098'/m.y.). The wrms of the velocity residuals is 0.40mm/yr, and that of the direction residuals is 20.5°. The pole position is also considered to be well constrained (case (3) in Figure 6).

In the later discussion, we will examine the results of case (1). Even if we use the Euler vector of the other cases, the essential part of our discussion would hardly be changed because the predicted velocities of GPS sites

![Figure 6. Euler pole between the Amurian and the Eurasian plates for cases (1) - (3). Error ellipses indicate 2σ.](image)

<table>
<thead>
<tr>
<th>Plate pair</th>
<th>Strategy</th>
<th>Pole</th>
<th>Angular Rate</th>
<th>Error Ellipse</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM-EU</td>
<td>case(1)</td>
<td>21.7°S, 108.0°E</td>
<td>-0.092</td>
<td>0.011</td>
</tr>
<tr>
<td>AM-EU</td>
<td>case(2)</td>
<td>50.2°S, 95.0°E</td>
<td>-0.081</td>
<td>0.004</td>
</tr>
<tr>
<td>AM-EU</td>
<td>case(3)</td>
<td>73.5°S, 40.4°E</td>
<td>-0.098</td>
<td>0.016</td>
</tr>
<tr>
<td>AM-NA*1</td>
<td>-</td>
<td>78.3°S, 16.7°E</td>
<td>0.029</td>
<td>-</td>
</tr>
<tr>
<td>AM-PH*2</td>
<td>-</td>
<td>46.8°S, 22.1°E</td>
<td>1.365</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2. Estimated Euler vectors of the relative motion of the Amurian plate relative to the Eurasian plate.

*1 EU-NA pole of NUVEL1.a [DeMets et al., 1994] was used.
*2 EU-PH pole of Kotake et al. [1998] was used.
5.2 Kinematics of the Amurian plate relative to its adjacent areas

Since there are few GPS stations in the Far Eastern region, it has been difficult to investigate the kinematics of this area. The Euler vector of AM obtained in this study is so reliable that we may discuss the kinematics of other adjacent tectonic blocks in order to confirm the necessity of its existence. There is one GPS station at Krasnoyarsk (KSTU) about 800 km northwest of the AM-EU boundary. Figure 1 (modified from Heflin [1998]) includes the velocity of KSTU relative to EU. The site velocity of KSTU is 2.26 ± 1.07 mm/yr to the east and 3.48 ± 1.07 mm/yr to the north, which shows a significantly different direction from that expected for AM, although the velocity is less reliable than other sites because of its short observation period. This supports that AM is distinguishable from the rest of the EU.

WUHN and SHAO are considered to be on the South China block (SC), and have little mutual movement. The velocities of these stations are consistent with those derived from earthquake strain rates within central and eastern Asia by Holt et al. [1995]. A left-lateral strike slip movement is known to exist along the E-W striking Qinling fault [Pelizier et al., 1985], and is considered to divide SC and the North China block. Our results are consistent with this long-term deformation.

Once the Euler vector of AM-EU is obtained, we can calculate Euler vectors for AM-NA and AM-PH. Since the Euler vector of EU-NA is given by NUVEL1a [DeMets et al., 1994], we can obtain an AM-NA Euler vector by combining these two vectors of AM-EU and EU-NA. For the calculation of the AM-PH Euler vector, it does not seem appropriate to use the EU-PH Euler vector of Seno et al. [1993], because they assumed the slip vectors of earthquakes occurring along the Nankai Trough to be representative of the motion of EU-PH. Kotake et al. [1998] estimated EU-PH Euler vector by using GPS site velocities on PH in a similar way as in this study. Using their results, we calculate the AM-PH Euler vector. The Euler vectors are estimated to be (78.3°S, 16.7°E, 0.029°lm.y.) for AM-NA and (46.8°S, 22.1°W, 1.365°lm.y.) for AM-PH.

6 Discussion

6.1 Baikal Rift and the Stanovoi Range

As stated before, the boundary of AM is generally diffused. The border between AM and EU, however, is best constrained along the Baikal Rift and Stanovoi Range. AM-EU Euler vector estimated in the present study suggests a nearly E-W extension along the Baikal Rift and a left-lateral strike-slip movement along the Stanovoi. Wei and Seno [1998] listed 13 earthquake slip vectors along the Baikal Rift and Stanovoi Range, and we may categorize them into two groups; nine of them with a NW-SE orientation and the remaining four showing a nearly E-W orientation. Our Euler vector is consistent only with the latter group.

Since the Euler vector of Wei and Seno [1998] was obtained by using slip vectors, it explains the slip vectors better than our Euler vector. However, their Euler vector does not satisfy the observed GPS site velocities of core sites; the site velocities expected of their Euler vector differ from the observed ones by 30° ~ 45° in azimuth and by one order of magnitude in length (Figure 7). It seems difficult to explain both the GPS site velocities and the
earthquake slip vectors by a single Euler pole. However, compared with the mutual coherency of the GPS site velocities, the directions of the slip vectors are rather scattered even along the Baikal Rift and Stanovoi Range. This suggests the existence of other tectonic forces to generate earthquakes, for example, the detachment of the Baikal region from AM. Further studies are needed to clarify the origin of this inconsistency.

6.2 Eastern margin of the Japan Sea and Sakhalin

As shown in Figure 7, the observed velocity of YUZH is close to that predicted by our Euler vector. The velocity field of northern Hokkaido shows an eastward motion with a rate smaller than that of YUZH [Miyazaki, 1999]. This suggests that the AM-NA plate boundary in the region from Hokkaido to central Sakhalin runs somewhat east of the previously proposed one shown in Figure 4. As seen in Figure 7, the observed velocity of OXA is different both in direction and in magnitude from that expected for the Euler vector of AM-NA. This implies that OXA does not belong to AM and that its boundary runs somewhere west of OXA.

A campaign observation was conducted in the Oshima-Olshima Island in Hokkaido in 1996 and 1999. We derived the velocity there by using the GPS data obtained in 1996 and 1999, and converted to that relative to NA. Although observation was conducted for 3 days in 1999, data from 1996 is limited to a single day; hence, it is likely that the obtained velocity (Figure 8) is not accurate enough to discuss the implication to the tectonics. If the results are accurate, they could suggest that the AM-NA boundary runs east of the Oshima-Oshima or the interplate coupling is almost full.

The convergence rate along the eastern margin of the Sea of Japan becomes 16 to 18 mm/yr. Several large earthquakes with slips as large as 3 m have recently occurred here, such as the 12 July 1993 Hokkaido-Nansei-Oki earthquake (Mw=7.8) and the 26 May 1983 Nihonkai-Chubu earthquake (Mw =7.7). Assuming that this is the characteristic size of interplate earthquakes like these and that the interplate coupling is 100%, the recurrence interval of characteristic earthquakes would be 200 years.

However, historic seismic activity studies suggest that this is not the case [Seno et al., 1996]. One possible explanation is that the interplate coupling of this area is less than 100%, which makes the recurrence interval longer. If the recurrence interval of this region is longer than 300 years, the seismic coupling should be smaller than 60%.
6.3 Nankai Trough

The slip vectors observed for earthquakes along the Nankai Trough are consistent in direction with those predicted by our AM-PH Euler vector, as demonstrated in Figure 9. Seno et al. [1993] presumed these slip vectors represented the EU-PH direction without considering the existence of AM. It is now necessary to revise PH Euler vectors by taking account of the AM movement. However, such revision would be minor, because the eastward movement of AM along the Nankai Trough is only about 1cm/yr, deflecting the EU-PH direction predicted by Seno et al. [1993] counterclockwise only by about 2°. This minor correction is much smaller than typical errors amounting to 15° of slip direction data.

Continuous GPS observations revealed northwestward motions at the southern tip of Shikoku Island. Assuming that the northwestward motions are caused by the coupling between EU and PH, several recent studies estimated the coupling strength by using the concept of backslip [e.g. Ozawa et al., 1999]. It was found in this study, however, that the motion directions of three GEONET sites in the Chugoku district coincided with those expected not for EU-PH but for AM-PH motion, suggesting that the interplate coupling between AM and PH affects not only the outer arc but also the inner arc of southwest Japan. The state of plate coupling along the Nankai Trough should thus be recalculated on the basis of the kinematic reference frame fixed to AM.

6.4 Implication for the velocity field of southwest Japan

So far the velocity field of the southwest Japan has been represented relative to the stable interior of EU [e.g. Sagiya et al., 2000]. This reference frame could serve as a neutral one and may have some advantages when we discuss the crustal velocity field of Japan as a whole. However, if site velocities are obtained relative to its belonging plate, it is possible to interpret them as the intraplate deformation. We demonstrated that southwest and northeast Japan are affiliated with AM and NA, respectively. Hence it seems appropriate to express the crustal velocities of southwest and northeast Japan relative to AM and NA, respectively. In the present paper, we briefly examine the features that are observed in the velocity field of southwest Japan relative to AM. More detailed discussions are found in Miyazaki and Heki [2001] and Heki and Miyazaki [2000].

Figures 10 shows the velocity field of southwest Japan relative to AM. Similary to the result that is shown in the previous sections, the eastward movement in Chugoku district found in the velocity field relative to EU changed its direction to the northwestward, due to the elastic deformation by the interaction with PH. As suggested by the velocity field of Japan relative to EU [e.g. Sagiya et al., 2000], it is also likely that the eastern margin of AM is affected by the collision with the northeastern Japan arc. In other words, the observed velocity field is probably a mixture of the largely elastic deformation from the interaction with PH and an elastic/non-elastic one from the interarc collision.

Separation of the observed field into two deformations was tried by Miyazaki and Heki [2001]. They pointed out that the collisional deformation pattern is consistent with focal mechanisms of crustal earthquakes in southwest Japan. Heki and Miyazaki [2000] extended their method to the Tokai district, the area where the collisional deformation is accommodated, and found that the convergence rate beneath the Tokai district is about one-third that of the Shikoku district. A clear understanding of
crustal dynamics in southwest Japan will help us determine if there is a causal relationship with the occurrence of inland earthquakes.

7 Conclusion

We analyzed GPS data from the Russian Far East, Korea, and China, together with five GEONET sites to determine the Amurian plate motion. The main conclusions are as follows:

1. The existence of the Amurian plate has been confirmed using GPS velocity data.
2. The Euler vector of the Amurian plate has been estimated. The obtained Euler vector predicts the Amurian plate movement that is consistent with geophysical and geological observations of relative plate motions along its boundary, with the exception of slip vector data from the Baikal Rift.
3. Our determination of the Amurian plate motion makes it possible to investigate the intraplate velocity field in the southwest Japan during the interseismic period.
4. The intraplate deformation in southwest Japan is characterized by interaction with the Philippine Sea plate at the Nankai Trough and interarc collision with northeast Japan.

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Toward the Next Stage of the Global Mapping Project
- Successful Completion of Phase 1 with Release of Global Map Version 1.0 -

Hiroshi UNE

Abstract

The Global Mapping Project has successfully completed its first phase cerebrated with the great number of participating countries and the release of Global Map Version 1.0 in November 2000.

In November 2000, “Global Mapping Forum 2000” was held in Hiroshima, Japan. The highlight of the Forum was a declaration of the release of the Global Map Version 1.0. As of the end of 2000, Global Map Version 1.0 for six countries was available for non-commercial users via the Internet. In addition, the data for more than ten other countries that are nearly completing the production of their Global Map will become available soon.

Not only within a global environmental context, the Global Map has also recently been attracting attention as a realistic framework dataset of various global geospatial initiatives such as the Global Spatial Data Infrastructure, Digital Earth Project and UN Geographic Information Working Group.

In May 2001, the Eighth Meeting of International Steering Committee for Global Mapping will be held in Cartagena, Colombia. One of the most important issues to be discussed at the meeting will be the target, strategy and action plans for the second phase of the Global Mapping Project.

1. INTRODUCTION

On 28 November 2000, “Global Mapping Forum 2000 in Hiroshima” was opened at the International Conference Center in Hiroshima with an assemblage of 250 specialists in geographic information and environmental science from 33 countries.

During the Forum, the start of provision of Global Map Ver. 1.0 was declared. It was made after a brief history of the Global Mapping Project, which was advocated in 1992 by the Japanese Ministry of Construction. At the same time, the website of the ISCGM became operative and provision of the Global Map data was officially started.

It became a red-letter day for the Global Mapping Project, because the most significant target of the first phase of the Project had been achieved.

This paper briefly reviews the first phase of the Global Mapping Project, introduces the newly released Global Map Version 1.0 and explains the recent relationship with other global initiatives.

2. Brief History of the Global Mapping Project

2.1. Getting International Consensus

At the United Nations Conference on Environment and Development held in Rio de Janeiro in 1992, Agenda 21, an action program for addressing global environment challenges while continuing to support sustainable economic development, was adopted. Eight chapters of Agenda 21, especially Chapter 40 on “Information for Decision Making,” describe the need for geographic information for sustainable development.

However, geographic information of scientific quality was still insufficient in those days to provide an adequate understanding of the state of the global environment. Consistent, reliable and accurate geographic information must be developed and such information must be easily accessible to the public, decision makers, and global environment researchers. In this context, the Ministry of Construction of Japan advocated the Global Map concept in 1992.

The first international meeting on the Global Mapping, International Workshop on Global Mapping was held in Izumo, Japan in November 1994. There, “The Resolution of Izumo Conference” was adopted, which
consists of eleven items, including: (1) promoting the preparation of Global Map by the year 2000, (2) periodic updating of Global Map, (3) promoting technical cooperation for creating the Global Map, and (4) establishing the Steering Committee for the promotion and coordination of Global Mapping.

The Second International Workshop on Global Mapping was held in Tsukuba, Japan in February 1996. The main objective of the workshop was to establish the International Steering Committee for Global Mapping (ISCGM). Consequently, it was resolved to establish ISCGM chaired by Prof. J. E. Estes consisting of fourteen directorates from thirteen National Mapping Organizations (NMOs), to establish the secretariat of ISCGM in GSI and to appoint four advisors. The number has now increased to eighteen members and seven advisors.

Thanks to the various activities for getting international agreement implemented by ISCGM and related organizations, the need of the Global Map for addressing global environmental issues has been well confirmed in international community, particularly at the United Nations. Paragraph 112 of the “Program for the further implementation of AGENDA21,” adopted at the UN General Assembly, June 1997, states “A supportive environment needs to be established ... to facilitate public access to information on global environment issues ... using ... such tools as geographic information systems and video transmission technology, including Global Mapping.”

In November 1998, the UN sent heads of NMOs a letter from Prof. Estes, Chairperson of ISCGM, inviting the NMO of each country and region to Global Mapping Project with a recommendation letter from Mr. Habermann, Director of the UN Statistics Division. Consequently, there has been a remarkable increase of participation in the Project. As of 17 October 2000, eighty-one countries and regions had participated in the project, and more than thirty-five countries and regions were waiting approval from their governments (Figure 1).

These activities are described in detail in Maruyama (1998).

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**Current Participation in Global Mapping Project**

*Fig.1 Current Participation in Global Mapping Project*
2.2. Principle of the Global Map

ISCGM defines the Global Map as "a group of global geographic data sets of known and verified quality with consistent specifications, which is a common asset of mankind with scientific quality for world-wide distribution at marginal cost." This definition clarifies three basic and important ideas about the Global Map: i) global coverage; ii) consistent specifications; and iii) easy accessibility.

(1) Global coverage

Most countries have national mapping organizations for mapping programs to ensure base map coverage of their own countries. Likewise, it is necessary to have global coverage of geo-spatial information to provide baseline data sets of our planet. To detect changes in the earth, we must frequently update the data. The spatial resolution of the Global Map is one kilometer on the ground.

(2) Consistent specifications

Better understanding of the earth sometimes requires direct comparison between different parts of the world. However, if the geodetic datum, mapping accuracy, classification criteria etc. are not consistent worldwide, an accurate understanding of the state of the earth may not be achievable. For example, total area of forest or desert would be different if the classification criteria are not consistent among countries or regions.

(3) Easy accessibility

Even though global geo-spatial information is developed with consistent specifications, it would be almost useless unless it is made widely available to the international community and used among different sectors of society. There exist a few data sets whose distribution is prohibited or limited to a specific community due to national security, political sensitivities and other reasons. Similar to the idea of national digital geo-spatial data framework, the Global Map should be open to the public and distributed at marginal cost. The spatial resolution of one kilometer on the ground would cause little concern for national security, as we are anticipating sub-meter pixel resolution imagery from commercial high-resolution satellites.

2.3. Global Map Specifications

The Global Map Specifications were first adopted at the Fifth ISCGM Meeting in 1998 and a minor amendment was made at the Seventh ISCGM Meeting in 2000. The full text of the Global Map Specifications is available at:

(1) Data Format

The format for vector data is the Vector Product Format (VPF) by United States National Imagery and Mapping Agency (NIMA), and for raster data, it is Band Interleaved by Line (BIL) with separate headers. The vector data consists of four layers (transportation, boundaries, drainage and population centers), and raster data consists of elevation, vegetation, land cover and land use.

(2) Geodetic Datum and Ellipsoid

The Global Map Specifications adopt combination of International Terrestrial Reference Frame 1994 (ITRF94) and the Geodetic Reference System 1980 (GRS80) ellipsoid as the current world geodetic system.

(3) Tiling

To manage the large amount of data, the Specifications use the tiling system. The size of one tile is five degrees in latitude by five degrees in longitude if it is located between zero degrees and forty degrees in latitude. There is no overlap or gap between tiles.

2.4. Development of the Global Map

ISCGM set the period of the first phase of GM development to the year 2000, when the Global Map version 1.0 was to become available. Member organizations have been producing GM of their own territories, while GSI and USGS EROS Data Center have created global data sets by converting existing global data, V-map Level 0, GLCC and GTOPO30. GSI has also been developing GM of Asian countries in collaboration with
National Mapping Organizations in these respective countries. As a result, Global Map version 1.0 for six countries is available now. It is expected that some forty countries will complete development of GM by the time of the Rio+10 conference.


Global Mapping Forum 2000 was held at International Conference Center in Hiroshima, Japan from 28 - 30 November, 2000. It attracted 250 specialists in geographic information and environmental science from 33 countries.

During the Forum, the start of provision of Global Map Version 1.0 was declared. It was made after a brief history of the Global Mapping Project which was advocated in 1992 by the Ministry of Construction of Japan and Version 1.0 data were released on this day through various activities. At the same time, the web page of the ISCGM became operative and provision of the Global Map data was officially started. Data to be provided on the Internet starting at the time of the declaration were the Global Map Version 1.0 of five countries: Japan, Lao P. D. R., Nepal, Sri Lanka and Thailand. They are the data that had been completed by this time and the ISCGM Secretariat got agreements on the conditions of provision. Global Map Ver. 0 data, which had been converted from existing global geographic information (GTOPO30, GLCC) according to Global Map Specifications, were also released. Non-commercial users such as governmental institutions, research organizations and private researchers, can download these data via the Internet free of charge. In December, Global Map Philippines were added. It is accessible at the following URL:

http://www.iscgm.org/

From the afternoon of the first day to the morning of the third day, 30 oral and 20 poster presentations were made. Delegates from various organizations, such as representatives of the United Nations among international organizations, heads of NMOs of respective countries, researchers from academia, and representatives of international research institutes made significant presentations on the state of Global Map development of each country, present status of geographic information, regional developments with geographic information, and application of the Global Map to disaster mitigation and global change research. These presentations impressed upon the participants that the Global Mapping has become a big international project with an international following; the Global Map has been developed firmly throughout the world; and applications of the Global Map have been started in various fields.

During the Concluding Session held at the end of the Forum, the “Hiroshima Statement for Global Map” was adopted unanimously. Mentioned in the Statement are: 1) a congratulatory message about the release of Version 1.0 of the Global Map, 2) thanks to 81 countries that have participated in the Global Mapping Project, 3) encouragement to those countries not yet committed to join the Global Map to join, 4) the challenge to maintain and enhance the Global Map and to implement policies that result in the widest possible access and use of the product; and 5) appreciation of the hospitality of the citizens of Hiroshima and recognition of their contributions to a truly peaceful world through the Global Map. (see APPENDIX)

4. Global Map as the Framework of Global Initiatives

The Global Mapping Project was originally started to provide necessary geographic information for addressing global environmental issues. However, because it is a set of basic geographic data, it can be used for not only global environmental purposes, but also for all applications that include geographic contexts. Owing to the release of Global Map Version 1.0, it has come to attract attention from various global initiatives such as Global Spatial Data Infrastructure (GSDI), UN Geographic Information Working Group (UNGIWG), Global Information and Early Warning System (GIEWS) by FAO, and Digital Earth Initiative as one of the most realistic projects that provides substantial global framework datasets.

The Global Spatial Data Infrastructure (GSDI) effort is roughly defined as encompassing ‘the broad
policy, organizational, technical and financial arrangements necessary to support trans-national or global access to geographic information." To date, GSDI activity has been principally comprised of a group of individuals representing national mapping agencies, international organizations, and standards organizations. Four GSDI Conferences have been held since 1996. The most recent Conference (GSDI14) held in March 2000 at Cape Town, South Africa, resolved to "strengthen relationships to with activities such as Digital Earth and the International Steering Committee on Global Map (ISCGM). Wherever possible, written statements of cooperation will be established to clearly delineate the partnerships necessary to advance the use SDI's as a core of critical decision-making at the local, national, regional and global levels." Fifth GSDI Conference is scheduled for May 2001 at Cartagena, Colombia, in conjunction with the 8th Meeting of ISCGM.

UNGIWG was established in March 2000 to coordinate activities and to formulate guidelines and policies concerning geographic information within the UN system. One of the principle objectives of the Working Group is to undertake the development and maintenance of the United Nations Geographic Database - a global database consisting of basic cartographic elements and toponymic information that would serve as a common geo-referenced framework on which information from various sources can be integrated for analysis. The ultimate goal of these initiatives is to make geographic information available to all UN staff for more efficient operations and better decision making.

The first phase of the database initiative is to integrate existing global datasets from both within and outside the UN system. The substantive work of the Global Mapping Project will be an important contribution to the proposed database (Chow and Pinther, 2000). The Global Mapping community looks at the UN Geographic Database Initiative as one of the major applications of the Global Map. The Secretariat of ISCGM is closely communicating with UN Cartographic Section to establish a sound channel of cooperation.

Digital Earth has been, until recently, an initiative led by the U.S. National Aeronautics and Space Administration (NASA), focusing upon the technology, applications, and organizational constructs needed to bring to life former Vice President Al Gore's vision of a "Digital Earth" for the future and the way citizens would interact with global information resources to better comprehend the complexity of our planet and our interactions with it.

Kline, Estes and Foresman (2000) stressed the importance of "synergy" of Global Mapping, GSDI and Digital Earth Initiative. They claimed that a "C4 challenge," i.e., communication, cooperation, coordination, and collaboration, is essential for all these efforts.

5. Future Plan

Global Map will be updated and upgraded in the next phase. One of the advantages of Global Mapping initiative is the big number of participating organizations. This makes it possible to assure the reliability of the final product through proper verification by each NMO in the world.

In addition, recent progress in space technology gives us opportunity to revise global-scale geographic datasets in a more consistent way. The MODIS sensor borne on the TERRA satellite launched by NASA in December 1999 makes us possible to update the GLCC dataset to a resolution of 250m. The GLI sensor borne on the ADEOS-2 satellite of National Space Development Agency of Japan (NASDA) scheduled for launch soon is also expected to be used for GLCC update. SAR interferometry data obtained in SRTM conducted in February 2000 can be used to update GTOPO30 to a higher resolution.

ISCGM is also discussing the possibility of including more data layers in GM specifications in the next phase. New layers under consideration are landform classifications, watershed boundaries and plant ecosystems/landform boundaries.

The 8th ISCGM Meeting will be held on 25 May 2001 in Cartagena, Colombia to focus on setting the target, strategy and action plans for Phase 2 of the Global Mapping Project. An enthusiastic discussion is expected at the Meeting.
The author would like to dedicate this paper to the late Professor John E. Estes, chairperson of ISCGM, who died suddenly on 9th March 2001.

References

Fig. 2 Example of Output Image of Global Map Version 1.0
Appendix

HIROSHIMA STATEMENT FOR GLOBAL MAP

We, the participants at the Global Mapping Forum 2000, being held in Hiroshima, Japan, adopt this statement, the Hiroshima Statement for Global Map, during the closing session of the Forum on 30 November 2000, to celebrate the release of Version 1.0 of the Global Map. This tangible product will enable nations of the world to join together in a common understanding of the actions needed to care for our fragile earth.

Recalling that in 1992, the nations of the world committed to the vision of globally sustainable development and a plan of action - Agenda 21.

Recalling also that in 1994, soon after the Rio Summit, the concept of the International Steering Committee for Global Mapping was formulated in Izumo, Japan, to create, through technical cooperation, a digital map of the world, a Global Map, by the year 2000, to support the achievement of Agenda 21.

We acknowledge the achievement and success of the ISCGM and note the significance of this statement being made in the beautiful city of Hiroshima, a symbol of peace and harmony to the people of the world.

We thank the 81 countries who have committed to validate and maintain their component of the Global Map.

We encourage those countries not yet committed to join the Global Map community. Your participation is crucial to the achievement of the global sustainable development vision.

The challenge for us now is to maintain and enhance the Global Map; to implement policies that result in the widest possible access and use of the product; and to continue to work together with individuals and groups dedicated to the cause of improved Global Map products.

We greatly appreciate the hospitality of the citizens of Hiroshima. Their tireless pursuit for peace reminded us of the importance of local actions for global issues, and the ISCGM Chairperson proposed that the school children of Hiroshima plant trees to spread their message to the whole world. Their commitment to harmonious global existence also encouraged us as we re-commit to the vision of a better, more sustainable, and truly peaceful world through cooperation in global mapping for the new millennium.
Development of Prototype Systems for Managing Spatio-temporal Information

Hidekazu HOSHINO, Norishige KUBO, Takeshi IIMURA, Akihiro IKEDA and Gousuke IITA

Abstract

This research is intended to develop techniques to manage spatial information (e.g. terrain, building locations, legal regulations, plant habitats) and temporal information (e.g. water level, rainfall, traffic volume) jointly.

We investigated how spatio-temporal information is used in public sectors which have introduced GIS. Products of GIS that are able to use spatio-temporal information (spatio-temporal information system) were also investigated. These investigations showed that spatio-temporal information should be managed, but is not managed because there are not enough spatio-temporal information system products and users do not know how to implement spatio-temporal information system for practical use.

Characteristics of temporal information were analyzed and basic functions were designed to create a spatio-temporal information system. Based on the design, three prototype systems for specific applications were developed and demonstrated advantages for managing spatio-temporal information.

1. Introduction

The great development of the information technology in recent years has made it possible for anyone to access information easily and freely. As a result, the kinds and quantity of the information that circulate in the world have increased.

In such an advanced information-oriented society, national organizations, enterprises and so on are required to respond to various issues relating to diplomacy, environment, economy, etc., rapidly and dynamically. All users want necessary information to be provided in a form which is easy to use anytime and anywhere.

As for uses of spatial information with GIS, most GIS can process only 2-dimensional information though spatial information has multiple-dimensional characteristics. In other words, there is neither processing for 3 dimensions of spatial information that has a height value like a building, nor for 4 dimensions that includes temporal information.

Taking these circumstances into account, we started researching the management of spatial information (e.g. terrain, building locations, legal regulations, plant habitats) and temporal information (e.g. water level, rainfall, traffic volume) jointly for the purpose of utilizing spatial information and developing the spatio-temporal information processing technology (Geographical Survey Institute, 1999; Iimura et al., 1998; Hoshino et al., 1999).

This paper reports on our research on the present status of utilization of spatio-temporal information in the public sector and GIS products. Then characteristics of temporal information are analyzed and basic functions are designed to implement spatio-temporal information system. Finally we present three prototype systems for specific applications and demonstrate advantages for managing spatio-temporal information.

2. Use case of spatio-temporal information

How spatio-temporal information is used or not used in the public sector was investigated regarding river management, disaster prevention, property management, road management and habitat management.

2.1 River management

Information on water volume and level consists of observation value and the time on the fixed point. For the present river management, observed information in continuing time is not necessary so observed information in the suitable interval is used. However in case of emergency, more detailed information can be observed by changing the time interval with which data are stored. The collected information is used for expressing spatial distribution of water volume and level, referring the value...
at the observed moment, and so on. By comparing water level and rainfall recorded during past floods with present water level and rainfall, applications such as formulating flood prevention measures may become possible.

2.2 Disaster prevention

When we have an earthquake, we have to grasp of the damage and take appropriate measures instantly and effectively. GIS for disaster prevention requires that accurate data on geological features and locations of building be stored in a spatial database. Essential information concerned with the scale of an earthquake includes time of occurrence, duration of shaking, lactation and seismic intensity.

2.3 Property management

Land and buildings are taxed every January first. If you want to refer to past property information, all you have to do is to know the taxation situation on January first of that year. On the other hand, if you manage the information on land or buildings separately, you will have to manage temporal information that includes the phenomena of generation, variation, extinction at a specific time.

2.4 Road and traffic management

Temporal information not only from past to present but also to future is necessary for road and traffic management. For example, future information could be a construction schedule. Temporal resolution such as year, month, day and hour is necessary for the temporal element. Moreover, attribute data, for example observation data on traffic sensors, need more detailed temporal information.

As a result of interviews with users, we found the following three requirements for spatio-temporal information systems:

a) to update a feature at any moment
b) to reproduce a feature at any moment.
c) to retrieve features at a certain moment in the same space.

2.5 Habitat management

In this case, the target object has the elements of past, present and future. The required temporal resolution is different depending on the feature. For example, moving objects such as wild animals have to be managed in days and months, while flora should be managed in years. However, there is nothing to adequately manage such temporal information on habitats and environment.

According to wildlife managers, it is necessary to analyze spatio-temporal information of moving wild animals, flora, land use, topographic data and so on comprehensively. Applications to the establishment of a reserve for wildlife, etc., are being attempted by utilizing past spatial information to understand changes over several years.

3. GIS products

GIS products which can be obtained domestically were listed. After that, we examined various products for functions required for spatio-temporal management. According to our research, there are about 40 kinds of products which support Japanese, 11 kinds that do not and 4 kinds of object oriented database systems. Most of these products manage past spatial information as time slice information. But they have almost no ability to process spatio-temporal information by, for example, comparing spatial information of 2 periods. However, we have found that GIS products do have such functionality.

3.1 DiMSIS-EX

DiMSIS-EX (Disaster Management Spatial information System - Extension) is a modified GIS software based on DiMSIS developed in the wake of the Hanshin-Awaji earthquake in Japan by a support group led by the Disaster Prevention Research Institute of Kyoto University (Hatayama, 1999).

3.2 ATOM

ATOM (Asahi Total Objective Management and evaluation system) is an engine of GIS that was developed by AERO ASAHI Corporation. This product is useful to develop GIS application of business support system.
3.3 ADWORLD-GIS

ADWORLD-GIS is a GIS software that was developed by Hitachi Information Systems. DiMSIS-EX has been adopted in this GIS engine.

4. Analysis based on research results

This investigation has led us to the following items related to the use of spatio-temporal information.

4.1 Needs for spatio-temporal information management

GIS users need to manage spatio-temporal information potentially. Unfortunately, many GIS products do not meet the needs of the user. Because almost no GIS products have spatio-temporal management functions, GIS users have given up trying to manage spatio-temporal information in GIS applications. We believe that it is important to present valid spatial information and temporal information together. Therefore we will show their advantages by developing the prototype systems for some application fields.

4.2 Management of temporal information

Two issues for GIS are how to acquire different information of a feature and how to manage it in a database. The temporal changes of a feature can be expressed as transitional information such as appearance, disappearance, deformation and movement in the real world and updating time of the object in the database. This makes it possible to manage each feature using temporal information as a key.

Although the temporal resolution to be recorded depends on the object, we can choose the year, month and day as units. When dealing with objects like land, houses and so on, time dependence is moderate, and we can also choose hour and minute as units when dealing with items like road construction and so on, where time dependence is frequent.

On the other hand, there might be some cases in which the time of changed information of a feature cannot be measured precisely. In those cases, the time scale is defined by the name of a Japanese era such as Meiji and the Christian era such as the twentieth century.

There are some features that can record time information to compare it with time information of other features. For instance, if we have only one time information that a building is older than a temple next door, we must record the information on the feature as topological temporal information. Owing to the circumstances mentioned above, we have to record necessary temporal resolution besides two kinds of time axes which are actual time and database time. In some cases we might have to record topological temporal information.

Many GIS products on the market do not take this approach. For temporal information of feature, a method to record it as an attribute of the figure has been adopted. Although this method enables us to make each feature on the database have temporal information and to reproduce the condition of the feature at the moment, it is difficult to reproduce the feature information in detail and dynamically at any time when the occasion demands.

In order to reproduce a feature at any moment, we must have a database that focuses on managing temporal information.

4.3 Database structure and data processing method suitable for managing spatio-temporal information

As we have already mentioned, a database which can be managed by each feature as a key based on temporal information would enable us to effectively reproduce information a feature has.

Next, we would like to discuss what kind of database structure is suitable for analyzing spatio-temporal information. In terms of the topology of spatial information, we are considering two methods with a database structure at the present time. One method is to describe the topology information of spatial information to the database in advance. We call it explicit topological database structure. GIS products generally use this database. The other one is a method that does not describe the topological aspects of spatial information to the database (Hatayama et al., 1999; Otomo et al., 1997), but generates topology of spatial information on demand. We call it implicit topological database structure. Since this method does not include topological information in the
database, it is not necessary to change the way of describing spatial information. In addition, it is easy to update.

Adopting implicit topological data structures, it reduces the quantity of the spatial information, while dynamically generating spatial topologic information. However, one of its disadvantages is that it needs more data processing time to analyze the spatio-temporal information. But it is reported that a practical processing speed can be achieved by using a high-performance CPU and a high-speed algorithm (Nonaka et al., 1999).

For these reasons, it is best to adopt implicit topological database structure in order to manage each feature using temporal information.

5. Design of basic function and development of prototype systems

5.1 Design of basic function

Proposed basic functions for implementing the spatio-temporal information system in this investigation are as follows.

1) Presentation
   - to set up or change time
   - to draw
2) Editor
   - to edit figures and attributes
3) Analysis
   - to compare the situations of different two periods and depict the changes
   - to express the historical log of attributes continuously
   - to search for the existence period until it becomes extinct after it occurs of spatial information
   - to search for mobile objects at any period

5.2 Development of prototype systems

As a result of these considerations, we designed functional requirements which a model spatio-temporal information system should have.

Additionally, we attempted to produce a prototype system for property management, road management and habitat management in order to show the advantages of integrating spatio-temporal information.

5.2.1 Source data of spatio-temporal information for developing prototype systems

1) Source data of spatio-temporal information for developing a prototype system for municipal property tax management

   We used following information about fictional land and buildings in a certain city in Japan.

   a) The spatial information
      - a cadaster with a scale of 1 to 1,000 for the years 1995, 1996 and 1997
      - topographic map with a scale of 1 to 25,000 for the years 1957, 1977 and 1996 published by GSI
   b) Temporal information
      - house information: - house number, classification of building, ownership
      - land information: - land parcel, classification of land, ownership

2) Source data of spatio-temporal information for developing a prototype system for road management

   a) Spatial information
      - Digital Map 2500 (spatial data produced from scale of 1 to 2500 map) "Hyogo-1" published by GSI
      - positioning information of road work, traffic sensors in the Chuou-ku, Hyougo-ku, Nagata-ku and Soma-ku districts in Kobe
   b) Temporal information
      - road work information: - project name, work schedule, construction site, type of work management
      - traffic sensor information: - sensor name, data of the traffic per quarter hour

3) Source data of spatio-temporal information for developing a prototype system on habitat management

   a) Spatial information
      - Digital Map 200000 (Map Image) Japan-6 published by GSI and JMC Map (vector data corresponding to a scale of about 1 to 200000) produced by Japan Map Center.
   b) Temporal information
      - Information on the distribution of Sika deer, vegetation
      - Date on the number of hunted, control killed, caught and observed Sika deer per 5-km from 1986 through 1995
      - Date of distribution of vegetation from 1960 through 1986
      - Position observation data of Sika deer per day from the...
first through the thirtieth of April

5.2.2 Hardware and software environment for prototype systems
1) Hardware
CPU: Pentium 233MHz or higher
Memory: 64MB or over
Data storage: about 650MB
2) Software
Operating system: Windows95 or WindowsNT4.0
5.2.3 Development tools of prototype systems
1) GIS engine
ATOM ver.2.0, 3.2
2) Programming language
Microsoft Visual C++ 5.0
Microsoft Visual Basic 5.0
5.2.4 Prototype system
1) Prototype system for property management
We developed a prototype system for property management that controls scattered time from the past to the present. We made a comparative function (Figure 1) of the space data in the target period where it is optional for 2 hours and the change indication function of the spatial information.

2) Prototype system for road and traffic management
This prototype system was developed in order to manage dynamic temporal information for road management from the past to the feature and from year to minute as temporal resolution. That database includes spatio-temporal information of road works and traffic congestion, and the developed function is necessary to manage road maintenance and traffic. The following function was made to understand the relation between the construction information and the traffic. It has functions which evaluate the conditions of the road work and traffic at any moment, show traffic changes as graphs dynamically at intervals of 15 minutes (Figure 2) and so on.

3) Prototype system of habitant management
We designed this prototype system to handle monitoring data of the behavior of the wild animals, an example of spatio-temporal information that changes rapidly. We developed it to understand the relation between temporal data of Sika deer movements and vegetation of potential habitat. We made functions which retrieve the path line (Figure 3) or distance of moving objects like Sika deer.

6. Conclusions
The results of our investigation of spatio-temporal information were as follows. In spite of existing needs of spatio-temporal information management, the accumulated information was not being used actively.
because product dealing with spatio-temporal information did not come into wide use.

Thus, we designed functions that a spatio-temporal information system should have. Additionally, we attempted to develop three prototype systems for property management, road management and habitat management in order to show the advantages of integrating spatio-temporal information.

First, as for the prototype system of property management, we designed functions needed to process polygon elements such as features of buildings, land and information about changes, and appearances and disappearances of the feature.

Secondly, for the prototype system of road management, we designed function needed to process line and point element such as roads and traffic sensors, and their attributes which can change like a kaleidoscope.

Thirdly, for the prototype system of habitat management, we designed functions needed to process information about moving objects.

Using these prototype systems, it is possible to integrate static information (e.g. land, plant habitats) and dynamic information (e.g. monitoring data of wild animals, weather information) by using temporal information. This makes it possible to analyze to more complicated phenomena.

We conclude that technology for spatio-temporal management such as managing the feature dynamically can help to increase the efficiency of businesses, hazard management, administrative services and so on.

Acknowledgement

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References


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Slope Gradation Maps as a Useful Tool for Detecting Landform Features

Izumi KAMIYA and Hiroshi P. SATO

Abstract

Slope gradation maps, which are easily driven from DEM, and which directly show slope of land surfaces without vegetational interference, are used to detect landform features. We found two geological problems using slope gradation maps. One concerns the area of serpentinite distribution. Though interpretation of slope gradation maps shows very clear serpentinite-like characteristics in the Kamuiokotan metamorphic belt, it does not in the Sangun metamorphic belt. An area of gabbro in the Sangun metamorphic belt looks just a serpentinite area on a slope gradation map. The other problem concerns lineament: a clear lineament was found on a slope gradation map. Hypothesizing the existence of some geological structure along the lineament, we found much indirect evidence supporting the hypothesis. In conclusion, slope gradation maps are useful in geology and geomorphology for finding unknown problems.

1. Introduction

Aerial photographs and remotely sensed images have been used to detect landform features prior to field surveys in geomorphology and geology. But such features are hard to detect by those materials, if the land surface is covered by dense vegetation. Slope gradation maps derived from ‘Digital Map 50m Grid (Elevation),’ nationwide DEM data, provide another way to detect landform features (Kamiya et al., 2000). The maps directly show land surface information without vegetational interference. This paper shows that slope gradation maps are useful in geology and geomorphology by giving examples in which we detected some landform features.

2. Methodology

We used the following Prewitt-operator-like formula to calculate slope (Kamiya et al., 2000).

\[ S_{x} = \frac{(H_{i,j+1} + H_{i,j+2} + H_{i,j}) - (H_{i,j+1} + H_{i,j+2} + H_{i,j})}{6Dx} \]

\[ S_{y} = \frac{(H_{i,j} + H_{i,j+1} + H_{i,j+2}) - (H_{i,j} + H_{i,j+1} + H_{i,j})}{6Dy} \]

\[ S = \sqrt{S_{x}^{2} + S_{y}^{2}} \]

where, \( S \) is the slope of grid \((2,2)\), \( H \) is the height of grid \((i,j)\), \( Dx \) is the grid interval in the x direction, and \( Dy \) is the grid interval in the y direction.

The calculated slope is reprojected into UTM; is output at a 1:200,000 scale using gradation, in which white corresponds to gentle slope and black corresponds to steep slope; and is overlaid with geological maps.

3. Examples of detecting landform features by slope gradation maps

Here we will show two examples in which slope gradation maps helped us to detect unknown geological and geomorphological features.

3.1 Distribution of serpentinite in the Sangun metamorphic belt.

Geological features restrict geomorphological features. Kinds of rock are one of the important influencing factors in slope gradation maps. Areas of serpentinite distribution have the following characteristics on slope gradation maps: (1) brain-like pattern is unclear, (2) little sharpness (low contrast and long intervals between white lines), and (3) white lines corresponding to ridges are wider than those corresponding to valleys (Kamiya et al., 2000). These characteristics are very clear in the Kamuiokotan metamorphic belt, Hokkaido Island, Japan, but not clear in the Sangun metamorphic belt, Chugoku Mountains, Japan (Fig. 1). Because peneploon remnants and river valleys cover the extent of Fig. 1, we have to interpret the slope gradation map in consideration of these geomorphological features.

Serpentinite is distributed from region A to H in Fig. 1 and other areas enclosed by the solid line in the figure (Teraoka et al., 1996). The above characteristics of the serpentinite-distribution area (1), (2) and (3) are clear...
in regions A, B and C; distinction from the surrounding parts is possible. Characteristic (3) is clear, but (1) and (2) are unclear in the other serpentine-distribution area, so distinction is difficult. White lines are more unclear in region D than north of it, in region E than north/west/south of it, in region F than north of it, in region G than north of it, and in region H than southeast/northwest of it. This means that regions D, E, F, G and H have more serpentine-like characteristics, but not enough to distinguish. We cannot explain the differences in the characteristics of serpentine-distribution area between the Kamuirotan metamorphic belt and the Sangun metamorphic belt now.

Gabbro is distributed south of region A in Fig. 1 (Teraoka et al., 1996). Typical serpentine-distribution area in sense of the slope gradation map interpretation. We divided the gabbro-distribution area into region X (east half) and region Y (west half) by the thin line shown in Fig. 1. Region X has typical serpentine-like characteristics of slope gradation map interpretation, and is not distinguishable from region A in the slope gradation map. Region Y has no serpentine-like characteristics, and is not distinguishable from the south of it on the slope gradation map. Because one mountain body comprises both region A and region X, there is no geomorphologic difference disturbing the interpretation between regions A and X, such as difference between peneplain remnants and river valleys. We cannot now explain the reason why the
slope gradation map and geology do not harmonize.

Above-mentioned arguments are summarized that some geological and geomorphological problems are discovered by using the slope gradation map.

3.2 Lineament around the Mashu Caldera

Fig. 2 is a slope gradation map around the Mashu Caldera, Hokkaido Island, Japan. We can easily find a lineament between A and B on the map. From the viewpoint of wide area, this lineament harmonizes with Akan-Shiretoko volcanic row (Editorial Committee of Hokkaido, Part I of Regional Geology of Japan, 1990). The row lies between the Shiretoko-dake volcano and the Meakan-dake volcano, and includes the Shiretoko-lozan volcano, the Sharidake volcano, the Mashu volcano and the Kutcharo volcano. Satoh et al. (1970), the Research Group for Active Faults of Japan (1991), and other geological literature do not mention a geologic structure corresponding to the lineament A-B.

We investigated the lineament A-B using the slope gradation map and other existing materials, hypothesizing that some geologic structure exists along it. The following are our results and considerations.

The Churui River flows northeast in region C of Fig. 2. We examined the slope gradation map and aerial photographs (CHO-78-2) to interpret the geomorphology. Fig. 3 shows the results. Pieces of valley walls of the Churui river valley discontinuously lie as almost straight

![Fig.2 Slope gradation map around Mashu Caldera](image-url)
lines (a-a' and b-b'). They (a-a' and b-b') lie along the lineament A-B. The northwest half of Fig. 3 is a part of main body of the Sharidak volcano (1,545m), which erupted from the Pleistocene to the Holocene, and which consists of pyroxene andesite (Sugimoto et al., 1959). Talus deposits and younger fan deposits cover the foot of the volcano (Sato et al., 1970) at the slope of 3-4 degrees. The slope is dissected by some branches of the Churui River. Discontinuous line c-c', which lies parallel to discontinuous lines a-a' and b-b', is a short lineament which consists of saddle points and lower edges of the terrace scarp. Line c-c' harmonizes with a fault d-d' described in Sugimoto (1960). These lineaments of a-a', b-b' and c-c' may be affected by the hypothetical geologic structure along the lineament A-B.

Volcanoes including Mt. Samakkenupuri (1,063m), Mt. Shibetsudake (1,061m) and Mt. Yorouushi (847m) lie straight on the lineament A-B in region D of Fig. 2. The volcanoes erupted in the early to middle Pleistocene, and consist of pyroxene andesite and olivine basalt (Editorial Committee of Hokkaido, Part 1 of Regional Geology of Japan, 1990; Sato et al., 1970). The row of volcanoes may be affected by the hypothetical geologic structure along the lineament A-B, but the probability is low because the volcanoes are much older than the other features mentioned here.

We examined aerial photographs (HO-83-2Y) to interpret the geomorphology in region E of Fig. 2, southwest end of region D. We found the short lineament shown in Fig. 4 along the lineament A-B. It consists of
two valleys (a, b) and two saddle points (c, d). The short lineament may be affected by the hypothetical geologic structure along the lineament A-B.

Region F in Fig. 2 is a part of the Mashu Caldera, which formed about 7,000 years ago (Katsui, 1996). The plane shape of the caldera wall is like an ellipse except for region F. However, the caldera wall lies outside the ellipse and its shape is unusually linear in region F. The linear part of the caldera wall is along the lineament A-B. As activities of Mt. Kamuiunupuri occurred after the caldera formation (Katsui, 1958), the caldera wall was probably deformed by the volcanic activities of Mt. Kamuiunupuri. The linear shape of caldera wall in region F suggests the existence of a geologic weak line along the linear caldera wall. This weak line is probably a part of the hypothetical geologic structure along the lineament A-B.

There is a linear valley along the lineament A-B in region G of Fig. 2. Both the valley in region G and the valleys surrounding region G dissect the foot of the Mashu Caldera. The slope of the caldera is covered by air fall deposits and pyroclastic flow deposits of the Mashu volcano, which erupted from ten and several thousands years ago to thousand years ago (Katsui, 1996; Satoh et al., 1970; Takahashi et al., 1980). Though surface geologic and geomorphic conditions are the same around region G, the direction of the valley in region G differs by 40 degrees from the direction of the surrounding valleys (radial from the center of the Mashu Caldera). The existence of the valley with exceptional orientation may be affected by the hypothetical geologic structure along the lineament A-B.

There is a linear row of small hills, along the lineament A-B, in region H of Fig. 2. The relative height of the hills is about 40 m. Pyroclastic flow deposits of the Mashu volcano cover the hills and surrounding area (Satoh et al., 1970; Takahashi et al., 1980). The row of hills may be affected by the hypothetical geologic structure along the lineament A-B.

A hot spring gushes from a crevice of tuff at point I in Fig. 2 (Sugimoto, 1960), near the lineament A-B. Another natural hot spring exists at point J in Fig. 2 (Editorial Committee of Hokkaido, Part 1 of Regional Geology of Japan, 1990), on the lineament A-B. The existence of the hot springs suggests the existence of geologic weak points, which may be affected by the hypothetical geologic structure along the lineament A-B.

These findings can be summarized as follows. (1) The lineament A-B was discovered on the slope gradation map. (2) We found much indirect evidence supporting the hypothesis that some geologic structure, especially a weak line, exists along the lineament A-B.

4. Conclusion

Two problems, on kinds of rock and on lineament, were discovered by examining slope gradation maps. We found that the slope gradation map did not harmonize with the existing geological literature in the former problem. We found much indirect evidence that supported the hypothetical geologic structure using the slope gradation map, existing literature and the aerial photographs in the latter problem. Slope gradation maps are useful in geology and geomorphology as a tool for discovering unknown problems, and as a tool that is free from vegetational interference.

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References
Current Status of Land Subsidence in Japan

Hiroshi P. SATO

Abstract

In Japan, land subsidence defined under the Basic Environment Law results from excessive pumping of ground water in areas where soft ground lies. Subsidence area has generally decreased recently in Japan, but increases temporarily nation-wide in dry years. The current status of the subsidence is reported and the efficiency of monitoring subsidence with GPS (Global Positioning System) and SAR (Synthetic Aperture Radar) interferometry is examined in this paper.

1. Introduction

Land subsidence in Japan has a long history. Since the early 20th century it began to damage buildings and public works such as open channels, levees and bridges. Hirono and Wadati (1939) first pointed out that this subsidence was caused by excessive pumping of ground water, and Tohno (1994) discussed the history briefly. Today, the Basic Environment Law defines subsidence as a kind of public nuisance. In legal terms, subsidence is defined as a lowering of the ground surface due to excessive pumping of ground water. Subsidence does not always occur in areas where ground water is pumped out. For example, in Japan it might occur in areas of soft ground such as Pliocene, Pleistocene or Holocene series (Tohno, 1990).

To date, laws or ordinances that regulate or control pumping of ground water have been enforced. Furthermore, countermeasures such as surface water resource development and voluntary ground water saving have been implemented. As a result, subsidence area is being gradually reduced.

However, the demand for ground water increases in dry years, because of shortages of surface water. Excessive pumping of ground water in dry years temporarily increases subsidence area across the nation. Even if subsidence area has been reduced, it is still important to monitor subsidence continuously. The purpose of this paper is to report current status of subsidence in Japan. The efficiency of monitoring subsidence with new technologies such as GPS (Global Positioning System) and SAR (Synthetic Aperture Radar) interferometry is examined in the last part of this paper.

2. Current status of subsidence

According to Environment Agency of Japan (2000), subsidence has occurred in 62 areas of 37 prefectures in the scope of annual data collection since 1978 by the Agency, which was renamed the Ministry of the Environment in January 2001. The 62 areas are shown by circles in Fig. 1. Prefectures where subsidence has not been observed are Iwate, Shiga, Nara, Wakayama, Shimane, Yamaguchi, Ehime, Oita, Kagoshima and Okinawa.

In order to regulate the pumping of ground water from wells and to prevent subsidence, two laws, that is, the “Industrial Water Law” and “Law Concerning the Regulation of Pumping-up of Underground Water for Use in Buildings” were enacted in 1956 and 1962, respectively. In the two laws, a regulated well is decided by 1) the diameter of its vent, 2) its use, 3) the area where it is located. Under these two laws, official permission is needed to dig a regulated well.

The areas regulated by the two laws and the yearly subsidence in these areas are shown in Tables 1 and 2. The two laws have successfully prevented subsidence in the areas. In Fig. 2, the two locations “F” and “G” are in a regulated area. The subsidence in the two locations began in the early 20th century, and the two laws ended the long history of subsidence there.

In order to prevent subsidence effectively in other areas in Japan, the Councils of Concerned Ministers for the Chikugo-Saga Plain, the Northern Kanto Plain and the
Fig. 1 Land subsidence in Japan in the dry years of 1978, 1984 and 1994

To date, land subsidence has occurred in the 62 areas that are marked by circles. The areas where subsidence occurred at a rate of 2.0 cm / yr or more and 4.0 cm / yr or more are shown by different types of circles. The rates are based on the results of leveling surveys conducted by the national and local governments. Names of the current major subsidence areas in the figure are as follows: CH: the Chikugo-Saga Plain area of Saga prefecture; NB: the Nobi Plain area of Gifu prefecture; NS: the Northern Kanto Plain area of Saitama prefecture; NT: the Northern Kanto Plain area of Tochigi prefecture; NI: the Northern Kanto Plain area of Ibaraki prefecture; MU: the Minami-Uonuma area of Niigata prefecture; KJ: the Kujukuri Plain of Chiba prefecture. The names are spelled out in Table 3. Data are from Environment Agency of Japan (1979, 1985, 1995).
### Table 1: Annual land subsidence in the areas regulated under the “Law Concerning the Regulation of Pumping-up Underground Water for Use in Buildings”

<table>
<thead>
<tr>
<th>Name of prefecture</th>
<th>Name of cities</th>
<th>Regulated area (km²)</th>
<th>Date regulation proclaimed</th>
<th>In the regulated area under the law</th>
</tr>
</thead>
<tbody>
<tr>
<td>Osaka</td>
<td>All of Osaka</td>
<td>203</td>
<td>1962.8.24</td>
<td>Maximum 12.5 cm in 1962; 0.7 cm in 1997</td>
</tr>
<tr>
<td>Tokyo</td>
<td>All of Tokyo (23 wards)</td>
<td>577</td>
<td>1963.6.14 1997.4.3</td>
<td>Maximum 19.5 cm in 1963; 1.2 cm (*) in 1997</td>
</tr>
<tr>
<td>Saitama</td>
<td>All of Kawaguchi, Uraya, Omiya, Yono, Warabi, Toda and Hatogaya</td>
<td>253</td>
<td>1972.4.3</td>
<td>Maximum 10.9 cm in 1972; 1.4 cm</td>
</tr>
<tr>
<td>Chiba</td>
<td>Part of Chiba and Ichihara; All of Ichikawa, Funabashi, Matsudo, Narashino, Kanagaya and Urayasu</td>
<td>564</td>
<td>1972.4.3 1974.6.28</td>
<td>Maximum 20.2 cm in 1962; 2.4 cm</td>
</tr>
</tbody>
</table>

Data are from each prefectural government and the Tokyo Metropolitan Government.

### Table 2: Annual land subsidence in the areas regulated under the “Industrial Water Law”

<table>
<thead>
<tr>
<th>Name of prefecture</th>
<th>Name of municipality</th>
<th>Regulated area (km²)</th>
<th>Date regulation proclaimed</th>
<th>In the regulated area under the law</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miyagi</td>
<td>Part of Sendai and Tagajo cities; Part of Shichigahama town</td>
<td>90</td>
<td>1975.7.11</td>
<td>Maximum More than 10 cm in 1972; 1.9 cm</td>
</tr>
<tr>
<td>Fukushima</td>
<td>Part of Haramachi city</td>
<td>41</td>
<td>1979.6.1</td>
<td>Maximum 3.0 cm in 1981; 0.5 cm (*)</td>
</tr>
<tr>
<td>Saitama</td>
<td>Part of Kawaguchi and Uraya cities; All of Yono, Soka, Warabi, Toda, Hatogaya and Yashin cities</td>
<td>154</td>
<td>1963.6.1 1979.6.1</td>
<td>Maximum 20.8 cm in 1963; 1.4 cm</td>
</tr>
<tr>
<td>Chiba</td>
<td>Part of Chiba, Ichihara, and Sodegaura cities; All of Ichikawa, Funabashi, Matsudo, Narashino and Urayasu</td>
<td>326</td>
<td>1969.9.11 1972.4.3 1974.6.28</td>
<td>Maximum 23.2 cm in 1970; 1.8 cm</td>
</tr>
<tr>
<td>Tokyo</td>
<td>All of Sumida, Koto, Kita, Arakawa, Itabashi, Adachi, Katsushika and Edogawa wards</td>
<td>254</td>
<td>1960.12.19 1963.6.1 1972.4.3</td>
<td>Maximum 18.9 cm in 1961; 1.2 cm</td>
</tr>
<tr>
<td>Kanagawa</td>
<td>Part of Kawasaki and Yokohama cities</td>
<td>73</td>
<td>1957.6.10 1959.3.6 1962.10.20</td>
<td>Maximum 10.1 cm in 1959; 1.0 cm</td>
</tr>
<tr>
<td>Aichi</td>
<td>Part of Nagoya city; All of Ichinomiya, Tashima, Konan, Bisai and Inazawa cities; All of Kiyosu, Kisogawa, Sobue, Heiwa, Shippo, Miwa, Jimokuji, Ohara, Kanie, Yatomi, Saya and Saori towns; All of Jushiyama, Tobishima, Tasuta and Hachikai villages</td>
<td>458</td>
<td>1960.5.17 1984.6.3</td>
<td>Maximum 6.4 cm in 1963; 1.3 cm</td>
</tr>
<tr>
<td>Mie</td>
<td>Part of Yokkaichi city; All of Kusu town</td>
<td>34</td>
<td>1957.6.10 1963.6.24</td>
<td>Maximum 4.1 cm in 1962; No subsidence</td>
</tr>
<tr>
<td>Osaka</td>
<td>Part of Osaka, Toyonaka, Suita, Takatsuki, Ibaraki, Yao, Neyagawa, Daio, Higashi-Osaka, Shinonawate, Kishiwada, Kainaka and Izumi cities; All of Settsu, Moriguchi, Kadoma and Izumi-Otsu cities; All of Tadaoka town</td>
<td>433</td>
<td>1958.12.14 1962.10.20 1963.6.1 1965.9.25 1966.5.17 1952.12.26</td>
<td>Maximum 15.1 cm in 1960; 0.7 cm</td>
</tr>
<tr>
<td>Hyogo</td>
<td>Part of Nishinomiya city; All of Amagasaki and Itami cities</td>
<td>95</td>
<td>1957.6.10 1960.10.7 1962.10.20 1963.6.1</td>
<td>Maximum 19.4 cm in 1957; 2.1 cm</td>
</tr>
</tbody>
</table>

Note: average value from 1993 to 1995 (*)

Data are from each prefectural government and the Tokyo Metropolitan Government.
Fig. 2 Temporal change in total yearly subsidence in Japan

The total yearly subsidence on a bench mark was calculated by leveling surveys. The “Industrial Water Law” and “Law Concerning the Regulation of Pumping-up of Underground Water for Use in Buildings” were enacted in 1956 and 1962, respectively. Names of the city, towns and wards where the bench marks exist are as follows: A: Muika town in Niigata prefecture; B: Shiroishi town in Saga prefecture; C: Washimiya town in Saitama prefecture; D: Nagashima town in Mie prefecture; E: Niigata city in Niigata prefecture; F: Nishi-Yodogawa ward in Osaka; G: Koto ward in Tokyo. Data are from each prefectural government and the Tokyo Metropolitan Government.

Nobi Plain established “Outlines of Measures for Preventing Land Subsidence” for the above three plains, which are shown in Fig. 2 as “B”, “C” and “D”, respectively. Subsidence in the three plains began to be recorded in the mid 20th century but the Outline for the Nobi Plain effectively reduced subsidence at location “D” in Fig. 2.

Pumping of ground water is also controlled by ordinances of local governments, i.e., 25 prefectures and 276 municipalities (Environment Agency of Japan, 2000). At locations “A” and “E” in Fig. 2, subsidence began to be recorded in the mid 20th century, but pumping of ground water is now regulated by ordinances.

Besides these laws, the Outlines and ordinances, surface water resource development and voluntary ground water conservation have also been implemented to prevent subsidence. As a result, subsidence has generally been declining. However, the demand for ground water increases in dry years, because of shortages of surface water. Recently, 1978, 1984, 1986 and 1994 were dry years in Japan and many areas had to ration water because of these shortages (National Land Agency of Japan, 1999). Fig. 3 shows the areas where subsidence increased temporarily to 2 cm/yr or more and 4 cm/yr or more in 1984 and 1994.

3. Current major subsidence areas in Japan

The Environment Agency of Japan uses annual leveling surveys to rank subsidence areas from one to ten according to their yearly subsidence. Table 3 indicates the annual ranks of the current major subsidence areas from 1990 to 1999.

In Table 3, we can see that only two areas, i.e., the Minami-Uonuma area of Niigata prefecture and the Northern Kanto Plain area of Tochigi prefecture, were ranked at the top two or more times during this period. The subsidence in the two areas is reported in detail in the next two subsections.

3.1 Subsidence in the Minami-Uonuma area of Niigata prefecture

Subsidence in the Minami-Uonuma area of Niigata prefecture is ranked for every year except 1990 in Table 3.
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Minami-Uonuma of Niigata prefecture</td>
<td>-</td>
<td>1</td>
<td>(5.2 cm in Muika town)</td>
<td>1</td>
<td>(5.7 cm in Muika town)</td>
<td>1</td>
<td>(7.3 cm in Muika town)</td>
<td>2</td>
<td>(5.3 cm in Muika town)</td>
<td>2</td>
<td>(5.6 cm in Muika town)</td>
</tr>
<tr>
<td>Northern Kanto Plain of Tochigi prefecture</td>
<td>1</td>
<td>(6.7 cm in Nogi town)</td>
<td>8</td>
<td>(3.6 cm in Nogi town)</td>
<td>2</td>
<td>(5.3 cm in Nogi town)</td>
<td>9</td>
<td>(2.3 cm in Nogi town)</td>
<td>2</td>
<td>(7.7 cm in Nogi town)</td>
<td>10</td>
</tr>
<tr>
<td>Northern Kanto Plain of Ibaraki prefecture</td>
<td>5</td>
<td>(4.3 cm in Sanwa town)</td>
<td>3</td>
<td>(4.3 cm in Sanwa town)</td>
<td>3</td>
<td>(4.8 cm in Koga city)</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>(5.6 cm in Koga city)</td>
<td>3</td>
</tr>
<tr>
<td>Northern Kanto Plain of Saitama prefecture</td>
<td>4</td>
<td>(4.4 cm in Karibashi town)</td>
<td>4</td>
<td>(4.2 cm in Karibashi town)</td>
<td>4</td>
<td>(4.7 cm in Karibashi town)</td>
<td>5</td>
<td>(3.2 cm in Washioniya town)</td>
<td>2</td>
<td>(4.4 cm in Washioniya town)</td>
<td>2</td>
</tr>
<tr>
<td>Kujukuri Plain of Chiba prefecture</td>
<td>6</td>
<td>(3.1 cm in Moba city)</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td>(2.5 cm in Moba city)</td>
<td>7</td>
<td>(2.3 cm in Isumi town)</td>
<td>7</td>
<td>(2.3 cm in Osami-Shirasato town)</td>
<td>4</td>
</tr>
<tr>
<td>Nobi Plain of Gifu prefecture</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6</td>
<td>(4.6 cm in Kaizu town)</td>
<td>3</td>
<td>(2.6 cm in Kaizu town)</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>(2.9 cm in Kaizu town)</td>
</tr>
<tr>
<td>Chikugo-Saga Plain of Saga prefecture</td>
<td>3</td>
<td>(4.5 cm in Ariake town)</td>
<td>5</td>
<td>(3.8 cm in Ariake town)</td>
<td>5</td>
<td>(4.3 cm in Ariake town)</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>(16.0 cm in Shiroishi town)</td>
<td>5</td>
</tr>
</tbody>
</table>

Note: 1) The ranking is by Environment Agency of Japan (1995, 2000). 2) The area where subsidence took place at the highest rate in one year is given a ranking of 1. The yearly maximum subsidence in each area is shown in parentheses. 3) - means unranked.
In this area, maximum subsidence of 5.3 cm/yr occurred in 1995. The rate, which was recorded on a bench mark in Muika town, was the highest rate of subsidence in Japan in 1995.

Fig. 4 shows the distribution of the yearly subsidence in the area in 1995. In that year, subsidence of 1 cm/yr or more occurred in a 3 km² area. In Muika town, which is located in the central part of the subsidence area, ground water was pumped out excessively to melt snow in winter (Photo). Yanaka et al. (1989) clarified that ground water of 46 million m³ in volume was pumped out from April 1985 to March 1986 and 65% of the volume was used to melt snow from December 1985 to March 1986. The Niigata Prefectural Government continuously monitors the ground water level and the amount of subsidence at the observation well (Fig. 5). The figure shows that the subsidence corresponds to the lowering of ground water levels when snowfall was recorded. Fig. 6 shows a geological profile of Muika town (Iwata et al., 1986).

Based on electric logging data and bore hole core samples, the stratigraphy of the deposits in Fig. 6 is as follows: AC1 formation (clay), AG1 formation (gravel), AC2 formation (clay, in Pleistocene) and BG1 formation (gravel, in Pleistocene) in descending order (Iwata et al., 1986; Yanaka et al., 1989). AC1 and AC2 formations were found to be somewhat over-consolidated by the past repeated lowering of ground water level (Tohno, 1994). Ground water in the BG1 formation was pumped out from 94% of ca. 2000 wells in the central part of Muika town between April 1985 and March 1986 (Yanaka et al., 1989).

The above information indicates that ground water is mainly pumped out from the aquifer of BG1 formation for snow melting between December and March, AC1 and AC2 formations are compressed, the clay layers scarcely rebound and the area has subsided considerably. The subsidence in the area is described in Tohno (1994) in detail.

3.2 Subsidence in the Northern Kanto Plain area of Tochigi prefecture

Subsidence of 2 cm/yr or more occurred in a 76
km² area in the Northern Kanto Plain area of Tochigi prefecture in 1994, which was a dry year. In 1996, the maximum rate of subsidence recorded there was 6.9 cm/yr in Nogi town, the highest in Japan that year (Table 3). Fig. 7 shows the distribution of the yearly subsidence in the area in 1996 (Tochigi Prefectural Government, 1997).

Fig. 8 shows monthly changes in ground water level and subsidence at a 150 m-deep observation well in Nogi town. The figure indicates that the ground water level decreased remarkably from April to August and the subsidence took place as a consequence. Ninety percent of the pumping of ground water for agriculture was concentrated between April and September, and ninety percent for water supply was concentrated between February and May (Environment Agency of Japan and Tochigi Prefectural Government, 1998). There is a possibility that the decrease of the ground water level from April to May was caused by the pumping of ground water for both agriculture and water supply. Fig. 8 also indicates that the ground scarcely rebounded though the ground water level ascended rapidly from September to October.

The volume of ground water pumped from April 1997 to March 1998 was investigated at Nogi town (Environment Agency of Japan and Tochigi Prefectural

Fig. 6  Geologic profile of the central part of Muika town in Niigata prefecture.

"A-B" indicates the location of the geologic profile, which is also shown in Fig. 4. The figure in Iwata et al. (1986) is simplified.
Government, 1998). As a result, it was found that total volume of ground water pumped from the 74 wells in Nogi town in 1998 was 10.46 million m³. It was also found that 8.6% of the total volume was pumped out 0-30 m below the ground surface, 3.2% was 31-60 m below, 1.3% was 61-100 m below, 53.9% was 101-150 m below and 31.6% was 151-200 m below the ground surface. These results indicate that almost all the ground water was pumped out from depths of more than 100 m. Furthermore, it was found that 88% of the total volume was used for agriculture, 6% was for buildings, 5% was for industries and 0.7% was for water supply.

Stratum compression was monitored at 33 m-deep and 90 m-deep observation wells, as well as at the above-mentioned 150 m-deep well (Tochigi Prefectural Government, 1999b). The data show that in 1996, stratum 0-33 m deep recorded rebound of +0.34 mm, stratum 33-90 m deep recorded compression of -21.23 mm and stratum 90-150 m deep recorded compression of -16.41 mm. Thus, the compression 33-90 m deep was about equal to compression 90-150 m deep.

Fig. 9 shows a geologic columnar section at the 150 m-deep well (Tochigi Prefectural Government, 1999b). The section contains upper clay layers of 1.8 m, 4.0 m, 7.6 m, 6.9 m and 5.5 m in thickness lying 3-4.8 m, 12-16 m, 29.5-37.1 m, 44.7-51.6 m and 59.3-65.2 m below the ground surface, respectively. The section also contains lower clay layers 39.0 m and 7.0 m thick lying at depths of 86.0-125.0 m and 143.0-150.0 m, respectively. It is inferred from referring to Akutsu (1965) that all clay layers except the layer 3-4.8 m deep are from the Pleistocene.

Judging from the above information, ground water is pumped out mainly from the aquifer of a Pleistocene.
deposit 101-200 m deep between April and August, the 33-150 m deep Pleistocene clay layers are compressed, the clay layers scarcely rebound and area has subsided considerably.

4. Effective monitoring of subsidence with GPS and SAR interferometry

The national and local governments have conducted successive leveling surveys to monitor subsidence, and they have monitored ground water levels and stratum compression at an observation well. But leveling surveys are lengthy and installing and maintaining wells are expensive. In order to monitor subsidence more effectively, new technologies should be introduced. Here, let us examine the effectiveness of GPS and SAR interferometry for monitoring subsidence.

4.1 Monitoring subsidence with GPS

In order to monitor subsidence, Krijnen and de Heus (1995) investigated GPS positioning precision on the vertical component of a baseline. A GPS survey was carried out in the province of Groningen, in north-eastern Netherlands from 24 May 1994 to 3 June 1994, with the five GPS receivers of Trimble. The total number of sessions was 33 and the longest baseline was 15 km. The software Bernese and precise ephemeris were used for processing the GPS data, and 5-8 mm in standard deviation was reported for the precision of the vertical component.

Krijnen and de Heus (1995) stated that GPS is a useful tool for monitoring subsidence. However, continuous monitoring is necessary in Japan, because pumping of ground water increases rapidly in dry or heavy snow years and can triggered serious subsidence.

In order to detect crustal movements, the Geographical Survey Institute of Japan has a highly integrated continuous GPS monitoring network called the GPS Earth Observation NETwork, or “GEONET” (Miyazaki et al., 1998), which is comprised of 947 observation stations nation-wide with an average baseline of 25 km in length. L1 and L2 carrier phases are observed every 30 seconds at the every station, and GPS data are processed with the software Bernese, IGS (International GPS Service) ephemeris and other post-processing methods. As a result, positioning precision is typically 5 mm horizontally and 1.5 cm vertically (Miyazaki et al., 1997). Since no studies on subsidence detection with GEONET have been reported yet, further investigation is
necessary to determine whether or not GEONET data is useful for detecting and continuously monitoring subsidence.

4.2 Monitoring subsidence with SAR interferometry

The monitoring of subsidence in a wide area requires lengthy leveling surveys, or a large number of expensive GPS survey stations. However, satellite monitoring can detect subsidence over a wide area at one time. For example, SAR interferometry on a satellite was used to detect subsidence in a wide area of the Northern Kanto Plain in 1994 by Nakagawa et al. (1999) using the L band (1.3 GHz frequency) on JERS-1 (Japanese Earth Resources Satellite-1). They concluded that a few cm subsidence could be detectable from the data. However, further investigation is necessary to detect subsidence successively in many areas using SAR interferometry.

5. Conclusion

The area of subsidence in Japan has been reduced recently, but in dry years serious subsidence takes place temporarily nation-wide.

Current subsidence conditions in the Minami-Uonuma area of Niigata prefecture and the Northern Kanto Plain area of Tochigi prefecture have been reported. As a result, it appears that intensive pumping of ground water in winter and/or spring from deep Pleistocene aquifers triggers a rapid decrease in ground water level, causing compression of clay layers near the aquifers that cannot rebound, resulting in considerable subsidence.

To prevent subsidence, it is necessary for national and local governments to monitor subsidence continuously, and take emergencies measures when needed. It is also necessary to monitor subsidence effectively with new technologies.

References


国土地理院報告

第47巻

目次

GPS観測から推定された東アジアのテクトニクスについて
……………………宮崎真一・松坂 茂・梅津 優・黒石裕樹・村上真幸・今谷寛哲郎 1
多田 優・新田 浩・中川弘之・板橋昭彦・唐沢正夫・大滝 修
石川典彦・石本正芳

地球地図の新たな展開に向けて
～地球地図第一版の提供による第一期の完成～
…………………………………………………………………………… 字根 寛 13

空間情報と時系列情報の統合化に関する研究開発
…………………………………………………………………………… 星野秀和・久保紀重・飯村 威・池田彰弘・飯田剛輔 21

傾斜図－地形的な特徴を捉えるための有用なツール
…………………………………………………………………………… 神谷 泉・佐藤 浩 29

わが国の最近の地盤沈下の状況について
…………………………………………………………………………… 佐藤 浩 35

3.2001