A decade of GEONET: 1994–2003 —The continuous GPS observation in Japan and its impact on earthquake studies—

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(Received February 4, 2004; Revised May 6, 2004; Accepted May 24, 2004)

The dense continuous GPS network of Japan, now called GEONET, has been operated since 1994 by the Geographical Survey Institute. GEONET provides precise daily coordinates of all the stations, with which displacement rates and strain rates are calculated nationwide. Various characteristics of tectonic deformation in the Japanese Islands have been revealed. GEONET is also quite useful in earthquake studies, precisely detecting co-seismic, post-seismic, and inter-seismic deformation signals. These observations are utilized to infer physical processes at earthquake sources. Slow slip events on plate boundaries have been found from GPS data. Such slow events provide an important constraint on the mechanism of faulting. On the other hand, there has been no success in detecting pre-seismic deformation. Lack of a precursory signal before the 2003 Tokachi-Oki (M8.0) earthquake has posed a serious question to short-term earthquake prediction. GEONET enables a good linkage between monitoring and modeling studies, opening a possibility of practical data assimilation. For further contribution to earthquake studies, it is necessary to continue GEONET with high traceability on the details in observation and analysis.

Key words: GEONET, GPS, crustal deformation, the Japanese Islands.

1. Introduction

The Japanese Islands are located at a complex plate boundary region where at least 4 tectonic plates meet (Fig. 1). Relative motion of these plates accumulates stress in the lithosphere, causing observable crustal deformation. Earthquake rupture occurs along crustal faults and/or along plate boundaries to release such tectonic stress. Therefore study of crustal deformation is one of the essential aspects in earthquake studies.

Observational study of crustal deformation is based on geodetic methods. In Japan, triangulation and leveling networks were established in the late 19th century. Those networks have been repeatedly occupied, revealing various tectonic, seismic, and volcanic deformations in the Japanese Islands. Various important data have been provided from those geodetic networks for earthquake studies. One special example is the crustal deformation data over a whole earthquake cycle along the Nankai Trough subduction zone during last 100 years (Thatcher, 1984).

Beginning from the late 1980's, the Japanese geodetic network has been innovated with the Global Positioning System (GPS). A pioneering continuous GPS network was established in the Kanto-Tokai region by the National Research Institute for Earth Science and Disaster Prevention (NIED) (Shimada and Bock, 1992). This network consisted of about 30 stations and successfully detected the crustal movements associated with a fissure eruption in east off the Izu Peninsula in July 1989 (Shimada *et al*., 1990).

Geographical Survey Institute (GSI), that is responsible for the reference frame and geodetic networks in Japan, started establishing its own GPS network late in 1993. Ever since, the GSI's GPS network called GEONET (GPS Earth Observation Network) has been successful in detecting significant crustal movement events and demonstrating its usefulness for earth sciences and disaster mitigation during the last decade (1994–2003). GEONET has become indispensable for the present-day earthquake studies.

The purpose of this paper is to review earthquake-related deformation studies based on observation of GEONET and to discuss what impacts the continuous GPS network brought to earthquake studies. Therefore technical aspects of GPS, such as the basics of GPS geodesy or details of a routine analysis, are out of scope of this review. GPS has various applications in different fields such as earth rotation, meteorology, ionospheric studies, and so on. Although those studies play important role in improving the accuracy of GPS measurement, I will omit those aspects of GPS and focus on crustal deformation studies in the following.

For the convenience of readers Figure 1 serves as an index map showing the major tectonic units and geographic names mentioned in this paper.

2. Overview of GEONET

Construction of a dense continuous GPS network by the Geographical Survey Institute (GSI) started in 1993. The network started as two independent networks. One was the COSMOS-G2 (Continuous Strain Monitoring System with GPS by GSI) network, a dense network in the southern Kanto

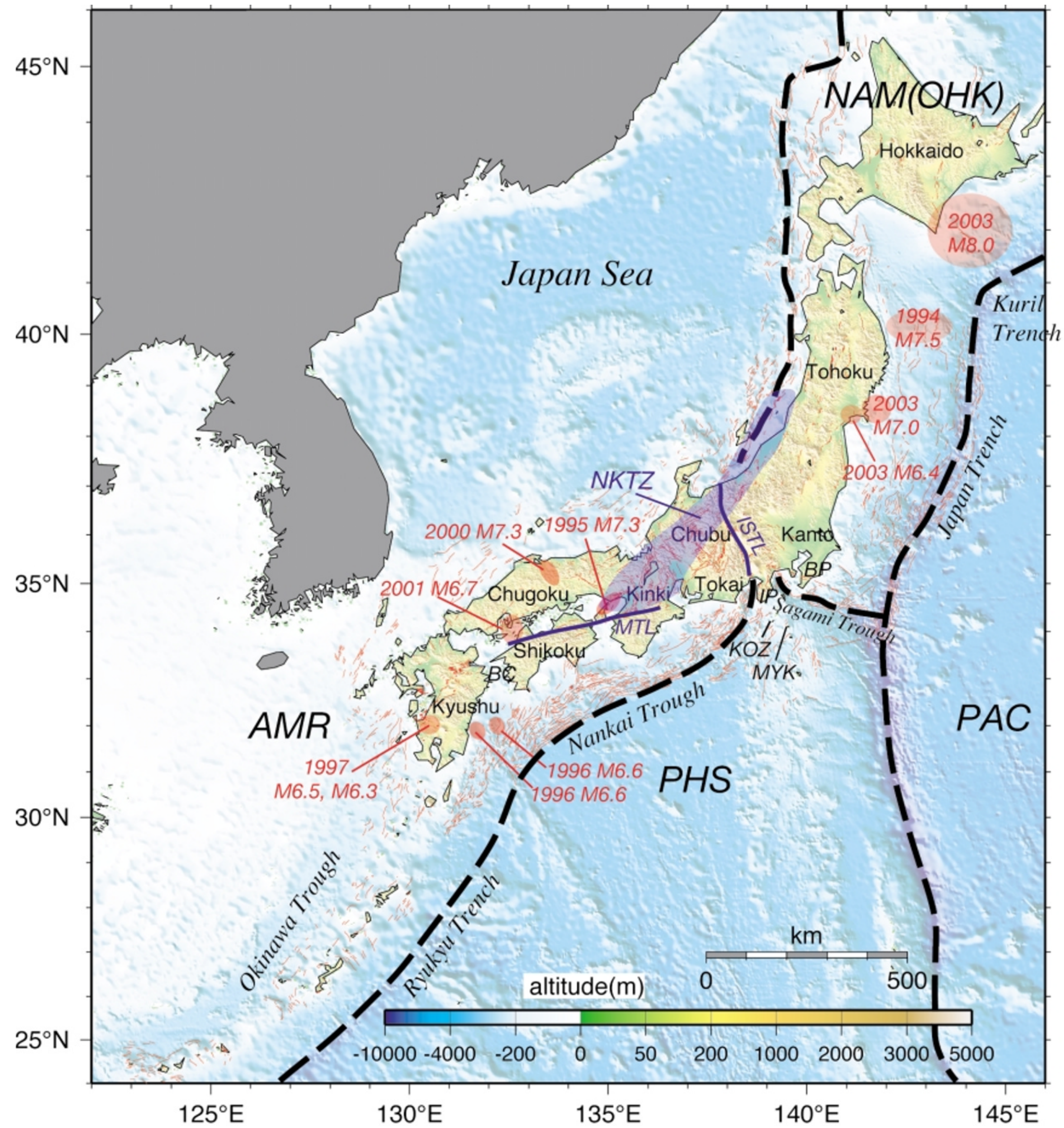

Fig. 1. Index map of the Japanese Islands. Source regions of conspicuous earthquakes during 1994–2003 are shown in red. PAC: Pacific Plate, PHS: Philippine Sea Plate, AMR: Amurian Plate, NAM: North American Plate, OHK: Okhotsk Plate, NKTZ: Niigata-Kobe Tectonic Zone (Sagiya *et al.*, 2000), ISTL: Itoigawa-Shizuoka Tectonic Line, MTL: Median Tectonic Line, BP: Boso Peninsula, IP: Izu Peninsula, BC: Bungo Channel, KOZ: Kohzu-shima, MYK: Miyake-jima.

and the Tokai region (Sagiya *et al*., 1995). 110 continuous GPS sites densely (average spacing of about 25 km) covered the Tokyo metropolitan area and the Tokai district, where the so-called "Tokai earthquake" is anticipated to take place (Ishibashi, 1981). Sagiya (1998a) reported the observation results of the COSMOS-G2 network.

GSI also constructed a nation-wide GPS network, called GRAPES (GPS Regional Array for Precise Surveying/Physical Earth Science), in the rest of the Japanese Islands with 100 continuous sites (Tsuji *et al*., 1995; Miyazaki *et al*., 1996). The Japanese Islands experienced significant seismic events just after GSI started the operation of this network. The tragedy of the 1995 Kobe earthquake prompted the government to promote earthquake researches. Continuous GPS network was approved as one of the basic observation networks to be constructed over Japan.

As a result, GSI's two GPS networks, COSMOS-G2 and GRAPES, were integrated and about 400 continuous sites were newly constructed to constitute the upgraded network called GEONET in April 1996 (Tada *et al*., 1997; Miyazaki *et al*., 1997). New stations have been successively added and the GEONET has become the largest regional GPS network around the world. It consists of about 1,200 continuous sites as of 2004.

A typical GEONET station is made of a 5 m tall stainless pillar equipped with a dual-frequency GPS receiver, a GPS antenna, and a modem connected to a digital telephone line (ISDN). All the GEONET stations were operated with 30 seconds sampling rate. GSI downloaded data from all the station on a daily basis. Recently, development of a broadband technology enables an epoch-by-epoch data transmission. Accordingly, GSI started collecting 1 Hz sampling data so as to be utilized for real-time monitoring of crustal deformation and other purposes. Those 1 Hz sampling data are transmitted to the control center at GSI on a real-time basis and temporarily stored. Then, the data are deleted after a while unless there is a special data request or a significant seismic/volcanic event. On the other hand, GPS receivers on site store 30 seconds sampling rate data, which are downloaded afterwards for permanent archiving and precise analyses.

Shortly after the completion of data downloading, the daily coordinates of each station are calculated in GSI. These rapid solutions, which are obtained about 1 day after the observation, are utilized for quasi-real-time monitoring of crustal movement all over Japan. In case of a significant volcanic/seismic activity, data downloading and rapid processing becomes much more frequent, every 3 hours, for example. GSI processes all the data again to calculate the final daily coordinate solution when the IGS (International GPS Service) final orbit becomes available.

All the GPS observation data, and routine daily coordinate solutions as well as variance-covariance matrix are archived at GSI. Various information of GEONET, including raw observation data and daily coordinate solutions, is available on the GSI's web page (http://www.gsi.go.jp/).

3. Tectonic Deformation Studies Using GEONET

3.1 Daily coordinates

GSI's routine solution is calculated using the Bernese GPS software (Hugentobler *et al.*, 2001). Since the start of the GEONET operation, there were several changes in the routine analysis strategy. Also an inappropriate phase center variation (PCV) model of GPS antennas was used for routine analysis, deteriorating the solution quality. In order to solve these problems, Hatanaka *et al.* (2003) re-analyzed GEONET data back to April 1996 to obtain daily coordinate solutions through a uniform analysis strategy with an appropriate PCV model (Hatanaka *et al.*, 2002a, b). GSI provides these revised solutions as the results of routine analysis. On average, repeatability of daily coordinates is a few mm in horizontal components and 10–20 mm in vertical component in a root-mean-square sense.

Basic observables of the Bernese software to estimate station coordinates are double differenced phase data, which are produced by combining phase data from pairs of stations. Therefore the routine solutions of GSI are a network solution. Station coordinates for the same day are not independent one another. Such a solution may have an error component common to all the stations. Tabei and Amin (2002) discussed removal of such a common noise. We can obtain a solution free from a network common noise by using another undifferentiating technique. The GIPSY/OASIS-II software can be utilized for that purpose (Zumberge *et al.*, 1997). Although the coordinate repeatability gets worse with such a technique, it is widely used in crustal deformation study because of its efficient calculation and its merit of no network noise.

With traditional geodetic method, temporal resolution was usually several years and at best a month or so. The GEONET data make the temporal resolution as short as 1 day, even shorter whenever it is necessary. Simultaneousness of getting coordinates is another benefit, especially when we try to resolve transient motion. And it is of course that GEONET solution is far superior to conventional geodetic survey data with its high precision. Regarding GEONET as a deformation array Ito and Hashimoto (2004b) applied the semblance method to extract the migrating deformation signal. Such an analysis would never be possible with conventional geodetic surveys.

3.2 Seasonal motion

Seasonal components in GPS coordinate time series are interesting findings with GEONET. Although many users of GSI's daily solutions had realized significant seasonal signals, Murakami and Miyazaki (2001) first discussed the seasonal signals in conjunction with the plate motion and speculated that plate interaction may have seasonality. Heki (2001, 2003a) noticed that the seasonal components in the Tohoku district has different phase shift between the Pacific side and the Japan Sea side, and concluded that the seasonal motion is caused by snow load in winter. On the other hand, Hatanaka (2003) investigated the relation between the seasonal signals and tropospheric delays, and found a positive correlation between them. His results indicate that at least a part of the seasonal signal is due to a scale error of the network solution caused by erroneous modeling of the tropospheric delay. Recently, Heki (2003b) claimed that seasonal change of GPS time series could be fully interpreted by the superposition of snow load, ocean tide, moisture in the soil and a few other effects. Those factors would surely contribute to seasonal signals in GPS time series, but the problem is that it is still unclear how much artificial signal is contained in the routine results of GEONET. Therefore the amplitude of the true seasonal signal is still an open question.

3.3 Velocity field

Once we obtain daily coordinates, it is rather straightforward to calculate corresponding displacement rate for each station, and the distribution of strain or strain rate for a particular time period. Miyazaki *et al.* (1997) obtained horizontal velocity vectors from 1 year long daily coordinate solutions of GEONET. Sagiya *et al.* (2000) analyzed 2.5 years time period of a similar dataset and calculated horizontal velocity vectors considering annual sinusoidal components as well as co-seismic steps. These results revealed the overall deformation pattern of the Japanese Islands.

The horizontal velocity vectors (Fig. 2, Sagiya *et al.*, 2000) were calculated with respect to the stable Eurasian plate based on Heki (1996). The first significant feature of Fig. 2 is the harmonization of the spatial distribution of the velocity vectors among neighboring GPS stations. Such a pattern demonstrates two characteristics of the deformation field: the high stability of the GEONET in monitoring steady crustal deformation, and the smooth nature of the crustal deformation during the time period of January 1997 to July 1999 while no major earthquake occurred in the region.

The velocity distribution also clearly indicates that the southwestern Japan is moving westward with respect to the Eurasian plate, which is important in discussing its tectonic affiliation. Along the Ryukyu island arc, however, GPS stations have trench-ward motion that is much faster than the expected plate motion as a part of the Amurian plate. Such a deformation pattern indicates an effect of back-arc spreading

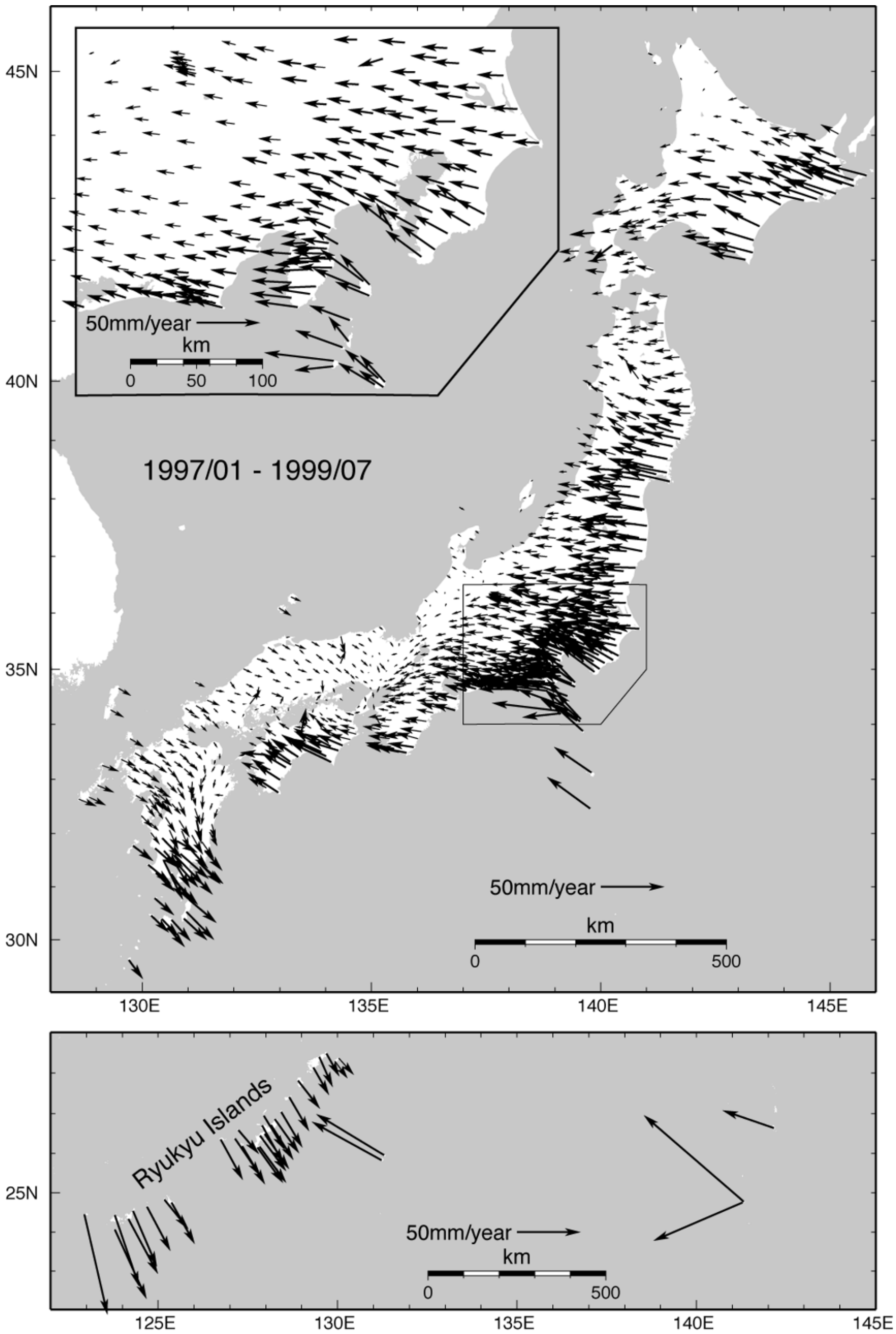

Fig. 2. Horizontal displacement rate vectors of continuous GPS sites. All the vectors are relative to the stable part of the Eurasian plate. Inset shows the magnification of central Japan (Sagiya *et al*., 2000).

at the Okinawa Trough and implies that the interplate coupling at the Ryukyu Trench is extremely weak or even not at all. This is consistent with the fact that there has been no megathrust earthquake known. Deformation pattern along the Ryukyu Islands arc is modeled by Fujihara *et al*. (2001), for example. Such a trench-ward motion is observed in other subduction zones with back-arc opening (e.g. Bevis *et al*., 1995; Kato *et al*., 2003), and probably it is a common feature for weakly coupled subduction zone.

We can identify significant northwestward motion along the Sagami-Suruga-Nankai Trough where the Philippine Sea plate is subducting beneath the Japanese Islands. Also along the Japan-Kuril Trench, northwestward motion is prevailing, that reflects the Pacific plate subduction. The data represent plate interaction along the subduction zone, and they are analyzed to estimate slip-deficit (or backslip) distribution on the plate boundaries as we will discuss later.

GPS daily coordinates are highly precise in their horizontal components but repeatability of the vertical components is much poorer. So vertical components have been neglected in scientific discussions. Aoki and Scholz (2003) conducted a principal component analysis to extract secular vertical sig-

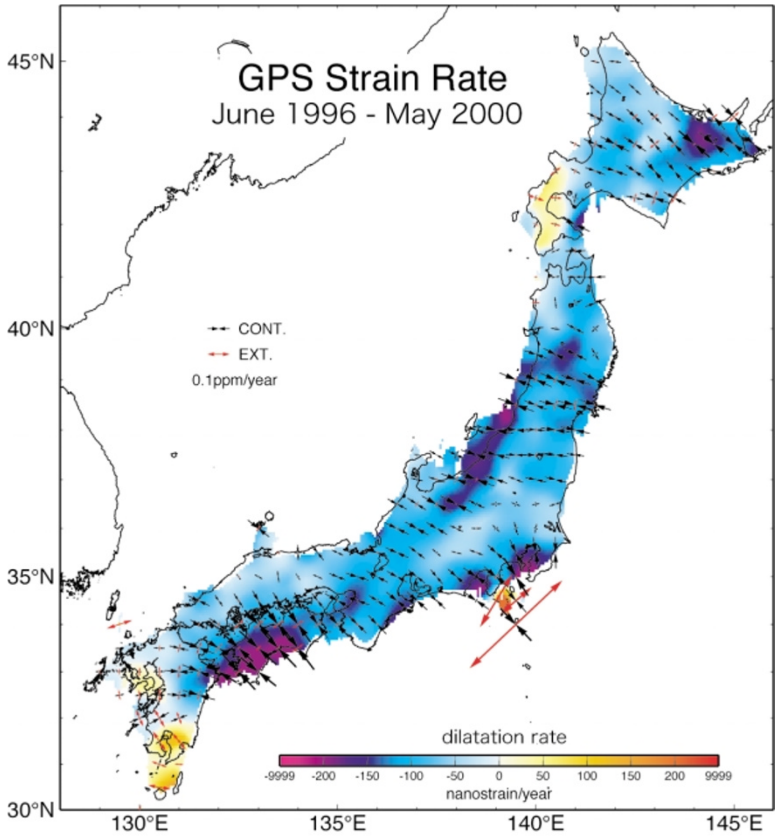

Fig. 3. Strain rate of the Japanese islands obtained from GEONET data. Strain rate was calculated in the same was as Sagiya *et al.* (2000), using the velocity data from June 1996 to May 2000. Dilatation rate is shown in color. Arrows denote principal strain rate axes.

nals from daily coordinate solutions of GEONET, and discussed crustal deformation of the Japanese Islands in terms of vertical velocity.

3.4 Strain rate distribution

Displacement rate vectors depend on the assumption of fixed point or the reference frame, and there are degrees of freedom for translation and rigid rotation. Therefore calculation of strain rate distribution is important for the interpretation of crustal deformation in conjunction with earthquakes.

There are several ways of strain rate calculation from the velocity data. Kato *et al.* (1998) applied the least-squares collocation technique to calculate continuous distribution of velocity vectors and they derived the strain rate field by spatial differentiation. For the calculation of velocity field, they estimated variance-covariance matrix as a function of distance between two arbitrary GPS sites to apply all the velocity data. Sagiya *et al.* (2000) applied the strain rate calculation method by Shen *et al.* (1996). They assumed a Gaussian type variance-covariance and introduced a distance-decaying constant (fixed as 35 km) to control the spatial correlation. Figure 3 shows principal strain rate axes and dilatation rate distribution calculated with the same method as Sagiya *et al.* (2000) using velocity data from June 1996 to May 2000. Resultant strain rate distributions of these studies are basically similar, but Sagiya *et al.* (2000) discussed more detailed feature of the strain rate distribution. They noticed that there is a continuously high (over 0.1 ppm/year) strain rate zone connecting the Japan Sea coast around Niigata and the Kinki district around Kobe, and named it the Niigata-Kobe Tectonic Zone. On the other hand, several regions are characterized by low strain-rate. The central Kanto, southern Chubu, Chugoku, and the northern Kyushu districts are such regions. Such a heterogeneous distribution of strain rate is an important finding from GEONET.

There has been a long discussion about the strain rate of the Japanese Islands. Geodetic estimates of strain rate were larger than geological estimates by an order of magnitude (Wesnousky *et al.*, 1982; Hashimoto, 1990; Shen-Tu *et al.*, 1995). According to the strain rate estimation by Sagiya *et al.* (2000), strain rate in small deformation areas is on the order of 0.01 ppm/yr, comparable to previous geological estimates, whereas large deformation areas have strain rate one order larger, consistent with previous geodetic estimates. The averaged strain rate over the Japanese Islands falls between the previous geodetic and geological estimates. Thus GPS observation partially solves the contradiction by incorporating heterogeneity of strain rate. In addition to the nationwide analyses, detailed analyses and discussions of regional strain fields have been done in the Tohoku district (Miura *et al.*, 2002), and in the Kanto-Tokai district (Itani and Ishibashi, 2003).

What GPS captures is an instantaneous snapshot of ongoing crustal deformation. Displacement rates based on GPS can be very different from long-term deformation rate. Mazzotti *et al.* (2001) discussed a permanent strain rate of central Japan, deduced by subtracting plate boundary effects at the Suruga and Sagami Troughs by Henry *et al.* (2001). On the other hand, El-Fiky (2000) tried to discriminate plastic strain from elastic strain based on GPS velocity data. Such a calculation requires physical constraints such as no volumetric change in plastic deformation. Hori *et al.* (2000) also applied a new technique for predicting stress to GEONET data. It is not clear if these new theories are useful in earthquake studies, and they need to be continuously tested with increasing GEONET data.

3.5 Plate motion and boundaries

Japan is located in a complicated plate boundary region where at least four tectonic plates, the North American (or the Okhotsk), the Amurian, the Philippine Sea, and the Pacific plates, interact one another (Fig. 1). The southwestern Japan has been considered as the eastern margin of the Eurasian plate. But Heki *et al.* (1999) used continuous GPS observation to demonstrate that the southwestern Japan, together with the northeastern China and the Korean Peninsula, constitutes an independent plate, called the Amurian plate.

Another controversy is whether the northeastern Japan belongs to the North American plate (Heki *et al.*, 1999) or it should be discriminated as the Okhotsk plate (Seno *et al.*, 1996; Wei and Seno, 1998). Secular motion of the northeastern Japan is rather difficult to estimate precisely because of the plate interaction effects by the subducting Pacific plate. Present crustal deformation in this region obtained from GPS observation mainly reflects elastic strain accumulation due to the interplate coupling along the Japan Trench. We need to correct observed deformation for such elastic strain accumulation in order to discuss secular motion of the northeastern Japan. However, this elastic strain correction is still not precise enough to finalize this plate affiliation problem.

As shown in Fig. 3, there is a belt of strain concentration along the Japan Sea coast in the northeastern Japan. This concentrated deformation corresponds to an incipient plate boundary between the Amurian (previously Eurasian) and the North American plates proposed by Kobayashi (1983) and Nakamura (1983). Then the new plate boundary hypothesis was confirmed by GEONET in terms of present-day deformation. The motion of the Sado Island is close to that of the western side of this plate boundary. Thus the GPS data has also benefited to identify the possible plate boundary location. However, the southward continuation of this boundary is controversial. The Itoigawa-Shizuoka Tectonic Line, running across the central Japan, is a major geologic boundary and a natural continuation of the plate boundary between the Amurian and North American plates as proposed by Nakamura (1983). On the other hand, the strain concentrated belt continues to the southwest, cutting across the Itoigawa-Shizuoka Tectonic Line, to reach around the source region of the 1995 Kobe earthquake. Historical seismicity and existence of many active faults along the Niigata-Kobe deformation belt strongly suggest this deformation belt is a presently active deformation zone.

Shimazaki and Zhao (2000) modeled this strain concentration as a collision zone by using dislocation theory. They were successful in explaining the horizontal deformation, but their model predicts significant uplift along the deformation belt, which was not observed. Iio *et al.* (2002) proposed a physical mechanism to generate the deformation belt by taking the plate interaction at the Japan Trench and a lower crustal heterogeneous beneath the deformation belt into account. Hyodo and Hirahara (2003) tried a finite element modeling to reproduce the deformation belt based on the model of Iio *et al.* (2002) and demonstrated that quantitative explanation is feasible.

At the northern end of the Philippine Sea plate, the Izu Peninsula is colliding with the Japanese mainland. Sagiya (1999) pointed out that the motion around the Izu Peninsula significantly departs from that expected from plate motion model (Seno *et al.*, 1993), and hypothesized an independent block called “Izu microplate”. The idea of Izu microplate was originally proposed by Hashimoto and Jackson (1993) based on triangulation data, and is now strongly supported by GEONET data. This conjecture has a consequence that the strain accumulation in the Suruga Bay is less than that along the Nankai Trough, implying a longer recurrence time of the Tokai earthquake. Similar idea was presented by Mazzotti *et al.* (1999), too.

4. Seismic Deformation

4.1 Coseismic and postseismic deformation

Shortly after the operation of GRAPES started in October 1994, the M8.1 Hokkaido-Toho-Oki (Shakotan) earthquake occurred on October 4. This earthquake caused significant crustal displacement all over the Hokkaido with the maximum offset of over 40 cm at Nemuro (Tsuji *et al.*, 1995). The deformation data were analyzed to construct a source fault model (Tsuji *et al.*, 1995; Ozawa, 1996).

Following this event, the M7.5 Sanriku-Haruka-Oki earthquake occurred on December 28, 1994, east off the northern Tohoku region on the Japan Trench subduction zone. This earthquake was epoch-making because of its significant post-seismic deformation. Trench-ward displacements continued for more than a year after the earthquake and GPS precisely recorded the spatio-temporal evolution of displacements (Heki *et al.*, 1997; Nishimura *et al.*, 2000; Yagi *et al.*, 2003). This post-seismic deformation was interpreted in terms of after-slip along the plate boundary. The post-seismic moment release of this earthquake was even larger than the co-seismic one, providing a key to explain the weak seismic coupling along the Japan Trench (Kawasaki *et al.*, 2001). Heki and Tamura (1997) successfully obtained a short-term (from minutes to days) post-seismic deformation of this earthquake by applying a sidereal correction to their kinematic solution.

The M7.3 Hyogo-Ken-Nanbu (Kobe) earthquake occurred on January 17, 1995, 3 weeks after the Sanriku-Haruka-Oki earthquake. The network at that time was too sparse to resolve detailed slip distribution of this earthquake although the co-seismic displacement was clearly detected at several stations (Hashimoto *et al.*, 1996).

After April 1996, the upgraded GEONET has become capable of detecting co-seismic signals from inland earthquakes with magnitude around 6 or larger, and offshore or intermediate-depth earthquakes over M6.5. Co-seismic signals were observed for the 1996 Onikoube earthquake (August 11, M5.9), the 1996 Hyuga-nada earthquakes (Oct. 19, M6.6; Dec. 3, M6.6, Yagi *et al.*, 2001), the 1997 Kagoshima earthquakes (March 26, M6.5; May 13, M6.3, Fujiwara *et al.*, 1998), the 1998 Iwate earthquake (September 3, M6.1, Miura *et al.*, 2000; Nishimura *et al.*, 2001a), the 2000

Tottori-Ken-Seibu earthquake (October 6, M7.3, Sagiya *et al.*, 2002a), the 2001 Geiyo earthquake (March 24, M6.7), the 2003 Miyagi-oki earthquake (May 26, M7.0), the 2003 Miyagi-ken-Hokubu earthquake (July 26, M6.4, Nishimura *et al.*, 2003; Miura *et al.*, 2004a), and the 2003 Tokachi-Oki earthquake (September 26, M8.0, Koketsu *et al.*, 2004; Irwan *et al.*, 2004; Miura *et al.*, 2004b).

Active seismic swarms, mostly volcanic ones, are frequently accompanied by significant crustal deformations. GEONET has detected crustal deformations associated with seismic swarms in the eastern Izu Peninsula during 1995–1998 (Aoki *et al.*, 1999; Nishimura *et al.*, 2002), the Mt. Iwate Volcano in 1998 (Miura *et al.*, 2000; Nishimura *et al.*, 2001a), the Usu volcano in 2000 (Takahashi *et al.*, 2002), and around the Miyake-jima and Kohzu-shima in 2000 (Nishimura *et al.*, 2001b; Toda *et al.*, 2002; Ito and Yoshioka, 2002). The last example was caused by a magmatic activity beneath the Miyake-jima volcano and around the Kohzu-shima. This event was accompanied by 6 seismic events with magnitude over 6 in two months, and caused significant deformation all over the central Japan. GEONET recorded this unprecedented deformation event in a great detail (Nishimura *et al.*, 2001b).

Precise geodetic networks can detect not only deformation signals caused by contemporary events but also those related to "older" events. For example, the 1993 Hokkaido-Nansei-Oki earthquake (Tanioka *et al.*, 1995) left post-seismic deformation signals and were detected by GEONET, which were analyzed to estimate viscoelastic relaxation, amount of afterslip, and rheological structure of the asthenosphere (Ueda *et al.*, 2003).

High precision of GPS observation is an important merit for observing seismic deformation. For large earthquakes at subduction zones, GEONET provides enough resolving power for estimating variable slip distribution (e.g. Miura *et al.*, 2004b). However, as for the co-seismic deformation of inland earthquakes approximately smaller than Mw 7, almost all the data observed with GEONET can be well reproduced with a rather simple model such as a rectangular fault plane with uniform dislocation (e.g. Sagiya *et al.*, 2002a). It clearly indicates that the current spatial resolution of the GEONET stations is not enough to modeling the inland earthquakes with Mw 7 or smaller. Densification of GEONET will be necessary for high resolution. However, it is questionable in terms of the cost-efficiency because significant inland earthquakes are very infrequent.

The most important contribution of GEONET associated with the seismic deformation is the separation of co-seismic and post-seismic signals. With conventional geodetic survey techniques, although there have been some examples of successfully detecting post-seismic signals (e.g. Thatcher, 1984), it was fairly difficult to resolve purely co-seismic signals. In the Japan Trench, post-seismic deformation of the 1994 Sanriku-Haruka-Oki earthquake explicitly showed that the moment release in the geodetic band was twice as large as that in the seismic band (Heki *et al.*, 1997). Such observation is very important for understanding physical processes at plate boundaries.

Another contribution of GEONET is to shorten the time for analysis. In recent cases, a fairly precise co-seismic displacement and even a fault model can be estimated within 24 hours after the occurrence of large earthquakes. We may utilize such information to issue warning about aftershocks by static stress triggering and to find appropriate observation sites for detecting post-seismic displacements.

4.2 Slow earthquakes

One of important findings with GEONET, so far, is the detection of aseismic transient deformation. For example, several neighboring GPS sites in the eastern Boso Peninsula were displaced within a time interval about a week in May 1996 (Sagiya, 2004). The maximum displacement reached up to 20 mm while no significant seismic event occurred. An inversion analysis of the displacements indicated that an aseismic slip might have occurred on the surface of subducting Philippine Sea plate and the equivalent moment magnitude was estimated as 6.4. Similar slow slip events were also found in Bungo Channel in 1997 (Hirose *et al.*, 1999; Ozawa *et al.*, 2001) and in the Tokai area in 2001 (Ozawa *et al.*, 2002). The Tokai slow slip event attracted special attention because the slip was located adjacent to the presumed focal region of the anticipated "Tokai earthquake" stated by the Central Disaster Management Council. This slip event has been carefully monitored by GEONET and it is still continuing as of May 2004.

A repeating character of slow slip events was first recognized in Cascadia subduction zone in the northwestern United States and Canada. After the discovery of slow slip events by Dragert *et al.* (2001), Miller *et al.* (2002) found that similar events have repeatedly occurred with an average interval of 14 months.

Such repetitions of slow slip events were not found in Japan until October 2002, when a slow slip event occurred east off the Boso Peninsula. This event resembles the 1996 event in terms of its size, location, and the corresponding deformation pattern (Ozawa *et al.*, 2003). In addition, as a result of revisiting seismicity as well as borehole tiltmeter records, it seems highly likely that repeating events occurred in May 1983 and December 1990, with an average interval of 6.5 years. A repeating slow slip event is also reported in Bungo Channel in August 2003.

Another interesting topic associated with the slow slip event is low-frequency tremors. After Obara's (2002) discovery of low-frequency tremors along the Nankai Trough subduction zone, Rogers and Dragert (2003) found that slow slip events and low-frequency tremors occur simultaneously in Cascadia. Recently, Hirose and Obara (2003) reported that their borehole tiltmeters recorded small tilt changes synchronized to tremors. Probably tremors along the Nankai Trough are too frequent and the corresponding displacements are too small to be detected by GEONET.

It would be impossible to detect those slow slip events without GEONET. Highly precise coordinates as well as a good temporal resolution of GEONET made this discovery possible. Presently, implications of slow slip events for large earthquakes are studied in various ways, and physical mechanisms to generate such a slow slip event should be investigated. More and more examples in various locations are quite important in advancing the studies, and GEONET is indispensable for this purpose.

4.3 Inter-seismic deformation and slip deficit distribution

Crustal deformation in an inter-seismic period reflects the physical process of strain energy accumulation. Thus the monitoring of inter-seismic deformation is very important in considering future large earthquakes. Savage and Prescott (1978) proposed a model of inter-seismic deformation for transcurrent plate boundary, in which inter-seismic deformation is represented as a superposition of a steady block-wise plate motion and an interplate locking effect described as slip-deficit or backslip. This idea was applied to subduction zones by Savage (1983). Yoshioka *et al.* (1993) first analyzed the conventional geodetic data in the Tokai district to estimate slip deficit distribution on the plate boundary interface.

With high precision GEONET data, various analyses of inter-seismic deformation were widely conducted. For the southwestern Japan, Le Pichon *et al.* (1998), Ozawa *et al.* (1999), Ito *et al.* (1999), Nishimura *et al.* (1999), and Mazzotti *et al.* (2000) analyzed GPS velocity data to estimate slip deficit on the surface of the subducting Philippine Sea slab. Miyazaki and Heki (2001) refined the analysis taking the Amurian plate motion into account. According to the result of Miyazaki and Heki (2001), the Nankai Trough plate boundary is completely locked down to the depth of 25 km and a transition zone exists between the depth of 25 and 35 km where coupling gradually decreases. Ito and Hashimoto (2004a) analyzed conventional geodetic data for last 100 years to reconstruct a slip distribution on the Nankai Trough plate boundary. They utilize present GPS data to constrain slip deficit distribution through the entire earthquake cycle. In the Tokai district, Sagiya (1998b, 1999) estimated the slip deficit and discussed the absence of the anticipated “Tokai earthquake”. By taking inland deformation into account, Heki and Miyazaki (2001) estimated an even longer interval for the Tokai earthquake. However, these estimates of plate boundary locked zone in the Tokai district are inconsistent with the locked zone estimated from seismological analysis by Matsumura (1997). This controversy has not been solved yet.

Along the Sagami Trough in the southern Kanto district, Sagiya (1998b, 2004) estimated slip deficit distribution and discussed the recurrence interval of the 1703 and 1923 Kanto earthquakes. Full interplate locking is also estimated in this region, implying a recurrence interval of 200–300 years. This estimate is somehow shorter than the geological estimates of 380–990 years (Shishikura *et al.*, 2001).

Along the northeastern Japan, Le Pichon *et al.* (1998), Ito *et al.* (2000), Nishimura *et al.* (2000), and Mazzotti *et al.* (2000) analyzed the GPS velocity data to estimate slip deficit distribution. The analysis of Ito *et al.* (2000) and Mazzotti *et al.* (2000) covers the Kuril Trench off Hokkaido as well. Ito *et al.* (2000) and Nishimura *et al.* (2000) obtained similar results that slip deficit distribution is more or less heterogeneous. Recent seismological analyses of old earthquakes by Yamanaka and Kikuchi (2001) have shown that there are persistent patches on the plate boundary and the same patch repeatedly ruptures at different earthquakes. Variations in large earthquakes occurring in the same location can be explained by assuming different combination of persistent patches. Yamanaka and Kikuchi (2001) identified those persistent patches as areas of large co-seismic slip and called them “asperity”. Such a definition is different from the original usage of the same term as a area with large strength on a fault (e.g. Lay and Kanamori, 1981). Yamanaka and Kikuchi (2001) obtained an asperity distribution map along the Japan Trench based on their analyses. Such a heterogeneous plate coupling is also estimated from a study of repeating earthquakes (Uchida *et al.*, 2003) and reflectivity structure (Fujie *et al.*, 2002). On the other hand, Mazzotti *et al.* (2000) estimated almost complete locking of the plate boundary in the depth range of 0–60 km. Since other studies based on, essentially, the same dataset obtained heterogeneous distribution of interplate coupling (Ito *et al.*, 2000; Nishimura *et al.*, 2000), the result of Mazzotti *et al.* (2000) might be a little biased due to their analysis method. Heterogeneous nature of interplate coupling is one of important findings with GEONET.

Although previous studies were rather successful in resolving heterogeneous interplate coupling, land-based geodetic data have a limited resolving power for offshore plate boundaries. Therefore observation at the ocean bottom would be quite useful. There are a few groups elaborating in development of ocean bottom geodetic techniques by combining kinemtic GPS and acoustic sounding (e.g. Obana *et al.*, 2000). GEONET may act as a ground base for kinemtic GPS analysis with such a purpose.

All these analyses were conducted in a local or regional scale. Each analysis actually did not care what occurs outside of the region of interest. In order to understand the subduction process around the Japanese Islands, simultaneous estimation of slip deficit along all the plate boundaries is desirable.

In the source region of the 1994 Sanriku-Haruka-Oki earthquake, gradual changes in crustal deformation rate have been observed since the 1994 event. Nishimura (2000) analyzed continuous GPS data in this area to estimate slip or slip-deficit distribution on the plate boundary. His result showed that the significant afterslip right after the 1994 Sanriku-Haruka-Oki earthquake (Heki *et al.*, 1997) gradually decreased and turned into slip-deficit. This observation demonstrated that we can monitor so-called a healing process, a recovery process of the fault strength at the plate boundary after a large earthquake, by a careful analysis of GEONET data. It is important to translate such a kinematic description of the plate boundary into frictional parameters in order to understand the dynamics of the fault.

Inter-seismic deformation is also studied in inland areas. The average station spacing of GEONET, however, is usually insufficient to study detailed deformation patterns associated with inland earthquakes and active faults. Therefore installation of additional GPS sites has been done in several areas. It is worthwhile to point out that such studies with dense GPS network are much facilitated by the existence of GEONET.

With additional continuous GPS sites, Hirahara *et al.* (2003) studied the Atotsugawa fault. Sagiya *et al.* (2002b) studied the Itoigawa-Shizuoka Tectonic Line fault zone, and Miura *et al.* (2002) studied deformation of the Ou backbone range. Tabei *et al.* (2002, 2003) operated a campaign-type GPS array across the Shikoku and Chugoku district in the north-south direction, studying the deformation associated with the Median Tectonic Line.

An overall interpretation of the GPS velocity data of the entire Japanese Islands has not been conducted enough. Hashimoto *et al.* (2000) used GPS velocity data to revise their block-fault model (Hashimoto and Jackson, 1993), in which GPS velocities are interpreted as a superposition of rigid block motions and slip deficits at block boundary faults. However, such an analysis heavily depends on the assumed fault geometry. So it will be important to derive an appropriate block-fault geometry model itself based on GPS data.

4.4 Detection of pre-slip and earthquake prediction

The high precision and the real-time monitoring capability of continuous GPS observation are ideal features for its application to earthquake prediction. In particular, detection of pre-seismic crustal movements has been highly expected.

In December 1944, the Tonankai earthquake (M7.9) occurred offshore the Tokai district and the Kii Peninsula. The Military Land Survey was conducting a leveling survey near Kakegawa in the Tokai district during the time period of this earthquake. Mogi (1984) analyzed the leveling data and concluded that there was a more than 10 mrad anomalous accelerating tilt change within 3 days before the earthquake. Linde and Sacks (2002) interpreted this observation in terms of a pre-slip occurred on the plate boundary at the deeper extension of the co-seismic rupture area. There is no doubt that the present GPS network should be able to detect similar large pre-seismic crustal deformation if there is any.

However, recent results from GEONET do not necessarily support an optimistic view for detecting pre-seismic signals. On September 26, 2003, the 2003 Tokachi-Oki earthquake (M8.0) occurred. This earthquake was the first interplate M8 event around the Japanese Islands since GEONET has been operated. Irwan *et al.* (2004) analyzed both the 30-second and 1 Hz sampled GEONET data to investigate crustal deformation around the onset time of the earthquake. They failed to identify any precursory signal of the earthquake. We have to conclude that it was impossible to issue an earthquake warning based on GPS data in case of this event. Moreover, there is no report of pre-seismic signal detected from either the continuous monitoring of extensometers or borehole tiltmeters. The earthquake type and the size of the 2003 Tokachi-Oki earthquake is nearly the same as what expected for the anticipated Tokai earthquake (Ishibashi *et al.*, 1981).

It is of course that the case of the 2003 Tokachi-oki earthquake does not preclude existence of observable precursors for other earthquakes. However, it is also true that the 2003 Tokachi-Oki earthquake is a very strong negative example for short-term earthquake prediction based on monitoring crustal deformation. Unfortunately, we do not have a positive example of successful detection of precursory deformation signal with the same degree of reliability as this event. Even though earthquakes vary according to their localities, it is definitely important to have a successful example with state-of-the-art measurements. Without having a conclusive evidence for successful detection of pre-seismic signals, short-term earthquake prediction based on the pre-slip model would face severe difficulties. Continuous GPS is now charged with such a crucial role.

4.5 GEONET as a seismic array

In deformation studies, the sampling rate of GPS receivers is usually fixed as 30 seconds for static surveys. However, recent GPS receivers are capable of recording data with much higher sampling frequency such as 20 Hz. By recording GPS signals at high frequency, GEONET can record high frequency ground motion like a seismograph network. The kinematic analysis technique is applied to estimate rapid ground motion epoch-by-epoch. Miyazaki *et al.* (1998) reported a pioneering observation of ground shaking caused by the 1996 Hyuga-nada earthquake, recorded by 1 Hz sampling at a GEONET station. They compared the GPS-based displacement waveforms with those from seismometers and obtained satisfying results. Since a GPS-based displacement record would never saturate, it will be useful in recording ground motions especially in the near field of large earthquakes. Recently, Irwan *et al.* (2004) analyzed the 1-Hz sampling record of GEONET to estimate co-seismic displacement waveforms from the 2003 Tokachi earthquake.

In traditional kinematic analyses of GPS, it was necessary to assume a fixed station within about 100 km from the target station. In case of a large earthquake, strong seismic wave propagates and the fixed station may also have a significant shaking effect. Recently, by solving such a difficulty, Larson *et al.* (2003) and Bock *et al.* (2004) were successful in detecting seismic shaking caused by the 2001 Denali earthquake. By applying their techniques, GEONET may become a nationwide seismic array without saturation. We have to consider data storage for high sampling GPS data. The amount of 1 Hz data is 30 times larger than that with 30-second sampling rate. Probably it is not efficient to archive 1 Hz sampling data continuously at all the GEONET stations. We need to establish an appropriate principle how to archive 1 Hz GPS data.

5. Discussion

As discussed above, GEONET has many applications and high potential in various fields. It is not only a useful tool, but GEONET actually opened a new aspect for earthquake studies. With GEONET, we are able to monitor time-dependent deformation all over the Japanese Islands as if it is in our hands. Figure 4 shows snapshots of the deforming Japanese Islands created based on the actual routine analysis result of GEONET from April 1996 to December 2000 (Sagiya, 2003). An appropriate data processing with a bit of exaggeration (500,000 times in Fig. 4) provides us with those crustal deformation images, in which we can easily point out significant deformation events. Such a monitoring tool was not available for solid earth sciences before. In meteorology and oceanography, for example, such a continuous monitoring has been systematically linked with simulation systems to make a forecast. The forecast can be evaluated through comparison with actual monitoring data and the results are used to feed back to improve the simulation. Such a process, usually called data assimilation, has become possible in solid earth science with GEONET. Actually, GSI is conducting automated monitoring and a fault model analysis in the Tokai district in order to monitor the Tokai slow slip event. Thus the monitoring of the solid earth is steadily improving and coming close to the monitoring of the fluid earth, that is, the

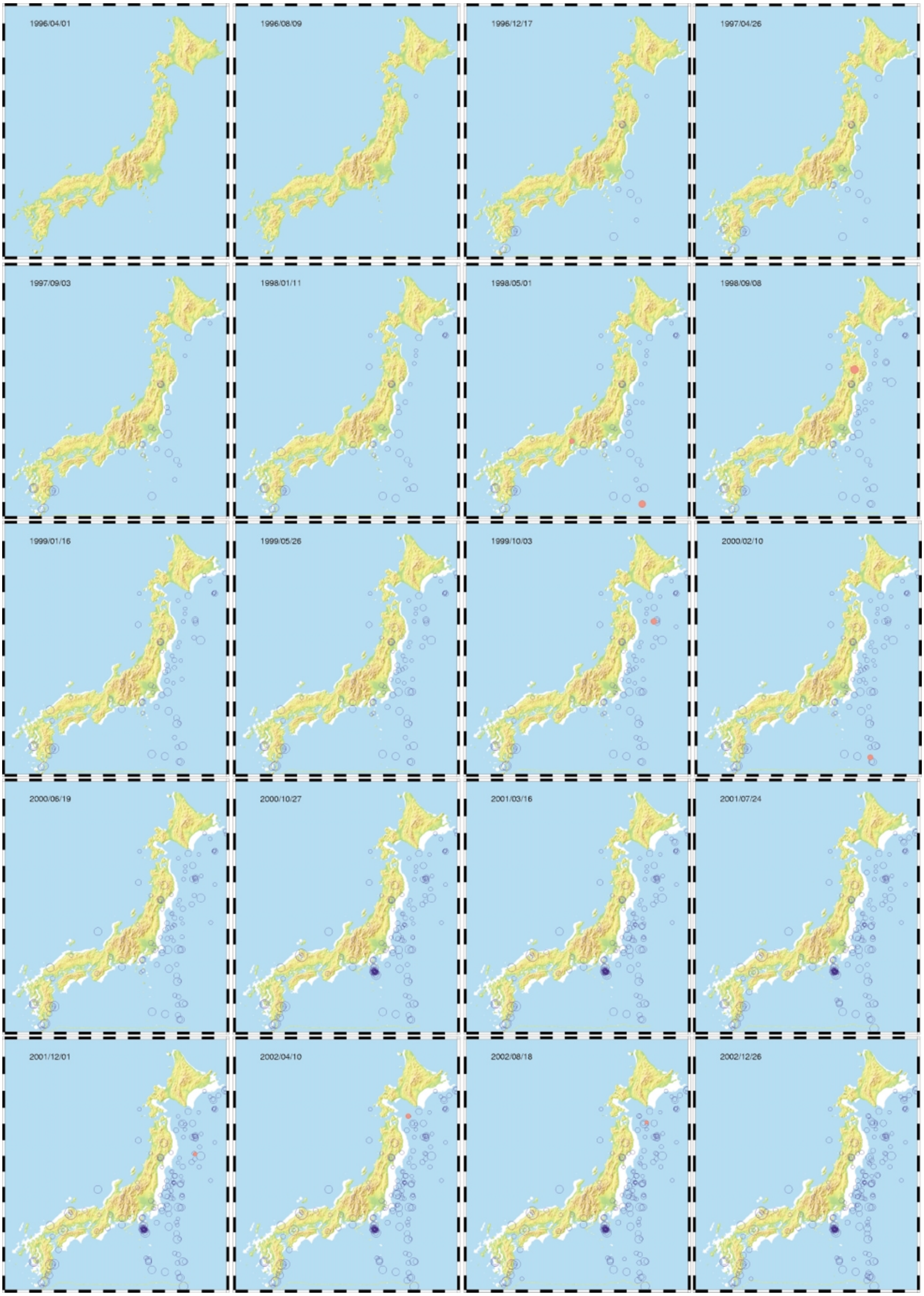

Fig. 4. Snapshots of the deforming Japanese Islands every 130 days from April 1996 to December 2002 calculated based on GPS coordinate data. Deformation calculated referring to Ohgata (950241) and is exaggerated by 500,000 times. Circles denote epicenters of shallow earthquakes larger than M5 (Sagiya, 2003).

atmosphere and the ocean.

Here I point out a few practical problems of GEONET. Presently, there is only one routine final solution for GEONET, publicized by GSI. GPS researchers know that a GPS coordinate solution is very sensitive to the analysis procedure. It can easily change by using different software and different analysis strategies. If we have only a single solution, we can never identify whether some characteristic of the solution is a true signal or an artificial one. Now so many GEONET users use this routine solution and majority of them do not have enough geodetic background to be aware of such a technical problem. So we definitely need another solution for cross checking. Another problem is the size of GEONET. So far there is no other GPS network in the world comparing with GEONET in its size. As a result, GPS software like Bernese cannot be fully tested for such a large network in other places. In other words, GEONET provides a rigorous test site for various GPS software. Therefore we should always keep those things in mind and to spare some time to reconsider the result thoroughly.

Finally, GEONET has greatly widened the scope of crustal movement observation. Its high frequency component overlaps with seismographs. On the other hand, observation history of GPS is still too short to reveal long-term deformation. It is a fundamental requirement for GEONET to keep monitoring as long as possible. It is also very important that observed data have a good continuity and traceability, that is, any change in the observation system or analysis steps has to be documented in details. With such attention, GEONET will become a truly indispensable geophysical tool and will contribute to solid earth sciences more and more.

Acknowledgments. The author express his sincere gratitude and applause to the GPS group of GSI for their effort in keeping operation of GEONET and making all the data available to public. This paper was significantly improved by comments of two referees (Profs. Teruyuki Kato and Kazuro Hirahara) and the associate editor (Dr. Anshu Jin).

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