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Crustal movements around the Beppu Bay area, East-Central Kyushu, Japan, observed by GPS 1996–1998

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In order to detect the crustal movement in the Beppu Bay area, where the highest intra-plate strain rates in Japan is expected, precise GPS measurements have been repeatedly conducted since 1994 at one-year intervals. The result shows N-S or NNE-SSE extension taking place at a rate of more than 10 mm/yr around Beppu Bay. This is essentially consistent with the result obtained by the geodetic survey conducted over the last 100 years, and it suggests a constant rate of crustal motion over the period. The result gives a strong constraint for future modeling of the stress field recovery in the area. However, we failed to identify whether the movement occurred at any specific fault. A denser array of GPS points is needed in the area, and especially near the major faults, in order to investigate possible fault-related motion.

1. Introduction

The Beppu Bay area, in the eastern part of central Kyushu, is located at the intersection of several of the tectonic boundaries of southwest Japan: the Median Tectonic Line (MTL), the Beppu-Shimabara Graben, and the subducting Philippine Sea plate (see Fig. 1). The area is well known as one of the largest active geothermal areas in Japan, and it contains active volcanoes and many hot springs. It is also characterized by gravity lows due to depression structures, which reflect the tectonic history of the area (Kusumoto *et al.*, 1999a). To reveal these characteristics, various kinds of geological, geophysical and/or geodetic surveys have been extensively conducted, and numerous results have been obtained (e.g. Matsumoto, 1979; Kamata, 1989; Kusumoto *et al.*, 1996). One remarkable result is that N-S extension, at an average rate of more than 10 mm/yr, have been detected by geodetic surveys conducted over the last 100 years (Tada, 1993). This surprising result is the fastest intra-plate deformation in Japan, but the observed main strain field can hardly be explained by the effects of the subducting plate (e.g. Hashimoto, 1985; Kusumoto, 1999). To explain the extension field, Tada (*ibid.*) argued that the area is the northeastern termination of the Okinawa Trough and that the extension is formed by a N-S spreading of the continental crust. However the subject is still under active discussion (e.g. Tsukuda, 1993; Kamata and Kodama, 1994) and the extension field has not yet been fully explained.

On the other hand, several studies investigate the history of the strain field from both geological and geophysical points of view (Itoh *et al.*, 1998; Kusumoto *et al.*, 1999a). These results suggest that the main stress field changed from a N-S extension to a W-E compression at around 1.5 Ma. Moreover, if the present N-S extension field is real, the area should experience a change in the main stress field at least one more time after 1.5 Ma. Itoh *et al.* (1998) highlighted the role of the convergence direction of the Philippine Sea plate as an important factor in explaining the stress field changes, although the physics of this process remain unclear. There is no doubt that the stress field change is of a key importance for understanding not only for the tectonic structure in the Beppu Bay area but also the tectonic history in southwest Japan. To investigate the mechanism of the stress field change, knowledge of the present day crustal movements is very important, and should provide a firm constraint for various numerical models of the crustal motion. However, the available geodetic data were based on repeated triangulation and trilateration survey, and no GPS results have been published so far. We therefore, decided to conduct precise GPS surveys to confirm the rate and direction of the recent crustal movements.

In this study, we aim to investigate the following questions; 1) whether the crustal movement is stationary or not, and 2) whether the movement occurs at any specific faults in the area or not. To investigate these subjects, we have conducted repeat GPS measurements in the Beppu Bay area since 1994 at one-year intervals. After 1996, we also employed GPS data obtained by GEONET (GPS Earth Observation Network of Geographical Survey Institute).

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Table 1. List of the GPS sites employed in this study. The site coordinates of WGS-84, measurement periods and observation type (TP) are shown. The meanings of the codes in the TP column are as follows; B: ASHTECH Z-X113 and ANT 700718, C: ASHTECH Z-X113 and ANT 700578, D: TRIMBLE 4000SSE and ANT 4000ST L1/L2 GEOD, E: TRIMBLE 4000SSI and ANT PERMANENT L1/L2.

STATION	CODE	LATITUDE D M S	LONGITUDE D M S	HEIGHT meter	OBS	TP
Koga	0087	33°43′50.598″	130°28′36.358″	49.111	95–98	B
Beppu	BGRL	33°17′01.297″	131°29′09.259″	106.571	96–98	C
Oita Univ.	BNDI	33°10′33.432″	131°36′47.180″	108.017	94–98	C
Musashi	MSAS	33°30′20.286″	131°42′30.901″	82.209	94–96	C&D
Ogami	OOGA	33°22′14.477″	131°34′29.822″	90.476	94–98	C&D
Saganoseki	SGSK	33°14′38.230″	131°52′14.510″	107.955	94–98	C&D
Sekinan	SKNN	33°10′54.893″	131°27′11.293″	154.011	94–96	C&D
Tateishi	TTIS	33°28′58.723″	131°28′55.829″	162.753	94–98	C&D
Innai	INNI	33°23′03.680″	131°17′29.098″	190.217	94–98	C&D
Kuju	KUJU	33°03′15.481″	131°19′29.064″	618.905	94–96	C&D
Aki	0088	33°27′41.569″	131°41′28.927″	51.360	96–98	B
Hita	0089	33°19′51.909″	130°58′04.151″	149.657	96–98	B
Oitasaeki	0090	32°55′28.520″	131°52′34.949″	40.441	96–98	B
Koishihara	0452	33°27′55.665″	130°49′43.497″	527.579	96–98	E
Kumamoto	0465	32°50′31.562″	130°45′53.254″	92.341	96–98	E
Seiwa	0466	32°44′26.346″	131°05′57.485″	725.414	97–98	E
Oitakunimi	0470	33°40′16.301″	131°33′50.988″	39.948	96–98	E
Honyabakei	0471	33°29′46.446″	131°10′08.147″	129.243	96–98	E
Yufuin	0472	33°15′14.559″	131°20′50.192″	487.994	96–98	E
Kuju	0474	33°00′32.507″	131°17′09.903″	579.996	96–98	E
Oitamie	0475	32°59′12.693″	131°35′16.231″	200.609	97–98	E
Hinokage	0477	32°41′05.409″	131°19′39.409″	346.636	96–98	E

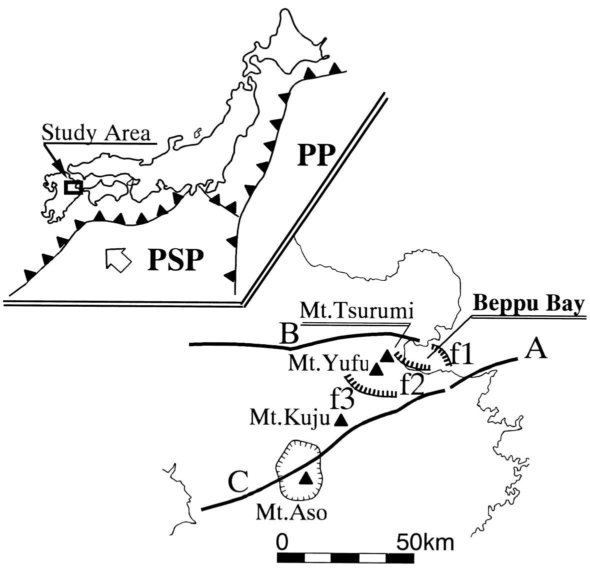

Fig. 1. Location map of the study area. PP: Pacific Plate, PSP: Philippine Sea Plate, A: Median Tectonic Line (MTL), B: Kurume-Hiji Line (KHL), C: Oita-Kumamoto Tectonic Line (OKTL), f1: Beppu Bay Cross Fault (BB), f2: Asamigawa Fault(AsF), f3: Tsuzura-Shonai Fault (TSF). (Modified from Sasada 1984 and NEDO, 1990).

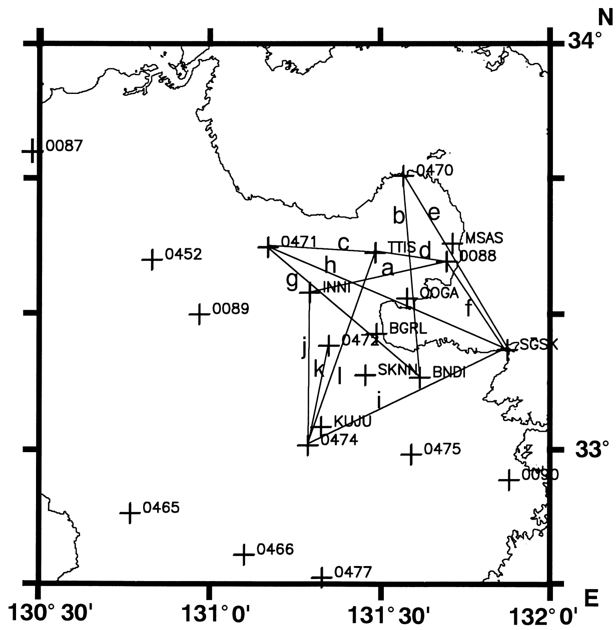

Fig. 2. GPS sites employed in this study. Lower case letters (a-l) show the baselines of which change rates are shown in Fig. 3.

Table 2. Change rates of baseline length. LENGTH: the baseline length determined from the 1996 observations, RMS: formal rms errors for the determination of corresponding baseline lengths, CHG RATE: base line change rate calculated to least squares fit a linear function to the baseline changes (see Fig. 3), STR RATE: strain rate calculated so as to be CHG RATE divided by LENGTH.

BASELINE	LENGTH	RMS 1996	RMS 1997	RMS 1998	CHG RATE	SD	STR RATE
	meter	mm	mm	mm	mm/y	mm/y	xE-7
0088-SGSK	29343.9558	0.8	1.5	1.0	10.2	3.45	3.48
0470-SGSK	55296.0688	0.7	0.9	0.7	7.66	2.01	1.39
SGSK-0477	80145.6407	0.8	0.8	0.8	7.41	1.23	0.92
0471-SGSK	71049.7923	0.7	0.6	0.9	4.67	1.45	0.66
0471-TTIS	29148.7526	0.6	0.5	0.6	1.03	0.30	0.35
TTIS-0477	89690.3374	0.8	0.8	0.8	13.5	2.72	1.51
0470-0472	50473.5704	0.7	0.8	0.8	4.47	1.53	0.89
0470-0474	77875.1002	0.7	0.8	0.8	10.5	3.36	1.35
0088-0477	92598.7065	0.9	1.5	1.0	7.63	8.81	0.82
0472-0474	27769.6865	0.6	0.7	0.7	5.29	2.98	1.90
0470-0477	111599.4499	0.9	0.9	0.9	11.0	7.47	0.99
0470-0465	118336.1885	0.8	1.1	1.0	1.13	3.61	0.10
SGSK-0474	60462.8592	0.6	0.7	0.8	7.19	1.84	1.19
TTIS-0474	55655.6888	0.7	0.7	0.8	11.9	0.55	2.14
BNDI-0477	60661.6129	0.8	0.9	0.9	9.88	2.92	1.63
OOGA-0477	79499.3111	0.8	0.8	0.8	6.62	6.26	0.83
INNI-0474	41633.8798	0.9	0.8	0.9	−2.90	3.37	−0.70
0470-BNDI	55117.0039	0.8	0.9	0.9	−0.46	0.13	−0.08
0088-INNI	38170.9358	0.9	1.7	1.0	−6.55	4.31	−1.72
0471-BNDI	54515.0081	0.8	0.8	0.9	−2.56	1.69	−0.47
TTIS-0090	72015.9536	0.7	0.7	0.9	−3.15	0.30	−0.44
TTIS-0088	19590.4145	0.6	1.6	0.9	−7.58	0.20	−3.87
0470-0090	87762.9267	0.8	1.3	1.0	−1.34	0.38	−0.15
0452-0472	53659.3855	0.6	0.8	0.8	−0.72	0.26	−0.13
0088-0472	39441.7176	0.7	1.4	0.9	−1.77	1.43	−0.45
0470-0089	67034.9098	0.7	1.2	0.9	−1.16	1.78	−0.17
0472-0089	36365.4020	0.6	1.0	0.8	−4.18	4.18	−1.15
0472-0090	61445.1645	0.7	1.1	0.9	−6.98	2.77	−1.14
BGRL-0090	53987.6389	0.8	0.8	0.9	−3.83	2.66	−0.71
SGSK-0090	35423.7421	0.7	0.6	0.9	−6.11	2.56	−1.72
0088-0452	80195.8883	0.6	1.7	1.0	−8.25	0.31	−1.03
0471-0088	48710.8874	0.6	1.6	0.9	−7.31	1.14	−1.50

2. GPS Observations

Figure 2 shows the distribution of GPS sites around Beppu Bay. Locations marked with four capital letters represent the sites newly established for this study, whereas the others with four digit numbers belong to GEONET. Due to logistic reasons, our sites have been selected from public school buildings, which are located on basement rock or similar solid foundations. The GPS sites distributed around Beppu Bay are at an almost equal spacing of 20 km.

The first GPS observations were carried out in August 1994. Since then, to avoid the effects of any seasonal changes, observations were carried out in August every year until 1998. After 1996, following to the establishment of GEONET, we suspended observations at some of our sites so that they could be replaced by GEONET sites.

Table 1 summarized the locations of the sites and types of observations. In the following sections, to ensure the uniformity of the spatial distribution of the sites and to avoid large measurement errors in the earlier stage of the observations, we only discuss the results obtained by using the data after 1996 and the GEONET data.

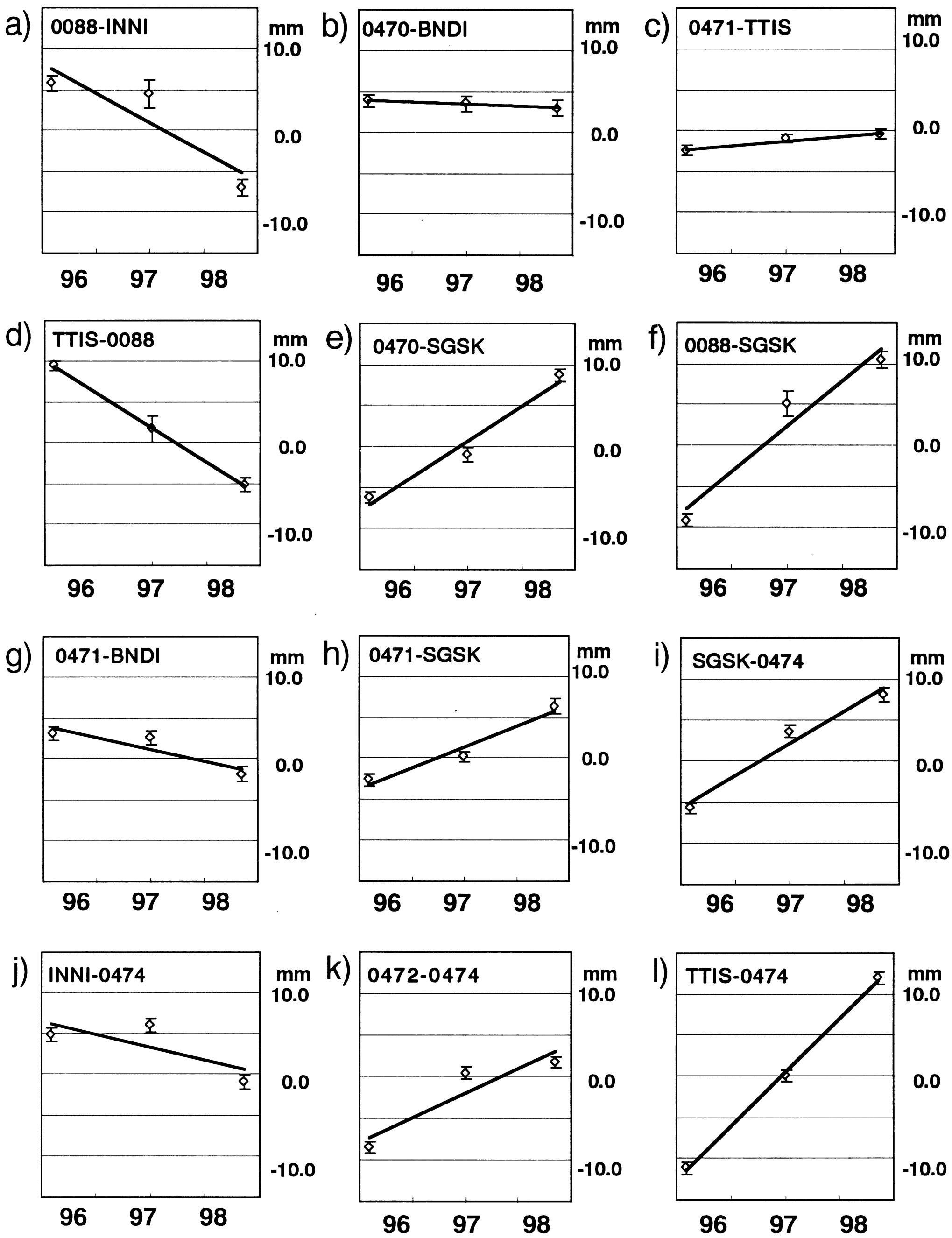

Fig. 3. Typical changes of baseline length for the selected combination of the sites. Solid lines are determined by least squares fitting and their rate and SD are listed in Table 2.

3. Results and Discussions

The observed data and the GEONET data at 30 seconds sampling intervals were processed using the Bernese GPS software version 4.0 with the IGS (International GPS Service) precise ephemerides. To obtain precise coordinates of the sites, we employed BGRL (Beppu Geothermal Research Laboratory) as a reference site. The coordinates of BGRL were determined in reference to the Tsukuba GSI site. For the purpose of validation, A GEONET site #0087 (Koga, near Fukuoka) was also selected as another reference site. We confirmed that there is no essential difference between the results obtained by using different reference sites.

Generally speaking, the obtained crustal movements show the north-west direction so that the movements are mainly due to the secular motion of the subducting Philippine Sea plate. However, our main interest in this study is in relative crustal movements around Beppu Bay. Thus we first employ baseline lengths instead of station coordinates, and discuss their changes. It should be noted that the baseline lengths are more accurate than the coordinates themselves, and they are free from the influence of the reference site selection.

Table 2 summarizes the results of the baseline changes, and some examples are shown in Fig. 3. In Fig. 3, it can be seen that N-S or NNE-SSW extension at a rate of 10mm/yr or more is dominant, especially between the sites across Beppu Bay, i.e., 0470-SGSK, TTIS-0474 and so on. On the other

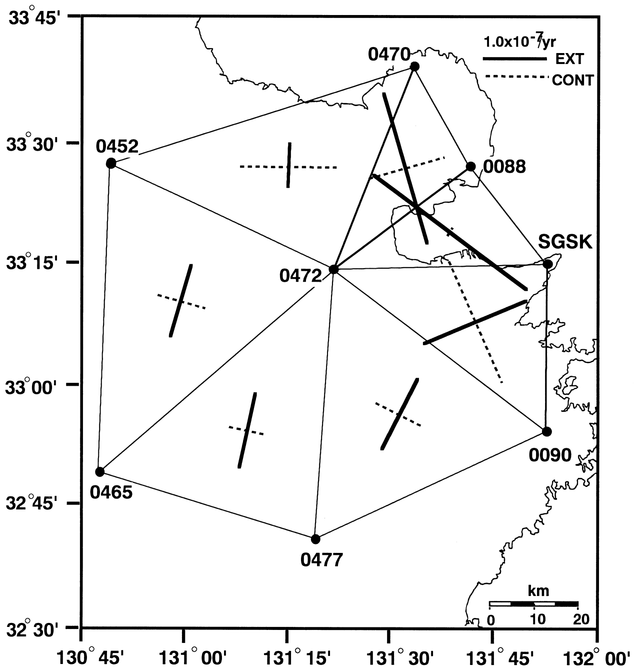

Fig. 4. Crustal strain rate observed by the GPS surveys. Solid lines and dotted lines mean extension and contraction, respectively.

hand, a rather large rate of contraction in the E-W or NW-SE direction was observed in the northern part, e.g. 0088-INNI and 0088-TTISS. These sites are essentially under the W-E compression field of southwest Japan. Hence the contraction is considered to be the result of the regional stress field.

Of note is that the baseline changes between BNDI and the northern sites (0470, 0471, etc.) show slight compression rather than extension. This fact suggests that a tectonic boundary lies between BNDI and SGSK, although uncertainties remain due to local instability of BNDI site.

Figure 4 shows the mean strain velocities calculated for seven triangular areas around site 0472. This figure gives a more intuitive comparison between the present results and the earlier geodetic results (figure 1 of Tada, 1984; figure 1 of Tada, 1993), and shows that they are basically consistent in both the extension rates and directions. Hence the rate of crustal movement is considered to be roughly constant at least in the time range of one year to one hundred years. In Fig. 4, the principal strain around Beppu Bay looks more complicated than the geodetic results. This figure suggests that the observed crustal movements include both the effects of local and regional stress. In other words, we need some other active sources in order to explain the extension fields, besides the regional stress originating in the subducting Philippine Sea plate. Kusumoto *et al.* (1999b) proposed an upwelling flow model to explain the history of the stress change and the extension fields as well. For evaluation of the model, we may need more precise locations and spatial resolution of the extension fields. In this study, however, it is still difficult to identify the exact location where the extension occurred, and we failed to obtain enough information to determine the sources of the extension. For these investigations, we need more precise mapping of the crustal movements using more dense GPS surveys and/or the InSAR technology.

4. Concluding Remarks

By means of GPS surveys, we determined the present crustal movements around the Beppu Bay area. The results are essentially consistent with those obtained by conventional geodesy, which represents the crustal movement during the last hundred years. This fact suggests that rate of crustal motion are stationary at least during this period. Also of importance is that the N-S extension has also been confirmed by precise GPS observations. This gives a constraint for the modeling of the stress field recovery. As discussed by Kusumoto (1999), passive extension caused by a mechanical interaction between plates is impossible in this area. Thus we inevitably need an active extension model, and hence this is one of the main subjects of future work.

To investigate the origin or the cause of the extension field, precise mapping of the crustal movement is also important. In this study, however, we failed to identify fault related motions in the area. It is obvious that the spatial resolution of GEONET is not enough for these purposes. We need more dense GPS sites, especially near the major faults or tectonic lines in the area. Moreover the recent InSAR technology should contribute to improve the spatial resolution. Such a combination of space geodetic techniques could reveal the mechanism of the crustal movements, and also resolve the nature of the extension field.

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