REPEATED MICROGRAVITY OBSERVATIONS, GPS SURVEY AND CONTINUOUS TILT MEASUREMENTS IN KUJU VOLCANO, CENTRAL KYUSHU, JAPAN

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SUMMARY- Observations of gravity, GPS and continuous tilt change were conducted after the 1995 eruption of Kuju volcano. There are 16 gravity observation points, 5 GPS observation points and 1 continuous tilt observation point. Gravity decreases (to a total of -90 micro-gals) were detected from 19 October 1995 to 13 January 1996 around new craters created by the eruption. From December 1997 to May 2001 the gravity increased in the area of the new craters and pre-existing fumarolic fields. An assessment of underground mass balance showed that the recharge of ground water increased gradually about three months after the eruption. The underground water flow is gradually reaching a new equilibrium state.

1. INTRODUCTION

Kuju volcano in central Kyushu began to erupt on 11 October 1995. The first sequence of eruptions was followed by a second sequence in December 1995. No eruptions occurred after December, but crater activities continued. There were three main fumarolic areas (called **A,** B and C regions) in Kuju volcano that already existed before the 1995 eruptions. The first eruption of October 1995 began with the creation of some new craters. The new craters area is called D region.

Repeated, precise gravity survey was started on 14 October 1995, to clarify gravity changes caused by the eruptions. The repeat gravity measurements were made at intervals of a few weeks to several months. Ground deformation was also monitored using single frequency GPS receivers and high precision tiltmeter, to detect any deformation (in three dimensional) caused by the 1995 eruptions.

2. REPEATED MICROGRAVITY SURVEY

We have been regularly conducting repeat gravity measurements at Kuju volcano. There are 16 observation points for these measurements (Figure 1). Precise gravity changes were measured using Scintrex CG-3 and CG-3M gravimeters. The measurements were repeated at intervals of a few weeks to several months. The two-way measurement method was used to evaluate the instrumental drifts and precision; observation errors are estimated at 10 micro-gals.

Figure 2 shows gravity changes at Kuju volcano. Rapid decreases of gravity were detected around the new craters from 19 October 1995 to 13 January 1996 (to a total of -90 micro-gals), then the rate of decrease became smaller. From December 1997 to May 2001, increases of gravity were detected in the area of the new craters and the pre-existing fumarolic fields.

Contours of long-term gravity changes are shown in Figure 3 (gravity decrease period) and Figure 4 (gravity increase period). During the gravity decrease period, observation points were limited. However, the contours in Figure 3 suggest that the center of the gravity decrease is in the area of the new craters. It appears that steam discharges fiom the new craters and the fumaroles were the cause of the long-term trend of gravity decrease. During the gravity increase period (Figure 4), the centre of the gravity increase is located in the area of the pre-existing fumarolic fields.

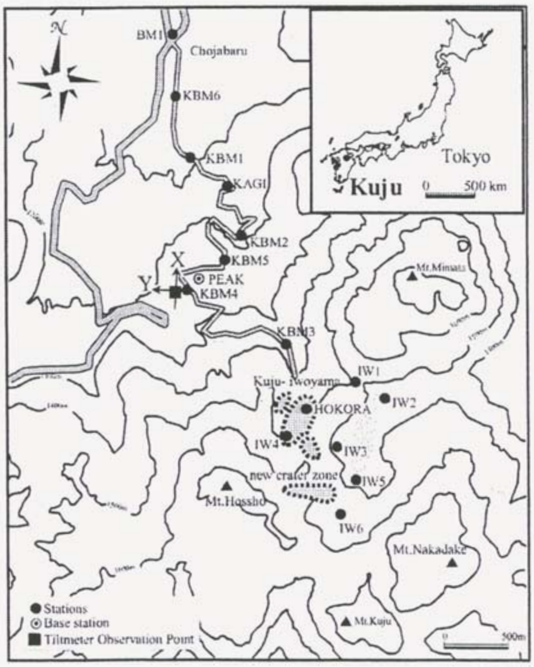

Figure 1. Location of Kuju Volcano, Central Kyushu, Japan where repeat gravity measurements and continuous tilt measurements were made.

The rapid decrease of gravity may be attributed to changes of the shallow water level because of vaporization of ground water heated by magmatic fluids. Gravity changes also occurred recently, about five years after the eruption, which may be attributed to seasonal variation of underground water level.

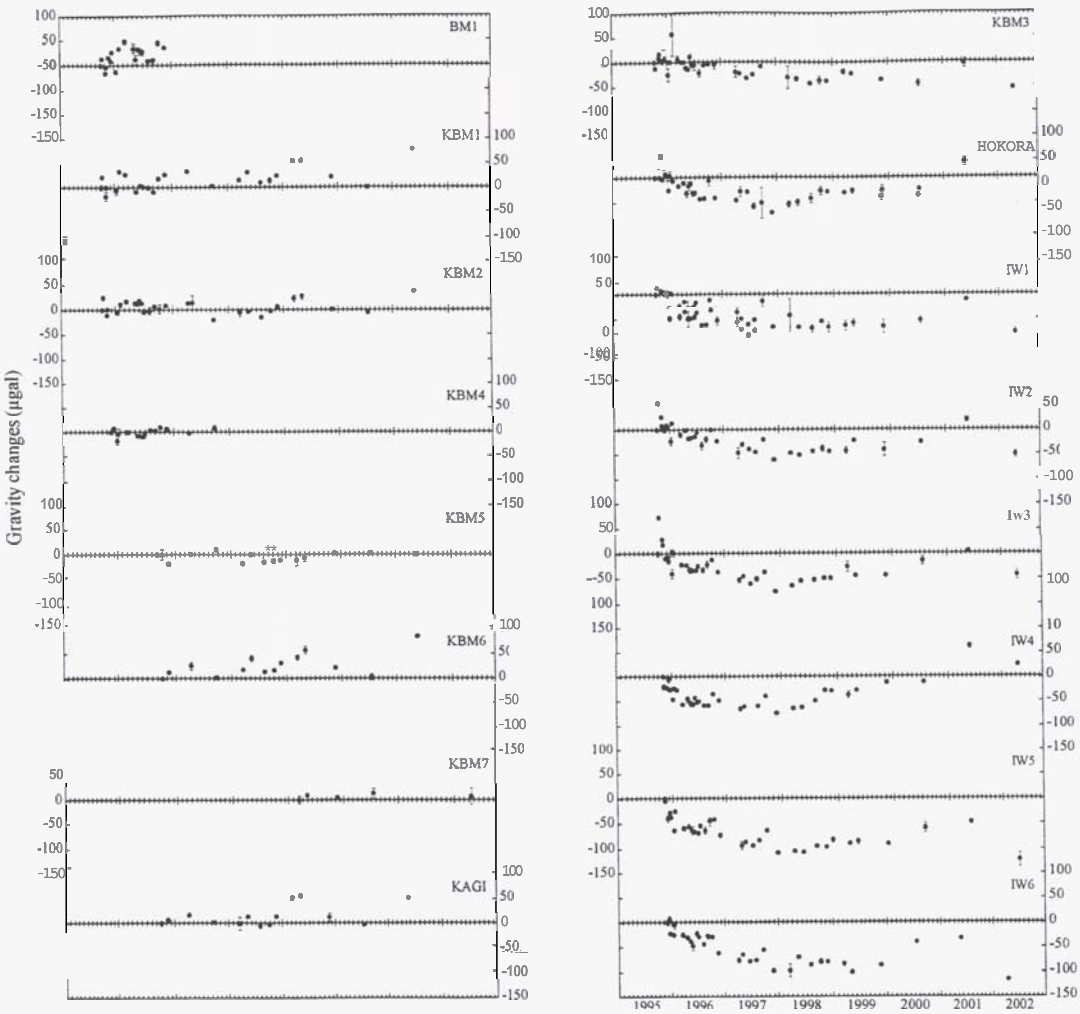

Figure **2.** Gravity changes at Kuju volcano. In these figures, the gravity value of the first measurement is set as zero.

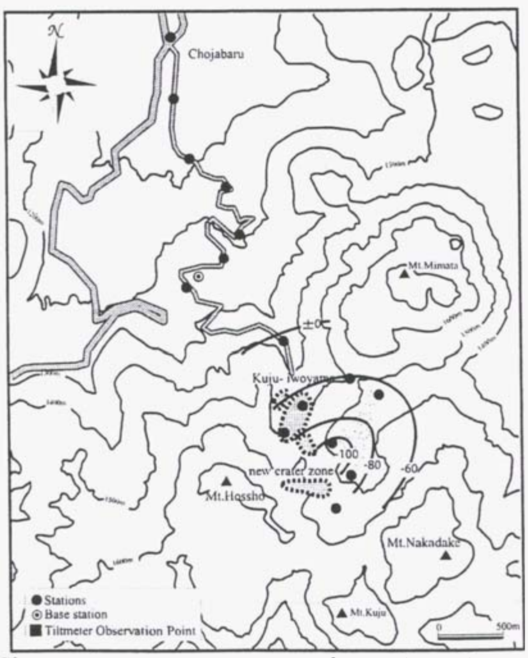

Figure 3. Contour map of gravity changes between mid-October 1995 and January 1996.

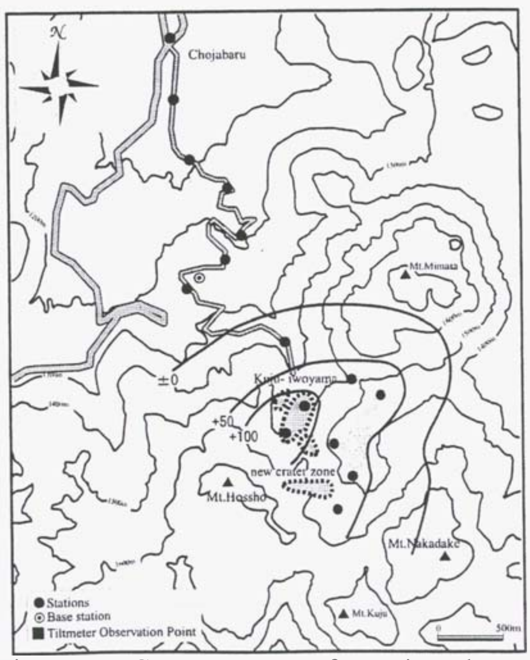

Figure 4. Contour map of gravity changes between December 1997 and May 2001.

By assuming that each contour line in Figure 3 and 4 forms a complete ellipse, underground mass balance (mainly water) can be assessed using the Gauss's theorem (La Fehr, 1965). Figure 5 illustrates the mass balance of the underground water.

During the period of gravity decrease (Figure 5 (a)), the rate of mass *decrease* estimated using the Gauss's theorem was about 55000 t/day. The total steam discharge rate, estimated by means of a remote sensing measurement of the maximum diameter of a volcanic steam plume (Jinguuji and Ehara, 1996), was about 89000 t/day. It has been suggested that 65% of the total steam discharge originated from meteoric water and the rest (35%) fiom magmatic water (Kazahaya et al., 1997). Hence, the contribution to the total discharge by the underground water reserved inside the mountain was 58000 t/day. The difference between 55000 t/day and 58000 t/day is thought to be the recharge to the underground water from the region around the new craters and the fumarolic areas.

Similarly, during the period of gravity increase (Figure 5 (b)), the rate of mass *increase* estimated using the Gauss's theorem was about 5500 t/day. The estimated total steam discharge rate was about 25000 t/day and the contribution by the underground water was 17000 t/day. Therefore, the recharge fiom the surrounding areas was about 22000 t/day.

The assessment of underground mass balance suggests that ground water recharge from the region around new craters was very small after the 1995 eruptions. However, the recharge started to increase gradually about three months later and the underground water flow is gradually reaching a new equilibrium state.

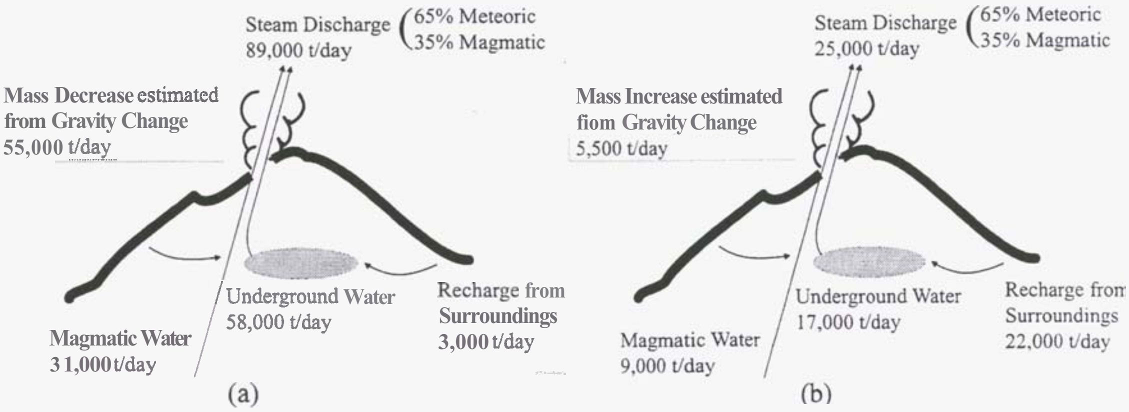

Figure 5. Mass Balance diagrams of underground water. (a) between mid-October 1995 and January 1996; (b) between December 1997 and May 2001.

3. REPEATED GPS SURVEYS

The GPS survey began in April 1999 at 5 observation points, to clarify ground deformation caused by the 1995 eruption. We have conducted the GPS observation 5 times up to present. Single fiequency GPS receivers (TOPCON GP-SX1) were used for the measurements. The session length was 1 hour and the sampling interval was 10 seconds. The GPS Software Win S/D Ver. 1.31 was used for the baseline analysis.

At each observation point, the session was repeated 10 to 20 times. The ephemeris is almanac data transmitted by the satellite, and the meteorological condition was standard (1013hPa, 20°C, 50%). In this study, the standard deviation was about 1-4ppm of baseline length. We calculated 95% confidence region, depends on the number of observations; it is defined as observational error. The accuracy of the baseline estimation is ±3mm.

Contractions of baseline up to 70mm were detected between April 1999 and May 2002 (Figure 6). Horizontal displacement vector was toward easterly direction in some stations (HOKORA, IW3) near the pre-existing fumarolic areas (Figure 8).

The location of pressure source was estimated by applying a point source model (Mogi, 1958) on the change in length of baselines. The calculations of deformation of the semi-infinite elastic body (Figure 7) were made using equation (1) (Yamakawa, 1955).

$$U_z = \frac{h}{R^3} K \qquad U_r = \frac{r}{R^3} K \qquad (1)$$

Where

$$R = (r^2 + h^2)^{1/2}$$

$$K = \frac{(\lambda + 2\mu) 3a^3 \Delta p}{2\mu(\lambda + \mu)}$$

λ, μ :Lame's constant

From equation (1), length of baseline ΔL (fiom P1 (x1, y1) to P2 (x2, y2)) was computed using equation **(2)** (Nishi et. al, 1995).

$$\Delta L = \frac{(x2-x1)X+(y2-y1)Y}{R_1^{\,3}\cdot R_2^{\,3}\,.L}K \qquad (2)$$

Where

$$X = (x2-x)R_1^{\,3} - (x1-x)R_2^{\,3}$$

$$Y = (y2-y)R_1^{\,3} - (y1-y)R_2^{\,3}$$

$$R_1 = \left\{(x1-x)^2 + (y1-y)^2 + h^2\right\}^{1/2}$$

$$R_2 = \left\{(x2-x)^2 + (y2-y)^2 + h^2\right\}^{1/2}$$

$$L = \left\{(x1-x2)^2 + (yl-y2)^2\right\}^{1/2}$$

From equation (2), the location of the pressure source can be estimated.

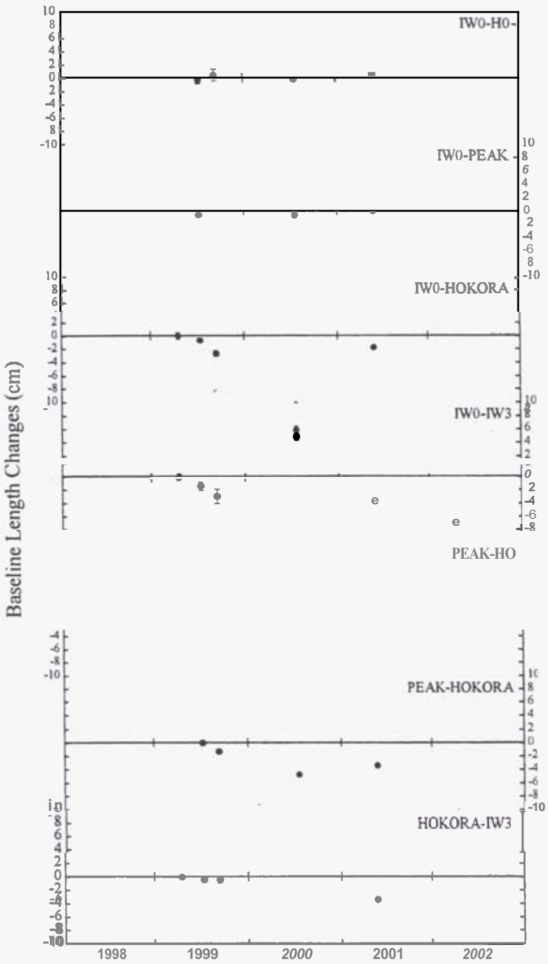

Figure *6*. Baseline length changes at Kuju volcano. In these figures, the baseline length of the first measurement is set as zero.

The pressure source is estimated to be in the **A** region (one of the pre-existing fumarolic fields) at approximately 700m depth (Figure **8).**

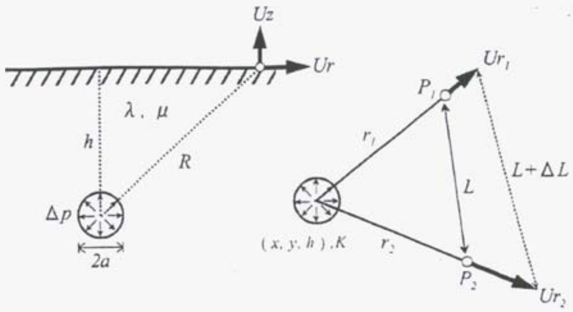

Figure 7 Schematic illustrations of a point source model and the method to calculate length change of baseline (modified Nishi, et. al, 1995)

In this study, dual fiequency GPS receivers, commonly used for this kind of measurements, were not used. The survey was conducted using single frequency GPS receivers, which are portable and comparatively low-priced. The results **of** observations prove that sufficient accuracy can be achieved in this type of baseline observations.

4. CONTINUOUS TILT MEASUREMENTS

We used a Pinnacle Technologies high precision borehole tiltmeter (5500 series). At the core of the tiltmeter is a pair of orthogonal bubble levels with a precise curvature. Electrodes detect minute movements of the air bubble within a conductive fluid as the fluid seeks the lowest spot in the sensor. This tiltmeter can resolve tilt as little as 1 nano radian.

The tiltmeter site is located on the northern side of Mt. Hossyo, inside a 12m drilled hole. The X and **Y** axis are designated north and west, respectively. From September ***2002,*** two more sites will be established at the foot of Kuju volcano.

We eliminated the effects of earth tide using the BAYTAP-G program (Tamura et al, 1991). BAYTAP-G (Bayesian Tidal Analysis Program - Grouping Model) is **a** general analysis program for earth tides and crustal movements, which includes the analysis of Bayesian model. The observed tilt was separated into trend, earth tide and irregular noise components.

The E-W component of tilt was 35 micro radian down to the east fiom October 2000 to March 2002. The N-S component of tilt was down to the south fiom October 2000 to February 200 1. After that, the **N-S** component of tilt changed to down to the north (Figure 9).

The azimuth of tilt was down in southeasterly direction from October 2000 to February 2001. This direction is pointing toward the pre-existing fumarolic fields and a pressure source estimated from the repeated GPS survey. However, fi-om February **2001** the direction changed to northeastern down.

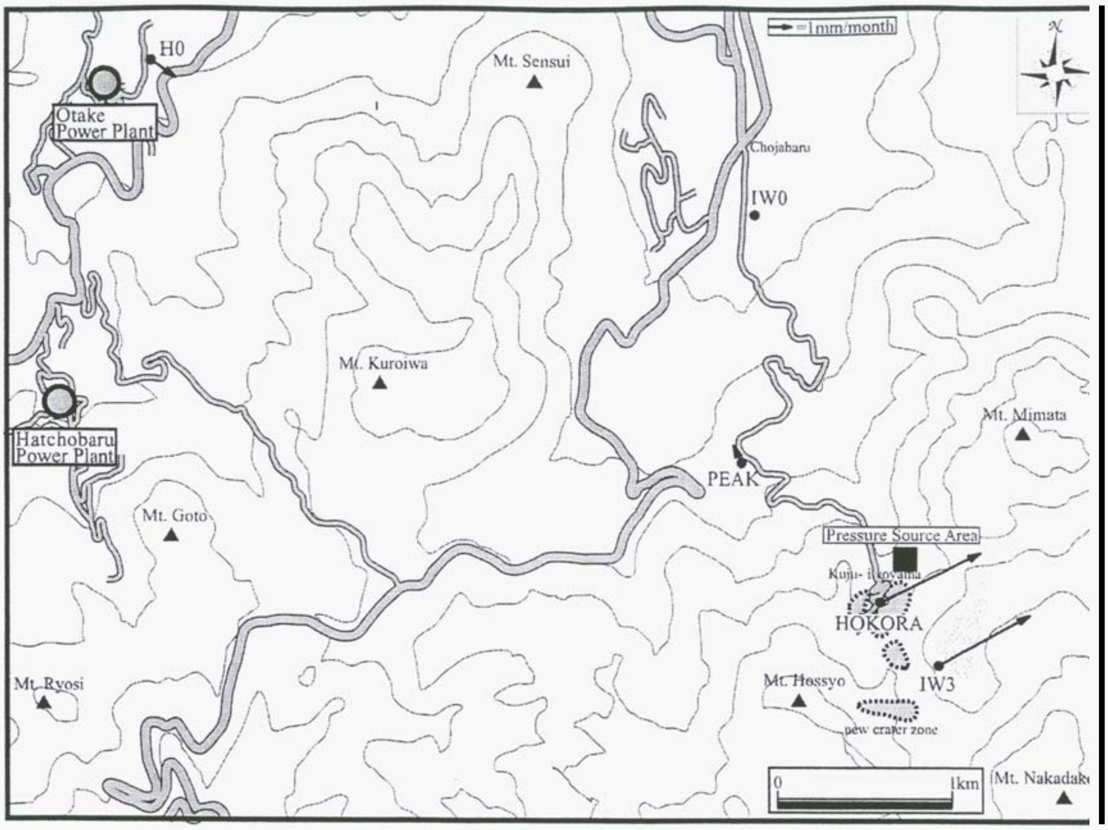

Figure **8.** Horizontal displacement vector map from April **1999** to May **2002.** Closed square **shows** estimated pressure source applying the point source model (Mogi, **1958).**

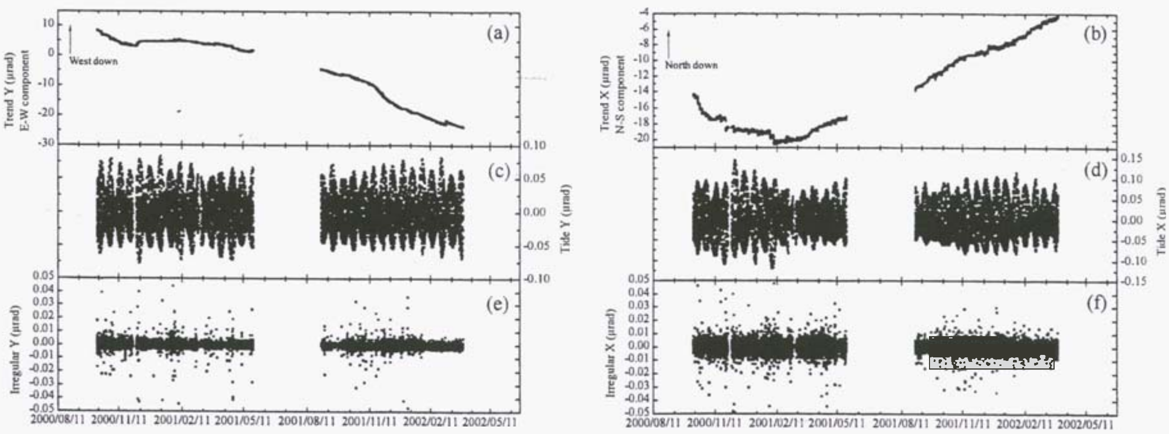

Figure **9.** Tilt observational data from October **2000** to March **2002:** (a) Tilt **Y** and (b) Tilt X are the variations of tilt after the effects of earth and irregular noise have been eliminated; (c) and (d) are the effect of earth tide; (e) and (f) are irregular noise.

5. CONCLUSIONS

We have conducted observations of gravity, GPS and continuous tilt changes following the **1995** Kuju eruption. From the results, the following conclusions can be drawn:

Rapid gravity decreases, to a total of **-90** micro gal, were detected in the new craters between **19** October **1995** and **13** January **1996,** then the rate of gravity decrease became smaller. Between December **1997** and May **2002,** gravity increases were detected in the area of the new crater and the pre-existing fumarolic fields.

During the gravity decrease period, the center of the gravity decrease is located in the area of the new craters. During the gravity increase period, the center of the gravity increase occurred in the area of the pre-existing fumarolic fields.

An assessment of underground mass balance showed that the underground water recharge **was** very small after the **1995** eruption. However, about three months later, the recharge started to increase and the underground water flow is gradually reaching a new equilibrium state.

Contractions of baseline up to 70mm were detected from April 1999 to May 2002. Horizontal displacement vector was toward easterly direction in some stations (HOKORA, IW3) near the pre-existing fumarolic areas.

The pressure source is estimated to be located in the A region (one of the pre-existing fumarolic fields) at approximately 700m depth.

The long-term tilt trend was 6 micro radian down in southeasterly direction from 9 October to 4 November 2000. This direction is pointing toward the pre-existing fumarolic fields and a pressure source estimated from the repeated GPS measurements. However, since December 2000 the direction has changed toward northeastern down.

6. REFERENCES

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- Drilling on N-S line.
- Temp profile of wells.
- B is the main geoth aquifer.
- MT methods to be used.
Compare TDEM with MT.