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ON THE POSSIBILITY OF DETECTING ABSOLUTE CRUSTAL UPLIFT AT SYOWA STATION, ANTARCTICA

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Abstract: There is a great deal of evidence concerning crustal uplift, after deglaciation, in the vicinity of Syowa Station (69.0°S, 39.6°E) from tide gauge data, seismic evidence, raised beaches, marine terraces, etc. The geomorphological and tide gauge data show that crustal uplift is going on around Syowa Station. Local earthquake activity corroborates the crustal uplift, and it is an intermittent phenomenon. Sea level falling of 4.5 mm/y was found using data in 1975–1992. This falling rate is consistent with geomorphological data. If the crustal uplift of 5 mm/y continues for 10 years, the total uplift obtained will be 5 cm. The total amount of the vertical crustal uplift would produce a change of about 15 μGal in gravity. Repeated measurements of absolute gravity over many years might detect absolute value of vertical crustal movement. Absolute gravity measurements at Syowa Station were made to establish one of the IAGBN (International Absolute Gravity Basestation Network) stations. Continuous observation by a SCG (Superconducting Gravimeter) was also started at Syowa Station. The SCG observation is believed to provide the highest sensitivity and highest resolution data for study of vertical crustal movement. Using the absolute gravimeter together with the SCG will provide significant insight into the absolute elevation change.

key words: local earthquake, raised beach, sea level change, gravity change, superconducting gravimeter

1. Introduction

The edge of the Antarctic Continent and its surrounding islands are places where crustal uplift has occurred after deglaciation. Characterization of crustal movement and estimation of sea level change have been accomplished using a variety of classical high precision methods. Recently, space geodetic techniques, such as GPS (Global Positioning System) and VLBI (Very Long Baseline Interferometry), have improved on the classical techniques. All of these techniques are used in the relative sense. The relative displacement along the vertical coordinate can be detected with an accuracy at the mm~cm level. Absolute movement along the vertical component such as in the determination of crustal deformation and sea level change has recently come to be discussed because of the inherent difficulty in measuring such a value absolutely even by new techniques. Vertical crustal movement will produce a change in gravity. Therefore, an absolute gravimeter is, in principle, an unique tool to measure the absolute value of vertical crustal movement.

The Japanese Antarctic Station "Syowa" (69.0°S, 39.6°E) located on East Ongul Island in Lützow-Holm Bay, East Antarctica was designated to be a part of the

International Absolute Gravity Basestation Network (IAGBN) by the International Association of Geodesy (IAG). Consequently, absolute gravity measurements were carried out at Syowa Station in the austral summer seasons of 1991–92, 1992–93 and 1994–95 (FUJIWARA *et al.*, 1993; HANADA and TSUBOKAWA, 1994; TSUBOKAWA and HANADA, 1994; KAMINUMA *et al.*, 1996).

At Syowa Station, additional observations using equipment such as a tide gauge, a superconducting gravimeter (SCG), broadband digital seismographs, and GPS are being conducted. Using various geodetic techniques, the absolute vertical crustal movement, and consequently, the absolute sea level change should be detected at Syowa Station if the observations are continued for several years.

2. Sea Level Change

At Syowa Station, the Japanese Antarctic Research Expedition (JARE) has made continuous tidal observations since 1966 using a mechanical pressure sensor tide gauge. Syowa Station is the only station in the coastal area of the Antarctic Continent where tidal observations have been continued for more than a quarter of a century; normally observations are disturbed by sea ice and tide gauges are not installed at most coastal stations in the Antarctic. The observations at Syowa Station also had problems in monitoring mean sea level up to the end of the 1970's. A new tide gauge using a strain gauge sensor was installed at Syowa Station in 1981, and thereafter the mean sea level has been monitored continuously.

Monthly mean sea level was therefore available using the new tide gauge from 1981 to 1987. A trend in sea level, falling at a rate of 9.5 mm/y, was obtained by ODAMAKI *et al.* (1991). This sea level change is measured relative to a land based bench-mark on East Ongul Island. The global mean sea level is estimated to have increased at the rate of 1–2 mm/y (WARRIK, 1993). Considering the rise of global mean sea level, the falling rate of mean sea level at Syowa Station should be over 10 mm/y. This value is too big as the value of crustal uplift on East Ongul Island to compare with the uplift rate estimated from geomorphological data as mentioned in the following section.

KAMINUMA and AKAMATSU (1992) noted that the larger inferred rate of uplift is not a continuous movement but an intermittent one. The crust around Syowa Station must have been uplifted during 1981–1987.

Recently MICHIDA *et al.* (1995) estimated the mean sea level change at Syowa Station using 18 years of data in 1975–1992. They obtained a trend of sea level falling with a rate of 4.5 mm/y. This value is consistent with the uplift rate estimated from the geomorphological data.

3. Raised Beaches

Raised beaches, and the emergent marine deposits, represent important observations for estimating vertical crustal movement, sea level change, ice advance and retreat, and hence environmental change in the polar regions. Syowa Station is located on East Ongul Island which is 4 km off of the Antarctic Continent across

Ongul Strait. Evidence of past glaciation is observed throughout the Ongul Islands: Erratic boulders, glacial scour, and various glacial deposits etc. can be found in the snow free area. Shell fossils have been found on raised beaches on East Ongul Island and marine deposits have been identified on beaches from 0.5 to 16 m asl (above sea level) (HAYASHI and YOSHIDA, 1994). Crustal uplift following deglaciation is continuing in the Ongul Islands at present.

Holocene raised beaches, marine terraces and their emergent marine deposits have been reported in and around Syowa Station (*e.g.* HAYASHI and YOSHIDA, 1994; IGARASHI *et al.*, 1995a). These raised beaches and marine terraces have been formed by the relative lowering of sea level caused by the crustal uplift. Generally the highest elevation of raised beaches in the coastal area of the Antarctic Continent is around 20 m asl and the trend of crustal uplift, caused by deglaciation, in Antarctica is estimated to be 2.5 mm/y on average, the possible maximum being 5–6 mm/y during last several thousand years (*e.g.* YOSHIDA and MORIWAKI, 1979).

According to OMOTO (1977), the maximum height of raised beaches around Syowa Station is 22 m on East Ongul Island, 19 m on Teöya (Island) 3 km south of East Ongul Island, and 35 m on Ongulkalven (Island) 5 km west from East Ongul Island as shown in Fig. 1. IGARASHI *et al.* (1995b) recently reported that the height of

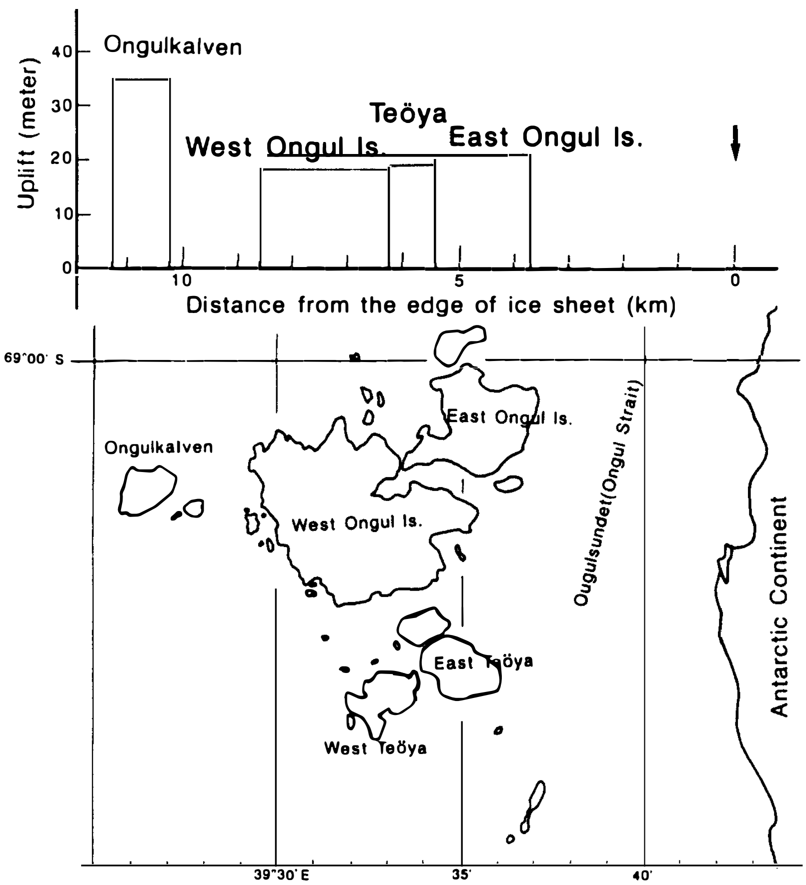

Fig. 1. The maximum height of raised beaches around Syowa Station. The origin of the horizontal axis is taken as the edge of the continent, the front of the Antarctic ice sheet.

the raised beach on West Ongul Island is 18 m.

The raised beaches, hence the crustal uplift, are a reflection of the regional isostatic rebound. The thinned ice sheet still extends to the coastal areas at present; however, crustal uplift coincident with deglaciation appears to be continuous since the Holocene.

4. Local Earthquakes

No large earthquakes of magnitude greater than 5 have been located in the Antarctic Continent; smaller magnitude earthquake activity is detected by the worldwide seismic network and local earthquakes are located by some local seismic networks in the Antarctic. A tripartite seismic array was established at Syowa Station in 1987 for studying the local seismicity (AKAMATSU *et al.,* 1988). Ten local earthquakes were located by the tripartite array during the 29 months from June 1987 to October 1989 (Fig. 2).

A process for the local earthquake activity in the vicinity of Syowa Station was suggested by KAMINUMA and AKAMATSU (1992) as follows:

1) Local earthquakes around Syowa Station are inferred to be caused by the tectonic stress which is accumulated by the crustal uplift after deglaciation, as the earthquakes are located in the coastal and offshore areas (Fig. 2).

2) The crustal uplift is not a linear phenomenon but a block movement, because the locations of epicenters are in the coastal and offshore areas, and the height of elevated beaches increases with distance from the continental edge (Fig. 1).

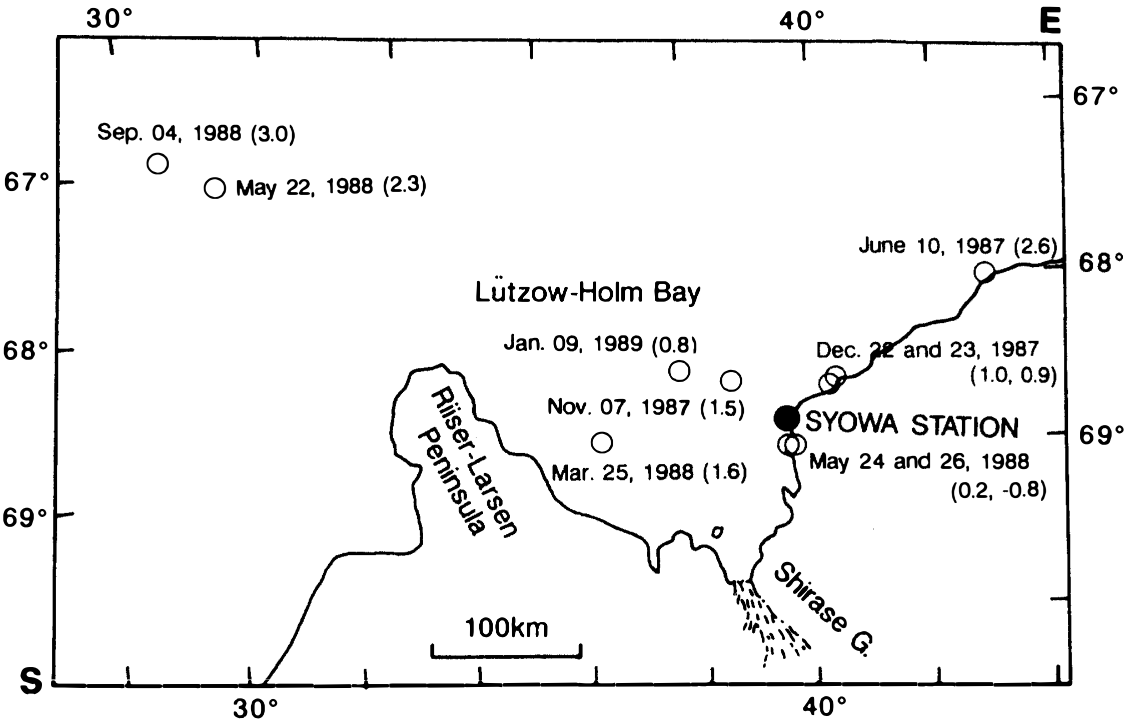

Fig. 2. Locations of local earthquakes with magnitudes in the parenthesis in the vicinity of Syowa Station recorded from June 1987 to October 1989.

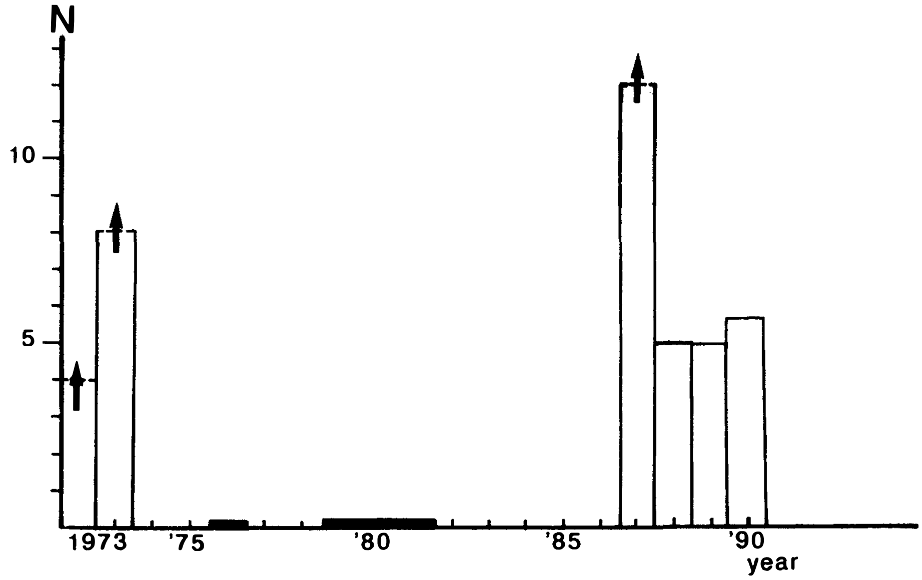

Fig. 3. The annual number of local earthquakes in the vicinity of Syowa Station counted on the routine observation seismograms and the tripartite array from 1972 to 1990. The arrows indicate that the actual number of earthquakes is more than that shown in the figure. The solid lines show periods during which no local earthquakes were detected although seismologists were wintering over and scaling seismograms carefully during that time.

3) The tectonic stress accumulates among the block boundaries, and earthquakes are caused by the stress.

4) The rate of stress accumulation is very small, so that only small, micro/ultra-micro earthquakes occur in the coastal and offshore areas.

5) The crustal uplift occurs only for a few years during one decade/more. The occurrence of earthquakes corresponds with the intermittent crustal uplift (Fig. 3).

This process can explain the discrepancy between the 10 mm/y falling of the sea level and 3–6 mm/y uplift of raised beaches from geomorphological data. The uplift rate of raised beaches of 3–6 mm/y is the mean value during the last 5000 years, while the rate of sea level falling from tide gauge data is averaged over several years. If crustal uplift occurs intermittently, the rate of the uplift might be larger than 3–6 mm/y as shown by Odamaki *et al.* (1991) and Michida *et al.* (1995). The sea level fall of 10 mm/y appears to correspond to the crustal uplift in the 1980s.

The period of local earthquake activity around Syowa Station corresponds to the same period when the 10 mm/y sea level fall was obtained. The local earthquake activity must indicate that the crustal uplift occurs intermittently. The crustal uplift occurred during the last few years at the end of the 1980's.

5. Discussion

Many observations on solid earth geophysics have been carried on at Syowa Station. The observations are oceanic tide, gravity, earthquakes, GPS tracking, etc.

Evidence concerning crustal uplift, after deglaciation, in the vicinity of Syowa Station from oceanographical, geomorphological and seismological phenomena has

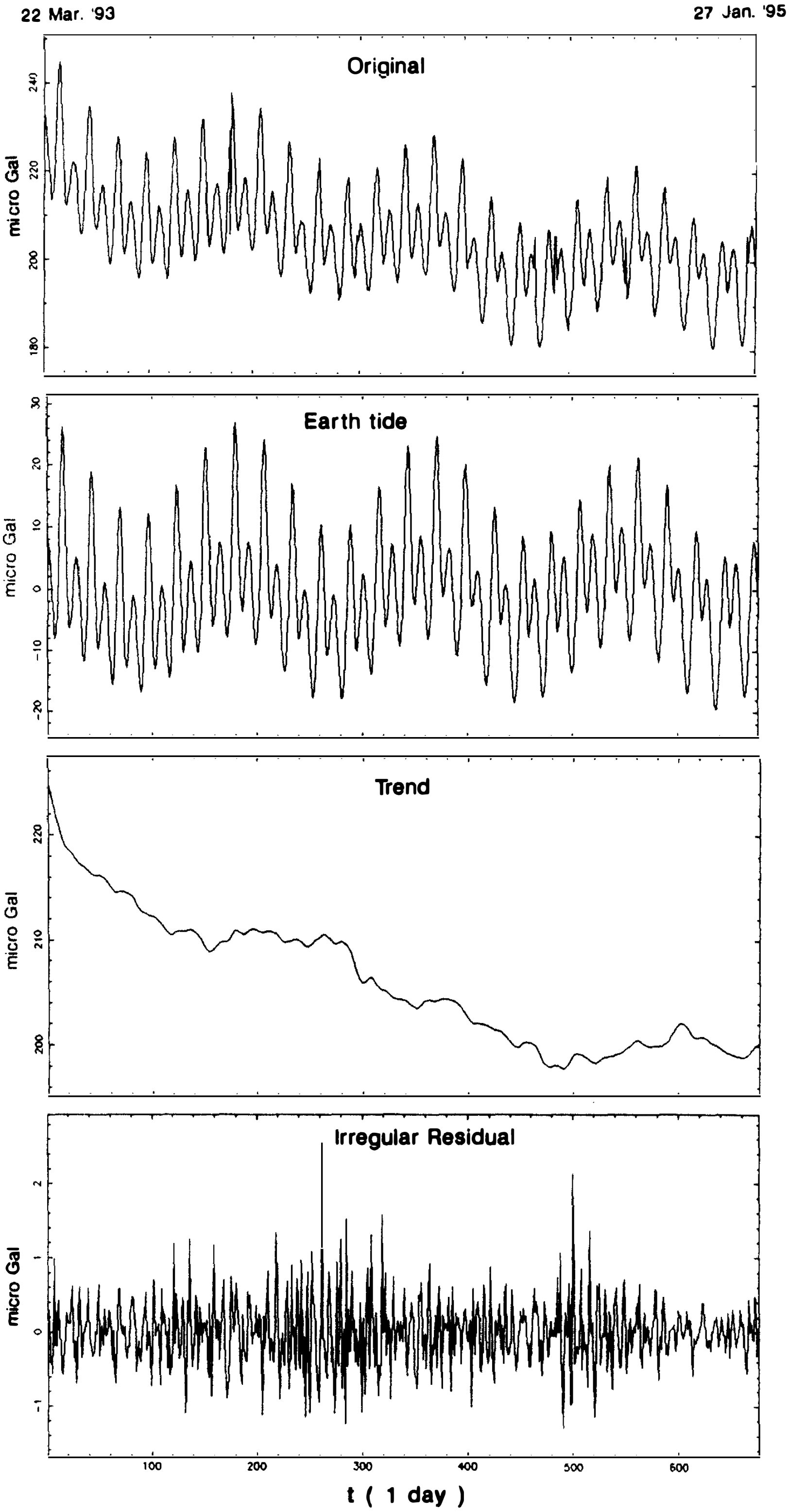

Fig. 4. The observed records of the SCG at Syowa Station from 22 March 1993 to 27 January 1995 (Compiled by T. SATO of JARE-34). The original with a 24-hr sampling interval is shown at the top, followed by earth tide, long term trend and irregular residual.

been discussed. Raised beaches and marine terraces which are recognized along the coast of the Antarctic Continent are one of the accepted facts indicating that crustal uplift has been continuing. Sea level fall of 10 mm/y would be caused by the absolute crustal uplift at least in 1981–1987. The mean sea level change at Syowa Station was obtained at a rate of -4.5 mm/y using the data in 1975–1992. Local earthquake activity corroborates the crustal uplift. Considering the above facts, the crustal uplift in the vicinity of Syowa Station must be larger than 5 mm/y, the mean rate of sea level fall at Syowa Station, since the rate of global sea level rise over the last 100 years is estimated to be in the range of 1–2 mm/y from world wide data.

If the crustal uplift of 5 mm/y continues for 10–20 years, the total uplift obtained will be several centimeters. The total amount of vertical crustal movement would produce some ten μGal change (1 $\mu\text{Gal}=10^{-8}$ m/s^2) in gravity. The accuracy of each absolute gravimeter is considered to be less than several μGal; however, there is a 10–20 μGal difference among the absolute values which were measured by different absolute gravimeters at the same point. Even at this level of accuracy, repeated measurements of absolute gravity over many years might detect the absolute values of vertical crustal movement in the coastal area in Antarctica where crustal uplift is surely taking place. Absolute gravity measurements at Syowa Station were made using four different absolute gravimeters to establish the IAGBN in the three austral summer seasons (FUJIWARA *et al.,* 1993; HANADA and TSUBOKAWA, 1994; TSUBOKAWA and HANADA, 1994).

Continuous observation by a SCG was also started at Syowa Station in March 1993 (SATO *et al.,* 1995). The original output of the SCG is shown in Fig. 4. The SCG observation is believed to provide the highest sensitivity and highest resolution data for not only study of the earth's core dynamics but also for the study of the vertical crustal movement. JARE is planning to continue the SCG observation for several years. The SCG is a gravimeter to detect gravity change on the order of 10–30 nGal (1 $\text{nGal}=10^{-11}$ m/s^2).

If the vertical crustal uplift, with rate of 10 mm/y, continues for three years, the total amount of uplift is estimated to be 3 cm, and hence absolute gravity change is expected to be about 10 μGal if the density of the earth is assumed to be constant. This amount of gravity change is detectable with the SCG. Using the absolute gravimeter together with the SCG will allow significant insight into the problem of absolute elevation change. This will be particularly valuable if both the SCG and absolute gravity data sets are available continuously for several years.

Global absolute crustal uplift is equivalent to the expansion of the earth's radius. Thus, the gravity technique is probably the only way to detect changes of a few centimeters in the earth's radius. If the absolute crustal uplift is detected, absolute change of global sea level can be verified. The measurements of absolute crustal uplift by gravity techniques must therefore be a great contribution toward identification of environmental changes which are related to sea level change. Syowa Station is the only Antarctic station where measurements of absolute gravity, and observations of SCG, oceanic tides, GPS, long-period seismographs etc. are carried on. As a result, Syowa Station is able to detect the absolute crustal uplift after deglaciation.

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