近畿地方における重力の精密相対測定

メタデータ	言語: ja 出版者: 静岡大学地球科学教室 公開日: 2008-01-25 キーワード (Ja): キーワード (En): 作成者: 里村, 幹夫 メールアドレス: 所属:
URL	https://doi.org/10.14945/00000246

静岡大学地球科学研究報告 11 （1985年7月） 1～55頁
Geosci. Repts. Shizuoka Univ., 11 (July, 1985), 1-55

PRECISE RELATIVE MEASUREMENTS OF GRAVITY IN KINKI DISTRICT, JAPAN

Mikio SATOMURA*

Abstract Gravity measurements have repeatedly been carried out in the area around Lake Biwa since 1971 in order to detect the secular change of gravity. In addition, through the examination on characteristics of LaCoste & Romberg gravimeters, we proposed the method of measurement at the stations with almost equal gravity value in order to carry out the gravity measurement more accurately. And therefore, another precise gravity measurement has been carried out at stations where the gravity value is almost equal to that of reference station (Geophysical Institute of Kyoto University; 979.70775 gals), along the levelling route in the area covering Lake Biwa and the Kii Peninsula since 1972. Besides them, the precise gravity measurement has also been carried out at stations with the gravity value 979.686 gals in due consideration of their distribution.

The accuracy of the results was investigated in many points of view, and it was ascertained to be usually about 10 μgals in standard deviation.

The results obtained by the gravity measurements were compared with the results obtained by levelling surveys, by water level observations of the lake, by oceanic tidal observations, by underground water level observations and by geodetic control surveys. The gravity change was not in a good correlation with the vertical movement obtained from levelling surveys, but it was with the movements obtained from the observations of water level and oceanic tides. The precise gravity measurement is less accurate than the levelling survey when the vertical movement is to be obtained in a short distance. However, it is a very great advantage that the precise gravity measurement can directly connect two stations which are located far apart. The levelling survey cannot realize this advantage, while the observations of water level and oceanic tides have this advantage. The results of the present investigations may be ascribed to this advantage.

On the other hand, the gravity increase was found at the tip of the Kii Peninsula, and this may be partly explained by the areal contraction caused by the push of the Philippine Sea Plate.

Received March 25, 1985

* Institute of Geosciences, Faculty of Liberal Arts, Shizuoka University, Shizuoka 422, Japan.

CONTENTS

1. Introduction

The gravity value at a point on the earth depends on the followings;

a) attraction by the earth's mass including the ocean water and atmospheric gas,
b) centrifugal force by the rotation of the earth, and
c) attraction by the celestial bodies.

It had been thought for a long time that the gravity field on the earth is eternally unchanged with the lapse of time, but the advancement of gravity measurement changed its thought. When periodic variation such as tidal and atmospheric effects is not considered, the change of gravity value at a point on the earth can be produced by the followings;

a) change of the dimension and mass of the earth,
b) change of the rotation of the earth,
c) change of the gravitational constant,
d) change of mass distribution of the earth interior, as a whole,
e) redistribution of masses just under the earth surface, and
f) movement of the earth surface (the point of measurement).

In all cases mentioned above, the secular change of gravity can be substantially investigated by the absolute measurement of gravity. In fact, the accuracy of the absolute measurement of gravity recently reached at an order of μgals by an employment of the method of free-fall (*e. g.*, HAMMOND, 1978, FALLER *et al.*, 1982) or free rise and fall observation (*e. g.*, SAKUMA, 1973; OOE *et al.*, 1982) in order to examine non-tidal gravity change. SAKUMA (1973) found a change of gravity amounting to about 30 μgals by his absolute measurements between 1966 and 1972 at Sevrès. At the present time, however, it is not easy to carry out an accurate absolute measurement of gravity at many stations in the world. The hypothesis on the secular change of gravity field derived from the movement of earth core was introduced for its cause (VOGAL, 1968; BARTA, 1971; 1978), but either absolute measurement or worldwide relative measurement of gravity should be performed for such investigation.

On the other hand, relative measurement of gravity in local or regional area can be used only to investigate the last two cases mentioned above; *i. e.*, redistribution of masses just under the earth surface and movement (practically vertical movement) of the earth surface. However, such relative measurement of gravity is easier, more rapid and in a wider area to be carried out accurately at many stations than absolute measurement or worldwide relative measurement.

The vertical crustal movement can be measured by the levelling survey. When both the gravity measurement and the levelling survey are simultaneously carried out, we are able to obtain the information on mass redistribution or density change just under the earth surface. Levelling surveys usually take a great deal of labour and much time. On the contrary, a relative measurement of gravity can be carried out over a wider area, in a shorter period of time and at a cheaper cost than the levelling survey. It is therefore thought that repeated precise relative measurements of gravity may be one of the effective and economical methods for detecting the vertical crustal movement, though the gravity measurement is originally not a method to detect it, if their accuracy is comparable with that of levelling surveys. As a result, investigations on whether the secular change of gravity difference among some stations is detectable or not have recently been made in many regions of the world (*e. g.*, MORELLI and HONKASALO, 1975).

As it was impossible to obtain the high precision in gravity measurements, no substantial study on secular change of gravity appeared before 1950 except a few pioneer researches (*e. g.*, ISHIMOTO and TUZI, 1929).

The employment of a portable gravimeter of spring type enables the relative measurement of gravity to be carried out more easily and rapidly. Some detections of secular change of gravity were reported by means of Worden and North American gravimeters in Japan (*e. g.*, IIDA *et al.*, 1950; 1952; JITSUKAWA and TAJIMA, 1962; KUBOTERA and SUMITOMO, 1965).

In Kinki District, gravity measurements were carried out several times between 1950 and 1962. One gravity change amounting to 0.1～0.3 mgal was observed during the period of 1950～1953 (ICHINOHE, 1955), and the other amounting to 0.3～0.6 mgal was also observed during the period of 1952～1962 (ICHINOHE *et al.*, 1963). Both results show that gravity value increased on both shores of the southern part of Lake Biwa during the periods concerned.

The employment of LaCoste & Romberg gravimeter in the gravity measurements has enabled them more accurate, and investigations to detect time change of gravity difference have been made not only in Japan but also in many regions of the world. In Japan, time change of gravity by a LaCoste & Romberg gravimeter was first detected in Izu-Ooshima Island (FUJII *et al.*, 1964a), but it was achieved by comparing the result obtained by a LaCoste & Romberg gravimeter with that by a North American gravimeter. Another gravity measurement was carried out by a LaCoste & Romberg gravimeter in 1967 in Izu-Ooshima Island, and gravity decrease of 0.8～0.9 mgal was detected near the volcanic crater (INOUYE *et al.*, 1968).

Matsushiro Earthquake Swarm, which began in August 1965 in the central part of Japan, provided an appropriate test field to investigate the time change of gravity caused by seismic activity. A series of gravity measurements were carried out in the area of active crustal deformation by the Geographical Survey Institute (GEOGRAPHICAL SURVEY INSTITUTE, 1967; 1968), the Geological Survey of Japan (SEYA, 1968) and the

Earthquake Research Institute of the University of Tokyo (HAGIWARA and TAJIMA, 1973; TAJIMA and IZUTUYA, 1974). A dilatancy water diffusion model was applied to the Matsushiro Earthquake Swarm and it was discussed from the data of gravity measurements (FUJITA and FUJII, 1974; NUR, 1974; KISSLINGER, 1975).

The studies on time change of gravity were also reported by many overseas researchers (*e. g.*, BARNES, 1966; HUNT, 1970; SCHLEUSENER and TORGE, 1971; BOULANGER and SCHEGLOV, 1971).

Needless to say, a most accurate gravity measurement is highly required in order to detect the time change of gravity. Test measurements were carried out to check the accuracy of a LaCoste & Romberg gravimeter (FUJII *et al.*, 1964b). A special case to carry it was experimentally constructed to reduce the drift of the gravimeter (HAMILTON and BRULÉ, 1967).

On the other hand, theoretical studies were also made on the secular change of gravity as the result of crustal deformation and underground mass movement (*e. g.* FUJII, 1969; TAZIMA, 1970).

The International Association of Geodesy (IAG) recognized the importance of improving gravity measurements, and a Special Study Group on "Special Techniques of Gravity Measurements" was established at the General Assembly of the IAG held at Lucerne in 1967, and many researchers engaged in this study (HONKASALO, 1971).

Under these circumstances of researches on the precise gravity measurement and on the secular change of gravity in the world, we started the precise gravity measurements in about 1970.

2. Purpose of the Investigations

As we have mentioned in the Chapter 1, to detect the time change of gravity has been one of the most important aims of investigation in gravimetry since 1960's, and many pioneer researches on time change of gravity have been carried out. The precision of the gravity measurement, however, has not always been sufficiently reliable to detect small gravity changes. We started an investigation for detecting the time change of gravity in the area near Kyoto in 1971. Two areas around Lake Biwa and in the Kii Peninsula were chosen in Kinki District to carry out precise gravity measurements.

We were interested in the area around Lake Biwa; first, it is close to Kyoto, and therefore the gravity measurements can be carried out easily, accurately and within a short time; secondly, in Kinki District including this area, gravity measurements had repeatedly been carried out between 1950 and 1962 by using North American and Worden gravimeters, and the results showed that gravity value had increased on the shore of Lake Biwa, but the results obtained by such gravimeters were not so accurate that they could not tell whether the gravity increase was real or not; thirdly, in this area two more precise gravity measurements were carried out in 1964 and 1967 by using LaCoste & Romberg gravimeters, but the methods of precise gravity measurements were not yet refined and such data had some questions on the accuracy to detect the secular change of gravity. We started the precise gravity measurements along the route around Lake Biwa in 1971 with LaCoste & Romberg gravimeter G-196 (NAKAGAWA *et al.*, 1972; SATOMURA and NAKAGAWA, 1972), and they have been carried out almost every year.

Next, we paid attention to the area in the Kii Peninsula. It is not far apart from Kyoto, and in this area there is much possibility to prove that a large gravity change accompanies a large scale of crustal movements. According to geophysical studies made so far, the ground gradually subsides at ordinary times, while an abrupt uplift occurs at the times of great earthquakes, in the Kii Peninsula (MIYABE, 1955). Therefore, it is highly expected to measure the gravity change of a large scale in this area. In general, the southern part of the Kii Peninsula has a high gravity anomaly, while the northern part has a low one. We could, therefore, find many gravity stations with a similar gravity value all over the area. The rectilinear distance between the two extreme stations was about 200 km in north and south. Gravity stations were specially chosen from the first order bench marks with small gravity differences in 1970, along the levelling route of the area covering Lake Biwa and the Kii Peninsula (NAKAGAWA and SATOMURA, 1973). Such measurements became the topic of conversations of researchers on gravimetry of those days in order to increase the accuracy in gravity measurements, because they were almost relieved from the irregularity of dial screw of the gravimeter, the determination error of scale values and others. We had tried to examine the validity of such measurements through performing the gravity measurements (NAKAGAWA and SATOMURA, 1971). Similar precise gravity measurements have been carried out in the Muroto Peninsula and in Tōkai District (SHICHI *et al.*, 1983) in Japan, and also in some overseas areas (*e. g.*, KIVINIEMI, 1974; GROTEN, 1975; ELSTNER *et al.*, 1978; HIPKIN, 1978).

The Geodetic Society of Japan organized a Working Group for Gravity Measurements and Precise Levelling, and held three symposia on "Gravity and Precise Levelling" in 1969, 1970 and 1971. Many reports were presented at the symposia (*e. g.*, WORKING GROUP FOR COMPARING THE GRAVIMETERS IN JAPAN, 1969; NAKAGAWA and SATOMURA, 1971). The necessity for making fundamental examinations to investigate the characteristics of LaCoste & Romberg gravimeters was emphasized at the symposia (NAKAGAWA, 1971).

After the symposia, we examined cooperatively the characteristics of LaCoste & Romberg gravimeters (model G) at Kakioka in 1973 (NAKAGAWA *et al.*, 1973) and at Mizusawa in 1974 (NAKAGAWA *et al.*, 1974). The following points were investigated for nine LaCoste & Romberg gravimeters;

a) scale values of the gravimeters,
b) effect by turning the measure screw of the gravimeters,
c) effect due to voltage change of the connected battery,
d) effect due to meteorological disturbances, and
e) influence due to vibration during the transportation.

Similar examinations were also carried out in many countries (*e. g.*, KIVINIEMI, 1974; DUCARME *et al.*, 1976; HIPKIN, 1978; GERSTNECKER, 1978; KANNGIESER, 1982).

We also carried out the precise gravity measurements cooperatively in East Hokkaidō (IZUTUYA *et al.*, 1976; OHKAWA *et al.*, 1976), in the Miura and Bōsō Peninsulas (TAJIMA *et al.*, 1976), in Tōkai District (ICHINOHE *et al.*, 1983) and in the Muroto Peninsula (TAJIMA, 1975); where large earthquakes periodically occur by interaction of oceanic and continental plates. Not only co-seismic gravity change but also inter-seismic one are expected in those regions (FUJII, 1972; FUJII and NAKANE, 1972). Large co-seismic change of gravity was observed during the Earthquake off Nemuro Peninsula of 1973 ($M=7.4$) (FUJITA *et al.*, 1975), but it was later found to be not co-seismic change but either after-seismic change or a measuring error (OHKAWA *et al.*, 1976). Izu Hantō-oki Earthquake ($M=6.9$) occurred in 1974. After this earthquake, the eastern part of Izu Peninsula became tectonically active, and some gravity changes were detected there (HAGIWARA *et al.*, 1976a; 1976b; 1977; 1978; 1980).

A gravity increase amounting to 0.1 mgal was reported on both shores of the southern part of Lake Biwa between 1964 and 1971 (NAKAGAWA *et al.*, 1972; SATOMURA and NAKAGAWA, 1972). Hypotheses that the basement rises and that the density of sediments increases by compaction, led to a conclusion that a viscosity of basement is 6×10^{20} poises (NAKAGAWA and SATOMURA, 1975b), but there are few geological evidences which support the hypotheses. The results obtained between 1971 and 1975 were consistent with the results of levelling surveys. They seem to support the view that repeated precise gravity measurements are substituted levelling survey as a more rapid and economical method (NAKAGAWA and SATOMURA, 1976; 1977).

We have also repeated the precise gravity measurements in volcanic regions; that is, Aso Volcano (KUBOTERA *et al.*, 1974; 1978; 1984; KUBOTERA and SATOMURA, 1985) and Iwaki Volcano (SATOMURA and ICHINOHE, 1975).

We have confirmed the validity of precise gravity measurements in order to detect secular change of gravity, through our many performances of the gravity measurements. We recommended the method of the precise gravity measurements to the IAG (NAKAGAWA and SATOMURA, 1975a), presented the relation between gravity change and vertical movement obtained from the levelling surveys, and recommended to both the International Gravity Commission (IGC) and the IAG that such measurements were economical methods to detect the vertical movement. Through some recommendations including ours, the IAG recommended to develop the precise gravity measurements (NAKAGAWA, 1975), and many researchers started the studies on precise gravity measurement and on secular change of gravity in response to the recommendation. Of course, we have energetically continued to carry out the precise gravity measurements in the areas around Lake Biwa and in the Kii Peninsula.

We have successively published the results and discussed their interpretations. And now we collectively analyzed, in the present article, the total of our former data obtained by LaCoste & Romberg gravimeters around Lake Biwa and in the Kii Peninsula and new data not only of the measurements concerned but also scale values of the gravimeters employed; and discussed on the results of gravity change obtained in the areas concerned during the past decade, by comparing with some other data such as levelling surveys, oceanic tidal observations and so on.

3. Location of Stations and Method of Measurements

3–1. Around Lake Biwa

In the area around Lake Biwa, gravity measurements have repeatedly been carried out since 1950, but a North American gravimeter and a Worden one were employed in the measurements before 1956. These results are less accurate than those obtained by using LaCoste & Romberg gravimeters, so that we discuss only the results obtained by LaCoste & Romberg gravimeters in the present article. Only one LaCoste & Romberg gravimeter was used in these gravity measurements in 1964 and 1967. Measured stations were chosen mainly from the first order bench marks, while some stations were not bench marks but on the road near bench marks which could not be found, or on the stone steps of shrines or temples which, we judged, would remain intact. These stations are not suitable for the stations of repeated precise gravity measurements, because the gravity change measured cannot be told to result whether from the movement of measured station or from the underground mass redistribution.

We started a new series of precise gravity measurements in 1971 at the same stations as in 1964 and 1967, but some stations which were not bench marks were changed to the nearest bench marks. Location of the main measured stations is shown in Fig. 1, and their details are shown in both Table 1 and Note 1.

Table 1. Description of the stations in the area around Lake Biwa

	Latitude	Longitude	Height		Latitude	Longitude	Height
Kyoto Univ.	35°01′.7 N	135°47′.2 E	59.86 m	B.M. 10500 (former)	35°27′.2 N	136°15′.8 E	101.21 m
B.M. 241	35 01.6	135 46.4	53.58	Kinomoto	35 30.1	136 13.7	120.
Keage	35 00.5	135 47.4	60.	B.M. 10506	35 32.5	136 12.5	147.45
B.M. 215.1	35 00.4	135 47.4	58.92	Hannoura	35 30.0	136 11.4	140.
B.M. 215	34 59.6	135 48.2	63.16	Yanokuma	35 30.7	136 09.1	105.
Kyoto Col. Pharm.	34 59.2	135 48.8	55.	Sakaebashi (former)	35 30.1	136 08.1	90.
B.M. 213	35 00.1	135 52.4	90.47	Sakaebashi (new)	35 30.1	136 08.1	90.
Seta (Karahashi)	34 58.2	135 54.5	89.	Ōura	35 29.2	136 07.6	95.
B.M. 211.1	34 58.2	135 54.5	91.35	Kaizu (Fukuzen-ji)	35 27.6	136 04.6	90.
B.M. 210.1	34 59.2	135 56.6	109.49	Kaizu (Saiei-ji)	35 27.6	136 04.4	90.
Yasaka Shrine	34 59.2	135 56.0	100.	2nd Order B.M. 3851	35 27.2	136 04.0	87.30
2nd Order B.M. 1330	35 01.2	135 55.9	86.95	Makino	35 27.7	136 02.6	105.
Kusatsu JHS	35 00.7	135 58.0	95.	Kitashinpo	35 26.7	136 02.2	105.
B.M. 209.1	35 00.9	135 57.8	97.07	Yū	35 24.2	135 59.4	140.
Kusatsu (Dental)	35 00.8	135 57.7	97.	B.M. 1328	35 24.2	136 00.4	124.00
B.M. 209	35 01.7	135 58.5	93.86	B.M. 1326	35 23.8	136 02.4	87.24
B.M. 208.1 (former)	35 02.7	135 59.2	97.22	B.M. 1323	35 20.7	136 01.9	96.76
B.M. 207.1	35 03.6	136 01.4	99.27	B.M. 1322	35 19.6	136 01.7	91.17
B.M. 206	35 05.0	136 04.8	113.95	B.M. 1320	35 17.7	136 01.0	86.95
B.M. 205.1	35 05.6	136 05.9	99.59	B.M. 1316	35 14.8	135 58.4	91.34
B.M. 204.1	35 06.7	136 08.0	100.38	B.M. 1312	35 11.7	135 55.4	104.36
Higashioiso (Pass.)	35 07.8	136 10.0	103.	B.M. 1311	35 10.8	135 55.0	97.92
B.M. 203.1	35 07.8	136 10.0	104.55	B.M. 1310	35 10.0	135 55.4	87.12
Gokashō (Zenjū-ji)	35 09.2	136 12.0	108.	B.M. 1309	35 09.1	135 55.5	95.50
B.M. 202.1	35 09.2	136 11.9	107.99	B.M. 1308	35 08.4	135 55.6	89.24
B.M. 200	35 13.8	136 15.5	104.52	B.M. 1307	35 07.3	135 55.3	87.80
Hikone	35 16.4	136 15.6	95.	B.M. 1305	35 05.3	135 53.8	87.21
B.M. 198.1 (former)	35 16.5	136 17.1	102.80	Karasaki (Shrine)	35 02.7	135 52.6	87.
B.M. 198.1 (new)	35 16.5	136 17.1	101.68	B.M. 1302	35 02.7	135 52.5	86.36
Emperor Meiji	35 18.7	136 19.0	118.	B.M. B-2	35 09.3	135 54.4	230.
B.M. 197	35 18.8	136 19.2	114.79	B.M. B-5	35 09.4	135 52.1	150.
Samegai	35 19.6	136 21.3	140.				
Kashiwabara	35 20.5	136 24.5	177.				
Sekigahara JHS	35 21.4	136 28.1	120.				
B.M. 193	35 21.5	136 28.2	123.01				
Sekigahara (Shrine)	35 21.6	136 28.3	122.				
Ibuki	35 22.9	136 22.8	180.				
B.M. 10495	35 24.7	136 20.1	131.13				
Uchibo	35 25.6	136 17.9	113.				
Kohoku	35 26.7	136 14.6	99.				

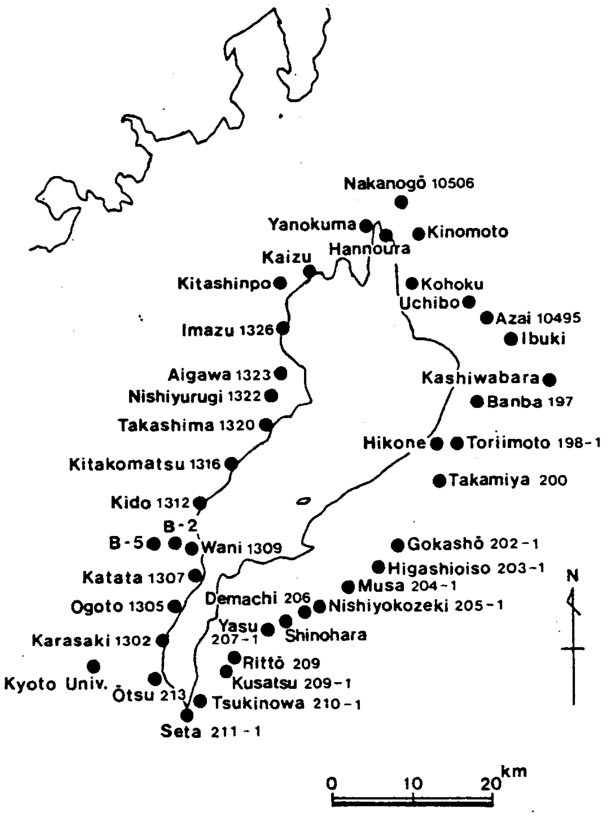

Fig. 1. Location of the main measured stations in the area around Lake Biwa.

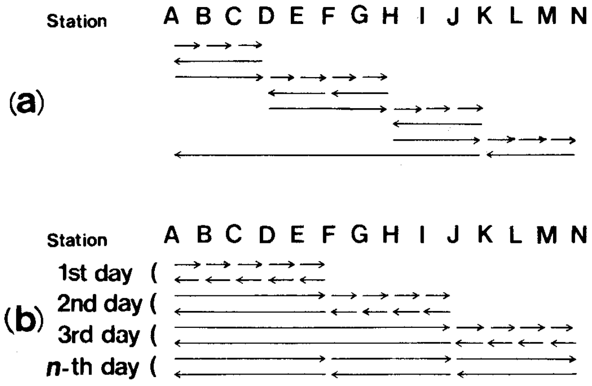

Fig. 2. Schemes of the measured order of the stations.
(a) One-way measurements making the small loops.
(b) Going and returning measurements.

In 1964 and 1967, one-way measurements making the small loops were carried out as shown in Fig. 2 (a). These measurements were completed at all stations in a few days. To be concrete, we measured in 1964 as follows;

first day : Kyoto — 1 station — Ōtsu — Seta — Ōtsu — 1 station — Kyoto — Seta — 4 stations — Shinohara — 1 station — Seta — Kyoto,

second day : Kyoto — Seta — 1 station — Shionohara — 4 stations — Gokashō — 1 station — Shinohara — Gokashō — 2 stations — Hikone — 1 station — Gokashō — Hikone,

third day : Hikone — 2 stations — Kashiwabara — Hikone — Kashiwabara — 3 stations — Kinomoto — Kashiwabara — Kinomoto — 5 stations — Imazu — Kinomoto — Imazu, and

fourth day : Imazu — 4 stations — Kitakomatsu — 1 station — Imazu — Kitakomatsu — 5 stations — Ogoto — 1 station — Kitakomatsu — Ogoto — 1 station — Ōtsu — 1 station — Ogoto — Kyoto,

In 1967 we measured as follows;

first day : Kyoto — 1 station — Ōtsu — 10 stations — Gokashō — 3 stations — Kyoto,

second day : Kyoto — 1 station — Gokashō — 9 stations — Uchibo — Gokashō,

third day : Uchibo — 5 stations — Kinomoto — 3 stations — Imazu — Kitashinpo — 1 station — Kinomoto — Uchibo,

fourth day : Kinomoto — 1 station — Kitashinpo — Imazu — 11 stations — Ōtsu — 2 stations — Imazu, and

fifth day : Imazu — 4 stations — Ōtsu — Kyoto.

After 1971, a going and returning measurement was adopted as shown in Fig. 2 (b); the connection was made directly from the reference station (Geophysical Institute of Kyoto University) every day in order to determine gravity values at the measured stations as accurately as possible. Every measurement included at least three so-called "connective stations"; *i. e.,* the reference station, the first station and the last station of that day. Another measurement only at the connective stations was also carried out. For example, in 1977 we measured as follows;

first day : Kyoto－Ōtsu－10 stations－Hikone (twice)－10 stations－Ōtsu－Kyoto,
second day : Kyoto－Hikone－8 stations－Kinomoto(twice)－8 stations－Hikone－Kyoto,
third day : Kyoto－Ōtsu－Hikone－Kinomoto－Imazu(twice)－Kinomoto－Hikone－Ōtsu－Kyoto,
fourth day : Kyoto－Imazu－8 stations－Kinomoto(twice)－8 stations－Imazu－Kyoto, and
fifth day : Kyoto－Ōtsu－9 stations－Imazu (twice)－9 stations－Ōtsu－Kyoto.

Since 1971, we had measured almost in the same way as this; some other measurements were added to these measurements when some troubles took place. Almost all measurements were carried out by means of a single gravimeter; namely, G-83 in 1964, G-29 in 1967, G-196 in 1971 ∼1977 and July 1980, and two gravimeters G-196 and G-534 after 1979 except July 1980.

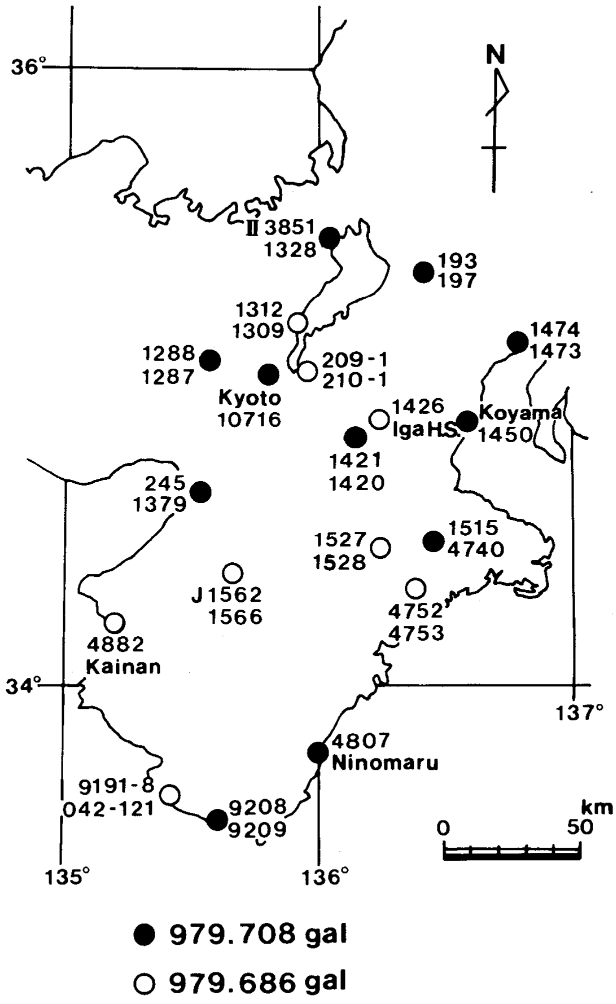

Fig. 3. Distribution of the iso-gravity stations in Kinki District.

3—2. In Kinki District

When we started the precise gravity measurements in 1971, we had never carried out precise calibrations on scale values of LaCoste & Romberg gravimeters, so the obtained results contained uncertainty of an order of 10^{-4} on the scale values. As for gravity measurements in Kinki District, we had to select the gravity stations where the gravity difference was less than about 1 mgal in order to obtain the gravity difference from a reference station with the accuracy of 10 μgals or better by avoiding the irregularity of dial screw of the gravimeter, the determination error of scale values and others.

As mentioned in the Chapter **2**, we could find gravity stations with a similar gravity value all over the Kinki District. Along the levelling route of the area covering Lake Biwa and the Kii Peninsula, such first order bench marks were chosen in 1970, as gravity stations, as gravity differences from the Gravity Station of Geophysical Institute of Kyoto University (reference station in the present study and its gravity value is 979.708 gals) are smaller than 4 mgals (later, we narrowed down to smaller than 1 mgal) －hereinafter, referred to as "the iso-gravity station" in the present article － (NAKAGAWA and SATOMURA, 1971). Besides them, the first order bench marks with the gravity value of 979.686 gals±1 mgal were added to the iso-gravity stations in due consideration of their distribution, in 1973. In another words, two sets of the iso-gravity networks were established in the area covering Lake Biwa and the Kii Peninsula. One more first

Table 2. Description of the iso-gravity stations

	Latitude	Longitude	Height
	N	E	m
11.0.	35°01′.7	135°47′.2	59.86
11.1.	35 00.5	135 47.4	60.
11.2.	35 00.4	135 47.4	58.92
11.3.	34 59.6	135 48.2	63.13
11.4.	34 59.2	135 48.8	55.
11.5.	34 57.1	135 49.3	50.
11.6.	34 56.6	135 49.2	31.81
12.1.	34 45.8	136 07.8	147.94
12.2.	34 45.9	136 07.6	145.
12.3.	34 45.7	136 07.5	140.
12.4.	34 45.8	136 08.2	150.
12.5.	34 45.7	136 08.3	150.
12.6.	34 46.4	136 08.5	141.94
31.1.	34 48.9	136 12.1	177.
31.2.	34 48.5	136 12.5	180.
31.3.	34 47.6	136 12.7	195.
31.4.	34 46.4	136 13.2	220.
31.5.	34 49.1	136 12.8	185.
31.6.	34 49.5	136 13.2	188.76
13.1.	34 49.1	136 34.9	1.49
13.2.	34 48.9	136 34.7	2.73
13.3.	34 48.8	136 34.4	1.10
13.4.	34 48.8	136 33.7	5.
13.5.	34 48.6	136 34.2	3.
13.6.	34 48.5	136 34.1	1.32
14.1.	34 24.6	136 27.9	72.34
14.2.	34 24.4	136 27.7	75.
14.3.	34 24.6	136 28.0	70.20
14.4.	34 24.8	136 28.4	68.33
14.5.	34 26.9	136 26.4	100.
14.6.	34 27.0	136 26.5	95.73
14.7.	34 27.0	136 24.0	115.
32.1.	34 24.7	136 14.3	209.42
32.2.	34 24.9	136 14.4	208.
32.3.	34 24.6	136 14.3	210.
32.4.	34 24.5	136 14.0	210.
32.5.	34 24.4	136 13.8	215.
32.6.	34 24.3	136 13.5	217.04
	N	E	m
33.1.	34°17′.2	136°22′.7	158.36
33.2.	34 17.3	136 22.8	155.
33.3.	34 17.2	136 22.9	157.86
33.4.	34 17.1	136 22.4	161.73
33.5.	34 16.9	136 22.4	160.
33.6.	34 16.6	136 22.0	169.12
15.1.	33 45.4	136 01.6	8.77
15.2.	33 45.4	136 01.6	13.
15.3.	33 48.1	136 02.5	40.
15.4.	33 43.6	135 59.7	40.
15.5.	33 42.8	136 00.0	30.
15.6.	33 42.0	135 59.5	35.64
16.1.	33 30.2	135 35.8	7.34
16.2.	33 30.2	135 35.5	15.
16.3.	33 30.3	135 35.8	20.84
16.4.	33 30.2	135 36.1	15.
16.5.	33 30.4	135 35.0	5.
16.6.	33 30.5	135 34.8	6.07
34.1.	33 34.3	135 25.9	7.78
34.2.	33 34.1	135 26.1	5.
34.3.	33 34.0	135 26.0	5.
34.4.	33 35.3	135 27.0	15.
34.5.	33 35.6	135 27.2	15.
34.6.	33 34.4	135 25.8	12.98
35.1.	34 05.7	135 07.3	5.
35.2.	34 06.2	135 09.2	15.
35.3.	34 06.6	135 09.5	6.56
35.4.	34 07.0	135 09.2	20.
35.5.	34 08.5	135 11.6	2.69
35.6.	34 10.0	135 12.6	7.72
35.7.	34 09.1	135 12.7	2.40
36.1.	34 18.8	135 36.5	84.57
36.2.	34 18.9	135 37.3	88.51
36.3.	34 18.9	135 37.6	93.68
36.4.	34 22.2	135 44.8	138.01
36.5.	34 21.2	135 42.6	120.
36.6.	34 20.8	135 41.9	105.
36.7.	34 20.8	135 41.9	104.00

(continued to the next page)

Table 2. (continued)

	Latitude	Longitude	Height		Latitude	Longitude	Height
	N	E	m		N	E	m
17.1.	34° 34′.6	135° 28′.9	5.	38.1.	35° 11′.7	135° 55′.4	104.36
17.2.	34 35.0	135 29.1	2.95	38.2.	35 10.8	135 55.0	97.92
17.3.	34 36.1	135 29.5	2.09	38.3.	35 10.0	135 55.4	87.12
17.4.	34 35.4	135 30.5	10.	38.4.	35 09.1	135 55.5	95.50
17.5.	34 35.5	135 31.9	10.	38.5.	35 08.4	135 55.6	89.24
17.6.	34 34.8	135 31.8	13.	38.6.	35 07.3	135 55.3	87.80
17.7.	34 34.4	135 31.9	14.74				
				20.1.	35 02.2	135 33.1	98.69
37.1.	34 59.2	135 56.6	109.49	20.2.	35 02.6	135 34.5	100.
37.2.	34 59.2	135 56.0	100.	20.3.	35 01.2	135 35.6	100.
37.3.	35 01.2	135 55.9	86.95	20.4.	35 00.9	135 31.7	150.
37.4.	35 00.7	135 58.0	95.	20.5.	35 01.4	135 32.6	130.
37.5.	35 00.9	135 57.8	97.07	20.6.	35 02.6	135 32.8	100.50
37.6.	35 01.7	135 58.5	93.86				
				21.1.	35 06.0	136 46.9	−0.54
18.1.	35 18.8	136 19.2	114.79	21.2.	35 06.3	136 46.1	−0.5
18.2.	35 18.7	136 19.0	118.	21.3.	35 05.9	136 46.5	−0.5
18.3.	35 19.6	136 21.3	140.	21.4.	35 05.2	136 46.6	−0.5
18.4.	35 21.4	136 28.1	120.	21.5.	35 04.8	136 47.2	−0.5
18.5.	35 21.6	136 28.3	122.	21.6.	35 05.7	136 45.6	−0.49
18.6.	35 21.5	136 28.2	123.01				
19.1.	35 27.2	136 04.0	87.30				
19.2.	35 27.6	136 04.4	90.				
19.3.	35 27.6	136 04.6	90.				
19.4.	35 27.7	136 02.6	105.				
19.5.	35 24.2	135 59.4	140.				
19.6.	35 24.2	136 00.4	124.00				

order bench mark and four or five sub-stations were subjointly established near each bench mark in 1973, in order to keep the stations as long as possible and also to confirm the accuracy of gravity change measured (NAKAGAWA and SATOMURA, 1973; 1975a). The distribution of the stations thus established is shown in Fig. 3, and their detailed descriptions are shown in both Table 2 and Note 2. In Fig. 3, each circle consists of six or seven gravity stations; namely, two bench marks (we call them "main stations") and four or five sub-stations.

Gravity measurements at the main stations along the route of Kyoto—the Kii Peninsula—Kyoto were carried out both clockwise and counterclockwise by means of three LaCoste & Romberg gravimeters G-34, G-196 and G-210 during the period of three days on either way in 1972 (NAKAGAWA and SATOMURA, 1972). Similar measurements were repeatedly carried out by means of two or three LaCoste & Romberg gravimeters in 1974 (G-34, 196 and 210), 1975 (G-34, 196 and 210), 1978 (G-118, 196 and 210), 1980 (G-196, 534 and D-36) and 1981 (G-196 and 534) at the main stations which were specially established in the area covering Lake Biwa and the Kii Peninsula. Another gravity measurement was carried out at two main stations and four or five sub-stations by means of a single LaCoste & Romberg gravimeter G-196 inside of each circle in Fig. 3 in every measured year.

The gravimeter was always set up in the same direction (usually northwards) at the same station in order to avoid the geomagnetic effect to the gravimeter.

4. Method of Calculation and Its Results

The scale value of the LaCoste & Romberg gravimeter was given by the manufacturer. Through international and domestic connections of gravity, it had been ascertained that the scale value involved errors with an order of 10^{-4}.

A calibration on the scale value of eight LaCoste & Romberg gravimeters including the G-29, G-196 and G-210, which were employed in the present investigations, was carried out in 1976, in order not only to make clear the differences among the scale values of the gravimeters but also to determine the most reliable gravity values at the measured stations. The calibration line was established between Hokkaidō and Okinawa, referring to the International Gravity Standardization Net 1971 (IGSN 71) (MORELLI *et al.*, 1974) and the Japan Gravity Standardization Net 1975 (JGSN 75) (GEOGRAPHICAL SURVEY INSTITUTE, 1976), and its maximum gravity difference was about 1.6 gals. The correction factors for the scale values of the gravimeters were calculated using the data obtained by the calibration (NAKAGAWA *et al.*, 1977a). The correction factor 1.000473 thus obtained was used in the present calculation, for the G-210.

An international gravity connection was carried out with three LaCoste & Romberg gravimeters G-29, G-118 and G-223 in 1974 at gravity stations in Tokyo, Moscow, Potsdam and Paris (SETO and TAZIMA, 1975). Another international connection of gravity was undertaken by means of two LaCoste & Romberg gravimeters G-29 and G-196 in 1975 at gravity stations in Kyoto, Tokyo, Oahu-Honolulu, Los Angels, Mexico City, Lima and Santiago (NAKAGAWA *et al.*, 1977b). The maximum gravity differences of the both connections were about 1.8 gals and 2.1 gals, respectively. Using the data obtained by these connections and referring to both the IGSN 71 and the JGSN 75, correction factors for the scale values of the LaCoste & Romberg gravimeters G-29, G-118 and G-196 were determined, by assuming that each correction factor for each gravimeter is given by a function of second degree to the gravity value (NAKAGAWA *et al.*, 1978). Revised tables of the scale values were made and used in the present calculation for the gravimeters G-29 and G-196. Their values are shown in Tables 3 and 4.

In the case of the gravimeter G-83, GEOGRAPHICAL SURVEY INSTITUTE (1976) had obtained its correction factor in the calculation of the gravity values of the JGSN 75, and it was found to be 1.0005. No correction factors had been obtained yet, in cases of the G-34, G-534 and D-36. They were determined in the present calculation by considering the results of the simultaneous measurements with the gravimeters G-196 and G-210. Their values are 1.0003 for the G-34, 1.0005 for the G-534 and 1.0015 for the D-36, and were used in the present calculation.

Tidal corrections were made under the assumption that the tidal factor of gravity (δ-factor) is 1.2 and phase lag is 0°; they are obtained from the tidal observation by using an Askania gravimeter at the reference station. The corrections of instrumental height were made using the normal value of free-air gradient (3.086 μgals/cm).

Drift corrections of the gravimeters employed and the determination of gravity difference were simultaneously made through calculation of all

Table 3. Revised table of the scale values for LaCoste & Romberg gravimeter G-29

Counter reading	Value in milligals	Factor for interval	Counter reading	Value in milligals	Factor for interval
000			3200	3396.959	1.04890
100			3300	3501.849	1.04894
200			3400	3606.743	1.04894
300			3500	3711.637	1.04899
400			3600	3816.536	1.04898
500			3700	3921.434	1.04898
600			3800	4026.332	1.04897
700			3900	4131.229	1.04892
800			4000	4236.121	1.04891
900			4100	4341.012	1.04891
1000			4200	4445.903	1.04885
1100			4300	4550.788	1.04880
1200	1300.000	1.04854	4400	4655.668	1.04879
1300	1404.854	1.04849	4500	4760.547	1.04874
1400	1509.703	1.04848	4600	4865.421	1.04869
1500	1614.551	1.04843	4700	4970.290	1.04863
1600	1719.394	1.04842	4800	5075.153	1.04863
1700	1824.236	1.04837	4900	5180.016	1.04857
1800	1929.073	1.04831	5000	5284.873	1.04852
1900	2033.904	1.04831	5100	5389.725	1.04846
2000	2138.735	1.04825	5200	5494.571	1.04836
2100	2243.560	1.04830	5300		
2200	2348.390	1.04829	5400		
2300	2453.219	1.04834	5500		
2400	2558.053	1.04839	5600		
2500	2662.892	1.04848	5700		
2600	2767.740	1.04853	5800		
2700	2872.593	1.04862	5900		
2800	2977.455	1.04867	6000		
2900	3082.322	1.04871	6100		
3000	3187.193	1.04881	6200		
3100	3292.074	1.04885	6300		

the data concerned by the least squares method. The observation equations are as follows;

$$g_i = g_0 + \Delta g_j + a_k t_i + b_k$$

where, i : a serial number of the measurement,

j : a serial number of the gravity station,

k : a serial number of the day when the measurement was carried out,

g_i : measured value corrected earth tides and instrumental height (known),

g_0 : value of the first measurement at the reference station, free from the error (unknown),

Δg_j : gravity difference between the reference station ($j=1$) and the j-th station (unknown but $\Delta g_1 = 0$),

a_k : drift rate of the k-th day (unknown),

t_i : time difference between the first measurement of that day (k-th) and i-th measurement (known), and

b_k : drift accumulation before the first

Table 4. Revised table of the scale values for LaCoste & Romberg gravimeter G-196

Counter reading	Value in milligals	Factor for interval	Counter reading	Value in milligals	Factor for interval
000			3200	3402.550	1.04817
100			3300	3507.367	1.04825
200			3400	3612.192	1.04832
300			3500	3717.024	1.04840
400			3600	3821.864	1.04845
500			3700	3926.709	1.04848
600			3800	4031.557	1.04854
700			3900	4136.411	1.04860
800			4000	4241.271	1.04868
900			4100	4346.139	1.04878
1000	1100.000	1.04496	4200	4451.017	1.04883
1100	1204.496	1.04508	4300	4555.900	1.04890
1200	1309.004	1.04522	4400	4660.790	1.04898
1300	1413.526	1.04536	4500		
1400	1518.062	1.04553	4600		
1500	1622.615	1.04571	4700		
1600	1727.186	1.04588	4800		
1700	1831.774	1.04605	4900		
1800	1936.379	1.04623	5000		
1900	2041.002	1.04640	5100		
2000	2145.642	1.04658	5200		
2100	2250.300	1.04676	5300		
2200	2354.976	1.04692	5400		
2300	2459.668	1.04710	5500		
2400	2564.378	1.04725	5600		
2500	2669.103	1.04741	5700		
2600	2773.844	1.04756	5800		
2700	2878.600	1.04768	5900		
2800	2983.368	1.04780	6000		
2900	3088.148	1.04792	6100		
3000	3192.940	1.04801	6200		
3100	3297.741	1.04809	6300		

measurement of the k-th day (unknown but $b_1=0$).

When two or three gravimeters were employed, one series of equations obtained by one gravimeter were arranged in such a way as one series are followed by the next obtained by another gravimeter. The maximum number of the data was 720 and that of the unknown parameters was 208 in the calculation of the measurement between January and March, 1980, which was simultaneously carried out both around Lake Biwa and at the iso-gravity stations. This method depends on the assumption that the gravimeter shows a constant drift rate in the day and shows another rate in the night. It was found to be important to take the difference of drift rate between day and night into consideration, especially when the gravimeters of an old type like G-29 and G-83 are employed, through the experimental researches with LaCoste & Romberg gravimeters (NAKAGA-

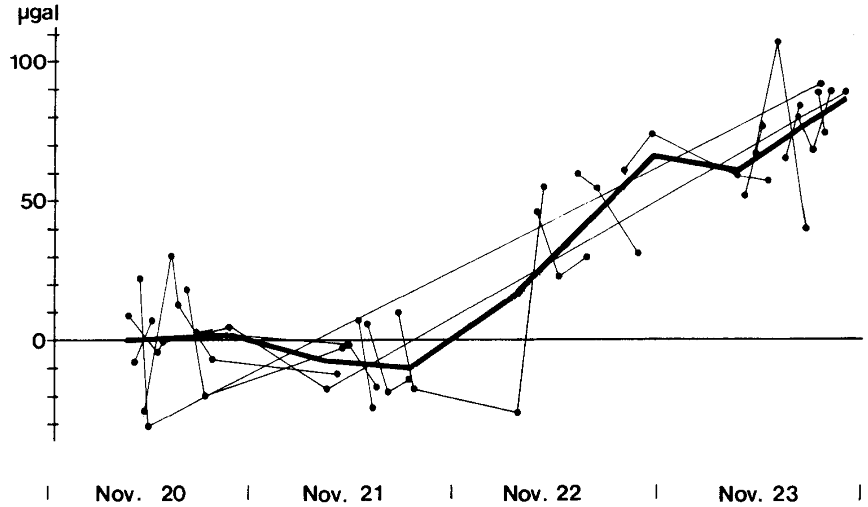

Fig. 4. Calculated drift of gravimeter G-83 for the measurements in 1964. A thick line shows the calculated drift and each thin line shows the change of readings at a station.

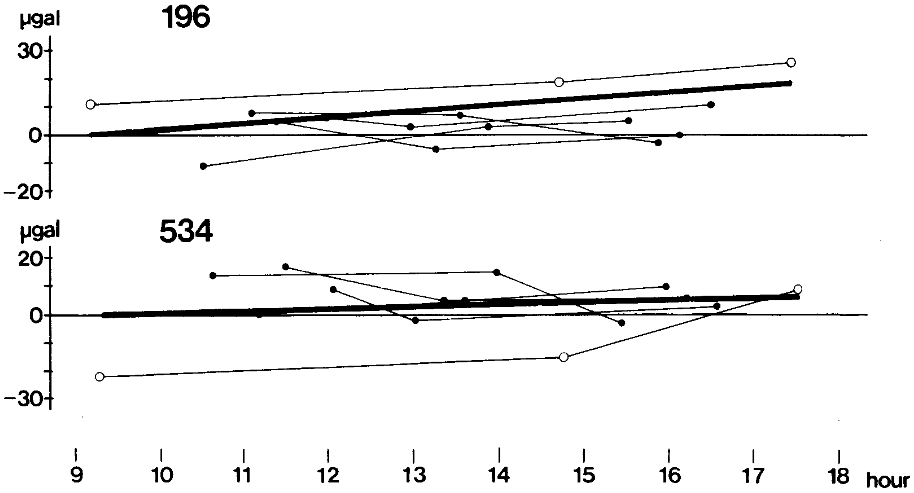

Fig. 5. Calculated drifts of gravimeters G-196 and G-534 for the measurements in 1984. Thick lines show the calculated drifts and each thin line shows the change of readings at a station. Open circles show the readings at the reference station (Kyoto).

WA *et al.*, 1974). The drifts calculated by this method were shown in Figs. 4 and 5 for the measurements in 1964 and 1984, respectively.

The readings had few jumps, when the gravimeter suffered some accidents like mechanical shocks or troubles of connected battery. When the jump was observed, we temporarily treated the day's results as another day's ones in the present calculation.

In gravity measurements at the main stations of iso-gravity, one-way measurements of Kyoto—the Kii Peninsula—Kyoto were carried out both clockwise and counter-clockwise during three or four days on either way. When such method of

Table 5. Results of the gravity measurements in the area around Lake Biwa

Period of measurement	Nov. 1964	Apr. 1967	Sept.–Oct. 1971	Aug.–Sept. 1972	Sept. 1973	Jan.–Apr. 1974	Sept.–Oct. 1975	Dec.–Feb. 1975-1976
Gravimeters employed (L & R)	G-83	G-29	G-196	G-196	G-196	G- 34 G-196 G-210	G-196	G- 34 G-196 G-210
	μgals	μgals	μgals	μgals	μgals	μgals	μgals	μgals
	979	979	979	979	979	979	979	979
Kyoto Univ.	707750	707750	707750	707750	707750	707750	707750	707750
B.M. 241			711986±10	711970± 6	711994± 9		711962± 8	
Keage					708246± 9	708239±13		708232±13
B.M. 215.1					708275± 9	708269±13		708260±13
B.M. 215					707371± 9	707364±13		707352±13
Kyoto Col. Pharm.					707291± 9	707289±13		707277±13
B.M. 213	689487±17	689466±17	689489± 5	689496± 5	689497± 5		689483± 6	
Seta (Karahashi)	689752±14	689722±17	689791± 8	689785± 9	689797± 9		689802± 8	
B.M. 211.1					689269± 9		689273± 8	
B.M. 210.1	686017±24	685984±22	686029± 7	686042± 7	686051± 5	686043± 7	686047± 8	686046± 6
Yasaka Shrine						686285±12		
2nd Order B.M.1330					686861± 9	686850±12		686861± 9
Kusatsu JHS					686605± 9	686604±12		686609± 9
B.M. 209.1					685830± 5	685824± 7	685807± 8	685821± 6
Kusatsu (Dental)	686208±24	686178±22	686239± 8	686240± 9	686255± 9		686233± 8	
B.M. 209					687001± 9	686998±12		686993± 9
B.M. 208.1 (former)	687765±17	687738±22	687845±10	687842± 9				
B.M. 207.1	687450±25	687384±21	687485± 8	687461± 7	687472± 9		687465± 8	
B.M. 206	689384±27	689347±15	689411± 5	689424± 5	689427± 9		689412± 8	
B.M. 205.1	688448±27	688480±21	688514±10	688558± 9			688525± 8	
B.M. 204.1	690271±27	690239±21	690296± 7	690307± 7	690306± 9		690293± 8	
Higashioiso (Pass.)	688759±28	688710±21	688737± 8	688756± 9	688763± 9		688763± 8	
B.M. 203.1					688260± 9		688246± 6	
Gokashō (Zenjū-ji)	681860±29		681885± 7	681881± 7	681898± 9		681883± 8	
B.M. 202.1								
B.M. 200	694899±36	694861±22	694878± 7	694863± 7	694862± 5		694879± 8	
Hikone		703278±23	703322± 8	703332± 9	703337± 9		703327± 8	
B.M. 198.1 (former)	704484±43	704448±23	704565±10	704556± 9	704566± 9		704563± 8	
B.M. 198.1 (new)								
Emperor Meiji					707225± 9	707210±12		707220±10
B.M. 197	707983±42	707934±25	707947± 5	707954± 5	707978± 9	707956± 6	707962± 8	707953± 6
Samegai					707686± 9	707660±12		707683±10
Kashiwabara	698590±35	698612±25	698604± 8	698601± 9	698640± 9		698602± 6	
Sekigahara JHS					707600± 9	707582±12		707575±10
B.M. 193					708347± 9	708322± 6	708325± 6	708321± 6

May–July 1976	Nov.–Dec. 1977	Feb.–Mar. 1978	Sept. 1979	Feb.–Mar. 1980	July 1980	Dec. 1980	Jan.–Mar. 1981	May 1984
G-196	G-196	G-118 G-196 G-210	G-196 G-534	G-196 G-534 D-36	G-196	G-196 G-534	G-196 G-534	G-196 G-534
μgals 979 707750	μgals 979 707750	μgals 979 707750	μgals 979 707750	μgals 979 707750	μgals 979 707750	μgals 979 707750	μgals 979 707750	μgals 979 707750
708217± 7		708216±12		708224±13			708238±11	
708256± 7		708272±12		708263±13			708287±11	
707353± 7		707378±12		707370±13			707372±11	
707274± 7		707289±12		707293±13			707275±11	
689480± 5	689482± 4		689499±15	689514± 7	689491± 7	689502± 6		
689255± 7	689251± 7			689260±10		689265± 8		
686050± 5	686038± 7	686062± 7		686050± 7		686054± 8	686058± 7	
							686294±11	
		686871±13		686873±13			686879±11	
686592± 7		686611±13						
685822± 7	685809± 7	685840± 7		685826± 6		685843± 8	685844± 7	
686986± 7		686999±13		687017±13			686992±11	
687465± 5	687447± 7			687480±10		687482± 8		
689411± 7	689416± 7			689434± 7		689426± 8		
688521± 7				688540±10		688555± 8		
690290± 7	690306± 7			690325±10		690321± 6		
688255± 5	688250± 7			688275±10		688270± 8		
681888± 7	681891± 7							
682124± 7	682119± 7			682134±10		682141± 8		
694863± 7	694866± 7			694873±10		694894± 8		
703325± 7	703346± 4			703372± 7		703371± 8		
704563± 7	704580± 7							
704707± 7	704718± 7			704713±10		704713± 8		
707227± 7		707240±12		707230±13			707227±11	
707954± 5	707969± 7	707965± 7		707962± 6		707969± 6	707971± 7	
707672± 5		707692±12		707690±13			707687±11	
698613± 7	698612± 7			698624± 7		698623± 8		
707584± 7		707588±12		707590±13				
708332± 7		708322± 7		708332± 7			708335± 7	

(continued to the next page)

Table 5. (continued)

Period of measurement	Nov. 1964	Apr. 1967	Sept.–Oct. 1971	Aug.–Sept. 1972	Sept. 1973	Jan.–Apr. 1974	Sept.–Oct. 1975	Dec.–Feb. 1975–1976
	µgals	µgals	µgals	µgals	µgals	µgals	µgals	µgals
	979	979	979	979	979	979	979	979
Sekigahara (Shrine)					708638± 9	708607±12		708620±12
Ibuki	703873±39	703837±26		703871± 9	703886± 9		703871± 8	
B. M. 10495				711347± 9	711389± 5		711372± 8	
Uchibo	715530±39	715532±22	715515± 8	715498± 9	715514± 9		715528± 8	
Kohoku	713714±39	713712±31	713734± 7	713745± 9	713747± 9		713763± 8	
B. M. 10500 (former)		719139±30	719187±10	719170± 9	719202± 9			
Kinomoto		714229±24	714243±10	714235± 9	714241± 9		714261± 8	
B. M. 10506		717563±29	717567±10	717573± 9	717597± 9		717592± 8	
Hannoura	713184±39	713204±29	713220± 5	713231± 5	713240± 9		713234± 6	
Yanokuma	703249±40		703279±10	703275± 9	703271± 9		703276± 8	
Sakaebashi (former)	711123±40	711105±24	711105± 7					
Sakaebashi (new)					710808± 8		710777± 8	
Ōura					711341± 9		711323± 8	
Kaizu (Fukuzen-ji)	708352±40	708371±29	708393± 7	708398± 9	718409± 9	708412± 6	708404± 8	708421±12
Kaizu (Saiei-ji)					707933± 9	707940±12		707949±12
2nd Order B. M. 3851					706036± 9	706014±12		706025± 7
Makino					707771± 5	707784±12		707793±12
Kitashinpo		704401±24	704441±10	704428± 9	704422± 9		704425± 8	
Yū					707566± 9			707553±12
B. M. 1328					707610± 9	707611± 6	707600± 8	707599± 7
B. M. 1326	704406±35	704395±23	704452± 7	704443± 9	704449± 9		704452± 8	
B. M. 1323	698984±37	699005±27	699052± 8	699043± 9	699049± 5		699051± 6	
B. M. 1322		696402±24	696467±10	696472± 8	696840± 9		696461± 8	
B. M. 1320	689624±41	689670±23	689709± 5	689713± 6	689716± 9		689708± 8	
B. M. 1316	692042±28	692037±27	692092± 7	692112± 9	692093± 9		692090± 8	
B. M. 1312	685732±33	685700±23	685760± 8	685762± 9	685761± 9	685760± 7	685741± 8	685758± 7
B. M. 1311					685151± 9	685133±12		685129±13
B. M. 1310					685717± 9	685719±12		685690±13
B. M. 1309	686316±32	686319±21	686368± 7	686376± 9	686389± 9	686382± 7	686362± 8	686367± 7
B. M. 1308					685636± 9	685631±12		685624±13
B. M. 1307	686458±31	686447±27	686537±10	686554± 9	686549± 9	686552±12	686535± 8	686522±13
B. M. 1305	683818±22	683776±21	683857± 8	683866± 9	683840± 9		683842± 8	
Karasaki (Shrine)	681841±23	681868±27	681935± 7	681946± 9	681931± 9			
B. M. 1302				682073± 9	682061± 9		682048± 8	
B. M. B-2								
B. M. B-5								

May–July 1976	Nov.–Dec. 1977	Feb.–Mar. 1978	Sept. 1979	Feb.–Mar. 1980	July 1980	Dec. 1980	Jan.–Mar. 1981	May 1984
μgals	μgals	μgals	μgals	μgals	μgals	μgals	μgals	μgals
979	979	979	979	979	979	979	979	979
708620±7		708617±12		708619±13			708624±11	
703870±7	703892±7			703907±10		703885±8		
711378±7	711380±7			711389±10		711386±8		
715533±7	715517±7			715544±10		715515±8		
713765±7	713752±7			713779±10		713752±8		
714257±8	714250±4			714265±8		714257±6		
717592±8	717582±7			717596±10		717586±8		
713240±8	713241±7			713237±10		713222±8		
703305±8	703291±7			703308±10		703293±8		
710805±5	710806±7			710820±10		710801±8		
711331±7	711348±7			711359±10		711335±8		
708414±7	708410±7	708418±13		708430±10		708416±6	708421±11	
707952±7		707939±13		707981±13			707965±11	
706024±5		706046±7		706056±6			706063±7	
707791±7		707767±13		707786±13			707776±11	
704446±6	704456±7			704464±10		704446±8		
707561±7		707551±12		707507±13				
707606±5	707615±7	707615±7		707618±6	707609±7	707611±8	707613±7	
704471±5	704479±4		704465±18	704471±10	704464±5	704468±8		
699065±7	699070±7		699054±18	699061±10	699050±7	699041±8		
696483±7	696493±7		696482±18	696481±10		696477±8		
689702±4	689735±7		689736±18	689727±10		689734±6		
692093±7	692099±7		692095±18	692101±10	692108±7	692105±8		
685747±7	685762±7	685765±7	685745±18	685758±6	685763±7	685773±8	685765±7	
685127±7		685112±13		685147±13			685134±11	
685685±5		685689±13		685695±13			685704±11	
686368±5	686366±7	686386±7	686370±14	686373±6	686374±7	686381±8	686385±7	686382±6
685613±7		685614±13		685621±13			685641±11	
686513±7	686541±7	686532±13	686553±18	686554±10		686567±8	686568±11	686559±6
683833±7	683862±7		683877±18	683867±10	683873±7	683880±8		
682055±7	682059±7		682055±18	682054±10		682067±8		
681846±7								681888±6
673518±7								673552±6

Table 6. Results of the iso-gravity measurements

Period of measurement	Mar. 1972	Jan.–Apr. 1974	Nov.–Mar. 1975–1976*	Feb.–Mar. 1978	Jan.–Mar. 1980	Jan.–Mar. 1981
Gravimeters employed (L & R)	G- 34 G-196 G-210	G- 34 G-196 G-210	G- 34 G-196 G-210	G-118 G-196 G-210	G-196 G-534 D- 36	G-196 G-534
	μgals	μgals	μgals	μgals	μgals	μgals
	979	979	979	979	979	979
11.0. (Kyoto)	707750	707750	707750	707750	707750	707750
11.1.		708239±13	708232±13	708216±12	708224±13	708238±11
11.2. (215.1)		708269±13	708260±13	708272±12	708263±13	708287±11
11.3. (215)		707364±13	707352±13	707378±12	707370±13	707372±11
11.4.		707289±13	707277±13	707289±12	707293±13	707275±11
11.5.		707186±13	707162±13	707170±12	707177±13	707158±11
11.6. (10716)	708173± 6	708179± 6	708161± 7	708176± 7	708192± 7	708188± 7
12.1. (1420)	707998± 7	708010± 5	708004± 7	708018± 7	708018± 8	708012± 7
12.2.		706807±12	706810±12	706829±12	706816±14	706805±11
12.3.		708329±12	708327±12	708346±12	708335±14	708311±11
12.4.		707204±12	707197±12	707219±12	707209±14	707187±11
12.5.		707492±12	707479±12	707493±12	707491±14	707479±11
12.6. (1421)	707163± 7	707164± 5	707148± 7	707172± 7	707181± 8	707173± 7
31.1.		687202± 6	687180± 6	687201± 7		
31.2. (Iga H. S.)		686686±12	686685± 9	686710±12	686727± 7	686699± 7
31.3.		686132±12	686121± 9	686143±12	686158±14	686121±11
31.4.		686172±12	686171±12	686190±12	686186±14	686183±11
31.5.		685110±12	685100± 9	685127±12	685133±14	686113±11
31.6. (1426)		681419± 6	681402± 6	681425± 7	681422± 7	681419± 7
13.1. (1451)	705930± 7	705917± 6			706006± 7	705990± 7
13.2. (Koyama)		706356±11	706359± 7	706395± 7	706406± 7	706368±11
13.3. (023-014)		707407±11	707390±12	707435±12		
13.4.		706696±11	706686±12	706724±12	706725±13	706706±11
13.5.		707432±11	707447±12	707471±12	707471±13	706438±11
13.6. (1450)	708080± 7	708076± 4	708066± 7	708088± 7	708090± 7	708084± 7
14.1. (4740)	707021± 7	707004± 4	706999± 5	707037± 6	707044± 6	707019± 6
14.2.		706912±11	706890±12	706934±11	706926±13	706904±10
14.3. (042-331)		707251±11	707226±12	707241±11	707249±13	707221±10
14.4. (042-332)		708689±11	708670±12	708695±11	708712±13	708683±10
14.5.		707478±11	707462±12	707496±11	707479±13	707488±10
14.6. (1515)	708049± 7	708034± 5	708021± 5	708055± 6	708060± 6	708049± 6
14.7.		706603±11	706571±12	706604±11	706597±13	706606±10

(continued to the next page)

Table 6. (continued)

Period of measurement	Mar. 1972	Jan.–Apr. 1974	Nov.–Mar. 1975–1976*	Feb.–Mar. 1978	Jan.–Mar. 1980	Jan.–Mar. 1981
	μgals	μgals	μgals	μgals	μgals	μgals
	979	979	979	979	979	979
32.1. (1527)		686848± 6	686840± 6	686868± 6	686875± 7	686860±10
32.2.		687043±11	687040±12	687072±12	687075±12	687051±10
32.3.		686512±11	686505±12	686530±12	686547±12	686521± 6
32.4.		686835±11	686813±12	686856±12	686879±12	686838±10
32.5.		686287±11	686282±10	686303±12	686326±12	686302±10
32.6. (1528)		684656± 6	684651± 6	684679± 6	684683± 7	684660± 6
33.1. (4752)		686139± 6	686123± 6	686166± 6	686179± 7	686144± 6
33.2.		686859±11	686832±12	686883±11	686893±12	686864±10
33.3. (042-308)		685770±11	685737±12	685790±11	685804±12	685776±10
33.4. (042-307)		685608±11	685599±12	685635±11	685711±12	685686±10
33.5.		685640±11	685599±10	685647±11	685661±12	685641±10
33.6. (4753)		684726± 6	684699± 6	684737± 6	684752± 7	684713± 6
15.1. (4807)	708796± 8	708782± 6	708786± 5	708799± 5	708814± 6	708785± 5
15.2.		707863±11	707860±11	707893± 5	707899±12	707895±10
15.3.		707043±11	707040±11			
15.4. (Ninomaru)		708307±11	708307±11	708320± 5	708342± 6	708314± 5
15.5.		707395±11	707406±11	707441± 9	707439±12	707445±10
15.6. (4967)	708282± 8	708281± 6	708280± 5			
16.1. (9209)	710791± 7	710769± 6	710770± 6	710779± 6	710809± 7	710792± 6
16.2.		708185±11	708203±11	708207±11	708221±13	708228±10
16.3. (042-144)		707637±11	707631±11	707649±11	707677±13	707667±10
16.4.		708049±11	708062±11	708086±11	708094±13	708084±10
16.5.		707489±11	707490±11	707500±11	707507±13	707511±10
16.6. (9208)	707610± 7	707589± 6	707590± 6	707608± 6	707624± 7	707613± 6
34.1. (042-121)		686303± 5	686288± 6	686315± 6	686329± 7	686301± 6
34.2.		686808±11	686811±11	686838±11	686853±13	686793±10
34.3.		686544±11	686550±11	686563±11	686597±13	686541±10
34.4.		686149±11	686140±11	686155±11	686183±13	686136±10
34.5.		686186±11	686179±11	686205±11	686230±13	686177±10
34.6. (9191-8)		686544± 5	684522± 6	684549± 6	684567± 7	684527± 6
35.1.		686950±12	686929±12	686960±12	686966±13	686938±10
35.2.		686670±12	686649±12	686666±12	686671±13	686648±10
35.3. (4887)		687018±12	687007±12	687020±12	687023±13	686992±10
35.4.		686255±12	686231±12	686256±12	686257±13	686231±10
35.5. (Kainan)		685639± 6	685633± 6	685644± 6	685649± 6	685629± 6
35.6. (4881)		685868±12	685841±12	685867±12	685859±13	685839±10
35.7. (4882)		687056± 6	687040± 6	687068± 6	687071± 6	687044± 6

(continued to the next page)

Table 6. (continued)

Period of measurement	Mar. 1972	Jan.-Apr. 1974	Nov.-Mar. 1975–1976*	Feb. Mar. 1978	Jan. Mar. 1980	Jan. Mar. 1981
	μgals	μgals	μgals	μgals	μgals	μgals
	979	979	979	979	979	979
36.1. (1567)		686874±12	686835±12	686860±12	686859±14	686814±12
36.2. (024-092)		686206±12				
36.3. (1566)		685506± 5	685485± 7	685507± 7	685516± 8	685476± 9
36.4. (1559)		686052±12	686035±12	686066±12	686040±14	686028±12
36.5.		686105±12	686100±12			
36.6.		686488±12	686472±12	686487±12	686488±14	686462±12
36.7. (J1562)		686974± 5	686964± 7	686979± 7	686998± 8	686963± 9
17.1.		707741±12	707736±12	707742±12	707758±14	707726±11
17.2. (J246)	707788± 9	707786± 8				
17.3. (245)	707450± 9	707427±12	707424± 7	707431± 7	707465± 8	707430± 7
17.4.		707942±12	707937±12	707953±12	707961±14	707928±11
17.5.		707433±12	707434±12	707439±12	707462±14	707436±11
17.6.		708300±12	708296±12	708291±12	708306±14	708275±11
17.7. (1379)		707838± 8	707831± 7	707829± 7	707864± 8	707831± 7
37.1. (210.1)		686043± 7	686046± 6	686062± 7	686050± 7	686058± 7
37.2.		686285±12				686294±11
37.3.		686850±12	686861± 9	686871±13	686873±13	686879±11
37.4.		686604±12	686609± 9	686611±13		
37.5. (209.1)		685824± 7	685821± 6	685840± 7	685826± 6	685844± 7
37.6. (209)		686998±12	686993± 9	686999±13	687017±13	686992±11
18.1. (197)		707956± 6	707953± 6	707965± 7	707962± 6	707971± 7
18.2.		707210±12	707220±10	707240±12	707230±13	707227±11
18.3.		707660±12	707683±10	707692±12	707690±13	707687±11
18.4.		707582±12	707575±10	707588±12	707590±13	
18.5.		708607±12	708620±12	708617±12	708619±13	708624±11
18.6. (193)		708322± 6	708321± 6	708322± 7	708332± 7	708335± 7
19.1. (Ⅱ3851)		706014±12	706025± 7	706046± 7	706056± 6	706063± 7
19.2.		707940±12	707949±12	707939±13	707981±13	707965±11
19.3.		708412± 6	708421±12	708418±13	708430±10	708421±11
19.4.		707784±12	707793±12	707767±13	707786±13	707776±11
19.5.			707553±12	707551±12	707507±13	
19.6. (1328)		707611± 6	707599± 7	707615± 7	707618± 6	707613± 7
38.1. (1312)		685760± 7	685758± 7	685765± 7	685758± 6	685765± 7
38.2. (1311)		685133±12	685129±13	685112±13	685147±13	685134±11
38.3. (1310)		685719±12	685690±13	685689±13	685695±13	685704±11
38.4. (1309)		686382± 7	686367± 7	686386± 7	686373± 6	686385± 7
38.5. (1308)		685631±12	685624±13	685614±13	685621±13	685641±11
38.6. (1307)		686552±12	686522±13	686532±13	686554±10	686568±11

(continued to the next page)

Table 6. (continued)

Period of measurement	Mar. 1972	Jan. Apr. 1974	Nov. Mar. 1975−1976*	Feb. Mar. 1978	Jan. Mar. 1980	Jan. Mar. 1981
		μgals	μgals	μgals	μgals	μgals
		979	979	979	979	979
20.1. (1288)		709501± 8	709493± 8	709501± 8	709508± 9	709498± 9
20.2.		706757±12	706756±13	706762±13	706785±14	706756±12
20.3.		707131±12	707111±13	707134±13	707154±14	707112±12
20.4.		706965±12	706961±13	706975±13	706986±14	706966±12
20.5.		708394±12	708389±13	708387±13	708401±14	708388±12
20.6. (1287)		709905± 8	709893± 8	709893± 8	709894± 9	709892± 9
21.1. (1474)		709653± 8	709677± 8	709698± 8	709724± 9	709716± 9
21.2.		708396±12	708430±13	708496±13		
21.3.		708302±12	708341±13	708402±13	708426±14	708424±12
21.4.		707389±12	707418±13	707459±13	707502±14	707488±12
21.5.			707720±13	707748±13	707781±14	707768±12
21.6. (1473)		706777± 8	706811± 8	706847± 8	706876± 9	706877± 9

* Local gravity measurements by means of a single gravimeter were carried out in 1976.

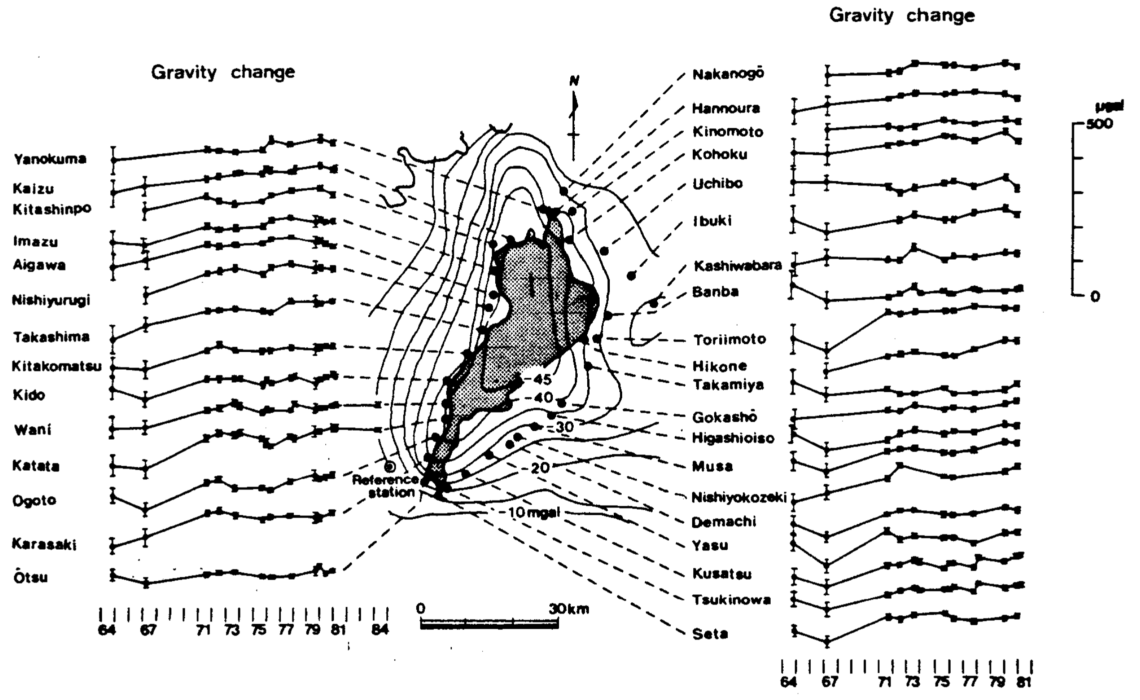

Fig. 6. Apparent secular change of gravity in the area around Lake Biwa under the assumption that the gravity value at the reference station has not changed during the whole period concerned.

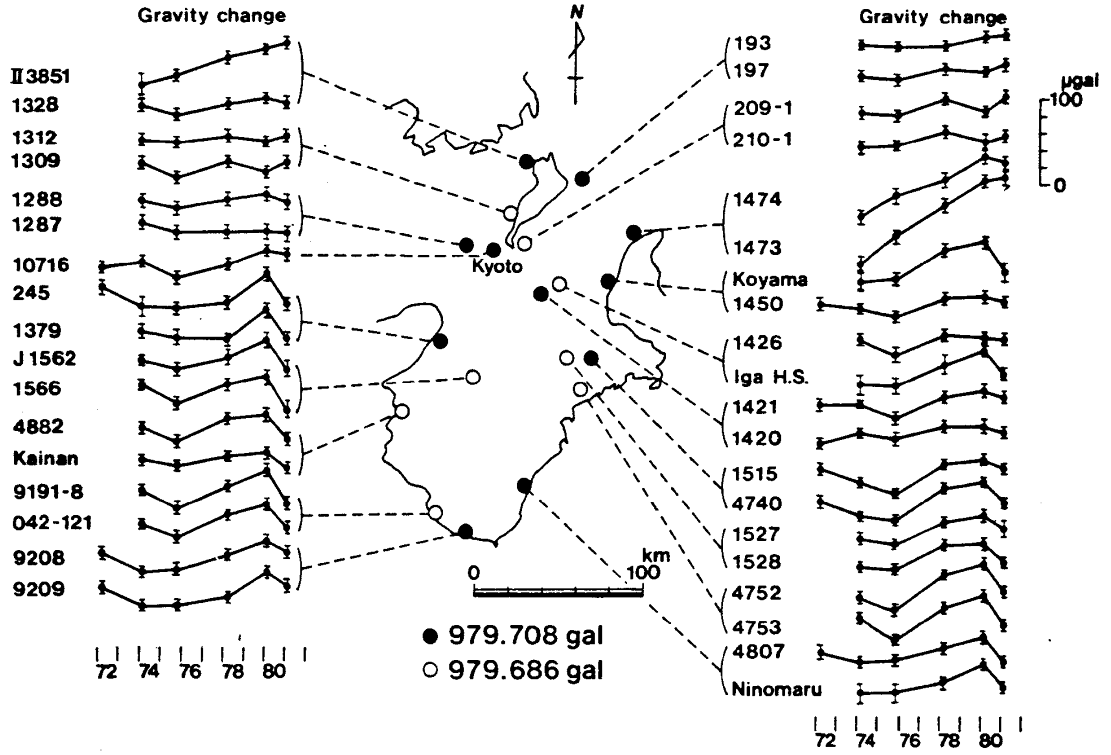

Fig. 7. Apparent secular change of gravity at the iso-gravity stations in Kinki District under the assumption that the gravity value at the reference station (Kyoto) has not changed during the whole period concerned.

measurement was adopted, it was difficult to obtain stable results by the method of calculation mentioned above, because there were no direct connections from the reference station (Kyoto) from morning to night except the first and last days. We have therefore calculated under the assumption that the drift rate was constant through the whole course of three or four days.

Results thus obtained are shown in Table 5 for the area around Lake Biwa and in Table 6 for the iso-gravity stations.

Apparent secular changes of gravity were calculated from these data under the assumption that the gravity value at the Gravity Station of Geophysical Institute of Kyoto University has been constant during the whole period concerned. They are shown in Fig. 6 for the area around Lake Biwa and in Fig. 7 for the iso-gravity stations.

5. Reliability of the Results

Before discussing the secular change of gravity, the following two problems must be investigated;

a) accuracy of the results obtained, and

b) propriety of the assumption that the gravity value at the Gravity Station of Geophysical Institute of Kyoto University has been constant.

5−1. Accuracy of the results obtained

Almost all measurements in the area around Lake Biwa were carried out with only one La Coste & Romberg gravimeter. Therefore, it is difficult to get the accuracy of the results around Lake Biwa exactly. As the calculation for getting the gravity differences between one station and the reference station was made by using the least squares method, the standard deviation of each result was also obtained and it is also shown in Tables 5 and 6. It includes many kinds of errors which can be regarded as random errors such as errors due to meteorological conditions, and it can be a criterion of the accuracy of the gravity difference obtained. However, it was obtained from the calculation process and we cannot simply think that it means the accuracy itself, because it does not include the systematic error; for example, the error produced by the difference of scale value, the periodic error caused by the eccentricities of the gears in gravimeter and the error caused by uncertainty of the adequacy to make the assumption that the drift rate is constant to time in a day. Each error source is examined here.

a) Effect due to unclamping

Instrumental drift following unclamping of the LaCoste & Romberg gravimeter G-275 was investigated by HIPKIN (1978). According to his result, an exponential drift was observed after unclamping, and it amounted to almost 40 μgals in 2 hours. He recommends that equilibrium value after rapid drift is more reliable than the value before rapid drift. Similar drift was observed in the case of the LaCoste & Romberg gravimeter G-493, but its amount was much less in the case of the G-196, as shown in Fig. 8. Moreover, it was clarified that such drift depended on ambient temperature according to our investigations (NAKAGAWA *et al.*, 1974); for example, reading of the gravimeter increased when

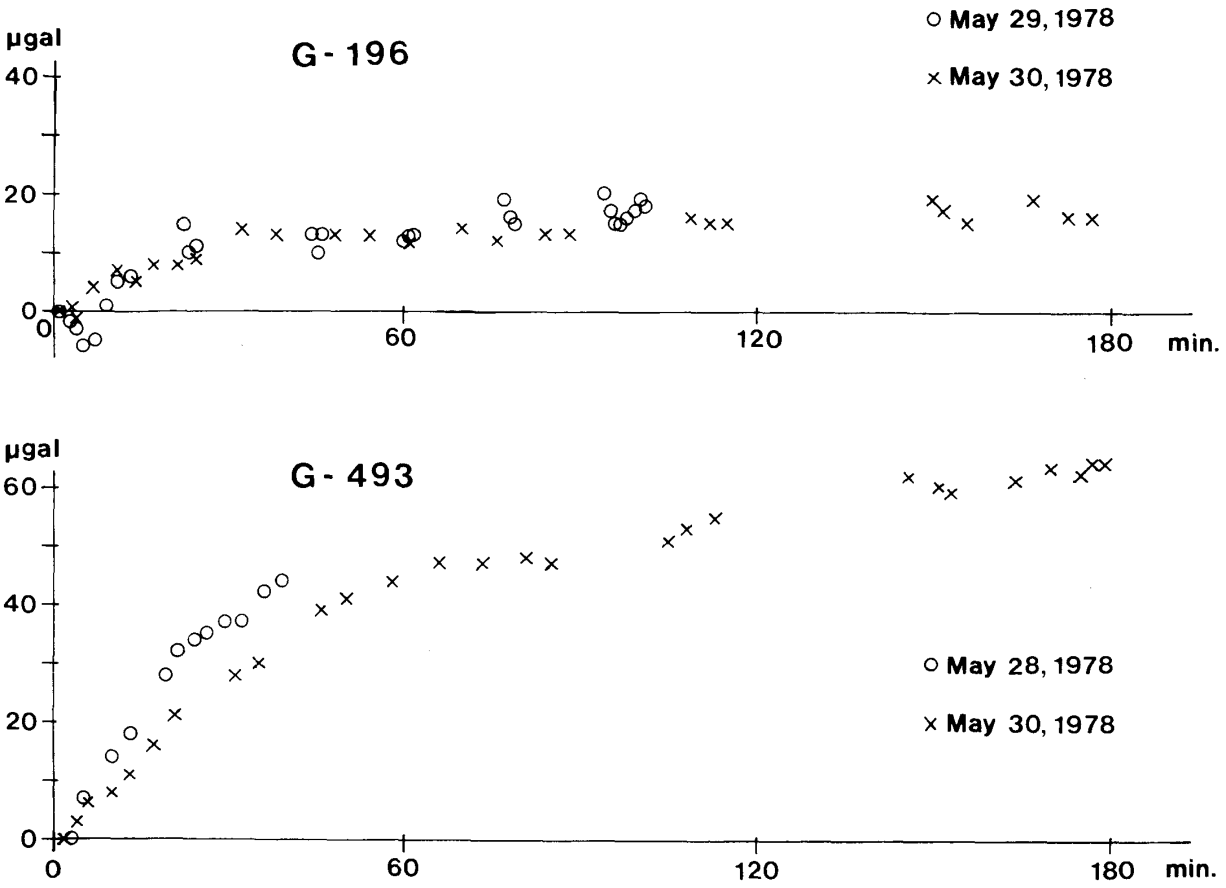

Fig. 8. Examples of instrumental drift following the unclamping of the measure system for LaCoste & Romberg gravimeters.

the ambient temperature decreased, and there were some phase lags between change of the ambient temperature and response of the gravimeter's reading, in the case of the gravimeter G-31. From these investigations, it follows that the gravity measurement should be carried out within ten minutes just after the gravimeter was taken out of its carrying case and the clamp of the measure system was released. The value was read three times just after the clamp was released. When the difference between the maximum value and the minimum one of the three values was more than 0.01 gravimeter's counter unit (about 10 μgals), the value was read one more time. We recorded the times when the gravimeter was taken out of its carying case and when the clamp was released at every measurement in order to check the time duration from when it was taken out of the case to when the last value was read, and it was usually less than five minutes.

The rapid drift which was mentioned in this section, may be caused by heat of the light for the levels and optical system of the gravimeter (TSUKAMOTO, 1983).

b) Effect due to turning the measure dial of gravimeter

It was pointed out that the effect by turning the measure dial of the gravimeter cannot be ignored when the gravity value differs much from that at the last station and therefore the measure dial must be turned much to find the gravimeter's reading (SETO, 1976). Though this effect was not so severe except the gravimeter G-29 through our examinations (NAKAGAWA *et al.*, 1973), it is probable that it influences considerably when the gravity difference from the last station is large. This effect, however, reduces as time goes by from turning it, and the measure dial was therefore adjusted to the prospected value as much as possible just after finishing the last measurement.

c) Meteorological effects

The effect by change of atmospheric pressure to the reading has been investigated with some LaCoste & Romberg gravimeters (KIVINIEMI, 1974; NAKAI, 1975). However, the investigations of this effect with the LaCoste & Romberg gravimeters which were employed in the present measurements have not been enough, and the correction value for atmospheric pressure is not obtained yet. The results of examinations by other LaCoste & Romberg gravimeters made by KIVINIEMI and NAKAI imply that the effect by air buoyancy is so small that almost all of the effects by atmospheric pressure are due to attraction of air mass. Taking the air attraction into consideration, the new gravity difference is only 1～2 μgals more or less than the former gravity difference.

As described in **a)**, there are some phase lags between change of ambient temperature and response of the gravimeter's reading. When the gravity measurement is carried out within ten minutes, it can be thought that the effect due to the ambient temperature is negligible, because it is always similar temperature inside the carrying case.

d) Effect due to the ground noises

Through laboratory experiments by the La Coste & Romberg gravimeter G-365 which was put on a vibrating platform, HANADA (1977) found that the vibration center of light beam of the gravimeter shifted and that the direction and amount of zero-point shift varied with the period of vibration. Fortunately ground noises are so small at the most measured stations of the present investigations that the gravimeter beam scarcely vibrates in the measurement. It can be thought that the effect due to the ground noises is negligible in the present measurements.

e) Effect due to the earth tides

The correction of the earth tides was made mainly by using a formula by LONGMAN (1959), but newer astronomical constants were also taken into consideration, and the formula which was not expanded by Legendre's polynomials was

Table 7. δ-factors observed at the reference station by means of the Askania gravimeter (Gs-15) No. 217 (after NAKAGAWA *et al.*, 1975)

Constituents	δ-factor	Phase lag (degree)
M_2	1.195 − 1.199	2.92 − 2.94
S_2	1.155 − 1.160	4.40 − 4.47
K_1	1.195 − 1.217	0.40 − 0.62
O_1	1.202 − 1.217	0.70 − 0.81

Two values given for δ-factor and phase lag are due to the method of analysis.

used. NAKAI (1979) made a more precise program for computing the tidal forces. The maximum difference between the present results and the NAKAI's is about 2 μgals.

The tidal factor of gravity was assumed to be 1.2 and the phase lag was assumed to be 0°.

Tidal observations of gravity were carried out by Askania gravimeters at Geophysical Institute of Kyoto University which is the reference station of the present investigations (NAKAGAWA, 1962b; NAKAGAWA *et al.*, 1975). The data obtained through them were analyzed in detail, and the newer results of the four main constituents are shown in Table 7. The results shown in Table 7 involve the phase lags due to the gravimeter's and filter's responses. According to an investigation on the same system as this by VOLKOV and ZASIMOV (1973), these phase lags were estimated to be 1°.85, 1°.92, 0°.96 and 0°.89 for M_2, S_2, K_1 and O_1 constituents, respectively. The real phase lags are therefore estimated to be 1°.07～1°.09, 2°.48～2°.55, −0°.56～−0°.34 and −0°.19～−0°.08 for M_2, S_2, K_1 and O_1 constituents, respectively; they are almost negligible except S_2 constituent.

Every station has its own value of tidal factor of gravity. Gravimetric tidal observations were carried out at Chikubu Island in Lake Biwa and at Shionomisaki in the Kii Peninsula by a Worden gravimeter (ICHINOHE *et al.*, 1956), and at Shionomisaki also by an Askania gravimeter Gs-11 (NAKAGAWA, 1962a). Their results are shown in Table 8. The tidal factors of gravity obtained by the Askania gravimeter Gs-11 are smaller than those by other gravimeter at Kyoto and Shionomisaki, but the difference among the stations is not clear.

Judging from these data, the error caused by the uncertainty of tidal factor and phase lag and by approximate calculation of theoretical tidal forces is estimated to be less than 5 μgals.

f) Effect due to instrumental height

The height difference between the top plate of a gravimeter and the top of a bench mark (instrumental height) was not measured before 1967. The correction of instrumental height was therefore made by reading the height from the photographs or the sketches of measurement. Then, the accuracy of the instrumental height is about ±1 cm, which corresponds to about ±3 μgals of gravity. Since 1970, the instrumental height has been directly measured at every measurement, so that the error due to the uncertainty of the instrumental height does not matter.

The value of free-air gradient of gravity is not same at every station, but the present calculation is based on its normal value (3.086 μgals/cm). The change, however, of the instrumental height at the same station is so small that the error due to the difference between the two values of normal free-air gradient and real one is negligible in fact.

The error due to the correction of the instrumental height is thought to be less than 5 μgals before 1967 and less than 1 μgals after 1971.

g) Effect due to the drift of gravimeter's readings

As described in the Chapter 4, the drift of a gravimeter was corrected under the assumption that the drift rate was constant within a day. But it has recently been proposed that not only a linear term but a quadratic term to the time; that is, a parabolic drift should be taken into account,

Table 8. δ-factors observed in Kinki District by means of a Worden gravimeter and an Askania gravimeter for M_2 constituent

Location	δ-factor	Phase lag (degree)	Period of observation	Gravimeter employed	Reference
Kyoto	1.18	1.96	June–July 1954	Wordon 217	ICHINOHE *et al.*, 1956
Chikubu Island	1.21	1.20	Sept.–Oct. 1955	Worden 217	ICHINOHE *et al.*, 1956
Shionomisaki	1.23	2.42	Nov.–Dec. 1955	Worden 217	ICHINOHE *et al.*, 1956
Kyoto	1.143	1.12	June–July 1957	Askania 111 (Gs-11)	NAKAGAWA, 1962a
Shionomisaki	1.141	0.23	Jan.–Feb. 1958	Askania 111 (Gs-11)	NAKAGAWA, 1962a
Kyoto	1.115	1.24	June–July 1958	Askania 111 (Gs–11)	NAKAGAWA, 1962a
Kyoto	1.139	1.91	July 1957– May 1959	Askania 111 (Gs-11)	NAKAGAWA, 1962b
Kyoto	1.138	2.40	Aug. 1959– Aug. 1960	Askania 111 (Gs-11)	NAKAGAWA, 1962b

and this method is practically used in some gravimetric analyses (*e. g.*, KIVINIEMI, 1974).

The present measurement is only a set of going and returning measurements in a day except in 1984. This measurement is not suitable to apply an analysis under the assumption that the real drift is the parabolic one. The test calculation of applying the parabolic drift for the present measurement showed that the standard deviation of quadratic coefficient of the drift was two or three times greater than the coefficient itself or more, and that the standard deviation of the gravity differences was also two or three times greater than that by the analysis based on a linear drift. Judging from these facts, it is unreasonable to apply the analysis based on the parabolic drift in the present case.

In 1984, going, returning and one more going measurements were carried out at five stations near Lake Biwa by using two gravimeters in order to check the efficiency of analyses based on parabolic drifts. The drift rate of each gravimeter's readings for that day, however, was almost constant as shown in Fig. 5, and the standard deviations of the gravity differences among the five stations based on parabolic drifts were greater than those based on linear drifts. However, it is more probable that the values of the gravimeters do not sometimes have linear drifts but have parabolic or more complicated ones.

Comparing the results obtained through an analysis assuming the linear drift with those obtained through another one assuming the parabolic drift, the error due to the non-linear drift is thought to be less than 5 μgals.

h) Effect due to calibration curve

As described in the Chapter 4, correction factors for scale values of gravimeters were taken into consideration in the present investigations. These factors are referred to the IGSN 71 and JGSN 75. They are 1.000633 in the vicinity of the gravity value at Geophysical Institute of Kyoto University for the G-196 and 1.000473 for the G-210. The other international gravimetric connections were carried out two times by using serveral LaCoste & Romberg gravimeters which include the G-196 and G-210, along the Circum-Pacific zone. Their purpose was to make a precise calibration of scale values of the gravimeters employed and to offer useful data for the sake of the reform of the IGSN 71 (NAKAGAWA *et al.*, 1981; 1982b). The correction factors were determined by the results of the two gravimetric connections to be 1.000492 and 1.000582 for the G-196, and 1.000522 and 1.000515 for the G-210.

The difference between the factors in the present investigations and those newly determined was 0.00005~0.00015 for the two gravimeters. The maximum gravity difference from the reference station is less than 30 mgals and therefore the error caused by the uncertainty of scale values will be less than 4 μgals for both the G-196 and G-210. As for the other gravimeters, we do not have enough data to show such an error, but it may be the same order as for the G-196 and G-210.

Such bench marks were chosen, as gravity stations, as gravity difference from the reference station is smaller than 1 mgal or as gravity value is within the range of 979.686 gals ±1 mgal. In the gravity measurements at such stations, the error due to uncertainty of scale value is probably less than 0.1 μgal and it is practically negligible.

In addition, some periodic errors which were produced by both the eccentricity of a dial screw and gears of the gravimeter must be taken into account. The periods of the error depend on the ratios of gears. Possible periods are 1.00, 3.94, 7.88, 35.47, 70.94, 603 and 1206 counter units of the gravimeter (KIVINIEMI, 1974; BECKER, 1981; KANNGIESER, 1982). One counter unit corresponds to about 1.05 mgals. As can easily be seen from Fig. 5, the readings at the reference station were always larger than the calculated drift for G-196 and they were opposite for G-534 in 1984 except the last reading. It is much probable that they were caused by the periodic errors of the gravimeters.

When only the time change of gravity is discussed, and further, when the gravimeter readings are carried out at the same dial position of the same gravimeter at each measured station, the periodic errors of the gravimeter can be ignored. The gravimeter G-196 has been used in all gravity measurements since 1971, but there has been the drift amounting to about 1 mgal/year. The position of reading has therefore shifted gradually one measurement after another. Although the amplitudes of these periodic errors of the present gravimeters are not yet known, the errors due to these effects may be ±5 ~10 μgals or a little more, judged from Fig. 5 and the experimental results by KIVINIEMI (1974) and KANNGIESER (1982).

The errors due to effects explained in **a)~e)** are already included as random errors within the standard deviations obtained by the least squares method. When plural gravimeters were used in the measurement, the errors due to effects explained in **f)~h)** are also included within the standard deviations calculated by the least squares method. When a single gravimeter was used, these errors are not included in the standard deviations given in Tables 5 and 6. Real deviations, therefore, must be greater than those in both of the two tables by several μgals at the station whose gravity difference from Kyoto University is small, or about ten μgals at the station whose gravity difference is large.

5−2. Gravity value at the reference station

The Gravity Station of Geophysical Institute of Kyoto University was used as reference station and it is firmly constructed on a stable bedrock. However, it cannot be said that the gravity value at the reference station has been constant only because of the fact. We carried out a continuous observation of gravity during the period of more than 3 years by an Askania gravimeter at the reference station (NAKAGAWA *et al.*, 1975). It

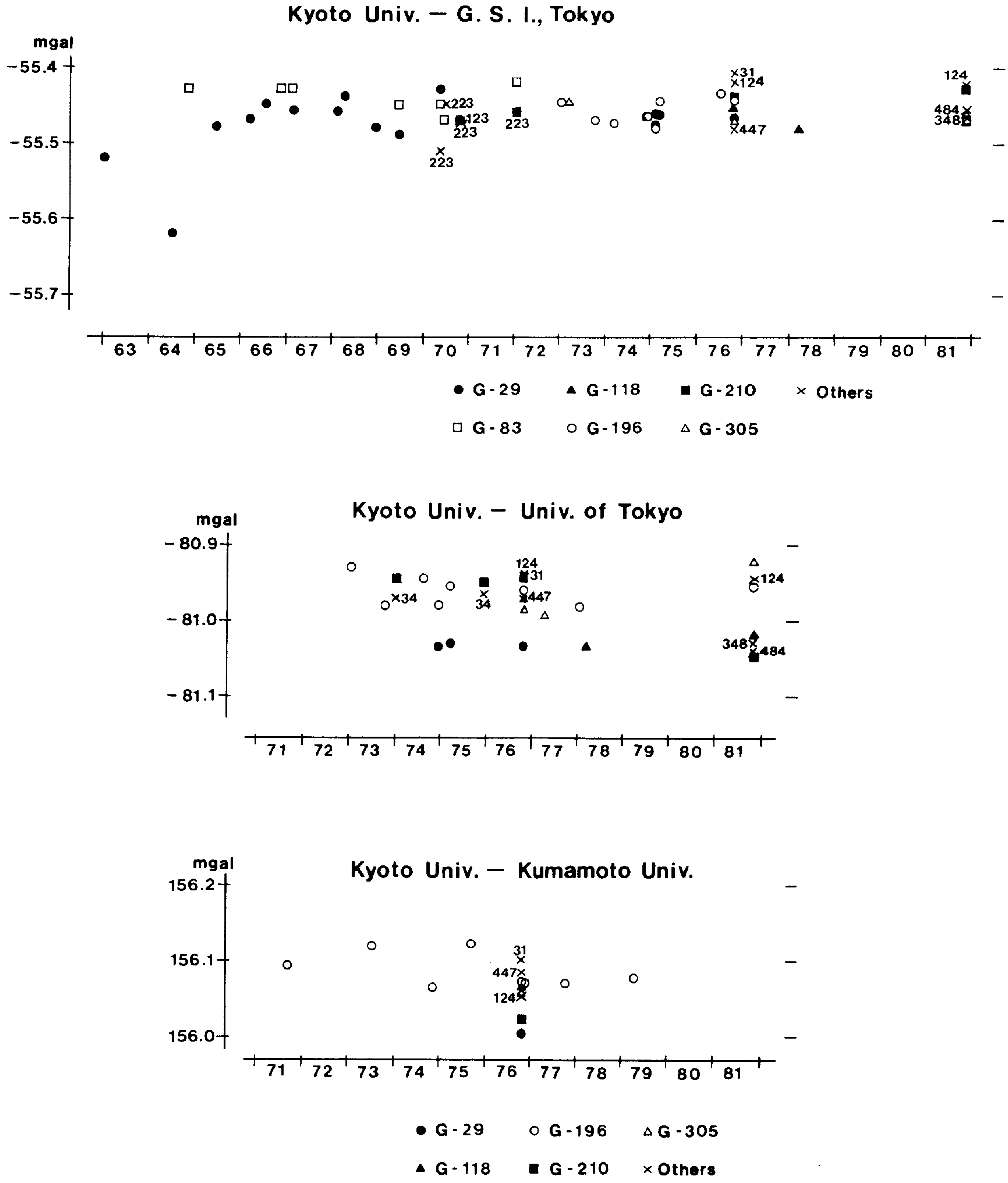

Fig. 9. Results of gravity connections performed by the former Geographical Survey Institute in Tokyo–Kyoto University, the University of Tokyo–Kyoto University and Kumamoto University–Kyoto University.

gives splendid data for the investigation on tidal variation of gravity, but the secular change of gravity at the station cannot be separated from the gravimeter's drift. Therefore, in order to examine whether the gravity value at a station changes or not, only the following three methods may be available;

a) to repeat absolute measurements of gravity,
b) to repeat gravity connections with a station where absolute measurements of gravity are repeatedly carried out, and
c) to repeat gravity connections with stations which are far enough from the station to make sure that the similar gravity changes do not occur simultaneously.

Unfortunately, precise absolute measurement of gravity started only some years ago in Japan (*e. g.*, MURATA, 1978; OOE *et al.*, 1982; HANADA *et al.*, 1982), and the results are not sufficient enough to help to detect secular change of gravity. However, the gravity connection between the Fundamental Gravity Station at the former building of the Geographical Survey Institute in Tokyo and that of Geophysical Institute of Kyoto University has been often carried out; their rectilinear distance is about 350 km. The results of the connections are shown in Fig. 9. These values are only those obtained with LaCoste & Romberg gravimeters. They were obtained by calculating with revised scale values for the G-29, G-118 and G-196 (NAKAGAWA *et al.*, 1978) or correction factors for other gravimeters (NAKAGAWA *et al.*, 1977a). These measurements are not much accurate. However, as can be seen from Fig. 9, it can be more properly to say that the gravity difference between both the stations has not changed since 1964 except for a few exceptional values, rather than to say that the gravity difference has changed.

The gravity connections with other gravity stations far from Kyoto had been seldom carried out, but some connections have been carried out since 1971. Fig. 9 also shows the results of the University of Tokyo ~ Kyoto University and Kumamoto University ~ Kyoto University connections. Even from these results, we cannot tell yet if the gravity value at the reference station has changed or not.

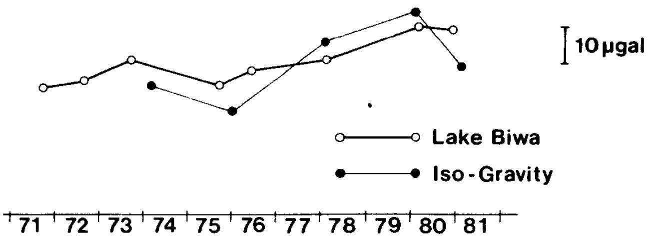

Fig. 10. Changes of the mean values of gravity differences from the reference station at 33 stations in the area around Lake Biwa and those at 36 stations of the iso-gravity measurements.

We can, therefore, use only the data obtained by the relative measurements themselves in Kinki District shown in Tables 5 and 6, in the attempt to prove the assumption that the gravity value at the reference station has been constant. First, we calculated the mean values of gravity differences from the reference station at 33 stations in the area around Lake Biwa; at these stations eight measurements were carried out during the period between 1971 and 1980. Second, we calculated the mean values of gravity difference from the reference station at 36 stations in Kinki District, where five measurements were carried out as iso-gravity measurements by means of two or three gravimeters. We excluded the values at B. M. 1473 and B. M. 1474 because the gravity values had increased due to the severe ground subsidence there. These results are shown in Fig. 10. Two results obtained by independent gravity measurements show the similar tendency. Consistent results were obtained by analyzing these data with the principal component analysis (FUKUDA, 1982). These facts may show that the

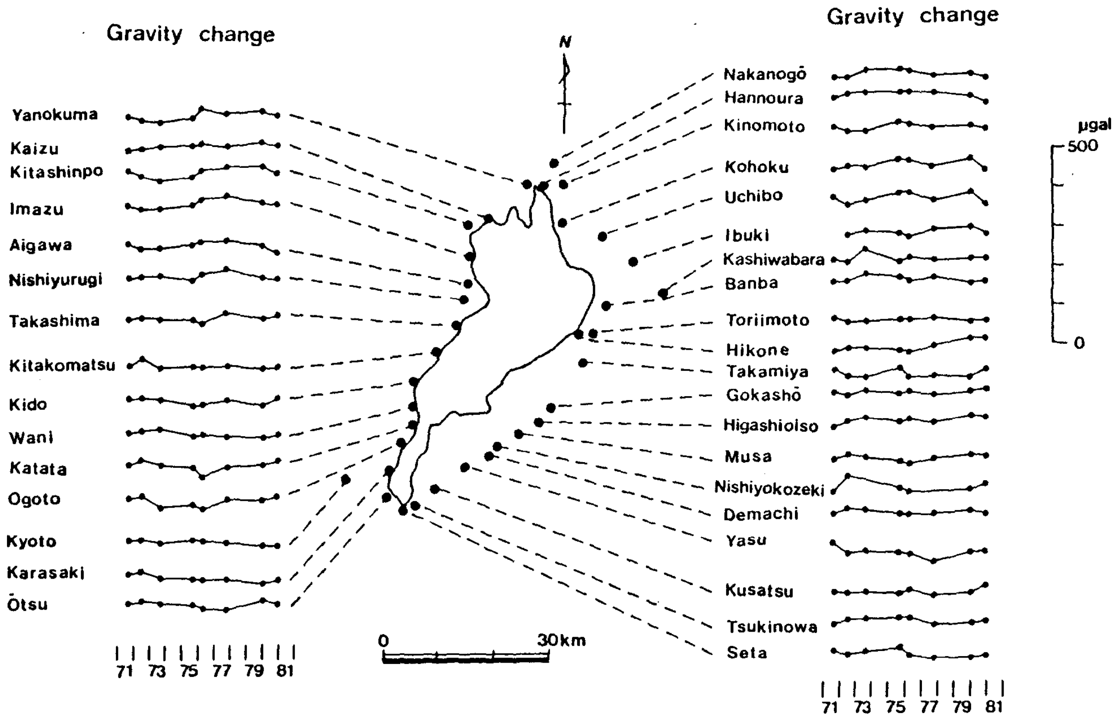

Fig. 11. Residual changes of gravity after eliminating the common change in the area around Lake Biwa.

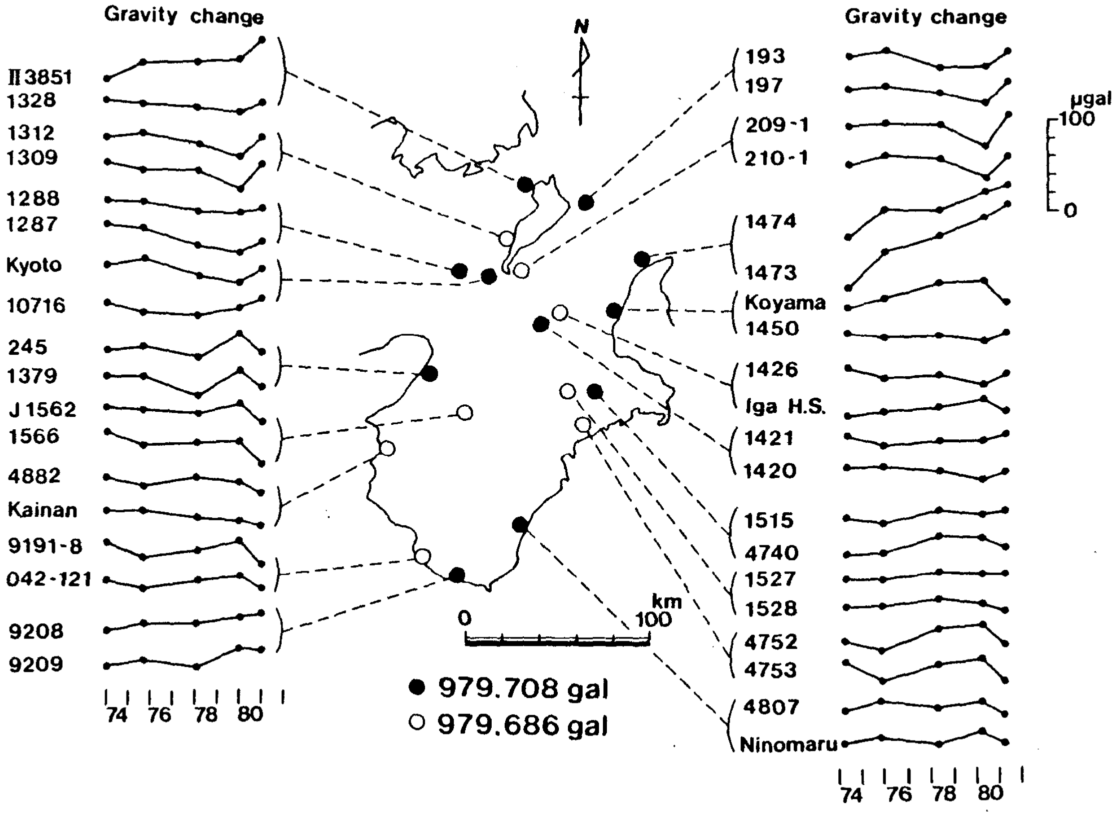

Fig. 12. Residual changes of gravity after eliminating the common change at the iso-gravity stations.

gravity values have changed in the same way in the whole area of Kinki District, but it may be interpretable that the gravity value at the reference station has changed in a contrary way to that given in Fig. 10. As the change of gravity value at the reference station amounts to only about 10 or 20 μgals, it is hidden in the error of Tokyo ~ Kyoto and Kumamoto ~ Kyoto connections, if it exists.

We did not have an opportunity, unfortunately, to carry out precise absolute measurements of gravity in the area concerned, but we have only measured gravity differences. Therefore, we cannot discuss the common change of gravity in the whole area of Kinki District, if it exists, but we may only discuss the residual change without the common change.

In the next two Chapters, we will discuss the residual change of gravity at each measured station, under the assumption that the change of mean values shown in Fig. 10 is due to the change at the reference station. The residual change is shown in Fig. 11 in the area around Lake Biwa and that obtained from the iso-gravity measurements is shown in Fig. 12.

6. Gravity Changes around Lake Biwa

Because a method to perform the precise gravity measurement was not established well before 1970, one-way measurement was employed at some stations in 1964 and 1967, as described in the Chapter 3. Therefore, its accuracy was estimated to be about 30~40 μgals in standard deviations as shown in Table 5 under the assumption that a drift rate of the gravimeter employed was to be constant within a day. Actual error might be somewhat larger than this amount in view of the circumstances when the gravity measurements were carried out; for example, the instrumental height was not measured in 1964 and 1967.

We have employed the going and returning measurements directly from the reference station and have repeated them at the so-called "connective stations" since 1971, in order to improve the accuracy of measurements. Standard deviations in the results of gravity measurements were almost less than 10 μgals.

As can be seen in Fig. 6, the gravity difference from the reference station increased from 1967 to 1971 on both shores of the southern part of Lake Biwa, while the change of gravity difference observed after 1971 was not so much. It is a question whether the amount of the change of gravity difference during the period from 1967 to 1971 was really more than an actual error in gravity measurements or not, so that we should not easily jump to any definite conclusion.

The gravity change after 1971 cannot be found

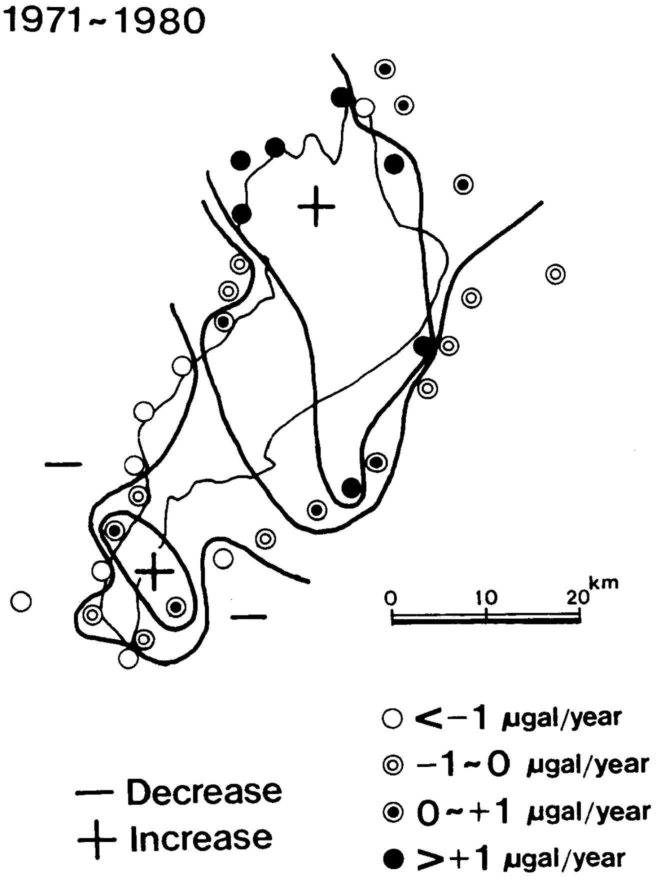

Fig. 13. Mean rates of gravity change assuming that the gravity change was linear to the lapse of time between 1971 and 1980.

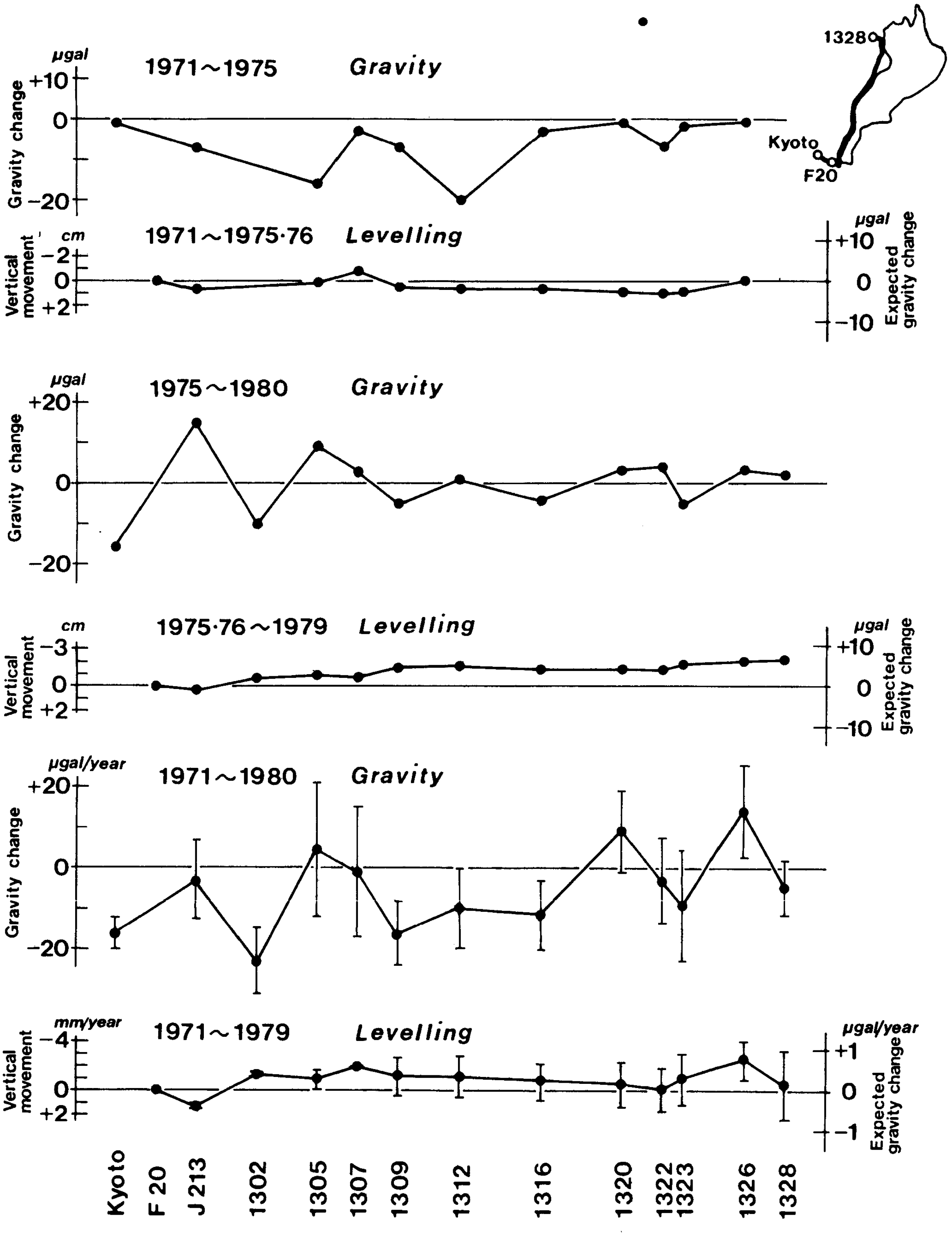

Fig. 14. Comparison of gravity change with vertical movement obtained from levelling surveys at the stations on the western shore of Lake Biwa.

so clearly in Figs. 6 and 11. As the gravity measurements were carried out almost once a year during the period between 1971 and 1980, the mean rates of gravity change were estimated by the least squares method assuming that the gravity change during this period was linear to the lapse of time. Their results are shown in Fig. 13. From Fig. 13, we can briefly find out the pattern that the gravity value increased along the northern shore of the lake and decreased along both the southern and western shores.

Levelling surveys during the period concerned were carried out along the western shore of the lake in 1971 and 1979 by the Geographical Survey Institute and in 1975/1976 by the Geophysical Institute of Kyoto University. Changes in gravity and in height found by levelling surveys are shown in Fig. 14. The tendency of the gravity change was similar to that of the vertical movement during the period between 1971 and 1975 (NAKAGAWA and SATOMURA, 1976; 1977), but the case was not so during the period between 1975 and 1980 (NAKAGAWA *et al.*, 1982a).

The comparison between gravity change during the period of 1971～1980 and vertical movement during that of 1971～1979 is also shown at the bottom of Fig. 14. It shows that the gravity change did not have the same tendency as the vertical movement. But, here, we should take a notice that the gravity change and vertical movement described here were obtained from about eight gravity measurements and three levelling surveys, respectively, during the period concerned. If more levelling surveys had been carried out during the period as in the case of the gravity measurements, another result of vertical movement might have been obtained.

Next, it must be examined the relation between gravity change and change of water level of Lake Biwa. As for the data on water level of the lake, six stations belonging to the Kinki Regional Construction Bureau of the Ministry of Construction are available; they are Mihogasaki (near Ōtsu), Hikone, Katayama (near Kohoku), Shiotsu (between Honnoura and Yanokuma), Ōmizo (near Takashima) and Katata. The vertical movement at each station was calculated from the monthly mean data of water level during the period of 1971～1980, under the two assumptions; first, the mean value of water levels at six stations shows the real change of water level of Lake Biwa; and second, the residual at each station from the mean value shows the vertical movement of the station. The results obtained at six stations are shown in Fig. 15. The water level must be affected by the water current, water temperature and atmospheric pressure, but their effects can be assumed to be negligible, because

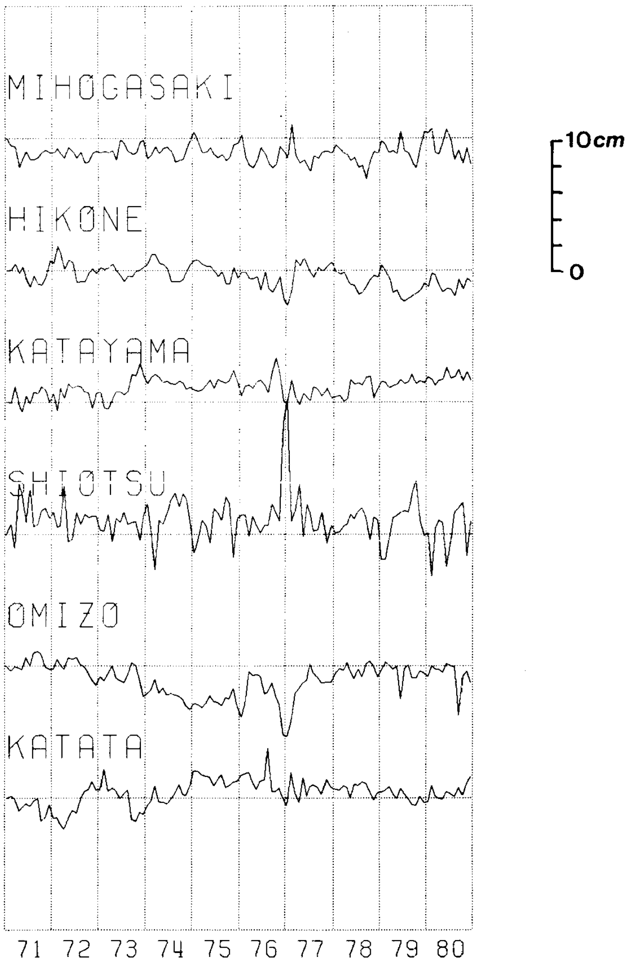

Fig. 15. Vertical movements obtained from the monthly mean data of water level of Lake Biwa.

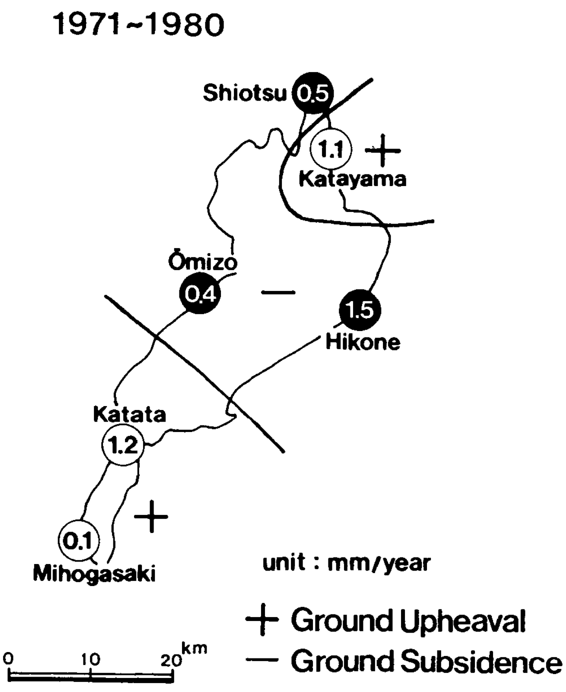

Fig. 16. Locations of water level stations and vertical movements obtained from their data. Open circle shows ground upheaval and closed one shows ground subsidence.

the monthly mean data were used and only the mean rates of the changes during 10 years were discussed. The rate of the movement was estimated assuming that it was linear to the lapse of time during this period like changes of gravity and levelling. The results are also shown in Fig. 16 as well as locations of the water level stations. The comparison of gravity change at the gravity stations near water level stations with vertical movement obtained from the data of water level is shown in Fig. 17. The gravity change is more similar to the vertical change obtained from water level data than that obtained from levelling surveys except Katayama Water Level Station. Katayama Station is located at 4 km apart from the Kohoku Gravity Station, while the other stations are located at distances of less than 2 km from the nearest gravity stations. But the amount of the gravity change is nearly five times greater than that expected from the water level change.

Dividing the period of 1971~1980 into three parts, we estimated the rate of gravity change in each period. The result is shown in Fig. 18. Fig. 18 shows the pattern of gravity change of a wave with a half-wave length of 10 km in the first period. It shows that the gravity increased on the northwestern shore and decreased on the southeastern shore during the second period. The gravity change during the last period shows the opposite tendency to that in the second period.

The rates of vertical movements were also estimated from water level data of Lake Biwa during the periods concerned. Their results are shown in Fig. 19. As can be seen from Fig. 19, the rates of vertical movements show a simple pattern in every period, but it is not similar to the pattern of the rates of gravity changes. We think it means that the obtained pattern is not reliable when the number of the data used is small, because the data of both gravity and water level have a certain quantity of errors.

As for underground water level, Developing Corporation for Water Resource of Ōtsu City has been measuring it at stations along some rivers which flow into Lake Biwa. Four of the stations to measure underground water level are located at distances of less than 2 km from gravity stations; that is, Nishiyurugi, Noguchi (about 2 km southeast of Takamiya), Reizenji (about 1 km north of Rittō) and Karihara (about 1 km east of Rittō). The measurement of underground water level started in 1974, and daily values are available from the Corporation's report. The comparisons of gravity change with change of underground water level are shown in Fig. 20. Fig. 20 shows the values of underground water level for the day when the gravity measurement was carried out at the nearest station. The gravity increase is expected when the underground water level goes up, but the data do not show a clear correlation between them. This fact may mean that the area concerned has complex hydrogeo-

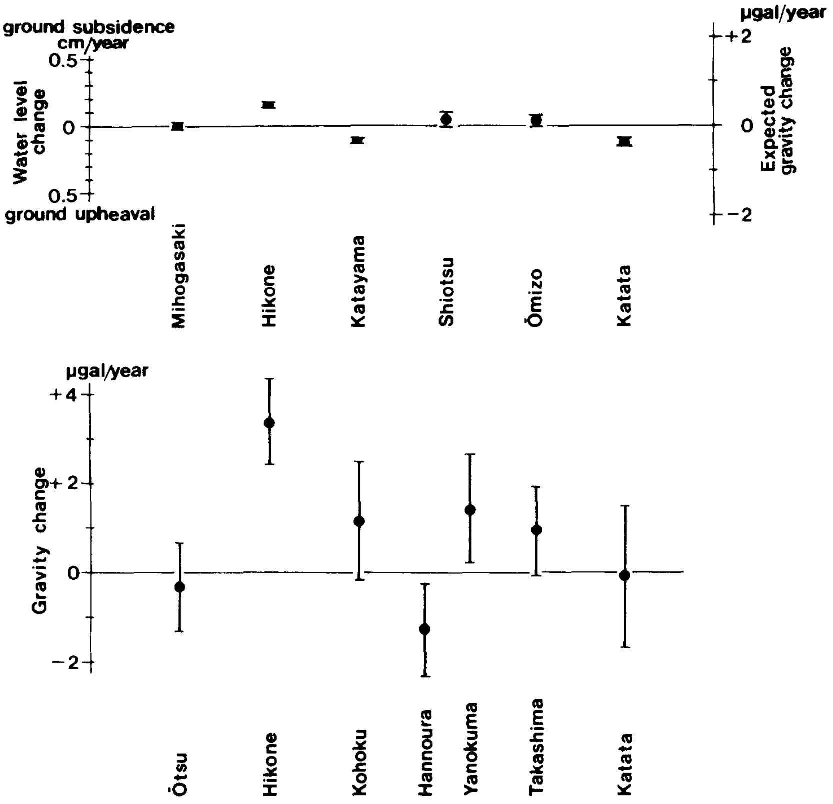

Fig. 17. Comparison of gravity change at the gravity stations near water level stations with vertical movement obtained from the data of water level.

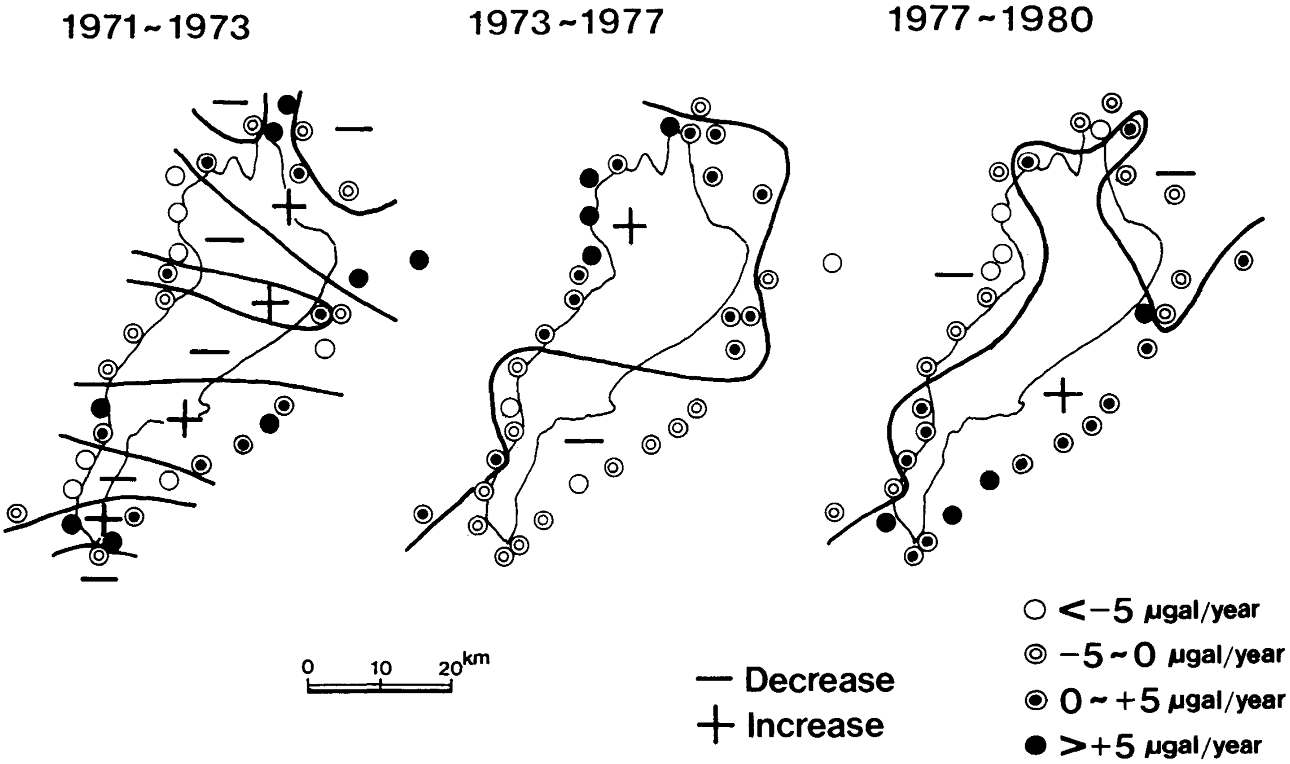

Fig. 18. The rates of gravity changes in three periods.

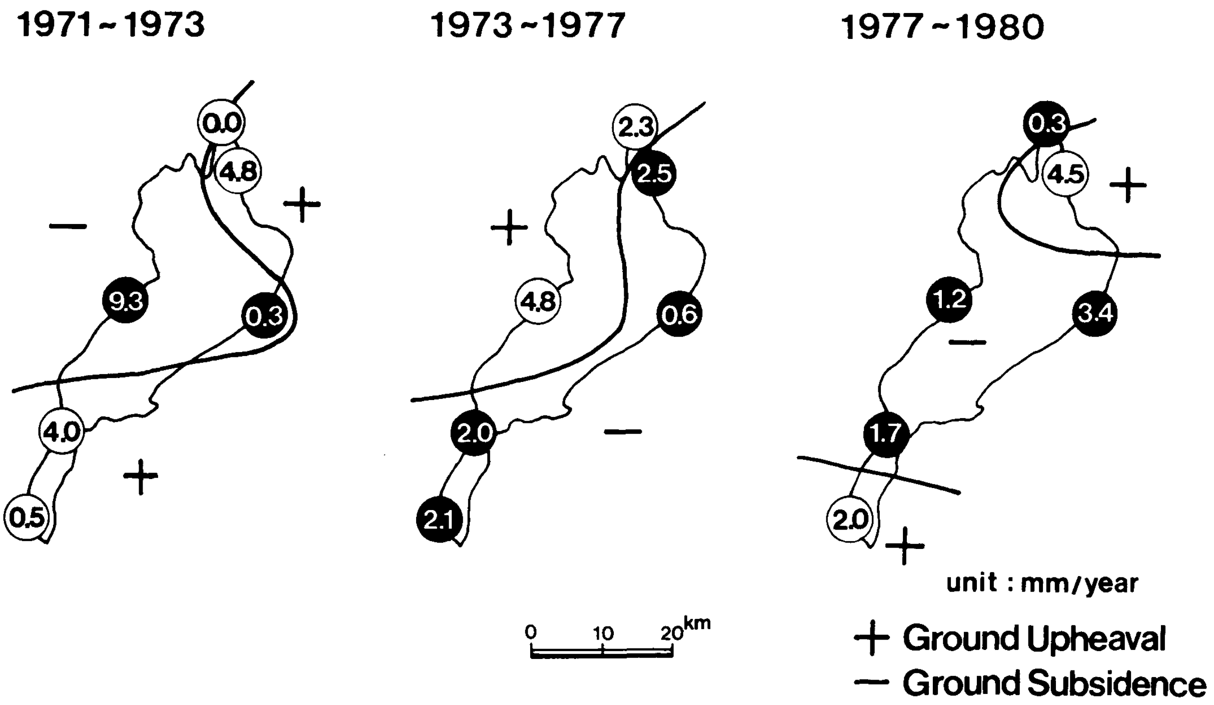

Fig. 19. The rates of vertical movements obtained from the data of water level in the three periods as in Fig. 18. Open circle shows ground upheaval and closed one shows ground subsidence.

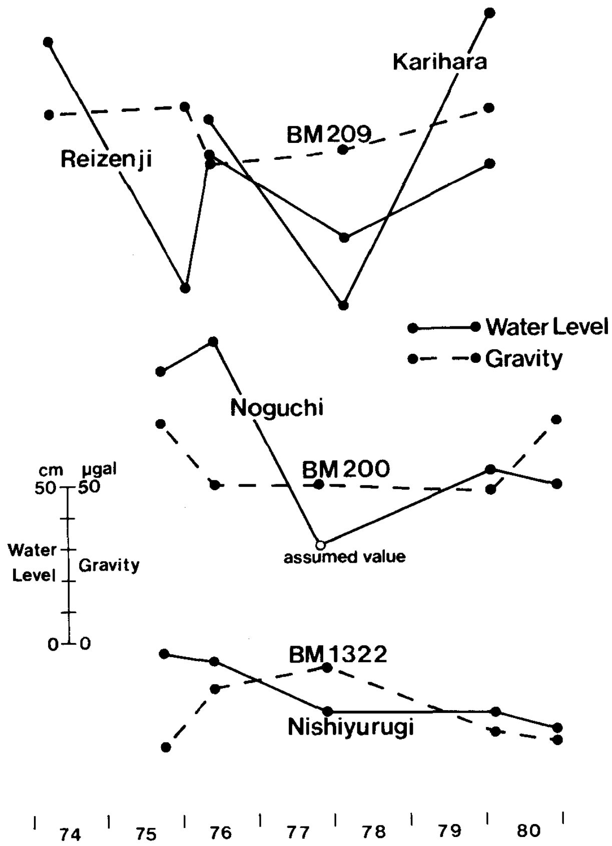

Fig. 20. Comparisons of gravity change with change of underground water level whose stations are located at distances of less than 2 km from gravity stations.

logy. In fact, an investigation by the Corporation shows that this area has complex hydrogeology. In Canada, the gravity change was in a good correlation with that of the underground water level at Cap Pelé, a region of simple hydrogeology, but the case was not so at York Point, a region of complex hydrogeology (LAMBERT and BEAUMONT, 1977).

Last, we consider the relation between the gravity change and the crustal deformation by geological investigations. According to the geological studies made so far, it is believed that Lake Biwa is a very old lake and its basement has been subsiding. On the other hand, Mt. Hira, which is located at the western extremity of Lake Biwa, has been rising, and there are active faults between the Lake Biwa and Mt. Hira (YOKOYAMA, 1983). Even if such crustal deformation is true, gravity change expected from such tectonic movements is so small that much time duration will be necessary for the amount of gravity change to exceed the present accuracy of measurement. For example, as Mt. Hira is very likely to rise at a rate of 1.5 mm/year (YOKOYAMA, 1983), it takes 30 years for the gravity decrease to amount to 10 μgals, and therefore it is impossible at this moment to find any correlation between the gravity change and such tectonic movements. In fact, the gravity measurements across the active faults between the Lake Biwa and Mt. Hira were carried out in 1976 and 1984. The gravity change amounting to 8 μgals was detected between the lakeside area (B. M. 1307 and B. M. 1309) and the mountain area (B. M. B-2 and B. M. B-5); but the change obtained is not large enough to be beyond the error in measurement.

Though it is obviously necessary to take long time to make sure gravity change caused by such crustal deformation, we will do more gravity measurements in the area near Lake Biwa, in order to investigate the relation between gravity change and westward movement of Lake Biwa or rising of Mt. Hira.

7. Gravity Changes in the Kii Peninsula

As described in the Chapter **3**, in order to detect the gravity change accurately, such the first order bench marks were specially chosen, as gravity stations (main stations), as gravity difference from the Gravity Station of Geophysical Institute of Kyoto University is smaller than 1 mgal (one set of the iso-gravity stations), or as gravity value is 979.686 gals±1 mgal (another set of the iso-gravity stations), along the levelling routes of the area covering Lake Biwa and the Kii Peninsula, and each of them had a few sub-stations. Gravity measurements at the main stations along the route in the Kii Peninsula were carried out both clockwise and counter-clockwise with two or three LaCoste & Romberg gravimeters. In addition, local gravity measurements were carried out among the main stations and the sub-stations. The gravity differences from the reference station were obtained from the data mentioned in the Chapter **4**. The standard deviation of the results obtained at the main stations is 6∼9 μgals.

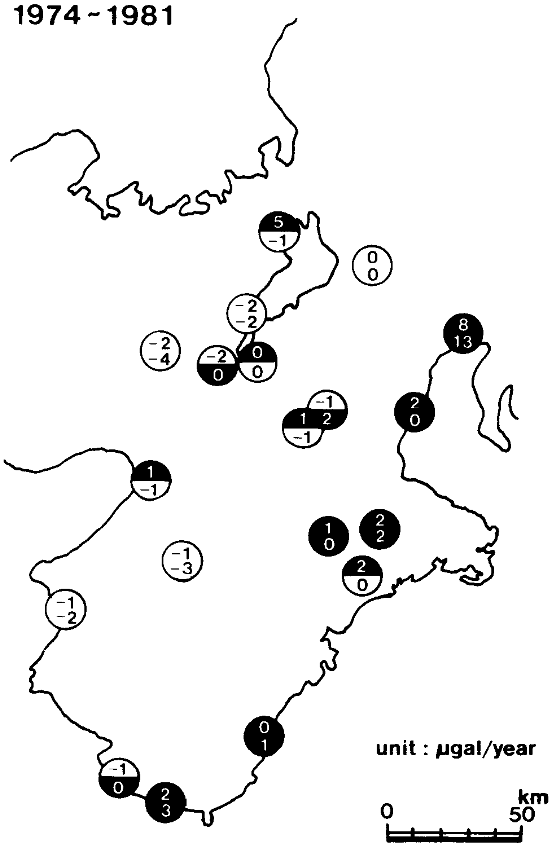

Fig. 21. Mean rates of gravity change at the main stations in Kinki District assuming that the gravity change was linear to the lapse of time between 1974 and 1981.

The mean rates of gravity change at the main stations were obtained by the same method as those at the gravity stations around Lake Biwa, and they are shown in Fig. 21. As can be seen from Fig. 21, the gravity increased in the southeastern part of Kinki District and decreased in the northwestern part.

Levelling surveys were carried out by the Geographical Survey Institute along the levelling routes of both the coast and inland areas of the Kii Peninsula in 1971/1972 and 1979. The comparison of gravity change with vertical movement which was obtained by the levelling surveys, is shown in Fig. 22. The gravity change shown in this figure was obtained by applying the least squares method as in the case of Lake Biwa. The correlation between gravity change and vertical movement is not so clear at almost stations. The gravity changes at both B. M. 1473 and B. M. 1474, however, are almost the same as the expected ones from vertical movements. This is the free-air change of gravity due to the ground subsidence by over pumped-up of underground water.

The vertical movement of the crust can be estimated by using the change of mean sea level. Next, we compare the gravity change with such crustal movement as that obtained by oceanic tidal observations. Oceanic tidal observations have been carried out at several stations along the coast of the Kii Peninsula by the Japan Meteorological Agency and the Geographical Survey Institute. KATO and TSUMURA (1983) analyzed the data between 1951 and 1982. They showed that Kushimoto, which is at the tip of the Peninsula, was subsiding at the rate of 0.9 mm/year, but Kainan and Wakayama, which are located at the foot of the Peninsula, were uplifting at the rate of 0.6 mm/year. These results are not similar to the vertical movements obtained from levelling surveys, but similar to the gravity changes. However, the amount of vertical movements derived from oceanic tidal observations is not enough for letting us to explain the gravity change measured.

The gravity change by the vertical movement

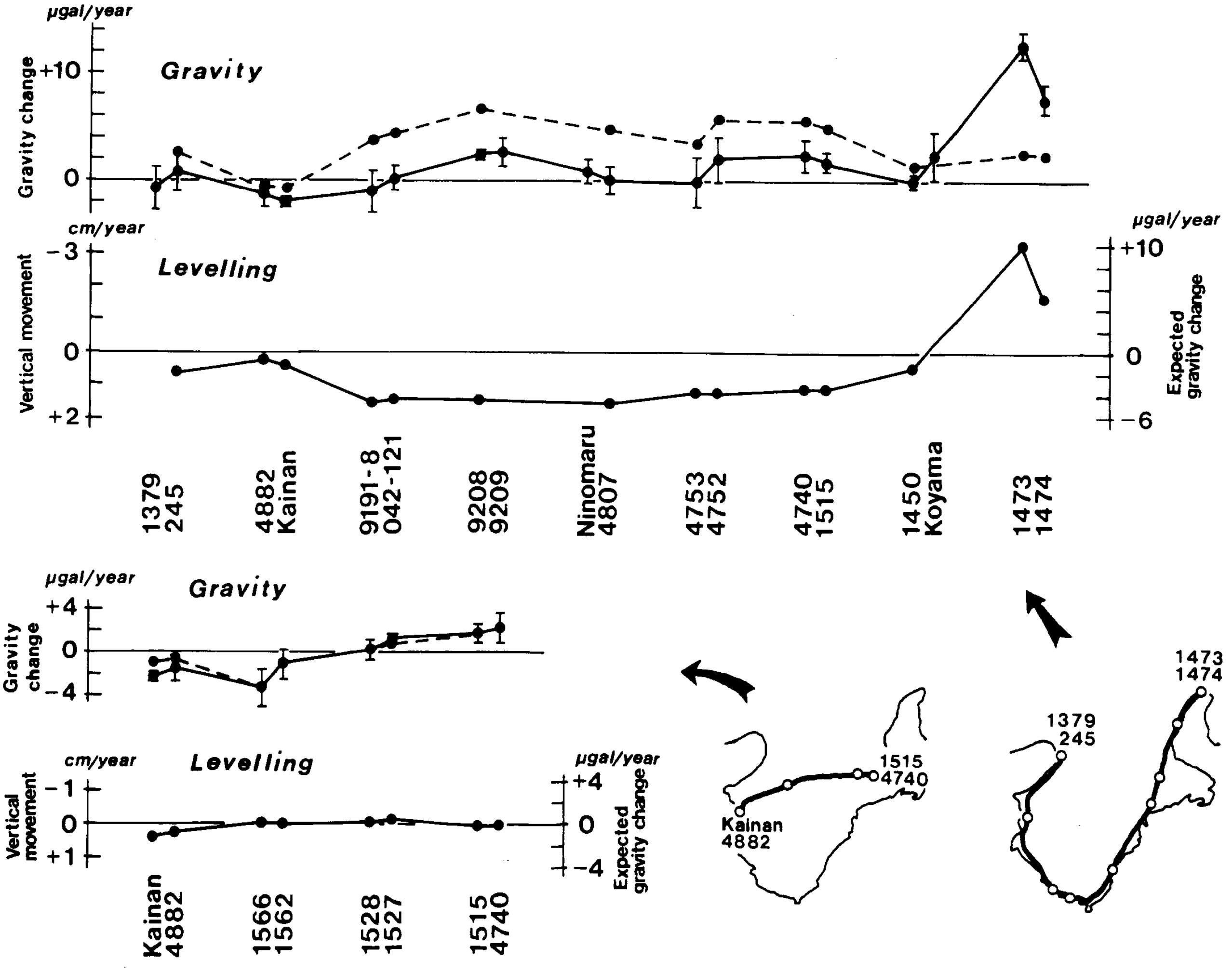

Fig. 22. Comparison of gravity change with vertical movement obtained from levelling surveys at the main stations. Broken lines show the gravity change which is reduced the effect of vertical movement.

stated above was reduced by free-air gradient and the reduced values are plotted with broken lines in Fig. 22. Fig. 22 shows that the gravity increased by about 5 μgals/year at the southern part of the Kii Peninsula. The geodetic control surveys were carried out three times at triangulation stations in 1901, 1949~1952 and 1978 (GEOGRAPHICAL SURVEY INSTITUTE, 1979). Areal dilatations between 1949/1952 and 1978 in the southern and eastern parts of the Kii Peninsula are estimated to be -1.4×10^{-5} per about 28 years (1950~1978); that is, the rate of areal contraction is 5×10^{-7} per year. We may think that such contraction is caused by the push of the Philippine Sea Plate. The direction of the motion of the Philippine Sea Plate is northwest relative to the Eurasian Plate near the area concerned (SENO, 1977), and the Plate subducts with a low angle from the Nankai Trough to the coast of the Kii Peninsula and the depth of its surface is about 30 km beneath the coast. The angle of subduction is steeper beneath the inland area (MIZOUE, 1977; FUKAO *et al.*, 1983). The leading edge reaches at the foot of the Kii Peninsula (SHIONO, 1974; 1982), and its depth is about 80 km (FUKAO *et al.*, 1983). The northwest–southeast cross sectional view of the Eurasian Plate and the asthenosphere under it just above the subducting Philippine Sea Plate may be assumed as drawn in Fig. 23 (b).

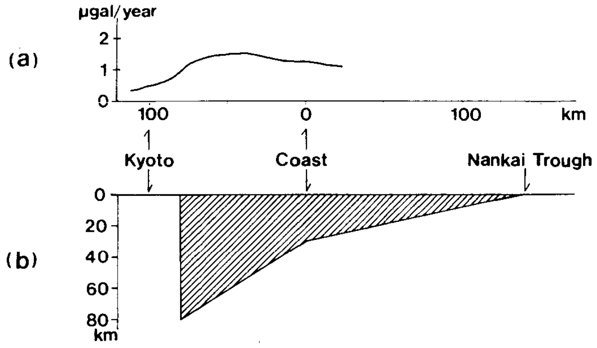

Fig. 23.
(a) Gravity change estimated by the density change of 10^{-6} g cm^{-3}/year in the cross section of (b).
(b) The cross sectional view of the northwest – southeast direction of the Eurasian Plate and the asthenosphere just above the subducting Philippine Sea Plate.

Let x and y coordinates be horizontal and z coordinate be vertical, and imagine a plate whose Young's modulus E and Poisson's ratio ν to be compressed by the stresses σ_x and σ_y ($\sigma_z=0$). The strains are described as

$$e_x=\frac{\sigma_x-\nu\sigma_y}{E},$$

$$e_y=\frac{\sigma_y-\nu\sigma_x}{E}, \text{ and}$$

$$e_z=\frac{-\nu(\sigma_x+\sigma_y)}{E}.$$

We assume $e_y=0$, then

$$\sigma_y=\nu\sigma_x,$$

$$e_x=\frac{1-\nu^2}{E}\sigma_x,$$

$$\therefore e_z=-\frac{\nu}{1-\nu}e_x.$$

The ratio of density change is

$$\frac{\Delta\rho}{\rho}=-(e_x+e_y+e_z)$$

$$=-\frac{1-2\nu}{1-\nu}e_x.$$

When $e_y\neq0$, this relation is $\frac{\Delta\rho}{\rho}=-\frac{1-2\nu}{1-\nu}(e_x+e_y)$ (HAGIWARA and TAJIMA, 1973).

Let $\nu=0.25$, $\rho=3\,\mathrm{g\,cm^{-3}}$ and $e=e_x+e_y=5\times10^{-7}$/year,

$$\Delta\rho=-\frac{1-2\nu}{1-\nu}e_x\rho$$

$$=10^{-6}\,\mathrm{g\,cm^{-3}}/\mathrm{year}.$$

We estimated the gravity changes obtained by the density change of 10^{-6} g cm^{-3}/ year in the Eurasian Plate with the cross section shown in Fig. 23 (b) by using the formula of TALWANI *et al.* (1959). Their results are indicated in Fig. 23 (a), showing that relative gravity increase is expected only about 1 μgal/year when the reference station is located in Kyoto. This amount is smaller than the reduced gravity change at the southern part of the Peninsula, but some parts of gravity changes may be expected to occur by the areal contraction.

HASHIMOTO (1981; 1982) investigated the stress field of this area derived from the movements of the Philippine Sea Plate and the Pacific Plate by using a three-dimensional finite element method, but the volume change was not discussed yet. Referred to his model, we calculated the density change by applying a two-dimensional finite element method to the model shown in Fig. 24. First, we calculated volume changes for the two cases; one is the case where only a negative buoyancy due to the density contrast (0.171 g cm^{-3}) between subducting plate and the surrounding mantle is taken into consideration as an external force, and the other is the case where two external forces of the negative buoyancy and a horizontal compressive force amounting to 500 bars generated by the underthrusting of the Philippine Sea Plate, are taken into consideration. Next, the volume compression (that is, density increase) due to compressive force by the Plate was obtained from the difference between the two volume changes, and its result was shown in Fig. 25. It indicates the existence of the compression not only in the sea-side area but also in the inland area, and the change of gravity difference expected from the contraction by the push of the Plate must be smaller than that calculated above. The result shown in Fig. 25 was obtained on the boundary condition that the northwest side was locked. In order to check the effect due to this assumption of the boundary condition, we enlarged the model to northwest by 40~80 km and calculated the density change. Its result was not much different from the original one.

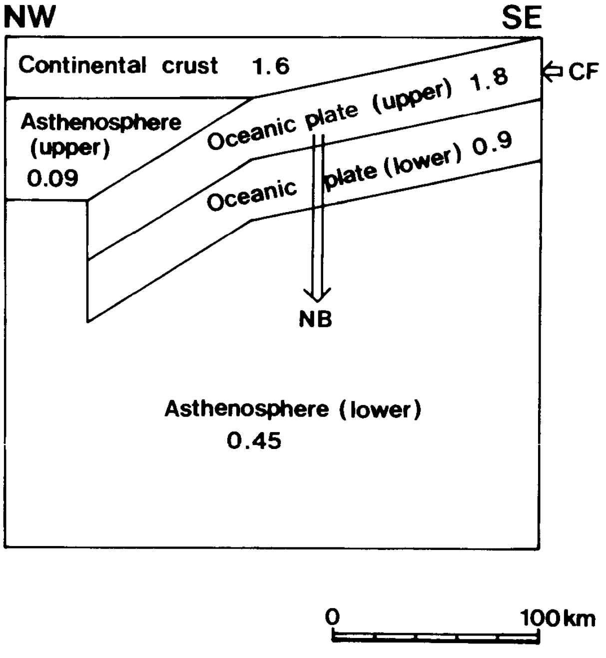

Fig. 24. A schematic representation of the finite element modeling of the northwest—southeast cross section. The values given in this figure show the Young's monduli (×10^6 bars).

CF : horizontal compressive force generated by the underthrusting of the Philippine Sea Plate.

NB : negative buoyancy due to the density contrast between the subducting Plate and the surrounding mantle.

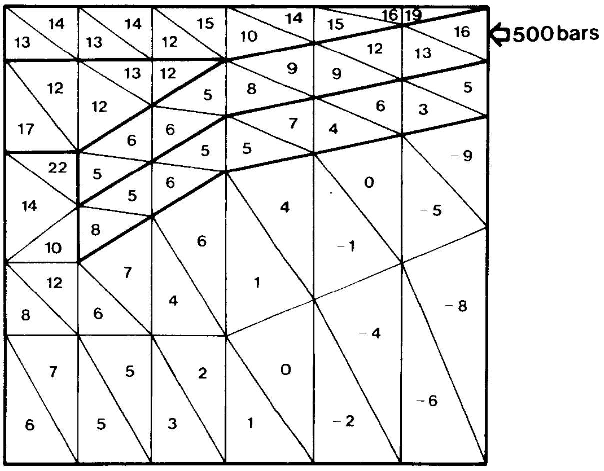

Fig. 25. Volume compression in the cross section shown in Fig. 24, calculated by applying the finite element method (unit in 10^{-5}).

Dividing the period of 1974~1981 into two parts, the mean rates of gravity changes were calculated in each period. The result is shown in Fig. 26. The result of the former half period is similar to that of the whole period (Fig. 21), but

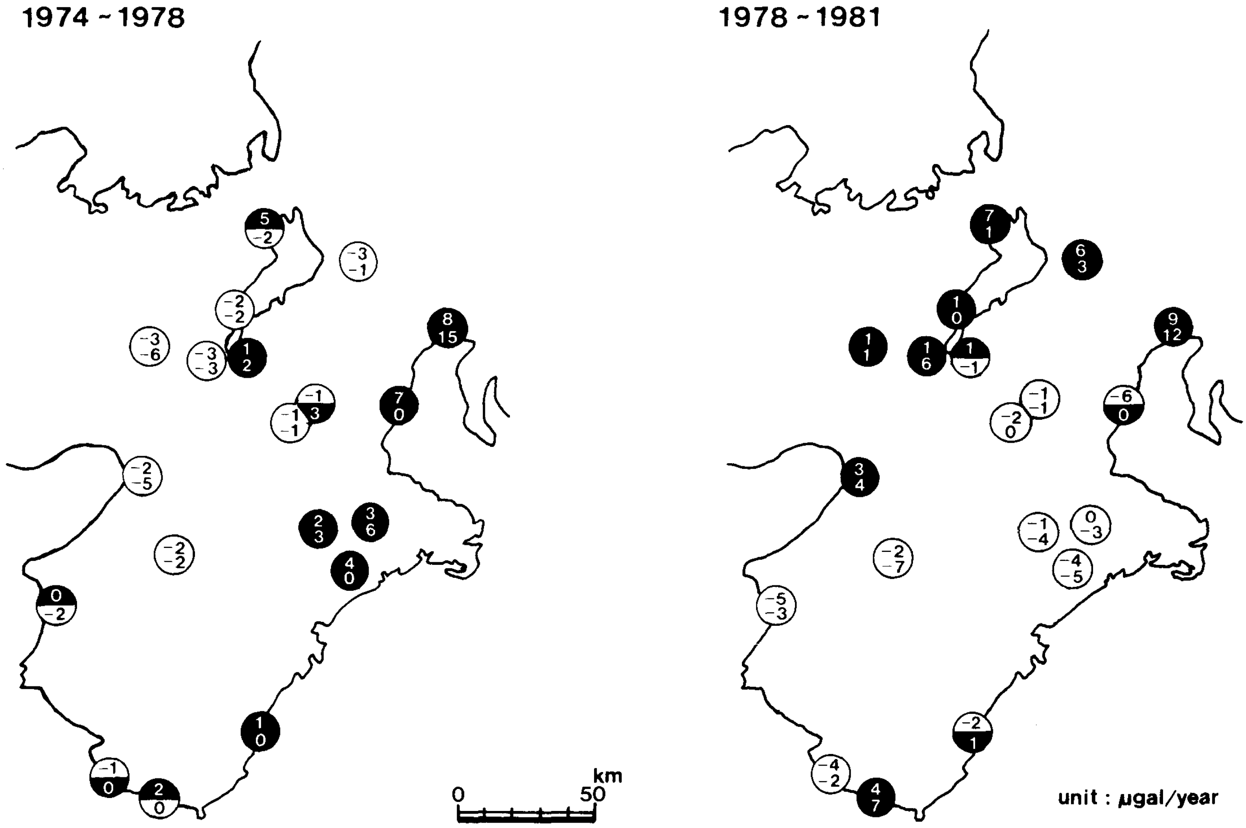

Fig. 26. Mean rates of gravity changes at the main stations in two periods.

that of the latter one stands in the reverse relation with the result of the whole period. We can notice the clear difference between the two periods on the eastern region of the Kii Peninsula; that is, the gravity increased by about 2~4 µgals/year in the former half period and decreased by the same rate in the latter one. In this region, the records of two oceanic tidal observation stations belonging to the Japan Meteorological Agency are available; *i. e.*, Owase and Toba. Both the results show the land subsides at a rate of about 1 cm/year before 1977 or 1978 and it changes to uplift with the similar rate after that, as shown in Fig. 27. The rate of 1 cm/year in the vertical movement corresponds to 3 µgals/year of gravity change. These results imply the change of crustal deformation in a wide area in about 1978. Harmonious evidences with the above-mentioned change were recognized in this year in continuous observations at many crustal movement observatories over a wider area in Japan (KASAHARA *et al.*, 1983).

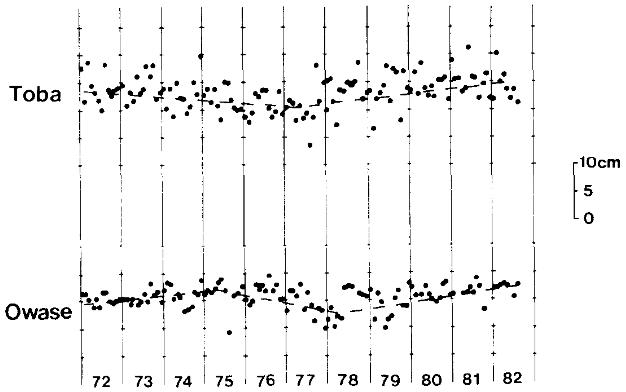

Fig. 27. The vertical movements at Toba and Owase deduced from oceanic tidal records. (after KATO and TSUMURA, 1983)

The relations between gravity and elevation changes obtained at B. M. 1473 and B. M. 1474 are shown in Fig. 28. Elevation changes were calculated with the net adjustment under the assump-

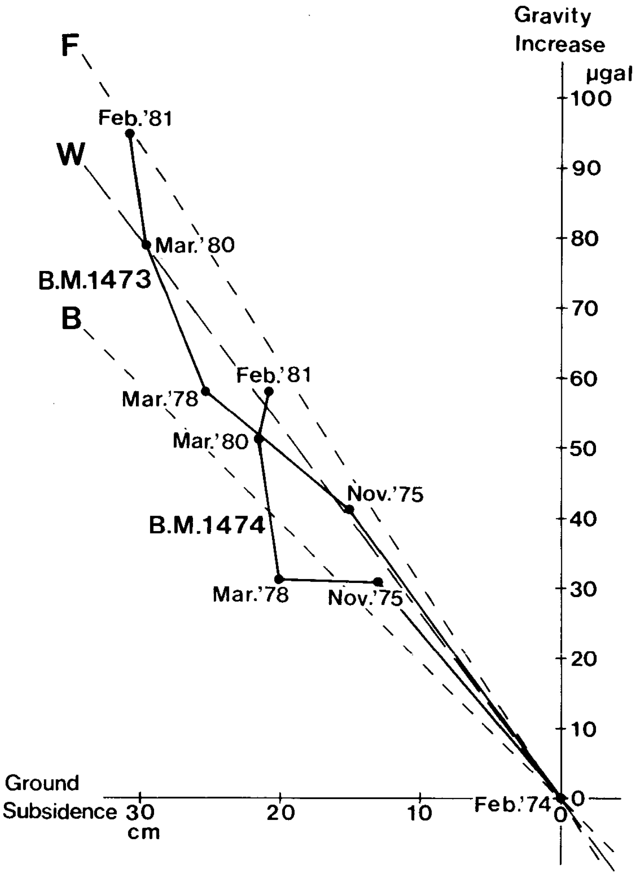

Fig. 28. Relations between gravity and elevation changes obtained at B.M. 1473 and B.M. 1474.

tion that the elevations at B. M. F39 (Toyoake City, Aichi Prefecture) and B. M. SF191-2 (Tarui Town, Gifu Prefecture) had been unchanged. **F**, **B** and **W** indicate free-air, Bouguer and water-saturated gradients of gravity, respectively. If the amount of the ground subsidence is as same as that of the pumped-up underground water, the gravity might change as the line **W**. The actual gravity change, however, was smaller than the expected gravity change from the line **W** till March 1978. Afterwards the amount of the latter was smaller than the former. This means that ground subsidence was greater than the amount corresponding to the volume of pumped-up underground water before March 1978. The ground subsidence had already started at about 1960, and then it may conclude that the underground water, which was pumped up until 1974 when the gravity measurements started, caused the ground subsidence with some delay of the phase. As the regulation against pumping underground water has been put in force since January 1976, the volume of the pumped-up underground water has thereafter been getting smaller. Under these circumstances, the ground subsidence practically stopped in 1978, but gravity increase still continued until 1980. This can be explained by recovery of underground water after the regulation against pumping.

Great earthquakes whose magnitudes are greater than 8.0 occur at the interval of about 100 years off Kii Peninsula. The last one occurred in 1946, and the period when we have carried out many precise gravity measurements, was in an inactive stage of the above-mentioned cycle of earthquake occurrence. When such a great earthquake occurs off Kii Peninsula, this area should be one of the most probable areas where a great deal of gravity change is expected to be observed in Japan. Not only the results but also the methods described in the present article will contribute as fundamental data to detect effectively the small gravity change related with seismic activity.

8. Conclusions

We have repeatedly carried out the precise gravity measurements during the period of more than 10 years in Kinki District in order to detect the secular change of gravity. Some bench marks were specially chosen for this purpose as the iso-gravity stations along the levelling routes of the area covering Lake Biwa and the Kii Peninsula. We recommended to the IAG, on the basis of our experiences of precise gravity measurements, that the iso-gravity measurement is the most useful one for detecting the secular change of gravity. The IAG recognized the importance of its method and the iso-gravity measurements are now carried out at many regions in the world for this purpose. As the period during which we have carried out the measurements was a seismically inactive stage of the tectonics in the area concerned, the gravity change was so small that we could not detect it clearly. However, we got the valuable data on the characteristics of gravimeters employed, the method to obtain the accurate gravity differences and the accuracy of the field gravity measurement through performing the precise gravity measurements.

The results obtained from the present investigations are as follows :

a) The accuracy of the gravity measurement by a single LaCoste & Romberg gravimeter is about 10 μgals in standard deviation when the drift rate of gravimeter's readings is assumed to be constant during the day of the measurement.

b) The scale value of the gravimeter must be examined in detail, especially when the precise gravity measurement is carried out at stations with a large gravity difference.

c) A going and returning measurement must be adopted at least in the precise gravity measurement. Direct connection from the reference station is also required to increase the accuracy of gravity measurements.

d) The gravity change was not in a good correlation with the vertical movement obtained from levelling surveys, but it was in a fine correlation with vertical movement derived from the observations of water level or oceanic tides.

e) The gravity increase was found at the tip of the Kii Peninsula, and it may be partly explained by the horizontal contraction of the crust by the push of the Philippine Sea Plate.

f) The observed gravity change agreed with the expected one from the vertical movement where the ground has severely subsided because of over pumped-up underground water. This proves that the precise gravity measurement is useful for detecting a certain underground change.

The results of gravity measurements through the present investigations must be the valuable and useful data in order to study the secular change of gravity in the area concerned, because the measurements were carefully performed after active discussions and many examinations about the methods of measurements and the characteristics of gravimeters. We used the same gravimeters, the same measured method and so on. We believe that a more reliable information on the secular change of gravity will be obtained within the next ten years or a little more, by repeating the similar gravity measurements with equal time interval.

However, some problems to solve hereafter still remain or arise through the present investigations; they are as follows :

a) When the relative measurements are carried out, it is a matter of course that we can obtain only the change of gravity difference and cannot obtain the absolute change of gravity value. And therefore, when we measure the secular change of gravity difference between two stations, we cannot tell to which station the change is due. A technique on absolute measurement of gravity has been much improved during these ten years, and the absolute measurement must be jointly carried out with the relative measurement of gravity.

b) It is a very great advantage that the precise gravity measurement can directly connect two stations which are located far apart. The levelling survey cannot realize this advantage, while the oceanic tidal observation and water level one have the same advantage. It may be ascribed to this advantage that, according to the results of the present measurements, the gravity change is nearly the same as the gravity change expected from oceanic tidal observation or water level one. When we take such advantage into account, a few stations must be selected carefully in a wide area and the direct measurements must be carried out between the reference and selected stations. This way of using the gravimeters is the most useful to detect the gravity change.

c) The gravity increase was found at the tip of the Kii Peninsula, and this may be explained by the areal contraction. Other direct measurements of gravity are necessary between the reference station (Kyoto) and the tip and between the easternmost and the westernmost in order to confirm whether this is true or not.

d) If the gravimeter's readings show a nonlinear drift, the going and returning measurement has a weak point. We did not find out the quadratic term of the drift curve by this measurement. However, when the stations are not so distant, one more measurement is expected to be added to the going and returning measurements on the same route in order to check the quadratic term of the gravimeter's drift.

e) The periodic errors which were produced by both the eccentricity of dial screw and gears of the gravimeter may affect much the accuracy of the results. We have selected the gravity stations where the gravity difference was less than about 1 mgal and tried to use the same gravimeters in the gravity measurements in Kinki District. However, there has been the gravimeter's drift and we cannot read the gravimeter at the same dial position of the same gravimeter at each station. We have found the periodic backrush of dial screw and gears for the gravimeter G-719; this is one of the appearances of periodic errors. The periodic errors must be examined in detail for all gravimeters used.

When we improve the method of gravity measurements upon the recommendations proposed above and repeat gravity measurements hereafter as frequently as possible, we are sure to be able to obtain more reliable results on gravity change. The method realized in Kinki District which was described in the present article can be applied to any other areas, and its application to more tectonically active areas than Kinki District might give more fascinating results on gravity change there. Needless to say, the levelling surveys must absolutely be combined at the same time and at the same station with gravity measurements in order to resolve the cause of the gravity change with time.

Acknowledgements

The author wishes to express his heartful thanks to Professor I. NAKAGAWA for his cordial guidance throughout the present investigations. Much of the investigations is indebted to his guidance. The author is also indebted to Professor I. NAKAGAWA, Messrs. H. TSUKAMOTO, U. MAGARI, K. FUJIMORI, T. HIGASHI, K. NAKAMURA and Professor N. SUMITOMO of Kyoto University, Mr. Y. FUKUDA of Hirosaki University, Mr. M. ŌZEKI of the Japan Meteorological Agency and his other colleagues of Kyoto University to carry out the gravity measurements together. The author wishes to express his sincere thanks to Professor T. ICHINOHE of Kyoto University for his generous encouragement and also to Professors T. DAMBARA and K. IKEZU of Shizuoka University for their useful revisions of the manuscript. The author is also indebted to Professors K. MIKUMO, N. SUMITOMO, T. TANAKA, Y. TANAKA and I. OZAWA of Kyoto University for their kind comments and also to Miss Y. SUZUKI, Messrs. K. NAKAYAMA and H. ANMA of Shizuoka University for their helps in preparing the manuscript.

The calculations were executed at the Data Processing Center of Kyoto University and that of Shizuoka University.

References

BARNES, D. F. (1966), Gravity changes during the Alaska Earthquake. *J. Geophys. Res.*, **71**, 451-456.

BARTA, G. (1971), On the hypothesis of the secular variation of gravity field. *Bull. Géod.*, **100**, 165-173.

———(1978), A possible change of gravity field of non-tidal character. *Boll. Geofis. Teor. Appl.*, **20**, 317-322.

BECKER, M. (1981), Results of circular error studies with LaCoste and Romberg gravity meters. *Bur. Gravimētr. Int., Bull. Inform.*, **49**, 72-94.

BOULANGER, Yu. D. and SCHEGLOV, S. N. (1971), On secular changes of gravity. *Bull. Géod.*, **100**, 175-178.

DUCARME, B., HOSOYAMA, K., VAN RUYMBEKE, M. and SATO, T. (1976), An attempt to use LaCoste-Romberg model G gravimeters at the microgal level. *Bur. Gravimētr. Int., Bull. Inform.*, **39**, A8-A18.

ELSTNER, C., HARNISCH, G. and ALTMANN, W. (1978), On the results of small range gravity measurements in GDR area in the period 1970 – 1976. *Boll. Geofis. Teor. Appl.*, **20**, 349-354.

FALLER, J. E., GUO, Y. G., RINKER, R. L. and ZUMBERGE, M. A. (1982), Advanced absolute gravity determination. *Proc. Gen. Meeting IAG, Tokyo*, 309-318.

FUJII, Y. (1969), On gravity change accompanied by the crustal deformation. *J. Geod. Soc. Japan*, **15**, 97-98. (in Japanese)

————(1972), Collision of plates and gravity anomalies. *J. Geod. Soc. Japan*, **18**, 58-61. (in Japanese)

————, KOGURE, S., INOUE, K. and SAKAMOTO, K. (1964a), Gravity changes in Ooshima Island. *Kagaku*, **34**, 622-623. (in Japanese)

————, ————, SAITO, T., INOUE, K. and MURATA, I. (1964b), On the reading accuracy and the scale factor reliability for the La Coste and Romberg Geodetic Gravity Meter G-29. *J. Geod. Soc. Japan*, **10**, 36-45. (in Japanese)

————and NAKANE, K. (1972), Crustal deformation and secular change of gravity accompanied by interaction of plates. *J. Geod. Soc. Japan*, **18**, 180-190. (in Japanese)

FUJITA, N. and FUJII, Y. (1974), Gravity change in Japan. *J. Geod. Soc. Japan*, **20**, 77-79.

————, ————and TADA, T. (1975), Crustal effects of a heavy offshore earthquake in eastern Hokkaido, Japan. *Tectonophysics*, **29**, 523-528.

FUKAO, Y., HORI, S. and UKAWA, M. (1983), A seismological constraint on the depth of basalt-eclogite transition in a subducting oceanic crust. *Nature*, **303**, 413-415.

FUKUDA, Y. (1982), Principal component analyses on the data of secular gravity change. *Abstract, 58th Meeting, Geod. Soc. Japan*, 45-46. (in Japanese)

GEOGRAPHICAL SURVEY INSTITUTE (1967), Report of Geodetic Survey Associated with the Matsushiro Swarm Earthquake (3), 43-44. (in Japanese)

————————(1968), Report of Geodetic Survey Associated with the Matsushiro Swarm Earthquake (4), 29-35. (in Japanese)

————————(1976), Establishment of the Japan Gravity Standardization Net 1975. *J. Geod. Soc. Japan*, **22**, 65-76. (in Japanese)

————————(1979), Horizontal strain in the southern part of Kinki. *Rept. Coord. Comm. Earthq. Pred.*, **22**, 179-183. (in Japanese)

GERSTENECKER, C. (1978), Instrumental improvements on a LaCoste-Romberg Model G-gravimeter for μGal measurements. *Boll. Geofis. Teor. Appl.*, **20**, 363-374.

GROTEN, E. (1975), Microgravimetry—High precision observations of small gravity differences—. *Bull. Géod.*, **115**, 41-56.

HAGIWARA, Y. and TAJIMA, H. (1973), Secular changes of gravity. *Publ. 50th Anniv. Great Kanto Earthq., 1923*, 311-327. (in Japanese)

————, ————, IZUTUYA, S. and HANADA, H. (1976b), Gravity changes in the eastern part of Izu Peninsula during the period of 1975～1976. *J. Geod. Soc. Japan*, **22**, 201-209. (in Japanese)

————, ————, ————and————(1977), Gravity change associated with earthquake swarm activities in the eastern part of Izu Peninsula. *Bull. Earthq. Res. Inst., Univ. Tokyo*, **52**, 141-150. (in Japanese)

————, ————, ————, NAGASAWA, K., MURATA, I. and ENDO, T. (1980), Gravity changes over the East-Izu uplift, Japan. *J. Phys. Earth*, **28**, 553-564.

————, ————, ————, ————, ————and SHIMADA, S. (1978), Gravity change during the Izu-Oshima-kinkai earthquake of 1978. *Bull. Earthq. Res. Inst., Univ. Tokyo*, **53**, 875-880. (in Japanese)

————, ————, ————and SATOMURA, M. (1976a), Gravity changes on Izu Peninsula. *J. Geod. Soc. Japan*, **22**, 17-22. (in Japanese)

HAMILTON, A. C. and BRULÉ, B. G. (1967), Vibration-induced drift in LaCoste and Romberg geodetic gravimeters. *J. Geophys. Res.*, **72**, 2187-2197.

HAMMOND, J. A. (1978), The AFGL absolute gravity system—a progress report. *Boll. Geofis. Teor. Appl.*, **20**, 401-408.

HANADA, H. (1977), Vibration characteristics of LaCoste & Romberg gravimeter. *Bull. Earthq. Res. Inst., Univ. Tokyo*, **52**, 29-48. (in Japanese)

————, TSUBOKAWA, T., OOE, M. and TSUBOKAWA, I. (1982), Absolute determination of gravity with transportable apparatus. *Proc. Gen. Meeting IAG, Tokyo*, 358-365.

HASHIMOTO, M. (1981), Three-dimensional stress distribution in southwestern Japan as expected from the configuration of the subducting Philippine Sea Plate (part 2). *Zisin* (*J. Seismol. Soc. Japan*), ii, **34**, 197-211. (in Japanese)

———(1982), Numerical modelling of the three-dimensional stress field in southwestern Japan. *Tectonophysics*, **84**, 247-266.

HIPKIN, R. G. (1978), A microgravimeteric network for secular gravity studies in Scotland. *Geophys. J. Roy. Astr. Soc.*, **52**, 383-396.

HONKASALO, T. (1971), Report of IAG Special Study Group No. 4.21 on "Special Techniques of Gravity Measurements". *Paper, XV Gen. Assemb. IUGG, Moscow*, 12p.

HUNT, T. M. (1970), Gravity changes at Wairakei geothermal field, New Zealand. *Geol. Soc. Amer. Bull.*, **81**, 529-535.

ICHINOHE, T. (1955), Study on change of gravity with time. Part II. Repeated gravity surveys in the Kinki District. *Mem. Coll. Sci., Univ. Kyoto*, Ser. A, **27**, 317-334.

———, NAKAGAWA, I and OKAMOTO, Y. (1956), Observations of the tidal variations of gravity (the second paper). *J. Geod. Soc. Japan*, **3**, 34-37. (in Japanese).

———, ———and SUMITOMO, N. (1963), On secular change of gravity. *Spec. Contrib. Geophys. Inst., Kyoto Univ.*, **1**, 37-41.

———, TSUKAMOTO, H., NAKAMURA, K., HIGASHI, T., NAKAGAWA, I. and SATOMURA, M. (1983), On the results of gravity measurements among Omaezaki, Kakegawa and Mori (after 1970). *Abstract, 60th Meeting, Geod. Soc. Japan*, 92-93. (in Japanese)

IIDA, K., HAYAKAWA, M. and KATAYOSE, K. (1950), Changes of gravity difference between Imaichi and Nikkō owing to the "Imaichi Earthquake". *Bull. Geol. Surv. Japan*, **1**, 136-138. (in Japanese)

———, ———and———(1952), Gravity survey of Mihara Volcano, Ooshima Island, and changes in gravity caused by eruption. *Rept. No.* 152, *Geol. Surv. Japan*, 24p. (in Japanese)

INOUYE, N., FUJII, Y. and KIZAWA, T. (1968), A study on the time change of gravity in Ooshima Island (1). *J. Geod. Soc. Japan*, **13**, 146-150. (in Japanese)

ISHIMOTO, M. and TUZI, K. (1929), Monthly means of the daily rates of the Riefler Clock on the Tōkyō Astronomical Observatory and their bearing on the occurrence of earthquakes. *Bull. Earthq. Res. Inst., Univ. Tokyo*, **6**, 355-357.

IZUTUYA, S., TAJIMA, H., HAGIWARA, Y., MURATA, I., NAKAGAWA, I. SATOMURA, M., YOKOYAMA, I., EHARA, S., OHKAWA, S., SETO, T., KANO, K., KOIZUMI, K. and NAKAI, S. (1976), Gravity changes observed in the eastern part of Hokkaido District. *Rept. on "Experimental Research for Detecting the Gravity Changes Related to Crustal Movements and Seismic Activities"*, 95-104. (in Japanese)

JITSUKAWA, A. and TAJIMA, H. (1962), Gravity surveys in the area of the Northern Miyagi Earthquake. *Bull. Earthq. Res. Inst., Univ. Tokyo*, **40**, 649-652. (in Japanese)

KANNGIESER, E. (1982), Investigations of calibration functions. temperature and transportation effects at LaCoste-Romberg gravimeters. *Proc. Gen. Meeting IAG, Tokyo*, 385-396.

KASAHARA, M., SHICHI, R., and OKADA, Y. (1983), On the cause of long-period crustal movement. *Tectonophysics*, **97**, 327-336.

KATO, T. and TSUMURA, K. (1983), Vertical crustal movements in Japan as deduced from tidal records (1951–August, 1982). *Rept. Coord. Comm. Earthq. Pred.*, **29**, 368-381. (in Japanese)

KISSLINGER, C. (1975), Processes during the Matsushiro, Japan, Earthquake Swarm as revealed by leveling, gravity and spring-flow observations. *Geology*, **3**, 57-62.

KIVINIEMI, A. (1974), High precision measurements for studying the secular variation in gravity in Finland. *Publ. Finn. Geod. Inst.*, **78**, 68p.

KUBOTERA, A., NAKAGAWA, I., FUKUDA, Y., SATOMURA, M., TAJIMA, H., OHSHIMA, H. and ISHIHARA, K. (1978), Precise gravity measurements over Aso Volcano. *Joint Geophysical and Geochemical Observations of Aso Volcano* (*August – December, 1977*), 23-30. (in Japanese)

———and SATOMURA, M. (1985), Repeated gravity measurements on the Aso Volcano. *Comparative Study of Physical Background of Volcanic Activity and Its Relation to Prediction of Eruption Disasters*, 64-68. (in Japanese)

———, ———, FUKUDA, Y., TSUKAMOTO, H. and UEKI, S. (1984), Precise gravity measurements over Aso Volcano (May 1979 and November 1981). *Joint Geophysical and Geochemical Observations of Aso Volcano* (*August – December, 1981*), 33-38. (in Japanese)

———, ———and SUMITOMO, N. (1974), Repeated gravity measurements on Aso Volcano. *Bull. Volcanol. Soc. Japan*, ii, **19**, 123-125. (in Japanese)

———and SUMITOMO, N., (1965), A gravity survey on Aso Caldera Kyushu District Japan (I). *Spec. Contrib. Geophys. Inst., Kyoto Univ.*, **5**, 139-150.

LAMBERT, A. and BEAUMONT, C. (1977), Nano variations in gravity due to seasonal groundwater movements: Implications for the gravitational detection of tectonic movements. *J. Geophys. Res.*, **82**, 297-306.

LONGMAN, I. M. (1959), Formulas for computing the tidal accelerations due to the moon and the sun. *J. Geophys Res.*, **64**, 2351-2355.

MIYABE, N. (1955), Vertical earth movement in Nankai District. *Bull. Geogr. Surv. Inst.*, **4**, 1-14.

MIZOUE, M. (1977), Some remarks on the characteristics of subcrustal earthquake activities. *Proc. Symp. Earthq. Pred. Res.*, 97-105. (in Japanese)

MORELLI, C., GANTAR, C., HONKASALO, T., McCONNELL, R. K., TANNER, J. G., SZABO, B., UOTILA, U. and WHALEN, C. T. (1974), The International Gravity Standardization Net 1971 (I.G.S.N.71). *Publ. Spéc.*, **4**, *Bull. Géod.*, 194p.

————and HONKASALO, T. (1975), Summary report on the activity 1971~1974 of section III (Gravimetry) of IAG. *Paper XVI Gen. Assemb. IUGG, Grenoble.*

MURATA, I. (1978), A transportable apparatus for absolute measurement of gravity. *Bull. Earthq. Res. Inst., Univ. Tokyo,* **53**, 49-130.

NAKAGAWA, I. (1962a), Some problems on time change of gravity. Part 1. On effect of oceanic tides upon the tidal variation of gravity. *Bull. Disast. Prev. Res. Inst., Kyoto Univ.*, **53**, 2-65.

————(1962b), Some problems on time change of gravity. Part 3. On precise observation of the tidal variation of gravity at the Gravity Reference Station. *Bull. Disast. Prev. Res. Inst., Kyoto Univ.*, **57**, 2-65.

————(1971), Some remarks on gravity survey. *J. Geod. Soc. Japan,* **17**, 67-75. (in Japanese)

————(1975), Report on the 16th General Assembly of the IUGG and the IAG; IAG Section III Gravimetry. *J. Geod. Soc. Japan,* **21**, 206-220. (in Japanese)

————and SATOMURA, M. (1971), On precise gravity survey at specially selected station with an almost equal gravity value, and an experiment on characteristics of LaCoste & Romberg gravimeters due to vibrations. *J. Geod. Soc. Japan,* **17**, 49-60. (in Japanese)

————and————(1972), On precise gravity measurement at stations of small gravity difference (Part 1). *J. Geod. Soc. Japan,* **18**, 17-22. (in Japanese)

————and————(1973), On precise gravity measurement at stations of small gravity difference (Part 2). *J. Geod. Soc. Japan,* **19**, 42-49. (in Japanese)

————and————(1975a), On precise gravity measurement at stations of small gravity difference. *Paper XVI Gen. Assemb. IUGG, Grenoble,* 4p.

————and————(1975b), Gravity measurements near Lake Biwa-ko. *Paleolimn. Lake Biwa Japan. Pleistoc.,* **3**, 181-193.

————and————(1976), On gravity changes detected near Lake Biwa-ko. *Rept. on "Experimental Research for Detecting the Gravity Changes Related to Crustal Movements and Seismic Activities"*, 79-83. (in Japanese)

————and————(1977), Gravity change observed near Lake Biwa, Japan. *Bull Géod.*, **51**, 213-217.

————, ————, FUKUDA, Y., NAKAI, S., SETO, T., TAJIMA, K., INOUCHI, N., HAGIWARA, Y., TAJIMA, H., IZUTUYA, S., YANAGISAWA, M., HANADA, H., TOMODA, Y., FUJIMOTO, H., FURUTA, T. and OHKAWA, S. (1977a), Calibration on scale constants of LaCoste & Romberg gravimeters (model G). *J. Geod. Soc. Japan,* **23**, 63-73. (in Japanese)

————, ————, ————, TSUKAMOTO, H. HIGASHI, T. and NAKAMURA, K. (1982a), Gravity changes observed during the past decade in Kinki District, Japan. *Proc. Gen. Meeting IAG, Tokyo,* 366-374.

————, ————, ICHINOHE, T. and SUMITOMO, N. (1972), On secular change of gravity near Lake Biwa-ko. *J. Geod. Soc. Japan,* **18**, 23-29. (in Japanese)

————, ————, NAKAI, S., SATO, N., TAJIMA, H., HAGIWARA, Y., IZUTUYA, S., SETO, T., TSUKAHARA, K., TAJIMA, K., OHKAWA, S., KOIZUMI, K., FUJIMOTO, H., SUDA, Y. and MISHINA, M. (1974), On characteristics of LaCoste & Romberg gravimeters (model G) (Part 2). *J. Geod. Soc. Japan,* **20**, 133-142. (in Japanese)

————, ————, ŌZEKI, M. and TSUKAMOTO, H. (1975), Tidal change of gravity by means of an Askania gravimeter at Kyoto, Japan. *J. Geod. Soc. Japan,* **21**, 6-15.

————, ————and SETO, T. (1978), An accuracy of scale constant of LaCoste & Romberg gravimeters (model G) revealed by international and domestic gravimetric connections. *Bur. Gravimétr. Int., Bull. Inform.*, **42**, I9-I30.

————, ————, ————, HASEGAWA, Y., TSUKAHARA, K., HAGIWARA, Y., TAJIMA, H., IZUTUYA, S., MURATA, I., NAKAI, S., NAKAGOMI, O., KOIZUMI, K., FUJIMOTO, H., UDAGAWA, Y. and ISHIHARA, T. (1973), On characteristics of LaCoste & Romberg gravimeters (model G) (part 1). *J. Geod. Soc. Japan,* **19**, 100-112. (in Japanese)

———, TAJIMA, H., IZUTUYA, S., KONO, Y., NAKAI, S., HIGASHI, T., SHICHI, R., FUJIMOTO, H., TAJIMA, K. and FUNAKI, M. (1981), Precise calibration of scale constants of LaCoste & Romberg gravimeters and international gravimetric connection along the circum-Pacific zone (the first half of the main investigation). *Rept. on "Precise Calibration of Scale Constants of LaCoste & Romberg Gravimeters and Contribution to the Reform of the International Gravity Standardization Net 1971 (Main Investigation in 1980)"*, 24p.

———, ———, ———, SHICHI, R., KONO, Y., FUJIMOTO, H., HIGASHI, T., NAKAI, S. and MURAKAMI, M. (1982b), Precise calibration of scale constants of LaCoste & Romberg gravimeters and international gravimetric connection along the circum-Pacific zone (the second half of the main investigation). *Rept. on "Precise Calibration of Scale Constants of LaCoste & Romberg Gravimeters and Contribution to the Reform of the International Gravity Standardization Net 1971 (Main Investigation in 1981)"*, 24p.

———, TANAKA, Y., SATOMURA, M., KATO, M. and OIKE, K. (1977b), International connection of gravity between Japan and South America. *J. Geod. Soc. Japan*, **23**, 82-87.

NAKAI, S. (1975), On the characteristics of LaCoste & Romberg gravimeter G 305. *Proc. Int. Lat. Obs. Mizusawa*, **15**, 76-83. (in Japanese)

———(1979), A subroutine program for computing the tidal forces for the practical use. *Proc. Int. Lat. Obs. Mizusawa*, **18**, 124-135. (in Japanese)

NUR, A. (1974), Matsushiro, Japan, Earthquake Swarm : Confirmation of the dilatancy-fluid diffusion model. *Geology*, **2**, 217-221.

OHKAWA, S., YOKOYAMA, I., SATOMURA, M. and NAKAGAWA, I. (1976), Gravity changes observed in the eastern part of the Hokkaido District (a supplementary report). *J. Geod. Soc. Japan*, **22**, 178-187. (in Japanese)

OOE, M., SUZUKI, T., HANADA, H., TSUBOKAWA T. and HOSOYAMA, K. (1982), Implementation of the free rise-and-fall (Sakuma type) apparatus for absolute measurement of gravity and obtained values at Mizusawa. *Proc. Gen. Meeting IAG, Tokyo*, 349-357.

SAKUMA, A. (1973), A permanent station for the absolute determination of gravity approaching one micro-gal accuracy. *Proc. Symposium on "Earth's Gravitational Field and Secular Variations in Position"*, 674-684.

SATOMURA, M. and ICHINOHE, T. (1975), Gravity measurements in the active region of earthquake swarm near Mt. Iwaki. *Abstract, Bull. Volcanol. Soc. Japan*, ii, **19**, 161. (in Japanese)

———and NAKAGAWA, I. (1972), Secular change of gravity near Lake Biwa-ko. *Contrib. Geophys. Inst., Kyoto Univ.*, **12**, 101-115.

SCHLEUSENER, A. and TORGE, W. (1971), Investigations of secular gravity variations in Iceland. *Z. Geophys.*, **37**, 679-701.

SENO, T. (1977), The instantaneous rotation vector of the Philippine Sea Plate relative to the Eurasian Plate. *Tectonophysics*, **42**, 209-226.

SETO, T. (1976), On stableness of sensitivity of the astatic type gravimeter. *Rept. on "Experimental Research for Detecting the Gravity Changes Related to Crustal movements and Seismic Activities"*, 111-118. (in Japanese)

———and TAZIMA, M. (1975), Gravity tie between Japan and Europe. *Paper XVI Gen. Assemb. IUGG, Grenoble.*

SEYA, K. (1968), On time variations of gravity in the period of the Matsushiro Earthquake Swarm. *Bull. Geol. Surv. Japan*, **19**, 581-596. (in Japanese)

SHICHI, R., YAMAMOTO, A., FURUMOTO, M. and SUMINO, Y. (1983), Establishment of the nets of precise gravity measurements in Tōkai District. *Abstract, 60th Meeting, Geod. Soc. Japan*, 96-97. (in Japanese)

SHIONO, K. (1974), Travel time analysis of relatively deep earthquakes in Southwest Japan with special reference to the underthrusting of the Philippine Sea Plate. *J. Geosci., Osaka City Univ.*, **18**, 37-59.

———(1982), Frontal shape of the seismic slab by normal subduction of a dead spreading axis and a preliminary applications to Southwest Japan. *J. Geosci., Osaka City Univ.*, **25**, 19-33.

TAJIMA, H. (1975), Gravity change associated with earthquakes and land-deformations. *Bull. Earthq. Res. Inst., Univ. Tokyo*, **50**, 209-272. (in Japanese)

———, HAGIWARA, Y., IZUTUYA, S., MURATA, I., NAKAGAWA, I. and SATOMURA, M. (1976), Gravity changes detected in the south Kantō District. *Rept. on "Experimental Research for Detecting the Gravity Changes Related to Crustal Movements and Seismic Activities"*, 85-93. (in Japanese)

———and IZUTUYA, S., (1974), Gravity changes during and after the Matsushiro Earthquake Swarm. *J. Geod. Soc. Japan*, **20**, 153-168. (in Japanese)

TALWANI, M., WORZEL, J. L. and LANDISMAN, M. (1959), Rapid gravity computations for two-dimensional bodies with application to the Mendocino submarine fracture zone. *J. Geophys. Res.*, **64**, 49-

59.

TAZIMA, M. (1970), Possibility of gravity change accompanying crustal movement. *J. Geod. Soc. Japan,* **16**, 60-67. (in Japanese)

TSUKAMOTO, H. (1983), On some causes of systematic errors of LaCoste & Romberg gravimeters. *Abstract, 59th Meeting, Geod. Soc. Japan,* 111-112. (in Japanese)

VOGAL, A. (1968), The question of secular variations in the earth's gravity field from massdisplacements in the earth's deep interior. *Bull. Géod.,* **88**, 223-226.

VOLKOV, V. A. and ZASIMOV, S. S. (1973), A note concerning the dampering and linearity of the tide-recording system Askania Gs-15. *Paper 7th Int. Symp. Earth Tides, Sopron.*

WORKING GROUP FOR COMPARING THE GRAVIMETERS IN JAPAN (1969), Simultaneous gravimetric field survey made between Mizusawa and Hachinohe. *J. Geod. Soc. Japan,* **15**, 6-8. (in Japanese)

YOKOYAMA, T. (1983), Natural History of Southwest Japan. *Sanwa-Shobō, Kyoto,* 294p. (in Japanese)

APPENDIX

Note 1. Descriptions of the gravity stations around Lake Biwa except bench marks established by the Geographical Survey Institute

Kyoto Univ.(京都大学)：The Gravity Station of Geophysical Institute, Kyoto University.

Keage(蹴上)：See Note 2 (11.1.).

Kyoto Col. Pharm.(京都薬大)：See Note 2 (11.4.).

Seta (Karahashi)(瀬田唐橋)：The lower landing stair in the square beside the Karahashi Bridge (near B. M. 211).

Yasaka Shrine(八坂神社)：See Note 2 (37.2.).

Kusatsu JHS(草津中学校)：See Note 2 (37.4.).

Kusatsu (Dental)(草津歯科医)：On road in front of Minami Dental Office (near B. M. 209.1).

Higashioiso (Pass.)(東老蘇地下道)：On underground passage under the Route 8 (near B. M. 203.1)

Gokashō (Zenjū-ji)(五箇荘善住寺)：On floor of bell tower in Zenjū-ji Temple (near B. M. 202.1).

Hikone(彦根)：On the uppermost stair in front of statue of "Naosuke Ii" at the Hikone Castle.

Emperor Meiji(明治天皇)：See Note 2 (18.2.).

Samegai(醒井)：See Note 2 (18.3.).

Kashiwabara(柏原)：On the lowermost stair in front of main shrine, Hachiman Shrine.

Sekigahara JHS(関ヶ原中学校)：See Note 2 (18.4.).

Sekigahara (Shrine)(関ヶ原神社)：See Note 2 (18.5.).

Ibuki(伊吹)：On step stone in front of lodging No. 5, Ibuki Weather Station.

Uchibo(内保)：On floor in front of monument stone for soul.

Kohoku(湖北)：On the lowermost stair in front of main building, Kohoku Kannon-dō.

Kinomoto(木ノ本)：On the lowermost stair in front of the big statue of "Jizō", Jōshin-ji Temple.

Hannoura(飯浦)：On the lowermost stair in front of main shrine, Hachiman Shrine.

Yanokuma(岩熊)：On the uppermost stone stair in front of the stage for Noh-play, Yaai Shrine.

Sakaebashi(栄橋)：On floor of the monument stone beside the Sakae Bridge (moved in 1972).

Ōura(大浦)：On the lowermost stair in front of main shrine, Hachiman shrine.

Kaizu (Fukuzen-ji)(海津福善寺)：See Note 2 (19.3.).

Kaizu (Saiei-ji)(海津西栄寺)：See Note 2 (19.2.).

Makino(マキノ)：See Note 2 (19.4.).

Kitashinpo(北新保)：On the lowermost stair in front of main shrine, Tenma Shrine.

Yū(蘭生)：See Note 2 (19.5.).

Karasaki (Shrine)(唐崎)：On stone floor of the well in Karasaki Shrine (near B. M. 1302).

Note 2. Descriptions of the iso-gravity stations

11.0. The Gravity Station of Geophysical Institute, Kyoto University, Sakyō-ku, Kyoto City.(京都市左京区京都大学理学部地球物理学教室)

11.1. On floor of the monument stone of "Cradle of Water-Power Generation", Okazaki, Sakyō-ku, Kyoto City.(京都市左京区岡崎)

11.2. B. M. 215.1, Awataguchi-Kachō-chō, Higashiyama-ku, Kyoto City.(京都市東山区粟田口華頂町)

11.3. B. M. 215, Hinooka-Tsutsumidani-chō, Yamashina-ku, Kyoto City.(京都市山科区日ノ岡堤谷町)

11.4. B. M. at the southwestern corner of the gymnasium, Kyoto College of Pharmacy, Misasagi-Nakauchi-chō, Yamashina-ku, Kyoto City.(京都市山科区御陵中内町京都薬科大学)

11.5. On the lowermost stair of the monument stone for soul, at the southeastern corner of parking area in front of the Sanbō-in Temple, Daigo, Fushimi-ku, Kyoto City.(京都市伏見区醍醐三宝院)

11.6. B. M. 10716, Daigo-Makinouchi-chō, Fushimi-ku, Kyoto City.(京都市伏見区醍醐槇ノ内町)

12.1. B. M. 1420, Naka-machi, Ueno City.(上野市中町)

12.2. B. M. inside of the main gate, Sūkō Junior High School, Marunouchi, Ueno City.(上野市丸ノ内崇広中学校)

12.3. On the monument stone of "Tōnishizaka", Nishiōte-chō, Ueno City.(上野市西大手町)

12.4. On cornerstone of the main gate, Tenma Shrine, Higashi-machi, Ueno City.(上野市東町天満宮)

12.5. On floor of the statue of "Kōbō-Daishi", Zenpuku-in Temple, Tera-machi, Ueno City.(上野市寺町善福院)

12.6. B. M. 1421, Hattori-chō, Ueno City.(上野市服部町)

31.1. Traces of B. M. 1425, Shindō, Iga Town, Mie Prefecture.(伊賀町新堂)

31.2. B. M. at the northern corner of the playground, Iga Senior High School, Kawahigashi, Iga Town, Mie Prefecture.(伊賀町川東伊賀高校)

31.3. On base stone of the monument of "the Meiji Coronation" near the main gate, Mibuno Elementary School, Kawahigashi, Iga Town, Mie Prefecture.(伊賀町川東壬生野小学校)

31.4. On base stone of the great votive lantern of the An'yō-ji Temple, Kōno, Ōyamada Village, Mie Prefecture.(大山田村甲野安養寺)

31.5. On the lowermost step of the upper stair in front of the monument stone for soul, Nishitsuge Elementary School, Shindō, Iga Town, Mie Prefecture.(伊賀町新堂西柘植小学校)

31.6. B. M. 1426, Shimotsuge, Iga Town, Mie Prefecture.(伊賀町下柘植)

13.1. B. M. 1451, Jike-chō, Suzuka City.(鈴鹿市寺家町)

13.2. 3rd Order Triangulation Station, Jike-chō, Suzuka City.(鈴鹿市寺家町)

13.3. B. M. 023-014, Isoyama-chō, Suzuka City.(鈴鹿市磯山町)

13.4. B. M. inside of the side-gate, Sakae Elementary School, Iwai-chō, Suzuka City.(鈴鹿市五祝町栄小学校)

13.5. B. M. at the southern corner of the Hachiman Shrine, Isoyama-chō, Suzuka City.(鈴鹿市磯山町八幡神社)

13.6. B. M. 1450, Isoyama-chō, Suzuka City.(鈴鹿市磯山町)

14.1. B. M. 4740, Ao, Ōdai Town, Mie Prefecture.(大台町粟生)

14.2. B. M. at the northeastern foot of the Hinokuchi Bridge, Takana, Ōdai Town, Mie Prefecture.(大台町高奈樋口橋)

14.3. B. M. 042-331, Takana, Ōdai Town, Mie Prefecture.(大台町高奈)

14.4. B. M. 042-332, Kamikusu, Ōdai Town, Mie Prefecture.(大台町上楠)

14.5. B. M. in the tea-garden in front of Itō's house, Asagara, Seiwa Village, Mie Prefecture.(勢和村朝柄)

14.6. B. M. 1515, Asagara, Seiwa Village, Mie Prefecture.(勢和村朝柄)

14.7. B. M. inside of the main gate, Sakura Nursery School, Kayumi, Iinan Town, Mie Prefecture.(飯南町粥見さくら保育園)

32.1. B. M. 1527, Tominaga, Iitaka Town, Mie Prefecture.(飯高町富永)

32.2. B. M. at the northwestern foot of the Kabata Bridge, Tominaga, Iitaka Town, Mie Prefecture.(飯高町富永川俣橋)

32.3. B. M. at the northeastern corner of Kabata Branch of Tenriism, Tominaga, Iitaka Town, Mie Prefecture.(飯高町富永天理教川俣分教会)

32.4. B. M. in courtyard, Kabata Elementary School, Tominaga, Iitaka Town, Mie Prefecture.(飯高町富永川俣小学校)

32.5. On floor stone of "Jizō" on roadside of the Route 166, Miyamoto, Iitaka Town, Mie Prefecture.(飯高町宮本)

32.6. B. M. 1528, Nanukaichi, Iitaka Town, Mie Prefecture.(飯高町七日市)

33.1. B. M. 4752, Koma, Ōuchiyama Village, Mie Prefecture.(大内山村駒)

33.2. On the uppermost stair in front of the main temple, Kokushō-ji Temple, Koma, Ōuchiyama Village, Mie Prefecture.(大内山村駒国正寺)

33.3. B. M. 042-308, Koma, Ōuchiyama Village, Mie Prefecture.(大内山村駒)

33.4. B. M. 042-307, Koma, Ōuchiyama Village, Mie Prefecture.(大内山村駒)

33.5. B. M. beside the tall pine-tree near the milestone, Koma, Ōuchiyama Village, Mie Prefecture.(大内山村駒)

33.6. B. M. 4753, Mayumi, Ōuchiyama Village, Mie Prefecture.(大内山村間弓)

15.1. B. M. 4807, Ida, Kihō Town, Mie Prefecture.(紀宝町井田)

15.2. B. M. in flower garden of the platform, Kii-Ida Railroad Station, Ida, Kihō Town, Mie Prefecture.(紀宝町井田紀伊井田駅)

15.3. B. M. in front of Minamimuro Minsei Hospital, Atawa, Mihama Town, Mie Prefecture.(御浜町阿田和南牟婁民生病院)

15.4. B. M. on the north side of parking area of Hotel Ninomaru, the ruins of the Shingū Castle, Shingū, Shingū City.(新宮市新宮ホテル二の丸)

15.5. On floor of the gate post of "Tōsen-ji Temple", Shimo-honmachi, Shingū City.(新宮市下本町東仙寺)

15.6. B. M. 4967, Hirotsuno, Shingū, Shingū City.(新宮市新宮広角)

16.1. B. M. 9209, Esumi, Susami Town, Wakayama Prefecture.(すさみ町江住)

16.2. On floor of the upper "Jizō" of the roadside, Esumi, Susami Town, Wakayama Prefecture.(すさみ町江住)

16.3. B. M. 042-144, Esumi, Susami Town, Wakayama Prefecture.(すさみ町江住)

16.4. B. M. inside of the main gate, Esumi Junior High School, Esumi, Susami Town, Wakayama Prefecture.(すさみ町江住中学校)

16.5. B. M. in public square in front of Mirozu Fire Station, Mirozu, Susami Town, Wakayama Prefecture.(すさみ町見老津消防署)

16.6. B. M. 9208, Mirozu, Susami Town, Wakayama Prefecture.(すさみ町見老津)

34.1. B. M. 042-121, Hiki, Hikigawa Town, Wakayama Prefecture.(日置川町日置)

34.2. On base floor of flag pole in Hikigawa Playground, Hiki, Hikigawa Town, Wakayama Prefecture.(日置川町日置)

34.3. B. M. behind the Seated Figure in Seaside Park, Hiki, Hikigawa Town, Wakayama Prefecture.(日置川町日置)

34.4. On the uppermost step of the main stair, Hachiman Shrine, Tanoi, Hikigawa Town, Wakayama Prefecture.(日置川町田野井八幡神社)

34.5. On floor of the largest "Jizō" in front of the Tentoku-ji Temple, Tanoi, Hikigawa Town, Wakayama Prefecture.(日置川町田野井天徳寺)

34.6. B. M. 9191-8, Hiki, Hikigawa Town, Wakayama Prefecture.(日置川町日置)

35.1. B. M. inside of the main gate, Hatsushima Junior High School, Hatsushima, Arida City.(有田市初島中学校)

35.2. On the southeastern corner of edge of the reservoir, Shimotsu Reservoir, Shimotsu, Shimotsu Town, Wakayama Prefecture.(下津町下津水源池)

35.3. B. M. 4887, Kami, Shimotsu Town, Wakayama Prefecture.(下津町上)

35.4. On the lowermost step of the upper stair in front of the main shrine, Awashima Shrine, Kata, Shimotsu Town, Wakayama Prefecture.(下津町方粟島神社)

35.5. B. M. at the Kainan Tidal Station, Shimizu, Kainan City.(海南市冷水海南験潮場)

35.6. B. M. 4881, Muroyama-Danchi, Kainan City.(海南市室山団地)

35.7. B. M. 4882, in front of the Kainan City Office, Hikata, Kainan City.(海南市日方海南市役所)

36.1. B. M. 1567, Tōge, Hashimoto City.(橋本市東家)

36.2. B. M. 024-092, Sada, Hashimoto City.(橋本市佐田)

36.3. B. M. 1556, Tsuma, Hashimoto City.(橋本市妻)

36.4. B. M. 1559, Nishiada, Gojō City.(五条市西阿田)

36.5. B. M. in front of the former gymnasium, trace of Uchi Elementary School, Imai, Gojō City.(五条市今井旧宇智小学校)

36.6. On the lowermost stair in front of the main shrine, Ebisu Shrine, Gojō, Gojō City.(五条市五条戎神社)

36.7. B. M. J1562, Gojō, Gojō City.(五条市五条)

17.1. B. M. inside of the main gate, Sen'yō Senior High School, Kurumano-chō-Higashi, Sakai City.(堺市車之町東泉陽高校)

17.2. B. M. J246, Yanagino-chō-Higashi, Sakai City.(堺市柳之町東)

17.3. B. M. 245, Anryū, Suminoe-ku, Ōsaka City.(大阪市住之江区安立)

17.4. B. M. in front of the main building, Faculty of Science, Ōsaka City University, Sugimoto-chō, Sumiyoshi-ku, Ōsaka City.(大阪市住吉区杉本町大阪市立大学理学部)

17.5. On the lowermost stair in front of the right hand monument stone, Amami Shrine, Yata-Tonda-chō, Higashisumiyoshi-ku, Ōsaka City.(大阪市東住吉区矢田富田町阿麻美神社)

17.6. On the lowermost stair of flag pole, Gadō-Hachiman Shrine, Amami-Gadō, Matsubara City.(松原市天美我堂八幡神社)

17.7. B. M. 1379, Minami-Hanada-chō, Sakai City.(堺市南花田町)

37.1. B. M. 210.1, Minamikasa-chō, Ōtsu City.(大津市南笠町)

37.2. On the lowermost stair in front of the main shrine, Yasaka Shrine, Minamiōkaya, Ōtsu City.(大津市南大萱八坂神社)

37.3. 2nd order B. M. 1330, Minamiyamada-chō, Kusatsu City.(草津市南山田町)

37.4. On base floor of the monument stone for students, inside of the main gate, Kusatsu Junior High School, Kusatsu, Kusatsu City.(草津市草津中学校)

37.5. B. M. 209.1, Hon-machi, Kusatsu City.(草津市本町)

37.6. B. M. 209, Kasagawa, Rittō Town, Shiga Prefecture.(栗東町笠川)

18.1. B. M. 197, Miyoshi, Maibara Town, Shiga Prefecture.(米原町三吉)

18.2. On floor beside the monument stone of "Rest Place of the Emperor Meiji", Banba, Maibara Town, Shiga Prefecture.(米原町番場)

18.3. On the uppermost step of the highest stair, Kamo Shrine, Samegai, Maibara Town, Shiga Prefecture.(米原町醒井賀茂神社)

18.4. B. M. beside the main entrance of the building, Sekigahara Junior High School, Sekigahara, Sekigahara Town, Gifu Prefecture.(関ヶ原町関ヶ原中学校)

18.5. On the lowermost stair in front of the main shrine, Hachiman Shrine, Sekigahara, Sekigahara Town, Gifu Prefecture.(関ヶ原町関ヶ原八幡神社)

18.6. B. M. 193, Sekigahara, Sekigahara Town, Gifu Prefecture.(関ヶ原町関ヶ原)

19.1. 2nd Order B. M. 3851, Nishihama, Makino Town, Shiga Prefecture.(マキノ町西浜)

19.2. On the lowermost stair in front of the main temple, Saiei-ji Temple, Kaizu, Makino Town, Shiga Prefecture.(マキノ町海津西栄寺)

19.3. On the lowermost stair in front of the main temple, Fukuzen-ji Temple, Kaizu, Makino Town, Shiga Prefecture.(マキノ町海津福善寺)

19.4. B. M. in front of the Makino Town Office, Hirukuchi, Makino Town, Shiga Prefecture.(マキノ町蛭口マキノ町役場)

19.5. On base stone of the old garden lantern, in the garden behind the main temple, Saikō-ji Temple, Yū, Imazu Town, Shiga Prefecture.(今津町藺生西江寺)

19.6. B. M. 1328, Kamihirobe, Imazu Town, Shiga Prefecture.(今津町上弘部)

38.1. B. M. 1312, Kido, Shiga Town, Shiga Prefecture.(志賀町木戸)

38.2. B. M. 1311, Hachiyado, Shiga Town, Shiga Prefecture.(志賀町八屋戸)

38.3. B. M. 1310, Kitahama, Shiga Town, Shiga Prefecture.(志賀町北浜)

38.4. B. M. 1309, Wani, Shiga Town, Shiga Prefecture.(志賀町和邇)

38.5. B. M. 1308, Ono, Shiga Town, Shiga Prefecture.(志賀町小野)

38.6. B. M. 1307, Mano-chō, Ōtsu City.(大津市真野町)

20.1. B. M. 1288, Chiyokawa-chō, Kameoka City.(亀岡市千代川町)

20.2. B. M. beside the monument stone of "Memory of the Russo-Japanese War", in front of the Hiyoshi Shrine, Kawarabayashi-chō, Kameoka City.(亀岡市河原林町日吉神社)

20.3. B. M. beside the monument stone of "Happy Get-Together" in courtyard, Hozu Elementary School, Hozu-chō, Kameoka City.(亀岡市保津小学校)

20.4. On base stone of the name post of "Byōshū-ji Temple", Byōshū-ji Temple, Hiedano-chō, Kameoka City.(亀岡市稗田野町苗秀寺)

20.5. B. M. behind the name post of "Ryōtan-ji Temple" at the entrance of the Ryōtan-ji Temple, Ōi-chō, Kameoka City.(亀岡市大井町龍潭寺)

20.6. B. M. 1287, Chiyokawa-chō, Kameoka City.(亀岡市千代川町)

21.1. B. M. 1474, Higashishijimi, Jūshiyama Village, Aichi Prefecture.(十四山村東蜆)

21.2. B. M. in front of the name post of "Jinmei-sha Shrine", Jinmei-sha Shrine, Kodakara-Shinden, Jūshiyama Village, Aichi Prefecture.(十四山村子宝新田神明社)

21.3. B. M. in front of the Jūshiyama Village Office, Kodakara-Shinden, Jūshiyama Village, Aichi Prefecture.(十四山村子宝新田十四山村役場)

21.4. On the left hand frame stone of the main temple, Daihō-ji Temple, Ōdakara-Shinden, Tobishima Village, Aichi Prefecture.(飛島村大宝新田大宝寺)

21.5. B. M. inside the main gate, Tobishima Elementary School, Motokinogō, Tobishima Village, Aichi Prefecture.(飛島村元起之郷飛島小学校)

21.6. B. M. 1473, Toriganji-Shinden, Jūshiyama Village, Aichi Prefecture.(十四山村鳥ヶ地新田)

近畿地方における重力の精密相対測定

里村幹夫

要旨

重力の経年変化を検出するために，琵琶湖周辺地域において，1971年以降，重力測定を繰り返し実施してきた．さらに，使用するラコステ重力計の特性実験を通じて，より精度の高い重力測定を実施するためには，ほぼ等しい重力値をもつ測定点を選んで実施する必要があることを認め，基準点（京都大学理学部地球物理学教室，$g=979.70775$ gal）とほぼ等しい重力値をもつ測定点を琵琶湖や紀伊半島を含む地域の水準路線に沿って選び，1972年以降，そこで精密重力測定を実施してきた．さらに，測定点の空間的分布を考慮して，ほぼ979.686 galの重力値をもつ測定点も選び，そこでも同様の精密測定を実施してきた．

重力測定結果の精度について，さまざまな観点から検討した．その結果，精密重力測定の精度は標準偏差で10μgal程度と考えられる．

重力測定により得られた結果を，水準測量，琵琶湖の水位測定，検潮，地下水位および三角測量の結果と比較した．得られた重力変化は，水準測量から得られた上下変動とはあまり相関を示さなかったが，湖水位や検潮記録から得られたそれとはかなりよい相関が認められた．短距離の範囲で上下変動を検出するには，精密重力測定は水準測量に比べ精度面で劣る．しかし，精密重力測定は，遠く離れている2点間においてもそれらを直接結合できるという利点がある．水準測量ではこれが不可能であるが，湖水位や検潮は重力測定と同じ利点をもっている．今回の結果は，これらに共通した利点の現われかもしれない．

一方，紀伊半島の先端部において重力の増加が観測された．この一部はフィリピン海プレートの押しによる陸側の地殻の圧縮により説明できるであろう．