12. *Notes on Correlation between Vertical Earth Movements and Gravitational Anomalies.*

By Naomi MIYABE,

Earthquake Research Institute.

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1. Recently, lines of levels have been rerun in various parts of Japan, and vertical displacements of the earth's crust are known to have occurred along these level lines during the last few decades. These vertical earth movements, as is well known, consist of two components, the one due to acute deformations of the earth's crust associated with the occurrence of earthquakes or volcanic eruptions and the other due to chronic movements integrated over time intervals corresponding to the successive levellings. As to the acute movements associated with earthquakes, Prof. M. Ishimoto[1] has discussed it in connection with his theory of the mechanism of earthquakes. Chronic movements of the earth's crust may, however, be regarded as being due to orogenic or epirogenic movements, and they may to a certain extent be related to geological structure, especially subterranean structure, of which we know next to nothing from the surface evidences. The amounts of the gravitational anomalies may indicate certain physical conditions of the subterranean structure. The theory of isostasy is supposed to elucidate gravitational anomalies, which are regarded as due principally to subterranean structure. On the other hand, however, it may not be necessary to regard the earth's crust as being everywhere in perfect isostatic equilibrium. It may therefore be possible to obtain some information regarding the origin of the chronic vertical earth movements if we could investigate the correlations between the vertical earth movements and the gravitational anomalies. This the writer discusses in the present paper.

2. The vertical movements of the earth's crust may also be detected through appropriate method of reduction from mareogram data from various stations covering some twenty years or more. The movements

1) M. ISHIMOTO, *Bull. Earthq Res. Inst.*, **11** (1933), 254.

of the sea level recorded in the mareograms contain several components due to astronomical and meteorological disturbances with semi-diurnal, diurnal, fortnightly, and annual periods. The annual mean values of the sea level therefore give the approximate mean sea level. For longer time intervals, however, several tens of years for example, the annual mean sea level oscillates with a period of about 19 years, the period of the motion of the moon's nodes. To obtain the component that may be due solely to crustal movements, these long-period oscillations of the annual mean sea level must be smoothed out. Examination of the actual curve showing the variation of the mean sea-level during tens of years shows that oscillations with periods of about 9·5 years and 19 years predominate. Hence, the annual mean sea level, h, is expressed as a function of the time, t, in the form

$$h = A + at + R_1 \sin(pt + e_1) + R_2 \sin(2pt + e_2),$$

where $p = 2\pi/T$ and T is the period of oscillation of mean sea level, that is 19 years. The constants in the above expression, A, a, R_1, R_2, e_1, and e_2 are determined by utilizing the data of annual mean sea level, measured continuously in these tens of years at various mareograph stations, by the method of least squares.[2] The constant a in the above expression denotes the rates of vertical displacements at the place where the mareograph station is situated. The values of a thus determined for the mareograph stations of Hanasaki, Ayukawa, Kusimoto, Hosozima, Aburatubo, Osyoro, Iwasaki, Wazima, Hamada and Hukabori are shown in Table I.

Table I. Values of a at various mareograph stations, which are considered as the rates of the vertical earth movements.

Mareograph Station		Longitude λ	Latitude ϕ	a
Pacific coast	Hanasaki	145° 35′ E	43° 20′ N	−4·3 mm./year
	Ayukawa	141° 30′ E	38° 13′ N	−0·6
	Aburatubo	139° 37′ E	35° 09′ N	−4·5
	Kusimoto	135° 46′ E	33° 28′ N	−4·8
	Hosozima	131° 40′ E	32° 25′ N	+4·0
Coast of Sea of Japan	Osyoro	140° 51′ E	43° 13′ N	−2·5
	Iwasaki	139° 55′ E	40° 35′ N	+0·3
	Wazima	136° 50′ E	37° 27′ N	−1·4
	Hamada	132° 06′ E	34° 52′ N	0·0
	Hukabori	129° 49′ E	32° 41′ N	−0·2

2) The value of a is thus calculated and published in *Bulletin of the Hydrographic Department of the Imperial Japanese Navy*, **7** (1933).

The geographical distribution of the mareograph stations is shown in Fig. 1, in which the numerical figures against the stations denote the values of a deduced from the data of corresponding stations.

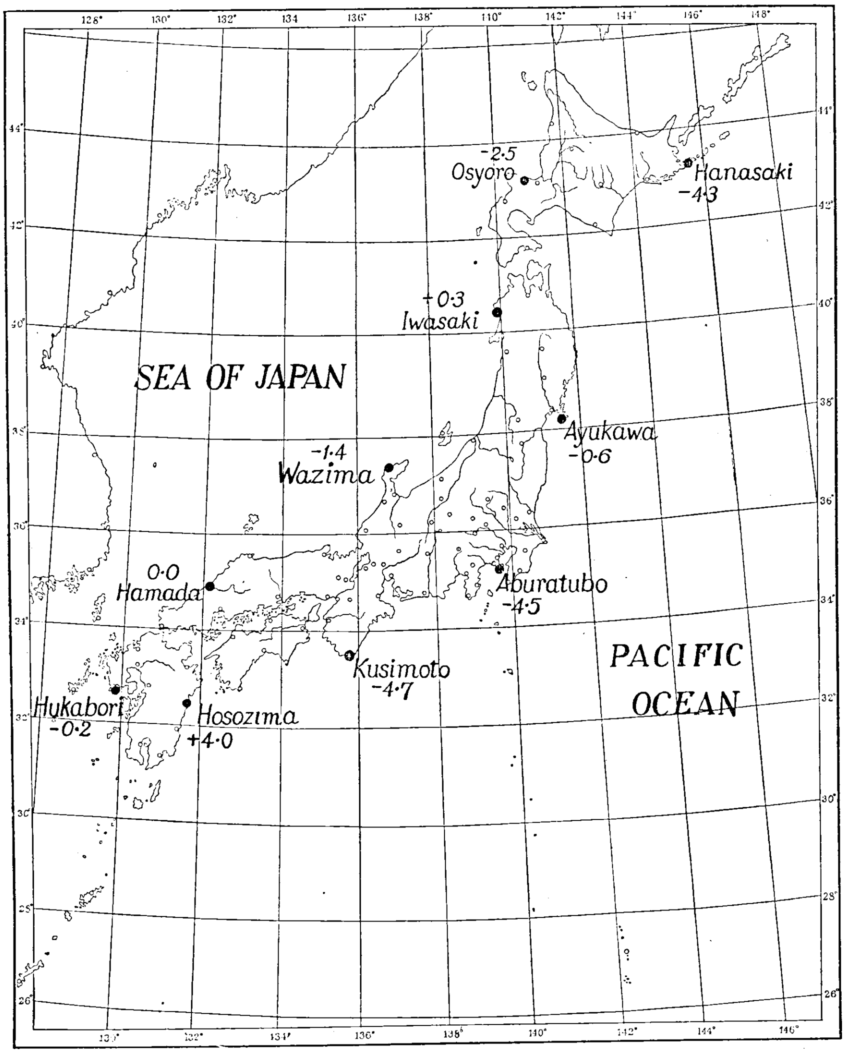


Fig. 1. Geographical distribution of mareograph stations.

As may be seen in the figure, the vertical movements of the earth's crust are upward at Hosozima and Iwasaki, whereas they are downward at the other stations. The rates of downward or upward movements of the earth's crust thus deduced are generally greater for stations along the Pacific coast than for stations along the Sea of Japan. Of these, the rate of downward crustal movement at Kusimoto amounts to 4·8 mm/year which is a vertical displacement of −144 mm., as integrated over a time interval of 30 years. It is interesting to note that the amount of vertical displacement thus calculated approximately agrees with the amounts of vertical displacements of the bench-marks situated near Kusimoto as shown by recent relevellings[3].

The values of a are plotted against the values of the gravitational anomalies[4] at the corresponding stations as estimated by interpolation, and shown in Fig. 2, in which we notice an approximate negative correlation; that is, the values of gravitational anomalies are negative for the mareograph stations Hosozima and Iwasaki, where the values of a are positive, whereas they are positive for Hanasaki, Ayukawa, Osyoro, Kusimoto, Wazima, Hamada and Hukabori, where the values of a are negative. The negative value of the gravitational anomaly at Aburatubo cannot be trusted, since the gradient of the gravitational anomaly is very large in this neighbourhood, hence difficult to say whether it is negative or positive. The positive correlation between Δg and ΔH in the Kwantô district, including Aburatubo, will be discussed later. The fact that the rate of vertical displacement of the earth's crust as deduced from the series of mareogram data are, on the whole, in negative correlation with the values of gravitational anomalies, suggests that chronic earth movements may now be in progress for the restoration of isostatic equilibrium. We feel the need of further investigations with respect to the vertical displacements of the bench-marks along the level lines.

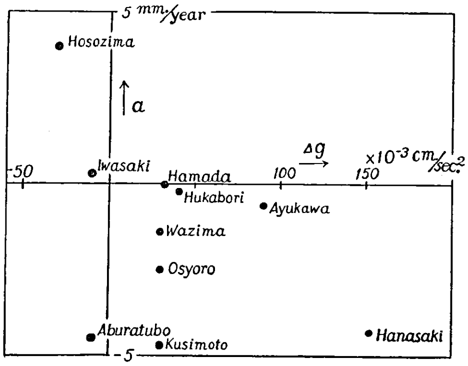


Fig. 2. Relation between Δg and a.

3. In order to obtain the values of the gravitational anomalies along

3) N. MIYABE, *Bull. Earthq. Res. Inst.*, 11 (1933), 278, etc.

4) The values of gravitational anomalies here employed are those reduced by Prof. Matuyama and Dr. Kumagai, Kyôto Imperial University, taking into account the effect of isostatic compensation, after Hayford; The paper was read at the 1933 meeting of the Gakuzyutu Kyôkai, at Hirosima.

the level lines, equi-anomaly lines are drawn by using the data of anomalies calculated by Prof. Matuyama and Dr. Kumagai, as shown in Fig. 3. From this figure, the gravitational anomalies along the level lines are estimated by interpolation and compared with the vertical displacements of the bench-marks that occurred during the 30–40 years interval.

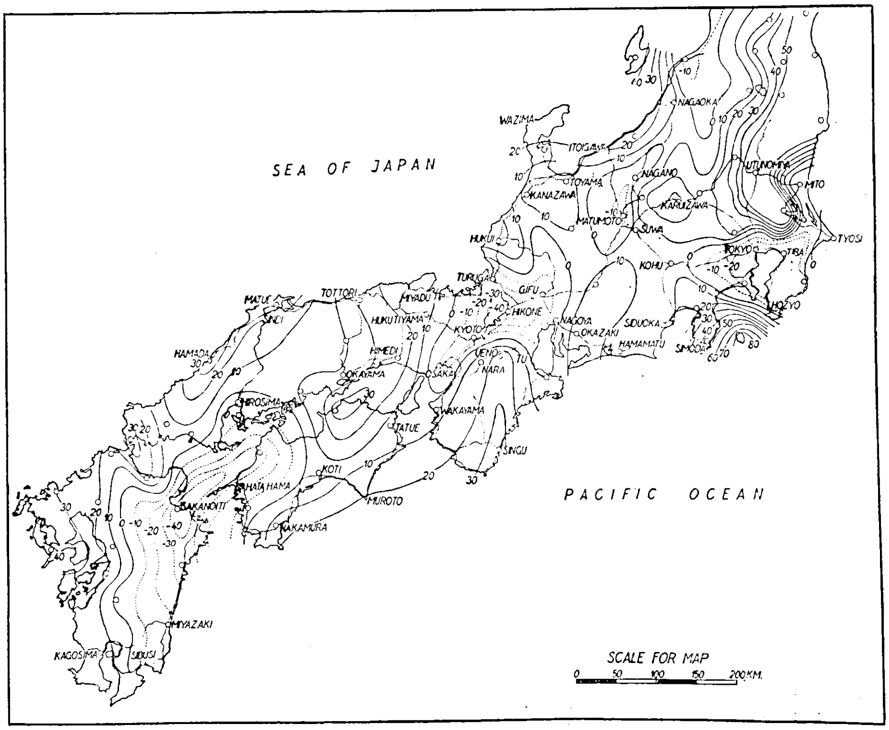


Fig. 3. Distribution of gravitational anomalies.

In Fig. 4, a, b, ... p, the mean vertical displacements for every 25 km. along the level lines are plotted against the values of the gravitational anomalies estimated in the manner described above for the same sections of the level lines.

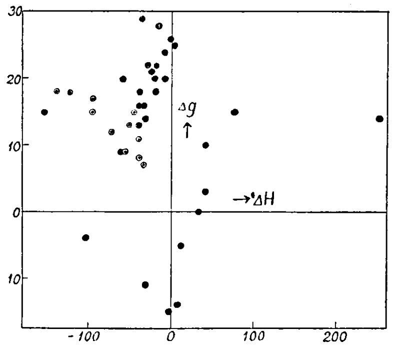
From these figures, we notice that although in several regions the correlation between the gravitational anomalies, Δg, and the mean vertical displacements, ΔH, is negative, in several others it is positive. The regions of positive correlations are

(i) the Kwantô districts,

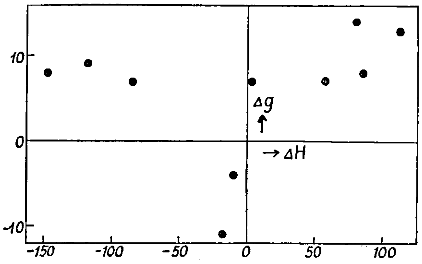
(ii) the regions in the neighbourhood of Toyohasi, Okazaki and Matumoto,

(iii) the Tango districts,

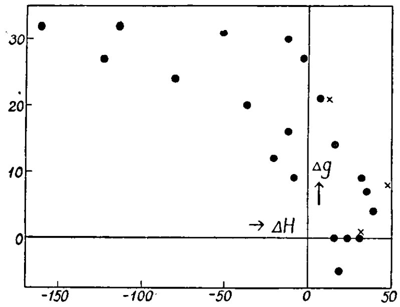
Fig. 4 Showing the relation between Δg and ΔH along the sections of levelling routes. Units for Δg and ΔH are 1/1000 cm/sec² and mm. respectively.



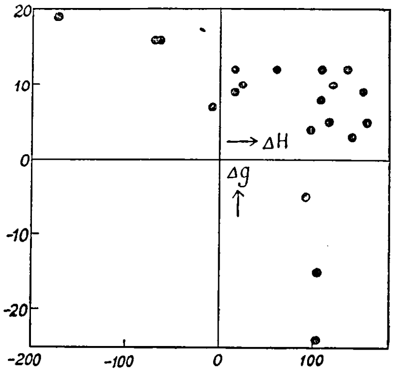
a) Along the coast of Sea of Japan.
⦿ : for the section between Takaoka and Nagaoka.



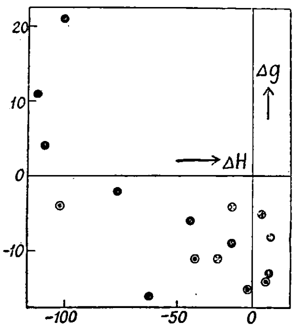
b) Kuwana-Okitu.



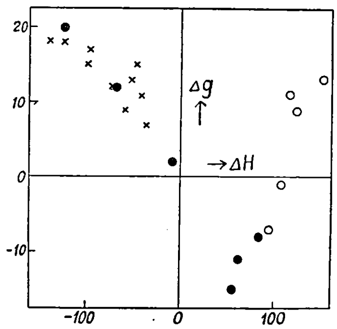
c) ● : Wakayama-Singû-Yokkaiti.
× : Issinden (Tu)-Ueno.



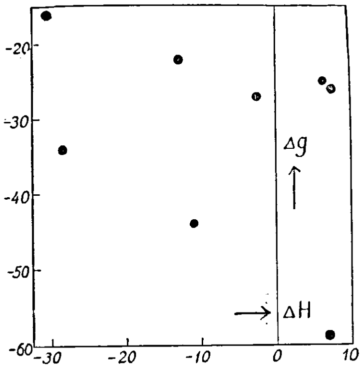
d) Along the Pacific coast of Sikoku. (Tatue-Muroto-Kôti-Susaki-Nakamura-Yabatahama)



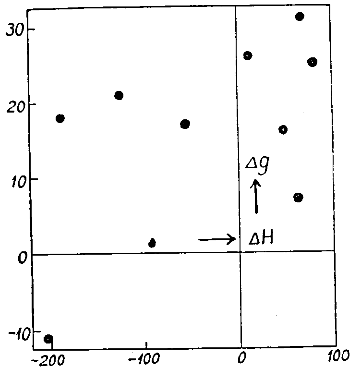
e) ● : Hukui-Nagoya.
⦿ : Miyake-Hukui-Daisyôzi (a section along the coast of Sea of Japan).
⊗ : Nagoya-Kuwana.



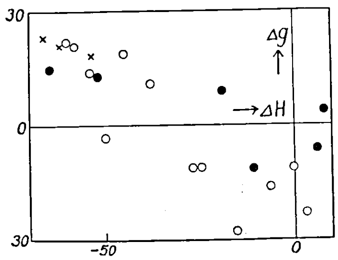
f) ● : Itoigawa-Matumoto.
× : Takaoka-Itoigawa-Nagaoka.
○ : Matumoto-Gihu.



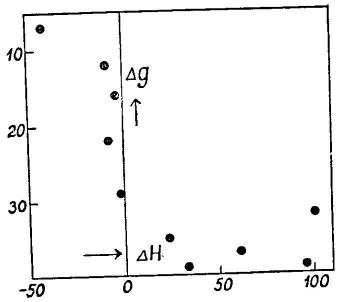
g) Bôsô Peninsula.
(ΔH is due to 1924–1932).



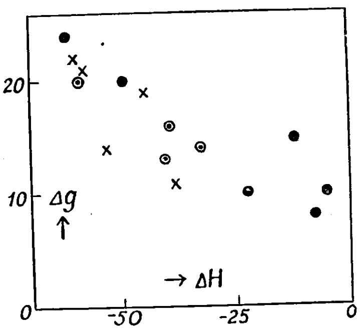
h) Simosuwa-Takasaki-Tokyo



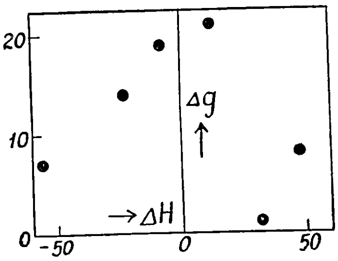
i) ○ : Okayama-Himedi-Osaka-Kyôto-Hikone.
× : Himedi-Yasika.
● : Yasika-Kyôto.



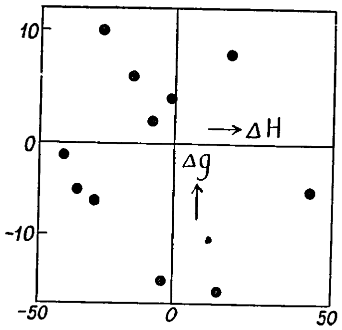
j) Kyûsyû (Miyakonozyô-Sakanoiti).



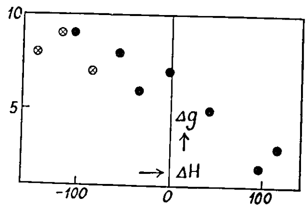
k) ⊙ : Akazaki-Tottori (along the coast of Sea of Japan).
● : Tottori-Okayama.
× : Okayama-Akasi.



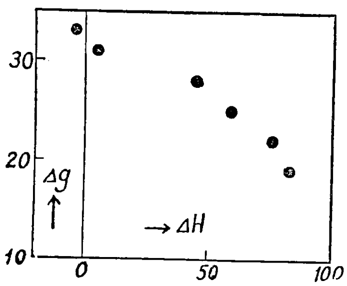
l) Sakai (Osaka)-Issinden.



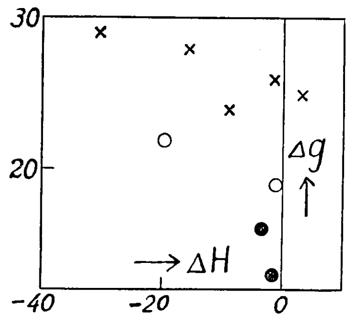
m) Simosuwa-Nagaoka.



n) ●: Simosuwa-Okitu.
⊗: Okitu-Simada.



o) Singû-Gôzyô (Kii Pen.).



p) ×: Hamada-Sindi.
○: Sindi-Miyosi.
●: Miyosi-Hirosima.

(iv) the regions in the neighbourhood of Nara and Ueno (Iga),

(v) the regions in the neighbourhood of Uwazima (Sikoku) and Hirosima,

(vi) The region in neighbourhood of Kanazawa,

These regions of positive correlation are shown in Fig. 5 by hachured zones along the level lines, while, in the same figure, the regions of negative correlation are the thick lines showing the lines of levels.

4. The negative correlation between the vertical earth movements and the gravitational anomalies may suggest, as already stated, that chronic earth movements are going on as a whole to restore the isostatic equilibrium of the earth's crust. Since, however, there are several regions where the correlation is positive, these crustal movements may not only be due to movements to restore the isostatic equilibrium, but to several other causes as well. The theories concerning the possible origins of the crustal movements are as follows;

i) Deformation of the earth accompanying changes in the period of rotation and "Polschwankungen",[5)]

ii) Continental drifts[6)] or flows of subterranean magmas,

iii) Changes in the configuration of the isothermal surfaces in the interior of the earth's crust,[7)]

iv) Movements to restore the isostatic equilibrium, probably due to the fact referred to in the foregoing paragraphs.

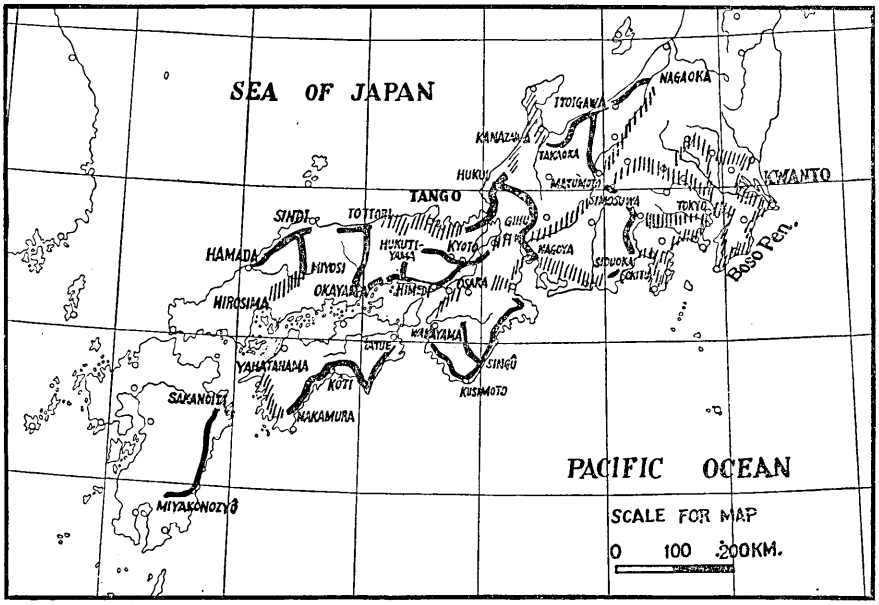


Fig. 5. Districts of negative (full lines) and positive (hachured) correlations.

The mode of general crustal movements are more or less disturbed by movements of the crustal blocks composing the earth's crust, which does not always follow the general crustal movement.[8)] The existence of these crustal blocks results in fluctuations in the curves superposed on the general crustal movements which may be smoothed out by taking the mean vertical displacements over every 25 km. of the lines of levels.

The measured crustal movements may of course be the results of the combined effects of the above mentioned possible origins. Hence, it

5) It may, of course, not always be appropriate to say that "Polschwankungen" is the origin of the crustal movements, but it is sometimes more appropriate to say that local deformation of the earth's crust is the cause of the "Polschwankungen".

6) A. WEGENER, "Die Entstehung der Kontinente und Oceane", (Braunschweig, 1929).

7) J. JOLY, "The Surface History of the Earth", (Dublin, 1923).

8) N. MIYABE, *Bull. Earthq. Res. Inst.*, **11** (1933), 278, etc.

is probable that in several districts, as stated in the preceding paragraph, the crustal movements to restore isostatic equilibrium are not apparent in those measured from the results of recent relevellings, when the movements due to the other causes are more predominant.

As for the crustal movements in the Kwantô districts, however, it is generally believed that they are associated with the destructive earthquake of 1923. This may be the probable cause of the positive correlation between Δg and ΔH, though we cannot explain it, since the post-seismic vertical earth movements in the Bôsô peninsula are found to be roughly in negative correlation with Δg. It may be related in some way with the positive correlation in the Kwantô and several other districts, that, as has been pointed out by Dr. C. Tsuboi[9], the frequent occurrence of earthquakes might be closely connected with negative gravitational anomalies.

The positive correlation between Δg and ΔH in the Tango district may also be due to conspicuous disturbances of the earth's crust in association with the destructive earthquake of 1927. Thus, so far as I am aware, vertical earth movements in association with destructive earthquakes are found to be in positive correlation with the gravitational anomalies. A similar case is found in region (v), mentioned in the preceeding paragraph. In this region, the gravitational anomalies are negative and the vertical earth movements, though not so conspicuous, are downward. Conspicuous earthquakes have occurred rather frequently in this region during the last few decades.

In the other districts, where the correlation is positive, that is, districts (ii) and (iv), conspicuous earthquakes have been rather rare. Considering the zone including these districts of positive correlation (ii), (iv), and (v), we notice that the region in the neighbourhood of Wakayama is also included. In this region, where have occurred an enormous number of earthquakes in the last few years, the earth's crust was found to have upwarped.[10] On the other hand, this zone is found approximately to coincide in position with the "median line" of Southwest Japan, a line of much significance in the geological structure of Japan.

5. From the foregoing discussions, we may roughly conclude that deformation of the earth's crust is in progress mainly to restore isostatic equilibrium, analogous with the crustal movements along the coast of

9) C. Tsuboi, *Proc. Imp. Acad.*, 5 (1929), 326.
10) A. Imamura, *Disin*, 4 (1932), 474, (in Japanese).

the Baltic Sea in Northern Europe[11], except in such districts as where the correlation between Δg and ΔH is positive. In these latter districts, orogenic or epirogenic movements other than isostatic seem to be predominant.

In conclusion, the writer wishes to express his sincere thanks to Professor Torahiko Terada for his kind advices and suggestions.

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12. 地殼の垂直變動と重力異常の分布

地震研究所 宮 部 直 巳

本邦各地に於て水準測量の再測が施行された結果，地殼の垂直變動に關する我々の知識はかなり豐富になつてきた．是等の變動の中には地震に伴つて起つた比較的急激な變動をも含んでゐる．併し，もつと緩徐な變動も勿論起りつゝあると考へなければならない．是等の緩徐な地殼の運動は色々な意味を持つものと考へられる．例へば，造山運動とか，造陸運動とか，又は地球全體としての變形に伴ふ樣な運動とかいふものゝ顯はれであるとも考へられる．

何れにしても，地殼が平衡の狀態に近づかうとする樣な運動が一つの主要な成分であらうとは考へるに難くない．そこで，垂直變動と，重力の異常の分布とを比較してみると，第5圖の實線で描いた水準線路に沿う地域では兩者が大體に於いて負の相關を示し，地殼が重力的平衡を恢復しやうとする樣な變動のあることが暗示される．たゞ，關東地方，丹後地方西南日本の中央線に沿ふ區域その他二三の地域で正の相關を示すところもあるが，其等の地域では地震の頻發其他の事情から，その他の重力的平衡への運動の著しい地域とは異つた意味の變動が卓越してゐると考へられる．

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11) A. WEGENER, *loc. cit.* 6).