Undulation of Electrically Conducting Layer

beneath Japan Islands*

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Summary

Geomagnetic variation anomalies in Japan, physically plausibe explanation of which has so far been difficult, are approximately accounted for by assuming an undulation of mantle conducting layer. The undulation seems to be correlated with that of high-temperature isotherm, 1200°C say.
The surface of the conducting layer is shallow in Japan Sea and off the Pacific coast of western Japan, while it is as deep as 200 km or more beneath the Pacific coast of north-eastern Japan. Extreme anomalies which have been unable to explain until recently are likely to be caused by island and peninsula effects on short-period geomagnetic variations.

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1. Introduction

The geomagnetic variation anomaly in Japan reflects an unusual distribution of the electrical conductivity in the earth's crust or upper mantle beneath Japan Islands. As has been summarized by the present writer (Rikitake, 1966), the anomaly is characterized by an enhancement of the vertical magnetic field (ΔZ) for geomagnetic bays and similar changes at observatories along the Pacific coast of central Japan. ΔZ is usually so large that its amplitude is about the same as that of ΔH (change in the horizontal field) at observatories in the central part of the anomalous area. The anomaly having been called by the writer the central Japan anomaly, no plausible way of accounting for such an anomaly has so far been put forward. It has rather been proved that an extremely artificial model should be assumed for reasoning the cause of the anomaly.

A research group for a more intensive study of the anomaly has been organized by Japanese geophysicists since 1963. To our great surprise a localized anomaly of opposite sign was then found by the organized observations in the north-eastern Japan (Kato, 1968). ΔZ is positive or downward for the central

Japan anomaly when ΔH points to the north, while ΔZ for the north-eastern Japan anomaly is directed negative or upward for the same ΔH. Hence, possible explanation of these anomalies becomes even more difficult. The distribution of $\Delta Z/\Delta H$ value when the geomagnetic field changes in the north direction is shown in Fig. 1 on the basis of the data available by now.

In additon to nation-wide observations, detailed observations of geomagnetic change have on the other hand been undertaken in parts of Japan. Sasai (1967, 1968 b) conducted a series of variographic work on an island about 100 km south of Tokyo. A conclusion that geomagnetic changes of short period are greatly influenced by the magnetic field produced by electric currents induced in the surrounding sea is reached by Sasai.

His work has then been extended to the central area of the central Japan anomaly (Sasai, 1968 a) where he found that ΔZ decreases very steeply towards inland. For a rapid change having a duration time of a few minutes, the rate of decrease is so large that ΔZ becomes about half within a distance of 50 km or so. As the work was carried out over Kii Peninsula, we may call such an effect on geomagnetic changes the peninsula effect, while the effect as mentioned in the last paragraph may also be called the island effect. It appears to the writer that both the effects play an important role on the interpretation of the Japanese anomalies.

Heat flow work has been very intensively conducted in and around Japan since 1955 (Horai and Uyeda 1963; Uyeda and Horai, 1964; Uyeda and Vacquier, 1968). It seemed difficult to correlate the heat flow distribution directly to the geomagnetic variation anomaly until recently. But the writer is now inclining to think that it is the time to discuss possible correlation between them.

In view of these geomagnetic and geothermal data accumulated in recent years, the writer thinks that it would be a good thing to present a model of the underground structure which possibly accounts for the geomagnetic variation anomalies in Japan.

2. Island and peninsula effects on rapid geomagnetic changes

Fig. 2 shows an example of spatial distribution of short-period geomagnetic change over Oshima Island about 100 km south of Tokyo. Changes in the horizontal intensity (ΔH) and declination (ΔD) are almost the same for all the stations. But ΔZ (change in the vertical field) shows a reversal between the northern and southern stations. It has been proved by Sasai (1968 b) that such a remarkable effect on geomagnetic changes could be ascribed to the induced electric currents in the surrounding sea. Care should be taken, therefore, for interpreting geomagnetic variations observed on an island. Sasai has also shown that the station on the west coast of the island (Fig. 2) is affected very little by the island effect. The fact that $\Delta Z/\Delta H$ amounts to 0.5 or thereabouts there indicates that the island is situated in an area covering the central Japan anomaly because $\Delta Z/\Delta H$ for a non-anomalous observatory is much smaller.

An example of simultaneous record at stations on Kii Peninsula in central Japan is shown in Fig. 3 (Sasai, 1968 a). We see a sharp peak in the Z trace for near-shore stations. The peak diminishes very quickly as we go inland. In the case of a rapid geomagnetic change as shown in Fig. 2, induced currents encircle the peninsula and a strong vertical field is produced at near-coast stations. It has been known that $\Delta Z/\Delta H$ ratio near the extremity of the peninsula amounts to 1.0 or more. Taking into account the spatial distribution of geomagnetic change thus made clear, however, it seems likely that only the most inland station is free from the peninsula effect. $\Delta Z/\Delta H$ ratio amounts to about 0.5 there, so that the central Japan anomaly could be accounted for provided an underground model which leads to a $\Delta Z/\Delta H$ ratio as large as 0.5

or so at maximum is formed. Interpretation of the Japanese anomalies has so far been difficult because it is required to explain the reason why a $\Delta Z/\Delta H$ value as large as 1.0 is observed. The situation has now changed very much because $\Delta Z/\Delta H$ values exceeding 0.5 seem to be ascribed to the peninsula effect, so that all we have to do is to look for a model which provides $\Delta Z/\Delta H$ ratios amounting to 0.5 at maximum.

3. Perfect conductor model which accounts for $\Delta Z/\Delta H$ values

It has been well-established that the conducting part of the mantle behaves as if it is perfectly conducting for a geomagnetic change having a duration time of 10 minutes or so. Let us assume that the major parts of the geomagnetic variation anomaly are caused by undulation of sub-surface perfect conductor. Even so, there is no unique way of determining the depth of conductor. In order to get at a crude configuration of the conductor, we shall proceed in the following way.

Let us for instance take a profile along a north-south line approximately perpendicular to the trend of the anomaly and passing through Kii Peninsula which is shown in Fig. 3. We skip observations at near-shore stations because they are likely to be contaminated by fields due to the peninsula effect. The $\Delta Z/\Delta H$ value at the most inland station is assumed to be explained by distortion of magnetic lines of force, which are originally almost horizontal, due to a sharp drop of the top-surface of the conductor. The distribution of $\Delta Z/\Delta H$ associated with such a step model has been given by Schmucker (1964). Having no information about the position of the step, it is arbitrarily assumed that the drop takes place under a point in the sea 50 km distant from the coast. In that case the top-surface drops from a depth of 50 km off Kii Peninsula. The depth of the conductor far off the Pacific coast is here taken as 50 km as suggested for the 1200°C isotherm by Watanabe (1968) and Uyeda (1968) on the basis of heat flow measurement. Strictly speaking, we have no stations farther north along the line concerned, but it is possible to have an interpolated $\Delta Z/\Delta H$ value at a point close to Japan Sea. $\Delta Z/\Delta H$ being negative and small there, the step imagined in Japan Sea is of small scale. The depth of the conductor under Japan Sea is assumed as 4 0 km because of high heat flow there.

The profile of the conductor can roughly be the one in which the top-surface beneath the land is expressed by a straight line connecting the bottom of the two steps. In this particular case, the shape of the subsided condcutor is nearly a half regular triangle. Magnetic lines of force over such a depression of conductor can be calculated with the aid of the relaxation method (e.g. Rikitake, 1966) as shown in Fig. 4. The horizontal and vertical fields as can be imagined from Fig. 4 seems roughly compatible with the geomagnetic variation anomaly actually observed although no detailed discussion is possible because of scanty observation.

A number of similar profiles are drawn mostly in western Japan and Hokkaido. In north-eastern Japan, it is difficult to form a profile perpendicular to the trend of the anomaly because most of short-period geomagnetic changes point to the north-south direction which roughly agrees with the trend. The writer relies therefore on the Parkinson vectors (Parkinson, 1959), by which we can obtain the direction of a plane in which vectors of geomagnetic bays and similar changes are confined, as given by Kato and his colleagues (Kato, 1968). At places, where we have no geomagnetic observation, sea floor for example, it cannot be helped to reply entirely on heat flow values assuming the thermal conductivity, rate of heat generation and dependence of electrical conductivity on temperature.

In Fig. 5 is shown the over-all distribution of the contours for the depth of the conductor from the earth's surface. One of the most remarkable things to be pointed out is certainly the contours in the western half of Japan Islands,

i. e. they run parallel to the axis of the islands. The area over which the central Japan anomaly of geomagnetic variation prevails is associated with a marked depression of the conductor which is as deep as 200 km or more. The underground structure immediately beneath the north-eastern Japan anomaly is not very clear because we need more detailed data for clarifying such a localized anomaly.

4. Discussion and conclusions

It is interesting to note that an analysis of the geomagnetic variation anomaly in Japan results in an extensive undulation of conducting mantle. The depths shown in Fig. 5 may roughly be interpreted as those of the 1200°C isotherm. Although Japan is one of the countries over which we have very dense heat flow measurements, it would not be possible to present such a detailed distribution of mantle temperature from heat flow data only.

The depression of conducting mantle exceeding 200 km along the Pacific coast of Honshu Island harmonizes well with the low heat flow area. The low-temperature mantle seems to be extended off the Pacific Ocean. In contrast to the Californian coast (Filloux, 1967), the sub-surface conductor is deep beneath the ocean, but it gets shallower as we go inland.

Uyeda (1968) called the latter type margin of continent the island arc type, while the former is called the normal continental margin type. The writer has no intention to discuss continental margins and island arcs in general. But the point that observation of short-period geomagnetic variations provides a powerful means for studying continental margins should be emphasized.

The cold mantle beneath the Pacific side of north-eastern Japan and the hot mantle off the Pacific coast of western Japan as seen in Fig. 5 are also supported by analyses of seismic surface waves (Kanamori and Abe, 1968).

Impossibility of accounting for the geomagnetic variation anomaly in Japan by a physically conceivable model has often been pointed out. After eliminating island as well as peninsula effects which are brought to light quite recently, however, it seems highly likely that the Japanese anomalies can be approximately explained by assuming a certain undulation of the mantle conducting layer. Such an undulation, which is possibly correlated to that of high-temperature isotherm, seems generally compatible with the mantle structure suggested from other geophysical elements such as heat flow, seismic surface waves and the like.

The above conclusion is reached by summarizing various work carried out by the members of a research group for conductivity anomaly in Japan. The discussions presented at a symposium held at Kakioka Magnetic Observatory on December 6 and 7, 1967 are especially helpful.

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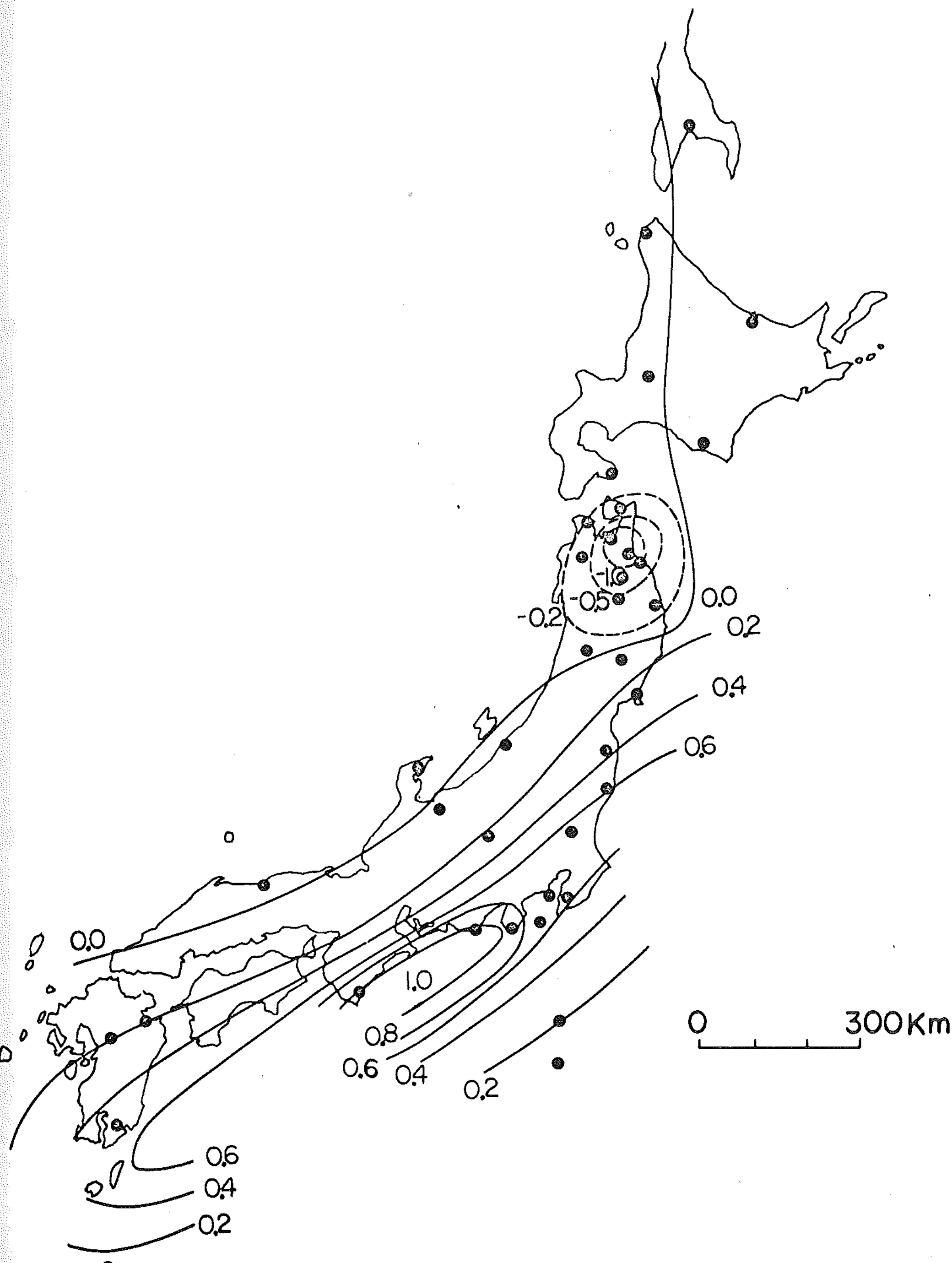

Fig. 1 ΔZ/ΔH value distribution over Japan for geomagnetic bays and similar changes.

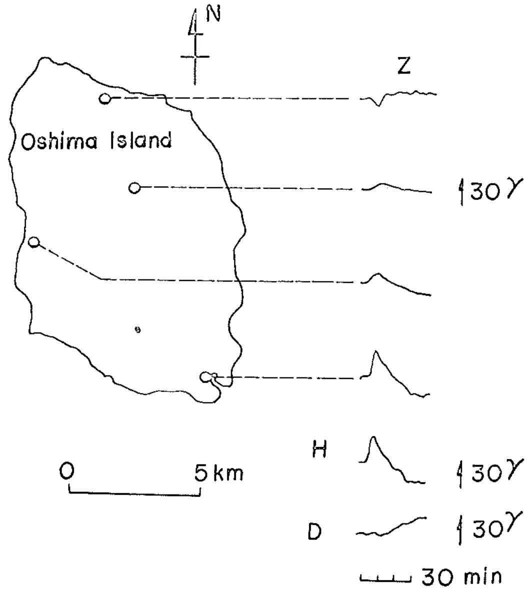

Fig. 2 Magnetograms simultaneously obtained at four stations on Oshima Island (After Sasai).

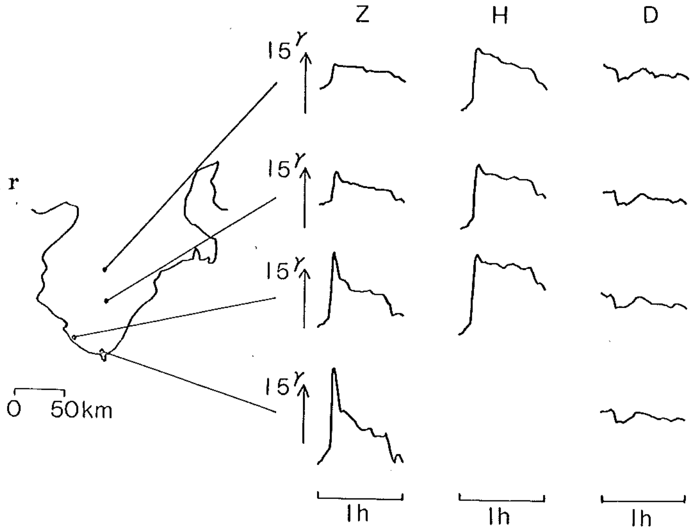

Fig. 3 Magnetograms simultaneously obtained at four stations on Kii Peninsula (After Sasai).

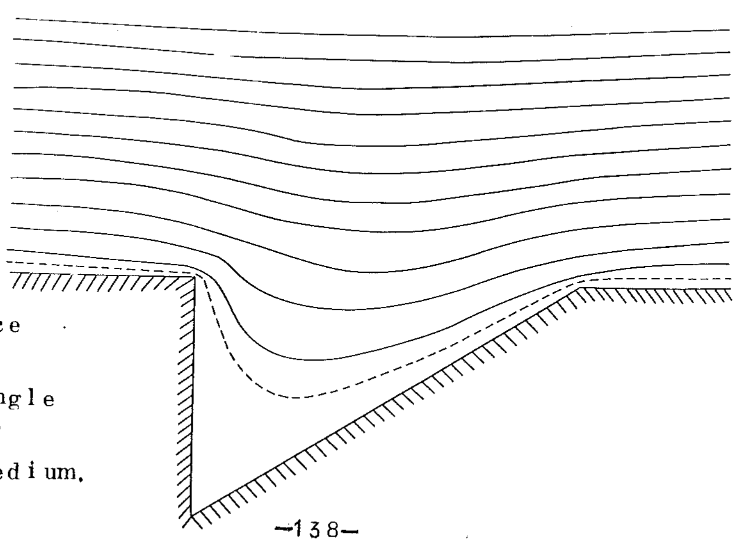

Fig. 4 Magnetic lines of force over a half regular triangle depression of conducting medium.

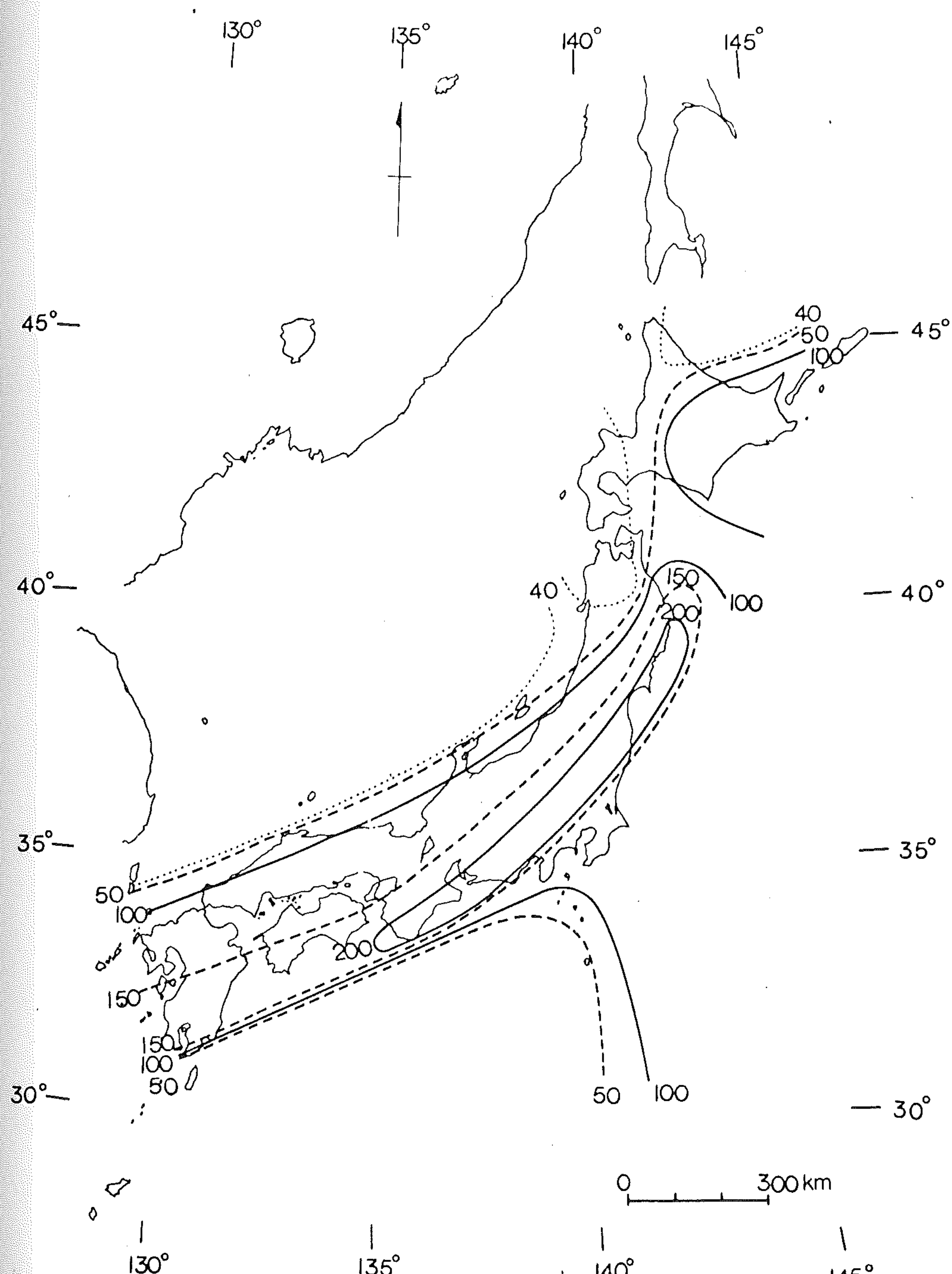

Fig. 5 Depths of mantle conducting layer in units of km underneath Japan Islands.