20. *Electrical State and Seismicity beneath Japan.*

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Summary

A hypothetical model of the upper part of the earth's mantle beneath Japan is proposed. In order to account for the low electrical conductivity as has been derived from the study on geomagnetic daily variation, it is assumed that the substance, which usually consists of the layer between the earth's surface and the depth of 400 *km*, wedges into the lower part under Japan as deep as 700 *km*, the width of the wedge being taken to be 200 *km*. By this model, we can roughly explain the low conductivity there as well as the occurrence of deep focus earthquakes, the latter being likely to be caused by the shearing stresses due to the buoyancy force.

1. Introduction

Geomorphological, geological and geophysical characteristics of orogenetic or mountain building zones have been investigated by many authors. One of the most typical examples is found along an arc connecting Kamchatka, the Kurile Islands, North-east Japan, the Seven Izu Islands and the Mariana Islands. East of the arc, there is the deep Japan trench, its depth exceeding 8,000 *m* at some places. A remarkable negative anomaly of gravity falls on the trench, while a positive one is associated with the Seven Izu Islands and the submarine ridges. As for the seismic activity in the region, we see a particular distribution of origins of earthquakes. Suppose a vertical plane perpendicular to the arc, the origins of earthquakes are distributed along a line dipping down from the Pacific side to the continent making an angle of about 45° from the horizontal plane. The upper end of the line terminates in the neighbourhood of the trench where a lot of shallow-focus earthquakes are occurring. Deep-focus earthquakes have been reported there even at a depth of 700 *km*. The belt under which we observe deep-focus earthquakes runs along the Mariana Islands and the Seven Izu Islands, crossing the main island of Japan and reaching somewhere under Vladivostock. It turns then to the north-east direction running along the north-west side of the Kurile Islands. The distribution of shallow, intermediate and deep focus earthquakes suggests that a curved surface or shell having special conditions related to earthquake occurrence exists under this area. The trench is roughly corresponding to the intersection of this surface or shell and the earth's surface, while the belt for the deep-focus earthquakes is likely to indicate the lower extent of the surface or shell.

The trend of volcanic zones is nearly parallel to the arc in question. Petrological examinations of volcanic rocks also enable us to imagine some special conditions in the earth's interior underneath the arc. Alkali rocks are usually found on volcanoes in the Pacific Ocean and on the continent, while calcalkali rock province are spread all over the arc. Along the belt of deep-focus earthquakes, calcalkali rocks are seldom found. Since it is generally accepted that alkali rocks are directly effused from the deep peridotite layer and that calcalkali ones are subject to chemical changes in the course of effusion by the influence of sedimentary rocks, the characteristic distribution of these rocks and its relation to the arc are, no doubt, closely related to the prevailing conditions in the earth's interior under the area.

The late Professor Y. Otuka[1] gave a geological interpretation of the arc mentioned above. Summarizing all the geomorphological, geological and geophysical knowledge, he tried to construct a geological model of the earth's interior which could account for all the phenomena observed there. He assumed that local changes in pressure occur within a zone with a certain width dipping about 45° NW, the zone intersecting the surface at the general trend of the north-west margin of the Japan trench. A highly viscous substance might be produced in the basaltic layer by the local pressure change supposed here, resulting in an upward motion in the layer. The upwarping and volcanic activity on the main island of Japan could be explained by this upward motion. The downward movement compensating the upward one would be the cause of the subsidence of the ocean floor. The formation of the trench could be explained in this way.

B. Gutenberg and C. F. Richter[2] have paid attention to the characteristics of the Kamchatka–Japan–Mariana arc. They showed a schematic section of the Hokkaido area in which we can clearly see the relation between the gravity anomaly, volcanoes, trench and foci of

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1) Y. OTUKA, *Bull. Earthq. Res. Inst.*, **16** (1938), 201.

2) B. GUTENBERG and C. F. RICHTER, *Seismicity of the Earth*. 2nd ed. (1954), 24.

earthquakes. J. Coulomb[3] has also shown the same section together with one for Java Island, while J. T. Wilson[4] has shown a generalized section across an active island arc.

The cause of the development of arcs of this sort has been discussed in relation to the nature of orogenetic process. The importance of convection currents which might occur in the earth's mantle has been suggested by many authors. The rupturing and yielding in the upper part of the mantle and crust might also be expected if we take the view that the outer shell of the earth is subject to thermal contraction, whence ruptures along conical zones such as indicated by deep-focus earthquakes may be formed. From the geophysical standpoint, however, both the theories of convection and contraction are not satisfactory because they are proposed on the basis of many assumptions. Some more direct evidence related to the physical state beneath the orogenetic belt would be needed for further discussion.

The writer and his colleagues[5,6,7,8,9] have been investigating the anomalous behaviour of transient geomagnetic variations in Japan. It was found that the anomaly has nothing to do with the exterior of the earth, but is caused by induced electric currents flowing in the earth, so that the electrical conductivity is distributed in a very complicated way under Japan. The investigations of short-period variations suggest that there must be a highly conducting passage of electric currents under the central part of Japan. This is likely to be a roughly circular circuit whose diameter is assumed to be a few hundred *kilometers*. Although the main parts of the circuit are presumed to lie at a depth of about 100 *km*, both the ends of the circuit would be connected with the conducting region of the mantle, the existence of such a conducting part having been well established by S. Chapman[10], A. T. Price[11] and the writer[12]. Meanwhile, an investigation of the same sort on geo-

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3) J. COULOMB, *Ann. d. Géophys.*, **1** (1945), 244.

4) J. T. WILSON, *The Earth as a Planet*, (1954), 156.

5) T. RIKITAKE, I. YOKOYAMA and Y. HISHIYAMA, *Bull. Earthq. Res. Inst.*, **30** (1952), 207; **31** (1953), 19, 89, 101, 119.

6) T. RIKITAKE and I. YOKOYAMA, *Journ. Geomagn. Geoelectr.*, **5** (1953), 59.

7) T. RIKITAKE and I. YOKOYAMA, *Naturwissenschaften*, **41** (1954), 420.

8) T. RIKITAKE and I. YOKOYAMA, *Bull. Earthq. Res. Inst.*, **33** (1955), 297.

9) T. RIKITAKE, I. YOKOYAMA and S. SATO, *Bull. Earthq. Res. Inst.*, **34** (1956), 197.

10) S. CHAPMAN and A. T. PRICE, *Phil. Trans. Roy. Soc. London A*, **229** (1930), 427.

11) B. N. LAHIRI and A. T. PRICE, *Phil. Trans. Roy. Soc. London A*, **237** (1939), 509.

12) T. RIKITAKE, *Bull. Earthq. Res. Inst.*, **28** (1950), 45, 219, 263; **29** (1951), 61.

magnetic daily variation in Japan suggests that there must be a low conducting region in the deeper part of the mantle, so that the low conducting state between the top and the depth of 400 *km*, which has been obtained as an average state of the earth, is likely to be extended as deep as 700 *km* under the central and north-east parts of Japan. Although much more observation will be necessary for establishing the electrical state under Japan, this sort of knowledge of the physical state of the earth's interior may add something of interest and importance to the geophysical interpretation of the arc and related phenomena.

The purpose of this paper is to attempt a new interpretation of the Kamchatka–Japan–Mariana arc and its underground structure with the aid of the newly obtained knowledge of the electrical state underneath the area.

2. The underground structure presumed from the conductivity distribution

As has been suggested by the study of geomagnetic daily variations in Japan, we shall start from the presumption that the electrical conductivity amounts to only 10^{-15} *emu* from the top of the mantle down to a depth of 700 *km* underneath the area. It is hardly possible to determine the accurate lateral boundaries of the low conducting region from the analysis of geomagnetic variations, because only a few observatories can be used for the analysis. Judging from the fact that no marked anomaly is observed at observatories in China or Kyushu, however, we may presume that the region is not so wide as to cover the continent or South Japan. It is likely that the region is spread under the central and north-east parts of Japan, while no information is obtained about the eastern boundary which probably lies under the Pacific Ocean. Under the circumstances, we shall assume that the low conducting region corresponds to the interior of the orogenetic arc, so that it would be possible to imagine that the elongated zone running along the Kamchatka–Japan–Mariana arc with a width of approximately 200 *km* wedges deep into the earth's mantle, a typical section being schematically shown in Fig. 1. Outside the hypothetical region, the conductivity is the same as that obtained for the average state of the earth, that is, it amounts to 10^{-15} *emu* down to a depth of about 400 *km* increasing steeply at this level to the order of 10^{-12} *emu*.

It is well known that the main parts of the electric conduction in the mantle are due to the motion of ions as has been experimentally proved by T. Nagata[13] and H. P. Coster[14] for rocks at high temperature. We can express the electrical conductivity σ as

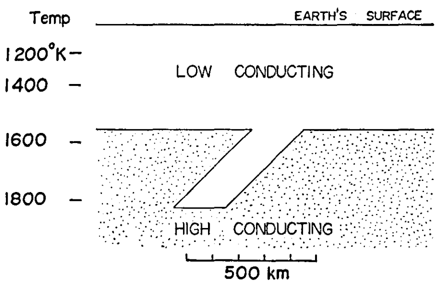

Fig. 1. Schematic cross section of the supposed model.

$$\sigma=\sigma_0 e^{-\epsilon_0/kT}, \qquad (1)$$

where ϵ_0, k and T denote respectively the activation energy, Boltzmann's constant and absolute temperature. On the basis of the theory of ionic crystals we can approximately estimate the changes in σ for a given combination of temperature and pressure. If we assume a distribution of pressure in the earth, we may obtain the distribution of temperature with the aid of the distribution of electrical conductivity as inferred from transient geomagnetic variations. The writer[15] has made this sort of estimate of temperature distribution in the earth down to a depth of 1500 *km*. In such a study, it is required that the activation energy of the substance composing the layer between the top of the mantle and a depth of 400 *km* is different from that below this level, otherwise a discontinuity does occur in the temperature distribution. The activation energy for the upper part amounts to 2.3 *eV* at zero pressure and temperature, while that below the depth of 400 *km* amounts to 1.8 *eV*. Although in the study it was assumed for the sake of convenience that there is a distinct discontinuity of the activation energy or substance, a gradual change of the substance is more likely to occur as has been pointed out by F. Birch[16].

Since, however, the low conducting region penetrates down to a depth of about 700 *km* under Japan, we might presume that the substance of large activation energy, which is usually found in a layer between the top of the mantle and a depth of 400 *km*, is wedging into the lower layer. The extent and shape of this wedge is thought to agree with the region stated before. The conductivity in this abnormal

13) T. NAGATA, *Bull. Earthq. Res. Inst.*, **15** (1937), 663.
14) H. P. COSTER, *M.N.R.A.S. Geophys. Suppl.*, **5** (1949), 193.
15) T. RIKITAKE, *Bull. Earthq. Res. Inst.*, **30** (1952), 13.
16) F. BIRCH, *Journ. Geophys. Res.*, **57** (1952), 227.

part of the mantle can be calculated following the method in the writer's previous paper[15]. On making use of the temperature and pressure distributions obtained respectively by the writer[15] and K. E. Bullen[17], the conductivity is calculated as given in Table I for respective depths.

Table I. Temperature, activation energy and electrical conductivity in the abnormal region.

Depth	Temperature	ϵ_0	$\log_{10}\sigma$ (σ in *emu*)
100 *km*	1180° *K*	2.5 *eV*	−15.0
200	1370	2.8	−15.0
300	1460	3.1	−15.0
400	1540	3.3	−15.0
500	1630	3.7	−15.6
600	1730	4.0	−15.6
700	1840	4.2	−15.7

Strictly speaking, however, hydrostatic equilibrium would not be retained, and, in such a case, the application of the simple theory of inoic crystals would fail. Gradual changes in chemical composition or crystal structure of the substances are also likely to occur, this requiring different activation energies between the top and bottom. But these points can not be discussed here in detail because no definite data are available.

As can be seen in Table I, the conductivity is kept almost constant amounting to the order of 10^{-15} *emu*, so that the existence of a low conducting region under the area down to the depth of about 700 *km* is consistent with the model of wedge-shape penetration of the upper layer as described above. If we do not assume such a wedge-shape penetration of the upper part of the mantle into the lower part, the low conductivity suggested from the analysis of geomagnetic variations would require abnormally low temperature distribution there. Since no special cooling mechanism which provides such a curious distribution of temperature is probable, it seems doubtful to suppose a low temperature region at a depth of 700 *km* or so. If we give up this alternative, we may now presume that the supposed wedge-shape penetration would possibly be the only model which accounts for the distribution of conductivity.

17) K. E. BULLEN, *An Introduction to the Theory of Seismology*, (1947).

3. Possible relation between the underground structure, seismicity and other phenomena

Now we are in a position to examine what sort of phenomena would be expected from the supposed underground structure of the Kamchatka-Japan-Mariana arc. First of all, the penetrating part of the upper layer will be subject to a force of buoyancy because the density of the substance at the lower part of the mantle is larger than that of the upper layer. Strictly speaking, this sort of discussion should be made by taking into account the elasticity. However, accurate investigations in this line would be difficult to carry out because of the complicated shape of the model, so that a simplified treatment will naturally be applied as is the case for the theory of isostasy. Assuming that a solid mass is wedging into a fluidal substance, the force vertically acting on the mass becomes

$$F=\int(\rho_1-\rho_2)gdV\ , \tag{2}$$

where ρ_1, ρ_2, and V denote respectively the density of the fluid, that of solid, gravity and volume of the solid pushed into the fluid. The integral should cover the whole volume of the solid in the fluid. If we assume the model of the underground structure stated in the last section, the force for a vertical section with unit thickness is given as

$$f=L\int_{h_1}^{h_2}[\rho_1(h)-\rho_2(h)]g(h)dh\ , \tag{3}$$

where L is the horizontal length of solid part. ρ_1 and g can be obtained from Bullen's study[17)], while ρ_2 at great depths can be inferred by the formula

$$\frac{1}{\rho_2}=\frac{1}{\rho_{00}}(1-\chi_{00}P+\alpha_{00}T+\cdots), \tag{4}$$

where ρ_{00}, χ_{00} and α_{00} respectively denote the pressure, compressibility and thermal expansion coefficient of the substance at zero pressure and temperature, while P denotes the pressure. On taking the following values

$$\rho_{00}=3.3\ g/cm^3\ ,$$
$$\chi_{00}=0.90\times10^{-12}\ cgs\ ,$$
$$\alpha_{00}=1.7\times10^{-5}\ ,$$

and the same temperature and pressure distributions as before, ρ_2 is calculated as given in Table II together with ρ_1 and g.

Table II

Depth	ρ_1	ρ_2	g
400 km	3.64 g/cm^3	3.66 g/cm^3	998 cm/sec^2
500	3.89	3.78	1000
600	4.13	3.94	1001
700	4.33	4.12	1000

With these values given in Table II, the right-hand side of (3) can be numerically calculated, whence we obtain

$$f=0.80\times 10^{17}\ dynes/cm,$$

provided we assume $L=200\ km$. Thus we see that this order of buoyancy force is acting on the supposed wedge-shaped part.

At the boundary between the wedge and the surrounding material, therefore, there should be some shearing stresses because the wedge is constantly going to rise up. The stress per unit area in the dipping plane is easily given as

$$s=\frac{1}{2}\frac{f}{\sqrt{2}}\frac{1}{\sqrt{2}(h_2-h_1)}=6.7\times 10^8\ dynes/cm^2.$$

It is known that the strength of the earth amounts to the order of $10^9\ dynes/cm^2$ for rocks which are usually found in the crust. It is not known what value the strength will take as far in the interior as 700 km in depth though experiments at high pressure generally show that the strength become larger by some factor. We see, then, that the substance near the boundary of the supposed wedge is always subject to a large stress slightly under its breaking point. If it is so, we may understand the reason why earthquakes occur along the dipping plane. The fact that no earthquake whose depth exceeds 700 km is observed is also compatible with the hypothesis that the upper layer wedges down to that depth as is supposed from geomagnetic studies.

A rough estimate suggests that there will be an anomally of gravity of 10 $mgal$ or so at the earth's surface right up the region, because light material is penetrating heavy one. However, the anomaly of this origin is likely to be masked by the one that originates in or under crust.

4. Discussion and concluding remarks

From what we have been dealing with in the above, it is found that the model constructed on the basis of geomagnetic studies roughly accounts for the occurrence of deep-focus earthquakes under the area concerned. As a consequence of shearing stresses near the boundary of the supposed wedge, some fractures could be formed along the boundary. If so, magma may rise up from there. Though the idea of this sort is speculative, the distribution of alkali and calcalkali rocks stated in the Introduction is now becoming acceptable. Hence, there is a possibility that some effusive rocks might come up from as low a depth as several hundred *kilometers*. The trend of volcanic zones is also understandable provided we presume the presence of such fractures as mentioned above.

Turning to the electric circuit which has been suggested from studies on short-period geomagnetic variations, we failed to find any direct relation between the circuit and the underground structure presumed here. It is possible to speculate that this circuit under the central part of Japan might be closely related to those fractures supposed above. However, no satisfactory interpretation will be effected from such a highly speculative discussion, so the geological interpretation of such an electric circuit will remain unknown.

Finally, the cause of the supposed wedging of the upper mantle into the lower part should be examined. This is also a matter of speculation. But if we suppose a sort of convection in the mantle, it might be possible to think of a dragging force which gives rise to the wedge described above. This assumption is also favourable for constructing a deep trench at the earth's surface. It is not necessary to assume that the convection is now prevailing. If we assume that some convection had existed at some time in the past when the material in the mantle had had more fluidity, the supposed structure could be formed.

The writer would not like to put much stress on such a matter of speculation. But the point that the underground structure deduced from geomagnetic studies with a few assumptions approximately accounts for the occurrences of deep-focus earthquakes seems of interest and importance.

In conclusion, the writer wishes to express his sincere thanks to Messrs. I. Yokoyama, S. Uyeda and K. Kasahara with whom he discussed the matter in detail.

20. 日本地下の電気的性質と地震発生に関する一仮説

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地磁気日変化の解析より推定された日本地下の電気伝導度が低いという結果に基づいて，通常地表から深さ 400 *km* までをしめている物質が日本中部および東北部に於て，約 700 *km* の深さまではいりこんでいるという模型を考えた．地球内の温度および圧力分布を考慮する時，この模型は要求される電気伝導度を与えまたこの貫入部分に働く浮力を計算すると，地球中間層を構成している物質の限界強度に近い数値が求められる．したがつて，この貫入部分の境界に沿つて深発地震が起りやすいと考えられる．