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22. *Electrical Conductivity Structure beneath the Central Part of Japan as Inferred from Magnetotelluric Fields at the Yatsugatake Magnetic Observatory.*

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Abstract

Impedance tensor elements were determined for periods between 20 and 240 min from the magnetic and telluric fields observed at the Yatsugatake Magnetic Observatory. The skew calculated from impedance tensor elements is much larger than 0.2, a critical value for two-dimensionality which implies that the structure is three-dimensional or the electric field observed at the Observatory is affected by local current channeling. It is found that such a channeling effect is expected in Z_{11} and Z_{21}, whereas Z_{12} is unlikely to be affected by a local effect and can be used for inferring the regional conductivity structure.

Three models of conductivity structure account relatively well for either the observed apparent resistivity or the observed phase, although the resolution is rather poor because of scatter in observed values. It is concluded that the conductivity structure beneath the central part of Japan is characterized by a conducting layer having a conductivity of 0.01 S/m and existing at a depth range of 30-50 to 100 km. This layer might reflect a small fraction of partial melt or conducting water.

1. Introduction

A phenomenon of electromagnetic induction has been used as one of the means of obtaining information on the physical state within the earth (*e.g.* RIKITAKE, 1966). It is well known that varying magnetic fields usually originating outside the earth induce electric currents in a conducting earth. The inductive response depends on the electrical conductivity of earth materials and the period of varying fields. If the response is obtained for various periods, a conductivity distribution within the earth can be inferred on some assumptions.

In the case of a method called magnetotellurics (MT), the impedance is usually used as a response function (CAGNIARD, 1953). In a

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simple case, it is obtained as the ratio of a horizontal component of the induced electric field to a horizontal magnetic field orthogonal to the electric component. Both fields are to be observed at the earth's surface. If the conductivity structure is laterally uniform, the depth distribution of the electrical conductivity can be determined, at least in principle, from the data obtained at a certain station. In this sense, the magnetotelluric method is apparently very powerful.

However, the conductivity structure is by no means simple, particularly in a geologically complicated region such as Japan. In such a case, induced currents are strongly disturbed by local conductivity inhomogeneities and, therefore, careful considerations are required in interpreting results of observations. One of the most representative examples of current perturbation is obtained at a coastal area which is a clear boundary separating highly conducting sea-water from a resistive land.

The Yatsugatake Magnetic Observatory is located in the central part of Japan far from coastal areas as shown by YA in Fig. 1, and an effect of perturbation at coasts is unlikely to be considerably large there. Moreover, another effect of a mantle conductivity anomaly called the Central Japan Anomaly (RIKITAKE, 1969; HONKURA, 1974) is expected to be small at YA as indicated by a small induction arrow shown in Fig. 1. Therefore, the data obtained at the observatory should provide valuable information on the conductivity structure beneath Central Japan.

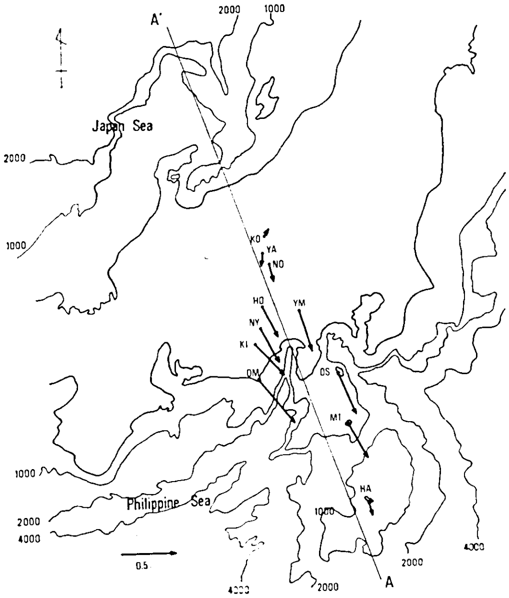

Fig. 1. Location of the Yatsugatake Magnetic Observatory denoted by YA. Arrows indicate induction arrows at a period of 60 min. The sea depth is given in meters.

Unfortunately electric currents leaking from the electric railways greatly contaminate the induced electric field at the observatory. The ratio of signal to noise is so poor that an accurate estimate of impedance is by no means obtained even at the time of a great magnetic storm. However, during some days from late November to early December, 1975, electric noises were greatly reduced because of service suspension of the railways. Thus the magnetotelluric method could be applied to geomagnetic and telluric field variations observed at the observatory.

2. Data analysis

If the conductivity structure is laterally uniform, the NS component of the electric field should be correlated with the *D* component of the magnetic field. A similar correlation should also exist between the EW and *H* components. Then the period-dependent impedance is obtained from either one of the above two pairs. However, as can be seen in Fig. 2, no clear correlation exists between the NS and *D* components and also between the EW and *H* components. Therefore, the observed data should carefully be analyzed and interpreted.

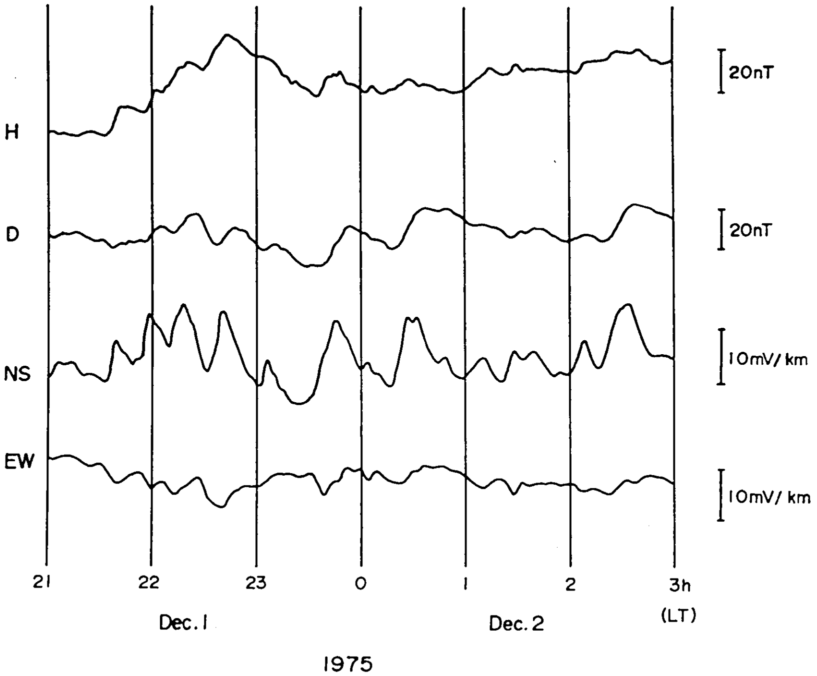

Fig. 2. An example of geomagnetic and telluric variations observed at the Yatsugatake Observatory. *H* and *D* indicate the northward and westward components of the magnetic field, and NS and EW denote the northward and eastward electric fields, respectively. Bars indicate scale length for 20 nT and 10 mV/km.

In a general case, the relation between the observed electric and magnetic fields is expressed in terms of an impedance tensor as

$$\begin{pmatrix} Ex \\ Ey \end{pmatrix} = \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} \begin{pmatrix} H \\ D \end{pmatrix}$$

where Ex and Ey denote the northward and eastward components of the electric field, respectively, and Z_{11}, Z_{12}, Z_{21}, and Z_{22} are impedance tensor elements. They are complex functions of frequency or period. Four records were selected for analysis, each of them having a duration ranging 14 to 22 hrs. Impedance tensor elements were determined for periods between 20 and 240 min. At periods shorter than 20 min the electric field data are considerably contaminated by noises and impedance tensor estimates were not stably obtained.

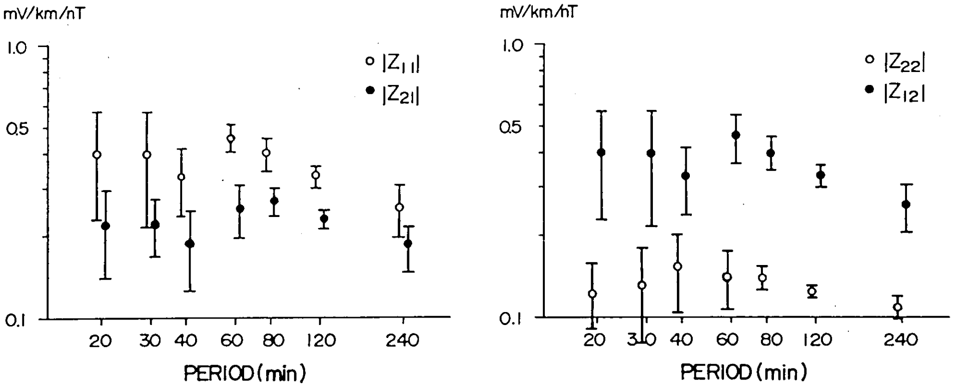

Fig. 3. $|Z_{11}|$, $|Z_{21}|$, $|Z_{12}|$, and $|Z_{22}|$ given in mV/km/nT for various periods between 20 and 240 min. Error bars indicate the standard deviations.

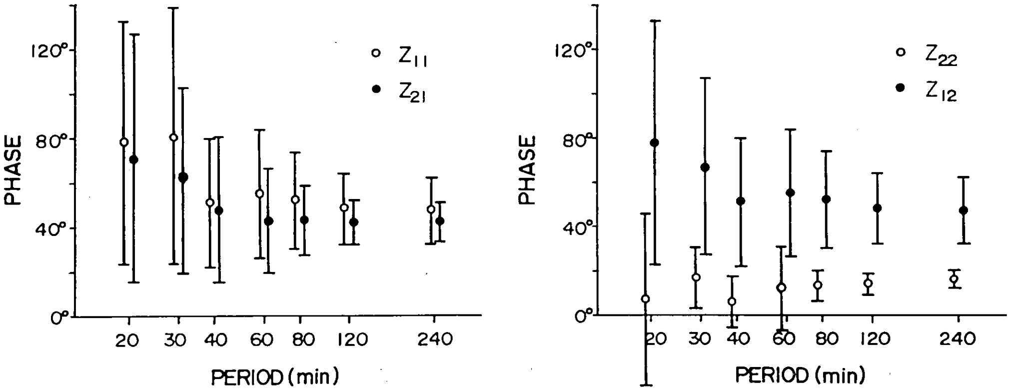

Fig. 4. The phases of impedance tensor elements, Z_{11}, Z_{21}, Z_{12}, and Z_{22}, given in degrees for various periods between 20 and 240 min. Error bars indicate the standard deviations.

Figure 3 shows $|Z_{11}|$, $|Z_{21}|$, $Z_{12}|$, and $|Z_{22}|$ in mV/km/nT for various periods between 20 and 240 min. Circles and bars denote the means and the standard deviations, respectively. The phase of each element is shown in degrees in Fig. 4. Error bars denote the standard deviations. Note that some phases are modified so that all the phases can be compared on the same basis.

3. Interpretation of impedance tensor elements

Off-diagonal elements, Z_{12} and Z_{21}, should be much larger than diagonal elements, Z_{11} and Z_{22}, for inferring the conductivity structure on one-dimensional approximation. However, diagonal elements are comparable to or even larger than off-diagonal ones as shown in Fig. 3. On the other hand, the possibility of two-dimensional treatment is judged on the basis of a criterion concerning the skew. The skew is defined by

$$\text{skew}=\frac{|Z_{11}+Z_{22}|}{|Z_{12}-Z_{21}|}$$

and if it is smaller than 0.2 or so, a two-dimensional treatment can be considered to be reasonable. As shown in Fig. 5, the skew is much larger than 0.2 for various periods, which implies either that the structure is actually three-dimensional or that the observed electric field is affected by local channeling of electric currents even though the structure can approximately be treated as being one- or two-dimensional in a regional scale.

Although impedance tensor elements seem to be very complicated, as shown above, there are some indications that allow one to infer the behavior of the induced electric fields near the Yatsugatake Observatory. The phases of Z_{11} and Z_{21}, which correspond to the phases of the southward and westward electric fields relative to that of the northward magnetic field, are almost the same. Therefore, the direction of electric currents induced when the magnetic field varies in the northward direction can be determined. It is shown from $|Z_{11}|$ and $|Z_{21}|$ that the currents tend to flow in an approximately southwestern direction.

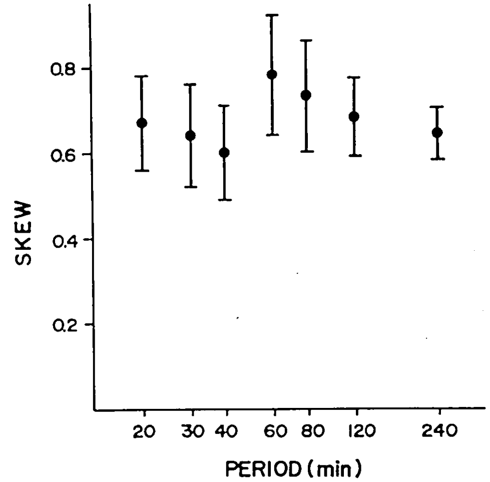

Fig. 5. The skew at various periods between 20 and 240 min. Error bars indicate the standard deviations.

Z_{11} and Z_{21} would not be

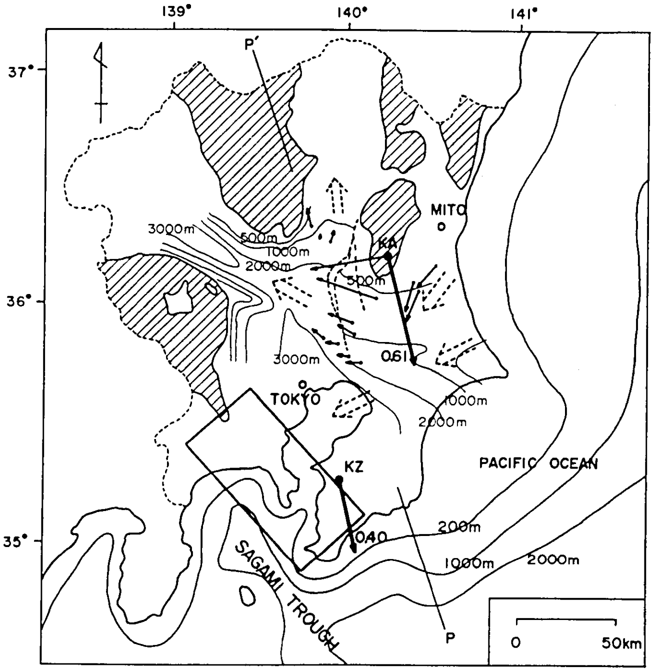

Fig. 6. Distribution of the direction of induced electric currents for the northward magnetic field as shown by small arrows in the Kanto Plain (after YANAGIHARA and YOKOUCHI, 1965). The depth to the basement is given in meters. Dashed arrows indicate the pattern of current flow to be expected for the northward magnetic field (after HONKURA, 1977).

appropriate for estimating the electrical conductivity structure, because they may have something to do with induced currents flowing in the thick sedimentary layer in the Kanto Plain. Figure 6 shows a distribution of the direction of induced currents for the northward magnetic field (YANAGIHARA and YOKOUCHI, 1965). The Yatsugatake Observatory is located close to the thick sedimentary layer lying northwest of the Kanto Plain, where strong current-concentration along thick sediments is expected (HONKURA, 1977).

A somewhat different nature is recognized in Z_{12} and Z_{22}, which describe the northward and eastward electric fields for the eastward magnetic field. In this case, the phase of Z_{22} is considerably different from that of Z_{12}, the latter being nearly equal to the phases of Z_{11} and Z_{21}. It is likely that a phase of 40°-50° represents the phase of the regional electric field and the phase of Z_{22} is anomalous. Although the origin of such an anomalous field is unknown, Z_{22} should not be used for estimating the conductivity.

It is concluded from the above consideration that Z_{12} may reasonably be used for further analysis. A two-dimensional approximation for a regional structure would not be unreasonable, taking into account the nature of the spatial extent of the Japan arc, the Philippine Sea, and the Japan Sea. Then, Z_{12} corresponds to the impedance in the H-polarization case. It is well known that in the H-polarization case the electrical conductivity can approximately be inferred from a one-dimensional model, if an observation site is located relatively far from the conductivity boundary as is the case for the Yatsugatake Observatory (JONES and PRICE, 1970). Therefore, in the next section, $|Z_{12}|$ and the phase of Z_{12} will be used to investigate the conductivity structure beneath the central part of Japan.

4. Electrical conductivity models

The apparent resistivity (ρ_a) can be determined from $|Z_{12}|$ as

$$\rho_a = 0.2T\,|Z_{12}|$$

where T denotes the period in sec and ρ_a is given in ohm·m. Figure 7 shows the apparent resistivity determined for various periods. The phase is also shown in Fig. 7.

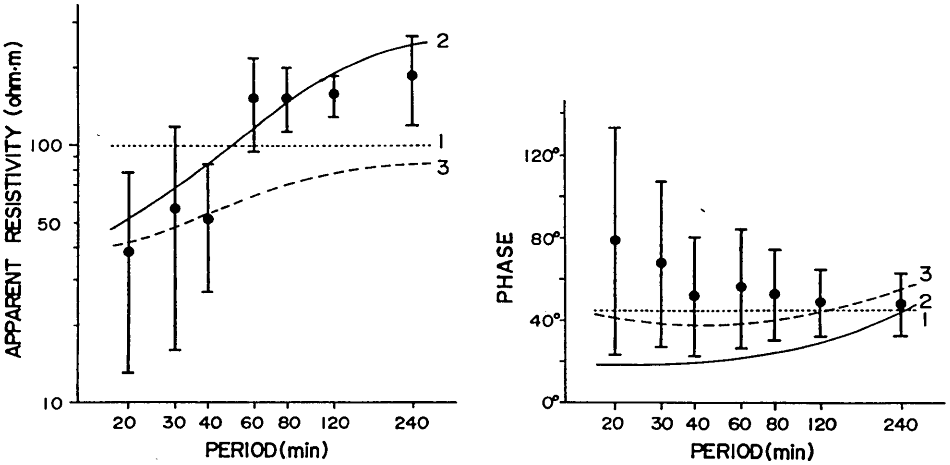

Fig. 7. The apparent resistivity and phase determined for various periods between 20 and 240 min. Dotted, solid, and dashed lines indicate the calculated results for conductivity models 1, 2, and 3 (see Fig. 8), respectively.

Model calculation can analytically be made for layered-earth models (*e.g.* SCHMUCKER, 1970). In this paper, however, calculations were made by making use of a numerical method used by HONKURA (1973). Figure 8 shows three typical models that can account for either the apparent resistivity or the phase. The most simple model is certainly a uniform conductivity model, model 1, and in this case a conductivity of 0.01 S/m well accounts for the phase and approximately for the

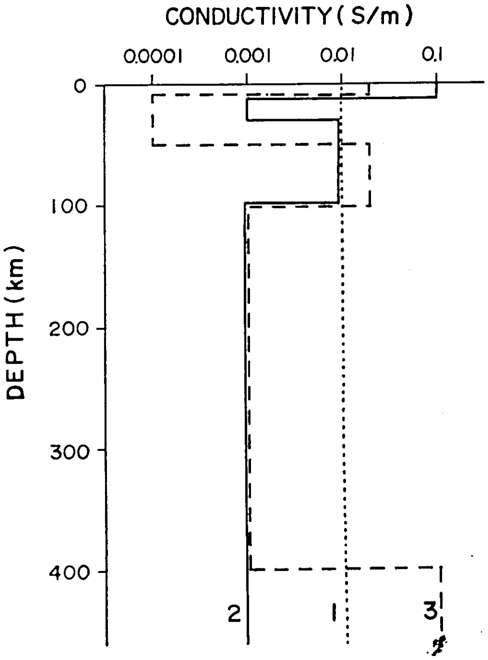

Fig. 8. Conductivity models 1, 2, and 3.

apparent resistivity as shown in Fig. 7. However, in this model a discrepancy appears in the period dependence of the apparent resistivity. Model 2 well accounts for the apparent resistivity as shown in Fig. 7 but the calculated phase is smaller than the observed one except for the longest period of 240 min. In the case of model 3, a good agreement is seen in the phase. Also the period characteristic of the apparent resistivity is not far from the observed result, although the apparent resistivity is too low at long periods.

In view of large errors in estimating the apparent resistivity and phase, it would not be worth searching for a model which can account for both the apparent resistivity and phase. Application of an inversion method to the present data would also be meaningless. An important point here is the common feature recognized in models 2 and 3; a conductivity of 0.01 to 0.1 *S*/*m* down to a depth of 10 km, a low conductivity of 0.001 to 0.0001 *S*/*m* to a depth of 30–50 km, a conductivity of 0.01 *S*/*m* to a depth of 100 km, and again a low conductivity of 0.001 *S*/*m*.

5. Discussion

It would be interesting to compare the model obtained in this paper with other conductivity models in the central part of Japan. HONKURA (1974) put forward a model which accounts for transfer functions determined from short-period geomagnetic variations observed at some stations in the central part of Japan. Figure 9 shows a cross section of the conductivity structure along a line shown in Fig. 1. As can be seen in this figure, the agreement between the observed and calculated results is good, although this model is not a unique one. In fact, RIKITAKE (1975) showed that the model put forward by RIKITAKE (1969) can account for the observed results as well as the model of HONKURA (1974).

As shown in Fig. 9, the conductivity amounts to 0.01 S/m below a depth of 30 km in the central part of Japan. A less conducting layer below 100 km shown by models 2 and 3 in Fig. 8 affects little the calculated results shown in Fig. 9, since the response is largely controlled by highly conducting layers. The conducting surface layer shown in Fig. 8 might be rather a local one and its effect on a regional distribution of transfer functions would not be very remarkable. The effect of local perturbation by such a conducting layer is unknown at present but it may have something to do with an anomalous electric field as represented by the phase of Z_{22}.

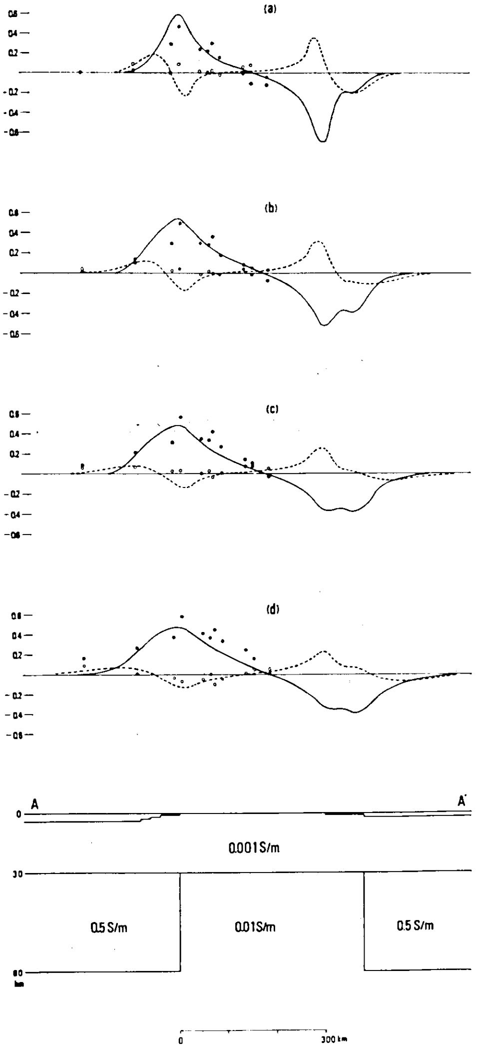

Fig. 9. A model of conductivity structure along a line A-A' shown in Fig. 1. The observed and calculated transfer functions are shown by dots and lines, respectively (after HONKURA, 1974).

Conducting layers beneath the Philippine and Japan Seas have such an extremely high conductivity as 0.5 S/m and, therefore, they were interpreted in terms of partial melting (HONKURA, 1975). The conductivity of 0.01 S/m at the depth range of 30 to 100 km is unlikely to be interpreted in terms of the temperature only. That is because the inversion of conductivity at a depth of 100 km would not be explained unless a compositional change exists at this boundary. An alternative interpretation will be possible by introducing a smaller fraction of partial melt or conducting water. If the former is the case, the layer would be a poorly developed partial melting zone. If the latter is the case, such water might be released as a result of a dehydration process of serpentinite and similar water-bearing rocks (ANDERSON *et al.*, 1976). The depth range of 30 to 100 km approximately agrees with a region where conditions of pressure and temperature required for the occurrence of a dehydration process are generally satisfied, except for a very high temperature area (KITAHARA *et al.*, 1966). Such a hehydration process may have something to do with the subduction of the oceanic crust beneath the Japan arc (ANDERSON *et al.*, 1976).

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22. 八ヶ岳地磁気観測所における地磁気・地電流から推定される中部日本下の電気伝導度構造

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八ヶ岳観測所では地電流 2 成分の観測を行っているが，電化線から漏れる電流が原因と思われる

ノイズが非常に大きく，誘導電流の観測はほぼ不可能となっている．しかし，1975年11月の終りから12月の初めにかけて電車が止まり，地電流の良好な記録が得られた．この時の記録を解析して，地磁気・地電流変化の特性を調べた．短周期変化の多い区間を4つ選び，それぞれから周期20分～240分のインピーダンステンソル要素（Z_{11}，Z_{21}，Z_{12}，Z_{22}）を計算して各周期に対して平均を求めた．もっと短い周期に対しては短周期ノイズのため正確には求まらない．

インピーダンステンソル要素から求めた skew は，いずれの周期でも0.2よりかなり大きく，一次元および二次元的取り扱いをする場合には注意を要する．そこで，八ヶ岳観測所付近における誘導電流の特性として次のように考えた．磁場変化が北向きの時，Z_{11}，Z_{21} の位相はそれぞれ40°～50°となり，両者はほぼ等しい．これに対し，磁場が東西方向に変化する時は様子が異なる．Z_{12} の位相は Z_{11}，Z_{21} とほぼ同じであるが，Z_{22} の位相はこれらとかなり異なる．Z_{11}，Z_{21}，Z_{12} の位相の共通性からみて，磁場に対して，40°～50°の位相が八ヶ岳観測所付近を流れる誘導電流の位相であろうと考えられる．そうすると，10°程度の位相をもつ Z_{22} が異常な誘導電流を表わしていることになる．この誘導電流がどういう原因によるものかは不明である．

中部日本において日本列島がほぼ東西に延びていることを考えると，Z_{12} は *H*-polarization case のインピーダンスに対応する．このことから，Z_{12} を用いて中部日本下の電気伝導度構造を推定することは妥当であろうと思われる．Z_{12} から見かけ比抵抗が求まるが，この見かけ比抵抗と Z_{12} の位相を説明するモデルを考えた．観測値を比較的よく説明するモデルに特徴的なことは，深さ30～100 kmに0.01 S/mの電気伝導度をもつ高伝導層が存在することである．この層の原因として，低率の部分溶融か，あるいは電気伝導度の高い水の存在が考えられる．