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An Interpretation of Seismotectonics in the Central Northeastern Japan Arc Using Conductivity Data

By

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Abstract

Wideband (0.002～20,000Hz) magnetotelluric measurement (MT) observations have been conducted along three traverses in order to image the resistivity profile. The data are expected to provide independent constraints to improve the understanding of seismo-tectonics and geology in the region where the Pacific plate subducts beneath the Eurasian plate. Analysis was performed to obtain 2-D models on the basis of the impedance tensor corrected for the effects induced by the subsurface 3D inhomogeneity. The static shift effect was also corrected using the results from transient electromagnetic measurements (TEM) at each MT site. Smooth two-dimensional georesistivity models were obtained assuming NS direction as the regional 2D structural strike, which is inferred from the GBD decomposition procedure and is in general agreement with the strike of geological units in the region. The whole crust is seen to be homogeneous without enhanced conductivity in the lower crust where the conductivity is relatively low, in general agreement with results in the northern part of the Tohoku district, but contrary to the stable continental crust. The profiles delineate two clear near surface conductive anomalies in the fracture zone between Dewa Hill and the Central basin region and in the Kitakami, Abukuma river regions of Quaternary or Tertiary sediment as well as several small scale conductivity anomalies. Conductors or their boundaries in the crust in the west of the Sekiryo Mountain Range generally correlate well with mapped faults or pre-Tertiary tectonic lines, and several buried faults are suggested. The northernmost cross section is more complex possibly because of the presence of Quaternary volcanoes and an active geothermal source area in the vicinity.

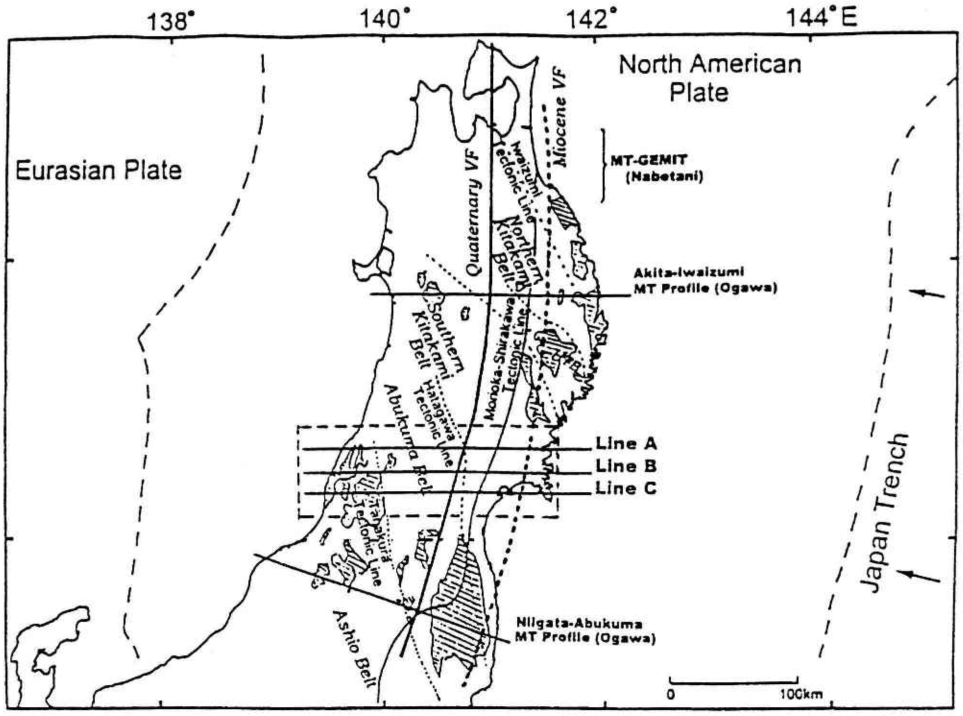
Key words : Seismotectonics, Conductivity, Active fault, Northeastern Japan arc

1. Introduction

Knowledge of georesistivity distribution is expected to provide valuable constraints in understanding tectonics, seismicity, and metamorphic activity. Combined use of the georesistivity data with other geophysical data such as gravity, geomagnetism, and elastic parameters is essential to reveal the regimes of crust and upper mantle. The Tohoku area is located in a typical subduction zone with active volcanic and seismic activity (Fig. 1). The structure of deep crust in the region has been investigated using seismic and electromagnetic approaches since 1990 (Yokokura *et al.*, 1992) to construct geodynamic model of the island arc. We are responsible for a portion of the study directed form electromagnetic measurements.

The geological and tectonic setting is briefly described here and reference should be made to Fujinawa *et al.*, 1997 and Ogawa (1992) for more detail. The Tohoku district is divided into the Green-Tuff region in the west and the Non-Green Tuff region in the east by the Morioka-Shirakawa Line parallel to the roughly south-north Quaternary volcanic front (Fig. 1, 2). The Green Tuff region has experienced intense volcanism during early Miocene and Quaternary volcanism along the backbone ranges around the Quaternary VF as shown in Fig. 1. Quaternary volcanism gave rise to a chain of volcanoes and an associated geothermal field which are located at the

(a)



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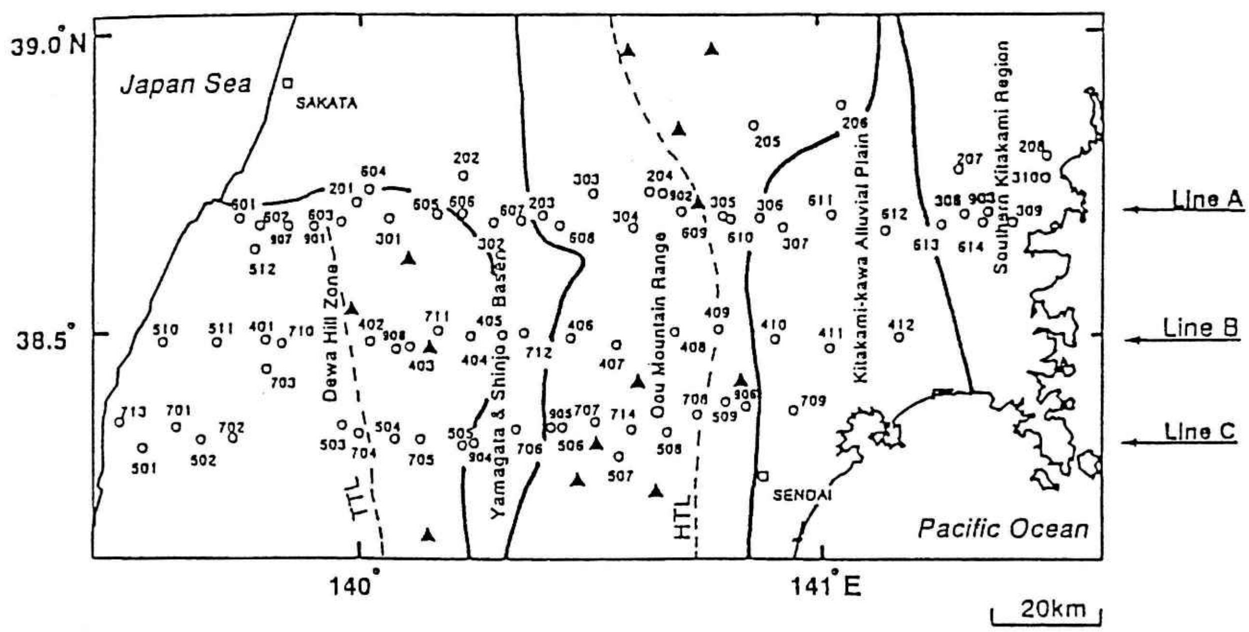

Fig. 1 (a) Simplified geological map in the northeast-Japan arc in the pre-Tertiary and the three MT profiles A, B, C. Miocene and Quaternary volcanic fronts are shown with several tectonic lines. The MT transects to the north of the present study area (Akita-Iwaizumi) and to the south of the present study area (Niigata-Abukuma) by Ogawa (1992) are shown. The northernmost parts have been surveyed by Nabetani and his group (e.g., Nabetani *et al.*, 1993). (b) Location of the MT measurement sites and geologic divisions (after Geological Survey of Japan (ed.), 1995). Triangles denote Quaternary volcanoes. TTL is the Tanakura tectonic line and HTL is Hatagawa tectonic line. TEM measurements were also conducted at each site.

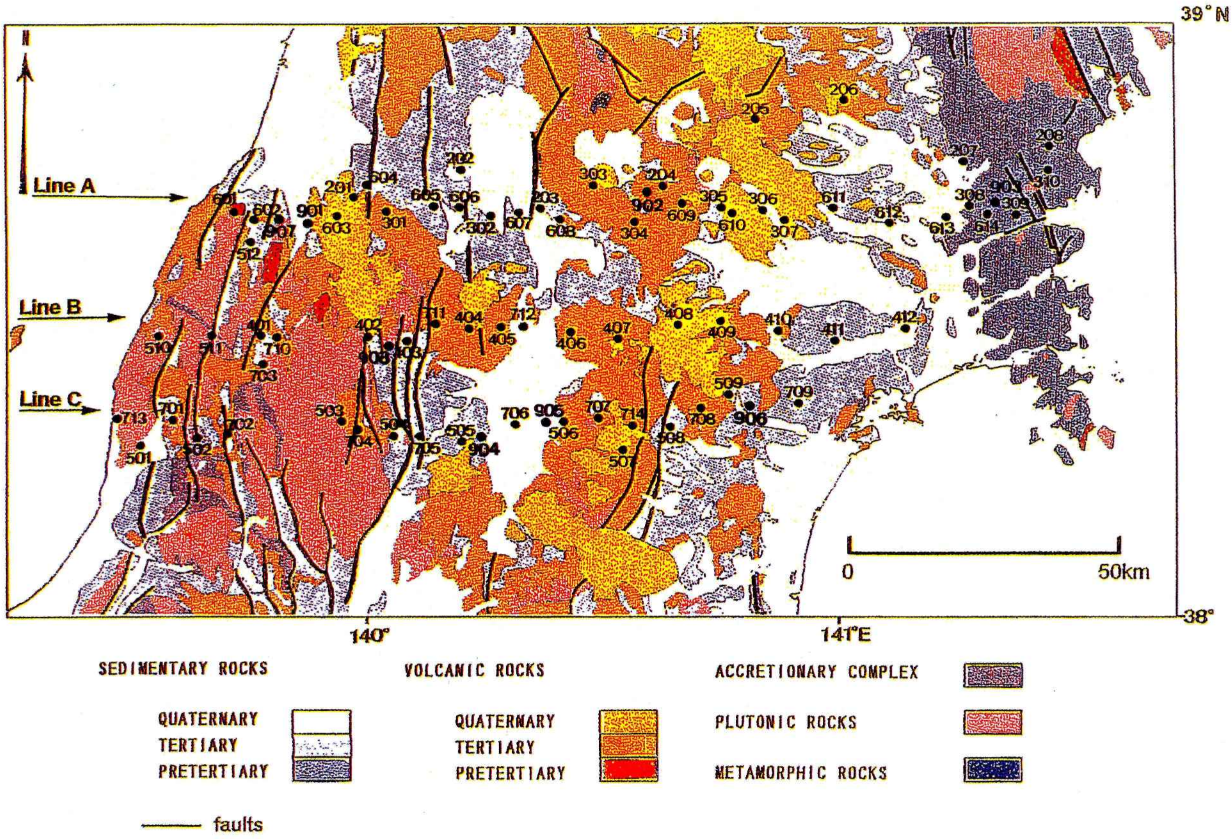

Fig. 2 Surface geology (Geological Survey of Japan (ed.), 1995) and the MT observation sites along lines A, B, and C.

intersecting region of the present volcanic front and pre-Tertiary tectonic lines. Thick Neogene and Quaternary marine sediments accumulated in the inter-mountain and back-arc basins.

The Non-Green Tuff region is composed of the Northern Kitakami, the Southern Kitakami and the Abukuma subregions, each of which is bounded by the pre-Tertiary tectonic lines of the Hayachine, the Hatagawa and the Tanakura, respectively. The basement rocks of the Northern Kitakami Belt are part of the Asian continental convergent margin sequence and are composed of resistive Triassic and Jurassic marine sediments. The Southern Kitakami Belt is accreted Paleozoic and Mesozoic formations and granites. Late Cretaceous left-lateral strike-slip motion along the Hatagawa tectonic line juxtaposed the southern Kitakami and Abukuma belts. The Cretaceous age Tanakura tectonic line separates NE-Japan and SW-Japan.

The Historical background of the MT survey in northeast Japan is discussed in a previous work (Fujinawa *et al.*, 1997). In this report we constructed 2-D conductivity models using the impedance tensors corrected for galvanic effects. Tensor distortion was corrected using the GBD procedure (Groom and Bailey, 1989, 1991 ; Groom *et al.*, 1993) taking account of the static-shift effect. The TEM (Transient Electromagnetic Measurements) is known to be one of the most reliable methods of inferring the site gain which can not be obtained by the GBD technique (Sternberg *et al.*, 1988).

In northeastern Japan an extensive seismic network has been constructed by Tohoku University (e.g., Hasegawa *et al.*, 1991) which has supplied detailed information on seismic activity such as Conrad and Moho depth (Horiuchi *et al.*, 1982), structure of the subducted Pacific plate (Umino and Hasegawa, 1975), and seismic velocity structure (Hasemi *et al.*, 1984 ; Obara *et al.*, 1986 ; Zhao *et al.*, 1992). These seismic structures could be more clearly interpreted if the georesistivity structure was known, especially because georesistivity is known to be sensible to pore water and partial melt of rock more or less governing the seismic process there. Particular attention is focused on the lower crust conductivity in relation to conductive lower crust (CLC) in the stable continent (e.g., Jones, 1992 ; Simpson, 1998).

2. Observation and Data

Here the observational procedure is introduced briefly by referring to Fujinawa *et al.*, (1997) in more detail. Broadband magnetotelluric data were acquired at 78 observation sites in the central part of the northeastern Japan arc on three traverses (Lines A, B, C from north to south) with a of length about 150 km running approximately east-west from the coastal area of the Pacific Ocean and that of the Japan Sea (Fig. 1, 2). Data on five magnetotelluric field components (0.0018 Hz~20kHz) were obtained at sites 37, 19, and 22 on lines A, B, C, respectively. The remote reference technique (Gamble *et al.*, 1979) was adopted in order to obtain MT data of better quality. Observation of two sites at a distance of about 70 km apart were conducted simultaneously, and one site was treated as the reference site for the other. However, the procedure did not work well in the case that the data quality at the reference site is not good. The magnetotelluric impedance tensor, tipper were calculated through ordinary procedures as well as the apparent resistivity ρ_a, phaseϕ, ordinary skew and phase sensitive skew (Vozoff, 1972 ; Swift, 1967 ; Kaufman and Keller, 1981 ; Bahr, 1988).

Data quality is from fair to good, and generally poor in the urban areas along the plain area of heavily populated zone. Several method of obtaining better quality data were adopted in addition to the remote reference measurements technique, as is described in the previous work (Fujinawa *et al.*, 1997). Attempts were made to apply the robust processing of MT data using an algorithm (Larsen *et al.*, 1996) (Yamane *et al.*, 1998). It was found that the processing is generally effective for obtaining equally reliable estimates of the impedance tensor as those given by a time consuming manual editing to delete outlier or noisy data intervals. However, very poor data could not be recovered by the procedure, mainly because of the insufficient quality of data at the reference point (Larsen J. C., private communication). Therefore, we used the impedance tensor calculated from the dataset through several data editing procedures (Fujinawa *et al.*, 1997) by letting a full application of the robust processing to a future work.

3. Static shift

In the distortion parameters, the site gain factor related to the static-shift due to charge accumulation at boundaries has not been calculated using the GBD procedure, and needs to be inferred. Several correction methods for the static-shift (Jiracek, 1990) have been proposed. We relied on the direct measurement method of TEM (Sternberg *et al.*, 1988), using the TEM-FAST ProSystem (AEMR Co., Ltd.). We adopted a coincident type TEM measurement using a rectangular antenna configuration with a total length of between 200 m to 300 m. A longer loop was used when the S/N ratio was not enough to provide a sufficiently small error bar in the longest time interval of data acquisition prescribed, usually at the site of high resistivity in the southern Kitakami belt (Fig. 2) where the signal response is too low (Miura *et al.*, 1997 ; Fujinawa *et al.*, 1998).

The apparent resistivity was calculated using the asymptotic late time response (Spies and Eggers, 1986). One-dimensional analysis of TEM data is used to obtain a layered model for shallow depth, providing us with an independent estimation of apparent resistivity and phase corresponding to those resulting from MT measurements at higher frequency bands. TEM synthetic apparent resistivity was found to agree with the observed MT apparent resistivity within the observation error bar at 85% of the sites. Frequency distributions of apparent resistivity and phase are merged to those of MT measurement.

The frequency independent bias in the apparent resistivity curves in the overlapping frequency range of the two measurements is taken as the static-shift. Averaging in frequency domain enabled us to estimate plausible static-shifts. The estimation was conducted for the two orthogonal components, TE and TM modes, defining the TE mode as that electric field directs north-south and magnetic field east-west. At two MT sites the two phase curves do not have good matching with the results of unsuccessful estimation of the shifts by this method.

The amounts of shifts are turned out to be less than 0.2 decades at 70% points. The simple mean value of the absolute value of the shift $\bar{S}$ and the standard deviationσ are,

$$\bar{S}=0.084 \text{ decades},$$
$$\sigma=0.24 \text{ decades}$$

Values and distribution of the static shifts obtained by Meju (1996) at more than one hundred site by means of the TEM method are generally in accord with the present result.

4. Subsurface Distortions

We have already shown that the resistivity structure in the survey region can be well approximated as a two-dimensional model (Fujinawa *et al.*, 1997 ; Kawakami *et al.*, 1997). This inference was based on the 3-D structure parameters calculated using the impedance tensors as well as from geological and tectonical considerations. Moreover, the subsurface 3

-D heterogeneity has been quantitatively estimated by means of a practical method of Groom and Bailey (Groom and Bailey, 1989, 1991 ; Groom *et al*., 1993) to provide the corrected 2-D impedance Z_{2D} from the observed tensor Z_{ob},

$$Z_{ob}=R(\phi)\begin{bmatrix}1 & -t\\ t & 1\end{bmatrix}\begin{bmatrix}1 & e\\ e & 1\end{bmatrix} g \begin{bmatrix}1+s & 0\\ 0 & 1-s\end{bmatrix} Z_{2d}R(-\phi)$$

where ϕ, $R(\phi)$, t, e, g, and s are the regional strike direction, rotation matrix to the coordinates system aligned to assumed 2D structured direction, the trust, the shear, the site gain, and the local anisotropy, respectively. The decomposition procedure provide values for the parameters ϕ, t, e, but not g, s.

It is indicated that the method provides a reasonable estimation of the 3-D heterogeneity effects giving the regional strike direction to be north-northwest to south-southwest, which correlates with the strike of the geological units and the axis of the island arc (Kawakami *et al*., 1997). The data provided an example to demonstrate the effectiveness of the GBD procedure in an apparently very complex situation of unstable estimation of the principal direction on the basis of Swifts (1967) definition. It is also noted that the decomposition method did not work at some sites where there were large-scale 3-D structures in deeper layers or large shear angles of one of the distortion parameters, and especially at the sites of large culture noises.

The regional strike in the 2-D modeling can safely be assumed to be north-south, (Fig. 7 of Kawakami *et al*., 1997). However, it is to be noted that the deeper layers were to be treated carefully because of the finite amount of 3-D structure effect which were not effectively corrected by the galvanic distortion consideration possibly due to the difference of the structural trend of the Neogine units with nearly parallel to the trench axis in comparison with the trend of the basement rock of pre-Tertiary age (Kimura *et al*., 1991).

5. 2-D modeling

We relied on the 2-D inversion algorithm of GRRI (Yamane *et al*., 1996). The algorithm is an extension of the RRI algorithm (Smith and Booker, 1991), in which the smoothness constraint of the model profile is included to measure the goodness of a model. Free parameters in the inversion are determined by trial and error.

In Fig. 3 the final 2-D models along the three traverses are shown. We presented only the TM mode models since our principal aim was to provide a plausible 2-D model in this work . And it is known that the TM mode can image the resistivity profile fairly well in the presence of 3-D heterogeneity (Wannamaker *et al*., 1984). The convergence is judged rather subjectively to see the extent of the fit of the observed data with synthetic data under consideration of sufficient smoothness of the 2-D model. We could get generally good fitness of the model to the data though there are appreciable mismatch at some frequencies region at several sites.

Line A

In the previous report (Fujinawa *et al*., 1997) an isolated conductive anomaly in the Central (Sekiryou) Mountain Ranges (SE) under site 204 was suggested. A supplemental MT observation conducted at site 902 just west of the problematic site 204 (Fig. 1) indicated that the data at site 204 should be discarded in the reasonable 2-D modeling in the present work. Another conductive anomaly near the Pacific coast (PC) around sties 308, 309 was discussed in same detail by comparing the TE and TM mode, and it was suggested that it was caused by a 3-D anisotropy. A supplementary observation at site 903 near the conductive anomaly indicated that the anomaly PC may not be real but apparent, caused by the 3-D effect as well as fair data quality at site 308.

The two prominent conductive bodies, CB around the Central Basin (around sites 605～203) and KK east of the Central Mountain Range around the Kitakami River (around sites 306～612), are nearly the same as in the previous model confirming the assumption that the 3-D heterogeneity effect was not large at those regions (Kawakami *et al*., 1997). However, weak conductive bodies extending from the middle crust to the Moho depths under sites 611 and 612 near KK may be caused by an inappropriate mesh design. A smaller subsurface conductor west of CB at around Higashi-Tagawa is manifest in the new model as well as in the old model. It is just east of the crossing point of the pre-Tertiary tectonic line, Tanakura tectonic line (TTL) with transect Line A suggesting the Quaternary structure to be influenced by the pre-Tertiary structure underneath.

Line B

As is seen in Fig. 3 the eastern part of the profile is characterized by a thin conductive layer near the surface, quite different from that on Line A. The pre-Tertiary rocks of the Central Mountain Range seen under sites 712, 406, 407 are resistive, in the order of 1,000 Ohm·m. The resistive body under site 412 is suggested to correspond to the Cretaceous sediments extending to the Southern Kitakami Mountain on the grounds of the nearby geology and the comparison

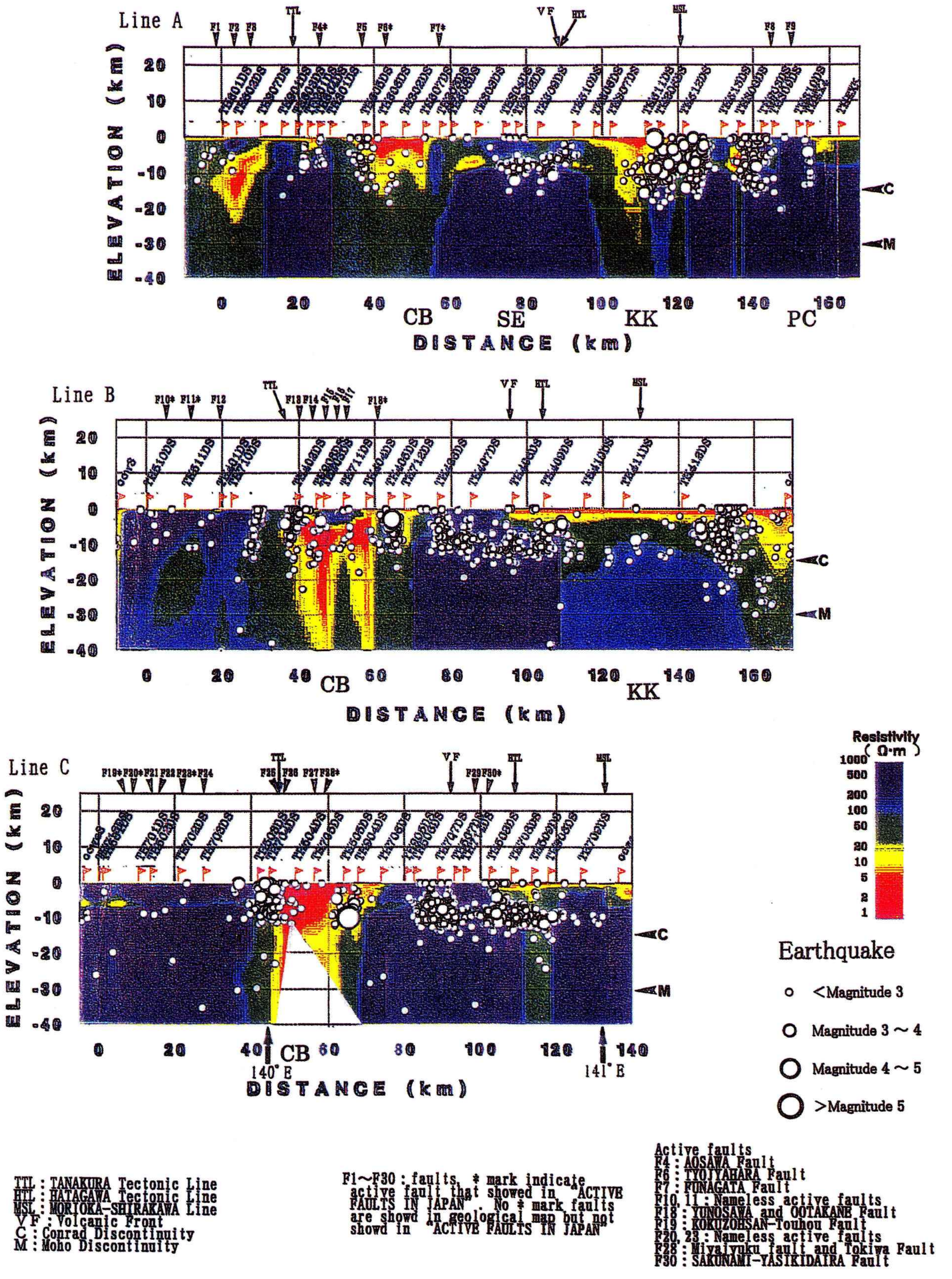

Fig. 3 Two-dimensional resistivity model for the TM mode at the three transects using the impedance tensors corrected for subsurface galvanic distortions using the GBD procedure and the measurement result of the TEM method. Earthquake hypocenters determined by Tohoku University are overwritten with active faults (Fi*) and geological lineaments (Fi).

with the northern and southern transects. A clear conductive anomaly can be seen to the west of the Yamagata basin (sites 402-404). The conductor corresponds well with the fracture zone (Fig. 1, 2).

A vertical striping of the western conductive anomaly CB reaching the Moho depth may be more or less caused by an inappropriate mesh design and/or limited measurement frequency in the MT data at a conductive region of very small value of skin depth of about 15 km. However, we can not deny the possibility of a vertical extension of the conductive signature corresponding to major faults up to more than Conrad depth referring to a penetration of 15-18 km in the western Quebec (Calvert *et al.*, 1995 ; Tournerie and Chouteau, 1998). A resistive region in the upper crust west of the conductive fracture zone is thought to correspond to the plutonic rocks around Mt. Asahi. It is to be noted that the lower crust in the region is relatively more resistive in comparison with the upper crust.

Line C

The model on C (Fig. 3) is very similar to that of the northern traverse B : existence of a thin conductive body east of the Central Mountain Range and the most prominent conductor existing dominantly in the fracture zone and with a small scale in the western half of the Central Basin. The conductor CB is interpreted as dominantly reflecting the fracture or fault zone in the region from sites 704 and 706. But vertical striping under the conductor east of the pre-Tertiary Hatagawa tectonic line (HTL) has almost disappeared owing to the 3-D heterogeneity correction and the supplement of site 906 east of the problematic site 509. It can be seen that conductive sediment in the middle of the Yamagata basin is very shallow. From the very sharp contrast between the conductive body extending from the center of the Central basin and a very resistive body in the Central Mountain Range we imagine that there is geological boundary in the immediate ricinity of site 706 dividing the Central Mountain Range and the Central Basin.

Larger static-shifts were observed at sites 507, 503, and 703 (Kawakami *et al.*, 1998). However, the new resistivity distribution does not differ considerably from previous ones. It may be induced that the synthetic 3-D effects are not only caused by the so-called static-shift, but also by shearing and twisting of the impedance tensor (Groom and Bailey, 1989, 1991).

6. Lower crust

The continental lower crust has been shown to be generally characterized by enhanced conductivity (Haak and Hutton, 1986 ; Jones, 1992, Simpson, 1998) (CLC) though with a considerable degree of variability, and the feature is used to explain the seismic lower crust, and the fluid rich weak layer of CLC has been incorporated into geodynamic models (Schmeling and Marquart, 1990 ; Kaufman and Royden, 1994). The profiles along the three transects indicate the following features of the lower crust in comparison with the upper crust.

Line C

The profile shows generally resistive except at the two conductive bodies CB, KK with a resistivity of several hundreds ohm•m has already been noted. On the Dewa Hill west of CB, the Central Mountain Range, and under the conductive body near the Pacific coast, resistive materials are imaged in the present model with resistivity larger than 1,000 ohm•m. The resistivity on both sides of CB appear to be smaller in the deeper part in comparison with the upper part. However, it is due to defects of the model as can be seen from the fitting curve of the apparent resistivity curve : there is a large discrepancy between the observed and theoretical values in the lower frequency range, suggesting that the lower crust is rather resistive compared with the upper crust on line C.

Line B

It is hard to discriminate the upper crust from the lower crust in terms of the resistivity value from the 2-D result along traverse B except for the conductive bodies showing more or less vertical striping (Fig. 3). The 1-D model also indicates almost homogeneous resistivity in the whole crust and upper mantle in the Dewa Hill characterized by pluton and in the Central Mountain Range. We can even see a somewhat increasing resistivity distribution toward the deeper region under the subsurface conductor KK. Uniform or rather increased resistivity in the deeper part of the crust was also found in the northern and southern transects (Ogawa, 1992 ; Ogawa *et al.*, 1992) about 100 km distant from our survey area (Fig. 1 of Fujinawa *et al.*, 1997). However, enhanced conductivity in the Akita-Iwaizumi-transect was found under the very resistive pluton of several thousand ohm•m (Ogawa *et al.*, 1992) indicating existence of regional variability.

Line A

Conductors are seen to be limited in the upper crust if the vertically downward striping is taken into consideration. In addition, the general property of the resistivity profile from the point of view of comparing the upper and lower crust is the same as in the case of line B. The resistivity distribution does not seems to decrease downward from the upper crust to the lower crust, but seem to increase even until deep in the mantle depth of about 100 km.

The lower crust is not seen to be more conductive than the upper crust, but uniform through the whole crust, or even instances where the lower crust is more resistive as in lines B and C.

The feature is in sharp contrast to the general property in the continent (Haak and Hutton, 1986 ; Jones, 1987, 1992 ; Simpson, 1998). We need more thorough investigation of the region by supplements detailed MT traverse in the observation gap between our traverse and those of Ogawa (1992). Compilation of those data as well as at other island arcs would reveal whether the case in the central section of the northeastern Japan arc is exceptional or not.

On the other hand, it is important to remember that the resistivity in the lower crust is in the range of several hundreds to 100 ohm•m. The value is classified as normal for the lower crust by Haak and Hutton (1986). Therefore we can assume that the lower crust in the region is conductive as in the continent, but the upper crust is not resistive contrary to the case in the general stable crust. If it is in the normal region to be easily deformed as ductile substance, the lower crust is suggested to be a weak layer being capable of transfering tectonic stress as in a stable continent (Simpson, 1998).

The enhanced conductivity has been explained by the presence of saline fluids, black shale and/or graphite, and partial melt (Jones, 1992 ; Simpson, 1998). The partial melt hypothesis (Chen *et al.*, 1996) may be discarded for this case because of the scarce S-wave reflector distribution in the survey area (Hasegawa *et al.*, 1998) under the condition that the present measurement technique can detect partial melt state of rock. The saline fluids are probably enhancing the conductivity on the premise of the interconnected network. The fluids is trapped below the impermeable layer at Conrad (Jones, 1987) with the result of a ductile lower crust without appreciable seismic activity.

Then we need an explanation of the comparably more conductive upper crust in the present survey area being contrasted to the general image in the stable continental crust. One very simple model could be built on the basis of the trapped water model of Jones (1987) and Hyndman (1988). But in the case of an active plate margin the saline fluids may not be enough sealed in the lower crust owing to the insufficient sealing effect in the midcrust (Honkura, 1988). In point of fact, T. Yokokura (Private communication) suggests the breakdown of the sealing in the backarc region on the basis of transparent Conrad and Moho discontinuity deduced from the seismic exploration measurements. The present result partially supports their idea, but not in the forearc. Mineral deposition at a temperature of 370°C (Fournier, 1991) may not grow sufficiently in the metamorphic process at the active plate margin owing to the breakdown of the chemical equilibrium which is known to provide greenshift to amphibolite faces (Hyndman, 1988). At any rate, we need more data concerning the conditions under which the relatively conductive upper crust is built at the subduction zone.

7. Seismicity

In Fig. 3 the resistivity model is overlapped by a vertical cross section of hypocenter of earthquakes of focal position within a EW strip with 20 km width centered each traverse. In addition, Fig. 4 shows the hypocenter of earthquakes in the upper crust with focal depths of between 0 to 15 km around the MT observation sites with the resistivity distribution at the mid-point of the upper crust (depth 7.5 km) being overwritten. Seismic data are supplied from the dense seismic network of Tohoku University. In Figs. 3 and 4 the pre-Tertiary tectonic lines, Tanakura (TTL), Hatagawa, (HTL), and Morioka-Shirakawa (MSL) are included with the Quaternary Volcanic Front (VF) (see Fujinawa *et al.*, 1997 and references therein in more detail). The historical earthquakes are also shown by star symbols (☆). Seismicity is to be discussed by the use of the vertical (Fig. 3) and horizontal (Fig. 4) images of resistivity distribution overlapped with hypocenter distribution.

It can be seen from Fig. 3 and 4 that prominent conductive bodies in the backarc side are well correlated with the active faults (F*) and geological lineament (F) in the region of the fracture zone west of the Central Basin, the Shinjo basin (around sites 606 ～203 on line A, Fig. 1), the Yamagata basin (around sites 405～406 on line B, and around sites 904～506 on line C). Seismicity is very high in these regions indicating that stress is relaxed in this fracture zone, where water circulation is suggested to make the crust weak enough to induce earthquakes. The seismic activities seen at the conductivity contrast dividing the Central basin and the Central Mountain Range suggest a long buried fault which extends from the geological lineament F5 in the north, and connects with F16 or F17 in the south. It illustrates the usefulness of conductivity information to interpret seismicity as well as to find or confirm buried-faults from the standpoint of earthquake risk assessment.

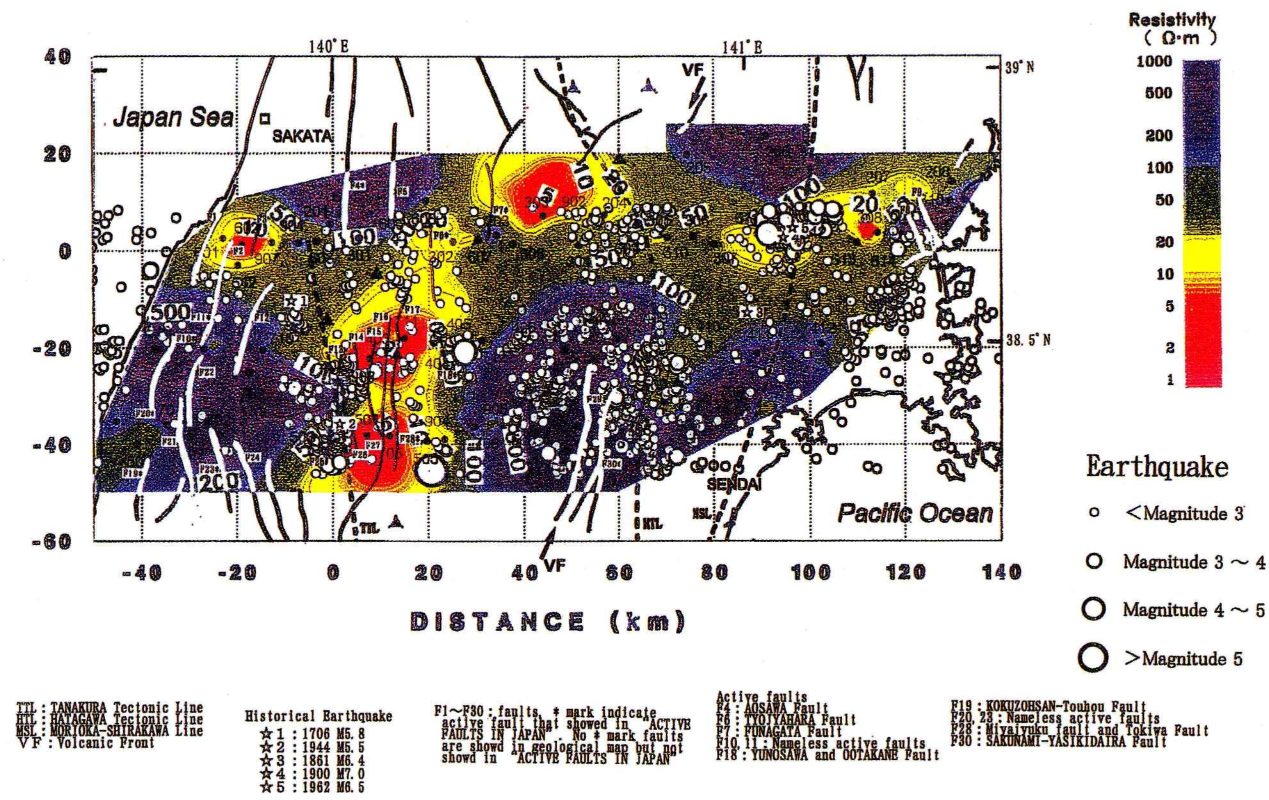

Fig. 4 The horizontal resistivity distribution at a depth of 7.5 km in the midst of the upper crust is overwritten by earthquake hypocenters determined by the dense seismic network of Tohoku university as well as historical earthquakes. Solid curves attached with number F* indicate active faults (Active Fault Research Group, 1991), and the solid curve marked F indicate active faults or lineament (Geological Survey of Japan, 1995).

In and around the resistive Dewa Hill west of the Central basin the seismicity is very low in comparison with that in the fracture zone depite the existence of several designated faults as can be seen in Fig. 3 and 4. Absence of water in the region can be assumed from the low seismicity in the regions. In the Central Mountainous Range we can see a completely contrasting seismo-tectonics situation. The apparently very resistive regions are seismically very active around the volcanic front (VF), in contrary to the cases in the fracture zone west of the Central Mountain Ranges. The region might be characterized as the stress concentration region inducing active seismicity.

There are several isolated spots of high seismicity. We can see two moderate earthquakes along the eastern edge of the conductor corresponding to the Central basins, around site 405 on line B and site 904 on line C. These epicenters seem to be aligned on a line connecting the active fault F7* (Funagata Fault ; Active Fault Research Group, 1991) passing west of site 203 on the northern side and the northern tip of another geological lineament (Geological Survey of Japan, 1995) to the remote south of the site 706 (Fig. 1). It is noted that the line exhibits the regions of large contrast of resistivity, the conductive western block and the resistive eastern block. It is possible to consider that the line corresponds to the block boundary separating the resistive Central Mountain Range and the conductive Central Basin range. The boundary is well in accord with a geological boundary there (Fig. 2). The region is also known as a Vp velocity anomaly (Zhao *et al.*, 1992). The line may be classified as another buried fault of considerable extent which have not been identified before on active fault maps (Active Fault Research Group, 1991) or geological maps (Geological Survey of Japan, 1995).

Several kilometers north-west of site 710 there is concentrated seismicity and a moderate earthquake of magnitude 5.8 (☆ 1) occurred in 1706. Recent as well as historical seismic activity in the region indicate that it is connected by an active fault. However, we can not see any anomalous conductivity anomaly at least under the present limit of the resolving power. Furthermore, we have found no trace of active faults or geological lineaments. The region is difficult to approach for MT measurement though we have tried several times to fill the observation gap of such a long distance between site 710 and its neighbouring site to the east, site 402. Accordingly, we have no means now to investigate the curious seismicity there.

In the region around site 612 on traverse A about 20 km south of site 206, we can see very active seismic region, where moderate earthquakes of magnitude M 7.0, and M 6.9 have occurred in 1900, and 1962 respectively. Those earthquakes have caused a fair amount of damage around the region including Sendai City. The region can be characterized as being on the eastern edge of the KK conductor (Fig. 3) and on the Shirakawa-Morioka line (Figs. 3 and 4).

It is generally envisaged that the lower crust is ductile with a good correlation between the depths to the conductive lower crust with the upper crust seismic limits as well as having brittle-ductile transition temperature (Meissner and Strehlau, 1982 ; Stanley, 1989 ; Adam, 1978 ; Hyndman and Shearer, 1989 ; Simpson, 1998). The brittle-ductile transition depth in the Central Mountain Range was calculated by comparison of precisely relocated micro-earthquakes distribution with temperature distribution using the P wave velocity (Hasegawa *et al.*, 1998). The homogeneities of resistivity distribution in the crust may be essential to provide good estimation of temperature using only the seismic velocity *Vp* (Sato *et al.*, 1989). Earthquakes surrounding the Miyagi-ken-hokubu earthquake (1962) in the past and a more recent one in 1981 (☆ 3, M 6.4) extend to site 509 indicating a higher conductivity in comparison with the surrounding sites. The line also corresponds to the boundary between the Tertiary sediment rock east of the Central Mountain Range and Tertiary volcanic rocks (Fig. 1), which are roughly parallel to the Sakunami-Yoshokidaira fault (F*3). We propose that the line is also a buried fault which could be confirmed by a resistivity survey.

The lower crust is characterized predominantly as aseismic. However, there are some differences in the activity (Fig. 5). Firstly, we can note that the seismicity is extremely low in the highly resistive region. An anomalously higher seismicity can be seen at around the geothermal area in the approximate vicinity of sites 204, 305, a Quaternary volcanos, the Komagatake and Onikobe shown by the symbol near site 204. It is indicated by Hasegawa *et al.*, (1998) that these correspond to low-frequency earthquakes which can be related to magma activity.

8. Conclusion

Disregarding apparently inappropriate the data such as data representing very local character or very poor quality data, 2D models are obtained through the GRRI inversion algorithm, which is an extension of the RRI inversion constraining the smoothness of the resistivity profiles. The profiles show that,

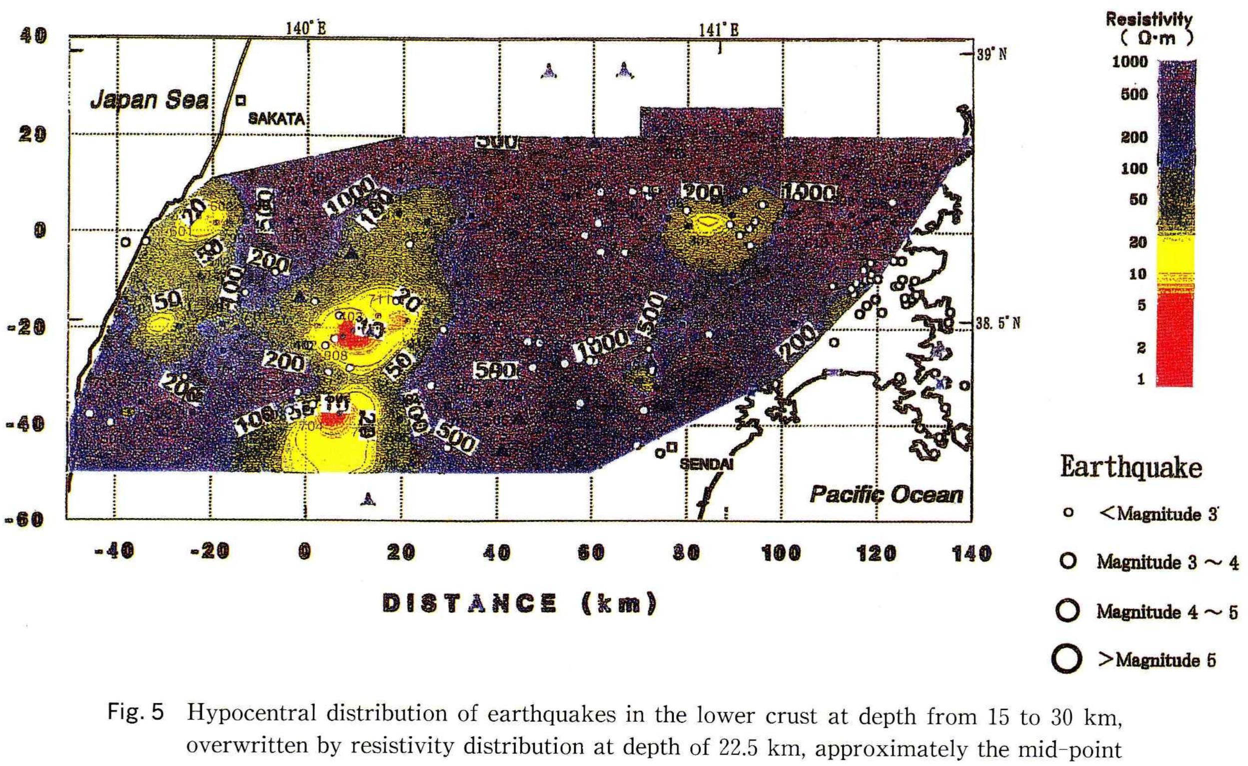

Fig. 5 Hypocentral distribution of earthquakes in the lower crust at depth from 15 to 30 km, overwritten by resistivity distribution at depth of 22.5 km, approximately the mid-point of the lower crust.

1) The crust has uniform conductivity in the resistive region generally in accord with the northern part of the region. The values of the resistivity bodies are of several hundreds of ohm•m suggesting that the upper crust is relatively conductive in comparson with the major part of the stable continent. The upper crust is thought to be wet and strong and to be associated with active seismicity.
2) In the fracture zone west of the central basin region there is a good correlation between faults, geological lineament and seismicity.
3) Active seismicity around the boundary of the Central Basin and the Central Mountain Range may be due to buried faults. The same can be said of some of the localized regions of high seismicity in the forearc region.
4) Many of faults associated with scarce seismicity are characterized by higher resistivity.
5) The geothermal area has a more conductive character with small spatial extent.

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比抵抗分布から見た東北地方中部地域におけるサイスモテクトニクス

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要 旨

プレートの運動・変形・相互作用を統一的に解明するため，地磁気電流法（MT 法）によって，深部地殻の電磁気的性質の探査を，平成3年度から，測線酒田―石巻間（測線 A），山形県月山南部から宮城県黒川（測線 B），朝日岳―蔵王線（測線 C）で行った．モデルの滑らかさを拘束条件としたインバージョンにより2次元モデルを求め，得られた2次元比抵抗分布に基づき，東北地方中部地域におけるサイスモテクトニクスの解明を図り，以下のような結論を得た．

1）新庄，山形盆地近傍の低比抵抗体は，数 Ω・m で深度数 km におよんでいる．その低比抵抗体の西縁は活断層の密集した破砕帯に対応しており，地震活動との対応も良い．東縁は，脊梁山地との境界をなしており，大規模な潜在断層の存在が推定される．

2）北上川河谷域の表層部の薄い低比抵抗体は，表層の堆積層とグリーンタフに対応していると思われる．

3）宮城県北部の地震多発地域は，低比抵抗となっている．地磁気異常領域ともなっており，地震発生が地下流体と関係していることを示唆している．

4）出羽丘陵では，多くの活断層が検知されているが，同地域の地震活動は低く，高比抵抗となっている．

5）脊梁山地では，比抵抗が比較的高いのも拘わらず微小地震が多く，地震発生のメカニズムは，出羽丘陵東部とは違いがある．

キーワード：サイスモテクトニクス，東北地方，比抵抗，活断層