Studies of the Georesistivity Structure in the Central Part of the Northeastern Japan Arc

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Wideband magnetotelluric measurements were conducted along three traverses in the central Tohoku district of the northeastern Japan arc. These data provide independent constraints for understanding seismo-tectonics and geology where the Pacific plate subducts beneath the Eurasian plate. Smooth two-dimensional models of the data acquired along the three transects were obtained using the Generalized Rapid Relaxation Inversion algorithm. Modeling suggests that the area can be reasonably treated as two-dimensional with the structural direction being north-south in agreement with the strikes of geological units. The three 2-D models correlate well with the regional geological morphology in the central part of the Tohoku district which is divided by three high altitude regions. The resistivity profiles indicate two clear conductive anomalies in the Central Basin Range and in the Kitakami, Abukuma river regions that show considerable variability in each of the three 2-D models. Boundaries of conductive bodies correlate well with mapped faults, including those of pre-Tertiary age. The northernmost cross section is more complex possibly because of the presence of Quaternary volcanoes and an active geothermal source area in the vicinity.

1. Introduction

Investigations of georesistivity distributions provide valuable geophysical constraints for developing models of tectonics and metamorphic activity, particularly as a complement to other geophysical parameters such as seismic velocity, gravity, and geomagnetism. A joint research project of the subduction zones in the northeastern Japan arc has been conducted using seismic and electromagnetic methods (Yokokura et al., 1992). Presented here is a portion of the study devoted to magnetotelluric measurements.

Crustal structures in the area have been investigated extensively by using seismic explosions (Yoshii and Asano, 1972), P wave tomographic imaging (Hasemi et al., 1984; Obara et al., 1986; Zhao et al., 1990; Hasegawa et al., 1991; Zhao et al., 1992) and Q structure (Tsumura et al., 1996). Heterogeneous properties of the Earth’s crust and upper mantle have been used to interpret local geodynamic condition relating to seismic activity and volcanic eruptions (e.g., Hasegawa et al., 1991).

Lithologies, temperature, pore fluid, partial melt of rock or conductive minerals can be inferred from the electrical resistivity. With this information it is possible to impose more or less independent constraints in the modeling of the complex tectonics in the area (e.g., Jones, 1992).

The geological and tectonic settings in the Tohoku area are briefly summarized here following Ogawa (1992). 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). The Green Tuff region has experienced intense volcanism during early Miocene and Quaternary volcanism along the backbone ranges around the Quaternary volcanic front (VF) in Fig. 1. The Miocene volcanic front is located about 60 km east of that in Quaternary (Tatsumi et al., 1989). Quaternary volcanism gave rise to a chain of volcanoes and an associated geothermal field which are
Fig. 1. Simplified geological maps in the northeast-Japan arc in the pre-Tertiary (revised from figure 3-2 of Ogawa, 1992) and the three MT profiles A, B, C. Miocene and Quaternary volcanic fronts (Tatsumi et al., 1989) are shown with several tectonic lines. The MT transects north of the present study area (Akita-Iwaizumi) and south of the present study area (Niigata-Abukuma) by Ogawa (1992) are shown. The northernmost parts have been surveyed by Nabetani et al. (1992), Nabetani and Fukuta (1993, 1995a, 1995b), Nabetani and Maekawa (1994), Nabetani and Kimura (1996).
Fig. 2. Surface geology (Geological Survey of Japan, ed., 1995) and the MT observation sites along Line A, B, C.
located at the intersecting region of the present volcanic front and pre-Tertiary tectonic lines. Thick Neogene and Quaternary marine sediments accumulated in the intermountain 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 (Saito and Hashimoto, 1982). Late Cretaceous left-lateral strike-slip motion along the Hatagawa tectonic line juxtaposed the southern Kitakami and Abukuma belts (Taira et al., 1983). The Cretaceous age Tanakura tectonic line separates the NE-Japan and SW-Japan.

In the Tohoku district the structural trend of the Neogene units is nearly perpendicular to the subduction direction of the Pacific plate. But those units are also affected by the structure of the basement rocks of pre-Tertiary age (Kimura et al., 1991) suggesting the existence of three-dimensional resistivity structures.

In northeast Japan, detailed MT surveys have been conducted in the northernmost region (Nabetani et al., 1992; Nabetani and Fukuta, 1993; Nabetani and Maekawa, 1994; Nabetani and Fukuta, 1995a, b; Nabetani and Kimura, 1996), the northern region (Ogawa, 1992), the southern region (Ogawa, 1992), and the central region (Utada, 1987). The three present traverses are situated between the two surveys of Ogawa (1992) and one traverse is the same as that of Utada (1987). However the present observations are more extensive in frequency and number of observation sites. Our data will be combined with other data into a networked-MT survey for longer period ranges (Uyeshima et al., 1995, 1996) to cover the whole of Japan including the region of area shown in Fig. 2 leading to a more complete georesistivity structure of the northeast Japan arc. The results of these studies provide for a more complete understanding of the seismo-tectonics and geology in the central part of northeastern Japan arc.

2. Observations

Magnetotelluric data were acquired in the central part of northeastern Japan arc along three transects (Lines A, B, C, from north to south) of about 150 km length running approximately east-west (Figs. 1 and 2). Five broadband components of magnetotelluric field data (0.0018 Hz–20 kHz) were obtained at 33, 18, and 19 sites on Lines A, B, C, respectively (Fig. 2), using a tensor magnetotelluric acquisition system (manufactured by EMI Inc.). Redundant magnetic sensors were used to reduce local noises for the AMT frequency bands through comparing quality of the two data obtained by two sensors or signal enhancement by adding individual data at each sample time. The remote reference technique (Gamble et al., 1979) was utilized by simultaneous measurements at a pair of sites separated by about half of the transect length, i.e., about 70 km, synchronized by quartz-crystal clocks. Electric fields were estimated using 100 m dipoles grounded with Pb-PbCl2 electrodes. These electrodes were immersed in porous pots filled with saturated NaCl solution and were buried about 50 cm underground. The magnetic fields were measured by two kinds of induction coil sensors: BF-4’s and BF-6’s, manufactured by EMI Inc., and by 3-component flux gate magnetometers (S-100, manufactured by Narod Geophysics Inc.).

Measurement at a site was generally conducted for three days. In order to get better quality data several precautions were made: to find sites with less cultural noise, careful monitoring of the MT parameters during recording, and data acquisition of the lower frequency data at night to minimize man-made noise. Parts of the data including higher amplitude outliers were deleted before Fourier transformation and then data with low coherencies between electric and perpendicular magnetic fields were discarded. Visual comparison of single and remote reference processing results lead to selecting the mode with the better quality.

From the impedance tensor Z,

\[ E = ZH \] (1)
relating the horizontal electric field $E$ and horizontal magnetic field $H$ for frequencies from 20 kHz to 0.0018 Hz, we calculated MT apparent resistivity $\rho_a$, phase $\phi$, tipper magnitude $T$, tipper strike $T_i$, impedance strike $\phi_0$, and ordinary skew and phase sensitive skew following Vozoff (1972), Swift (1967), Kaufman and Keller (1981), and Bahr (1987). Examples of observed data are shown in a later section (Fig. 5).

3. Structural Parameters

The range of data quality is from fair to good. The data quality was poor in the urban areas along the Japan Sea coast and was worst along the heavily populated Pacific coast. Generally the lowest and highest frequency bands were most distorted by cultural noise. The sites with large coherency occasionally exhibited bias caused by cultural noise. Noise contaminated data were deleted before inversion.

At several sites the two orthogonal apparent resistivity curves showed splitting at the highest frequency due to static shifts induced by the surface inhomogeneity of the resistivity distribution. To obtain a reasonable resistivity model, the static shift must be accounted for. Several methods have been proposed to correct static shift using additional information. For example, assuming deep structure continuity (Jones, 1988) and/or direct measurements of shallow structure by dc or electromagnetic methods (Sternberg et al., 1985).

The full analysis of static shift and local distortions, however, are beyond the scope of the present report and are treated in other papers (partly in Kawakami et al., 1997). The application of the transient electromagnetic measurements (TEM) to help to understand static shift is underway and will be reported upon soon (Fujinawa et al., 1997). According to the experimental results to date we can say that the distortion of the resistivity profile due to the static shift does not generally exceed ±0.3 decades in general agreement with the statistical evaluation of the effect at about 140 sites by Meju (1994). The static shift effect will be taken account for semi-quantitatively using the observed shifts later in the interpretation of the 2D resistivity model obtained.

3.1 Strike direction

The principal axes and tipper strikes were calculated from the observed impedance tensors and the magnetic transfer function, respectively, to infer the structural strike direction. There is considerable scatter over the frequency ranges for the impedance strike but less scatter for the tipper strikes. The direction of the geological structures and the coastline in the northeastern arc is NNE-SSW while the pre-Tertiary structural line is NNW-SSE. The two strikes inferred from MT data, especially the tipper strikes, align generally in a north-south direction. A preliminary impedance tensor decomposition analysis (Fujinawa et al., 1996; Kawakami et al., 1997) using the Groom-Bailey method (Groom and Bailey, 1989) also indicates that the regional direction is approximately north-south. Therefore the MT data were rotated to a fixed coordinates system of NS (y-axis) and EW (x-axis) for the two-dimensional analysis.

3.2 3-D effects

Impedance polar diagrams (IPD) provide an indication of structural dimensionality. The measured IPD's indicate that the near surface is generally one-dimensional, the upper crust is two-dimensional and the lower and upper mantle is slightly three-dimensional. The patterns of the depth distribution of the structural dimensionality were grouped in close correspondence to the six geological units divided by three high altitude regions, the Dewa Hill, the Central Mountain Range and the southern Kitakami Mountains running nearly north-south in the area. The three-dimensional features at depth might reflect the tectonic changes in this area occurring after the Neogene when a change of the subduction direction occurred (Kimura et al., 1991).

The degree of three-dimensionality can be more quantitatively evaluated using the ordinary skew (Swift, 1967) and the phase sensitive skew (Bahr, 1987). Analysis of the skew on the three transects show that the skewness is less than 0.3 at almost all the sites and over the whole frequency range indicating a
limited influence of three-dimensional heterogeneity in the data for depth shallower than about 100 km. The phase-sensitive skew is not small, however for longer period of 500 sec indicating 3-D structure at mantle depth consistent with the 3D feature of the IPD noted previously. Our concern in the present work is shallower than Moho at about 30 km, and thus a 2-D modeling is assumed to be appropriate for these data. More detailed analysis of the three-dimensional effects due to 3D galvanic distortion (Bahr, 1987; Groom and Bailey, 1989, Groom and Bahr, 1992; Jones et al., 1993) also suggests that the crust can be treated as a two-dimensional to a fairly good approximation (Kawakami et al., 1997).

However, some regions are locally complex. For instance, site 606 at a period of about 100 sec has a skew value larger than 0.5. The phase sensitive skew of Bahr (1987) is also high in some localized regions where the ordinary skewness is large, indicating that distortions represent large scale structure, instead of local distortion caused by shallow heterogeneity. Some sites, such as those along the Pacific coast have large skewness values for both ordinary and phase-sensitive skews, possibly owing to the genuine geological complexity or cultural noise in the area.

4. Two-Dimensional Analysis

We have shown that the regional georesistivity structure in the northeastern Japan is approximately two-dimensional on the basis of the MT data, the coastline, mountain ranges, subduction geometry. We used a two-dimensional inversion program GRRI (Lee et al., 1995; Yamane et al., 1997) based on the RRI algorithm (Smith and Booker, 1991). The RRI algorithm applies the smoothness operator-concept originally used by Rodi et al. (1984) and Sasaki (1989). In the GRRI the model roughness is expressed by second derivative as introduced in RRI. The GRRI inversion enables us also to account for topography effects, and moreover the CPU run-time is reasonably short which allows for runs with several choices of free parameters, such as mesh scale and smoothing parameters.

In the Occam procedure (Constable et al., 1987) the functional $U$ for measure of goodness of a model is related to the deviation of observed data from theoretical values $F(m)$ depending on the model $m$ and a measure of the roughness of the profile. The functional is to be minimized:

\[
U = W(d - F(m))^2 + \alpha^2|Cm|^2
\]

where $W$ is a covariance weighting operator, $\alpha$ a smoothing parameter, and $C$ a matrix operator which provides a measure of the roughness of the model parameter. The magnitude of $\alpha$ trades off roughness against data fit, and was chosen by trial and error procedures. Uchida (1993) developed an inversion scheme to determine free parameters including the smoothing parameter $\alpha$ by a statistical approach, the ABIC minimization method (Akaike, 1980). However we chose the value of parameter $\alpha$ through trial and error procedure.

In our 2D inversion we used a smoothed impedance tensor derived from the one-dimensional Bostick inversion (Bostick, 1977). This means that the data were treated without error so that the weighting matrix $W$ becomes a unit matrix. The degree which this procedure represents the observed data will be illustrated later.

The resistivity of the ocean is fixed to be 0.2 ohm-m for the top 50 m, and below this is extrapolated from the profiles near the coasts. The geology underlying the ocean near the Pacific coast is assumed to be pre-Tertiary (Kimura et al., 1991) and thus similar to that in southern Kitakami. Similarly, we assume continuation of the resistivity profile under the ocean also near the Japan Sea from the tectonic history in the region (Kimura et al., 1991).

To improve convergence in the inversion process, the total frequency range was divided into 3 overlapping parts of five decades each. While inverting the low frequency data, the shallower part of the model was fixed using the inverted resistivities derived from the high frequency inversion results.

In the present study we discarded data from the lowest ($f < 0.009$ Hz) and highest frequencies ($f >$
9 kHz) due to large noise contamination at many sites. The frequency domain was divided into sets of 35 frequencies spaced equally on a logarithmic scale. The spatial mesh design for horizontal and vertical coordinates was generally based on the consideration of the spatial site geometry, and was finally determined from model simulation test by trial and error. The reproducibility and the accuracy of the forward calculations were checked under the limited computer resources and the skin depth of the highest frequency used. Along the observation lines, extending about 150 km east-west, the horizontal mesh increment had a Δx of 1,500 m. In the outer regions on both sides of the observation area, an exponentially increasing mesh was constructed resulting in a total 123 x-nodes on Line A. The vertical mesh interval Δz increased downward starting with 25 m in the uppermost 20 layers and increased up to 3,000 m for the lowermost three layers in the modeling area. Additional nodes, added to the bottom of the mesh to approximate infinity in order to match the boundary conditions, resulted in a total of 57 z-nodes. Lines B and C have a slightly smaller number of x-nodes because of the wider site spacing.

In some inversion algorithms the initial two-dimensional model can affect the final model, because of local minimum value for the evaluation function $U$ (deGroot-Hedlin and Constable, 1990). In such cases starting from an initial model which is similar to the real structure could lead to an acceptable inversion model. For example, Wu et al. (1993) adopted a one-dimensional starting model deduced from the inversion of a spatially averaged TM mode impedance. In the GRRI method the initial model is usually a uniform half-space because the algorithm has proven to be highly independent on the initial model chosen. Synthetic tests have verified that the GRRI algorithm can recover a reasonable resistivity model even starting from unrealistic models (Yamane et al., 1997). For the Tohoku data the value of the starting uniform half-space resistivity was 100 ohm-m based on the averaged value for 1-D model.

5. 2-D Model

The final two-dimensional models for the three transects obtained by inverting only the TM mode are shown in Fig. 3. We also obtained the solutions for TE and joint mode inversions with equal weights on the TE and TM mode data using almost the same free parameters. In the presence of three-dimensional heterogeneity the TM model is known to provide a realistic two-dimensional model (Wannamaker et al., 1984). Therefore, for presentation purposes here, we presented only the TM mode solution.

Convergence was obtained after about 10 to 15 iterations. Inversion model convergence is judged rather subjectively by inspecting the difference of the model structure between successive iterations, the magnitude of the residual difference (Observed-Calculated (O-C)) of the observed data value from the theoretical value, and the smoothness of the model in reference to the data spacing. Plots of the differences of the field data from the synthetic data calculated from the 2-D model of the TM mode are shown in Fig. 4, (a) for apparent resistivity, and (b) for phase. Here the residual $R(\rho)$ for the apparent resistivity $\rho$ is,

$$R(\rho) = |\log \rho_o / \rho_c|$$  \hspace{1cm} (3)

and that $R(\phi)$ for the phase $\phi$,

$$R(\phi) = |\phi_o - \phi_c|$$ \hspace{1cm} (4)

where the suffixes o and c denote observed and calculated quantity, respectively.

On Line A, the apparent resistivity residuals are not large except under site 310 in the Pacific coast where the phase misfit is also large. The site had large cultural noise making it quite difficult to get good quality data. The site will be visited again in order to have better data. Large residual can also result from a geological boundary. On Line B the residual is acceptably small except at depth under the site 408. On Line C a large deviation of about 0.3 logarithm relative residual occurs at around 10 sec under sites 508 and 708. A large misfit is also seen under the Japan Sea coast and under the site 713.
5.1 Line A

On Line A there are narrow conductive anomalies in the Central (Sekiryou) Mountain Ranges (SE) and in the west of the coastal region of the Pacific Ocean that extend to depth of 40 km in the case of the inversion that all the 33 site data are used. To evaluate the repeatability and sensitivity of the GRRI algorithm to small deep and apparently unreal structures, the starting model was smoothed under sites 204, 609, 305, 610, 611 and 206. The inversion procedure was then started from the modified resistivity distribution. A lack of resolution with depth resulted in slight differences in the impedance curve at the

Figure 3 shows several conductive regions common to all three lines. In particular, two conductive anomalies west and east of the Central Mountain Ranges are evident on each transect. The conductive anomaly west of the Mountain Range corresponds to the Central Basin, the Shinjo Basin on Line A and Yamagata Basin on Lines B and C. The Central Basin Anomaly (CB) reaches to the Moho depths on Lines B and C, but is rather shallow on Line A, possibly due to the variable depression of the region along the structural axis that developed in the Tertiary period. In the interpretation of the anomalies especially the vertically elongated conductive anomaly we need to take account of the magnetotelluric impedance tensor distortions due to the subsurface inhomogeneity. So that the penetration through the Moho should not be taken seriously. The eastern conductive anomaly around the Kitakami River (KK), east of the Central Mountain Range, is thin compared with that of the CB on Lines B and C. The western boundary of the KK corresponds to the pre-Tertiary Hatagawa tectonic line.
Fig. 4. Pseudosections of the misfit between the data and model response for the final TM mode models on the three profiles A, B, C shown in Fig. 3. (a) logarithm ratio of observed and calculated apparent resistivities. (b) absolute difference between the observed and calculated phases.
lower frequencies after an iteration. However the small differences for the assumed profile provided an inverted solution which was similar to the original model before the modifications. Therefore it is suggested that the deeper structure under site 204 is due to data variation possibly related to real geology and not numerical artifacts. The long conductive stripe under site 206 in the resistivity model using whole sites is concluded to be treated more carefully because the site is located many kilometers northward away from Line A where the geology is rather different from the neighboring point 611.

Inspection of those isolated anomalies one by one lead us to infer that some of anomalies are caused by the local heterogeneity around the observation sites, for instance, because of being extremely different from the neighboring sites. However the anomaly at site 204 (SE) is likely related to the geothermal activity at the nearby Onikoube and Narugo Quaternary volcanoes. The static shift of TM mode data at site 204 is 0.13 decade and that at site 609 is 0.0 decade (Fujinawa et al., 1997) suggesting that the anomaly SE would be less prominent than as seen in Fig. 3. The vertical elongation of SE apparently penetrating through the Moho should be reconsidered by fully taking account of the effect due to the surface heterogeneity of the resistivity distribution such as partially tried in Kawakami et al. (1997).

The 2-D inversion models without the sites that differ radically from neighboring sites result in a smoother version of the model for transect A as shown in Fig. 3, and little change to those on Lines B and C. Channeling effects due to local heterogeneity can be estimated, for instance, by the impedance tensor decomposition technique of Groom and Bailey (1989). An impedance distortion analysis conducted on the three transects (Kawakami et al., 1997) show that there are surface distortions which could not be neglected but that are small enough to assure that the two-dimensional treatment is valid and the regional strike is near north-south.

In order to check the effect of the assumed strike direction in the inverted solution we obtained the model assuming a structural strike of 25 degrees (rotated clockwise from north) for on Line A taking into consideration the ambiguity of the observed principal axis. The rotated result is not so much different from the unrotated case except that the slim vertical conductive stripe appearing in the model is less prominent and the misfit between the data and model response is reduced.

The TE mode solutions with the same choice of inversion procedures (though not shown here to save space) is compared to that of the TM mode on Line A. The models of the two modes exhibit generally the same pattern and magnitude of resistivity distribution, especially the four conductive anomalies CB, SE, KK, and that near the Japan coast (JS) under site 602, though there are a little bit difference of extent and value of the resistivity.

However it is seen that the model for the TM mode on Line A, for example, has a higher conductivity in the upper crust beneath the sites 308, 309 (PC anomaly) underlying very resistive regions. On the other hand the feature is resistive in the TE mode. The depth of this feature is about the Conrad, and is thus comparable to the case in south-eastern British Columbia (Eisel and Bahr, 1993). The discrepancy in the TE and TM mode solution extended to west to the eastern edge of the anomaly KK under site (612): the upper crust is resistive (~100 Ω·m) in the TM mode, but it is very conductive in the TE mode including the deeply penetrating (~5 Ω·m) conductive part extended from the site 611 and 206. A bit small region of this anisotropy is also seen under the uppermost crust in the western end of the CB anomaly.

The effect of the static shift is to be estimated semi-quantitatively on the basis of the TEM measurements (Fujinawa et al., 1997). Magnitudes of static shifts of the TM mode data on Line A are almost less than 0.2 decade except at two sites: 0.47 decade at site 602, 0.6 decade at site 308. We could not get data at site 308 owing to too large resistivity. We can imagine that the general feature of the resistivity distribution does not much differ from that shown in Fig. 3. The apparently clearest conductive bodies CB would be more limited in the horizontal direction because of +0.17 and +0.15 decade shift at site 605 of the western end and 203 of eastern end of CB, respectively. Another conductive bodies KK would become less prominent because of the about +0.2 decade shift on the sites 307 (+0.17), 206 (+0.16) and 612 (+0.21) except 0.0 on the central site 611. The apparent conductive anomaly under the site 602 near the Japan coast (JS) would be less prominent to be comparable to those at Lines B and C because of +0.47 decade shift at 602 and 0.0 decade at 603.
5.2 **Line B**

For the inversion on Line B the mesh was nearly the same as on Line A being determined on the basis of the synthetic test. As is seen in Fig. 3 the eastern part of the profile is characterized by a thin conductive layer in the near 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, of order 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 with the northern and southern transect. West of the Central Mountain Range a clear conductive anomaly under the Yamagata basin can be seen. A comparison of the TE and joint profiles indicates that 3-D effects are possible at sites 510, 511, 401, 402, 403, and 408 which are all near conductivity boundaries as can be seen from Fig. 2. A conductive region in the upper crust near the Japan Sea could be a true structure corresponding to the thick Neogene marine sediments extending to the Japan Sea (Kimura *et al.*, 1991).

Results of the GRRI inversion with and without taking into consideration the topography are quite similar, except at 404 where there is a vertical shift and a difference at very shallow depths at site 410. The inversion results for the 25 degree rotated data are quite similar on the eastern side, but different on the more complex western side with the faulted zones being most prominent as well in the vicinity of site 511.

The magnitude of static shift of TM mode data on Line B turned out to be almost less than 0.2 decade except +1.15 decade at site 711, +0.44 at site 510, 0.39 at site 407, and −0.51 at site 710 (Fujinawa *et al.*, 1997). Thus we can suspect that western half of the conductive anomalies, especially the vertical striping, is assumed to be largely influenced by the shifts. The anomaly CB on Line B would be nearly similar to that on Line A. The horizontally flat anomaly KK on Line B would not be so much different to that shown in Fig. 3 because of the small shift of less than 0.1 decade at all sites in the region except +0.2 on the easternmost site 412.

5.3 **Line C**

Many tests have been conducted to infer the most appropriate values of free parameters in the inversion of Line C. In the inversion of Line C we obtained solutions with and without constraining the shallowest 1.4 km depth during the low frequency inversion for deeper structures. The profile shown in Fig. 3 is the solution obtained by the inversion with constraints. The inversion without constraining the shallowest part results in a narrow vertical conductor, which is thought to be unrealistic. Comparisons were also made for inversions using different meshes and frequency ranges. Those results are all similar which provides evidence that the GRRI code is stable for choices of mesh and frequency. The inversion model for data rotated by 25 degrees was basically the same as the unrotated inversion, except at site 506. The unrotated resistivity value at 506 is about 200–300 ohm-m at the lower frequencies, but the rotated one is about 80 ohm-m indicating some three-dimensional effects may be present around the site.

In Fig. 5(a) are shown two orthogonal components of the true observed data expressed as apparent resistivity and phase for Line C. Figure 5(b) shows simulated TM mode observation data (1) used in the inversion and the model responses (dotted line) in the middle frequency ranges (b), at the sites on Line C. As was noted, the “observed data” in the inversion (a) is actually derived by means of the 1-D Bostick inversion to best fit the observation data. It can be seen that the simulated data is almost the same as that obtained by smoothing the original data. We can see generally good fitness of the model obtained to the data except in several frequency region at some sites. The true observed data (Fig. 5(a)) have large confidence limit of 90% especially at longer period range at site 506, 714, and 713.

The static shifts of TM mode data on Line C turned out to be less than 0.2 decade in magnitude except +0.93 on site 507, 0.41 at site 503, and 0.40 at 703 (Fujinawa *et al.*, 1997). So that the most prominent conductive anomaly CB on Line C would be more limited in the horizontal direction because of the relatively large shift at the western half of the CB with the result of similar profiles of the CB at three Lines A, B, C. The conductive anomaly KK would be less prominent because of the relatively large shift of 0.2 decade at both side of the apparent anomaly compared to very small shift of 0.0 decade in the middle of the KK. The long vertical striping apparently reaching to the Moho under the site 509 is possibly caused
Fig. 5. Observed data at sites on Line C shown as two orthogonal components of apparent resistivity and phase with error bars corresponding to 50% confidence limit (a). Smoothed data used in the 2D inversion and the calculated model response from the final model shown in Fig. 3.

by the spurious effect of the subsurface resistivity heterogeneity. The effect should be estimated by the impedance decomposition analysis taking account of the site gain factors.

6. Discussion

The model cross-sections provide many interesting features that can be discussed in terms of the geology, tectonics, seismic activity, and volcanic activity. The general georessitvity distribution for an area of about 40 km width from north to south is reasonably two-dimensional model as suggested by the
similarity of the three profiles along the three transects. However three-dimensional heterogeneity are important particularly near geological boundaries and cannot be neglected. The clearest evidence of conductive bodies are found west and east of the Central Mountain Range: the conductive sediments in the Shinjo and the Yamagata basins west, and the Kitakami or Abukuma River regions in the east. The resistivity profiles correlate well with the six geological divisions in the northeast Japan Arc (Oide et al., 1989).

The profile on Line A exhibits more complex features possibly due to the active geothermal area in the SE. A high correlation of models on Lines B and C shows a steep dip inclination which can be seen in between the Central Basin and the Central Mountain Range. The Tanakura tectonic belt consists of a Cretaceous strike slip fault that divides NE-Japan and SW-Japan is located near sites 603, 402, and 503 in Lines A, B, and Line C, respectively. All these sites are well correlated with the western boundaries of
conductive regions. The Ashio belt south of the Tanakura tectonic line was developed in the course of Jurassic subduction (Otsuki and Ebirio, 1978). The Hatagawa tectonic line can also be seen in the resistivity profile at around site 409 on Line B and at site 508 on Line C, respectively. The Hatagawa tectonic line divides the Central Mountain Range and the Kitakami River region of Quaternary sediments. The eastern limits of the Central Mountain Range also correlate well with the crossing of the Hatagawa tectonic line of late Cretaceous left-lateral strike slip at site 305 on Line A, at site 408 on Line B, and at 508 on Line C.

The most prominent conductors are seen in the Central Basins, the Shinjo Basin on Line A, and the Yamagata Basin on Lines B and C. The Basins are located between the Dewa Hill which upheaved post than the Pliocene and the Central Mountain ranges which uplifted in the Miocene. The resistivity is very low, less than 10 ohm-m, reflecting middle and late Miocene marine sediments. The conductor in and around the Yamagata basin reaches from the surface to the Moho depth on Line C and underlies a resistor on Line B. The region around Line B is the transition zone between the Shinjo Basin and the Yamagata Basin where the geomagnetic anomaly is small in comparison to the central parts of the two neighboring Basins. The resistive bodies seem to extend to Moho depth in contrast to thethose on the Akita-Iwaizumi profile (Ogawa, 1992).

It is noted from comparison of Fig. 2 and the CB anomalies that the part of the vertical elongated conductive bodies of each CB are situated not in the midst of the Basins but in the peripherals of fault rich region. This suggests that the fractured regions are conductive because of large content of water intruded from the surface or surrounding rocks. However more careful treatment is indispensable such as taking account of the subsurface heterogeneity effects.

The top layers east of the Central Mountain range are very conductive. On Lines A and B, those conductor correspond to the Kitakami River region, and to the Sendai plain on Line C. There is considerable variation in the conductive structures along the regional strike caused by the difference in tectonics. Surface geology is Quaternary volcanic rock east of the Hatagawa tectonic line on Line A but consists of middle or late Miocene sediments on Lines B and C.

Along the Pacific coast the resistivity profile is characterized by the existence of resistive bodies. The region at around Line A included in the Southern Kitakami belt there are pre-Tertiary basement exposures of metamorphic lock. But near Lines B and C there are conductive zones underlain by resistive bodies with greater than several thousand ohm-m of Paleozoic and early Cretaceous ages. The Central Mountain range is quite resistive throughout the entire crust on Lines B and C. This mountain range is characterized by the late Neogene uplift (Kimura et al., 1991) that exposed Cretaceous plutons. However the region on Line A near around site 204 belongs to an active geothermal field related to the Quaternary volcanoes Onikoube and Narugo and has narrow conductors that extend deep into the crust. A more detailed observation is needed to delineate extension of the isolated conductive bodies.

West of the Central Basin, the Dewa Hill region (especially Mt. Asahi on Lines B and C) contain resistive rocks thought to correspond to the early and late Cretaceous plutons exposed by Pliocene uplift. West of the Tanakura tectonic line on Line A, the region is underlain by an extensive conductor. Also suggested on Lines B and C are small scale conductors. The region around Line C is the southernmost part of the Shonai plain of Quaternary-aged sediment which is underlain by thick Neogene marine sediments extending to the continental shelf of the Japan Sea.

We have limited our discussion to the resistivity structures which are in direct relation to geology. Interpretations with regards to geophysical parameters are left to a future paper.

7. Conclusions

We have collected 70 sites of broadband magnetotelluric data along three transects in the central part of the northeastern Japan Arc subduction system. We can summarize results of the data analysis as follows.

1) The NS strike of georesistivity structures used in two-dimensional modeling is based on impedance polar diagrams, tipper strike directions, and an impedance tensor decomposition analysis.
Overall conformity of inversion results between the three profiles is consistent with the assumption of a 2-D georesistivity structure and with used geology and topography.

2) Clear upper crustal conductive anomalies deduced from the one- and two-dimensional inversion models includes the Central Basin west and the Quaternary sediment layer east of the Central Mountain Range on the three transects. Those anomalies seems to be more or less influenced by the impedance distortions due to the subsurface resistivity heterogeneity.

3) Vertically elongated part of the conductive body in the Central Basin is thought to correspond to the fractured region near faults.

4) The northernmost Line A has complex features including a conductive zone at the Central Mountain Range reflecting active Quaternary volcanoes.

5) Mountain Ranges at the Dewa Hill, Central Mountain Range, and southern Kitakami Mountain are characterized by resistive pre-Tertiary basement rocks.

6) The Tanakura and Hatagawa tectonic lines of late Cretaceous age are seen to divide conductive sediments from the pre-Tertiary basement rocks.

7) Further studies are needed to correct fully the surface local heterogeneous effects leading to the distortion of the impedance tensor by means of the impedance tensor distortion analysis taking account of the directly measured site gain factor.

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