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Resistivity structure across Itoigawa-Shizuoka tectonic line and its implications for concentrated deformation

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We investigated the deep crustal resistivity structure across Itoigawa-Shizuoka Tectonic Line (ISTL), one of the most dangerous active intraplate faults in Japan, by use of wide-band magnetotelluric (MT) method. The 28 MT stations were aligned perpendicular to the ISTL. A two-dimensional model was created in transverse magnetic (TM) mode where electric currents flow in N60°W-N120°E directions. The model showed good correlations with the surface geology. In particular, we found a thick ($\sim$6 km) surface conductor to the east of ISTL which corresponds to the heavily folded sedimentary layer. The Japan Alps to the west of the ISTL is characterized by the resistive upper crust, where the pre-Tertiary rocks crop out. The Japan Alps is underlain by a conductor below 15–20 km depth, which is consistent with the low seismic velocity anomaly. We also found a localized shallow conductor corresponding to the Mt. Tateyama volcano. The most important feature is the conductor in the mid-crust directly under the area of active folding to the east of the ISTL. This may imply a localized zone of fluids because of the enhanced porosity in a shear zone. The recent seismicity clusters in the resistive crust underlain by the conductor, and this suggests the fluid involvement in earthquake generation processes.

1. Introduction

The magnetotelluric (MT) method can produce electrical resistivity images of the deep crust and upper mantle by measuring natural electromagnetic signals at the earth surface in a wide frequency band at many site locations (e.g., Jones, 1992). As the resistivity of rocks is sensitive to distributions of fluids, MT can be a powerful tool in investigating the fluid involvement in the earthquake generation processes. Unsworth *et al.* (1999) report the effectiveness of MT in delineating the fracture zones as conductive features in the San Andreas Fault zone in California. MT can also characterize the deeper structure of the seismogenic zones in terms of electric resistivity (Lemonnier *et al.*, 1999; Honkura *et al.*, 2000; Ogawa *et al.*, 2001; Mitsuhata *et al.*, 2001).

The objective of this study is to image the deep structure across Itoigawa-Shizuoka tectonic line (ISTL, see Fig. 1), which is believed as the Eurasian/North American plate boundary on land (Kobayashi, 1983; Nakamura, 1983). In particular, the northern segment of the tectonic line is regarded as one of the most dangerous active faults in Japan. This study is a part of the multidisciplinary project to study the deep slip process on faults that might precede large intraplate earthquakes.

2. Previous Magnetotelluric Studies in Seismogenic Regions

Recent MT studies in Japan over seismically active regions have detected several conductors under the seismogenic zones. The high seismicity clusters in the resistive region near the resistivity boundary or in the resistive region underlain by conductor (Ogawa *et al.*, 2001; Mitsuhata *et al.*, 2001).

Ogawa *et al.* (2001) collected MT data on a 90 km long profile with 34 stations in the back arc of the Northeast Japan (profile 1 in Fig. 1). The present day high seismicity is regarded as aftershocks of two historically known large intraplate earthquakes, Senboku earthquake (M7.1 in 1914) and Rikuu earthquake (M7.2 in 1896). The MT data showed strong two-dimensionality and anisotropic responses at the periods around 100 s. The resistivity model required three mid-crustal conductive blocks that were not connected in a horizontal direction. The correlations of the conductors to the seismic scatterers and to the low velocity anomalies suggest that the conductors represent fluids. Clusters of seismicity near the edges of conductors (Umino *et al.*, 2000) suggest that the intraplate seismicity might result from the migration of the fluids to less permeable regions of the crust (Ague *et al.*, 1998).

Mitsuhata *et al.* (2001) presented the results of detailed MT profiling around a seismically active region in the forearc of Northeastern Japan (profile 2 in Fig. 1). The current seismicity is interpreted as aftershock of Northern Miyagi Earthquake (M6.5) in 1962. A two-dimensional inversion revealed the existence of a deep conductive zone and overlying resistive zone in the upper crust. They found that the micro-earthquakes occur just above the deep conductor and in the resistive zone, and that several S-wave reflectors are just above the deep conductor. Since the S-wave reflectors

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suggest the existence of fluid beneath them, the deep conductor was interpreted as a fluid-filled zone. They suggested that the seepage of the fluid from the conductive fluid-filled zone to the resistive granitoid pluton might trigger the earthquakes swam.

These previous studies found a consistent relationship between electromagnetic images and regions of high seismicity, which are aftershock regions of historically known large intraplate earthquakes (Fig. 2(a)). Namely, the high seismicity corresponds to the resistive area underlain by the conductor, or the one near the conductor. This suggests the fluid involvement in generating the aftershocks.

In this study, we are most interested in the earthquake potential of the region where intraplate earthquakes may happen in the near future (Iio and Kobayashi, 2002). We evaluate two such test sites in Japan. One is the northern segment of ISTL in Nagano prefecture; the other is Nagamachi-Rifu line in Miyagi prefecture (e.g., Sato *et al.*, 2002). The hypothesis that we plan to test is that the quasi-stationary slip in the lower crust precedes the incidence of a large intraplate earthquake (Fig. 2(b)). The slip area must be localized as expected by geological observations at the outcrop of the fossil shear zones (e.g., Fujimoto *et al.*, 2002). We test if the fluid is involved in the localization of the deep slip process. In this paper we show MT results from one of the test areas, Itoigawa-Shizuoka tectonic line.

3. Geological Background

ISTL is a geological boundary between the Pre-Tertiary unit to the west and the Neogene units to the east. The Pre-Tertiary basement deepens to the east. The northern segment of the ISTL is an active thrust fault. The recurrence time of the earthquake faulting is estimated as less than 1000 years from the trenching of the active segment in Matsumoto (Fig. 3) (Okumura *et al.*, 1994).

In the Miocene, at the time of the Japan Sea opening, ISTL was created as a normal fault in an extensional tectonics. The Minochi belt (Fig. 3) is made up of thick (several kilometers)

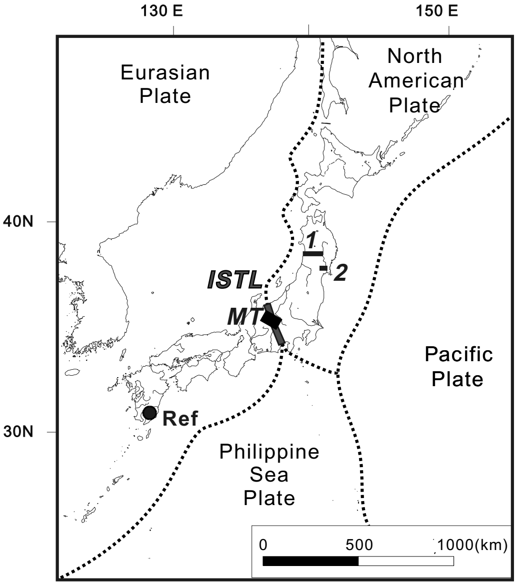

Fig. 1. Location of Itoigawa-Shizuoka Tectonic Line (ISTL) as part of the plate boundary between the North American plate and the Eurasian plate. Ref is the remote reference site for MT. Two profiles identified as 1 and 2 denote the locations of the previous MT survey over intraplate earthquake regions (Ogawa *et al.*, 2001; Mitsuhata *et al.*, 2001), respectively.

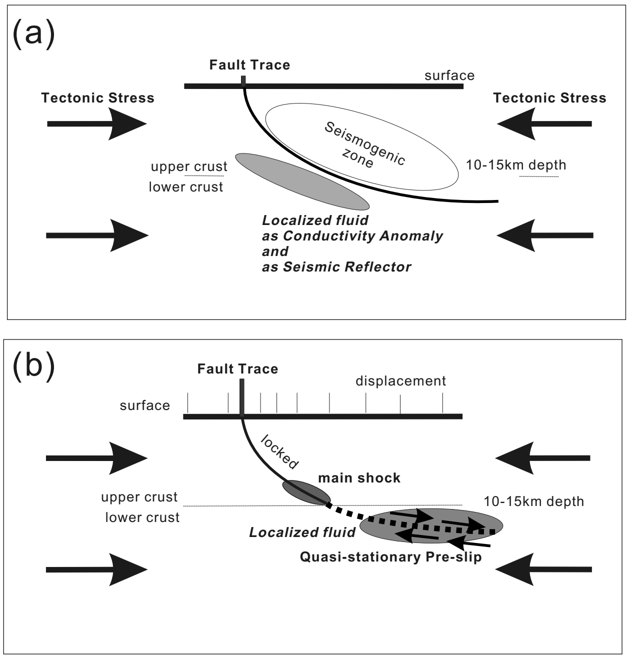

Fig. 2. Schematic resistivity models for (a) after and (b) before the large intraplate earthquakes.

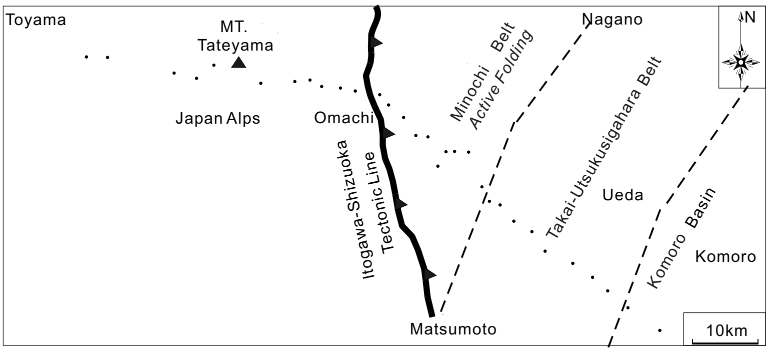

Fig. 3. MT site locations and major geological units.

layers of marine sediments and volcanics, which deposited under the Miocene extension tectonics. Later to the present, ISTL was reactivated in a compressional tectonics as a reactivated fault (Sato and Ikeda, 1999). The tectonic compression also folded the Minochi belt to the east of the ISTL. These geological observations are consistent with the geodic results that show large shortenings in the Minochi belt of 30 ppm per 100 years (Sagiya *et al.*, 2002). Thus this area is thought suitable to test the hypothesis of deep slip in active faults.

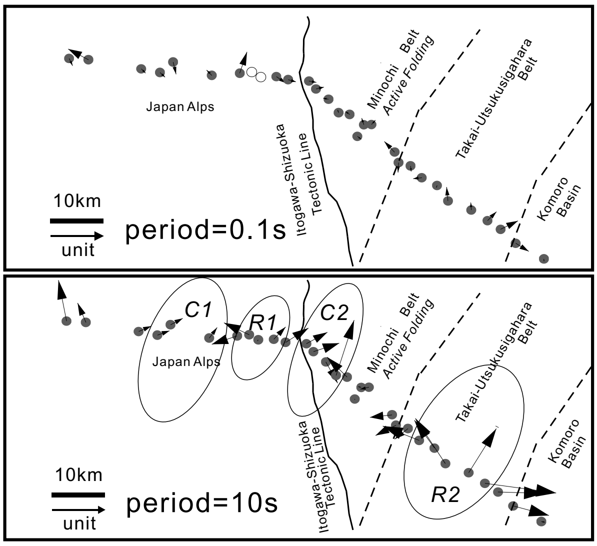

Fig. 4. Real parts of the induction vectors at the period of (a) 0.1 s and (b) 10 s. The vectors point to conductors and the unit length corresponds to 10 km. At 10 s, they point toward the conductive anomalies (C1, C2) and away from the resistive anomalies (R1, R2).

The Japan Alps (the Hida mountain range) is located west of ISTL. According to Ikeda (1996), the basic topography was created in the Miocene in the extensional tectonics. The continuation of the regional tensile stress created Quaternary monogenic volcanoes such as Mt. Tateyama, which is characterized by the youngest granitic intrusion on Earth (Harayama, 1992). In order to investigate the deep structure of ISTL, we must also analyze the surrounding regional structure around the target area (Ogawa, 2002).

4. Magnetotelluric Observations

The 100 km long MT profile of 28 stations runs across the ISTL (Fig. 3). From the west to the east, it crosses the Japan Alps (Hida Mountains), the Minochi belt (area of active folding), the Takai-Utsukusigahara belt (area of elevated basement), and the Komoro collapse basin.

The data were collected in September 2000 using 6 wideband MT instruments (Phoenix MTU5 system). The period range covers from 3×10^{-3} s to 2,000 s. Since the DC electric railways severely affect the measurements, the time series analysis was focused on the nocturnal data when there were fewer trains. We also had simultaneous remote reference measurement site operating on Kyushu island (Ref in Fig. 1), which is approximately 900 km away from the study area. Using remote reference technique (Gamble *et al.*, 1979), we could reduce the unwanted cultural noise mainly from leakage currents of DC railways in the study area.

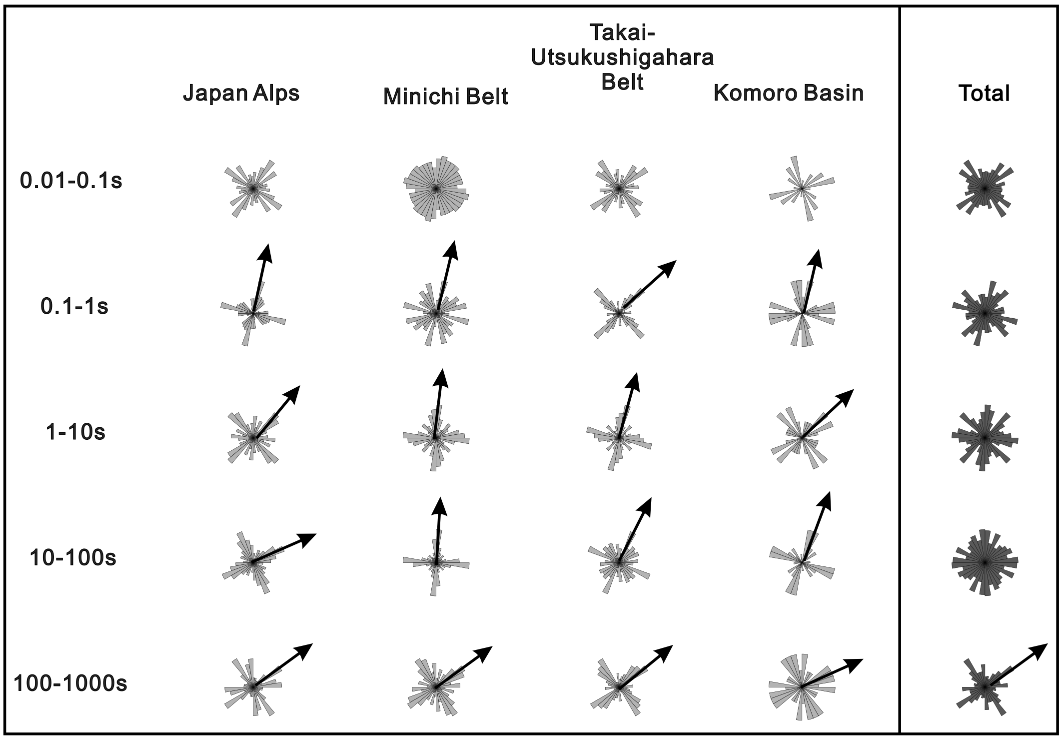

Fig. 5. Strike estimates from the Groom-Bailey tensor decompositions, where distortion parameters were set site-dependent and period-dependent. This shows the period and spatial dependence of the directional properties of the resistivity structure. Note that the $\pi/2$ ambiguities are also included in each diagram.

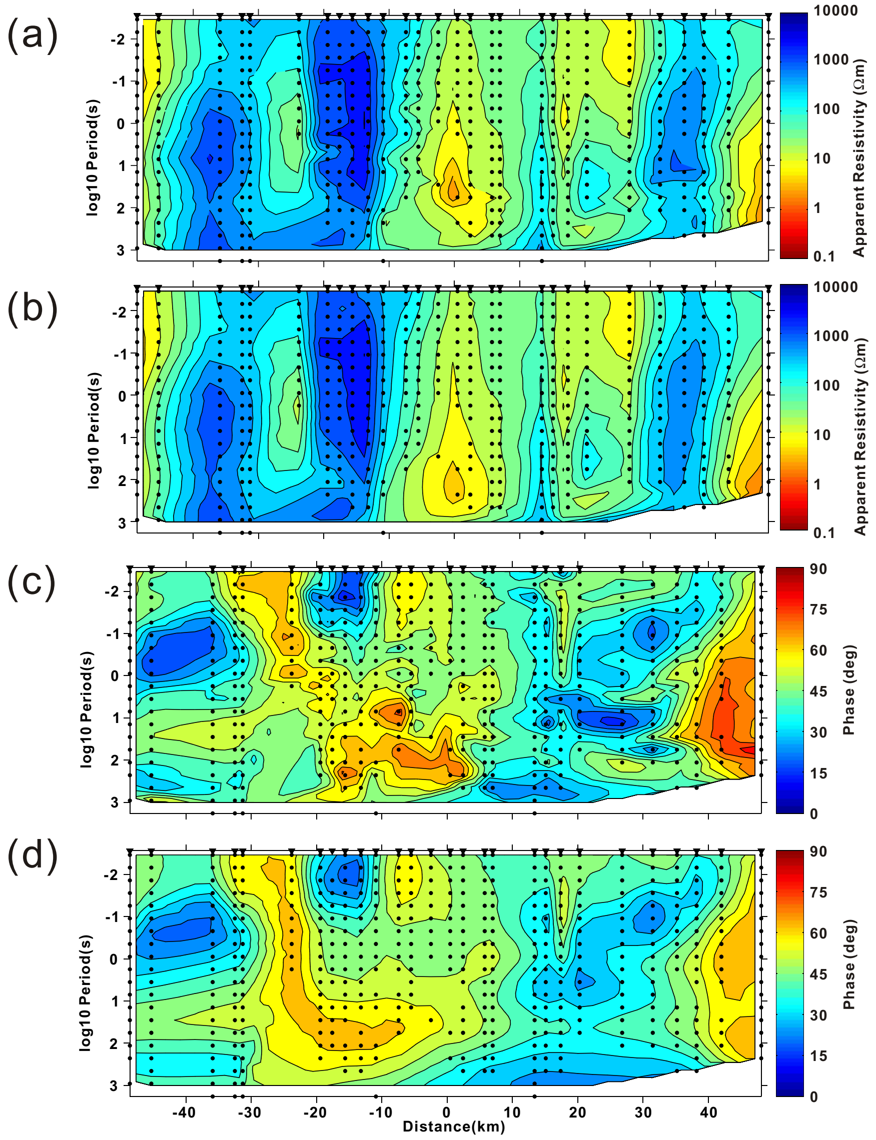

Fig. 6. Pseudo-sections for the observed and calculated apparent resistivity and phase for the TM mode (electric current in N60°W-N120°E direction); (a) observed apparent resistivity, (b) calculated apparent resistivity, (c) observed phase, and (d) calculated phase, respectively.

5. Checking Dimensionality

Prior to the two-dimensional analyses, we diagnosed the dimensionality of the data, by the induction vectors and the impedance strike distributions.

5.1 Induction vectors

Induction vectors show the regional resistivity contrast inferred from magnetic fields. Figure 4 show the real parts of the induction vectors at the periods of (a) 0.1 s and (b) 10 s. In the short period (Fig. 4(a)) the vectors are small and there is no regional distribution. However, at the period of 10 s (Fig. 4(b)), we have concentrations of induction vectors to C1 in the Japan Alps and C2 below the western part of the Minochi belt (active folding zone). Resistive anomalies can also be identified as the vectors point outward at R1 and R2. These anomalies are consistent with the mid-crustal structure as shown later.

5.2 Impedance strike estimates

We estimated strike directions from individual impedance data, by tensor decompositions (Groom and Bailey, 1989). Figure 5 shows the distribution of strike estimates for period-dependent, site-dependent decompositions. We can see the consistency within each geologic unit and within each decade band of periods. Only in the longest period band (100–1000 s), we have consistent direction over the whole profile. In the shorter periods, the strike estimates mostly fell between N0°E and N45°E. As a preliminary modeling, we took N30°E as a regional strike direction, which follows the major geological boundaries east of ISTL.

6. Two-Dimensional Magnetotelluric Modeling

We assumed that the regional strike direction as N30°E. As seen from Fig. 3, the assumed strike is consistent with the surface geological divisions to the east of the ISTL. However, obviously the ISTL is oblique to this direction.

The southward extension of the eastern geologic units, especially Minochi belt, is chopped by the ISTL. As the Minochi belt has thick conductive surface layers (as shown later), the use of just the TM mode here may be more reliable

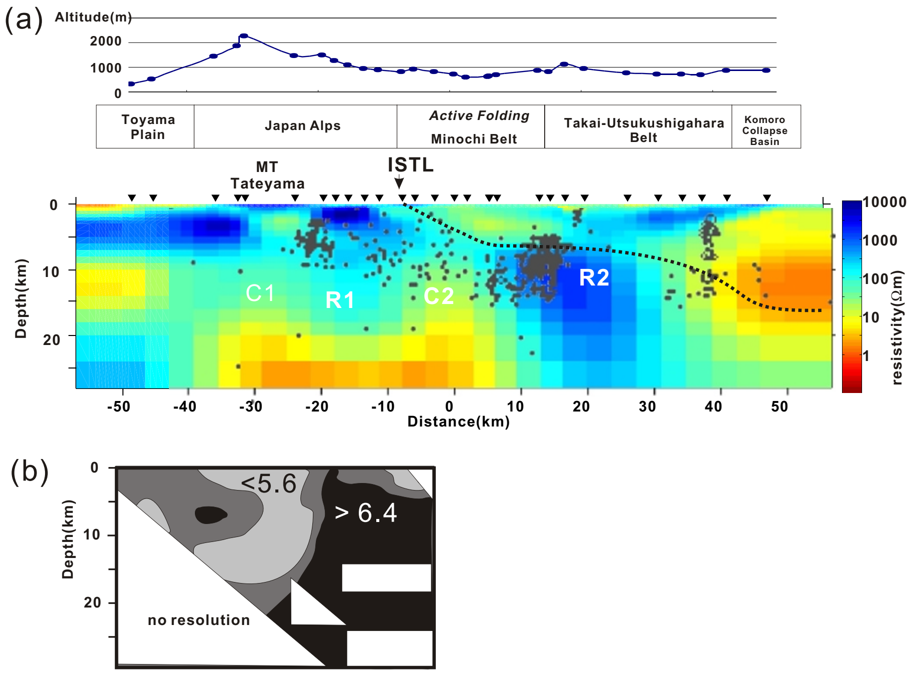

Fig. 7. (a) A two-dimensional resistivity model and the seismicity along the profile. The resistivity model used TM mode only where electric field is across the assumed strike direction of N30°E. Altitude of the sites and geological belts are also shown. (b) Seismic tomography result over the Japan Alps, simplified from Matsubara *et al.* (2000).

than using both TE and TM modes (Wannamaker *et al.*, 1984; Ogawa, 2002).

We used a uniform earth of 100 Ωm as the initial model. The inversion had a constraint that the resistivity structure should be spatially smooth (Ogawa and Uchida, 1996). Thus the obtained model is the smoothest model that can fit the data. Figure 7 shows the resistivity model. The rms converged to 1.02 with an assumed error floor of 10% in apparent resistivity and the equivalent in phase.

Figure 6 shows the comparisons between observed and calculated apparent resistivity and phase. The major features in the observations were explained by the model, although, the observed phase data seem noisy at −20 km to +5 km in the period range between 1s to 1,000 s.

The heterogeneity in the mid crust at 10–20 km depth (Fig. 7) comes from the data in the 1–100 s periods. We have conductors and resistors where we have high phase ($>45°$), and low phase ($<45°$) respectively. The distributions of the induction vectors at the period of 10 s (Fig. 4(b)) also show consistent features. The induction vectors point to the areas of high phase in the periods of 1–100 s.

7. Discussion and Conclusion

To the east of the ISTL, the Minochi belt is a conductive layer, 6 km thick, corresponding to the actively folded sedimentary and volcanic layers. Below 10 km depth, there is a conductor, whose top deepens towards the east. The deep conductor disappears beneath the Takai-Utsukusigahara belt. There is a possibility that such a high conductivity anomaly represents a zone of enhanced porosity due to strong shear in the localized deformation area (Ogawa *et al.*, 2001; Wannamaker *et al.*, 2002).

In Fig. 4, also shows earthquake hypocenters determined by the Japan Meteorological Agency (Yuzo Ishikawa, personal communication). These hypocenters are generally located in resistive regions near the boundaries. Very few hypocenters are located within conductors. These may imply that the earthquakes are triggered by migration of fluid to less permeable (more resistive) crust (Ague *et al.*, 1998; Ogawa *et al.*, 2001; Mitsuhata *et al.*, 2001).

Under the Japan Alps, the lower crust and the upper mantle are relatively conductive. We calculated the variance of the resistivity of each blocks and found that the tops of the deep conductors at 10–20 km are well resolved but the deeper continuations to the upper mantle are not.

We can compare our resistivity model with the seismic tomography result to a depth of 15 km around the Japan Alps. Seismic tomography (Matsubara *et al.*, 2000) revealed two zones of low P-wave velocity. One is located at 4 km depth and the other at 15 km depth (bottom of the upper crust) under Mt. Tateyama, central part of the Japan Alps. Our MT result has the corresponding low resistivity anomalies at both levels. From Vp/Vs analyses, Matsubara *et al.* (2000) inferred that the low velocity anomaly at 15 km depth can be explained by rocks with 5% partial melt having tube-like pore geometry. We can estimate the porosity from the resistivity model using Archie's law. If we assume melt resistivity as 0.01 to 0.1 Ωm (Haak and Hutton, 1986), and the cementation factor as 1.3 to 2, the corresponding porosity to the resistivity of 30 Ωm at 15 km depth will be 0.2 to 6%. If the melt is 0.1 Ωm and the cementation factor is 2, MT and seismic result can give consistent porosity estimates.

Although ISTL is located the edge of the tomography study area, and the tomography shows high Vp velocity towards the ISTL (Fig. 7(b)). On the other hand, MT result showed that the mid crust east of ISTL is conductive. This may seem inconsistent with the seismic tomography. However, this might be caused by the different sensitivity to the structure (Yoshihisa Iio, personal communication). If there is a fluid distribution in a film-like geometry, there is a possibility that MT can resolve the anomaly, but seismic methods cannot. If we assume a crustal fluid resistivity as 0.04 Ωm as a typical crustal fluid resistivity (Nisbett, 1993), we can infer the porosity from the Archie's law. Corresponding to the possible cementation factors ($m = 1.3$ to 2), the porosity estimates for 30 Ωm conductive anomaly will be 0.6–3.7%. If we assume a film-like geometry (i.e., smaller m), the porosity less than 1% will be preferred.

From the geological investigations, ISTL requires double-ramp geometry as shown by the dotted lines in Fig. 7 (Hiroshi Sato, personal communication). This is required to explain the development of the geological structure to the east of ISTL, especially the uplifting of the basement in the Takai-Utsukusigahara belt. If we assume this geometry, the deep extension of the fault will be within the conductor under the Komoro Collapse basin as shown in Fig. 7. This conductor may accommodate the deep slip of the fault.

This magnetotelluric dataset still demand further multi-dimensional modeling of the resistivity structure. The planned coincident seismic reflection profiling in 2002 will reveal the geometry of the fault in detail and advance the geophysical and geological implications of the resistivity structure, in particular the deep conductor under the folding area and the deep extension of the fault in the lower crust.

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