GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 19, PAGES 3741-3744, OCTOBER 1, 2001

Magnetotelluric imaging of fluids in intraplate earthquake zones, NE Japan back arc

Yasuo Ogawa[1], Masaaki Mishina[2], Tadanori Goto[3], Hideyuki Satoh[4], Naoto Oshiman[5], Takafumi Kasaya[5], Yukie Takahashi[6], Tadashi Nishitani[6], Shin'ya Sakanaka[6], Makoto Uyeshima[7], Yuji Takahashi[7], Yoshimori Honkura[8], and Masaki Matsushima[8]

Abstract. Intraplate earthquake zones in the back arc of NE Japan were imaged by wide-band magnetotelluric (MT) soundings. The 90km long MT profile of 34 stations extends over the two topographic features, the Dewa Hills and the Ou Backbone Range, which were uplifted by thrust faults. MT data show two-dimensionality and strong TE/TM anisotropic responses at the periods around 100 s. After tensor decompositions with regional strike of N12°E, two-dimensional inversion was carried out where static shift was also a model parameter. The final model is characterized by conductive blocks in the mid-crust to account for the anisotropic responses. Correlation of the conductors to the seismic scatterers and to the low velocity anomalies suggests that the conductors represent fluids. High seismicity clustering near the rims of conductors suggests that the intraplate seismicity results either from the migration of the fluids to less permeable crust or from local stress concentration near the structural boundary.

1. Introduction

We made wide-band (0.003 – 2000 s) MT soundings across the back arc side of NE Japan, which is known as a typical island arc (Fig. 1). The study area was under extension in the Miocene, when the Japan Sea opened and the normal fault system was created [*Sato*, 1994], but the area is now under compression. The normal faults were reactivated as thrust faults, a process known as inversion tectonics. Two large intraplate earthquakes were historically recorded in the area, Senboku earthquake (1914, Magnitude 7.1) and Rikuu earthquake(1896, Magnitude 7.2) [*RGAFJ*, 1991] as shown by large circles in Fig. 1. The current micro-earthquake activities surrounding these large earthquakes are thought as aftershocks [*Umino et al.*, 2000]. Recently, there were varieties of geophysical campaigns in order to study the intraplate earthquake zones in NE Japan [*Asano et al.*, 1999; *Umino et al.*, 2000; *Sato et al.*, 2001; *Iwasaki et al.*, 2001]. Reflection seismology revealed the geometry of the two major faults (Senya Fault and Kitakami Lowland Western Boundary Fault (KLWBF)) beneath the Ou Backbone Range [*Sato et al.*, 2001]. These faults uplifted the Ou Backbone Range by pop-up under the tectonic compression. The reactivation of Kitayuri Thrust Fault uplifted the Dewa Hills [*Sato and Ikeda*, 1999]. Objectives of the magnetotelluric study are (1) imaging fracture zones with high porosity as conductive anomalies [*Unsworth et al.*, 1999] and (2) characterizing seismogenic zones by use of resistivity [*Lemonnier et al.*, 1999; *Mitsuhata et al.*, 2001].

[1]GSJ, Tsukuba, Japan, Now at Tokyo Institute of Technology, Tokyo, Japan
[2]RCPEVE, Tohoku University, Sendai, Japan
[3]JAMSTEC, Yokosuka, Japan
[4]ISV, Hokkaido University, Sapporo, Japan
[5]DPRI, Kyoto University, Kyoto, Japan
[6]Akita University, Akita, Japan
[7]University of Tokyo, Tokyo, Japan
[8]Tokyo Institute of Technology, Tokyo, Japan

Paper number 2001GL013269.
0094-8276/01/2001GL013269$05.00

2. Data Acquisition

We had two campaigns in 1998 and 1999 for the whole profile, one across the Dewa Hills and the other across the Ou Backbone Range (Fig. 1). This region is the back arc of NE Japan, west of the Quaternary volcanic front. However it does not go through local anomalies such as geothermal fields nor volcanoes. We used up to 11 units of five–component (three magnetic and two telluric components) wide-band MT system (Phoenix–V5 and MTU5) and 5 units of two component telluric system (Phoenix MTU2E). All of these equipments were synchronized using GPS. As for the sites only with telluric channels, magnetic fields were taken from another site in order to calculate impedances. The different locations of electric and magnetic fields were taken into account in later two-dimensional modeling. Clean time–series data for remote reference were given by Esashi station of Mizusawa Geodetic Observatory, Geographical Survey Institute, which is more than 30 km away southeast of the survey area (Fig. 1). Remote referencing improved the data quality in the period range longer than 1 s.

3. Dimensionality of the Data

We investigated the two-dimensionality of the data by strike estimates from Groom–Bailey decompositions [*Groom and Bailey*, 1989] where distortion parameters were completely unconstrained, i.e., they were period-dependent and site-dependent. Fig. 2 shows the histograms of the strike estimates for each decade of period and for each of the two MT campaigns. We note in the periods of 1–1000 s that the two–dimensionality is well supported for both profiles around N0–20°E. In the shorter period range (<1 s), however, the histograms scatter more reflecting the complex surface geology along the survey line. Thus, we focus on long periods (1–1000 s) for two-dimensional modeling for the whole profile.

We used N12°E as a regional strike for the whole area in the period range of 1–1000 s, by use of multi–site multi–

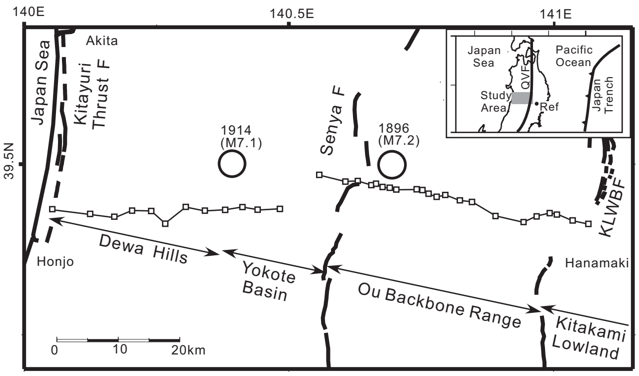

Figure 1. Two magnetotelluric(MT) survey profiles in the back arc of NE Japan. Open squares tied with lines denote MT sites. Two large circles are epicenters of historically known large earthquakes. Thick lines denote active faults [*RGAFJ*, 1991]. KLWBF stands for Kitakami Lowland Western Boundary Fault. Ref and QVF in the index map are the reference site (Esahsi) and the Quaternary volcanic front.

period decomposition codes [*McNeice and Jones*, 2001]. Shorter period data (<1 s) were not used for further analysis. The decomposed data with a consistent strike direction of N12°E are compiled as pseudo-sections in the left column of Fig. 3. Here the MT sites are projected perpendicular to the two-dimensional strike. Fig. 3 shows a clear difference in the two modes. At around 100 s period, TM mode shows low phase (sensing resistors at depth), whereas TE mode shows high phase (sensing conductors at depth). This anisotropic response must be explained by two-dimensional modeling.

4. Two-dimensional Modeling

We inverted the apparent resistivity and phase data that were decomposed. Inversion code of *Ogawa and Uchida* [1996] was used where the static shift is also a model parameter. The data misfit (S) was minimized under the three constraints; shallow (<10 km) roughness R_1, deep (>10km) roughness R_2, and static shift L2 norm G. The following U was minimized with optimized trade-off parameters (α_1, α_2, β).

$$U = S + \alpha_1^2 R_1 + \alpha_2^2 R_2 + \beta^2 G \qquad (1)$$

The initial model was a uniform earth of 100 Ω·m with fixed structures of oceans on both sides as 0.25 Ω·m, which represent the Japan Sea and the Pacific Ocean. The final model is shown in Fig. 4. The rms of data misfit was 1.84 with error floor of 10% in apparent resistivity and an equivalent for phase. The comparisons between the observed and the calculated pseudo-sections are given in Fig. 3. The overall fit between the observed and calculated apparent resistivity and phase was good. The misfits are evident in the long period (>300 s) in the TE mode phase. This was not significantly improved by introducing a vertical conductor in the upper mantle.

5. Discussion

Fig. 4 shows the final model with other geophysical data. Underneath the Dewa Hills lies a thick (∼ 10 km) conductive layer, representing marine sedimentary and volcanic layers at the time of Japan Sea opening in the Miocene [*Mitsuhata et al.*, 1999]. The sub-vertical resistive block (>1000 Ω·m) between the two conductors (C1 and C2) may imply the basaltic intrusions of the submarine volcanism in the Miocene.

Deep extensions of surface active faults are inferred by reflection experiment beneath the Ou Backbone Range [*Sato et al.*, 2001] and by structural geology beneath the Dewa Hills [*Sato and Ikeda*, 1999]. These were plotted on Fig. 4 using thick solid and broken lines, respectively. There are no clear conductors corresponding to these fault geometries. This could be because the fracture zones are too narrow for MT.

The anisotropic responses at the periods of ∼100 s were not explained by the ocean effect alone, but they required the existence of three conductive blocks (C1 to C3) in the mid-crust. The conductors must be horizontally separated, so that they are sensed only by TE, not by TM mode. The horizontal gaps between the three conductors correspond to the places where TM mode phase is low in the period range of 1–100 s (Fig. 3, distances at ∼-20 km and at ∼15 km).

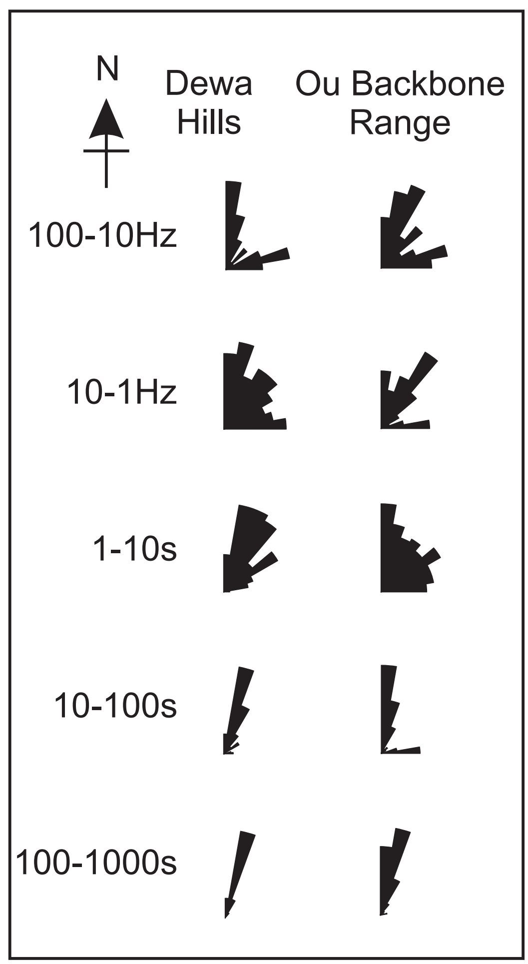

Figure 2. Rose diagrams showing histograms of the geological strike from tensor decomposition for the two profiles. The left and right columns are for sites over the Dewa Hills and over the Ou backbone Range, respectively.

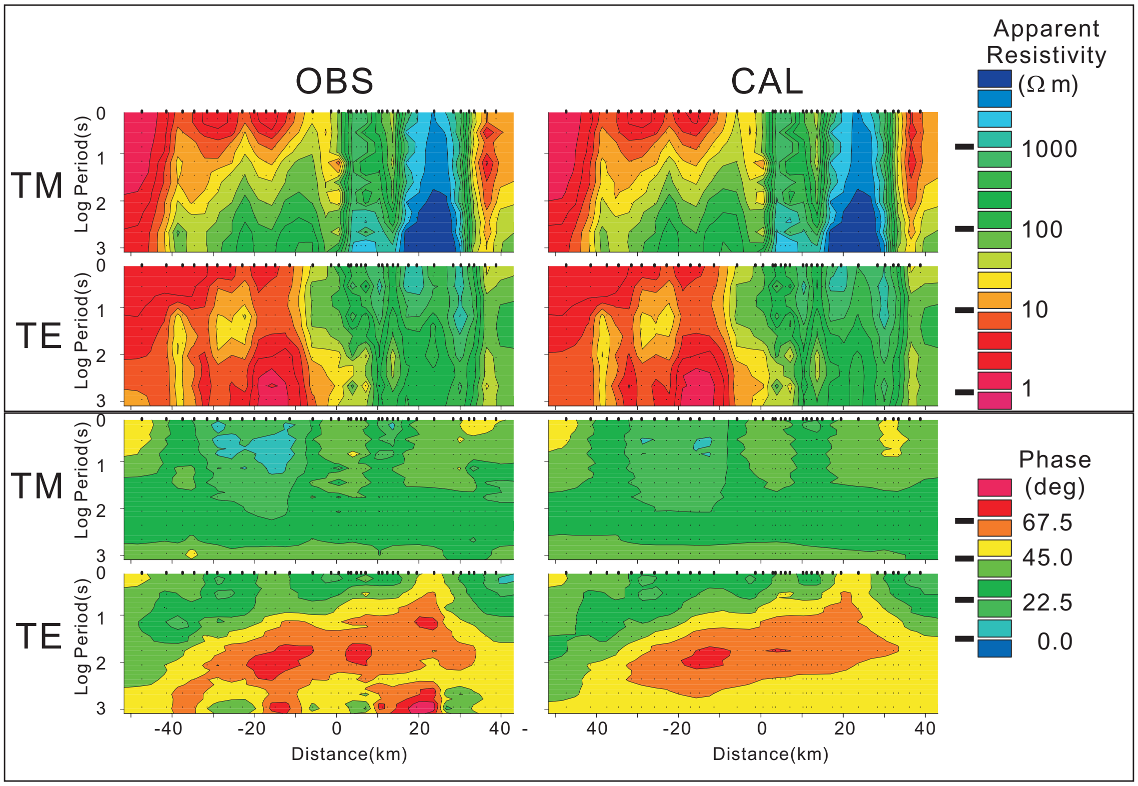

Figure 3. Left and right columns are the observed (decomposed) and the calculated pseudo–sections. Calculated apparent resistivity includes static shifts. From top to bottom, plotted are apparent resistivity for TM and TE modes and phase for TM and TE modes.

Ogawa[1987] found this anisotropic response by his MT data with narrow band (16-256 s periods) and sparse (20 km) site spacings and made a model where 40km–wide conductor lies in the lower crust (at 15–30km depth). The current study showed that the causative anomalies lie in upper crust, rather than in the lower crust, if we take the refraction seismology results (sub–horizontal lines in Fig. 4) into account [*Iwasaki et al.*, 2001]. Then the conductors may not be interpreted as the fluid trap at the brittle-ductile boundary under the thermal control.

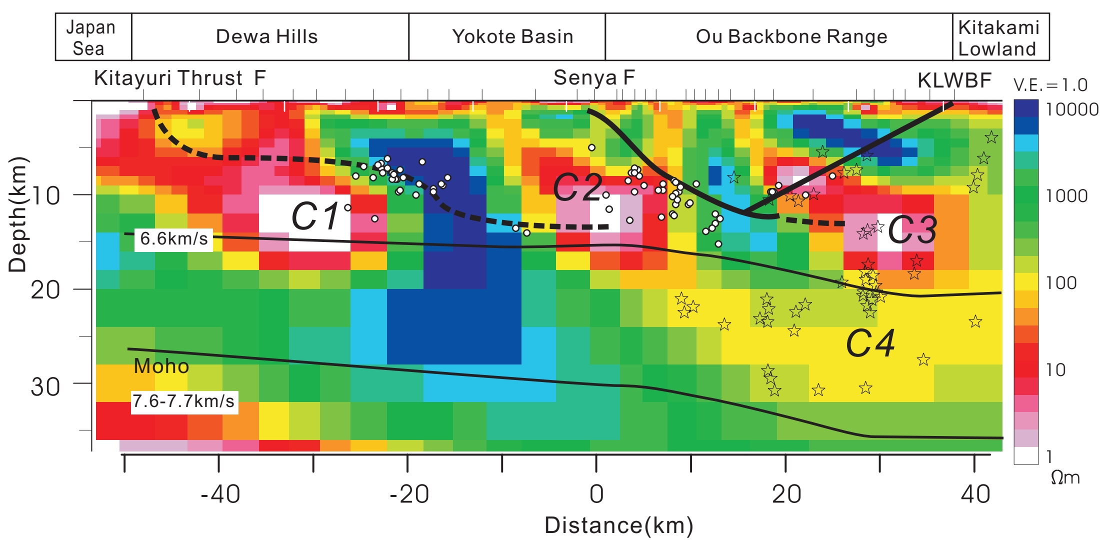

Figure 4. Final resistivity model with no vertical exaggeration. Distinct mid-crustal conductors are identified as C1 to C4. The thick sub-horizontal lines represent major velocity structures from seismic refraction experiment [*Iwasaki et al.*, 2001]. V–shaped lines underneath the Ou backbone range are fault images inferred from deep seismic reflection experiment [*Sato et al.*, 2001]. The thick broken line as an extension of Kitayuri Thrust Fault is estimated from structural geology [*Sato and Ikeda*, 1999]. The white dots denote hypocenters by *Umino et al.* [2000]. The stars denote seismic scatterers identified at the seismic refraction experiment and S-wave reflectors using natural earthquakes [*Asano et al.*, 1999].

Array seismic observations over the eastern half of the Ou backbone range mapped seismic scatterers (stars in Fig. 4) using natural and artificial seismic sources [*Asano et al.*, 1999]. The distribution of the scatteres correesponds well to the conductores (C3 and C4). Seismic velocity tomography over the Ou backbone range [*Sato et al.,* 2001] detected distinct low velocity anomalies corresponding to C2 and C3 blocks. These correlations suggest that the mid-crustal conductors will be interpreted as fluids.

Umino et al., [2000] relocated microearthquake hypocenters beneath the Dewa Hills and the Ou Backbone Range, as seen by small open circles in Fig. 4. The seismicity is high near the edge of the conductors (C1 to C3). This is consistent with model of *Ague et al.* [1998], if the intraplate earthquake swarms are triggered by fluids which migrate into less permeable crust. Alternatively, the high seismicity might be due to local stress accumulation near the fluid reservoir.

The three conductors (C1 to C3) are horizontally separated by resistive gaps and they are located in the upper crust rather than in the lower crust. Thus an interpretation of the top of the conductor as trapped metamorphic fluids at the brittle-ductile boundary (e.g., *Jones*[1987]) may be difficult. The conductors may imply fluids accommodated by the enhanced porosity due to local stress accumulation.

6. Conclusion

MT data across the back arc of the NE Japan showed strong two-dimensionality and anisotropic responses in the two modes. These required three distinct conductive blocks in the mid-crust, which are horizontally separated. The conductors imply zones of fluids, as they correspond to the seismic scatterers and to the low seismic velocity anomalies. Current seismicity, as aftershocks of the large earthquakes ∼100 years ago, clusters around the edge of the mid-crustal conductors. This suggests that the seismicity is triggered by the migration of fluids to the less permeable (more resistive) crust, or results from local stress accumulation near the structural boundary.

Acknowledgments. This project was funded by Ministry of Education, Science, Culture and Sports (promotion of new programs on study and observation for earthquake forecast), Science and Technology Agency (basic research at the national research institute) and the Kagami Foundation. The field data were acquired by Research Group for Crustal Resistivity, Japan. We also acknowledge Forestry Offices and landlords for permissions. Remote reference data were provided by Geographical Survey Institute. Seismic data and fruitful discussions were given by H. Sato, N. Hirata, T. Iwasaki, A. Hasegawa, N. Umino, Y. Asano, Y. Iio, Y. Kobayashi, and C.K. Rao. Two anonymous referees improved the manuscript.

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T. Goto, Japan Marine Science and Technology Center, Yokosuka, 237-0061, Japan

Y. Honkura and M. Matsushima, Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Tokyo, 152-8550, Japan

T. Kasaya and N. Oshiman, DPRI,Kyoto University, Kyoto, 611-0011, Japan

M. Mishina, RCPEVE, Tohoku University, Sendai, 980-8578, Japan

T. Nishitani, S. Sakanaka, and Y. Takahashi Institute of Applied Earth Sciences, Akita University, Akita, 010-8502, Japan

Y. Ogawa, Volcanic Fluid Research Center, Tokyo Institute of Technology, Tokyo, 152-8550, Japan, (e-mail: oga@ksvo.titech .ac.jp)

H. Satoh, Institute of Seismology and Volcanology, Hokkaido University, Sapporo, 060-0810, Japan

Y. Takahashi and M. Uyeshima, ERI, University of Tokyo, Tokyo, 113-0032, Japan

(Received April 2, 2001; revised June 15, 2001; accepted June 28, 2001.)