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Electromagnetic View of the Seismogenic Zones Beneath Island Arcs

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1. Introduction

The ring of fire is well-known by its intense seismic as well as volcanic activities. Most of those activities in the world are concentrated in this narrow circle around the Pacific rim. The Japanese Islands are one of the greatest island arcs in the circum-Pacific area and thus are located along the so-called seismogenic zone which is globally very unique in the sense that it consists of not only a very cold (i.e., old) but also a warm (young) subduction zone (Fig. 1). Namely, the very thick Pacific plate is subducting beneath northeast Japan while the relatively thin and young Philippine Sea plate is sliding under southwest Japan. The oldest parts of each subducting plate are approximately ~140 (Hirano et al., 2006) and ~30 Ma (Wang et al., 1995) respectively for the Pacific plate and the Philippine Sea plate at each trench's outer rise, although the latter age is more variable along the Nankai trough to the Ryukyu trench than the former along the Japan trench. The two subducting plates with different thermal states affect differently the seismic as well as the volcanic activity on the Japanese Islands, which makes the island arc an ideal place to conduct a comparative study on seismogenic zones with a contrasting tectonic setting. We, therefore, will pursue this theme as the main topic of this chapter.

From a geophysical point of view, there are a lot of physical properties that can give constraints on the current dynamics taking place beneath island arcs. Electrical conductivity is a physical property that can be determined independently of elastic properties such as seismic P- and S-wave velocities. Furthermore, it is known to be a strong function of subsurface temperature and very sensitive to presence of melts and/or fluids such as water. The electrical conductivity of the Earth's mantle as well as the seismic velocities changes discontinuously when phase changes dominate in the ongoing physical process at critical depths such as 410km and 660km. These features are very useful in interpreting the characteristics of the geophysical structure beneath an island arc because a joint interpretation of the electrical and elastic structures can provide further constraints on the island arc's thermal and physical states. For instance, fraction of fluids and/or melts can be estimated more precisely if the electrical properties are determined with known seismic geometries/boundaries as a priori information.

In addition, subduction-driven injection of surface water into the Earth's crust and mantle, and its circulation in the Earth have been a recent matter of hot debate in various

disciplines in the geoscience community since Karato (1990) first pointed out a possible strong effect of water on the upper mantle properties (especially on electrical conductivity). A series of laboratory measurements has been conducted so far. However, those experimental results seem to differ severely in a quantitative sense. For example, Huang et al. (2005) reported a huge effect of water on electrical conductivity of both wadsleyite and ringwoodite, the two major minerals in the mantle transition zone. On the contrary, Yoshino et al. (2008) claimed that there is no need to include hydrous minerals in the mantle transition zone in order to explain the electrical conductivity profile determined by electromagnetic (EM) field works. The same contradiction is applicable for the asthenosphere, viz., there exist contrasting experimental results of strong (Wang et al., 2006) and weak (Yoshino et al., 2006) dependence of olivine conductivity on water content. Abundance of water in the mantle transition zone is important in the sense that it can form a filter just above the 410km discontinuity (Sakamaki et al., 2006) to segregate geochemical components in the lower mantle from those in the upper mantle (Bercovici & Karato, 2003). Coexistence of the geochemically enriched lower mantle and the very depleted upper mantle has been a long-lasting enigma in the geosciences community, and thus we need to identify a reasonable differentiation mechanism. Because there is no doubt that the mantle transition zone has high potential as a water reservoir (Inoue et al., 1995), this issue definitely requires further research. On the other hand, water in the crust is important in the sense that it can be the sources for shallow earthquakes, deep low-frequency tremors and volcanic activities in the seismogenic zones of the island arcs (e.g., Obara & Hirose, 2006). It seems to have become a consensus that the subduction-driven water injection is strongly dependent on thermal states of each subducting plate beneath the island arcs. Namely, cold and warm subduction zones behave quite differently in terms of the amount and depth of water release from the slabs. This means that a report on electrical images beneath different parts of the Japanese Islands is nothing but the aforementioned comparative study itself.

Northeast Japan can be classified into the cold subduction regime and thus thought to have high potential, in turn, for water supply to the deep mantle (Iwamori, 2004). Injection of water into the deep mantle seems to produce electrical conductivity anomalies of regional to semi-global scale beneath back-arc regions. Furthermore, those electrical anomalies are present irrespective to whether the subducting slab is stagnant at the 660 km seismic discontinuity (Ichiki et al., 2006) or plunging into the lower mantle (Booker et al., 2004), although their surface manifestations look, naturally, quite different (Worzewski et al., 2010). Arc volcanism in northeast Japan is known to be three-dimensional (3-D) as typically depicted by Tamura et al.'s (2002) hot-finger model. A two-dimensional (2-D) east-west slice of a 3-D P-wave seismic tomography (Mishra et al., 2003) at 39.5N showed a nearly uniform distribution of moderately fast velocity above the subducting Pacific plate within the slice. It can be attributed to the fact that the slice covers a non-volcanic part, viz., a region between the hot fingers, of the well-developed island arc. An electrical section (Toh et al., 2006), which covers the non-volcanic part of northeast Japan, reveals a resistive shallow mantle and a conductive anomaly beneath the back-arc region at depths 150-200 km. The electrical conductivity anomaly can be interpreted as a direct manifestation of slab dehydration associated with collapse of the high-temperature type serpentine such as antigorite. An EM 2-D section of northeast Japan at crustal depths (Ogawa et al., 2001) revealed several high conductive anomalies in

the lower crust that are considered to bear geofluid. The source of the lower crustal geofluid is attributed to the convection in the wedge mantle beneath northeast Japan, which is compatible with the distribution of the Quarternary volcanoes on the volcanic front as well.

Although the arc volcanism relevant to northeast Japan looks 3-D in terms of its structure, the magma source can be unique and simple. It stems from the deep mantle behind the mature island arc. On the contrary, that of southwest Japan cannot be presumed as simple as northeast Japan, if one studies basalt samples of this area (Iwamori, 1991; Kimura et al., 2003). The alkaline, sub-alkaline and adakite basalt magmas of southwest Japan imply multiple sources for its magma production in the mantle including slab-melting of the hot and young Philippine Sea plate. The presence of the adakite magma is a signature of fluid originating from the slab. Toh and Honma (2008) reported a possible mantle plume in the west of the Kyushu Island of southwest Japan, which can be another candidate of the multiple magma sources. On the other hand, seismic and EM observations on land have revealed coincidence of lower crustal conductors and epicenters of both deep low-frequency events and earthquakes in the upper crust, which suggests presence of crustal fluid (e.g., Kawanishi et al., 2009). 2-D slices of Nakajima & Hasegawa's (2007) 3-D seismic tomography results beneath southwest Japan imply the presence of a deep mantle plume released not from the Philippine Sea plate but from the Pacific plate that is located well below the younger plate. However, the link between the two kinds of fluid is still missing and needs further research, especially based on marine geophysical data or a combination of land and marine data.

In the following, we will first describe the principle and methods of electrical conductivity determination by EM field works. The principle and methods section will be followed by an EM case study on northeast Japan to illustrate usefulness of the principle as well as the methods. Thirdly, the EM image beneath southwest Japan will be presented and discussed in contrast to that of northeast Japan. Finally, results of the whole comparative study will be summarized and concluded.

2. Principles and methods in EM field works

There exist lots of methods for delineating subsurface electrical conductivity structures by field works. They are classified broadly into two categories: one to make use of transient response of the conducting Earth in time domain, and the other is to derive the Earth's stationary response as a function of location in frequency domain. The latter category is often adopted irrespective to observation locations (viz., on land or at sea) and hence readers are advised to refer to standard textbooks for the former category (e.g., Kaufman & Keller, 1983). We will describe briefly the principles and typical methods in the frequency domain here in this section.

The principle of the EM methods in frequency domain is to use amplitude ratios and phase differences between different time-varying EM components observed on the Earth's surface including the seafloor rather than to model observed time-series themselves. Amplitudes of the raw time-series are dependent on each event, i.e., they differ from time to time. However, their ratios and phase differences are constant for a particular frequency and a fixed site, provided that one is really looking at induced parts of temporal variations by external

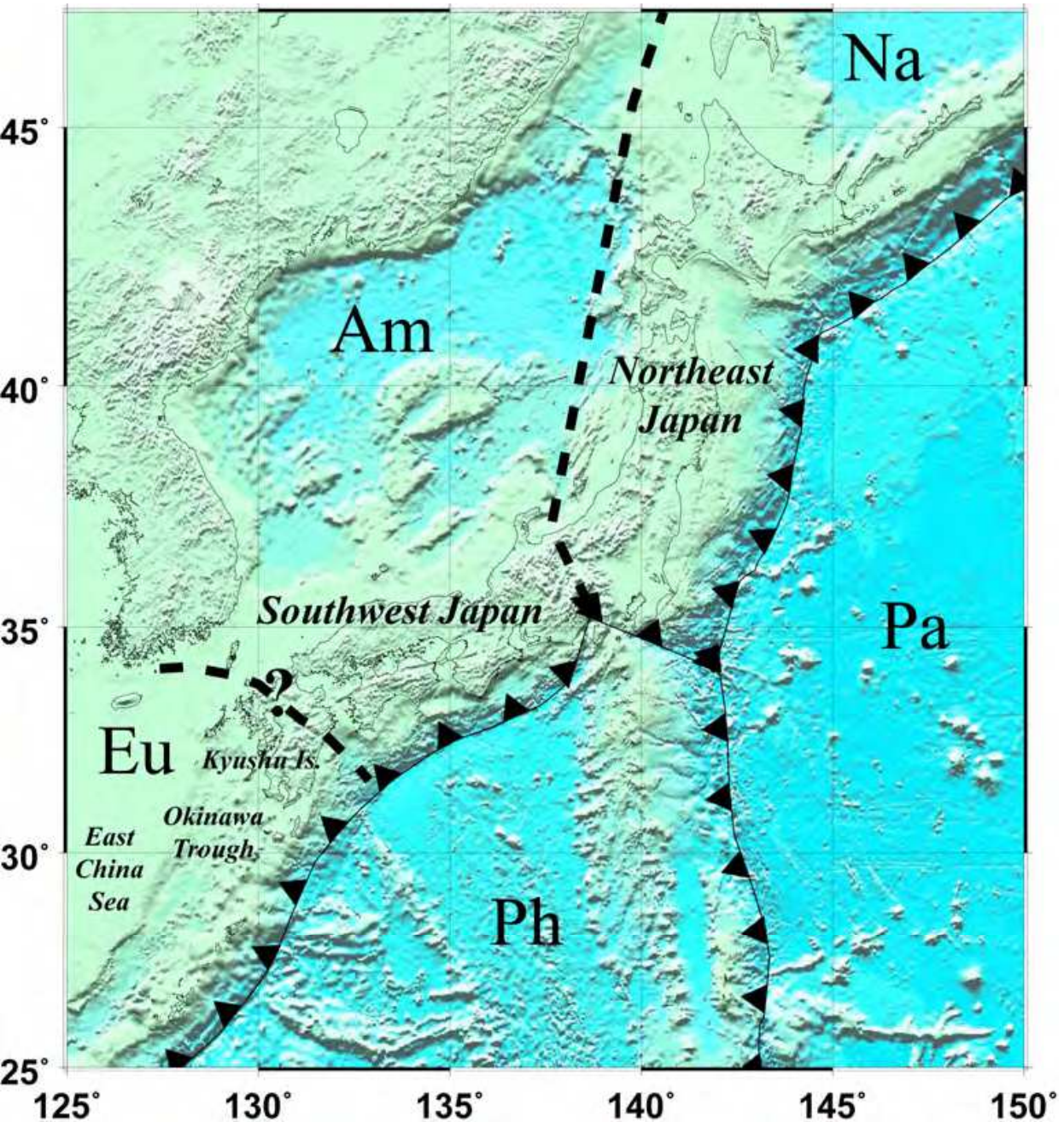


Fig. 1. Tectonic plates around the Japanese Islands. Pa: Pacific Plate, Ph: Philippine Sea Plate, Na: North American Plate, Eu: Eurasia Plate, Am: Amurian Plate.

geomagnetic disturbances. Another fundamental assumption of the frequency-domain EM methods is that the external source fields are either stationary plane waves or at least waves with known simple geometries such as dipole fields. If this assumption is applicable, the EM responses, p and q , of the conducting Earth can be estimated by the following linear regression formula in frequency domain:

$$W(f) = p(f) \cdot U(f) + q(f) \cdot V(f) \tag{1}$$

where U , V and W are the observed EM components and f is the frequency in concern. U , V and W are given by Fourier transforms of the observed time-series for respective EM

components. If the source field is stationary enough, stable estimates of the Earth's EM responses (p and q) can then be yielded by standard stacking methods that divide the whole time-series into a number of segments of a suitable length.

There are several variants of the frequency-domain EM method represented by Eq. (1) because many combinations of EM components in the regression equation are possible. Of those, the geomagnetic depth sounding (GDS) method, the magnetotelluric (MT) method and the horizontal geomagnetic transfer function (HGTF) method are often favoured in actual field works since each method has its own distinct physical meaning and advantages. We will give succinct summaries of those methods in the following three subsections.

2.1 Geomagnetic depth sounding method

This method is a case of $U=B_x$, $V=B_y$ and $W=B_z$, where B_x , B_y and B_z denote the northward, eastward and downward geomagnetic components, respectively. The GDS method is usually applied when lateral contrast of the subsurface electrical structure is expected to be strong. This is because the anomalous B_z is most likely to be induced by the external inducing field of plain wave form than any other EM components. Vertically propagating plane waves have B_x and B_y components alone. As for its detailed physical meaning and the graphical representation of the method, refer to Section 2 of Toh & Honma (2008).

In cases where the inducing source field can be approximated by a global-scale axial dipole, it is known that the Earth's scalar impedance Z is given by the following formula (e.g., Schultz & Larsen, 1987);

$$Z(f) = -\pi i f R_E \tan(\theta) \frac{B_r(f)}{B_\theta(f)}, \quad (2)$$

where R_E , θ , B_r and B_θ are the mean radius of the Earth, co-latitude, radial and southward geomagnetic components, respectively. The ratio of the two geomagnetic components is equivalent to the Earth's EM response function $p(f)$ if $W=-B_z$, $U=-B_x$ and $V=0$. Eq. (2) is often invoked to estimate the Earth's one-dimensional (1-D) impedance at long periods (typically $T > 4$ days) for EM forcing by the magnetospheric ring currents. The global-scale ring currents can produce temporal variations of axially symmetric magnetic dipole fields that are the premises of the valid application of Eq. (2). In order to determine tensor impedances, however, it is required to measure not only the vector geomagnetic field but also the vector (or rather 'horizontal') geoelectric field, which will be described in the next subsection.

2.2 Magnetotelluric method

The MT method needs two linear regression equations in which two sets of (U , V , W) are substituted: (B_x , B_y , E_x) and (B_x , B_y , E_y). E_x and E_y are the horizontal geoelectric components. The resultant EM response functions are neither scalar nor vector but tensor, which are elements of the so-called 'MT impedance tensor'. Namely, the MT impedance tensor is defined by the following matrix formula:

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} B_x \\ B_y \end{pmatrix}. \quad (3)$$

Z_{ij} ($i, j = x, y$) denotes each tensor element. The frequency f is intentionally dropped off from each variable in Eq. (3) for simplicity.

The MT impedance tensor is originated from the MT scalar impedance as in Eq. (2), which is a complex ratio of mutually orthogonal geomagnetic and geoelectric components. If the Earth's electrical conductivity varies in the vertical direction only, an external geomagnetic field variations polarized in a particular horizontal direction induces toroidal telluric currents in the Earth perpendicular to the magnetic field. It is the 1-D complex ratio of the MT scalar impedance $Z(=E/B)$, which has already appeared in Eq. (2). In this case, it follows that $Z_{xx}=Z_{yy}=0$ and $Z_{xy}=-Z_{yx}=Z$. If we substitute the magnetic field $(H_x, H_y)^T$ into Eq. (3) instead of the magnetic induction $(B_x, B_y)^T$, it is straightforward to show that the physical dimension of each impedance tensor element becomes ohm. Thus, the primary physical meaning of the MT impedance is the resistance of the Earth. However, if we use 'magnetic induction' in place of 'magnetic field', the MT impedance has a physical dimension of 'velocity'.

When the subsurface electrical structure elongates in a specific direction and x -axis is aligned to the structural strike, the diagonal elements of the MT impedance tensor vanish again while the absolute values of off-diagonal elements are not necessarily equal to each other. It is well-known that the Maxwell equations decouple into two independent modes in 2-D cases: one mode involves E_x, B_y, B_z and Z_{xy} alone and the other E_y, E_z, B_x and Z_{yx} . The former combination is called 'TE-mode' or 'E-polarization' while the latter is called 'TM-mode' or 'B-polarization' borrowing the nomenclatures of the EM wave-guide theory. It is evident that the GDS responses appear only in TE-mode for 2-D cases. The MT impedance tensors can be defined even for 3-D cases and remain being powerful tools in estimation of electrical structures. However, we need to work with full tensors rather than more simpler antisymmetric tensors after pertinent coordinate rotations in the horizontal plane.

2.3 Horizontal geomagnetic transfer function method

If one substitutes two sets of (U, V, W) , (B_x^0, B_y^0, B_z) and (B_x^0, B_y^0, B_z) , into the linear regression formula (Eq. (1)), you will end up with the following matrix equation with a 2×2 matrix:

$$\begin{pmatrix} B_x \\ B_y \end{pmatrix} = \begin{pmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{pmatrix} \begin{pmatrix} B_x^0 \\ B_y^0 \end{pmatrix}. \quad (4)$$

The vector $(B_x, B_y)^T$ is horizontal geomagnetic variations at the observation site in concern while $(B_x^0, B_y^0)^T$ is that of a reference site. Both the observation site and the reference site can be either on land or at the seafloor. In any land-sea combinations, each element, K_{ij} ($i, j = x, y$), of the horizontal transfer function matrix in Eq. (4) constitutes another set of EM response functions representative of the electrical properties of the Earth. Among the various combinations, an interesting pair is a seafloor observation site and a near-by reference site on land. This combination involves vertical shears of each horizontal geomagnetic component, which are measures of the net electric currents induced in the ocean. The pair, therefore, is called as the vertical gradient sounding (VGS) method, which is a good alternative of the seafloor MT method when geoelectric measurements at the seafloor are missing. As for details of the VGS method, refer to Ferguson et al. (1990) and references therein.

The goal of the EM methods described above is to derive electrical conductivity structures that can explain the spatial distribution as well as the frequency dependence of the Earth's

EM response functions thus derived. We will illustrate how to estimate electrical structures that are compatible with EM field works by introducing a few case studies in and around the Japanese Islands using the two subsequent sections.

3. EM view of the seismogenic zone beneath northeast Japan

Northeast Japan is classified into the cold subduction regime and thus said to be the very spot of on-going water supply into the deep mantle (Iwamori, 2004). Injection of water into the deep mantle can produce electrical conductivity anomalies beneath back-arc regions. In order to image such kind of anomalies, we constructed a seafloor MT array in the Japan Sea (Toh et al., 2006).

The seafloor array consisted of six ocean bottom electromagnetometers (OBEMs) that are capable of measuring both vector geomagnetic and horizontal geoelectric fields in addition to horizontal tilt variations. The attitude data were used to rotate each measuring frame at the seafloor back to a common reference frame in the horizontal plane. Directions of the geomagnetic north at each site were estimated using the averages of the horizontal geomagnetic components in order to carry out azimuthal corrections. The thus corrected EM time-series were further processed by the robust remote reference MT response estimator in frequency domain (Chave et al., 1987) to yield MT impedance tensors in Eq. (3). The seafloor MT response functions, together with those at four sites on land, were used in the subsequent 2-D inversion to explain their spatial distribution as well as the frequency dependence.

To construct a 2-D electrical model of northeast Japan, a Reduced Basis OCCam's (REBOCC) inversion method (Siripunvaraporn & Egbert, 2000) was applied to the land and sea MT impedances observed at the latitude of 39.5N. The REBOCC inversion is a variant of Occam inversion (Constable et al., 1987), which works with sensitivity matrices in data space instead of the conventional model space. This significantly reduces the size of the sensitivity matrices required in the course of the inversion procedure. Because the REBOCC inversion prefers high correlation of the final model with a priori model, it was possible to build in the basic tectonic model of northeast Japan such as the presence of the thick and resistive subducting Pacific plate. The known 2-D section for crustal depths (Ogawa et al., 2001) was also included in the REBOCC inversion as another a priori information. The inversion converged at an rms of 3.55 using both TE and TM mode responses.

The derived electrical 2-D section (Toh et al., 2006), which is an EW slice of the non-volcanic part of northeast Japan, reveals a resistive shallow mantle and a conductive anomaly beneath the back-arc region at depths 150-200 km (Fig. 2). The electrical conductivity anomaly can be interpreted as a direct manifestation of slab dehydration associated with collapse of the high-temperature type serpentine (Iwamori, 1998) rather than that of a group of minor hydrous phases such as phlogopite (Tatsumi, 1989). To test the robustness of the anomaly, we examined changes in the rms when the anomaly was replaced by a normal and uniform mantle conductivity of 3.3×10^{-2} S/m. It turned out that the rms increase is too large to explain the observed MT data by the normal conductivity if we mask the anomaly surrounded by the black-dashed lines in Fig. 2. However, the increase was marginal if we do the same thing for the anomaly surrounded by the white-dashed lines. We, therefore, concluded that the anomaly surrounded by the black-dashed lines is required by the MT data.

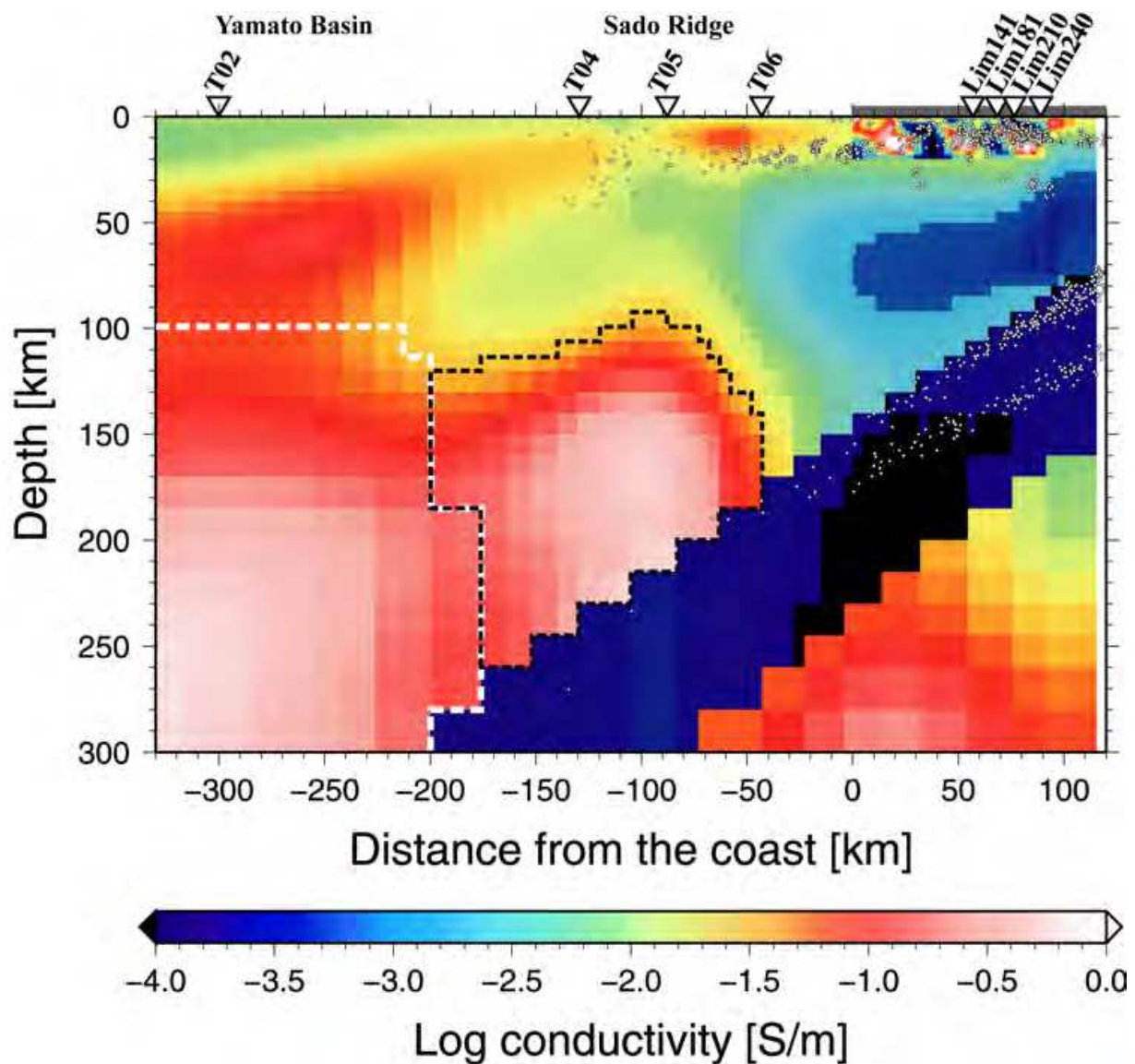


Fig. 2. The 2-D electrical conductivity model of northeast Japan at the latitude of 39.5°N. The inverted triangles with labels indicate the locations and names of the observation sites. The horizontal gray bar represents the island arc of northeast Japan, while dots denote hypocenters in this region. The areas surrounded by black- and white-dashed lines are those masked in the F-tests (See text for details). Reproduced from Toh et al. (2006).

The Pacific plate is subducting beneath New Zealand as well. Wannamaker et al. (2009) derived a 2-D electrical cross-section beneath the South Island of New Zealand using a wide-band MT dataset on a densely distributed profile perpendicular to the island arc strike. They found three conductivity anomalies beneath the fore-arc region, the volcanic front and the back-arc region. The fore-arc conductor can be regarded as a natural result of dehydration from a younger and thus relatively hot subducting plate. The age of the Pacific plate there is approximately twice as young as northeast Japan (70-75 Myr). The conductor at the volcanic front is no wonder if the MT transect traverses a volcanic part of the island arc. However, there is a significant difference in the depth of dehydration beneath the back-arc region. They concluded the back-arc dehydration to occur at depths ranging from 75 to 100 km and attributed the process to breakdown of amphibole-zoisite. It is natural that the

depth of the back-arc dehydration as well as the collapsing minerals at that depth differs in the case of northeast Japan and the South Island of New Zealand, since the different ages mean different thermal effects of the subducting plates on the wedge mantle. In the case of the South Island of New Zealand, the temperature may be too high for the hydrous minerals to penetrate deep into the mantle beneath its back-arc region.

4. EM view of the seismogenic zone beneath southwest Japan

Southwest Japan makes a good contrast to northeast Japan in terms of Volcanology, Seismology and Geomagnetism in the sense that:

1. The subducting slab is much younger (and thus warmer) than that of northeast Japan (e.g., Iwamori, 1998).
2. Not only the structure but also the source of volcanism seems 3-D with its peculiar distribution of volcanoes and multiple sources for the magma production (e.g., Iwamori, 1991; Kimura et al., 2003).
3. The region shows a more distinct relation of its seismic and volcanic activity to 'geofluid' typically appearing to the very linear distribution of the upper crustal hypocenters along the Japan Sea coast (Kawanishi et al., 2009), which coincide well with the volcanic front and the lower crustal conductors. It is also noteworthy that deep low frequency events, which are also signatures of the presence of 'geofluid', occur in this region as well (e.g., Obara & Hirose, 2006).

In the following, we will try to illustrate how the magma source can be multiple in southwest Japan and how the subducting young slab influences the seismogenic zone beneath southwest Japan by reviewing an EM study in and around the Kyushu Island and the ongoing field work in the back-arc region of southwest Japan.

4.1 Mantle plume in the west of Kyushu Island

It has been long known that if one calculates GDS responses using short-period vector geomagnetic variations observed in southwest Japan, they end up with $|p(f)| \ll |q(f)|$ and $q(f) > 0$ where $p(f)$ and $q(f)$ are the transfer functions (i.e., the GDS responses) appeared in Eq. (1). This implies that there exists a prominent electrical conductivity anomaly in the west of southwest Japan. In order to identify the intensity of the conductivity anomaly and its spatial extent, a genetic algorithm inversion (e.g., Sambridge & Drijkoningen, 1992) of the observed GDS responses using non-uniform thin sheet approximation (McKirdy et al., 1985) was applied.

The genetic algorithm inversion converged at an rms of 3.20 after 112 iterations. Because we worked with 50 models per iteration, the best model in Fig. 3 is the result of more than 5000 forward calculations using the non-uniform thin-sheet approximation. It is evident that the model can give no constraints on the spatial extent both in westward and southward directions. This is due to the spatial distribution of the original GDS dataset that were mainly collected on land in southwest Japan. Direct EM measurements at the seafloor both in the south and west of the model in Fig. 3 will be indispensable for any further improvement in spatial resolution of the derived model.

The surface conductance (a product of the layer thickness and its electrical conductivity) anomaly model in Fig. 3 has two intriguing features in terms of arc volcanism if the distribution can be interpreted as that of a subsurface mantle plume:

1. The plume can be one candidate of the multiple magma sources suggested by Iwamori (1991).
2. There seems to exist a short volcanic chain that branches out from the main volcanic front on the Kyushu Island.

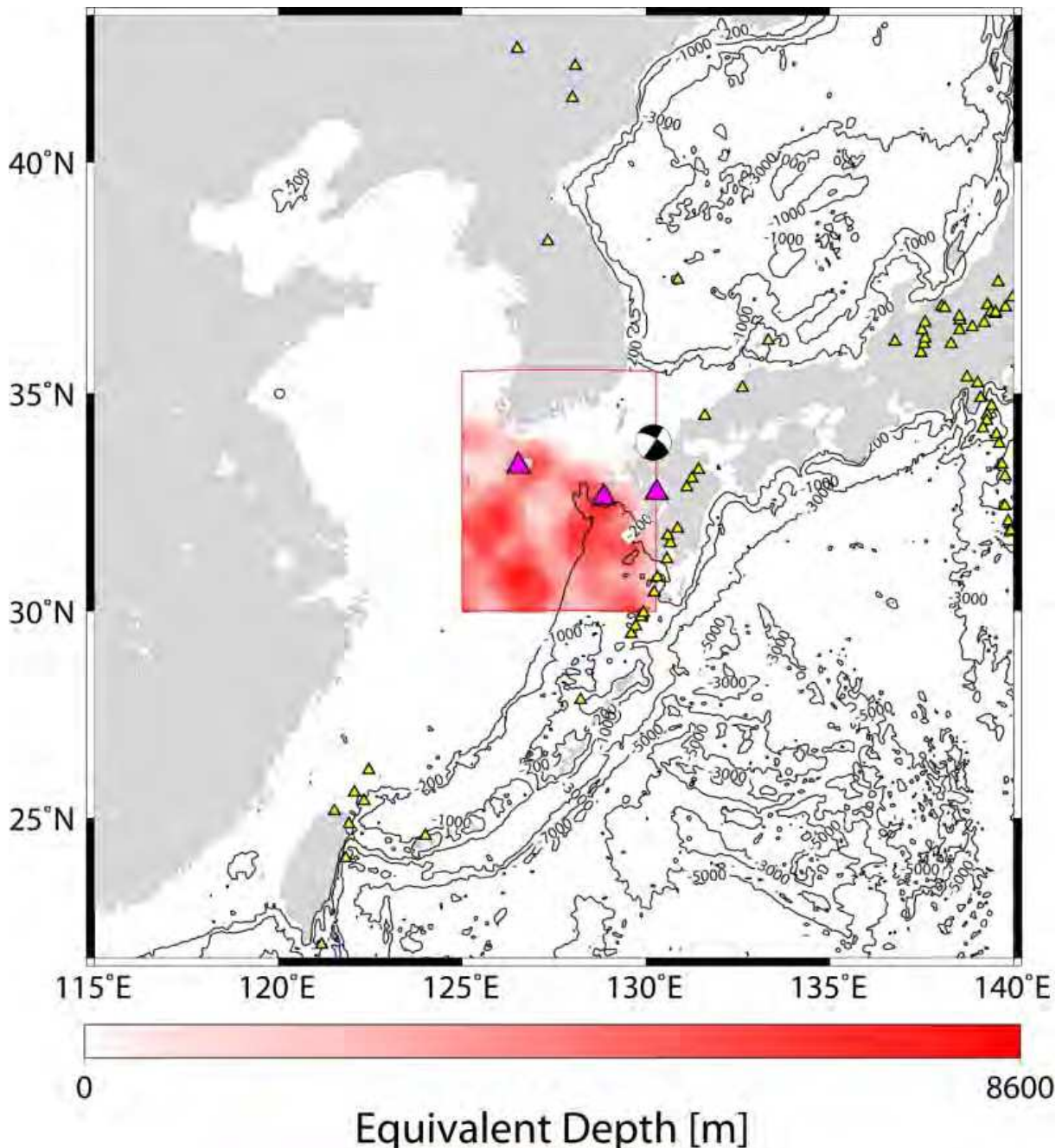


Fig. 3. Result of the genetic algorithm (GA) inversion in search for the optimized conductance distribution within the surface thin sheet. Additional conductance [S] required by the GA inversion is shown by the white-to-red scale. Bathymetric contours are also shown. Triangles denote Quarternary volcanoes in the East Asia (yellow) and on the small volcanic branch (magenta) such as the Unzen Volcano and the Cheju Island. The focal mechanism of the main shock of the west off Fukuoka Prefecture earthquake (Mw 6.7) is also shown. Reproduced from Toh & Honma (2008).

Presence of a regional-scale mantle plume in the middle of the East China Sea has been favoured by many researchers (e.g., Ichiki et al., 2006) since Miyashiro (1986) first claimed its existence. It is noteworthy that the geological strike of the volcanic branch is nearly parallel to the northeastern boundary of the partly discovered anomaly. A vertical slice of a seismic tomography result (Zhao et al., 2000) cutting through the northern Kyushu Island from the northwest to southeast direction has also imaged a low velocity branch toward the back-arc region. Another interesting evidence is the occurrence of the west off Fukuoka Prefecture earthquake near the edge of the electrical anomaly. Even though the direct cause of the earthquake is probably due to the extensional regional stress field in the back-arc region of the Kyushu arc induced by the mantle upwelling (Wei & Seno, 1998), the focal mechanism implies a lateral motion between the Eurasian plate and the Amurian plate.

4.2 2-D electrical section of southwest Japan

One major characteristic of the seismicity in southwest Japan is that the epicenters tend to concentrate within a belt of about 4-9 km wide parallel to the coast line of the Japan Sea (Kawanishi et al., 2009). Most of the focal depths there are shallower than approximately 10km and thus the earthquakes are occurring in the upper crust. In the seismic belt, several large earthquakes of M6.2-7.4 also occurred in 1943, 1983 and 2000, respectively. Furthermore, quaternary volcanoes, such as the Daisen and Oginozen Volcanoes are located in the seismic belt while the basalt that formed the Oki Islands in the back-arc region is much older (> 5 Myr) and of different composition (Kimura et al., 2003).

Wide-band MT observations have been made along a number of north-south profiles on land since 1998 so as to reveal high conductivity regions beneath the seismic belt on each MT profile. It is noteworthy that the earthquakes seem to occur on the boundary between the upper resistive crust and the highly conductive body in the lower crust. The high conductivity regions found beneath each wide-band MT profile may form a connected conductive zone extending in an almost east-west direction. Coincidence of the hypocenter distribution with the upper surface of the conductive zone as well as the presence of deep low-frequency events suggests that crustal fluid must involve the focal mechanism in the seismogenic zone.

In order to clarify the relation among the mantle dynamics in the back-arc region, the lower crustal conductors found on land and the complicated volcanism, seafloor EM observations were conducted off southwest Japan together with MT measurements on land. We laid out two seafloor MT arrays, one traversing the non-volcanic region in the eastern part of southwest Japan and the other running through a volcanic ridge including the Oki Islands. These seafloor arrays are indispensable to image the subducting Philippine Sea plate, a possible source of the crustal fluid and seismicity of the region.

Figure 4 shows the result of 2-D finite element forward modeling of the eastern profile, which ended up with an rms of 3.3. Note that the electrical section is a product of not inversion but forward modeling, although the finite element code was improved to give high precision even at locations very close to the coastline as well as those on the rugged bathymetry/topography. It was not until a superior differential scheme (Li et al., 2008) and triangular elements suitable for describing complicated bathymetry/topography had been adopted that the good precision in forward calculation was achieved.

The 2-D model shows that the lower crustal conductor has seaward extension at least more than 30 km further north of the coastline. Because we were unable to identify the tip of the

subducted Philippine Sea plate beneath the volcanic front of the profile, it is unlikely that the lower crustal conductor beneath the volcanic front stems from the slab melting at least for this particular portion of the island arc. Another major feature of the model is that it has a deep (> 100 km) conductor in the back-arc region. This conductor may be attributed to the magma source for the volcanism that made the Oki Islands. However, it is difficult to relate the conductor to the slab melting or the dehydration from the Philippine Sea plate, since the plate initiated its subduction too recently to allow itself enough penetration toward the back-arc region. It is more appropriate to regard it as a result of mantle upwelling from the deeper slab, i.e., the Pacific plate, whose subduction beneath the back-arc region of southwest Japan has been clearly imaged by recent seismic tomography studies (e.g., Nakajima & Hasegawa, 2007).

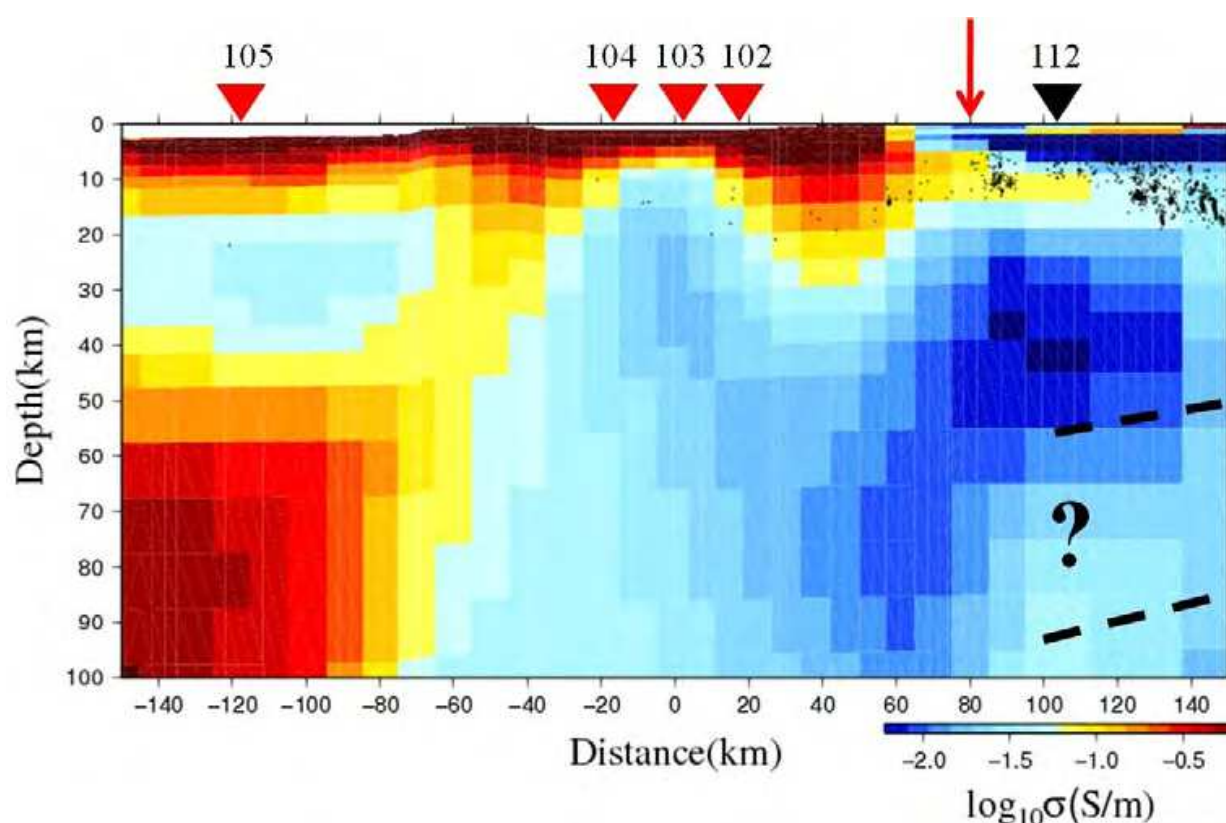


Fig. 4. The 2-D electrical section around the land-sea boundary of southwest Japan. The red vertical arrow indicates the location of the coastline of the Japan Sea. The red and black inverse triangles are the seafloor and land EM observation site, respectively. Small black dots show the distribution of hypocenters. Estimated location of the edge of the subducted Philippine Sea plate is also shown by thick dashed lines.

5. Conclusion

The very cold and thick subducting plate beneath northeast Japan can supply water deep into the back-arc region (Iwamori, 1998), which forms 3-D counter flows to generate arc volcanism of that part of the Japanese Islands (Tamura et al., 2002). Because of this scenario, the magmatic source of northeast Japan can be simple enough to be approximated by 'uni-source' magmatism even though the magmatic structure itself can remain 3-D. The seismogenic zone

beneath northeast Japan is governed by its regional stress field rather than by the presence of 'geofluid'. Major earthquakes of this region are mostly related to the processes involved with the plate boundary. However, the geofluid in northwest Japan is important for generation of hazardous inland earthquakes as well as water circulation in the wedge mantle.

The scenario by the warm and thin subducting plate beneath southwest Japan is more complicated than that of northeast Japan. In terms of Volcanology, the structure as well as the magma source is 3-D in the sense that there are several firm evidences for the presence of multiple magma sources (Iwamori, 1991; Toh and Honma, 2008) and 3-D seismic structures (Nakajima & Hasegawa, 2007). Because the subducting plate is too warm to carry the surface water deep into the mantle, there occurs major dehydration from the slab beneath the fore-arc region that causes much more geofluid-related seismic activities in southwest Japan (e.g., Obara & Hirose, 2006) than in northeast Japan. The young slab commenced its subduction several million years ago to have the penetration of its edge as close as just beneath the Japan Sea coast. The shallow penetration resulted in production of adakite magmas, which is a signature of slab melting and gives the volcanism in southwest Japan further complexity. However, it also turned out that the mantle upwelling in the back-arc region of southwest Japan is governed by not the warm slab but the cold slab further below the warm slab.

6. Acknowledgment

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7. References

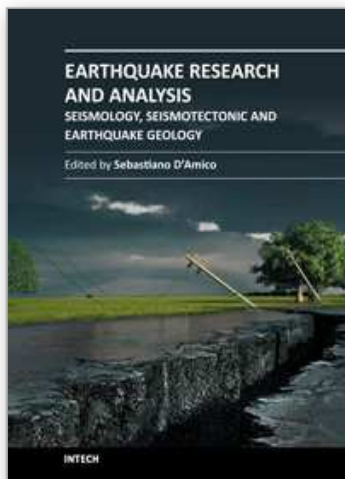
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