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Estimation of thermal structure in the mantle wedge of northeastern Japan from seismic attenuation data

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[1] We estimated thermal structure in the mantle wedge of NE Japan by applying the experimental results of olivine-dominated rocks to seismic attenuation data. Obtained temperatures at a 40 km depth are 1000–1130°C and 960–1090°C beneath the volcanic front and the back-arc side, respectively. We cannot obtain the areas with a temperature higher than 1400°C in the mantle wedge, which have been inferred from petrological studies. This is perhaps due to the localization of such anomalous areas. The obtained temperature is higher than that of the wet solidus of peridotite in the greater part of the back-arc side, which suggests that the addition of aqueous fluids plays an important role in generating melts in the mantle wedge. *INDEX TERMS:* 7218 Seismology: Lithosphere and upper mantle; 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 8124 Tectonophysics: Earth's interior—composition and state (1212); 8180 Tectonophysics: Tomography. **Citation:** Nakajima, J., and A. Hasegawa, Estimation of thermal structure in the mantle wedge of northeastern Japan from seismic attenuation data, *Geophys. Res. Lett.*, *30*(14), 1760, doi:10.1029/2003GL017185, 2003.

1. Introduction

[2] The northeastern (NE) Japan arc is a typical island arc, where the Pacific plate subducts beneath the land plate at a rate of ~10 cm/yr, and the volcanic front (VF) is formed sub-parallel to the trench axis (Figure 1). It is considered that aqueous fluids released by dehydration reactions of minerals in the subducting crust cause partial melting in the mantle wedge, resulting in the generation of arc magmas. Recent works by *Wyss et al.* [2001] found that areas with high b-values are distributed at ~150 km depth in the subducting slab and suggested that these high b-vales are caused by the presence of fluids supplied by dehydration reactions of minerals in the slab. It has been proposed that the low-velocity zones imaged in the mantle wedge of NE Japan by seismic tomography are the pathways of the ascending magmas or fluids [*Hasegawa et al.*, 1991; *Zhao et al.*, 1992; *Nakajima et al.*, 2001]. Thermal structure in the mantle wedge is essential to confirm whether the low-velocity zones are caused by melts or aqueous fluids. Temperature is a key parameter in understanding magma generation mechanisms and in controlling mantle dynamics in the arc.

[3] Thermal structure in NE Japan has been estimated based on petrological analyses [e.g., *Tatsumi et al.*, 1983], numerical simulations [e.g., *Iwamori and Zhao*, 2000] and seismological observations [e.g., *Sato*, 1992; *Sato et al.*, 1998]. It is difficult to image three-dimensional (3-D) temperature distribution by the former three methods although 3-D thermal structure is essential in understanding magmatic processes of arc volcanism. *Sato* [1992, 1994] estimated 3-D thermal structure in the mantle wedge using seismic attenuation data. However, the spatial resolution of temperature is not enough to discuss 3-D heterogeneity in details. This paper estimates 3-D thermal structure in the mantle wedge of NE Japan, based on the recent high-resolution P-wave attenuation structure and laboratory measurements.

2. Data and Method

[4] Figure 2 shows three vertical cross sections of P-wave attenuation structure by *Tsumura et al.* [2000]. High-attenuation (Low-Q) zone is continuously distributed in the mantle wedge along line C (the southernmost part). It corresponds to low-velocity zones imaged by seismic tomography [*Zhao et al.*, 1992; *Nakajima et al.*, 2001]. On the other hand, the results for the northern parts (lines A and B) do not exhibit continuous high attenuation in the mantle wedge. High-attenuation zones are confined to just beneath the Moho near the VF and to the deep portion of the back-arc side.

[5] Seismic attenuation depends on many physical conditions. Composition, temperature, fluid content, pressure and frequency play an important role in attenuation variation. A small variation in major element chemistry has a small effect on creep and is likely to have little effect on anelasticity [*Karato*, 2003]. We thus ignored composition variation in mantle rocks. The anelastic properties of upper mantle peridotite have been studied in the laboratory, and several experimental measurements conducted at high temperature conditions [e.g., *Kampfmann and Berckhemer*, 1985] revealed that the presence of melt has little effect on anelasticity.

[6] Anelasticity in minerals or rocks at high temperatures and low frequencies can be written as follows [e.g., *Karato*, 2003]:

$$Q^{-1}(f, P, T) \propto f^{-\alpha} \exp\left[-\frac{\alpha H^*(P)}{RT}\right], \qquad (1)$$

where f is the frequency [Hz], α is a constant, $H^*(P)$ is the activation enthalpy [kJ/mol], P is the pressure [GPa], R is a gas constant and T is the temperature [K]. We have the relation $H^*(P) = E^* + PV^*$, where E^* is the activation energy [kJ/mol] and V^* is the activation volume. V^* is estimated from the relation $V^*/E^* = 3.3 \times 10^{-2}$ [GPa^{-1}], by *Kampfmann and Berckhemer* [1985].

[7] Xenoliths from the mantle have been found at Ichinomegata in NE Japan (a gray star in Figure 1). The

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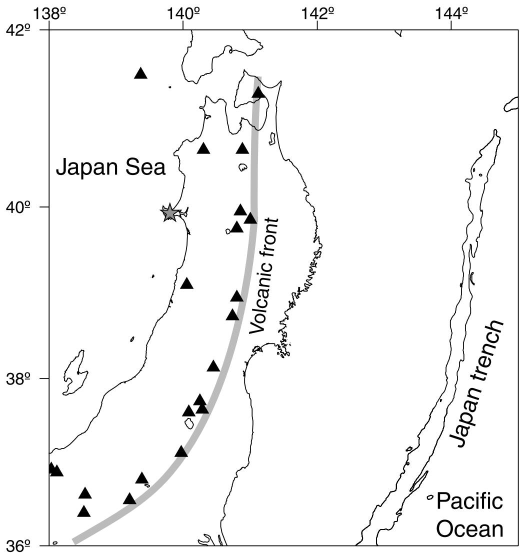

Figure 1. Map showing the study area. Locations of active volcanoes and the volcanic front are shown by the solid triangles and the shaded line, respectively. The gray star denotes location of Ichinomegata where xenoliths from the mantle have been found.

most abundant xenoliths are spinel-lherzolite, which reached the surface by explosive eruptions of basaltic magmas about 10,000 ago. *Aoki* [1987] estimated the equilibrium temperatures from pyroxenes in ultramafic xenoliths, and obtained temperatures of 800–1000°C around depths of 30 km for spinel- and spinel-plagioclase lherzolites and websterites. *Takahashi* [1986] estimated the range of temperatures from preheating to partial melting stages of the mantle to be 1000–1100°C at depths of 30–50 km, based on the fact that hornblende-bearing spinel-lherzolites have been dominantly found at Ichinomegata. The possible geotherm beneath Ichinomegata was proposed by *Kushiro* [1987] and temperature at a depth of 40 km is 1000–1050°C. We therefore adopted a reference temperature, T_0, of 1025°C at a 40 km depth. This depth approximately corresponds to a pressure of 1.33 GPa, which was selected as a reference pressure, P_0. According to the results by *Tsumura et al.* [2000], an average value of Q^{-1} around Ichinomegata at a 40 km depth is approximately 0.0035. We adopted it as a reference value of Q^{-1}, Q_0^{-1}. Equation (1) can be written as follows by using these values:

$$Q_0^{-1}(f,P_0,T_0)\propto f^{-\alpha}\exp\left[-\frac{\alpha H^*(P_0)}{RT_0}\right] \tag{2}$$

From Equations (1) and (2), we obtain,

$$T=\left[\frac{H_0^*}{H^*}\frac{1}{T_0}-\frac{R}{\alpha H^*}\ln\left(\frac{Q^{-1}}{Q_0^{-1}}\right)\right]^{-1}. \tag{3}$$

[8] Values of Q^{-1} of Equations (1)–(3) represent intrinsic attenuation, while the observed Q^{-1} values are caused by not only intrinsic attenuation (Q_i^{-1}) but also scattering attenuation (Q_s^{-1}). However, if the seismic albedo β (= Q_s^{-1}/Q^{-1}) is nearly constant in space, the effect of the scattering attenuation would become less significant in Equation (3) since a relative value, Q^{-1}/Q_0^{-1}, is used here. This assumption could be supported by the result of *Hoshiba* [1993] that β is 0.1–0.3 for frequency ranges of 4–8 Hz beneath the Japan Islands and there are no large spatial variations in β.

[9] Parameters in Equation (3) for olivine-dominated rocks have been constrained by several experiments [e.g., *Jackson et al.*, 1992], and range from 0.1 to 0.3 for α and from 400 to 600 for E^* [e.g., *Karato and Spetzler*, 1990]. Seismological observations also obtained a value of 0.1–0.3 for α [e.g., *Flanagan and Wiens*, 1998]. We used values of 0.2 and 500 for α and E^*, respectively, in Equation (3). Applying the observed Q^{-1} value to Equation (3), we can obtain a temperature at each point. In this study, we assume that the observed anomalies in Q^{-1} are caused by the thermal effect. This is supported by a recent study by *Roth et al.* [2000], in which they concluded that observed attenuation anomalies in the Tonga-Fiji region are primarily caused by thermal anomalies.

3. Results and Discussion

[10] Figures 3 and 4 show the estimated temperature variations. Temperature at a 40 km depth is 920–1130°C and is relatively high beneath active volcanoes. At greater depths, temperatures in the mantle wedge of the southern part seem to higher compared with those in the northern part. High temperature zones imaged in the mantle wedge are inclined sub-parallel to the down-dip direction of the subducting slab (Figure 4). They are consistent with the inclined low-velocity zones in the mantle wedge [*Zhao et al.*, 1992; *Nakajima et al.*, 2001].

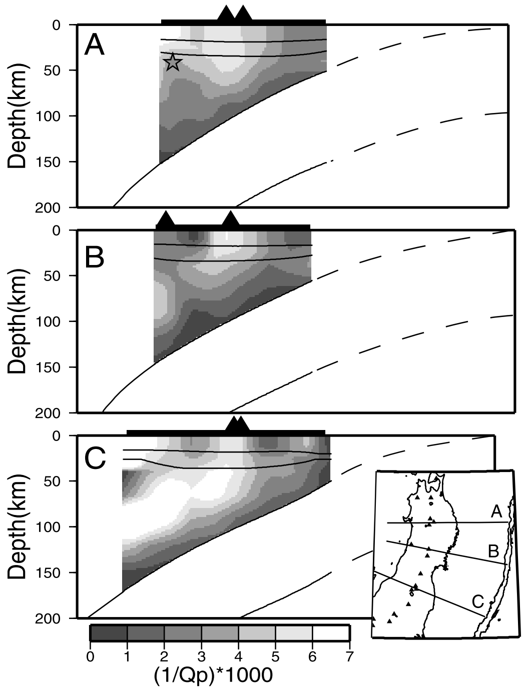

Figure 2. Cross-sectional views of Qp structure [*Tsumura et al.*, 2000] along lines in the inserted map. Qp^{-1} values are shown by the black and white scale at the bottom. The solid triangles and solid lines represent active volcanoes and seismic velocity discontinuities, respectively. The gray star denotes the location of a reference region, at which the temperature and the value of Qp^{-1} were used as calibrations.

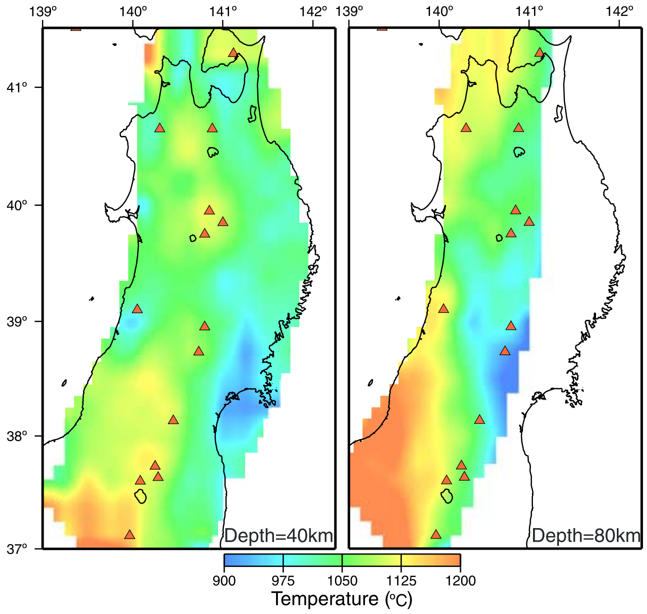

Figure 3. Map showing the estimated temperature. The temperature is shown by the color scale at the bottom. The red triangles represent active volcanoes.

[11] The uncertainty in T_0, α, E^* and Q^{-1} may introduce errors into the estimated temperature. We calculated estimation errors in the temperature by the error propagation, in which we used the following value for the error in each parameter: $dT_0 = 50°C$ ($dT_0 = 100°C$), $d\alpha = 0.1$, $dE^* = 100$ kJ/mol and $dQ^{-1}/Q^{-1} = 0.2$ [*Tsumura et al.*, 2000]. Two plausible estimation errors in the reference temperature are assumed. As a result, we obtained the estimated error of ±90°C and of ±130°C for $dT_0 = 50°C$ and $dT_0 = 100°C$, respectively.

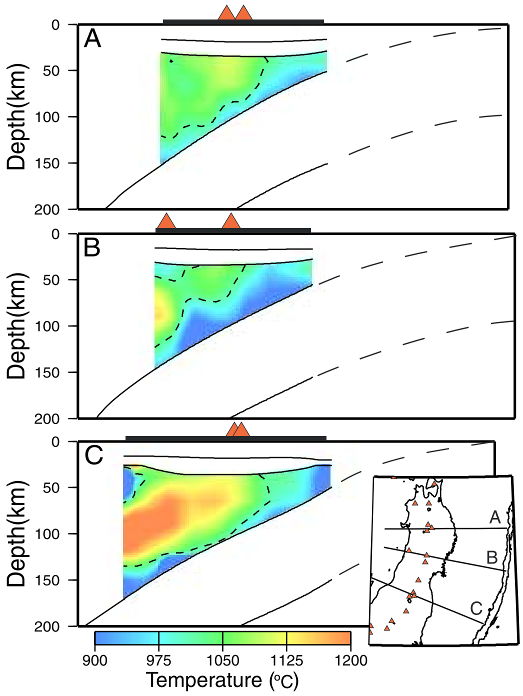

Figure 4. Cross-sectional views of thermal structure along lines in the inserted map. The color scales are the same as in Figure 3. The black bar at the top of each figure denotes the land area. The solid lines denote seismic velocity discontinuities. The broken lines in the mantle wedge show the wet solidus of peridotite [*Kushiro et al.*, 1968].

Table 1. Comparison of Estimated Temperature in the Uppermost Mantle of NE Japan at a 40 km Depth

Data/Method	Back-arc, °C	Volcanic Front, °C	Fore-arc, °C
Xenoliths[a]	1000–1050	-	-
Simulation[b]	-	800–1000	-
Heat Flow[f]	980 ± 70	980 ± 70	600 ± 110
Seismic Attenuation[c]	∼1000	∼970	∼850
Seismic Velocity[d]	-	1150–1200	-
Seismic Attenuation[e]	$T_H = 0.79$[g]	$T_H = 0.82$[g]	$T_H = 0.73$[g]
This study	960–1090	1000–1130	920–1020

[a] *Kushiro* [1987].
[b] *Iwamori and Zhao* [2000].
[c] *Sato* [1992, 1994].
[d] *Sato et al.* [1998].
[e] *Takanami et al.* [2000].
[f] from *Sato* [1994].
[g] $T_H = T/Tm$, Tm: Dry solidus of peridotite in Kelvin.

[12] The temperatures for the mantle wedge of NE Japan estimated in previous studies are summarized in Table 1. Estimated temperatures by various methods range from 800°C to 1200°C at a 40 km depth beneath the VF. Temperature estimated from seismic velocity data appear to be slightly higher. We infer that this discrepancy is mainly caused by the following two factors. One is due to the spatial resolution of velocity structure: spatial resolution of the velocity structure is better as nearly twice as that of the attenuation structure and thus the velocity data can image smaller scale heterogeneity. The other is due to the method of *Sato et al.* [1998], in which the effect of anelasticity has not been taken into account in temperature estimation.

[13] The back-arc region exhibits the temperatures of 960–1090°C at a 40 km depth. The temperatures estimated in this study almost agree with those in the previous studies beneath the back-arc side. It seems that there are no large differences beneath the VF and back-arc side between the temperatures estimated in this study, T_Q, and those estimated from the heat flow data. This suggests that H_2O content is not high at this depth because T_Q was estimated by applying the experimental results in dry condition to the attenuation data. These results are consistent with the suggestion of *Kushiro* [1987] that the amount of H_2O is less than 0.2 wt% and of *Sato* [1994] that the average H_2O content is less than 0.1 wt%.

[14] On the other hand, the temperature in the fore-arc side varies from 600°C to 1020°C. The temperature estimated from the heat flow data is approximately 600°C. The temperature calculated in this study is too high in comparison even if the estimation error is taken into consideration. One likely candidate for this discrepancy is the presence of free H_2O and/or hydrous minerals. A high H_2O content has an effect similar to that of high temperature [*Karato*, 2003]. When there is a high H_2O content in fore-arc region, observed attenuation may contain its effect and the temperature estimated from the experimental results of dry olivine-dominant rocks would be overestimated. An alternative candidate is the condition in fore-arc region. The application of Equation (1) to the fore-arc region may be inappropriate since Equation (1) is valid for the condition close to solidus

[e.g., *Karato and Spetzler*, 1990] and a different mechanism may produce attenuation in the fore-arc region.

[15] *Tatsumi et al.* [1983] suggested, based on petrological study on primary magmas, that a region with temperatures higher than 1400°C is present in the mantle wedge of NE Japan. We could not image such high temperature regions in this study. Petrological study on primary magmas is applicable to regions where magmatism occurs, but these regions are possibly localized within the mantle wedge [*Sato*, 1992]. Spatial resolution of temperature in the present estimation is comparable to that of attenuation structure and is about 30–50 km [*Tsumura et al.*, 2000]. If high temperature regions are localized as *Sato* [1992] pointed out, they will not affect the bulk anelastic properties of the mantle and cannot, therefore, be detected by a seismic attenuation study.

[16] The temperature obtained in this study is lower than that of dry solidus of peridotite [e.g., *Kushiro et al.*, 1968] but the majority of the mantle wedge in the back-arc side exhibits higher temperatures than those of wet solidus (broken lines in Figure 4). This suggests that aqueous fluids released by the dehydration reactions of the slab minerals are important for magma generation in the mantle wedge of NE Japan, although small-scale, localized melts may not require aqueous fluids.

4. Conclusions

[17] We estimated 3-D thermal structure in the mantle wedge of NE Japan by applying the results of laboratory study on dry olivine dominated rocks to observed attenuation data. The recent high-resolution attenuation data provided better constraints on thermal structure. The obtained temperatures at a 40 km depth are 1000–1130°C and 960–1090°C beneath the VF and the back-arc side, respectively. Comparing these temperatures with those inferred from the heat flow data shows there is little aqueous fluid at this depth. We could not image the areas with temperatures higher than 1400°C in the mantle wedge, which have been inferred from the studies on the generation of primary magmas. This is possibly due to the localization of such anomalous areas and the limitation in spatial resolution of this study. Although the obtained temperature is lower than that of dry solidus of peridotite, it is higher than that of wet solidus in the greater part of the back-arc side. This suggests that the addition of aqueous fluids is required to generate melts in the mantle wedge.

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