Thermal structure of the island arc crust, northeast Japan

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Full paper

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Abstract

The thermal structure of the Japan island arc, one of the most active parts of volcanism, occupying over 10 percent of the worldwide volcanoes, remains an enduring problem. The key to understanding geothermal development is estimating the temperature distribution in the deep crustal depth of island arcs. This study extracts the temperature component from deep crustal seismic tomography. The deep crustal temperature map shows that the deep crustal high-temperature zone along the volcanic front (the Ou Backbone Mountains) and the high-temperature parts extend towards the Quaternary volcanos in the west, which corresponds to the hot finger model. The deep crustal high-temperature part also exists around Iide mountain, where no Quaternary volcanoes exist. The high-temperature part without volcanic activity suggests heat transfer due to high-temperature fluid from the mantle. A deep crustal low-temperature zone develops along the Miocene rift around the eastern margin of the Japan Sea. The low temperature probably reflects the small heat generation due to the small amount of radioactive elements in the mafic crust.

Introduction

The temperature distribution of the crust of the Honshu arc in the Japan Archipelago is essential to elucidate the thermal structure of the island arc crust, e.g., heat diffusion from the mantle, radiative decay heat inside the crust, heat advection by mantle fluid. According to the petrological and numerical models of the mantle wedge, the maximum temperature of the Moho in northeastern Japan is estimated to be about 1000°C (e.g., Tatsumi et al., 1983; Honda, 1985). The geothermal gradient map in the Japan Archipelago is also obtained from the temperature measurement using drill holes (Tanaka et al., 2004). However, the geothermal gradient exceeds 50°C/km over a wide area, and the temperature of the lower crust in the northeast Honshu arc is exceptionally high, extrapolated to be about 1000 to 1500°C. Such supra-solidus or supra-liquidus temperatures cause partial or complete melting extensively, which contradicts the actual distribution of active volcanoes. Geothermal gradients estimated from drill holes effectively elucidate the temperature structure near the uppermost crust but cannot be directly applied to estimate the temperature in the deep crust. Therefore, to elucidate the thermal structure inside the deep crust, a different approach is needed to estimate temperature. This study introduces how to extract temperature components from crustal seismic tomography and clarifies the deep crustal temperature distribution.

Crustal Lithology

Previous research discussed the constituent rocks of the lower crust of the Tohoku Honshu arc by comparing elastic wave velocities of rocks and minerals and seismic tomography (Nishimoto et al., 2008; Ishikawa, 2017; Ishikawa et al.,2014). The lower crust is generally characterized by a moderate to slightly higher Vp/Vs ratio and is interpreted to be mainly composed of mafic rocks, e.g., hornblende gabbro. Exceptionally, the Kitakami Mountains show a low Vp/Vs ratio, which suggests that rocks with quartz as the main constituent mineral are distributed in this unique lower crust.

In this study, the constituent rocks of the upper crust of the northeast Honshu arc are examined by using the seismic wave velocity data of Matsubara et al. (2019). Figure 1 shows P-wave velocities and Vp/Vs ratio from 40 to 38 ° north, respectively. The low Vp / Vs ratios shown in light blue are widely distributed in the upper crust. This feature indicates the widespread distribution of quartz, characterized by a low Vp/Vs ratio, as the significant constituent mineral in the upper crust. Some relatively high Vp/Vs ratios were distributed at the margin of Japan Sea, etc. At latitude 40 ° north, the upper crust along the coast of the Sea of Japan near latitude 140 ° east is characterized by a relatively high Vp/Vs ratio. The relatively high Vp/Vs ratio is interpreted as the crust being replaced by mafic rocks due to basaltic magmatism associated with Miocene rift activity (Matsubara et al., 2017). Similar relatively high Vp/Vs ratio mafic upper crusts are also distributed near 140.4 ° east longitude and 141.3 ° east longitude. At latitude 39.5 ° north, similar relatively high Vp/Vs ratio upper crusts are also distributed around 140-141.5 ° east longitude along the coastline of the Sea of Japan and around 141.3 ° east longitude near the Kitakami lowland. Vp/Vs tomography shows that the upper crust of the northeast Honshu arc is composed of rocks whose main constituent minerals are quartz, such as granites. By contrast, Vp/Vs tomography shows that the upper crust is also composed of mafic rocks in the Miocene rift crust, such as the eastern margin of the Sea of Japan. As will be discussed later, the difference in the constituent rocks of the upper crust affects the crust's temperature structure.

Method

This research aims to elucidate the temperature structure of the island arc crust of the northeast Honshu in the Japanese archipelago. Privious experiment studies on elastic wave velocity measurement clarified the temperature dependence of the elastic wave velocity of the lower crustal constituent rock (e.g. Nishimoto et al., 2008; Ishikawa, 2017; Ishikawa et al.,2014). Here, we will describe the temperature structure in the crust using seismic tomography of Matsubara et al. (2019). Petrologists believe that a typical constituent rock of the upper mantle is peridotite. Therefore, the velocity perturbation of seismic tomography of the upper mantle reflects the temperature perturbation from a perspective point of view. By contrast, geologists believe that the constituent rocks of the arc crust are more diverse and inhomogeneous than those of the upper mantle. Since the rock type and temperature largely control the seismic wave velocity, it is difficult to estimate the temperature perturbation in the crust from the seismic tomography.

According to the feature of elastic wave velocity of rocks and minerals, P wave velocity (Vp) and S wave velocity (Vs) have a distinct temperature dependence (Nishimoto et al., 2008; Ishikawa et al.,2014). On the other hand, the Vp/Vs ratio has minimal temperature dependence and mainly depends on rock types (Nishimoto et al., 2008; Ishikawa et al.,2014). Therefore, the velocity perturbation can be interpreted as a temperature component by extracting the seismic wave velocity (Vp/Vs ratio in a specific range) from seismic tomography (Fig. 2). In this study, the velocity data in the arbitrary Vp/Vs ratio region was first extracted as the temperature component from the seismic velocity data of Matsubara et al. (2019). Next, we estimated the deep crustal temperature, geothermal gradient, and depth of 300 ° C.

Thermal Structure

Mafic and ultramafic xenoliths are trapped in Quarternary volcanic rocks on the Oga Peninsula in the Tohoku region (Fig. 7). Petrological studies suggest that the xonoliths derived from the lower crust and upper mantle (Aoki, 1971). Elastic wave velocity measurements show that the Vp/Vs ratio of Ichinomegata mafic xenoliths ranges mainly from 1.74 to 1.80 (Nishimoto et al. 2008). Figure 3 show the P-wave velocity and Vp/Vs ratio at 20 km depth around Yamagata, northeast Japan. Extracting velocity data in a region with a constant Vp/Vs ratio at a depth of 20 km means removing the temperature component from velocity data. Figure 4 shows the extracted temperature component of P-wave velocity in the range of Vp/Vs ratio = 1.77 to 1.78. The extracted data are kriging-interpolated using Surfer software (Hulinks Inc, Japan).

In Figure 4, the high-velocity indicates a low-temperature crust, and conversely, the low-velocity indicates a high-temperature crust. For example, Ou Backbone Mountains have a hot crust, and the coastal areas of the Japan Sea have a cold crust. The extracted P-wave velocity distribution is helpful to interpret the distribution in the relatively hot and cold crusts. In addition, this study converts the extracted P-wave velocity distribution to the deep crustal temperature map and geothermal gradient map. This study assumes that the maximum geothermal gradient is 33 ° C / km and the maximum temperature at a depth of 25 km is 850 ° C. The assumption is in good agreement with the petrological temperature model (Kushiro, 1987). This study set the temperature of the minimum velocity point (maximum temperature point) at a depth of 20 km in the analysis area to 685 ° C. An example of the analysis procedure is shown below.

The minimum value of extracted P wave velocities (Vp/Vs ratio = 1.77 - 1.78) is 6.34 km/s. This study assumes that the temperature corresponding to 6.34 km/s is 685 ° C. Because the temperature derivative of the elastic wave velocity of the mafic xenolith from the lower crust in Ichinomegata at Oga Peninsula is approximately -1.0 × 10^{-3} km s^{-1} ° C^{-1} at high-temperature (Nishimoto et al., 2008)., the temperature derivative of the P wave velocity is assumed to be -1.0 × 10^{-3} km s^{-1} ° C^{-1}.

The temperature distribution is calculated from the temperature component of Figure 4a. Figure 4b shows the temperature distribution around Yamagata and surrounding areas at a depth of 20 km. The high-temperature zones over 600°C exist in the deep crust of the Ou backbone mountains, and the Iide Mountains are. In contrast to Ou backbone mountains, low-temperature zones of about 300°C are distributed along the eastern margin of the Japan Sea. The temperature map is converted into a geothermal gradient map (Fig. 5a) by assuming a linear geothermal gradient. Moreover, a depth contour map of 300°C is created from the geothermal gradient map. (Fig. 5b). The depth of 300°C is shallow around the Ou backbone mountains and the Iide Mountains and deep along the eastern margin of the Japan Sea. The feature shows the same tendency as the depth distribution D90 of intracrustal microearthquakes by Matsubara et al. (2020).

Using the same procedure, we determined a depth of 300°C from southwest Hokkaido to Hokuriku (Figure 6). The depth of 300°C is shallow around the Ou backbone mountains. It tends to be deep along the eastern margin of the Japan Sea from southwest Hokkaido to Hokuriku, similar to the depth distribution D90 of Matsubara et al. (2020) in the big perspective.

Figure 7 shows a depth contour map of 300°C in the northeast Honshu arc. The depth of 300°C is shallow around the Ou backbone mountains, and it deepens along the eastern edge of the Sea of Japan. The high temperature axis along the Ou Mountains corresponds to the upwelling flow in the wedge mantle accompanying slab subduction (e.g, Hasegawa et al 2005).

This feature is similar to the distribution of the lower limit D90 of the seismogenic layer obtained by Matsubara et al. (2020). The depth of brittle/ductile transition in the crust is controlled by temperature and fluid pressure and is thought to coincide with the lower limit of the seismogenic layer of the crust (Sibson, 1984). This study shows that the lower limit depth of the seismogenic layer in the crust reflects the thermal structure. In other words, the fluid pressure is almost uniform in the crust, indicating that the geothermal structure dominates the depth of brittle/ductile transition in the crust.

Figure 7 shows Quaternary volcanoes on the depth contour map of 300°C. The deep crustal temperature map shows that the deep crustal high-temperature zone along the volcanic front (the Ou Backbone Mountains) and the high-temperature parts extend towards the Quaternary volcanos in the west, which corresponds to the hot finger model proposed by Tamura (2002). The deep crustal high-temperature part also exists around Iide mountain, where no Quaternary volcanoes exist. The high-temperature part without volcanic activity suggests heat advection due to high-temperature fluid from the mantle. A deep crustal low-temperature zone develops along the Miocene rift around the eastern margin of the Japan Sea. The low temperature probably reflects the small heat generation due to the small number of radioactive elements in the upper crust, mainly composed of mafic rocks. Umeda and Asamori (2018) suggest that the helium isotope ratio is comparable to the mantle value, suggesting the existence of magma or related high-temperature fluids that have risen or penetrated since Quaternary.

Conclusion

This study estimated the temperature structure of the crust in the northeastern Honshu arc by extracting the temperature component from seismic tomography and classified the temperature structure into three types. The first is the heat diffusion pattern from the mantle. That is, it reflects the mantle convection pattern in the mantle wedge. The high temperature along the Ou Backbone Mountains and around Quaternary volcanoes corresponds to the hot fingers model of Tamura (2002). The second is the distribution pattern of radioactive decay heat in the crust. The low-temperature crust is distributed along with the Miocene rift crust, such as the eastern margin of the Japan Sea. Because mafic rocks are the primary constituent rocks, the heat generation due to radiative decay is very small. This low temperature corresponds to the extremely deep lower limit of the seismogenic layer on the eastern margin of the Sea of Japan. The third is heat transfer by hot fluid from the mantle. A high temperature compared to the high-temperature of the Ou Backbone Mountains exists around the Iide Mountains, where Quaternary volcanoes are not distributed. Because Umeda and Asamori (2018) suggest the existence of hot fluids from helium isotope ratio analysis, the high temperature in the Iide Mountains may reflect heat advection due to high-temperature fluids. Evaluation by a numerical calculation model for heat conduction considering radiative decay heat and high-temperature fluid is a future theme.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and analyzed during the current study are available from Matsubara et al. (2019).

https://www.hinet.bosai.go.jp/topics/sokudo_kozo/

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

The individual contributions of authors to the manuscript should be specified in this section.

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Figures

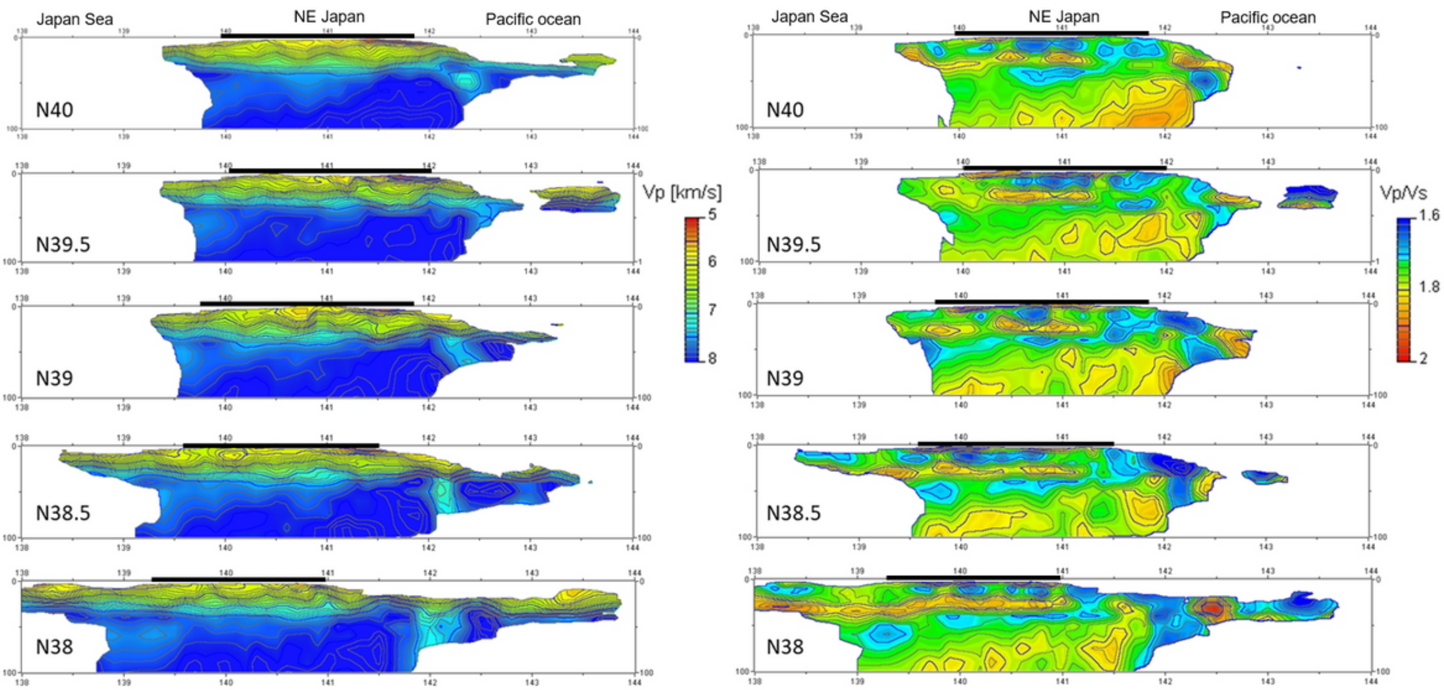


Figure 1

Vertical sections of Vp and Vp/Vs ratio along N40°, 39.5°, 39°, 38.5°, and 38°. This study used the seismic tomography data of Matsubara et al.(2019).

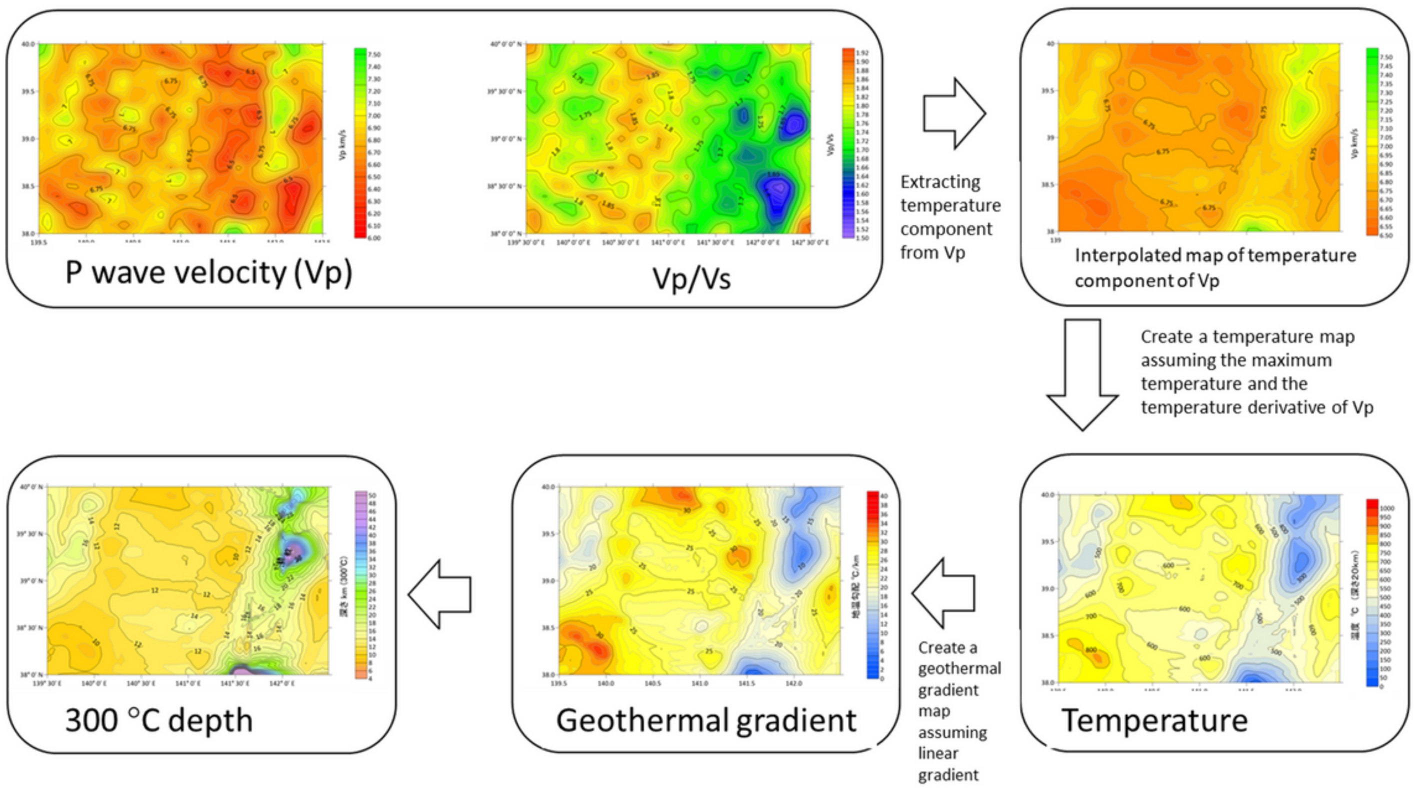


Figure 2

Procedure for estimating temperature structure from seismic velocity data. Using the velocity data in the region of arbitrary Vp / Vs ratio from the seismic tomography of Matsubara et al. (2019), this study extracted temperature components of the seismic wave velocity. This study estimated the temperature distribution in the deep crust, geothermal gradient, and depth of 300 ° C.

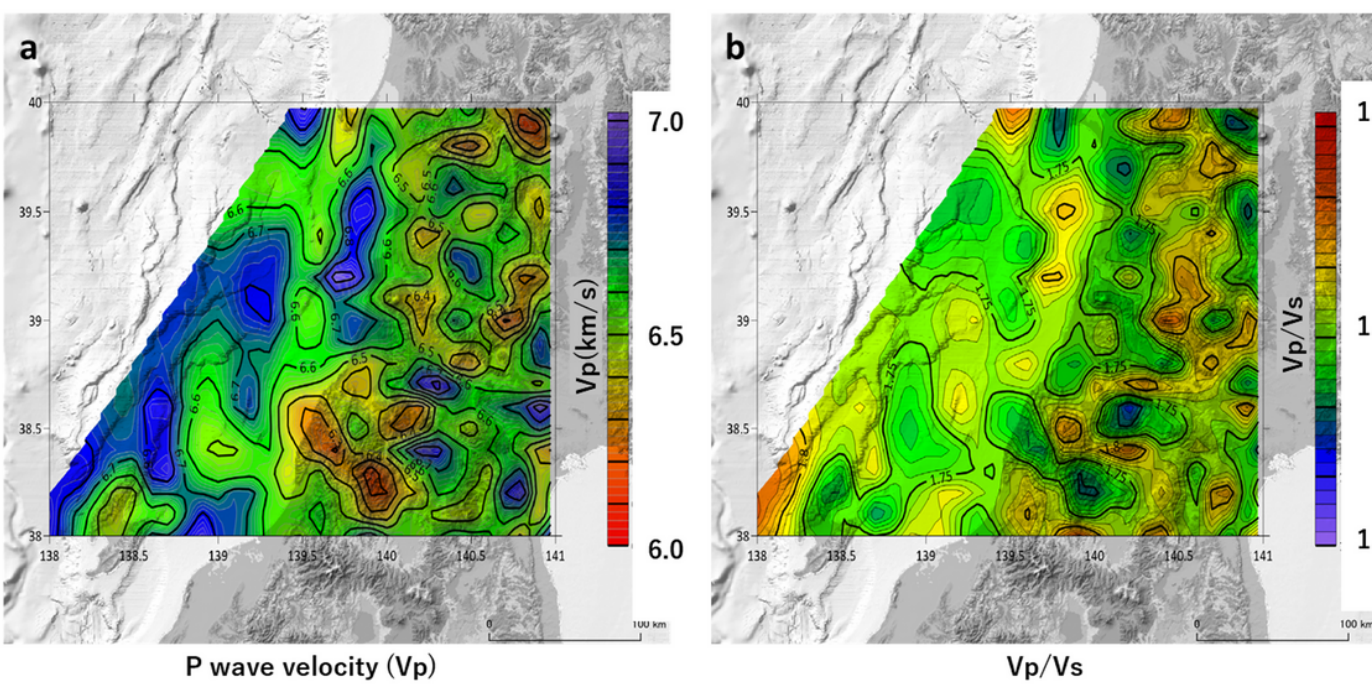
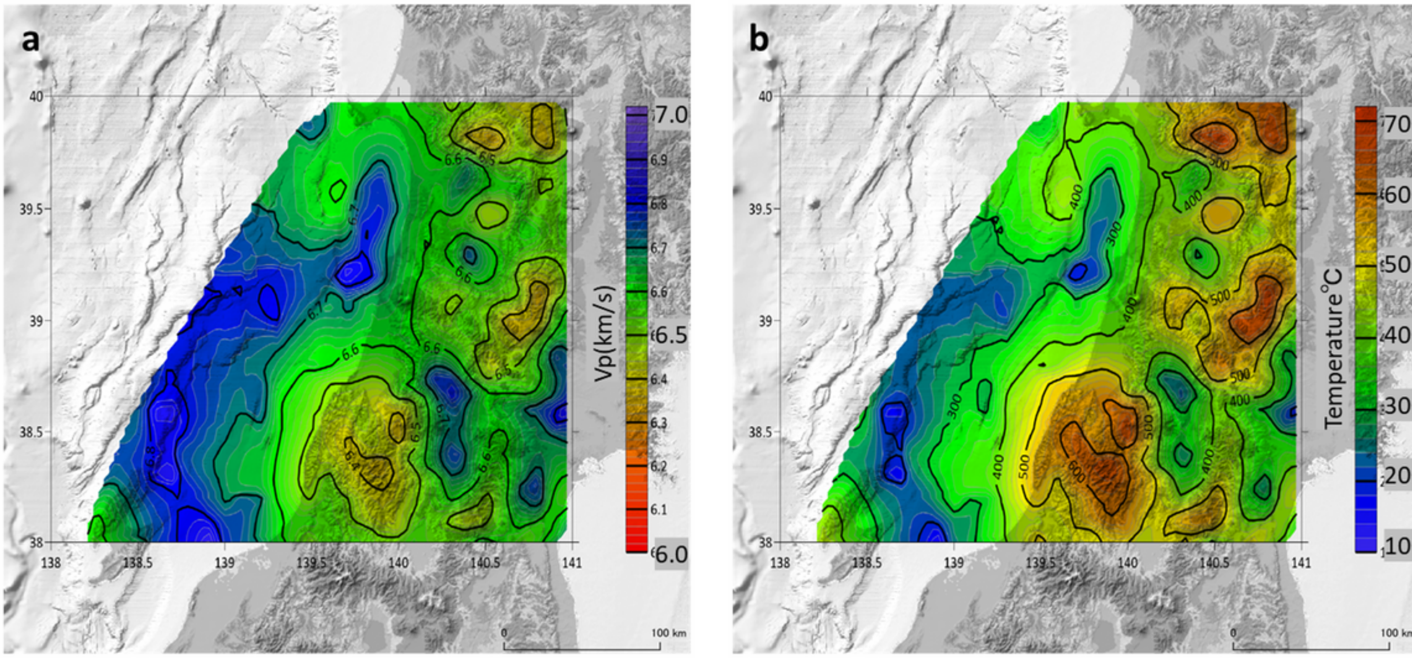


Figure 3

P wave velocity (Vp) and Vp/Vs at 20km depth around Yamagata, northeast Honshu. Seismic tomography of Matsubara et al. (2019）is used. The temperature map was created assuming the maximum temperature and the temperature derivative of Vp.



Temperature component extracted from Vp at 20km depth.

Temperature estimated at 20km depth

Figure 4

Temperature component of Vp and estimated temperature at 20km depth. First, velocity data in the region Vp / Vs = 1.77 to 1.78 was extracted from Vp / Vs data at a depth of 20 km. Then kriging interpolation was performed to create a temperature component map. The temperature map was produced assuming the maximum temperature of 685 °C and the temperature derivative of Vp = 1.0×10^{-3} km s^{-1} $°C^{-1}$.

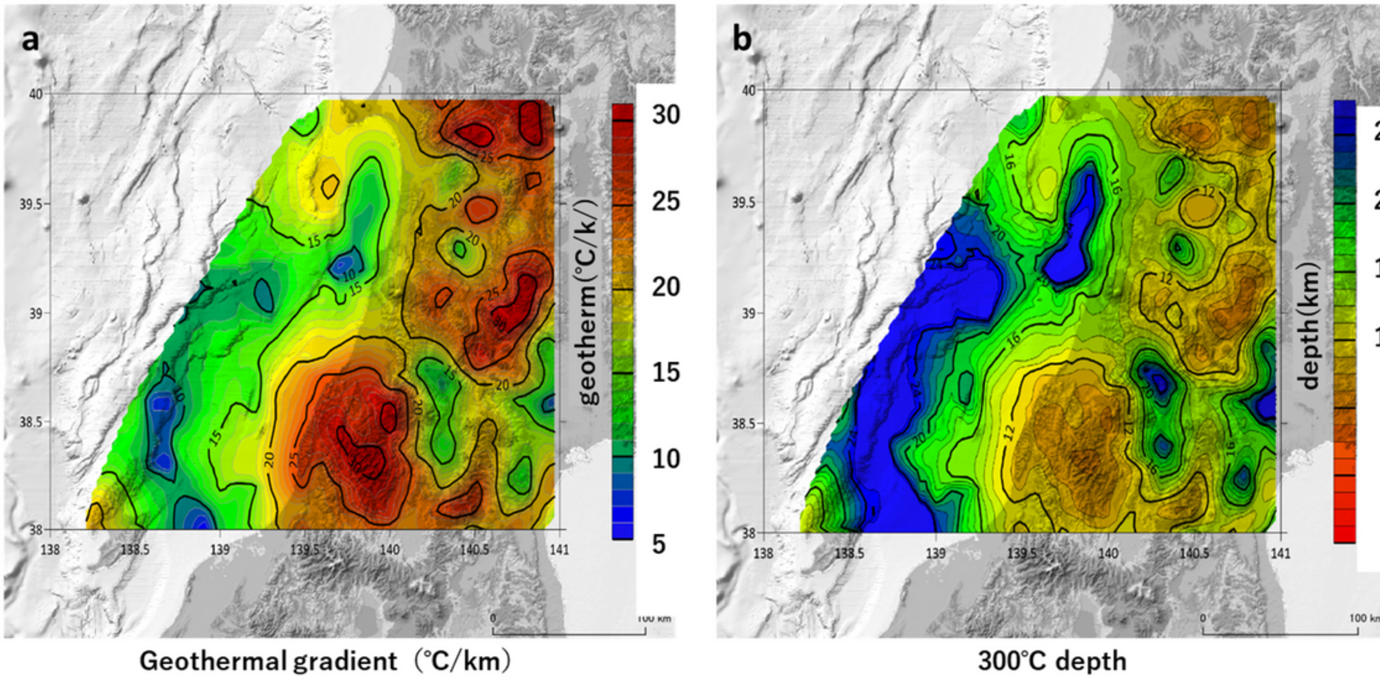


Figure 5

Geothermal gradient and 300 °C depth

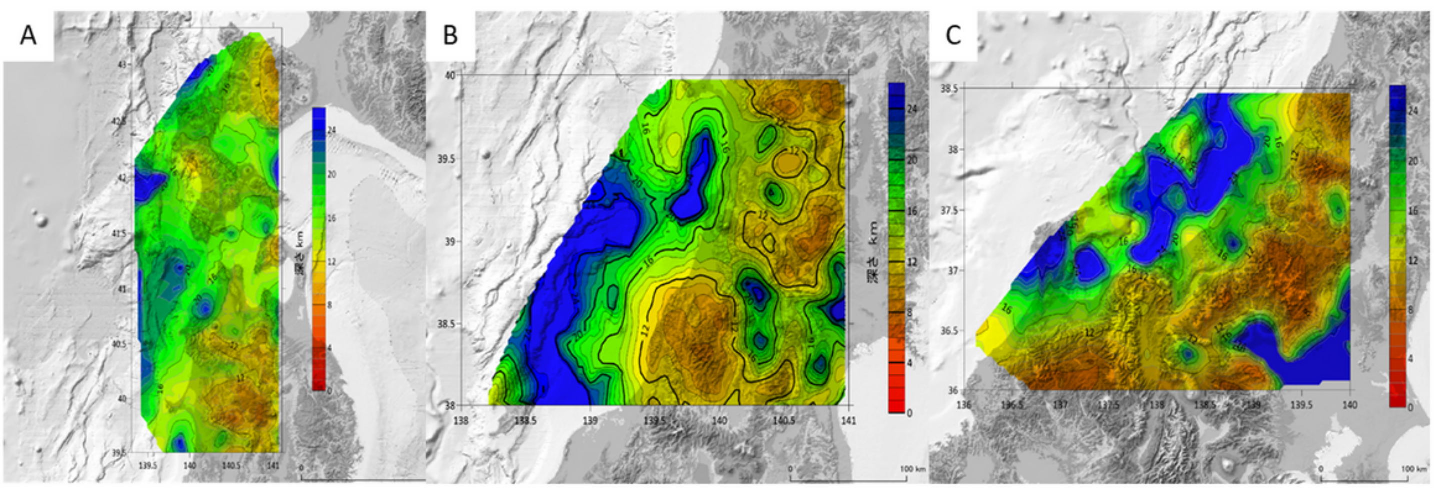


Figure 6

Depth of 300 ° C from southwest Hokkaido to Hokuriku along the eastern margin of the Japan Sea

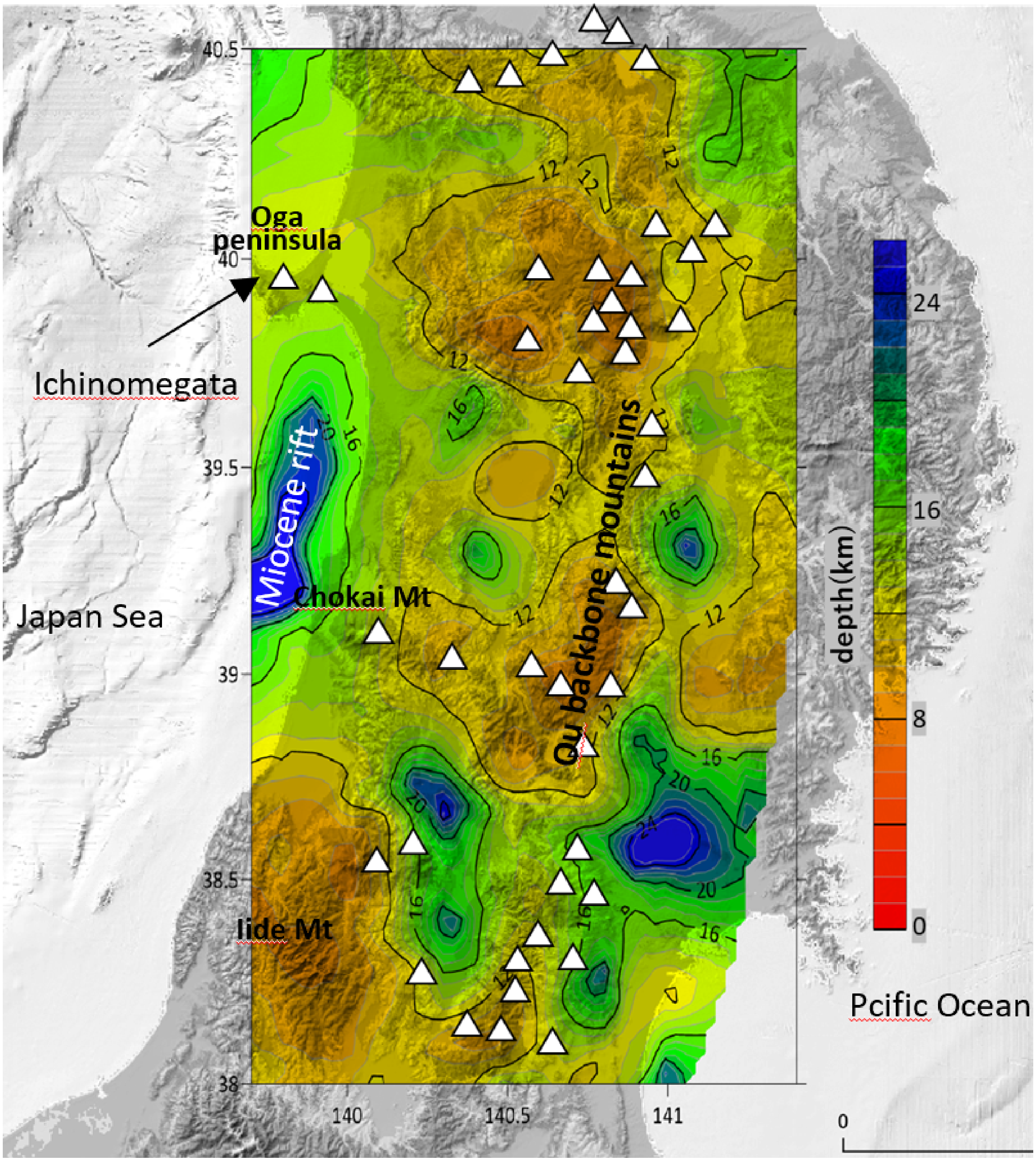


Figure 7

Quarternary volcanoes and 300 °C depth.

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