Slab dehydration and earthquake distribution beneath southwestern and central Japan based on three-dimensional thermal modeling

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(Citation)
Geophysical Research Letters,44(6):2679-2686

(Issue Date)
2017-03-28

(Resource Type)
journal article

(Version)
Version of Record

(URL)
https://hdl.handle.net/20.500.14094/90005031

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2016GL072295

Key Points:
- A correspondence between slab dehydration and earthquakes distribution beneath SW and central Japan was identified
- The occurrence of tectonic tremors and deep SSEs in SW Japan also relate to the interface with high slab dehydration
- The 3-D modeling method for slab dehydration distribution is a new subject in this research field

Supporting Information:
- Supporting Information S1

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Citation:
Ji, Y., and S. Yoshioka (2017), Slab dehydration and earthquake distribution beneath southwestern and central Japan based on three-dimensional thermal modeling, *Geophys. Res. Lett.*, *44*, 2679–2686, doi:10.1002/2016GL072295.

Received 13 DEC 2016
Accepted 28 FEB 2017
Accepted article online 2 MAR 2017
Published online 22 MAR 2017

Slab dehydration and earthquake distribution beneath southwestern and central Japan based on three-dimensional thermal modeling

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Abstract We developed a 3-D thermal convection model to estimate the thermal regime, water content distribution, and slab dehydration beneath southwestern and central Japan, where deep tectonic tremors and short-term slow slip events (S-SSEs) are frequently observed on the plate interface extending from the western Shikoku to the Tokai district. The results showed that the pressure-temperature (P-T) conditions for the S-SSEs, deep tectonic tremors, and regular earthquakes indicate that they probably originated from slab dehydration in association with subduction, resulting in a phase transformation from prehnite-actinolite/lawsonite blueschist to amphibolite with a large thermal gradient. Slab dehydration and the thermal gradient in the dip direction are considered key factors for controlling the seismogenesis of slow and regular earthquakes in the Philippine Sea plate beneath southwestern and central Japan, although the deep tectonic tremors are more complicated because they are likely favored by a comparatively low temperature gradient in southwestern Japan.

1. Introduction

The Philippine Sea (PHS) plate subducting beneath southwestern and central Japan is characterized by a young and hot seismogenic subduction zone, which provides some of the most varied sources of earthquakes and plate tectonic deformation in the world, such as tectonic tremors [*Obara*, 2002; *Idehara et al.*, 2014], low-frequency earthquakes (LFEs) [*Katsumata and Kamaya*, 2003], very low-frequency earthquakes [*Ito et al.*, 2007; *Ide et al.*, 2008], and slow slip events (SSEs) [*Obara et al.*, 2004; *Yoshioka et al.*, 2015] (Figure 1). Seismic tomography depicting the slab geometry reveals a regional variation of volcanism between the Kinki and Chubu districts, probably as a result of different dip angles; a larger dip angle contributes to more arc volcanism [*Nakajima and Hasegawa*, 2007]. The Kyushu district with active volcanism corresponds to a large dip angle for the underlying subducting PHS plate, and the subducting PHS plate imaged by seismic tomography reaches a depth of 200 km with earthquakes ($M > 2.0$) occurring deeper than 100 km, which are detected much more frequently in Kyushu than in Kinki and Shikoku. Figure 1 shows a tectonic map and the distribution of deep tectonic tremors [*Idehara et al.*, 2014], with colors indicating their focal depths. In the northernmost section of the Izu-Bonin arc, the focal depths of nonvolcanic tectonic tremors are scattered along a wide range of the subduction interface, varying from 10 to 50 km. Compared with the shallow tectonic tremors sporadically distributed on the landward side of the Nankai Trough [*Obara and Kato*, 2016], deep tectonic tremors are densely distributed along the 30 to 40 km isodepth contours of the subducted PHS plate near the continental Moho depth extending from eastern Kyushu to Tokai.

Impulsive *S* waves in the waveforms of tectonic tremors are indicative of LFEs [*Katsumata and Kamaya*, 2003], and migrations of tectonic tremors and S-SSEs [*Ide*, 2010] are well recorded, indicating a distributed in situ high pore fluid pressure on the plate interface. Many studies have suggested that slab dehydration would elevate the pore fluid pressure, which would cause tectonic tremors and S-SSEs [*Shelly et al.*, 2006; *Hirose et al.*, 2008; *Tahara et al.*, 2008; *Matsubara et al.*, 2009]. Water is transferred to the mantle wedge from the plate interface, which facilitates serpentinization of the wedge through metamorphic processes and eclogitization [*Zhao et al.*, 2002; *van Keken*, 2003; *Hyndman and Peacock*, 2003; *Hacker et al.*, 2003]; an example of this occurs at Kyushu [*Xia et al.*, 2008; *Abe et al.*, 2011]. Hydrofracturing associated with fluid migration has also been proposed as the mechanism of LFEs [*Katsumata and Kamaya*, 2003]. Slow slip events are concurrent with tectonic tremors [*Obara*, 2002; *Obara and Hirose*, 2006; *Idehara et al.*, 2014] in southwestern Japan and are probably related to the seismically and aseismically slipping plate interface, similar to that of Cascadia

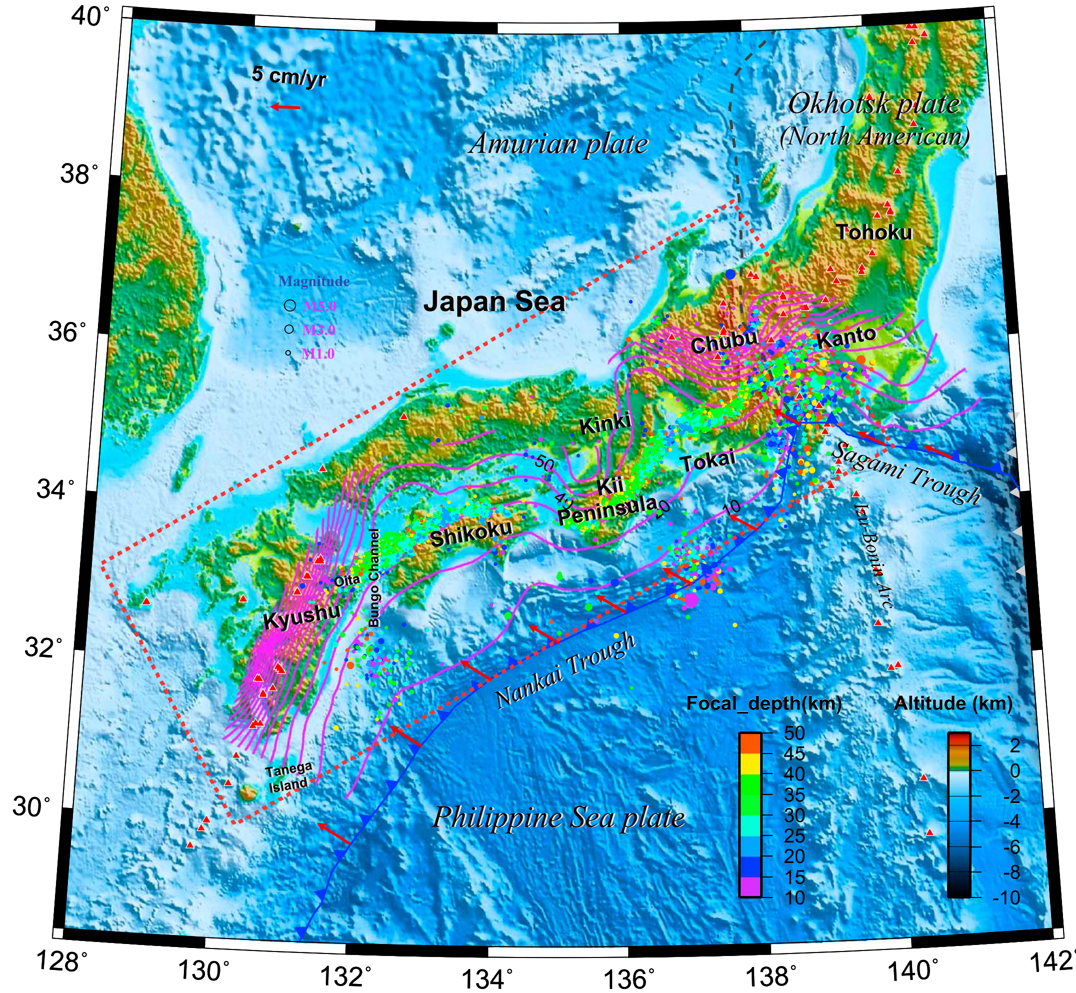

Figure 1. A tectonic map of southwestern and central Japan. The background color indicates the surface topography. The violet lines indicate isodepth contours on the upper surface of the PHS plate with an interval of 10 km [*Nakajima and Hasegawa*, 2007]. The red dashed lines show the model region for the subducted PHS plate. The small circles show the epicenter distribution of tectonic tremors during a period from 1 April 2004 to 31 March 2013, following *Idehara et al.* [2014], indicating their focal depths and magnitudes with colors and radii, respectively. Red arrows illustrate the plate motion velocity vectors of the PHS plate with respect to the Amurian plate along the Nankai Trough and with respect to the Okhotsk (North American) plate along the Sagami Trough. Red triangles indicate active volcanoes in Japan. The barbed thick blue lines mark the plate boundary between two neighboring plates. The dashed black line indicates the plate boundary between the Amurian and Okhotsk plates.

[*Igarashi et al.*, 2003; *Schwartz and Rokosky*, 2007]. However, the heterogeneous interplate thermal regime caused by oblique subduction of a highly curved oceanic plate associated with slab metamorphism, eclogitization, and dehydration remains elusive. Rate- and state-dependent frictional models that estimate velocity weakening and the nucleation of slip instability [*Ikari et al.*, 2013] account for stable fault slip or instability resulting in seismic events, with low normal stress attributable to the pore fluid pressure [*Perfettini and Ampuero*, 2008; *Segall et al.*, 2010]. For regular intraslab earthquakes, brittle failure and subsequent dehydration instability have been considered viable mechanisms for interpreting the seismic evidence from southwestern Japan [*Seno et al.*, 2001] due to the ease of stress buildup and strain localization.

However, no quantitatively determined dehydration at any specific subduction zone has been described in previous studies. Determining how to estimate the amount of dehydration and its spatial distribution remains a challenging topic in efforts to investigate the release and migration of slab fluids as well as their relationship with fault instability to generate aseismic SSEs, deep tectonic tremors, and subsequently triggered regular earthquakes [*Okazaki and Hirth*, 2016]. In this study, we use the results of a newly developed

3-D thermal model [*Ji et al*., 2016] to estimate slab dehydration in southwestern and central Japan. We evaluate the amount of water released into the mantle wedge, which facilitates serpentinization, and discuss its relationship with the distribution of deep tectonic tremors and regular earthquakes. The arbitrary 3-D geometry of the plate interface and the subduction velocity are considered in the calculation of the temperature distribution and the subsequent estimation of P-T-dependent dehydration.

2. Model Setting

The thermal simulations are shown in details in *Ji et al.* [2016]. In the 3-D parallelepiped thermal convection model of this study, the subduction history of the PHS plate beneath southwestern and central Japan follows *Mahony et al.* [2011] and *Clift et al.* [2013], in which a rotating plate motion relative to the Eurasian plate was reconstructed from approximately 15 Ma to 5 Ma. Next, we assume that the subduction of the PHS plate has been occurring since 3 Ma with a subduction velocity of 6 cm/yr and a direction of N58.8°W [*DeMets et al*., 2010]. The applied trenchward temperature boundary condition for the model is based on the plate cooling model suggested by *Grose and Afonso* [2013]. The age of the PHS plate along the Nankai Trough is inferred from seafloor magnetic anomaly data [*Okino et al*., 1999] and used for setting the trenchward temperature boundary with mantle flow presumed to be permeable, whereas the other three vertical boundaries are assumed to be adiabatic and permeable. The top boundary is set at 0°C and rigid, and the bottom is taken as adiabatic and permeable. The dimensions of the modeled region are 1800 km in the along-arc direction, 540 km in the direction normal to the Nankai Trough, and 200 km in depth, and the grid intervals are 15 km, 10 km, and 5 km, respectively. Viscosity for the wet olivine is prescribed, following *Hirth and Kohlstedt* [2003] and *Burkett and Billen* [2010]. The seafloor geometry of Etopo [*Smith and Sandwell*, 1997] is also incorporated into the model to better fit the observed surface heat flow obtained from bottom-simulating reflectors [*Ashi et al*., 1999, 2002], land boreholes and marine heat probes [*Tanaka et al*., 2004; *Yamano*, 2004], and Hi-net boreholes [*Matsumoto*, 2007].

Based on the calculated slab temperature, depth, and metamorphic processes involving hydrous mid-ocean ridge basalt (MORB) and ultramafic rocks [*Omori et al*., 2009; *Hacker et al*., 2003], we calculated the water content (maximum solubility) of the slab associated with phase transformations from serpentine-chlorite-brucite (15 wt %) to serpentinite-chlorite dunite (6.2 wt %) and then to harzburgite ($<$2 wt %) for ultramafic rocks and from prehnite-actinolite/lawsonite blueschist (4.4–5.4 wt %) to eclogite ($<$1.0 wt %) for MORB. Subsequently, the spatial variations of slab water content between neighboring grid cells along the subduction direction were derived, with units of wt %/km. The thermal and hydrous status is at the time of 0 Ma after the calculation of 15 Myr for plate subduction.

3. Results and Discussion

The calculated thermal regime of the subducted PHS plate in southwestern and central Japan is shown in Figure 2. The hypocenters of regular interplate earthquakes from 1 October 1997 to 28 February 2015 are displayed with colored spheres indicating magnitudes. The earthquakes are clearly clustered beneath the Bungo Channel and the offshore of eastern Kyushu, which is presumably attributable to a temperature increase from 300°C to 450°C corresponding to the thermal transition zone from brittle deformation to ductile creep [*Hyndman et al*., 1995]. However, a similar phenomenon is much less common in the Shikoku, Kinki, and Tokai districts, although the thermal conditions and the depth of the upper surface of the PHS plate are the same. The difference suggests that the thermal regime may not be the sole factor controlling interplate seismicity in the PHS plate beneath southwestern and central Japan. We investigated the thermal regime of the PHS plate in western Shikoku and the Bungo Channel, where long-term slow slip events occurred repeatedly, and found that the intraslab temperature there was lower by approximately 200°C than that in eastern Shikoku. The temperature gradient on the plate interface in the subduction direction may be another key factor determining the possible slab dehydration conditions and likely affects the distribution of slow slip events, deep tectonic tremors, and regular earthquakes [*Ji et al*., 2016]. The relationship among dip angle, slab geometry, and the subsequent slab dehydration is considered another potentially controlling factor requiring investigation.

In Figure 3a, the distribution of water content of the subducted PHS plate is reconstructed following the phase diagrams of hydrous MORB [*Omori et al*., 2009] and ultramafic rocks [*Hacker et al*., 2003]. Deep tectonic tremors (black dots) are also plotted in Figure 3a. Regular earthquakes and deep tectonic tremors occurred at

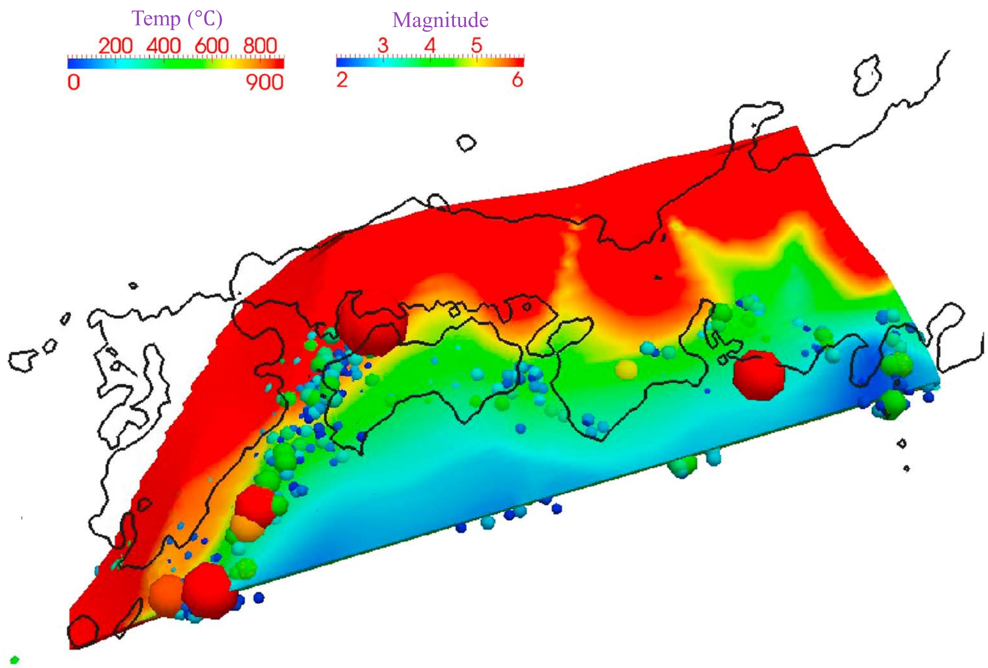

Figure 2. The calculated temperature distribution on the upper surface of the PHS plate. Colored spheres indicate interplate regular earthquakes during a period from 1 October 1997 to 28 February 2015, with magnitudes greater than 2.0. The plotted hypocenters are within a depth range of 0–200 km from the Earth's surface and a vertical depth range of −2 km to 7 km downward from the plate interface. The portion with temperatures above 900°C is shaded red.

the transition zone, where the slab water content decreases remarkably. However, the direct relationship between slab water content and seismicity appears unclear. Therefore, we further investigated the slab dehydration distribution along the subduction direction (Figure 3b). The results support the speculation about the effect of slab dehydration on the generation of earthquakes, clearly showing a high dehydration belt offshore along eastern Kyushu, extending from Oita, northeast of Kyushu, to Tanega Island; this is also the zone in which most of the earthquakes in southwestern Japan with magnitude greater than 5.0 and with a vertical depth range of −2 km to 7 km downward from the plate interface occur. Tokai is another region with extensive slab dehydration, and regular earthquakes and tectonic tremors occurred there (Figures 3a and 3b). In particular, we determined that slab dehydration of −0.01 wt %/km is equal to a release of 0.33 kg of fluid for a fraction of the upper slab with a volume of approximately 1 m^3/km if the density is assumed to be 3.3×10^3 kg/m^3. This calculation provides an amount as large as 10 kg/m^2 for the fluid upwelling into the mantle wedge if the thickness of the slab is assumed as 30 km. In addition, the spatial coincidence of deep tectonic tremors with high dehydration distribution is not identified on the plate interface as clearly as that for regular earthquakes.

The downdip limit of regular earthquakes is likely related to thermally driven conditionally stable ductile creep according to the numerical experiments [e.g., *van Dinther et al*., 2013]. Direct correlation of dehydration pattern with seismicity may be an oversimplification since both free water content and fluid/solid pressure ratio are strongly affected by a nonvertical fluid transport such as the solid rheology, compaction pressure, and fluid-assisted deformation [e.g., *Abers et al*., 2013; *Wilson et al*., 2014; *Zheng et al*., 2016]. Seismicity could likely represent fluid pathways in and above the slab [e.g., *Faccenda et al*., 2012]. These pathways are not strictly vertical and can follow the slab surface geometry [*Wilson et al*., 2014]. Free water content distribution does reflect not only dehydration processes but also fluid transport phenomena [e.g., *Wilson et al*., 2014]. Some of the regular earthquakes and deep tectonic tremors may reflect the fluid transport path which is not included in this model.

From the results, we found that the maximum slab dehydration for MORB is approximately −0.04 wt %/km offshore of eastern Kyushu, −0.06 wt %/km beneath the Bungo Channel, and −0.10 wt %/km in Tokai (Figure 3b). For the ultramafic rocks, the maximum slab dehydration beneath western Shikoku and Tokai is

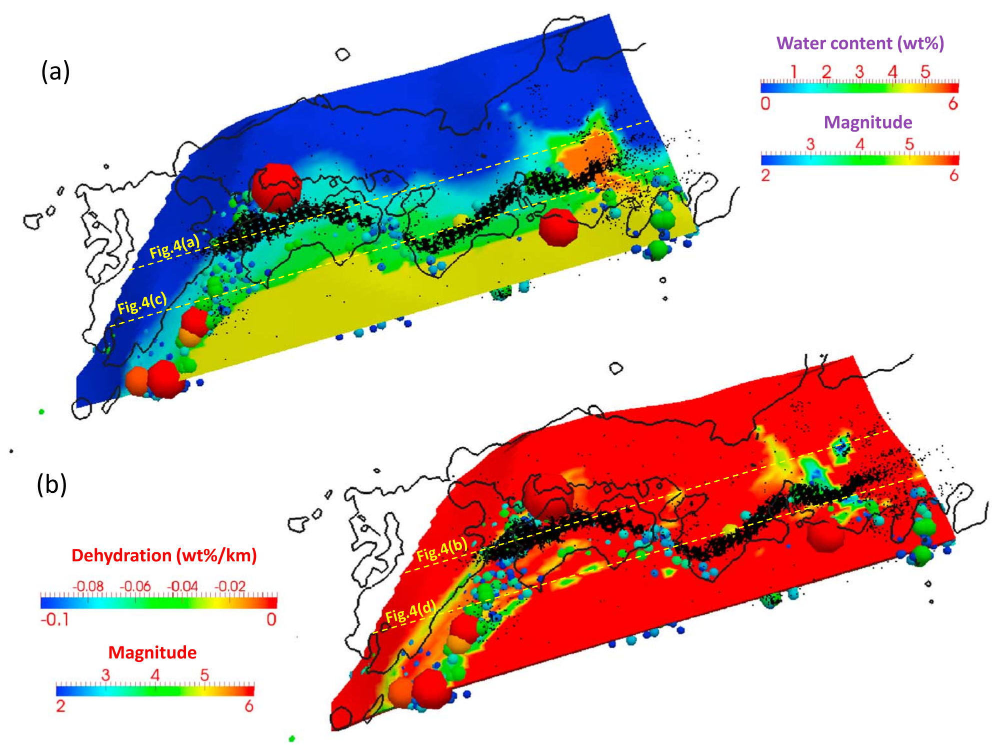

Figure 3. Colored spheres indicate interplate regular earthquakes during a period from 1 October 1 1997 to 28 February 2015, with magnitudes greater than 2.0. The plotted hypocenters are within a depth range of 0–200 km from the Earth's surface and a vertical depth range of −2 km to 7 km downward from the plate interface. Black dots indicate the epicenters of deep tectonic tremors [*Idehara et al*., 2014] during a period from 1 April 2004 to 31 March 2013. The yellow dashed lines indicate the locations of the cross sections in Figure 4. (a) The calculated slab water content distribution (wt %) on the upper surface of the PHS plate. (b) The calculated slab dehydration distribution (wt %/km) on the upper surface of the PHS plate in the subduction direction. The portion with dehydration $<$–0.1 wt %/km is shaded blue.

more than −0.20 wt %/km. The amount of water released from the lower PHS plate is expected to be approximately 10 times greater than the amount of water released by MORB.

Because the result of slab dehydration depends strongly on the subduction direction and because the PHS plate has undergone a significant rotation for approximately 10 Myr from 15 Ma to 5 Ma, we assume that the distribution of slab dehydration during the plate rotation period was different from the currently observed distribution. Presently, the PHS plate is subducting obliquely toward N58.8°W, which is nearly 30° westward from the trough-normal direction (N30°W). To investigate intraslab dehydration in more detail, two cross sections were taken: one passing through northern Shikoku (Figures 4a and 4b) and the other through the southern Kii Peninsula-Tokai (Figures 4c and 4d) in the ENE-WSW direction, where tectonic tremors were densely distributed. The distribution of water content within the two cross sections clearly shows hydraulic layers (encircled in Figures 4a and 4c), and the corresponding slab dehydration along the two cross sections exhibits an amount of approximately −0.1 wt %/km inside the slab (encircled in Figures 4b and 4d). Deep tectonic tremors appear to occur in the regions adjacent to areas with high slab water content and a large fraction of slab dehydration, especially where ultramafic minerals are present, with a maximum water content of 15 wt % in serpentine-chlorite-brucite [*Hacker et al*., 2003]. This maximal water content may not necessarily be representative because of incomplete and heterogeneous hydration [e.g., *Peacock*, 1987]. Regarding the fluid migration that elevates the pore fluid pressure and facilitates the fluid flow into slab microcracks, fluid outflows from the slab interior are expected to lubricate the slab interface and promote slip [*Melbourne and Webb*, 2003]. Rapid water flow is probably capable of triggering tectonic tremors when the flow dissipates into the overriding plate via the promotion of microfracturing [*Schwartz and Rokosky*, 2007].

The P-T conditions of earthquakes that occurred in the modeled MORB of the subducted PHS plate with a thickness of 7 km were investigated (Figure S1a in the supporting information). A low slope for the P-T paths of regular earthquakes (white circles) that occurred in the oceanic crust of the PHS plate was identified. The

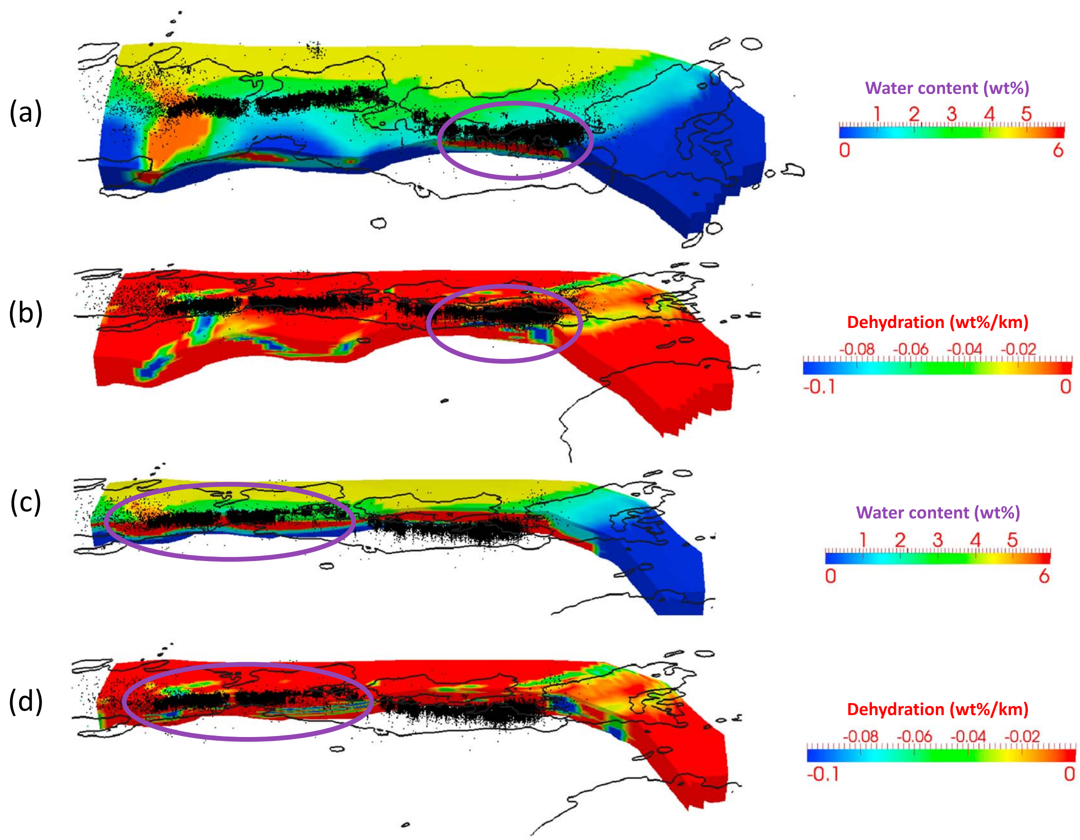

Figure 4. Relationships among slab water content, slab dehydration, and tectonic tremors beneath southwestern and central Japan. Black dots indicate the hypocenters of deep tectonic tremors [*Idehara et al.*, 2014]. The purple circle shows the tectonic tremors distributed at the cross sections which have been marked in Figure 3. (a) View of slab water content distribution (wt %) in the subduction direction on the upper surface of the PHS plate along the northern Shikoku in the ENE-WSW direction. (b) The slab dehydration distribution (wt %/km) in Figure 4a. (c) View of slab water content (wt %) along the southern Kii Peninsula and Tokai in the ENE-WSW direction. (d) The slab dehydration distribution (wt %/km) in Figure 4c.

results can be compared with those of previous studies [*Hacker et al.*, 2003], which indicate that the dip angle of the subducting plate correlates well with the slope of intraplate regular earthquakes under specific P-T conditions. The dip angle in Tohoku, Japan, which is considered to be a cold subduction zone, is much larger and thus has a higher slope in the P-T diagram. For depths as shallow as 10–25 km with background temperatures of 300–500°C, the occurrence of tectonic tremors is much less frequent than that of intraslab earthquakes. Such a phenomenon is also identified at depths deeper than 45 km. This pattern may be attributable to the different generation mechanisms of tectonic tremors. Extensive intraslab dehydration to facilitate the occurrence of tectonic tremors is less common at depths deeper than 45 km or shallower than 25 km beneath southwestern Japan. In Figure S1b, we can also see that within a range of slab dehydration from −0.10 wt %/km to approximately −0.20 wt %/km, the proportion of the occurrence of tectonic tremors is larger than that of intraslab earthquakes.

The metamorphism of the MORB of the PHS slab beneath southwestern and central Japan is inferred to be mainly from prehnite-actinolite/lawsonite blueschist to amphibolite, which has a gentle P-T slope and is quite different from that of cold subduction zones. Figure S1b shows a relationship between the temperature gradient and slab dehydration on the plate interface in the subducting direction. We recognize that most of the intraslab regular earthquakes which occurred in the MORB layer favor a temperature gradient less than 20°C/km and slab dehydration less than the absolute value of 0.25 wt %/km. The deep tectonic tremors are more complex because greater dehydration instead of a greater temperature gradient is favored. Both the intraslab regular earthquakes and the deep tectonic tremors can reach a maximum absolute value of approximately 0.30 wt %/km for slab dehydration and 30°C/km for the thermal gradient in this study. These values suggest that slab dehydration and the thermal gradient are important factors for controlling the seismogenesis of intraslab regular earthquakes and deep tectonic tremors in the oceanic crust of the PHS plate, although the details remain unclear and deserve in-depth investigation. The regular earthquakes and tectonic tremors seem to match different temperature gradient ranges with substantial slab dehydration beneath southwestern and central Japan.

4. Conclusions

Through the 3-D thermal convection model simulating the subduction of the PHS plate beneath southwestern to central Japan, we obtained the following results:

1. Slab dehydration from the MORB of the PHS plate contributes extensively to the distribution of interplate regular earthquakes clustering offshore of eastern Kyushu. The maximum slab dehydration for the MORB is approximately −0.04 wt %/km offshore of eastern Kyushu, −0.06 wt %/km beneath the Bungo Channel, and −0.10 wt %/km in Tokai.
2. The causes of deep tectonic tremors beneath southwestern and central Japan are related to large-scale intraslab dehydration beneath Shikoku, the Kii Peninsula, and Tokai. For the ultramafic rocks, the maximum slab dehydration beneath western Shikoku and Tokai can exceed −0.20 wt %/km.
3. Slab dehydration beneath southwestern and central Japan is mainly caused by phase transformations from serpentine-chlorite-brucite (15 wt %) to serpentinite-chlorite dunite (6.2 wt %) and then harzburgite (<2 wt %) for ultramafic rocks and from prehnite-actinolite/lawsonite blueschist (4–5 wt %) to amphibolite (<1 wt %) for MORB. The P-T path of regular earthquakes in the oceanic crust has a low slope in the P-T diagram, indicating a high thermal gradient.
4. Slab dehydration and the temperature gradient are important factors for controlling the occurrence of interplate and intraslab regular earthquakes and deep tectonic tremors beneath southwestern and central Japan. Deep tectonic tremors may occur with a lower temperature gradient than regular earthquakes under high slab dehydration conditions.

Acknowledgments

This work was partly supported by JSPS KAKENHI grant number 16H04040 and the collaborative research project between Research Center for Urban Safety and Security, Kobe University and Advanced Institute for Computational Science, Institute of Physical and Chemical Research, Japan. We thank P. Tackley for sharing the original code of stag3d developed in this study. We also appreciated the help of T. Gerya and an anonymous reviewer for their constructive comments that allowed to improve this paper. We also thank Japan Meteorological Agency (JMA) and S. Ide for providing us the data catalog of regular earthquakes and tectonic tremors, respectively. All the figures were created by the Generic Mapping Tools (GMT) developed by *Wessel and Smith* [1998] and Paraview software developed by Kitware Inc.

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