Finite Difference Method Simulations of High-frequency Trapped *P* Waves Using the Earth Simulator: Evidence of Velocity Increase in the Subducting Uppermost Oceanic Crust of the Philippine Sea Plate due to Dehydration Reactions

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To clarify detailed structural properties of the subducting oceanic crust, especially seismic velocity change due to dehydration, we analyzed high-frequency (1-16 Hz) trapped *P* waves during earthquakes that occurred near the oceanic crust of the Philippine Sea Plate. Distinct trapped *P* waves observed by dense seismic network in the Kanto-Tokai region, Japan, did not show any apparent frequency-dependent peak delay and dispersion. These observations indicate that the oceanic crust around source depths may be characterized by a uniform velocity structure, rather than layered structure. This hypothesis was examined by finite difference method simulations of seismic wave propagation conducted on the Earth Simulator. Simulations demonstrated that a short-distance waveguide due to a uniform velocity oceanic crust, which might be developed by the metamorphic-dehydration reactions in the uppermost oceanic crust at depths of 30-40 km, caused effective trapping of seismic energy and distinct non-dispersive trapped *P* waves.

Keywords: Philippine Sea plate, oceanic crust, dehydration reaction, seismic wave propagation, computational seismology

1. Introduction

Many geophysical phenomena, such as generation of arc volcanism and triggering of large earthquakes, are strongly related to fluid transportation into the mantle by subducting oceanic plates (e.g., Tatsumi, 1989 [1]; Magee and Zoback, 1993 [2]). Previous studies revealed that the hydrated oceanic crust, which is the uppermost part of a subducting plate, plays important roles for fluid transportation into the mantle (e.g., Iwamori and Zhao, 2000 [3]; Kawakatsu and Watada, 2007 [4])

Subducting oceanic crust is characterized by a low-velocity layer compared to surrounding structures, such as the mantle wedge and the oceanic mantle (e.g., Matsubara et al., 2005 [5]; Kawakatsu and Watada, 2007 [4]; Nakajima et al., 2009 [6]). Trapped seismic energy due to this layer are often observed as distinct later arrivals just after relatively weak direct-body waves in the subduction zone of the world (e.g., Fukao et al., 1983 [7]; Hori, 1990 [8]; Abers et al., 2003 [9]; Martin and Rietbrock, 2006 [10]). Thus, characteristics of amplitude and dispersion of trapped seismic waves enable us to investigate the structure of subducting oceanic crust.

By analyzing seismicity and later arrivals in the Kanto-Tokai region, Japan (see Fig. 1a), Hori (1990)[8] pointed out that the subducting oceanic crust of the Philippine Sea Plate could be detected as a low-velocity seismic waveguide down to a depth of 60 km. Meanwhile, Kamiya and Kobayashi (2000)[12], and Matsubara et al. (2005)[5] conducted travel-time tomography in the Kanto region and detected the low-velocity anomaly (LVA) of the mantle wedge at depths of 30-40 km, which was interpreted as being constructed by the dehydration from hydrated oceanic crust of the Philippine Sea Plate at this depth. Although the spatial resolution of travel-time tomography is insufficiently high to investigate the structure of the oceanic crust in detail, their results imply that structural change in oceanic crust due to dehydration is possible at this depth.

In this study, to detect velocity change in the subducting oceanic crust, we analyzed trapped *P* waves for several frequency bands observed in the Kanto-Tokai region and conducted finite difference method (FDM) simulations of seismic wave propagation using realistic velocity structure models. By using large-scale FDM simulations on the Earth Simulator, we were able to examine not only the travel times but also the amplitude and envelope shape of the filtered trapped *P* waves for frequencies up to 16 Hz. By comparison of simulated and observed seismograms, we demonstrated that the *P*-wave velocity in the uppermost oceanic crust of the Philippine Sea Plate increases up to approximately 7 km/s at depths of 40-50 km in this region, which is higher compared to the *P*-wave velocity in typical uppermost oceanic crust. It could be interpreted as a result of metamorphic-dehydration reactions in the subducting uppermost oceanic crust at shallower depths.

2. Observed characteristics of high-frequency trapped P waves

In the Kanto-Tokai region, Hori (1990)[8] pointed out that seismograms of local earthquakes, which occurred near the oceanic crust of the Philippine Sea Plate, are characterized by the prominent later phases. These phases are interpreted to propagate through the low-velocity oceanic crust of the Philippine Sea Plate as trapped *P* and *S* waves, respectively. Focusing on this observation by Hori (1990)[8], we analyzed trapped *P* waves recorded at Hi-net stations to clarify detailed structural properties of the subducting oceanic crust.

Figure 1b shows vertical velocity seismograms recorded at Hi-net stations (filled squares in Fig. 1a) during an earthquake with *Mw* 4.8 that occurred at a depth of 59 km on May 18, 2012. Distinct later arrivals were observed at distances of 90-130 km (gray line in Fig. 1b), several seconds after direct *P* arrivals. Apparent velocity of this phase was approximately 7 km/s and roughly corresponding to *P*-wave velocity in the gabbroic oceanic crust. Thus, this event occurred near the oceanic crust of the Philippine Sea Plate, and this phase was trapped *P* wave propagating through the deeper part of oceanic crust.

Figure 2a shows filtered vertical velocity seismograms recorded at three Hi-net stations (see Fig. 1a), where trapped *P* waves were clearly observed. In general, as frequency increases, seismic wave scattering due to small-scale velocity heterogeneities along propagation path becomes more dominant and then distorted seismograms characterized by frequency-dependent pulse broadening and peak delay were observed (e.g., Takahashi et al., 2007 [13]; Sato et al., 2012 [14]). Surprisingly,

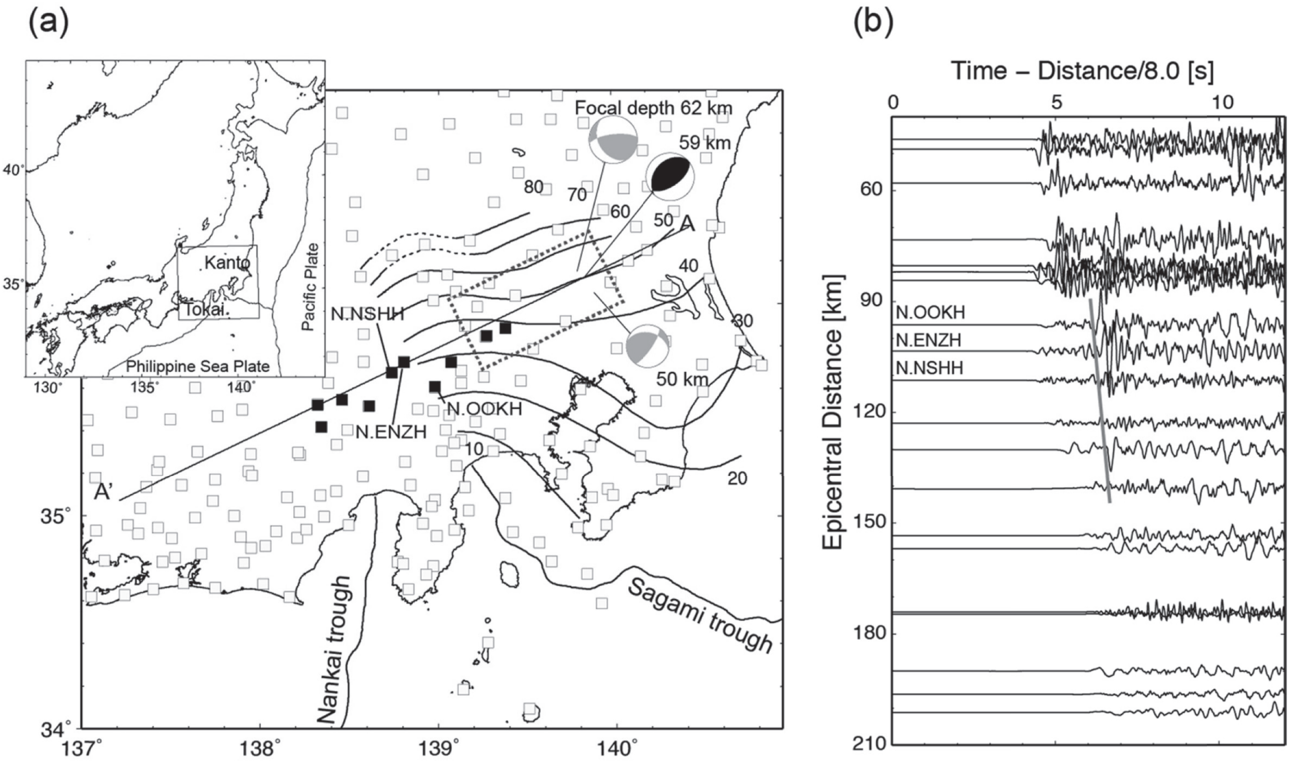

Fig. 1 (a) Distribution of Hi-net (squares) and analyzed earthquakes in the Kanto-Tokai region, Japan and (b) vertical velocity seismograms recorded at Hi-net stations (black filled squares) during an event that occurred at a depth of 59 km on May 18, 2012 (black focal sphere). The isodepth lines of upper surface of the Philippine Sea Plate by Hirose et al. (2008) [11] are shown at 10 km intervals in (a). Line A-A' is representing the area of 2D simulation in *x* direction and the region inside dotted rectangle in (a) is the area of 3D simulation in horizontal directions. Amplitudes in (b) were multiplied by each epicentral distance to compensate for effects of geometrical spreading of body waves.

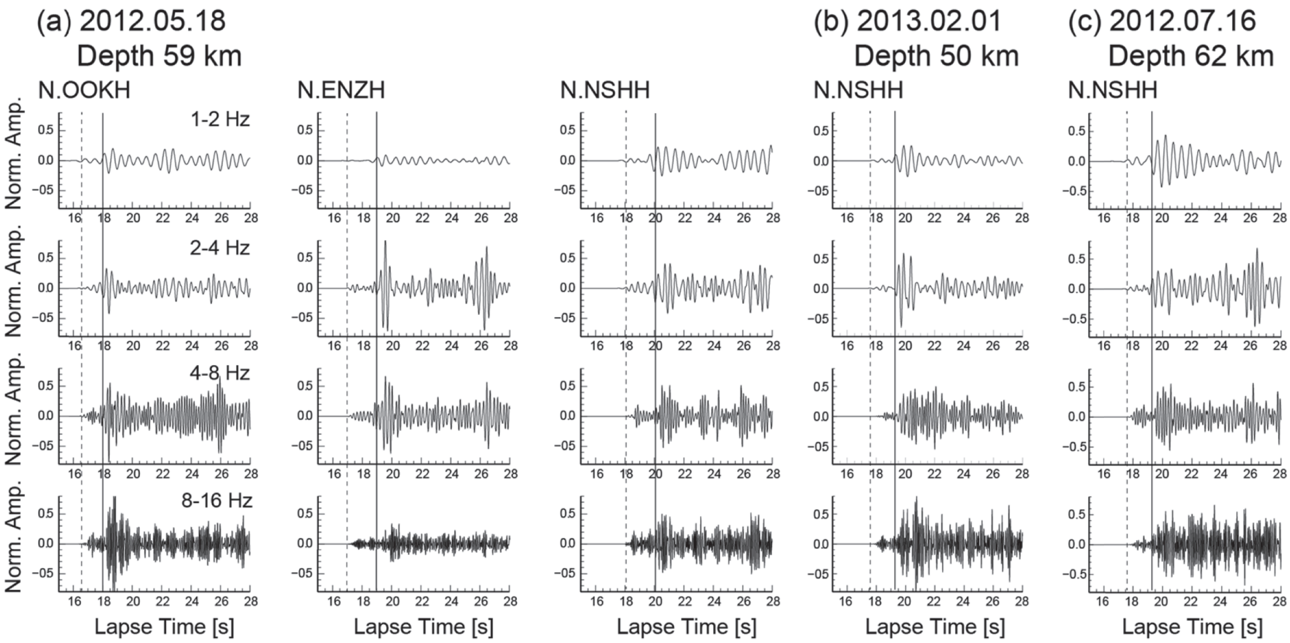

Fig. 2 (a) Filtered vertical velocity seismograms recorded at N.OOKH (96 km in epicentral distance), N.ENZH (103 km) and N. NSHH (111 km) during an event on May 18, 2012, (b) and (c) filtered vertical velocity seismograms recorded at N. NSHH during other two events (gray focal spheres in Fig. 1a). Locations of stations and epicenters are shown in Fig. 1a. Dashed and solid lines in each trace are onsets of *P* and trapped *P* waves, respectively.

trapped *P* waves were clearly observed irrespective of frequency, while seismograms became more complicated with increasing frequency. Furthermore, peak amplitudes and first arrivals of trapped *P* waves appeared simultaneously without significant dispersion or significant peak delay, except for waveform for frequency of 8-16 Hz at N.ENZH, where local site effects might not be negligible. During other events with similar epicenter locations and different depths (Figs. 2b and c), trapped *P* waves simultaneously arrived for all frequency bands examined in this study. These features indicate that observed trapped *P* waves without dispersion and peak delay might be caused by a specific velocity structure of the subducting oceanic crust, which effectively traps high-frequency *P*-wave energy.

3. Finite difference method simulation of seismic wave propagation

Our hypothesis was examined by two-dimensional (2D) FDM simulation of seismic wave propagation in realistic velocity structure models. The model of the 2D simulation covered an area of 327.68 × 102.4 km^2 in the horizontal and vertical directions (along profile A-A' in Fig. 1a), respectively, which was discretized by a small grid interval of 0.02 km. Unfortunately, realistic full three-dimensional (3D) simulation for frequencies up to 16 Hz is still too difficult. The propagation of seismic waves was calculated by solving the equation of motion in a 2D elastic medium based on the fourth-order staggered-grid FDM technique (e.g., Furumura and Chen, 2004 [15]; Takemura and Yoshimoto, 2014 [16]).

The background velocity structure was constructed using the Japan Integrated Velocity Structure Model (JIVSM) proposed by Koketsu et al. (2008) [17]. Assumed *P*-wave velocity (V_P) structure (Fig. 3a) included the two-layered oceanic crust, which consists of basaltic and gabbroic rocks, respectively (e.g., Murauchi et al., 1968 [18]). In JIVSM both oceanic crusts of the Philippine Sea Plate, hereafter referred to as "basaltic oceanic crust" and "gabbroic oceanic crust," have almost constant thicknesses of approximately 3 and 4 km, respectively. This thickness (3 km) of the uppermost layer of the Philippine Sea Plate (V_P = 4.8-5.2 km/s) was estimated by seismic reflection surveying near the Sagami Trough (Kimura et al., 2009 [19]). The thickness of the Philippine Sea Plate was assumed to be approximately 50 km (e.g., Kumar and Kawakatsu, 2011 [20]).

A double-couple point source was set at a depth of 50 km (star in Fig. 3a), which radiated *P* and *SV* waves with the source time function represented by a single-cycle Kupper wavelet with the dominant frequency of approximately 6 Hz. Source depth was modified from the original CMT solution (59 km) by trial and error, to set the source in the oceanic crust of the assumed velocity structure model (e.g., Miyoshi et al., 2012 [21]).

Simulation results of JIVSM are shown in Figs. 3b and 3c. High-frequency *P* waves propagated through the heterogeneous structure, repeating reflection and refraction at each velocity boundary (Fig. 3b). Trapped *P* waves (marked TP in Fig. 3b) efficiently propagated along the low-velocity oceanic crust and then trapped energy was released into the crust at depths of 30-35 km, because the impedance contrast between the top of the oceanic crust and the above media becomes small. Short-distance (< 60 km) waveguide in the oceanic crust caused trapped *P* waves after weak direct *P* waves in simulated seismograms (Fig. 3c). However, distinct trapped signals were not clearly observed for higher frequencies (8-16 Hz). Furthermore, arrival times of trapped *P* waves for frequencies of 4-8 and 8-16 Hz were delayed compared to those for frequencies below 4 Hz. Since *P*-wave energy for frequencies of 4-8 and 8-16 Hz with shorter wavelengths (0.42-1.7 km, assuming V_P = 6.8 km/s) was trapped in the basaltic oceanic crust rather than gabbroic oceanic crust or both, simulated trapped *P* waves were delayed and failed to explain observed non-dispersive features. These discrepancies between simulation and observation might be caused by a two-layered structure in the deeper oceanic crust.

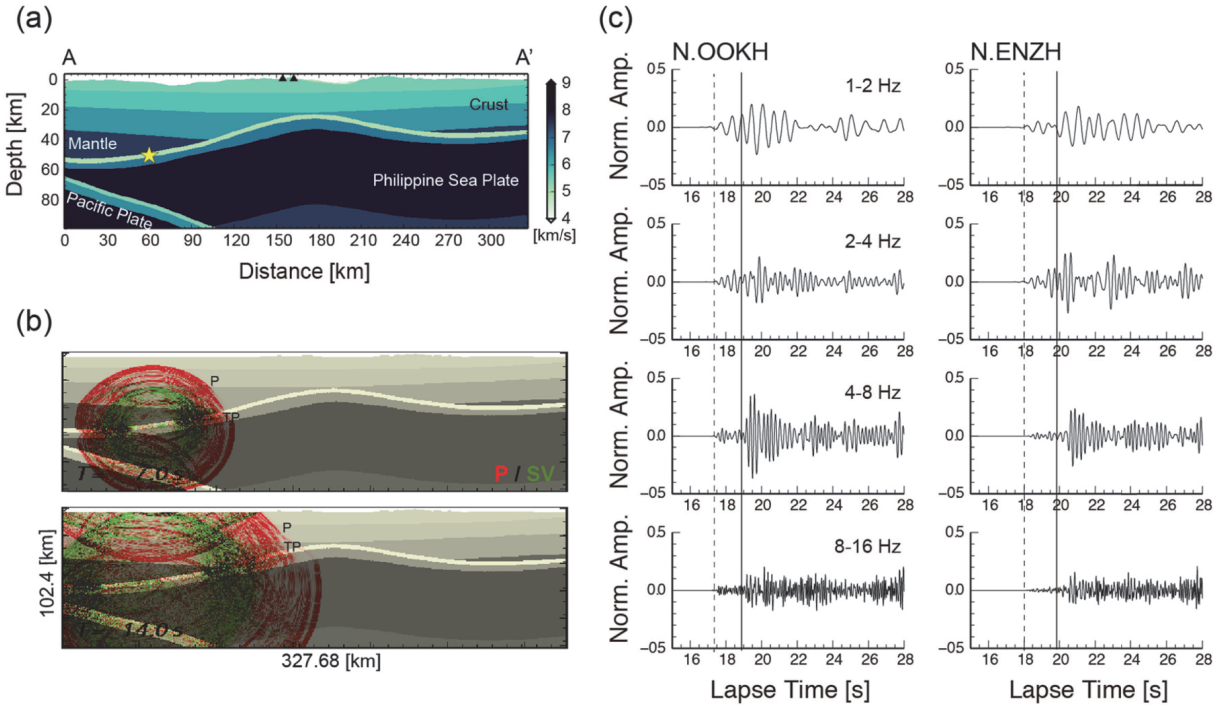

Fig. 3 (a) Assumed 2D *P*-wave velocity structure by JIVSM, (b) snapshots of seismic wave propagation at lapse times of t = 7 and 14 s, (c) simulated vertical velocity seismograms at N.OOKH (96 km) and N.ENZH (103 km). Star and filled triangles in (a) are hypocenter and seismic stations, respectively. Dashed and solid lines in each trace are onsets of *P* and trapped *P* waves, respectively.

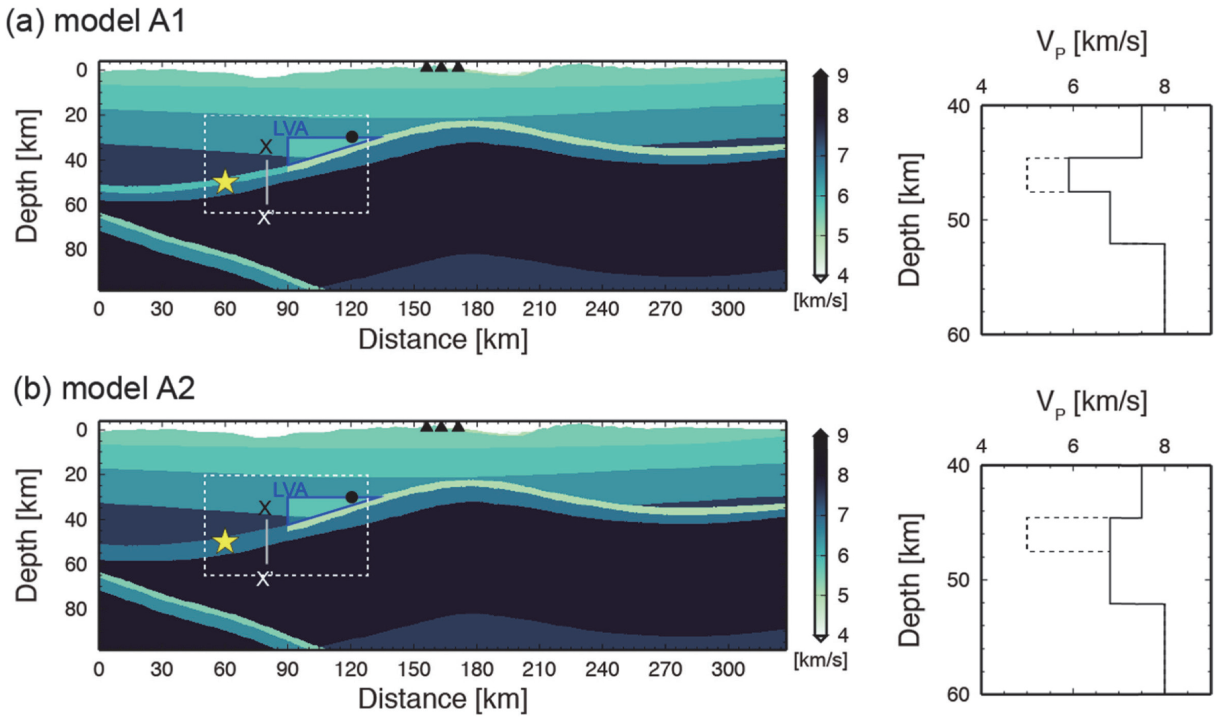

Fig. 4 *P*-wave velocity structure in the simulation model including the LVA of mantle wedge and velocity increase in basaltic oceanic crust of the Philippine Sea Plate at depths of 30-40 km: (a) model A1 and (b) model A2. Depth variations of *P*-wave velocity along vertical profile X-X' are shown in right part of figures. Solid and dashed lines are *P*-wave velocity structure around the oceanic crust in modified model and original JIVSM, respectively. Area of the LVA at depths of 30-40 km represented by blue triangle. The yellow star is the hypocenter. Dotted white rectangle and black circle are the area and seismic station of 3D simulation, respectively.

Along the profile A-A’ (Fig. 1a), the LVA of the mantle wedge just above the oceanic crust of the Philippine Sea plate at depths of 30-40 km was detected by the tomography studies (e.g., Fig. 7 and 8 in Matsubara et al., 2005 [5]). According to tomography studies, we considered that the metamorphic-dehydration reactions in the Philippine Sea Plate would occur around this depth and consequently cause an increase in the seismic velocity of metamorphosed bodies, especially in the basaltic oceanic crust. Thus, we simply modified the original JIVSM by introducing the LVA of the mantle wedge and velocity increase in the basaltic oceanic crust of the Philippine Sea Plate at depths below 40 km (Fig. 4).

Simulated vertical velocity seismograms of modified models are shown in Fig. 5. In model A1 (Fig. 5a), trapped *P*

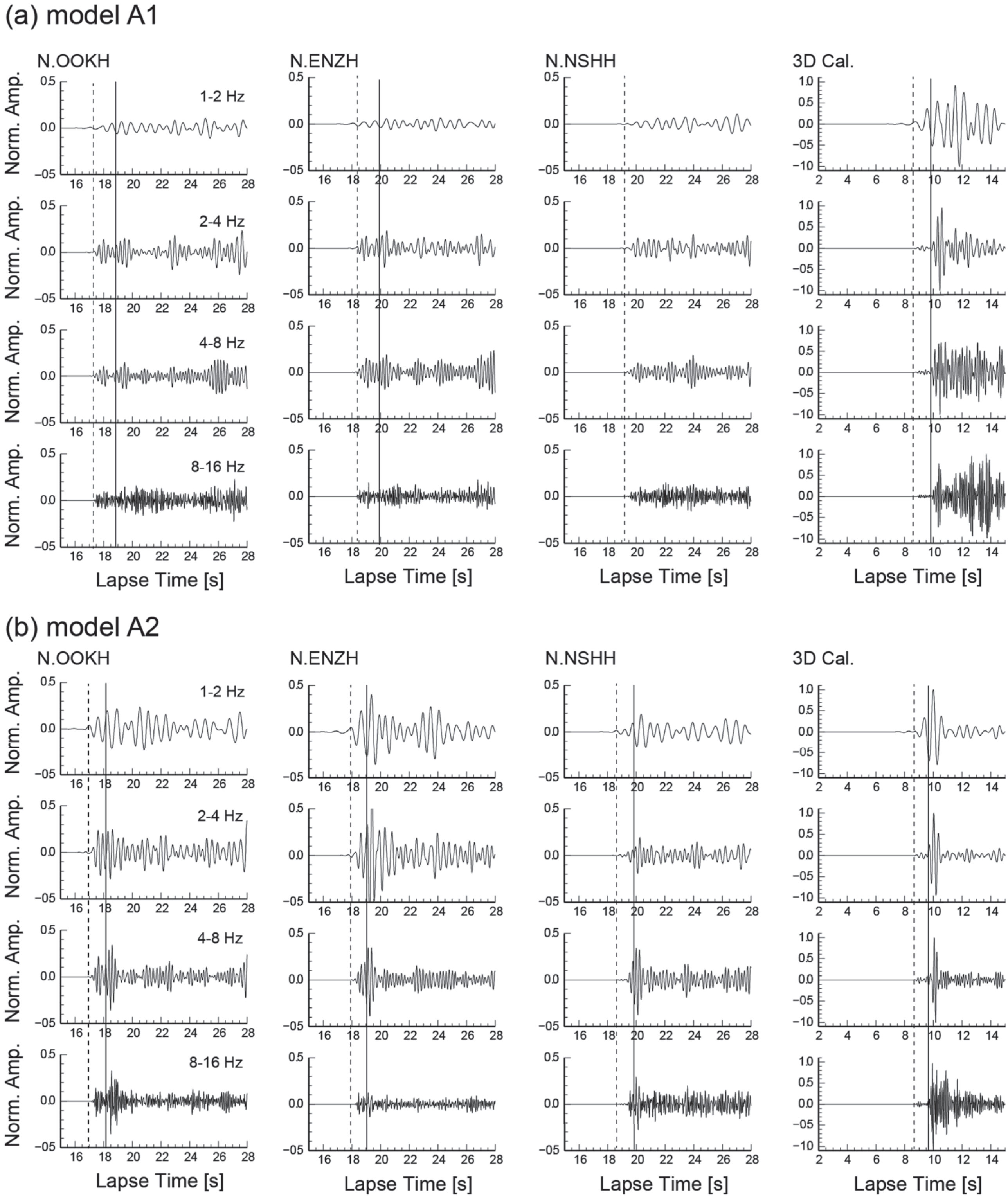

Fig. 5 Simulated vertical velocity seismograms at N.OOKH (96 km), N.ENZH (103 km) and N.NSHH (111 km) derived from (a) model A1 and (b) model A2. Station locations are plotted in right part of Fig. 4 (filled triangles). Seismograms derived from 3D FDM simulation are shown in right part of each figure. Dashed and solid lines in each trace are onsets of *P* and trapped *P* waves, respectively.

waves could not be distinguished easily for all seismograms especially at N.NSHH, and amplitudes of trapped *P* waves were comparable to those of other phases. Therefore, the modeled amount of velocity increase in the basaltic oceanic crust might be insufficient to develop trapped *P* waves. On the other hand, in model A2, which supposed the same *P*-wave velocity between basaltic and gabbroic oceanic crusts around the source depth, distinct trapped *P* waves were clearly observed for the all frequency bands (Fig. 5b). Observed travel times of trapped signals could also be reproduced by simulation for all frequencies, although simulated travel times of direct *P* waves were slightly delayed compared to observed travel times (Fig. 2). Short-distance waveguide in a uniform velocity structure of the oceanic crust (Fig. 4b) well developed distinct trapped *P* waves without dispersion and peak delay. The discrepancy between simulated and observed travel times of direct *P* arrivals might be improved by adjusting the *P*-wave velocity of surrounding structures.

4. Discussion and conclusions

According to comparison of simulated and observed waveforms, we concluded that the cause of distinct trapped *P* waves without dispersion and peak delay is a uniform velocity structure of the oceanic crust at depths below 40 km. We supposed that the dehydration of uppermost oceanic crust at depths of 30-40 km contributes to the formation of uniform velocity structures. On the basis of thermodynamic forward modeling, Kuwatani et al. (2011) [22] indicated that dehydration proceeds near the boundary between the greenschist and amphibolite facies, where chlorite is reacted out (e.g., Apted and Liou, 1983 [23]), at depths of approximately 40 km under the pressure-temperature condition of the subducting Philippine Sea Plate beneath southwestern Japan. This metamorphic-dehydration reaction is expected to generate about 2 wt% water and amphibolite rocks with *P*-wave velocity of approximately 7 km/s. Our seismological findings derived from the trapped *P*-wave analysis is very consistent with these results from mentioned geochemical studies.

The present simulations were conducted in 2D space and effects of 3D structures were not taken into account. To confirm the effects of model dimension, we additionally conducted 3D FDM simulation of seismic wave propagation. The area of 3D simulation (dotted rectangle in Fig. 1a and 4) covered the area of 81 × 40.5 × 45 km^3 discretized by a uniform grid size of 0.03 km. Significant difference between 2D and 3D (Fig. 5) simulations did not appear, while 3D calculation was limited in very early part of *P* waves.

Simulation result of model A2 reproduced observed frequency-independent onset and peak arrival of trapped *P* waves, while result of model A1 was characterized by seismograms with dispersion and peak delay especially for higher (>4 Hz) frequency bands. However, to examine more quantitative analysis for determining detailed structure of the deeper oceanic crust, such as depth variation, strength of velocity changes, attenuation structures, and differences between *P*- and *S*-wave structures, comparison of 3D calculations and observations should be required. Large-scale computer simulations in full 3D space will resolve such detailed properties of the subducting oceanic crust and dehydration process in the future study.

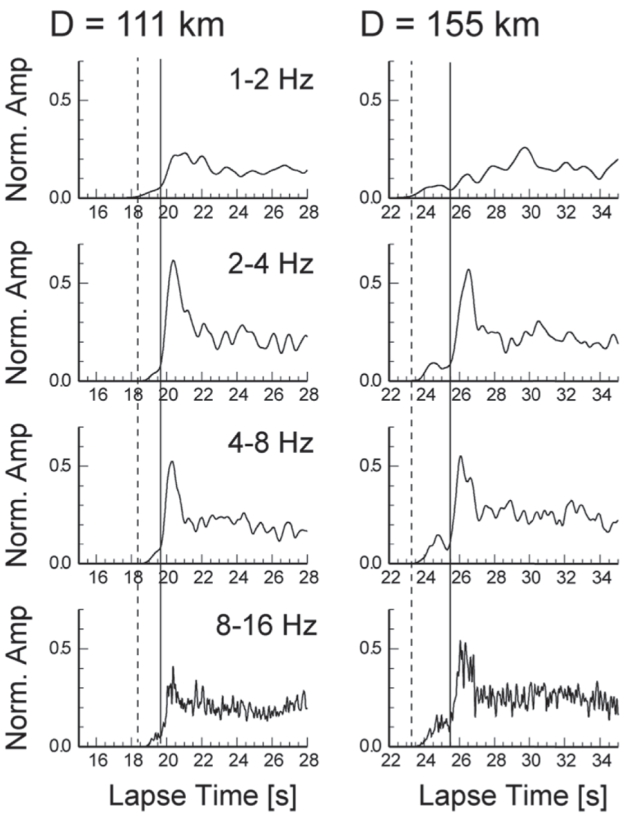

Fig. 6 Simulated RMS envelopes of the vertical component recorded at distances of 111 and 155 km derived from 2D simulations using model A2 with small-scale velocity heterogeneities. Each trace was normalized by its maximum amplitude. The dashed and solid lines in each trace are the onsets of the *P* and trapped *P* waves, respectively.

In our simulations, we did not consider the effects of seismic wave scattering due to small-scale velocity heterogeneities, which have potentials to decrease amplitudes and to delay peak arrivals of high-frequency signals. However, when small-scale velocity heterogeneities of crust and upper mantle were introduced into the simulation model (see Table 4 in Takemura and Yoshimoto (2014) [16] for detail parameters), distinct trapped P waves still remained as seen in observations (Fig. 6). The effects of trapping *P*-wave energy in the oceanic crust are sufficiently strong to preserve its amplitude at longer distances in a medium with small-scale velocity heterogeneities.

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地球シミュレータによる地震動シミュレーションより明らかとなったフィリピン海プレート海洋性地殻第２層における脱水反応による地震波速度の増加

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関東下に沈み込むフィリピン海プレートの海洋性地殻の構造を詳細に調べるため、高感度地震観測網 Hi-net で得られた関東下のフィリピン海プレートの海洋性地殻で発生した地震のトラップ P 波の性質を調べた。その結果、周波数によらず、直達 P 波の数秒後にピーク遅延や分散を伴わないパルス的なトラップ P 波が観測される。この観測を踏まえ、現実的な地震波速度構造モデルを含んだ地震動シミュレーションと観測記録の比較から、海洋性地殻第 2 層の地震波速度が深さ 30-40 km における脱水反応により増加し、深さ 40 km 以深においてほぼ一様な構造となることを明らかにした。分散およびピーク遅延をともなわないトラップ P 波の成因は深さ 40 km 以深で海洋性地殻が均質な構造をしており、効率的に P 波がトラップされたためと考えられる。

キーワード: フィリピン海プレート, 海洋性地殻, 脱水反応, 地震波動伝播, 計算地震学