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Significance of sediment reverberations on receiver functions of broadband OBS data: Comments on *Olugboji et al.* [2016] "Nature of the Seismic Lithosphere-Asthenosphere Boundary within Normal Oceanic Mantle from High-Resolution Receiver Functions"

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The significance of sediment layer (and also water layer) reverberations in seismic observation in the ocean is well recognized, and it has been one of the most challenging factors that hamper investigating deeper crustal and mantle structures [e.g., *Godin and Chapman*, 1999; *Zeldenrust and Stephen*, 2000; *Ball et al.*, 2014; *Ruan et al.*, 2014; *Bell et al.*, 2015; *Abe and Kawakatsu*, 2015; *Audet*, 2016]. *Olugboji et al.* [2016] (hereafter

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denoted as OPKS16) has recently, however, reported in this journal about their receiver function analyses of OBS data without considering this effect, and discussed about the nature of the seismic LAB beneath the ocean. While such an attempt is generally a welcome one to promote OBS related research, there is some concern about how the sediment reverberations might affect their results. This is a short comment on their analyses to draw attention of potential OBS data users to consider and recognize the significant effect of the sediment layer reverberations on OBS data.

The OBS data used in OPKS16 are from the Stagnant Slab Project [*Fukao et al.*, 2009] in which Japanese researchers deployed broadband ocean bottom seismometers (BBOBSs) in the Philippine Sea [e.g., *Isse et al.*, 2009; *Takeo et al.*, 2013]. Figure 1 shows P-wave spectra of three component seismograms at a station T06, for which OPKS16 shows their analysis result in their Figure 5. Spectra are calculated for 200-sec long seismograms that begin at 50 sec before P-wave arrivals. Horizontal seismograms are rotated into radial and transverse components, and spectra are averaged for about 50 events ($M_w > 6.0$) that occurred between November, 2006 and October, 2007. The dominance of horizontal components (especially the radial component) can be seen. It should be also noted that horizontal component spectra show distinct peaks at $\sim$0.2 Hz, $\sim$0.4-0.5 Hz, $\sim$0.8 Hz, etc. that are due to reverberations of nearly-vertically traveling S-waves in the sediment layer. It is possible to constrain the structure of the sediment layer by using this information [e.g., *Godin and Chapman*, 1999; *Zeldenrust and Stephen*, 2000; *Abe and Kawakatsu*, 2015], but here we just use the frequency 0.2Hz of the fundamental resonance to obtain a rough estimate of the S-wave speed of 240 m/s for an assumed thickness 300 m of the sediment layer (there is a trade-off between these two parameters).

Synthetic receiver functions (RFs) are calculated for such a sediment layer structure, and shown in Figure 2 (detailed characteristics of the effect of sediment reverberations to the RF analysis will be presented elsewhere [e.g., *Abe and Kawakatsu*, 2015; *Audet*, 2016]. Synthetic seismograms (with a slowness of 0.058 s/km) are calculated for a structure with a water layer (∼4600m thick for T06) plus the sediment layer (Vp=1600m/s, Vs=240m/s) over a half space (Vp=8180m/s, Vs=4720m/s) and for a structure with an additional crust layer (Vp=6780m/s, Vs=3660m/s, 6km thick) just above the half space. The extremely low Vs (i.e., high poisson ratio) is a general feature of marine sediment [e.g., *Hamilton*, 1971; *Shinohara et al.*, 2008]. In addition, to compare with a potential LAB signal, a discontinuity structure with a velocity reduction (10% in Vs) at a depth of 50km from the sea floor is modeled. The receiver is located on the top of the sediment layer to mimic the OBS observation situation. Although individual synthetic seismograms are not presented here, reverberations in the sediment and water layers dominate radial and vertical component seismograms, respectively, even for the case with a crustal layer. This indicates that RFs obtained from radial and vertical component seismograms are also dominated by the effect of reverberations. RFs are estimated by the spectral division (radial over vertical) with a water level of 0.01 (a low-pass Gaussian filter with a parameter $\alpha = 3$ is applied to mimic OPKS16's analyses).

Obtained RFs show a consistent pattern that has a positive peak at about 1 sec followed by a negative peak at about 3 sec later. The initial positive peak is due to the P-to-S converted phase at the bottom of the sediment layer. Because of the extremely slow S-wave speed in the sediment, this wave travels almost vertically to cause a large motion in the horizontal component to dominate it (as also seen in Figure 1). The direct P-wave is quite weak in the horizontal component for a similar reason. As a result, the initial part of the radial component is dominated by the P-to-S converted wave and its reverberation phases. The second negative phase in RFs observed at about 3-sec after the initial positive one is due to the first reverberation within the sediment layer, which will be followed by later reverberations in a similar fashion for some time to mask many possible crustal and mantle signatures; thus it is essential to model the effect of the sediment reverberation, as well as that of the water layer to discuss structure further below. Note that the "LAB signal" is hidden in the bottom figures in each panel of Figure 2 at about 6 sec (and later).

The aforementioned characteristics of the sediment layer reverberation in RF waveforms can be observed in OPKS16's analyses in their Figure S2 where they show radial RFs (labeled as "without LQT rotation" on the right panel B). Here we reproduce the figure as Figure 3.[1] In bottom right of Figure 3 squared by pink color, the largest positive peak just before 2-sec and the largest negative phase 3-sec later resemble the pattern that the sediment RFs predict (Figure 2). This indicates that the sediment reverberations are likely affecting the observed RFs in OPKS16. In the left panel of Figure 3 with the LQT rotation, RFs somehow become much cleaner, and positive peaks are all located at around zero time. Considering that the LQT rotation is nothing but a coordinate rotation from Z(vertical)/R(radial) to L(P-polarization)/Q(SV-polarization), it is not obvious how the LQT rotation makes such a drastic change in RFs. For example, why the amplitude of Q-RF (left panel of A) at zero time is not close to zero as expected for the Q-component which is perpendicular to the incident P-wave particle motion direction (i.e., L)? Also the transverse component energies (right panel of A and B), which might represent signals due to structural anisotropy, are almost completely removed after the LQT rotation, which seems rather unusual as the difference of the transverse component in two panels is whether deconvolution is done by L (in A) or Z (in B). Furthermore, the Q components show acausal energies, symmetric around the zero lag time, almost like an autocorrelation. Some explanation seems necessary.[2] The resulting stacked RF for the station T06 in bottom left of Figure 3, anyhow, shows a notable resemblance to those predicted by the sediment reverberation seen in Figure 2 except for a time shift. Some clarification by the authors seems to be needed. We suspect that this may not be just a coincidence and that the resultant RF may somehow reflect the effect of the sediment layer reverberations, which should not be interpreted as a signature from a deeper structure.

Comment on the rotation from vertical-radial coordinate to LQ coordinate for OBS data

We consider this should be avoided for P-RF analyses using OBS data [e.g., *Kumar et al.*, 2011; *Audet*, 2016]. This is because horizontal component and the vertical component records are severely affected by the signal (incoming P-wave) generated sediment-layer and water-layer reverberations, respectively. As far as we deal with them separately, there is a possibility of modeling their effects; but once we mix them together via LQ-rotation, it seems almost impossible to model them, and the deconvolution inherent of the RF analysis make it worse. Without modeling them, it seems impossible to discuss the detail of the deeper structure.

Comments on OPKS16

We hope that the significance of sediment layer reverberations for the RF analysis of OBS data has become clear, and their presence in the OBS data analyzed by OPKS16 is recognized. As to comments on *Olugboji et al.* [2016], we suggest that the following points should be considered seriously and further addressed by the authors.

1. The effect of sediment layer reverberations should be estimated and modeled first in the original horizontal component seismograms for each station.

2. The effect of sediment layer reverberations should be then incorporated in both RF analyses and waveform modeling. The effect not only affects the initial part of RFs but also the later part, as the reverberations are sustained, which makes modeling for deeper structure very challenging.

3. Although it is better to use the vertical-radial coordinate, if the authors prefer the LQT coordinate, figures like OPKS16's Figure S2 (Figure 3 here) should be shown for all the analyzed stations so that readers can judge the quality of RFs and the effect of sediment reverberations on RF waveforms. In this case, it seems that the authors need to explain how the LQT rotation cleans up RFs that allows them to make further interpretation. Also all the LQ-rotated RFs should be labeled so, instead of being labeled "radial" as seems to be now. Further how the rotation itself is conducted (e.g., how the angles between the vertical and L/Q directions are determined) should be described.

4. Until all above are incorporated in the analyses, further discussions on the deeper structure seem rather premature.

Acknowledgments. The first author (HK) had provided the data used in OPKS16 and had an opportunity of reading early versions of OPKS16 some time between around October, 2014 and March, 2015; he had made comments to the authors about the significance of the sediment layer reverberations. Unfortunately, these comments were not taken into consideration by the authors, and HK feels obliged to make this comment in public. The

significant effect of sediment reverberations on OBS RFs deserves proper and careful treatment, and we hope that this comment serves as a reminder in future analyses. We thank an anonymous reviewer for constructive comments on the manuscript. The BBOBS records of the Stagnant Slab Project are distributed by Pacific21 (http://p21.jamstec.go.jp/). Any additional data may be obtained from the corresponding author (H. Kawakatsu, hitosi@eri.u-tokyo.ac.jp).

Notes

1. It should be also noticed that the almost all RFs shown in OPKS16 are likely to be those with the LQT rotation, even though they are labeled as "radial" (e.g., Figures 5, 7, 9, 11, and many in the Supporting Information file); the vertical-radial to LQ coordinate rotation is better to be avoided in the RF analysis of OBS records as will be discussed later separately.

2. It is also not clear how the rotation itself is conducted (what is the reference model for it? etc.)

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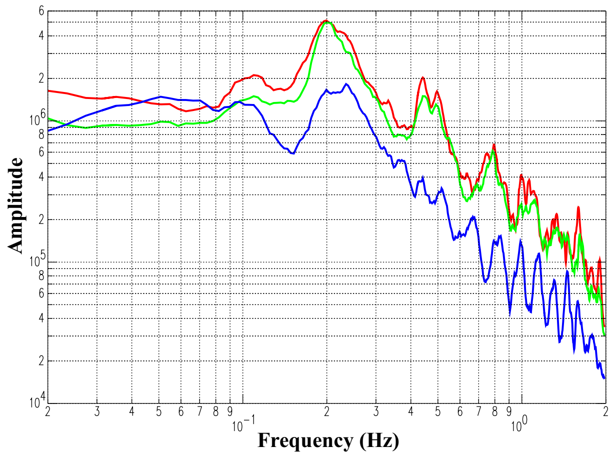

Figure 1. P-wave velocity spectra at station T06. Vertical (blue), radial (red) and transverse (green) component spectra are shown.

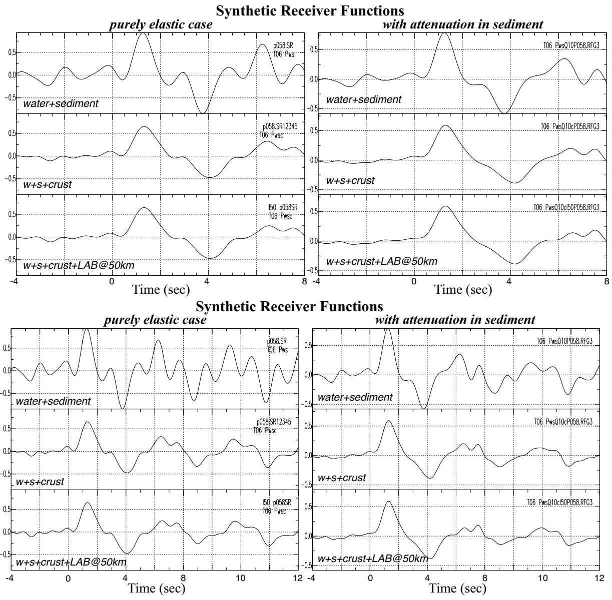

Figure 2. Two panels show the same synthetic radial RFs for station T06 with water and sediment layers over a half space (top), with an additional crust just above the half space (middle), and with an additional LAB structure (a velocity reduction of 10% at 50km from the sea floor) (bottom). RFs of a purely elastic case are shown on left, and those with inelastic sediment layer ($Q_s = 10$) are shown on right. The upper panel shows for a time window comparable to that of Figure 3, and the lower one for a longer time window to appreciate the reverberation effect. Note the consistent pattern of a positive phase at around 1-sec, followed by a negative phase 3-sec later. The exact timing of phases depends on the detail of the sediment structure, but the pattern is expected whenever there is a substantial sediment layer.

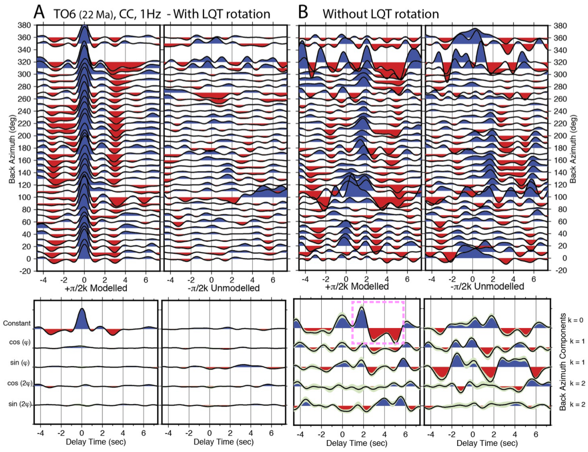

Figure 3. RFs of OPKS16 for station T06 (reproduction of their Figure S2). A box with broken pink lines indicates radial RFs that show the pattern predicted by the sediment reverberations.