The characteristics of body-wave records between forearc and backarc region at the Sumatra subduction zone from deep regional earthquakes

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Abstract. The Sumatra subduction zones have been known to produce large destructive earthquakes and tsunami, such as the 26 December 2004 M9 earthquake at the western offshore of Aceh. This large destructive earthquake usually occurred at the shallow portion of the subduction zone between 10 – 35 km depth, while the intermediate-to-deep earthquake usually occurred at the greater depth, deeper than 65 km along the subduction, which produces small to moderate earthquake with a magnitude between M3-5. Thus, these deep events along the subduction zone usually being neglected. However, the recent study has shown that an anomalous large ground movement associated with a deep earthquake at the subduction zone has been observed along the forearc region while in the backarc or at its epicenter, it remains low. Hence, the characteristics of the body-wave at these regions are different, which could be utilized for hazard mitigation. For this reason, this study aims to identify the body-wave characteristics between the forearc and backarc regions at the Sumatra subduction zone. Several selected deep regional earthquake records with a depth greater than 100 km provided by the Agency for Meteorology, Climatology, and Geophysics of Indonesia (BMKG) were analyzed. The finding indicates that the body-waves recorded in the forearc region are significantly different, with the main characteristics are; 1. Amplitude: preserve high amplitude, 2. Arrival time: shows a delayed signal of P- and S-waves, and 3. Spectral: conserve energy at low to high frequency and shows as a dispersion. These findings suggest that the signal recorded at the forearc region travel within the subducting slab, and the late arrival of the signal indicates that the seismic waves record at forearc travel at the top of the subducting slab, i.e., the oceanic crust, which is having lower velocity to the surrounding mantle.

1. Introduction
The Sumatra subduction zone located at the southwestern of Southeast Asian margin comprises of subduction of the oceanic Australian plate plunge under the continental Sunda plate that stretched over more than 1,200 km long [1] as it is shown in Fig. 1a. This subduction zone has a complete set up of a typical subduction system which is having a trench, forearc ridge, forearc basin, volcanic arc, and backarc basin, especially at the forearc ridge region, the Sumatra subduction system has a forearc island chain (Fig. 1b), where only limited numbers of subduction system have such features [1,2].

This subduction system has been known to produce large destructive earthquakes and tsunami such as the 26 December 2004 M9, which claimed as the worst natural disaster ever recorded in modern human history with more than 283,000 victims [3,4]. Such large destructive earthquakes mostly
occurred at the plate interface, and its epicenters are located between the trench – forearc ridge – forearc basin region at a shallow depth of the subduction processes [5]. The intermediate – deep earthquakes along this subduction zone occurred at the subduction interface, and intraslab with its epicenters are located between the forearc basin – backarc basin region, which most of them, has magnitude ranging between 3-5 or small to moderate earthquake (Fig. 1b), although a number of large earthquakes 7 ≤ M < 8 had happened at the southern portion of subduction zone or southern Sumatra with a depth between 500 – 600 km. The seismicity along this subduction zone dominates by the shallow depth earthquake and shows a clear Benioff seismicity distribution that reaches to the depth of more than 500 km [6–10] as it is seen in Fig. 1c. Thus, the intermediate – deep earthquake often being neglected.

Although the intermediate-deep earthquakes mostly generate small to moderate magnitude, recent studies have shown that an anomalous large ground movement associated with those earthquakes was observed at the forearc region while at its epicenter, which is located at the backarc region, remain low [11–13]. Not only showed large ground movement at the forearc region, but most of the intermediate-deep earthquake body-wave signals were also found to be delayed compared to the backarc receiving regional stations along the subduction zone [14, 15]. In the spectral domain, the intermediate-deep earthquake body-wave signal that received at the forearc region shows preserving the energy at low to high frequency, which shown as a dispersed signal, while the signal that received at the backarc region only sustain the low-frequency energy whereas the energy at higher frequency were found attenuate [12, 16–18]. These intriguing findings showed that the body-wave signal of an intermediate-deep regional earthquake received along the forearc region has an obvious characteristic compare to the signal received at the other region along the subduction zone.

Figure 1. (a) The Sumatra subduction zone located at the southwestern margin of Southeast Asian, where the Australian oceanic plate plunge under the Sunda continental plate with motion varies from the north to the south. The slab 2.0 [19] contours are colored at a particular depth, as it is shown in the information. The brown rectangle shows the study area, and the colored circle indicates the deep regional events used in this study, as shown in (b) and its cross-section transect, as shown in (c). (b) The rotated map of the study area shows the good coverage of the seismic station operated by the BMKG of Indonesia. The triangle symbols indicate the seismic stations operated by the BMKG, where selected stations, the triangle with green and red lines, indicate the forearc and backarc stations used in this study, respectively. (c) A clear Benioff zone seismicity that reaches to the depth of more than 200 km. The rainbow-colored circle indicates the selected intermediate-deep regional earthquake events used in this study, while the other high-resolution earthquake events are from [5].

There are numbers of factors that contribute to the body-waves signal which received at the forearc region shows such characteristics, several factors not limited to such as; the magnitude of an earthquake, receiver geometries, hypocenter location within the subducting slab, subducting slab characteristic, and subducting slab geometry [12, 17]. The broadband seismic station managed and maintained by the
Agency for Meteorology, Climatology, and Geophysics (BMKG) of Indonesia has its stations distributed and well covered the Sumatra subduction zone, resulting in a high spatial and temporal resolution of regional earthquakes recording as well as produces its definitive earthquake catalog [5]. By making use of the unique distribution of the receiving stations at the Sumatra subduction zone located at the forearc, which seated at 20 km above the plate interface, it may help us to understand the body-wave characteristics from the regional intermediate-deep earthquake, and this information is considered important for the hazard mitigation.

This study aims to identify the body-wave characteristics from the deep regional earthquake between the forearc and backarc receiving stations at the Sumatra subduction zone. Selected regional deep events and its recording station are being analyzed for their amplitude, arrival time, and spectral properties.

2. Regional intermediate-deep earthquake data

In this study, selected intermediate-deep regional earthquakes and its recording stations at forearc and backarc regions are being analyzed. The broadband seismometer operated by the BMKG has its sampling rate at 20 samples per second and has its flat response between 10⁻¹ Hz until its corner at 10¹ Hz. The analyzed signals were from 31 December 2013 to 13 July 2018, with earthquake magnitude ranging from 3 to 5.5 (avoid the complex source at larger magnitude) and depth between 100 to 350 km, reported by the BMKG.

Based on the regional earthquake catalog released by the BMKG, a total of 83 events following the criteria mentioned above and distributed along the margin, 30 events from those were analyzed. The seismograms were cut based on the origin time of the regional catalog to 10 minutes, and then the signals were deconvolved with its respective instrument response to displacement using the transfer function in the Seismic Analysis Code (SAC) [20, 21]. For having a clear detection of the S-wave signal, the two horizontal components of East-West and North-South were rotated to Great Circle Path (GCP) as the Radial and Transverse components. Then, manual picking of P- and S-wave throughout all selected events are performed. Table 1 shows the regional deep earthquake catalog from the BMKG analyzed in this study, with signal characteristics shown as A: amplitude which has a value of + and –, meaning as larger and smaller, respectively; AT: arrival time, which has value as +, -, and N, meaning earlier, later and normal, respectively; Sp: spectral which has value as A and D, meaning attenuation and dispersion, respectively.

| No. | Date (dd/mm/yyyy) | Origin Time | Mag. | Long. (dd.dd) | Lat. (dd.dd) | Depth (km) | Signal Characteristic Forearc | Signal Characteristic Backarc |
|-----|-------------------|-------------|------|--------------|-------------|------------|-----------------------------|-----------------------------|
| 1   | 31/12/2013        | 20:24:03    | 3.4  | 98.94        | 2.39        | 129        | D                          | N                          |
| 2   | 15/03/2014        | 10:58:46    | 5.2  | 98.99        | 2.76        | 170        | D                          | D                          |
| 3   | 16/07/2014        | 02:17:32    | 4.6  | 98.92        | 2.36        | 147        | D                          | D                          |
| 4   | 28/07/2014        | 22:02:34    | 4.4  | 99.74        | 0.38        | 150        | D                          | D                          |
| 5   | 03/08/2014        | 21:45:09    | 4.3  | 98.91        | 2.37        | 140        | D                          | D                          |
| 6   | 08/08/2014        | 16:57:01    | 4.6  | 98.98        | 2.38        | 156        | D                          | D                          |
| 7   | 05/09/2014        | 11:20:03    | 4.4  | 98.98        | 1.61        | 116        | D                          | D                          |
| 8   | 07/09/2014        | 18:13:29    | 4.3  | 98.98        | 2.01        | 129        | D                          | A                          |
| 9   | 08/09/2014        | 19:07:01    | 4.7  | 99.93        | 1.01        | 199        | D                          | D                          |
| 10  | 19/04/2015        | 18:40:26    | 5.1  | 99.01        | 1.86        | 126        | D                          | D                          |
| 11  | 17/06/2015        | 07:42:57    | 4.8  | 98.90        | 1.55        | 101        | D                          | D                          |
| 12  | 21/10/2015        | 21:04:31    | 4.6  | 98.94        | 2.34        | 156        | D                          | D                          |
| 13  | 07/12/2015        | 16:26:57    | 4.2  | 99.03        | 2.43        | 158        | D                          | N                          |
| 14  | 02/04/2016        | 18:16:42    | 4.5  | 98.89        | 1.81        | 123        | D                          | D                          |
| 15  | 02/01/2017        | 14:03:55    | 4.4  | 99.00        | 1.88        | 118        | D                          | D                          |
| 16  | 27/02/2017        | 11:47:26    | 4.5  | 99.35        | 1.71        | 175        | D                          | D                          |
### 3. Observation of body-wave signal from the intermediate-deep regional earthquake

#### 3.1. Seismogram amplitude characteristic

To compare the amplitude characteristic between two signals, in this study, we briefly cut the signal at 5 seconds before and after the P- and S-wave arrival based on the manual pick, a 10 seconds signal is analyzed to compare the amplitude, and it is shown in Fig. 2 (only shown for the P-wave).

The amplitude characteristic of the analyzed signals indicates that all records along the forearc observed higher amplitude, as it is shown in Table 1. Fig. 2 shows the amplitude comparison of an intermediate-deep earthquake record at two stations; one at forearc and the other at backarc. It is clearly seen an obvious large amplitude is observed at the forearc station while the backarc stations showed a small amplitude.

![Amplitude Comparison](image)

**Figure 2.** Displacement amplitude comparison of an event on 3 August 2014 M 4.3 at 140 km depth. The P-wave arrivals are set at 5 seconds for both signals. The forearc station GSI showed a significantly higher amplitude than the backarc station MNSI, while their distance to the source is almost similar: 189.58 km and 189.39 km, respectively.

#### 3.2. Arrival time characteristic

The arrival time of the body-wave signal at the forearc stations from the intermediate-deep regional earthquake was delayed compared to the body-wave signal at backarc stations. Fig. 3 shows that the signals that arrive at the forearc stations are delayed, while the backarc signal arrived according to the expected velocity.
Although the signals at forearc are observed delayed, the amplitude of these signals is observed preserved (Fig. 2 and 3). Thus, it must be travel through a media which is good quality or high Q, while having a lower velocity to the surrounding mantle.

![Figure 3. A Normal Move Out (NMO) with an apparent velocity of 7.9 km/s being applied to the Signal Stacking Subprocess (SSS) records of a deep regional earthquake on 2 April 2016 M 4.5 at a depth of 123 km. The y-axis is shown the time in second (s), the bottom x-axis is shown the distance in (km) while the top x-axis shown the station name with ticks indicate its distance to the source. The P-wave arrival of forearc and backarc stations are shown with blue and red arrows, respectively.](image)

3.3. Spectrogram characteristic

To have a complete analysis of the signal spectrum from the intermediate-deep earthquake in time and frequency domain, the 10 seconds body-wave signal, 5 seconds before and after the arrival for both P- and S-wave, were narrow bandpass with 0.5 Hz interval from 0.5 – 10 Hz. The Hilbert transform was performed to these narrow bandpass signals, and then an envelope is produced. The maximum amplitude of the envelopes for each narrow bandpass signal was then used to identify the arrival of maximum energy at each frequency interval. Through these processes, we could identify exactly the maximum energy of each frequency interval as well as its arrival time, which could help us to identify whether the analyzed signal was observed as a dispersion or an attenuation.

Fig. 4 shows that the intermediate-deep earthquake signal recoded at the forearc station displays notable characteristics, such as enriched high-frequency amplitudes. The arrival of each frequencies energy showed a delay of high-frequency energy relative to low-frequency signal about 1 – 3 seconds, as shown in Fig. 4 (a). Focusing on the high-frequency energy was one of the characteristics of a waveguide. On the other hand, the backarc station exhibit low high-frequency content or highly attenuated, sustain in low-frequency energy, and the high-frequency signal arrives earlier relative to the low-frequency signal.

The body-wave signal retrieved at forearc stations from the regional intermediate deep earthquake event exhibit a special characteristic. These characteristics are caused by a waveguide due to the existence of a low-velocity oceanic crust relative to the surrounding mantle at an intermediate depth of the subduction zone [12, 15–18, 22, 23]. This low-velocity oceanic crust that sits on top of the subducting slab act as a channel that facilitates the seismic wave to travel as a waveguide [22]. The dominant frequency of this waveguide is > 2 Hz and in agreement with the waveguide observed along the subduction zone around the world [22, 24, 25]. Thus, if we refer to the crustal model of AK135 [26], we could further estimate the thickness of this low-velocity layer of the oceanic crust, i.e., the AK135 [26] model for the crustal velocity at > 100 km depth is 8.05 km/s, and the dominant frequency that we observed > 2, thus the thickness of the layer could be represented by the velocity divided by the dominant frequency, which will give a thickness of 4 km. The thickness of the oceanic crust as thin as 4 km are in good agreement with other studies in this region [27–29].
Figure 4. 10 seconds of the body-wave signal; 5 seconds before and after the P-wave arrival. The arrival is always set at 5 seconds. The top panel shows the vertical component of a seismogram (BHZ) with the y-axis is the displacement in $10^{-3}$ meter (mm) while the bottom panel shows the spectrogram with the maximum energy at each frequency interval discussed in the text is shown by the ‘+’ sign. The y-axis of the bottom panel is the frequency (Hz), while both panels share the same x-axis, which is time in second (s). The color bar for the spectrogram is shown at the bottom as Power Density Spectral (PSD) in dB.

(a) Signal and spectrogram characteristics of the forearc station in this figure represented by GSI, while (b) for the backarc station represented by PSI.

The existence of the low-velocity layer to the depth of more than 100 km somewhat radical, as the gabbroic oceanic crust should have converted to eclogite at the shallower depth, which indicates that the Sumatra subduction zone exhibit a slow rate of conversion, which might correspond to the existing of a dry eclogite or mix between hydrated at the depth of more than 100 km along with the subduction processes [18, 24, 25].

Fig. 5 (a and b) may illustrate the interpretation of the observed characteristic of intermediate-deep signal records at forearc. A simple model of the Sumatra subduction zone was used to forward model the seismic ray from a source using MacRay [30]. As the model suggests, the earthquake source must be within the low-velocity layer of the oceanic crust, as it is shown in Fig. 5(b), which showed that most of the rays were trapped within that layer (low-velocity or the oceanic crust) and received at the forearc island region. If the source is within the oceanic slab, only limited rays were trapped, and most of them are refracted directly to the surface without spending time in the oceanic crust, thus did not sample the low-velocity layer and the signal arrive accordingly to the velocity model as it is shown in Fig. 3. These interpretations were commonly used to express the delay time of the body-wave signal arrived at the forearc stations [14].

Although the oceanic crust is found to have a lower velocity than the surrounding mantle, it is commonly known as a high quality (Q) material [14], indicating a preserve and focusing high-frequency energy observed at the forearc region. Thus, the characteristic of the ground movement associated with the regional intermediate-deep earthquake in the forearc region should consider these characteristics. In most cases, such as in Japan, Taiwan, Chile, and Alaska have shown that these amplified signals were found destructive and were not implemented in developing the regional ground-motion prediction equations (GMPEs) [11–13, 16, 17].
4. Conclusion

This study has shown a detailed characteristic of the body-wave signal observed at the forearc and backarc region at the Sumatra subduction zone. It is found that three main characteristics distinguish between those signals, i.e., amplitude, travel time, and frequency. The implication of this finding indicates that the existence of a low-velocity layer, presumably the oceanic crust existed at a depth of more than 100 km, which implies a slow conversion rate of the gabbroic oceanic crust to eclogite. This low-velocity layer of the oceanic crust has a thickness of about 4 km thick, and agree with the other subduction zone with similar findings. The enriched high-frequency energy caused by the oceanic crust (low-velocity layer) or a waveguide structure may affect the ground movement distributed at the forearc region anomalously compared to the other region along the subduction zone. Thus, the development of GMPEs at the Sumatra region need to include these characteristics, which will give more precise hazard mitigation for the forearc Islands as well as the Sumatra region. Implementation of the result findings and the development of GMPEs in the Sumatra region could be applied to the other subduction regions worldwide.

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