

# Comparison of crustal and upper mantle heterogeneity in different time periods: Indonesian subduction zone to northern Australia

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**Abstract** Earthquake events from the Indonesian subduction zone recorded in northern Australia show a long and high-frequency coda associated with both P and S waves. Regional events recorded by Warramunga array in northern Australia can separate out wave propagation through the mantle by focusing on the coherent signal across the medium-aperture array. Most of the incoherent wave components result from structures in the vicinity of the array with small-scale lengths of 1–2 km or smaller. The coherent phases with relatively rapid changes in waveforms are associated with the scattering of seismic waves by crustal and mantle heterogeneity, but in some case can be related to structural effects near the source. As the depth of the source increases, the coherent portion of the seismic wavefield tends to become much simpler, which suggests that the heterogeneity tends to weaken at depth with larger-scale length. We compare the coherent signal features of earthquakes from the Indonesian subduction zone that have occurred in recent years with those in the early 1980s, first studied by Kennett (Phys Earth Planet Inter 47: 319–332, 1987). The general characteristics of the coherent signal variation with depth in recent

years are the same as those observed in 1980s, but the variations are larger. This change suggests a stringer variation in heterogeneity with depth than before, which may bear important information about the dynamic processes and evolution of the crust and upper mantle.

**Keywords** Crust · Mantle · Heterogeneity

## 1 Introduction

A notable feature of seismic events along the front of the Indonesia subduction zone recorded at stations in northern Australia is a very long-duration coda with high-frequency content for both P and S waves. Generally, the onsets for both P and S waves show a low frequency ( $f < 0.25$  Hz), followed by large, high-frequency ( $f > 1$  Hz) arrivals. Kennett and Furumura (2008) showed that the frequency of extended coda for both P and S waves is usually greater than 4 Hz. Such records are very common at the Warramunga array (WRA) in northern Australia for events in front of the Banda Arc at about  $13^\circ$  epicentral distance (Kennett 1987), and indeed small Banda earthquakes ( $m_b \sim 3$ ) can be recognized immediately by their high frequency coupled with the time separation between P and S waves (approximately 2 min), even though these events cannot be readily located. Similar characteristics are found for earthquakes in Australia recorded on cratonic paths. The chaotic nature of the seismograms and strong variability between neighboring sites indicate a very strong scattering regime (see Fig. 3 of Kennett 1987). Other examples have been reported for major subduction zones such as the Nazca plate in South America (Snoke et al. 1974; Martin et al. 2003), the Vanuatu region (Chiu et al. 1985), the Cocos plate off Nicaragua (Abers et al. 2003), the Mariana basin (Ouchi 1981), and Pacific plate along the

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eastern seaboard of northern Japan (Iidaka and Mizoue 1991; Abers 2000; Furumura and Kennett 2005), that indicate common features in the heterogeneous structures of the subducted oceanic plate. However, northern Australia is one of the few locations where observations are possible on the plate that is being subducted.

There are several ways to investigate and characterize the heterogeneity in the Earth. The direct way to investigate the properties of the heterogeneity of the Earth is to analyze sonic well logs obtained by deep drilling holes into the Earth (Wu et al. 1994; Holliger 1996; Shiomu et al. 1997). However, this confines us to the knowledge of the uppermost part of the crust. An effective way to study the heterogeneity is to analyze the higher-frequency parts of broad-band seismograms, which bear valuable information about crustal and mantle heterogeneity. Kennett (1987) investigated the effects of crustal and upper mantle heterogeneity using coherent signals for the regional events in Banda Sea and New Guinea recorded at the WRA on 1 Hz seismometers. With the help of 3D numerical simulations, Furumura and Kennett (2005) showed that the anomalously large intensity and very long duration of high-frequency seismic signals recorded on the eastern seaboard of northern Japan from deep Pacific plate earthquake can result from the guiding of high-frequency seismic waves in the heterogeneous subducted plate, due to multiple internal scattering of seismic waves. Kennett and Furumura (2008) demonstrated that the complex patterns of high-frequency wave propagation observed at stations in northern Australia for subduction zones source in the Indonesian arc can be well interpreted by models with distributed stochastic heterogeneity through the lithosphere. Tkalcic et al. (2010) revealed the presence of small-scale heterogeneity in the upper mantle by investigating arrivals of seismic phases reflected from the core–mantle boundary (PcP waves) and those reflected from the inner-core boundary (PKiKP waves) at subcritical angles.

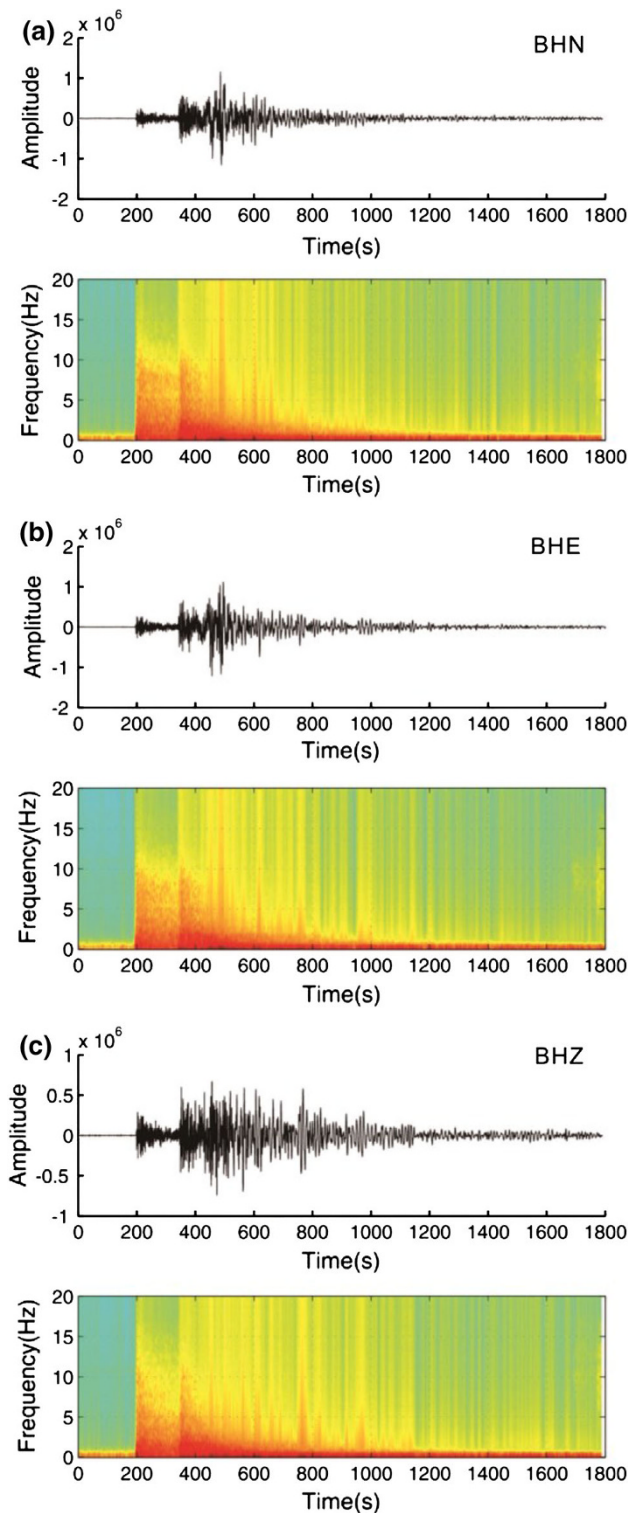
High-frequency arrivals can persist to epicentral distances of 2,000 km or more for paths within cratonic material. One reason is very high intrinsic  $Q$ , so that there is little difference in the frequency content of P and S waves propagating for a long distance from the subduction zone. Utsu (1966) firstly explained the cause of the anomalous intensity pattern in Japan using a model of the structure beneath northern Japan with a high  $Q$  dipping seismic layer and a low  $Q$  upper mantle above the seismic layer. Another reason is internal scattering from fluctuations in the elastic parameters inside the subducting plate, a new model proposed by Furumura and Kennett (2005), who showed a model of the subducting plate described by stochastic heterogeneity of P- and S-wave velocity and density. The proposed correlation length for the downdip direction along the subducting plate is much longer (10 km) than that in

thickness (0.5 km). The numerical simulations demonstrated that such elongated scatters inside the dipping plate can act as an efficient waveguide for higher-frequency seismic waves with a long coda generated by multiple scattering. Kennett and Furumura (2008) made use of similar ideas and from a suite of numerical simulations concluded that the strong internal scattering of seismic signals within the thick continental lithosphere is the main cause for the high-frequency stochastic waveguide in the Australian lithosphere and is helped by the high intrinsic  $Q$  value in continental structure.

Kennett (1987) analyzed short-period seismograms at far regional distances and inferred that the scale length of heterogeneity becomes larger as the depth increases. This result suggests that the crustal and upper mantle heterogeneity becomes weaker at greater depth. For the regional events from Banda Sea recorded at WRA, there is a progressive change in the features of the propagation pattern with increasing source depth. Shallow events give relatively complex behavior, while deep events display relatively simple features. We follow the work of Kennett (1987) to investigate the features resulting from stochastic Earth's heterogeneity. In this paper, we first analyze seismograms at different depths from the Banda Sea region by extracting the coherent part of signals and see similar characteristics to Kennett (1987). Borrowing the idea of a time lapse method (Lumley 2001), also known as 4D seismic method in exploration geophysics, we compare seismic events at depth from the same region at Banda Sea at two different periods, the early 1980s and the late 2000s. The main features are the same: (1) long coda wave durations but with high-frequency components; and (2) much more complex propagation pattern for shallow sources. To some extent, the behaviors in late 2010s are much more complicated than in the early 1980s published by Kennett (1987), which may indicate that the significant variations may hide some more important information on dynamic evolution of crustal and upper mantle.

## 2 Observations

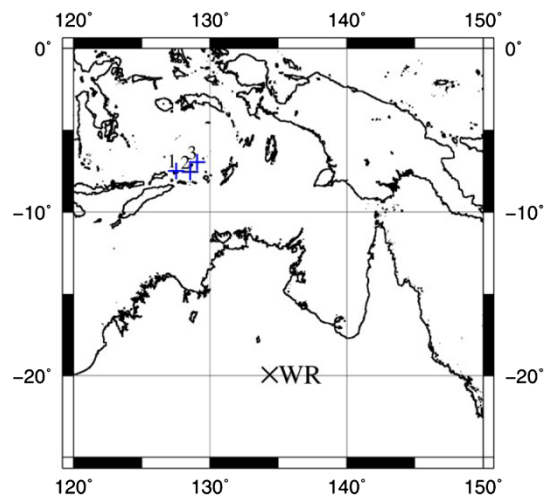
Events recorded by stations over a large aperture network cannot readily be used to study the crustal and mantle structure at the small scale, because the spatial sampling is too sparse to delineate the structure. Individual short-period seismograms usually show such complex seismic records that only prominent phases (e.g., P, S) can be recognized and others have to be identified with the help of the travel time for 1D reference models, such as the preliminary reference Earth model by Dziewonski and Anderson (1981), the IASP91 model of Kennett and Engdahl (1991), and so on.



**Fig. 1** An event in Indonesia recorded by station B1 and its time-frequency analysis: (a) BHN, (b) BHE, and (c) BHZ. The top panel shows the recorded three-component seismograms, and the bottom panel shows its corresponding power spectrum, which shows decay of the high frequency energy for both P and S

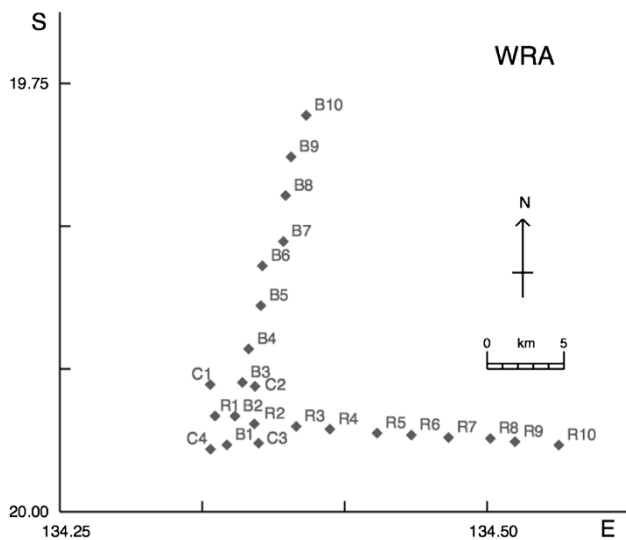
**Table 1** Epicentral information for events used in this and Kennett’s (1987) study

Event No.	Date a-mo-d	Lat. (°S)	Long. (°E)	Depth (km)	$m_b$	Delta (°)	Azimuth (°)
1	2009-10-16	7.57	129.45	35	4.9	13.21	159
2	2011-11-28	7.82	128.38	87.5	4.5	13.39	155
3	2010-10-26	7.58	128.40	191.5	4.7	13.59	156
4	1981-09-02	7.80	128.80	49 ± 14	4.8	13.22	157
5	1981-08-03	7.91	128.22	68 ± 18	4.9	13.35	154
6	1982-04-06	7.49	129.50	182 ± 17	4.6	13.23	159



**Fig. 2** Locations of chosen earthquake events (+) and broad-band stations (X) in the Northern Australia

Complex patterns of high-frequency wave propagation are observed at the stations of the WRA array in northern Australia for sources in the subduction zones of the Indonesian arc. The frequencies can reach 16 Hz for long propagation distance. Figure 1 shows the time–frequency analysis of an event (Event 1—Table 1) recorded at the three-component station WB2 at WRA (See Fig. 2). The short-time Fourier transform method is employed to produce time–frequency spectrum: the window length is 3.2 s, with an overlap of 3 s. In Fig. 1, the upper part of each panel shows the seismic record for a particular component, and the lower part panel shows the time–frequency spectrum. For this event, we have complex wave trains, rich in high-frequency energy (1–10 Hz or greater). Both the P and S codas are rich in high frequencies and sustained for



**Fig. 3** Configuration of the Warramunga Array (WR) with seismometer pits along the northern (B.) and eastern (R.) arms, station WB2 three-component short period recording

several minutes. The long duration is most likely due to 3D structural heterogeneities (Aki 1969; Aki and Chouet 1975; Kennett 1987; Neele and Snieder 1991) (Fig. 2).

The relatively close spacing of the seismometers in the WRA in northern Australia can give an effective local sampling of the wavefield and it is comparatively easy to follow the character of arrivals from receiver to receiver. The configuration of the array is shown in Fig. 3. Since 1999, the array consists of an L-shaped deployment of 19 vertical seismometers and 1 three-component seismometers, with a central cluster of 4 additional stations; previously only 20 vertical short-period seismometers were deployed. The spacing between pits is approximately 2.25 km. The array lies in a region of generally low relief with some rocky outcrops near the center of the array. There is therefore only a modest topographic component to the scattering of a seismic wave incident at the array.

Borrowing the idea of semblance (Neidell and Taner 1971) in association with seismic velocity stacking in exploration geophysics, we can measure multi-channel coherency conveniently. Stacking helps us to enhance coherent signals and suppress incoherent random noise arising from small heterogeneities near the array. Recently, some further methods for signal enhancement have been developed, e.g., the local correction method (Liu et al. 2009). Here, we use the semblance coefficient method to separate coherent signals from incoherent ones, as in the work of Kennett (1987). Before applying the method, we firstly align the peaks of the direct P waves to stack waveforms that are highly similar and then enhance the signal-to-noise ratio. This would avoid stack errors resulting from velocity estimation. The semblance coefficient is defined by

$$s(t) = \frac{\left[ \sum_{j=0}^{n-1} q(t,j) \right]^2}{n \sum_{j=0}^{n-1} q^2(t,j)}, \quad (1)$$

where  $n$  is the number of traces and  $q(t, j)$  is the amplitude at time  $t$  in the  $j$ th channel. The semblance coefficient is always a positive quantity. It can be considered as the normalized output/input energy ratio, where the output trace is a simple sum of input traces. The semblance with time indicates the strength of the coherent events arriving at the array.

The procedure can be summarized as:

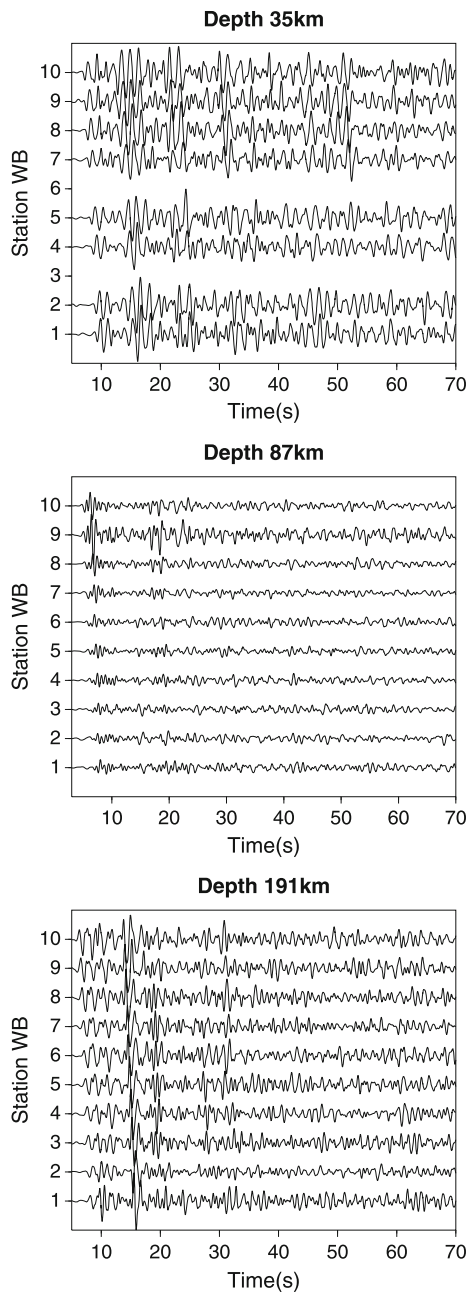
- (1) data preparation, which includes removing instrument response, de-meaning, de-trending and time-domain normalization;
- (2) aligning the peaks of the direct P waves to eliminate the effects of velocity error;
- (3) computing the semblance coefficient according to Eq. 1 within a given time window;
- (4) multiplying the semblance coefficient by every channel.

As a first step, time-domain normalization is used to remove the effects of different magnitudes of different events. The data are normalized by the peak of the first arrivals. The time window length is 0.35 s.

In our study at the WRA in northern Australia, rather obvious variability has been seen between the results for different events and even across the array itself. The opportunity of multi-station recording with quite closely spaced stations (1–2 km) allows us to use the signal-processing techniques to enhance the coherent part of the wavefield. Each station now has a high-gain, broad-band, vertical component sensor, and records at the sampling interval of 0.025 s. To reduce the effects of differing source functions and instrument responses and errors in earthquake depths and origin time, we perform the data processing described above. After these processing steps, we can study the influence of a variety of scales of Earth heterogeneities, from correlation lengths less than 2 km to features of a similar scale to the aperture of the array.

For the medium-aperture WRA array, we have a number of observations in a relatively small zone and are able to compare the coherent and incoherent portions of the wavefield as it traverses the array. The major source of the incoherent energy appears to be signal-generated seismic noise arising from small-scale structures in the vicinity of the array. The close spacing of the sensors (around 2 km) means that such scattering must arise at smaller scales than the pit spacing. The behavior of the more coherent part of the seismic records can provide valuable information on the character of the seismic parameter distribution in the mantle. We show that, for regional events in the Banda Sea

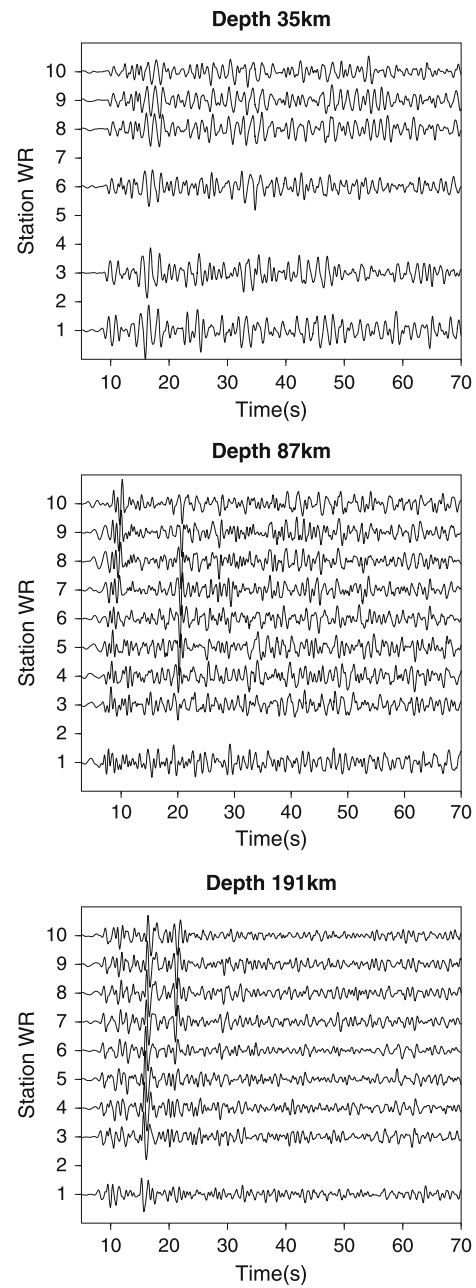




**Fig. 4** Broad-band filtered seismograms at the WB arm of WRA stations shown in Fig. 1. About 1 minute around the onset is shown. A band-pass Butterworth filter of 0.5–2 Hz with two poles is applied

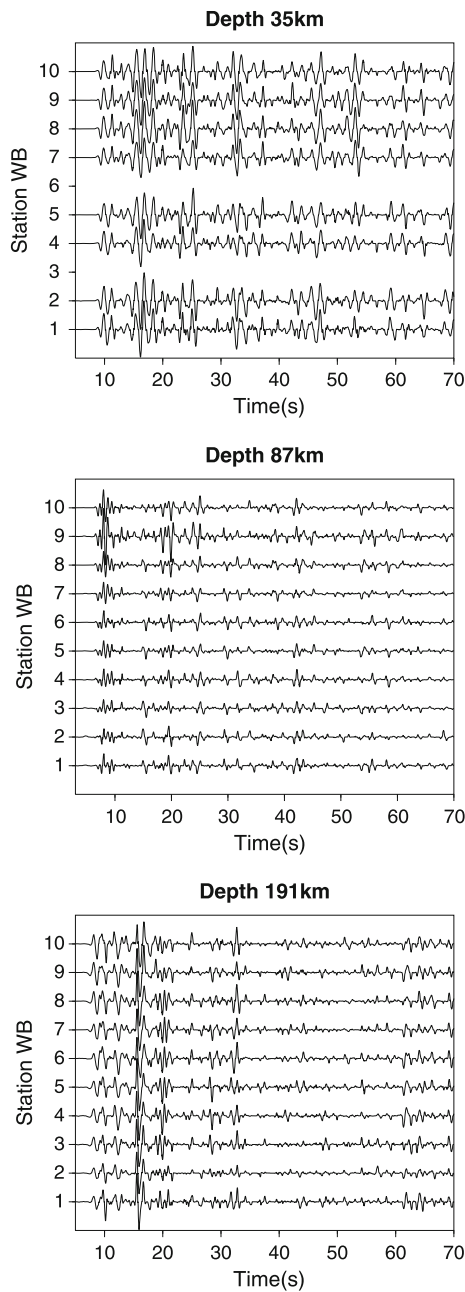
recorded at the WRA, there is a progressive change in the character of the propagation pattern with increasing source depth. Shallow events give relatively complex behavior, while deep events show much simpler behavior than shallow events.

The group of events used lie on the southern side of the Banda Sea arc to the east of Timor. The depth of the events in a similar location ranges from 30 to 200 km (see Table 1 events 1–3). All the sources are well located, with



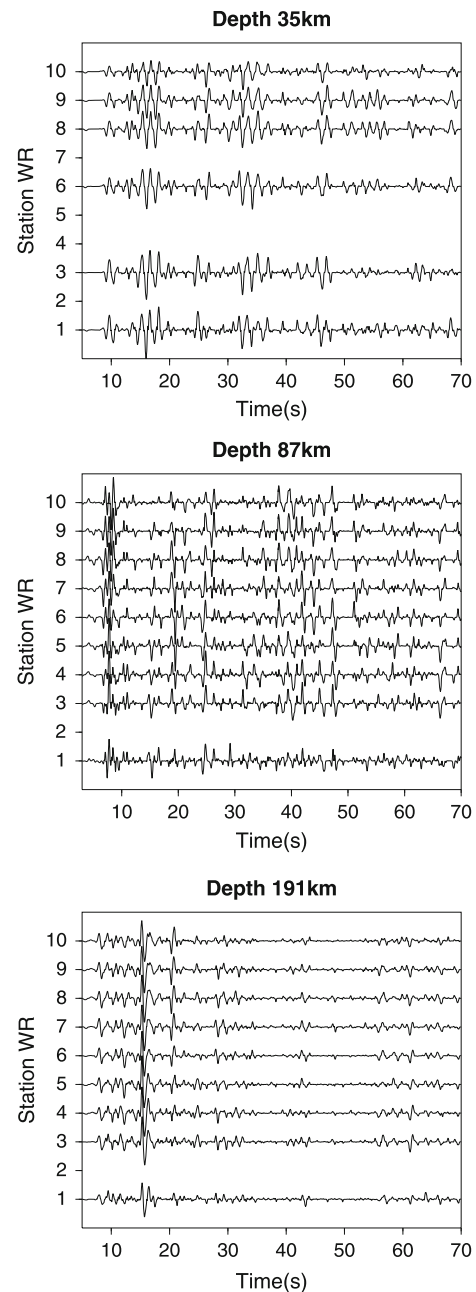
**Fig. 5** Broad-band filtered seismograms at the WR arm of WRA stations shown in Fig. 1. About 1 minute around the onset is shown. A band-pass Butterworth filter of 0.5–2 Hz with two poles is applied

magnitude of 5 or greater. Figure 4 displays the recorded P-signals from the northern WB arm of the array for about 1 min from the onset of the three events. Complex wave trains with high-frequency energy (1 Hz or higher) are observed for each of these events, although the crustal event 1 is not as rich in high-frequency content. The P codas last for minutes and vary noticeably from trace to trace. The coda amplitudes decline rapidly as the focal depth of the events increasing.



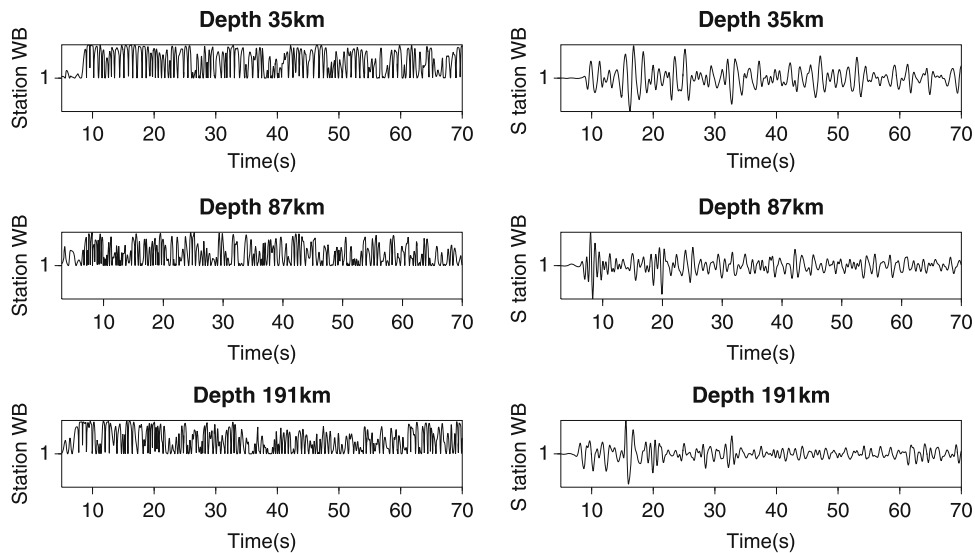
**Fig. 6** Semblance-enhanced traces for the WB arm of WRA for Banda Sea events shown in Fig. 4. The traces in each window are aligned on the picked first arrival times with the reference station WB1

In Fig. 5, we show the recorded P-signals from the eastern WR arm of the array for about 1 min from the onset of the three events. Once again we observe complex wave trains with high-frequency energy (1 Hz or higher) for each of these events, same as the ones observed by WB stations. The P codas last for minutes, and vary obviously from trace to trace. The coda amplitudes decline rapidly as the focal

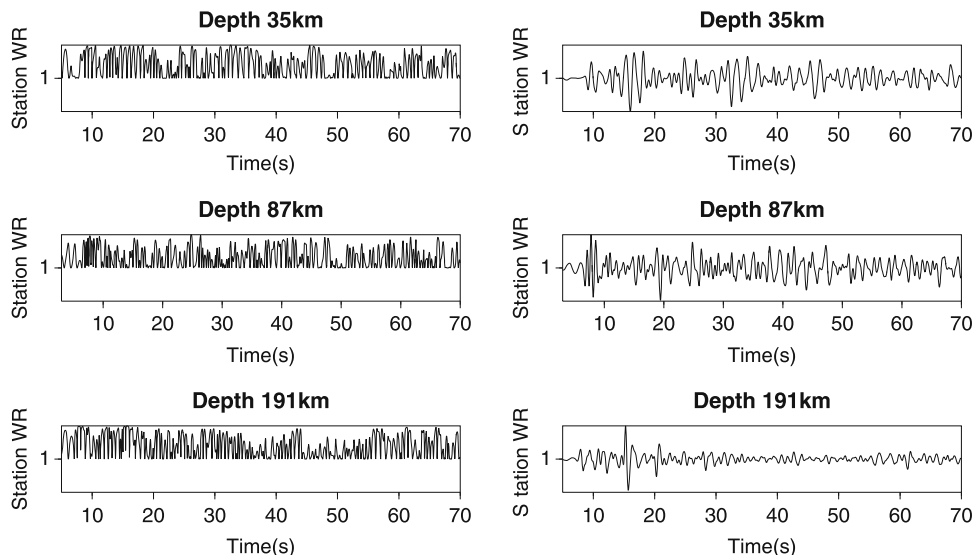


**Fig. 7** Semblance-enhanced traces for the WR arm of WRA for Banda Sea events shown in Fig. 4. The traces in each window are aligned on the picked first arrival times with the reference station WR1

depth of the events increases. The same phenomena for Banda Sea events were first reported by Kennett (1987). In both Figs. 4 and 5, the shallowest event 1 shows a slow decline in the amplitude of the P-wave coda, but close inspection of the seismograms (in Figs. 4, 5) reveals the presence of an underlying pattern of arrivals crossing the array. These phases are masked by a substantial chaotic



**Fig. 8** The semblance coefficients (*left panel*) and the semblance-enhanced trace after stacking (*right panel*) for the WR arm of WRA for semblance-enhanced events shown in Fig. 6



**Fig. 9** The semblance coefficients (*left panel*) and the semblance-enhanced trace after stacking (*right panel*) for the WR arm of WRA for semblance-enhanced events shown in Fig. 7

component, which varies strongly from trace to trace. The signals of events 2 and 3 contain much more high-frequency content than those of event 1.

An effective way of enhancing the coherent parts of the signal at an array is to modulate the stack traces with the semblance calculated for arrivals with a slowness characteristic of the appropriate phase from the source. In Figs. 6 and 7, we present the semblance-enhanced traces from the full WRA array for the seismic vents shown in Figs. 4 and 5. The semblance coefficients for both WB and WR arms are given in the left panels of Figs. 8 and 9, respectively. Correspondingly, the semblance stacking traces are also displayed in the right panels of Figs. 8 and 9 for WB and

WR stations. A striking feature of Fig. 6 is the increasing simplicity of the coherent energy with increasing focal depth. A similar example for such Banda Sea events was reported by Kennett (1987). Compared with Fig. 4, the later phases for event 1 emerge more clearly in Fig. 6. The general character of the enhanced section for event 1 shows a sequence of coherent events, but with more evident lower frequencies. The wavetrain arriving at the array contains numerous arrivals associated with surface reflections and multiples in the crust and uppermost mantle. For events 2 and 3, the enhanced record sections display much simpler features than that for event 1. Event 2 shows a very weak initial P onset, but then builds to significant amplitude. The

most prominent feature is the second arrival around 10 s after the first arrival. This suggests that we have captured the interference of retrograde and prograde branches of the arrivals from the 410 km discontinuity. As the depth of source increases, the coherent portion of the seismic field tends to become simpler, which suggests that the scale length of the heterogeneity is larger at depth.

We also observe separation of low- and high-frequency components in the waveforms. In Figs. 4 and 5, the seismograms show a low-frequency ( $f < 0.25$  Hz) onset followed by a large-amplitude high-frequency ( $f > 1$  Hz) signal. Similar examples have been reported in a number of other studies in strongly scattering environments (e.g., Iidaka and Mizoue 1991; Abers 2000; Furumura and Kennett 2005; Kennett and Furumura 2008). For subduction zones several studies have explained the feature as the trapping of waves in the waveguide formed by the thin, low wave speed zone corresponding to the former oceanic crust at the top of the plate (Abers 2000; Abers et al. 2003; Martin et al. 2003). However, the direct application of such a guided model to the observations for deep events (200–500 km) would be difficult because the low wave speed former oceanic layer may not be able to survive beyond a depth of about 110 km (Furumura and Kennett 2005). Some authors (Fuchs and Schulz 1976; Furumura and Kennett 2005; Kennett and Furumura 2008) have considered that such dispersion of the low- and high-frequency signals is produced in the quasi-lamina structure due to the delay of most of the high-frequency part of the P-wave signals due to multiple scattering from the internal heterogeneities, while the low-frequency waves with longer wavelength tunnel through such structures to behave like a refracted head wave propagating through high-velocity layer.

### 3 Coherent features of seismic events in different periods

During the past decades, thousands of earthquakes have happened in this region because of tectonic activities. The behavior of earthquakes is able to make the interior of the Earth more complex. The comparison of the scale length of the heterogeneity in different periods may help to reveal the dynamic processes and evolutions of the crust and the upper mantle. In this section, we compared two groups of events in different periods in the same region. The two groups of events are from the early 1980s (event 4–6) and the late 2000s (event 1–3), respectively. The depths of three pairs of events are chosen to be roughly same, so that we can compare the scales of the heterogeneities of the Earth at different depths reasonably.

The seismograms and enhance-stacked traces for WB stations for the Banda Sea events 4–6 are displayed in Figs. 3

and 4 of Kennett (1987), respectively. In Fig. 3 of Kennett (1987), seismogram at about 1 min around the P onset is shown. After enhancing the coherent part of signals, seismic phases can be seen more clearly. Figure 4 of Kennett (1987) shows a similar phenomenon as in Figs. 6 and 7. There is increasing simplicity of the coherent part with increasing focal depth. This indicates that the scale length of heterogeneity becomes larger as the focal depth increases.

Borrowing the idea of the time-lapse method extensively applied in geophysical reservoir analysis (Lumley 2001), we can compare the enhanced seismic phases shown in Figs. 6 and 7 and Fig. 4 of Kennett (1987). There is a striking difference in the complexity of coherent phases at the corresponding depth. Both Figs. 6 and 7 show much more complicated coherent phases than in Fig. 9. That is, the events in the late 2000s have much more coherent energy than those in the early 1980s. As firstly pointed out by Kennett (1987), the coherent parts of the seismic signals are related to internal scattering of seismic waves arising from the heterogeneous Earth. Thus, we may conclude that the internal Earth tends to become more complex. Intuitively, this may be due to the active tectonic plate, i.e., frequent earthquakes in this region.

Additionally, the observation of the nature of low-frequency P and S onsets and the length of high-frequency coda can be used to provide a rough estimation of the relative source location and depth in the plate (Furumura and Kennett 2005). Thus, by comparing the features of seismic events in different periods in the same region, we can estimate the depth of the subducting plate in different periods. Further, we may estimate the speed of the subducting plate, which will help us to understand the dynamic processes of the crust and upper mantle.

### 4 Conclusions

In this paper, we first investigate a long and high-frequency coda associated with both P and S waves, shown in seismograms from the Indonesian subduction zone recorded in northern Australia. It is confirmed that the long and high-frequency coda arises from the small-scale length of the Earth's heterogeneity. Applying the semblance method, the coherent signals are separated from the incoherent part. The coherent phases are related to the seismic scattering by the crustal and upper mantle heterogeneities, where the incoherent phases are associated with structures in the vicinity of the array with small-scale length of 1–2 km or smaller. A notable feature is that the coherent phases become simpler as the focal depth increases, which means that the scale length of the Earth's heterogeneity becomes larger. Comparison of the coherent feature in the late 2000s with those in the early 1980s published by Kennett (1987) shows that the general



characteristics of coherent signal variations with depth in the recent several years are the same as those observed in the 1980s. However, the coherent features display much more complexity than those in the 1980s in the same region. This suggests that the scale length of the Earth's heterogeneity becomes smaller. One possible reason is the frequent activity of the tectonic plate. To some extent, this may provide us some information on the dynamic processes and evolution of the crust and upper mantle.

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