Earthquake Depth Phase Extraction With P Wave Autocorrelation Provides Insight Into Mechanisms of Intermediate-Depth Earthquakes

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Abstract  Constraining the mechanism of earthquakes in subduction zones requires adequate estimates of source location and near-source elastic properties. In this study, we propose a P wave autocorrelation-based method to extract depth phase energy from teleseismic earthquakes with moment magnitude down to 4.0. We apply the method to improve location estimates of intermediate-depth earthquakes in the Japan and northern Chile subduction zones, which represent so-called cold and warm slabs, respectively, and which are both marked by double seismic zones. A positive correlation of slab age and double-seismic-zone width validates a thermally controlled model of slab morphology. The negative to normal differential times (and, thus, low or normal Vp/Vs) of the deep parts of the double seismic zones suggest that the intermediate-depth earthquakes considered here are not due to dehydration.

Plain Language Summary  Earthquake depth, which can be obtained by using depth phases, is critical for hazard mitigation and a better understanding of their mechanisms. Most techniques that use depth phases with teleseismic data require large events, even when array-based techniques are used, which limits comprehensive studies of subduction zone seismicity. Here we propose a new autocorrelation-based method to extract depth phase energy from teleseismic data generated by earthquakes with magnitudes as small as Mw 4.0. The application to Japan and northern Chile validates the robustness of the method, and the more precise delineation of the double seismic zones reveals a positive correlation between their widths and the age of the slab when it approaches the trench. Moreover, we find the differential times of sP and pP energy, which are sensitive to the average Vp/Vs between the events and the surface, are different between the upper and the lower layers in the double seismic zone, with the lower layer mostly showing negative to normal values and thus low or normal Vp/Vs. This indicates a lack of water in the lower layer and suggests that other mechanisms are needed to interpret intermediate earthquakes rather than dehydration.

1. Introduction

Since their discovery in the 1920s (Turner, 1922; Wadati, 1928), the mechanism of deep earthquakes remained enigmatic, in part, due to the absence of experimental evidence for rock rupture at high temperature and pressure. Transformational faulting can explain the peak of seismicity around 550 km and the cessation at 700 km (Green, 1995; Houston, 2007) and has been proposed as the likely cause of most deep-focus earthquakes (>300 km). For intermediate-depth (50–300 km) earthquakes, two main mechanisms have been proposed based on experimental, seismological, and geological evidence (Houston, 2007): dehydration embrittlement and thermal shear instability.

Dehydration embrittlement invokes the increase of pore pressure caused by metamorphic reactions (Hacker et al., 2003; Houston, 2007), which decreases effective friction and permits rocks to rupture. Many geophysical observations are consistent with this mechanism, such as pervasive normal faults in the outer rise of trenches that allow water to infiltrate before subduction (Grevemeyer et al., 2007; Ranero et al., 2003, 2005), the positive correlation of seismicity rate and fault density on incoming plates (Boneh et al., 2019; Shillington et al., 2015), thermal-controlled metamorphic dehydration from thermal-chemical modeling (Chen et al., 2019; Kita et al., 2006; Wei et al., 2017), and highly conductive anomalies above intermediate-depth earthquakes imaged using magnetotellurics (Vargas et al., 2019) or very low wavespeed anomalies from guided
waves (Shiina et al., 2013, 2017). Laboratory experiments also show evidence for dehydration-related brittle deformation (Dobson, 2002; Jung et al., 2004, 2009; Okazaki & Hirth, 2016), although cases exist where only slow slip events are observed (Chernak & Hirth, 2011).

An alternative mechanism has been proposed in which the thermal shear instability occurs due to the positive feedback between temperature-dependent viscosity and slip in a localized shear zone (John et al., 2009; Kelemen & Hirth, 2007). Kelemen and Hirth (2007) simulated quasiperiodic instabilities inside localized fine-grained shear zones in their numerical models, with a temperature of 600–800 °C and strain rate of $10^{-15}$ to $10^{-12}$ s$^{-1}$, which correspond well with the conditions of intermediate-depth earthquakes. This is consistent, for instance, with the high temperature during fault failures inferred from the high stress drop and low radiation efficiency of the intermediate-depth earthquakes of the Bucaramanga Nest (Prieto et al., 2013). Besides the numerical and seismic evidence, geological observations of pseudotachylites in subduction zones that are formed by melting during earthquake ruptures also indicate evaluated temperature above the melting points (Deseta et al., 2014; Obata & Karato, 1995; Ueda et al., 2008) and are, thus, consistent with a thermal shear instability mechanism.

Debate continues, however, over which of these mechanisms is active, or predominant, in the intermediate-depth range (e.g., Peacock, 2001; Reynard et al., 2010). To understand the mechanisms of intermediate-depth earthquakes better, accurate source locations and knowledge about elastic properties around the source region are of great importance. In this paper, we propose a new method to extract energy associated with the arrival of seismic depth phases (here, pP and sP) in order to determine earthquake depth more accurately. We also calculate the differential arrival time between sP and pP to characterize the Poisson's ratio around the source region to constrain the effect of dehydration. Similar to Tibuleac (2014) and Audet and Ma (2018), our method relies on autocorrelation to align the P wave, but we adopt a spectral broadening scheme to normalize the contribution of different frequency contents, which turns out to have a critical influence on the final results. Since the arrival time of depth phases changes more slowly with respect to epicentral distance than to depth, we can stack the autocorrelograms coherently with a simple move-out correction, thus greatly increasing the signal-to-noise ratio of depth phase energy by using the abundant distribution of broadband seismic stations at teleseismic distances (that is, $\Delta > 30^\circ$). This allows us to detect and extract depth phase energy from earthquakes that are smaller (down to $M_w 4.0$) than those considered in other array-based studies, which usually require large earthquakes ($M_w > 5.0$) to get a sufficient signal-to-noise ratio (Craig, 2019; Florez & Prieto, 2017). The proposed method, as well as other autocorrelation-based techniques, could be seen as time domain equivalents of the “cepstral” method (e.g., Bonner et al., 2002; Kemerait & Sutton, 1982), which has been used to detected echoes, such as pP and sP, after the first P wave arrival. Our method does not require a large signal-to-noise ratio, however, which makes it suitable for application to teleseismic data and, especially, for relatively small events ($M_w < 5.0$).

In the following sections, we will first introduce the data processing and then illustrate and validate our method with a $M_w 4.5$ intermediate earthquake in northern Chile. We then apply the method to intermediate-depth earthquakes in the Japan and northern Chile subduction zones, which are considered representatives of cold and warm slabs, respectively, and for which decent initial catalogs exist owing to data from local/regional seismic deployments. Finally, we analyze the result in terms of the width of double seismic zones and the relationship between depth phases differential times and discuss the effect of dehydration.

2. Data and Methods

2.1. Data Selection and Processing

We use the vertical component of broadband waveform data from earthquakes at teleseismic distances (from $30^\circ$ to $95^\circ$). Event epicenters and depths obtained from regional or global catalogs, such as Preliminary Determination of Epicenter (PDE) from National Earthquake Information Center (NEIC), International Seismological Center (ISC), or ISC-EHB (Engdahl et al., 1998), are used as initial estimates for calculating traveltime and then determining time windows consisting phases of interest. We cut the teleseismic waveforms using 10 s before and 100 s after the time of the P wave arrival calculated from the ak135 global wave speed model (Kennett et al., 1995), which is sufficient to include depth phases of intermediate-depth earthquakes. The waveforms thus selected are resampled to 10 Hz and tapered on both sides. We then filter them using a second-order Butterworth band-pass filter with low and high cutoff frequencies of 0.2 and 2 Hz,
Figure 1. (a) The location of the 11 April 2014 Mw 4.5 northern Chile earthquake (red star) according to the NEIC-USGS catalog and the distribution of stations (blue triangles) used for extracting pP depth phase. (b) Raw waveforms after bandpass filtering from 0.2 to 2.0 Hz. Red bars mark the theoretical P wave arrival using the global ak135 model. (c) The individual autocorrelograms and linear stacking (black line) and phase weighted stacking records (blue line) after move-out correction. The large P signals at 0 s are tapered out.

respectively. Removing instrument responses is not necessary as their spectral amplitude is flat in this frequency range. Finally, we autocorrelate the waveforms after spectral broadening (Pham & Tkalčić, 2017, equation (2)) using a frequency window length of 1.0 Hz. The spectral broadening is an important step in our data processing since it balances the frequency components so that the resultant autocorrelograms are not dominated by low-frequency components. This is similar to running-absolute-mean normalization (Bensen et al., 2007) in order to suppress the effects of large seismic events in the time domain.

Since the arrival time of depth phases associated with intermediate earthquakes changes slowly and is much less sensitive to epicentral distance than to focal depth, we apply a simple move-out correction to a reference epicentral distance. The correction time is calculated based on the initial location and the global 1-D velocity model ak135 (Kennett et al., 1995). We then stack all the individual autocorrelograms linearly to obtain the final autocorrelogram at the reference epicentral distance. In cases where station distribution is relatively sparse a phase weighted stack (Rost, 2002) can help to increase the signal-to-noise ratio. The envelope, that is, the energy associated with depth phases, is used to project back to the depth using a 3-D velocity model, if available, or ak135.

2.2. Validation With a Mw 4.5 Intermediate-Depth Earthquake in Northern Chile
We illustrate and validate our method using an intermediate-depth earthquake in northern Chile (moment magnitude Mw4.5, focal depth 111.3 km according to the NEIC-USGS catalog) and recordings from 1,948
Figure 2. (a) Individual and stacked autocorrelograms for the 11 April 2014 $M_w$ 4.5 northern Chile earthquake (Figure 1a) after move-out correction but without spectral broadening. Black and blue line in the stack autocorrelograms represent linear and phase-weighted stacking, respectively. (b) Stack autocorrelograms after move-out correction using different initial depths. (c) The move-out correction with respect to 70° using different event depths at different epicentral distances.

For this relatively small earthquake, the first arrivals are not clear at teleseismic distances (Figure 1b), making techniques based on first arrival identification challenging (e.g., Bonner et al., 2002; Craig, 2019). In contrast, our method based on $P$ wave autocorrelation (with move-out correction using the initial depth of 111.3 km to a reference distance of 70°) shows clearly the arrival of energy associated with the $pP$ and $sP$ phases, although $sP$ phase is weaker than $pP$ (more about this later). The first 60 s of 400 randomly selected autocorrelograms (Figure 1c) reveals $pP$ signal around 26.4 s, which becomes clearer after stacking. The $pP$ arrival time (along with ak135) allows the refinement of the focal depth from 111.3 km according to the NEIC-USGS catalog to 105.3 km.
Using autocorrelation to extract depth phase energy is not new and has been applied elsewhere for depth relocation with data from stations at both local and teleseismic distances (e.g., Audet & Ma, 2018; Tibuleac, 2014; Zhang et al., 2014). One of the main differences with our method is that we apply spectral broadening to increase the high-frequency content and facilitate depth phases detection. In fact, the stacking of autocorrelograms without spectral broadening does not show a clear depth phase signal either with linear or phase weighted stacking (Figure 2a). The spectrum of the autocorrelograms is squared after autocorrelation, which will cause the autocorrelograms dominated by even lower frequencies if the original (band-limited) signal has strong low-frequency components, as is usually the case for teleseismic data because of the attenuation of high-frequency components compared to that of low frequencies. The “spectral whitening” that we use also turns out to be important in applications of retrieving near station reflections (Oren & Nowack, 2016; Pham & Tkalčić, 2017, 2018).

We found our results do not critically depend on the actual depth used for move-out correction, as long as the correction depth is within 20 km of the true depth. We verified this by varying the move-out correction depth from 83 to 133 km and found all of them show coherent stacking, which leads to clear pP and sP energy. The sP phase is weaker for this event but still stands out with a larger amplitude than the noise (Figure 2b). This is not surprising since the difference in correction time between different depths is quite small. For this particular example, the correction time at 30° is less than 1 s for correction depths of 85 and 105 km (Figure 2c). Moreover, most stations are located between 50° and 80°, which further reduces the sensitivity to the actual depth used for move-out correction.

Structural heterogeneity in the mantle and topography near the depth phase reflections at the surface may degrade the coherency of the stack using the global array. However, we found the stacks are usually dominated by the most densely distributed stations. Indeed, for this earthquake, stacking data only from the stations in the United States also show a clear pP signal (supporting information Figure S1a). To assess the influence of bounce-point topography, we grouped stations in the United States into eastern and western parts based on the backazimuth of station and event pairs. The results still show coherent stacking. The P arrival using stations in the eastern United States shows a slightly delayed phase due to the high elevation of Andes, but this only has a minor effect since the envelope is used to determine the depth (Figure S1b).

A more straightforward way would be to stack the autocorrelograms along a depth phase arrival time curve predicted from a 3-D wavespeed model and use the depth that yields the maximum stack value. This is equivalent to stacking with move-out correlation based on the true depth. We found, however, that the effect on depth estimation is negligible if the initial depth is within 20 km of the true depth (Figure 2b), which is a reasonable tolerance given the uncertainty in focal depth estimates in global catalogs. For the test event used here, the focal depth from direct stacking based on a phase arrival time curve is 105.0 km (Figure S2), which is very close to the result (105.3 km) obtained from stacking after move-out correction.

3. Applications to Japan and Northern Chile Subduction Zones

Japan and northern Chile subduction zones are representative end members of cold (old tectonic plate) and warm (young) subduction, respectively (Müller et al., 1997). Intermediate-depth earthquakes in these regions are routinely located with local seismic data (e.g., Kita et al., 2006; Sippl et al., 2018). To refine the depth locations of earthquakes in these regions so that one can understand the mechanisms of intermediate-depth earthquakes better, we apply our method to extract the depth phase energy using the ISC catalog for Japan and a local catalog from Sippl et al. (2018) in northern Chile. We assume that the epicenter locations are relatively well constrained and use the additional constraints from depth phases only to improve estimates of focal depths.

From 2004 to 2018, for this region (139.0–143.0°E, 38.5–40.5°N) the ISC catalog includes 184 earthquakes with moment magnitude larger than 4.0 and focal depths ranging from 50 to 300 km. We applied our method to these earthquakes and manually checked all the stacked autocorrelograms. We successfully extracted 65 events with signal-to-noise ratio around the stacked pP or sP larger than 10.0. The smallest magnitude that still yielded acceptable stacks is Mw 4.0 (Figure S3). For the range of focal depths considered, the depth phases (pP and sP) are well separated in time. We apply a double-difference relocation algorithm (Florez & Prieto, 2017; Waldhauser & Ellsworth, 2000) to our pP and sP data in order to decrease the effect of 3-D wavespeed variation in the subduction zones. Unfortunately, the sparse source distribution only allows us to relocate a small fraction of events (Figure S4). Therefore, we also incorporate direct relocation by taking
Figure 3. Relocated earthquakes in (a) Japan and (b) northern Chile subduction zones. Black squares show the locations from ISC-EHB catalog. Red circles show relocated earthquakes in this study. Blue diamonds show the locations from Japan Meteorological Agency (JMA) and Sippl et al. (2018) in Japan and northern Chile subduction zones. Magenta diamonds show locations from Craig (2019). Black solid lines show the slab interfaces from Hayes et al. (2018). Black, blue, and magenta dashed lines show oceanic Moho (6 km from the slab interface), the upper layer (15 km from the slab interface), and the lower layer (45 and 29 km from the slab interface for the Japan and northern Chile subduction zones, respectively). Blue boxes in the inset figures show the study regions.

the average of depths determined by sP and pP if both are available. Otherwise, we determine the phase type based on the predicted arrival time range using a depth window of 40 km around the initial depth and then relocate accordingly in cases where we only have one clear depth phase (pP or sP). Although it relies heavily on the initial depths, we found little ambiguity in deciding the phase types (pP or sP), thanks to the good initial catalogs. We combine direct and double-difference relocation and take the average depth as our final depth, given that the difference between them is small (Figure S4). The relocation reveals a well-defined double seismic zone (Figure 3a), with a width of about 30 km between the upper and the lower layer, which is consistent with Brudzinski et al. (2007) and Florez and Prieto (2019).

In northern Chile, we extract all earthquakes from the catalog of Sippl et al. (2018) in our study region (70.5–68.5°W, 23.0–21.0°S) from 2007 to 2015, with magnitudes larger than 4.0 and depths from 40 to 100 km. This results in 227 earthquakes and we successfully relocated 84 of them, with 4.1 the smallest magnitude that still yields a useful stack (Figure S3). We note that the detectability does not correlate with event magnitude, both for Japan and northern Chile (Figure S3). Sometimes earthquakes with similar magnitudes and nearly the same station distribution show different stacking results (Figure S5), which may indicate the effects of earthquake focal mechanism due to heterogeneous stress distribution (Chang et al., 2017). Similar to the relocated events in the Japan subduction zone, the refined event depths also delineate a double seismic zone (Figure 3b), with a width of about 14 km between two layers, consistent with Rietbrock and Waldhauser (2004).

We compare our relocations with existing catalogs from Japan Meteorological Agency and ISC-EHB (Engdahl et al., 1998) in Japan, and ISC-EHB as well as catalogs from Sippl et al. (2018) and Craig (2019) in northern Chile. We found the new relocated events delineate the double seismic zones better, with less scattered events along different interfaces. It is not entirely surprising that our method using teleseismic depth
Figure 4. Residual of observed differential times between sP and pP and synthetic differential times using the global ak135 model in the Japan (a) and northern Chile (b) subduction zones. Negative values show advanced sP or delayed pP compared to that of ak135, indicating small average Vp/Vs. Small white circles show events only with either sP or pP. Solid and dashed lines are the same as Figure 3.

phases improves the depth locations in the catalog that are derived from local seismic data, considering relocations based on first arrival times suffer from the trade-off between earthquake origin time and depth.

Water and high pore pressure can increase the Vp/Vs dramatically in the source region (e.g., Audet et al., 2009; Kodaira et al., 2004; Peacock et al., 2011). To characterize the dehydration effect in the subduction zones better, we pick the differential arrival times \( \Delta t_{pP} = t_{pP} - t_P \) and \( \Delta t_{sP} = t_{sP} - t_P \) from stacked autocorrelograms with both clear pP and sP energy and then calculate \( (\Delta t_{obs}^{sP} - \Delta t_{obs}^{pP}) - (\Delta t_{exp}^{sP} - \Delta t_{exp}^{pP}) \), that is, the observed differential time between sP and pP, and compared them with the ones predicted from the global 1-D ak135 model (Kennett et al., 1995). The results are shown in Figure 4. For both the Japan and northern Chile subduction zone, we found most earthquakes with positive values, that is, advanced pP and thus larger Vp/Vs, are located in the upper layer of the double seismic zones inside the oceanic subducting slab. These earthquakes are mostly limited to above 80 km in Japan but continue deeper (to about 100 km) in the upper layer of the north Chilean slab. However, due to the large uncertainty in the slab interface (Hayes et al., 2018) and depth locations based on the 1-D wavespeed model, it is uncertain if these earthquakes are in the subducting oceanic crust or mantle. For the lower layer, we did not observe anomalous positive values in either subduction zones, indicating small Vp/Vs and, thus, a dry lower layer.

The differential time between sP and pP is sensitive to the average Vp/Vs between the event and the surface. In order to estimate Vp/Vs, we adopt an idea from double-difference relocation and take two events, one in the lower layer and the other in the upper layer. We then calculate the differential time relative to one another, which is most sensitive to the Vp/Vs between the upper and the lower layer (Figure S6). The obtained relative differential time between two events is smaller than the one calculated from ak135, indicating, again, decreased Vp/Vs between the two layers in the double seismic zone.
4. Discussion and Conclusions

In this paper, we investigated the possibility of using $P$ wave autocorrelation to detect energy associated with arrivals of the depth phases $pP$ and $sP$ to improve focal depth estimates of intermediate-depth earthquakes and characterize the $V_p/V_s$ ratio around the source regions. The method relies on the small sensitivity of depth phase arrival time with respect to epicentral distance, which allows stacking of data from all stations at a teleseismic distance to improve the signal-to-noise ratio of the phases of interest. Picking arrivals is not needed, and since the method can be applied to earthquakes with magnitude as small as the $M_w 4.0$, our analysis can benefit from more events than traditional studies. This also indicates the potential for wider application. For example, the application to the global intermediate to deep earthquake catalog could improve depth estimation of more small-magnitude earthquakes, which could help improve seismic imaging and tomography as well as the understanding of the mechanisms of those enigmatic earthquakes.

We applied this method to improve the depth of the intermediate earthquakes in two end members of subduction zones, the young/warm northern Chile subduction zone and the old/cold Japan subduction zone. Our results provide further evidence of the positive correlation between the slab ages and the width of double seismic zones, confirming that temperature plays a key role in controlling the geometry of double seismic zones. We note that this observation does not necessarily imply that dehydration embrittlement controls intermediate-depth earthquakes since the preferred condition of temperature ($600–800 \, ^\circ C$) in thermal shear instability mechanism also predicts narrow widths of double seismic zones in warm slabs.

Recently findings of correlation of seismicity rate and off-trench faults distribution (Boneh et al., 2019), deep hydration in the Mariana subduction zone (Cai et al., 2018), and high $V_p/V_s$ in the lower layer in northern Chile (Bloch et al., 2018) point to a dehydration embrittlement mechanism for intermediate earthquakes. However, the high $b$ value in the upper layer (Florez & Prieto, 2019) may lead to the dominance of upper layer seismicity in estimating the seismicity rate in the intermediate-depth range, thus suppressing the contribution of lower layer seismicity which may operate with other mechanisms. Hydration to about 24 km below the Moho in the Mariana subduction zone, as observed by Cai et al. (2018), may not be deep enough to reach the lower layer in the double seismic zone, whose width may reach 40 km (Brudzinski et al., 2007; Florez & Prieto, 2019). Neither in Japan nor Chile do we find anomalous $sP$ to $pP$ differential times for events in the lower layers of the double seismic zones, which argues against deep penetration of water into the upper mantle and, thus, dehydration embrittlement as the mechanism for the lower of the double seismic zone. This is somewhat inconsistent with Bloch et al. (2018), who observed very high $V_p/V_s$ in the lower layer. But the depth where they found anomalous $V_p/V_s$ (about 55 km) is shallower than what we observed with $sP$ to $pP$ differential time. Using a similar approach to Lin and Shearer (2007) and Bloch et al. (2018), we do not find high $V_p/V_s$ in the lower layer in the Japan subduction zone (Figure S7). It could be interesting to explore deeper regions in the lower layer of the double seismic zone in northern Chile using the approach of Bloch et al. (2018) to see if both measurements are consistent with each other and confirm if dehydration extends deeper in the lower layer in warm slabs.

The events that are above 80 and 60 km in the Japan and northern Chile subduction zones, respectively, seem located mostly in the oceanic crust according to global or regional slab models (Hayes et al., 2018; Kita et al., 2010) and may result from dehydration. This would be consistent with some observations, such as water infiltration in the trench outer rise (Ranero et al., 2003), positive correlation of seismicity rate and fault density (Boneh et al., 2019), and low velocity in the crust using guild waves (Shiina et al., 2017). Along with the low $V_p/V_s$ in the lower layer in the double seismic zones, this may indicate that two mechanisms operate on the intermediate-depth earthquakes (Florez & Prieto, 2019). In view of uncertainty in both slab interfaces and event locations, this needs further study.

The negative to normal to differential times in the lower layer indicates that earthquakes in the lower layer are not associated with anomalous high $V_p/V_s$ or dehydration. Combined with recent experimental results that suggest that thermal runaway could occur in both hydrous and anhydrous minerals (Ohuchi et al., 2017), our results are consistent with thermal instability for generating intermediate earthquakes, or stress transfer which requires little dehydration (Ferrand et al., 2017; Scambelluri et al., 2017), and argue against dehydration embrittlement as the primary mechanism, at least not in the lower layer of double seismic zones.
Acknowledgments

Comments and advice from the Editor (Gavin Hayes) and the two anonymous reviewers greatly helped us improve our manuscript. We acknowledge the fruitful discussion with Thanh Son Pham, which inspired us to extend the autocorrelation technique to extract depth phases. We thank Aurélien Mordret, Nori Nakata, Rachel E. Abercrombie, and Victor Tsai for many insightful discussions. Malcolm White’s comments on the early version of the manuscript are also appreciated. Most of the figures are generated using GMT (Wessel et al., 2013). Obspy (Beyreuther et al., 2010) is used for some of the data processing. Raw seismic waveforms were downloaded from the IRIS DMC (http://ds.noda/dmc/data/). Catalogs containing initial locations in northern Chile and Japan were obtained from Sips et al. (2018) and ISC (http://www.isc.ac.uk/iscbulletin/). The relocated catalog is provided in the supporting information.

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