Summary of Doctoral Thesis

Receiver function study of lithospheric structure in subduction zones, cratons and volcanic regions

沈み込み帯、安定陸塊および火山域における
レシーバ関数解析によるリソスフェアの研究

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1. General Introduction

The Earth hosts some typical discontinuities in the interior, from the shallow crust to the deeper mantle, the Moho, lithosphere-asthenosphere boundary, and the upper mantle discontinuities. The rigid lithosphere consists of the crust and upper mantle. Different types of plate tectonic processes occur on Earth, including spreading, subduction, collision, rifting, and sliding. As a result, the geometry and nature of the upper lithosphere vary globally, leading to rocks with different compositions and shear wave velocities (Christensen, 1996). Local and global tectonic processes affect seismic velocities globally, which calls for the investigation of the subsurface. The variations in seismic velocities for different tectonic settings and ages also contribute to the investigation of the geophysical evolution of the subsurface. Investigation of global areas could help us to determine if the different geophysical observations (such as volcanoes, slow slip, megathrust earthquakes, and inactive cratonic areas) in different tectonic settings are directly affected by seismic velocities and compositions. The use of a single method in different tectonic settings in the literature avoids a method-biased interpretation, which is highly considered in this thesis. In this thesis, we explore the variations in seismic discontinuities and seismic velocities across depth in the diverse tectonic settings of the Precambrian Gondwana regions, subduction setting (Chile and Alaska), and volcanic region (Mount Erebus).

2. Methods

We have used the methods of receiver function using iterative time-domain deconvolution (Ligorria and Ammon, 1990), H-k stacking (Zhu and Kanamori (2000)) and neighbourhood algorithm inversion (Sambridge, 1999). Receiver Function and inversion has been used for all the study regions. H-k has been applied to cratons, Sri Lanka and Mount Erebus in the Antarctica region.

Receiver Function

The receiver function (RF) technique is a well-known seismological method for obtaining information on Earth's interior structure, namely, layer thickness and seismic wave velocity. It is a time series derived from three-component seismograms that includes the response of the Earth’s structure near the receiver (Ammon, 1997). When a P(S) wave is incident on a geologic boundary with contrasting seismic velocities, a part of it is converted to an S (P) wave at that boundary, and multiple reflections occur in the layer between the boundary and Earth’s surface. In the case of the crust-mantle boundary (Moho), the P-to-S converted phase and its multiples are denoted by Ps, PpPs and PpSs, respectively. The amplitudes, arrival time, and polarity of the locally generated P-s phases largely depend on the shear velocity structure beneath the recording station, and can be modelled to estimate the layer thickness and velocities (Ammon et al., 1990; Ammon, 1991). By removing the effects from the raw seismograms of the mantle path and source, the resulting receiver function was obtained to reflect the responses to the structure beneath the receiver. We have used an iterative time-domain deconvolution method (Ligorria and Ammon, 1999). This method is based on the use of a cross-correlation function to estimate the lag and amplitude of spikes that comprise the final receiver function.

H-k stacking

The H-k stacking method was proposed by Zhu and Kanamori (2000) using teleseismic receiver functions. The amplitudes of the receiver functions at the predicted arrival times of the phases were summed up by this stacking algorithm, considering different crustal thickness H and Vp/Vs ratios. Without the need to identify the phases and picking arrival times, the time domain receiver functions were transformed directly into the H-Vp/Vs domain. The coherent stacking of the three phases provided the best estimate of H and Vp/Vs. The effects of lateral structural variation can be suppressed by considering receiver functions from different distances and directions (Zhu and Kanamori, 2000), and an average crustal model can be obtained.

Neighbourhood algorithm (NA) inversion

To reduce the effect of non-uniqueness and non-linearity, which are common problems in receiver function inversion (Ammon et al., 1990), Sambridge (1999) developed NA to find models of acceptable data fit. It consists of a direct search approach, that is fully non-linear and derivative-free. Instead of searching for a single model that is best suited to the data, we may use modeling to obtain a collection of models that preferentially sample the parts of the parameter space that have a strong match with the data. The NA finds an ensemble of models that sample the good data fitting regions of parameter space. In this method, synthetic receiver function is calculated using Thomson-Haskell matrix (Thomson, 1950; Haskell, 1953). The chi-square misfit function used to define the discrepancy between true and synthetic waveform.

3. Lithosphere structure beneath tectonically stable regions

3.1 Crustal structure beneath Precambrian cratons

We investigated the upper lithospheric structure beneath the Precambrian Gondwana cratonic regions using the receiver function method, H-k stacking, and NA inversion, by estimating the structure beneath 52 broadband stations. Beneath the stations investigated in this thesis, intra-cratonic variations in crustal thickness have been observed : 28–32 km in Pilbara; 36–42 km in Yilgarn; 46 km in Gawler; 36–41 km in Tanzania; 32–42 km in Kaapvaal; 35–40 km in Zimbabwe; and 36–43 km in Antananarivo. Diverse tectonics, such as vertical tectonics, could have an impact on intra-cratonic variations (Hickman, 2011). An episodic cycle of crustal thickness change was observed between early Earth regions. The Hadean regions show ~7 km of variation, followed by ~16–17 km in the Eoarchean and Paleoarchean. The variations in the Eoarchean and Mesoarchean were ~11 km and ~15 km respectively. The activity of plate tectonics over time, various processes of crustal regeneration, episodic recycling, and crust reworking are all potential explanations for the fluctuating crustal thickness that has been observed in Precambrian cratons (Capitanio et al., 2020). By correlating our Vp/Vs estimations to the experimental studies, it is seen that the Vp/Vs of the cratons are found to dominate in the range of 1.65–1.78, indicating felsic to intermediate composition of the Archean cratons. The observed range was wider than the global average Vp/Vs values (1.74–1.79), as reported by Kennett et al. (1995). Moreover, our results indicate that the older regions (Pilbara and Napier) are mainly concentrated in the felsic range, while the younger cratons are cluttered around the felsic-intermediate boundaries.

3.2 Crustal structure beneath a Gondwana fragment : Sri Lanka

We revealed the crustal architecture beneath Sri Lanka using three broadband stations from north to south, using receiver function, stacking, and inversion methods. Sri Lanka is bordered by Madagascar, India, Antarctica, and Africa in Eastern Gondwana (Dissanayake and Chandrajith, 1999). It has four lithological units: Highland, Wanni, Vijayan, and Kadugannawa

(Mathavan and Fernando, 2001). Results show 38 km crustal thickness and high average shear wave velocity (Vs 3.7–3.8 km/s) under Sri Lanka, low average Vp/Vs ratio (1.72) in the Highland Complex, and high Vp/Vs ratio (1.79). This shows that Sri Lanka's crust is felsic to intermediate, with granite to granodioritic rocks. The rocks of the Wanni Complex are felsic to mafic granulites. The crustal thickness and average Vp/Vs ratio of the Highland complex are identical to those of its Gondwana neighbours, indicating its unique location. Sri Lanka's average crustal shear wave velocity (3.7 km/s) is similar to its Gondwana neighbours.

4. Lithosphere structure beneath tectonically active regions: Deep slow slip and volcanic regions

4.1 Along-strike forearc and subducted upper slab structure beneath North Chile

In and around the regions of Iquique, Atacama and Valparaiso in North Chile, we investigated the structure beneath the subduction forearc using 21 broadband stations distributed within and outside the slow-slip regions. Slow slip was previously discovered in these regions by Ruiz et al. (2014), Socquet et al. (2017), Klein et al. (2018), and Ruiz et al. (2017). Here, we used the receiver function and inversion methods. Crustal thickness ranges from < 19 km to ~60 km (increasing inland); slab top ranges from ~30 to ~90 km; oceanic crustal thickness is ~5 to ~10 km; depth of oceanic Moho is 40 km to ~90 km; oceanic crust velocities are < 4 km/s; mantle velocities 4.2 to 4.9 km/s. Interestingly, the lateral variation of Vs velocity along the trench strike shows a trend, in which the shear wave velocities tend to behave relatively differently around Iquique in the northern region near the slow slip (~100 – 150 km north and south of 20ºS) compared to the southern part. Near the slow slip in Iquique, relatively lower bottom wedge-mantle velocities and oceanic crust velocities were observed. The opposite trend was observed for the velocities at the top of the subducting oceanic mantle. To the north of 22.5ºS, the oceanic mantle is dominated by very high velocities (>4.5 km/s), but the southern region has dominantly low S-wave velocities (less than 4.4 km/s). These velocities could have important implications in terms of the presence of fluids and their effect on the seismicity of the region. The subduction of the three ridges correlates well with the latitudes of the slow slip zones. We suggest the possibility that the incoming ridges and seamount subduction could play a vital role in the architectural properties of the lithosphere around the plate interface region, and could be a potential candidate for controlling the shear velocities around the plate interface region, especially around the bottom of the wedge mantle, oceanic crust, and top of the subducted oceanic mantle.

4.2 Lithosphere structure beneath South Alaska forearc subduction region

We investigated the structure beneath the subduction forearc, using 15 broadband stations, distributed within and outside the slow-slip regions. Here, we used the receiver function and inversion methods. The oceanic crust depth varied from ~20 km to ~80 km, oceanic crust thickness varied from ~5km to ~9 km, oceanic Moho was ~25 km–80 km; and the velocities at the top of the subducted oceanic mantle and bottom wedge dominated at ~4–4.5 km mostly (low range). The velocities at the top of the subducted oceanic mantle are dominated by lower velocities. This could be related to the subduction of the two oceanic crusts, the Pacific Plate and the Yakutat terrane. Christeson et al. (2010) suggested that the Yakutat microplate originated from an oceanic plateau. The velocities at the top of the oceanic crust were heterogeneous in the range of ~3–3.9 km/s, with the appearance of higher velocities approaching the Cook Inlet region, which is the region of slow slip. The slow slip regions detected in Alaska over time (Ohta et al., 2006; Wei et al., 2012; Li et al., 2018; Fu et al., 2015) were mainly confined to the Upper Cook Inlet (UCI) and the Lower cook Inlet (LCI) regions.

4.3 Crustal structure beneath Mount Erebus, Antarctica

We estimated the crustal thickness and Vp/Vs beneath the Mount Erebus region in Ross Island, Antarctica using the receiver function, H-k stacking, and inversion methods beneath the stations. The crustal thickness in the Mount Erebus region of Ross Island is shallow (<25 km), with significant variation between the directional segments. Extensive rifting could have caused crustal thinning, with major crustal tears and delamination beneath the segments. The Vp/Vs ratio was highly variable, ranging from ~1.6 to ~2.0. However, the Vp/Vs ratios were consistently high in the north west segments. The presence of lava deposits in the crust, trapped partial melts, and volcanic craters could potentially increase Vp/Vs ratios.

5. General Discussion

We obtained the velocity and discontinuity depths at different locations with varying tectonic settings. The high velocities in the mantle region were sharply dissected by the reduced negative jump of low velocities atop the subducted oceanic crust. We also observed variations in the receiver functions: the cratons show negligible backazimuth effects, no dip variation of the structure, and clear multiples. The subduction regions on the other hand, show clear phases from top of oceanic crust and subducted oceanic Moho. They have experienced high tectonic activity. The volcanic region also shows backazimuth variation, with directional thinning.

Using the similar techniques of receiver function, stacking and inversion in the diverse tectonic setting have allowed us to directly estimate the velocity structures without method bias effects.

Crustal thickness and Moho nature

The continental Moho discontinuity showed sharp to transitional nature beneath the tectonic settings (sharp in Sri Lanka, the Erebus region; sharp to transitional in cratonic regions. The nature of the Moho was very different in the subduction settings of Chile and Alaska. Although the continental Moho showed depth variation from ~19–60 km, the depth could not be recovered beneath some stations in this study. In Alaska, the continental Moho depth can be recovered from approximately five stations. Bostock (2013) suggested that delineating a clear Moho discontinuity as a sharp velocity boundary in complex subduction zone environments could be challenging. By experimenting with geophysical models in the worldwide forearc of the subduction region, this study inferred that serpentinization and fluid within the wedge can diminish the Moho signature of the overriding plate.

Vp/Vs as a measure of crustal composition

Capitanio et al. (2020) suggested crustal modification and delamination in the later part of the Archean. This could have resulted in the evolution and reworking of early crustal material, reducing the felsic component and thus increasing the Vp/Vs ratios for the relatively younger cratons. On investigating the trend with Vp/Vs and Moho depth, no relationship was found between them for the Precambrian cratons. This is different from the negative correlation between the Vp/Vs ratios and the Moho depths suggested by Chevrot and van der Hilst (2000), indicating crustal reworking to play a role in the variation of the observed (no association) and expected trends (negative correlation). The Vp/Vs ratios in Sri Lanka were similar to those found in the southeastern region of Madagascar (Andriampenomanana et al., 2017) and the Kerala Khondalite Belt of South India (Rai et al., 2013). Beneath the Mount Erebus region, the Vp/Vs ratio is highly variable, ranging from ~1.6 to more than ~1.8. Because the geographical extent of Mount Erebus is small, this indicates a high degree of crustal heterogeneity within a small localized region. High Vp/Vs ratios in the crust of more than 1.8 have also been observed beneath volcanoes in central Anatolia (Zhu, 2018). This is higher than the normal global average (1.74–1.79; Kennet, et al., 1995).

Subducted oceanic crust and oceanic Moho

The depth at the top of the subducted oceanic crust varies from ~20–90 km beneath the subduction settings. The estimations are consistent with the Slab 2.0 model (Hayes et al., 2018). They also showed backazimuth variation, with a deeper inner segment. The thickness of the oceanic crust ranges from ~5–10 km. This range is slightly wider than the global experimental studies of seismic refraction, which indicate an average thickness of oceanic crust of ~7 km, with extreme bounds of ~5–8 km (White et al., 1992). An oceanic crust thickness as high as ~15 km has been estimated previously in the offshore Iquique ridge, before subduction (Uieda et al., 2017). The depth of the oceanic Moho in Chile and Alaska varies from ~40–90 km and ~29–82 km, respectively, increasing inland. This could be attributed to the dip in the subducting slab. A sharp velocity discontinuity is observed in the Chile and Alaska regions.

6. General Conclusions

- Nature and variation of the Moho discontinuity: The thickness of the subducted oceanic crust varies between ~5–10 km. The large variation in the oceanic Moho was due to the dip and local heterogeneity in the region. A thin crust (<25 km thick) with directional variation was obtained beneath the active volcanic Mount Erebus. With advancing age in the Precambrian, alternate increasing and decreasing crustal thicknesses were recorded.
- Crustal composition inferred from Vp/Vs: Estimation of Vp/Vs was used as a measure of the crustal composition. The Vp/Vs ratio of the cratons was found to be mostly between 1.65 and 1.78, indicating that the Archean cratons have a felsic to intermediate composition, with older cratons in the felsic domain and younger ones in the felsic-intermediate boundary. In addition, a felsic-intermediate composition Vp/Vs was found for the first time in the Sri Lanka area. Vp/Vs beneath Mount Erebus, Antarctica, ranged from 1.6–1.8, suggesting diverse compositions below the plume.
- Variation of mantle seismic velocities: The mantle seismic velocities were diverse across different tectonic settings. In the Precambrian and volcanic regions, the velocities were >4 km/s. In the subduction regions, low seismic velocities were evident in between the mantle layers.