Large-scale crustal structure beneath Singapore using receiver functions from a dense urban nodal array

Karen H. Lythgoe[1], **Miranda Ong Su Qing**[1], **Shengji Wei**[1]

[1]Earth Observatory of Singapore, Nanyang Technological University, Singapore

Key Points:

- Robust receiver functions are generated from a temporary dense nodal array in a noisy urban environment.
- High frequency receiver functions reveal Singapore's crustal structure with direct implications for seismic hazard analysis.
- Azimuthal variations reveal distinct crustal structure on either side of the Bukit Timah fault.

Corresponding author: Karen Lythgoe, karen.lythgoe@ntu.edu.sg

Abstract

Geophysics has a role to play in the development of 'smart cities', for example through geohazard mitigation and subsurface imaging for underground construction. This is particularly true for Singapore, one of the world's most densely populated countries. Imaging of Singapore's subsurface is required to identify geological faults, model shaking from future earthquakes and provide a framework for underground development. A non-invasive geophysical technique that is well suited for urban areas is passive seismic surveys using nodes. Here, we image Singapore's crustal structure using receiver functions generated by a 40-day deployment of a dense nodal array. We generate high resolution receiver functions, despite the noisy environment and short recording time and also create common-conversion point images. Our results reveal a complex crustal structure, containing multiple discontinuities. Azimuthal variations indicate a distinct change in crustal structure on either side of the postulated Bukit Timah fault, which has implications for seismic hazard.

Plain Language Summary

By 2050 over two thirds of the global population is expected to live in cities (United Nations, 2018). Rapid urbanisation creates an ever pressing need to understand the subsurface of our cities, for example for underground development. Such dense population centres also increase the exposure to nearby natural hazards such as earthquakes. One technological advancement that allows us to image the subsurface of cities are passive seismic surveys using nodes. Nodes are small seismic instruments that can be deployed in urban areas such as schools and parks. We present results of a passive seismic survey using 88 nodes deployed in Singapore for 40 days. We generate high resolution receiver functions across the array, despite the short recording time, by using array stacking techniques. The dense nature of the array also allows continuous high frequency signals to be traced. Our results reveal that the structure of the crust is very different on either side of the Bukit Timah fault, which agrees with geological information. Ancient faults in peninsula Malaysia have been reactivated in the recent past due to stress transfer from the Sumatran subduction zone, therefore this geological fault under a densely populated urban centre warrants further study for seismic hazard.

1 Introduction

Increasing urbanisation creates an ever pressing need to understand the subsurface of our cities. 'Smart' cities aim to use technology to improve their liveability, economic and environmental stability. Geophysics, and seismology in particular, has a role to play in smart city development, for example through geohazard mitigation and subsurface imaging for underground construction. Technological advancements are allowing us to image cities in ways not previously possible. In particular, passive seismic surveys using nodes are a non-invasive acquisition advancement that are uniquely suitable for urban environments. Here we demonstrate one application of seismic nodes in the world's 'smartest city'.

Singapore is a densely populated city nation, and better understanding of its seismic hazard and subsurface structure is prescient. Singapore experiences shaking from earthquakes in Sumatra, which is only a few hundred kilometres away (Pan & Sun, 1996). The Mentawai segment of the Sumatran megathrust is the closest to Singapore and is predicted to rupture as a large earthquake in the near future (Sieh et al., 2008). Simulations of future earthquake scenarios in Singapore are needed to ensure it is properly prepared. Imaging the crustal structure below Singapore is also required for underground construction, resource development and identification of geological faults. Local geological faults pose an as yet unassessed seismic hazard. Although Singapore lies on the relatively stable Sunda continental shelf, old faults zones nearby have been reactivated due to stress transfer from the Sumatran megathrust. Several earthquakes, up to M_l5, have occurred within the Malay peninsula during the instrumental time period (ISC, 2019). For example a series of earthquakes up to $M_l3.7$ in 2007-2009, occurred on a previously unidentified fault 20 km from Kuala Lumpur (Shuib, 2009). It is therefore important to identify significant geological faults, especially in areas of high population density.

Conventional seismic surveys to image crustal structure are not well suited to urban environments. Such surveys typically use a network of large semi-permanent seismometers that use up valuable space and are deployed in relatively quiet environments. On the other hand, dense arrays of nodes are far better suited to urban environments. Seismic nodes can be deployed rapidly, directly into the ground and without any bulky equipment. Nodes – short period autonomous geophones - were originally developed in the energy industry for shallow land imaging with active sources (for example Manning et al. (2019)). However several recent studies have demonstrated the utility of nodes for passive seismic imaging on a lithospheric scale (Ward et al., 2018; Liu et al., 2018; Wang et al., 2019; Lin et al., 2013). One drawback of nodes compared to conventional instruments is their short battery life of approximately 1 month. However, the considerable cost saving of nodes compared to conventional instruments permits the acquisition of very dense surveys and receiver density is the principle factor controlling subsurface image quality.

A key passive seismic technique to image crustal structure is the receiver function method (Langston, 1979; Vinnik, 1977). The technique employs body waves generated by teleseismic earthquakes to isolate mode conversions at discontinuities below a receiver. In order to increase the signal above the noise, receiver function imaging typically requires stacking of more than one year of teleseismic body waves at a single station (for example Macpherson et al. (2013)). The long-time needed normally limits the application of the technique to seismic stations that have been active for several years. However nodal arrays can generate high resolution receiver functions despite their short recording time (Ward et al., 2018). This is because the dense station distribution permits stacking in space, in addition to stacking receiver functions over time. The close proximity of stations also permits higher frequency receiver functions to be used, since coherent mode conversions can be continuously traces between stations.

In this study, we image Singapore's lithospheric structure using teleseismic receiver functions generated from a short-period nodal array. The motivation behind the nodal array was to 1) illuminate the large scale crustal structure beneath Singapore to provide a skeleton framework for future smart city refinement and 2) assess the performance of a nodal array in a noisy urban environment. We show that nodes are fully capable of generating high frequency receiver functions, even in a noisy environment with only 1 month of data. Our results reveal a complex crustal structure, reflecting Singapore's complicated geological history. Azimuthal variations in receiver functions indicate a distinct change in crustal structure on either side of the postulated Bukit Timah fault, which has implications for seismic hazard in the world's third most densely populated country.

2 Geology of Singapore

The near surface geology of Singapore is relatively well known due to an abundance of shallow boreholes and building works. However the geological structure beyond several hundreds of meters is almost entirely unknown. The near surface is composed of three principle geological units – Bukit Timah granite, Jurong Group metasediment and quaternary sediments (Dodd et al., 2019) (Figure 1a). The Bukit Timah granite underlies central Singapore and is the most extensive geological unit. Quaternary sediments outcrop in eastern Singapore plus a small area in northern Singapore and overly Bukit Timah granite (Woon & Yingxin, 2009). The west of Singapore is composed of the Jurong Group – a sequence of lightly metamorphosed sediment that is highly folded and faulted (Leslie et al., 2019). The nature of the boundary between the Jurong Group and the Bukit Timah granite is not clear as the contact does not outcrop. One possibility is that the contact is an unconformity and that the Jurong Group also overlies Bukit Timah granite. Alternatively, the two units may be separated by a fault, often referred to as the Bukit Timah fault. The last geological unit is unconsolidated reclaimed land, which makes up over 20% of present-day Singapore.

3 Nodal array

A nodal array comprising 88 5Hz 3 component geophones was deployed across Singapore for a continuous 40-day period, from February to April 2019 (Figure 1a). Site locations were distributed across Singapore, with a denser profile located across the boundary between Bukit Timah granite and the Jurong Group. The largest station spacing was 8 km, for a node deployed on a nearby island. The smallest station spacing was 100 m for nodes deployed across the geological boundary. Site locations included parks, schools, nature reserves, weather stations, roadsides and industrial sites, and so had a range of ambient noise levels. In addition to the nodal array, 4 permanent seismic station operated by Singapore's Meteorological Service, were used.

4 Methodology

Receiver functions are time series composed of P-to-S converted waves generated at structural boundaries in the Earth beneath a seismometer. Teleseismic P-waves are used to compute receiver functions as they approximate a vertically incident plane wave. We construct receiver functions for earthquakes larger than $M_w 5.5$ with an epicentral

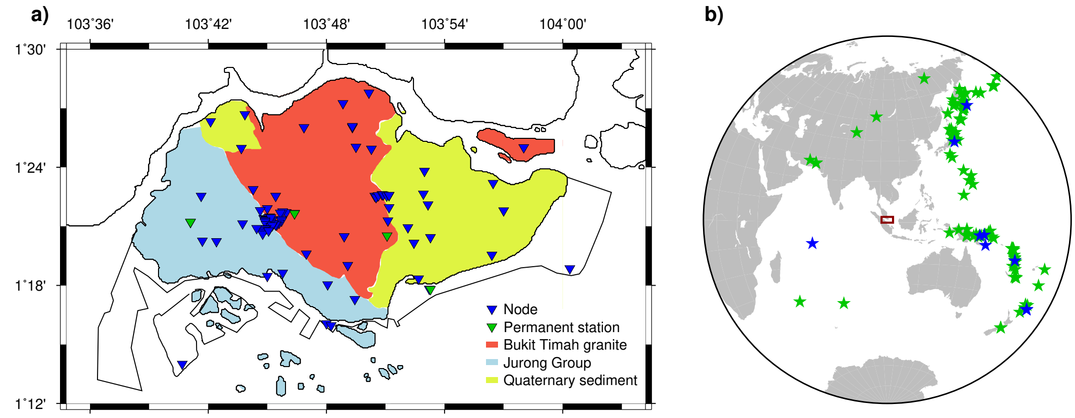

Figure 1. a) Map of Singapore showing broad geological units. Outer coastline marks the current coastline of Singapore which is built on reclaimed land. Blue triangles are locations of temporary nodes and green triangles are locations of permanent seismic stations. b) Earthquakes used to generate receiver functions. Blue stars show earthquakes used with the nodal array survey and green stars are earthquake used with the permanent stations.

distance from 30° to 90° - a total of 22 earthquakes during the acquisition time (Figure 1b). We process the raw waveforms by deconvolving the instrument response, removing the mean and linear trend, bandpass filtering from 0.05 – 10 Hz, and rotating the horizontal components into radial and tangential components. Removing the instrument response has the effect of boosting low frequencies relative to higher frequencies (Supplementary Figure 1).

Receiver functions are generated by a time-domain iterative deconvolution with a Gaussian low pass filter (Ligorría & Ammon, 1999). The Gaussian low pass filter removes high-frequency noise in the receiver function at the expense of resolution. A Gaussian width of 5 was chosen, which corresponds to a cut-off frequency of approximately 2.5 Hz. This value reduces noise while keeping as much high frequency signal as possible (Supplementary Figure 2). Using a dense nodal array in the United States, Ward et al. (2018) generated receiver functions for a Gaussian value up to 10 (approximately 4.8 Hz). However in our case, such high Gaussian values generate noisy receiver functions, because there is abundant man-made noise above approximately 3 Hz (Supplementary Figure 1 and 2). However our receiver functions still have over one octave more signal compared to conventional surveys (for example Macpherson et al. (2013). The dense acquisition means that coherent mode conversions can be traced between stations, which allows more high frequency signal to be utilised, even in an urban environment.

Receiver functions are quality controlled automatically and subsequently by visual inspection. From the 22 earthquakes that were used to generate receiver functions for the node data, 9 earthquakes produced receiver functions of sufficiently high quality. The earthquakes used to compute receiver functions are distributed in three azimuth bins: 280°for earthquakes near Fiji, 240° for earthquake near Japan and 75° for one earthquake that occurred in the Indian Ocean. Receiver functions were also generated for four permanent stations in operation in Singapore, composed of 1 broadband and 3 short-period instruments. On average 50 high quality receiver functions were generated per station from 229 suitable earthquakes (M_w greater than 5.5 in years 2012, 2013 and 2018).

5 Results

A receiver function profile across Singapore is shown in Figure 2. Stations within 7 km are projected on to the profile, which strikes across the geological units. Receiver functions with an azimuth between 200° to 300° are stacked at each station - this is approximately 90% of all high quality receiver functions and variations within this azimuth range are small. Receiver functions are also stacked in space. We stack all stations within a radius of 4 km, with the centre station doubly weighted. A radius of 4 km is chosen in this case to best increase signal while not smoothing across geological variations.

A clear Ps phase is seen at 4 seconds, matching the previous receiver functions of Macpherson et al. (2013). Additionally, intra-crustal discontinuities are present. In eastern Singapore there is a clear positive arrival between the direct P and Ps phases, with negative arrivals preceding and following the peak. This peak arrives at later times towards the centre of Singapore and then disappears completely. Conversely, western Singapore appears relatively homogeneous, with a negative arrival before Ps, which increases in amplitude further to the west.

In order to place the discontinuities at the correct location in depth, we utilise a migration method known as common-conversion point (CCP) stacking (Kosarev et al., 1999; Zhu et al., 2006). The amplitude at each point along the receiver function is back-projected to the conversion point using a background velocity model. We use a 1D velocity model generated by joint inversion of receiver functions and surface waves at a broad-

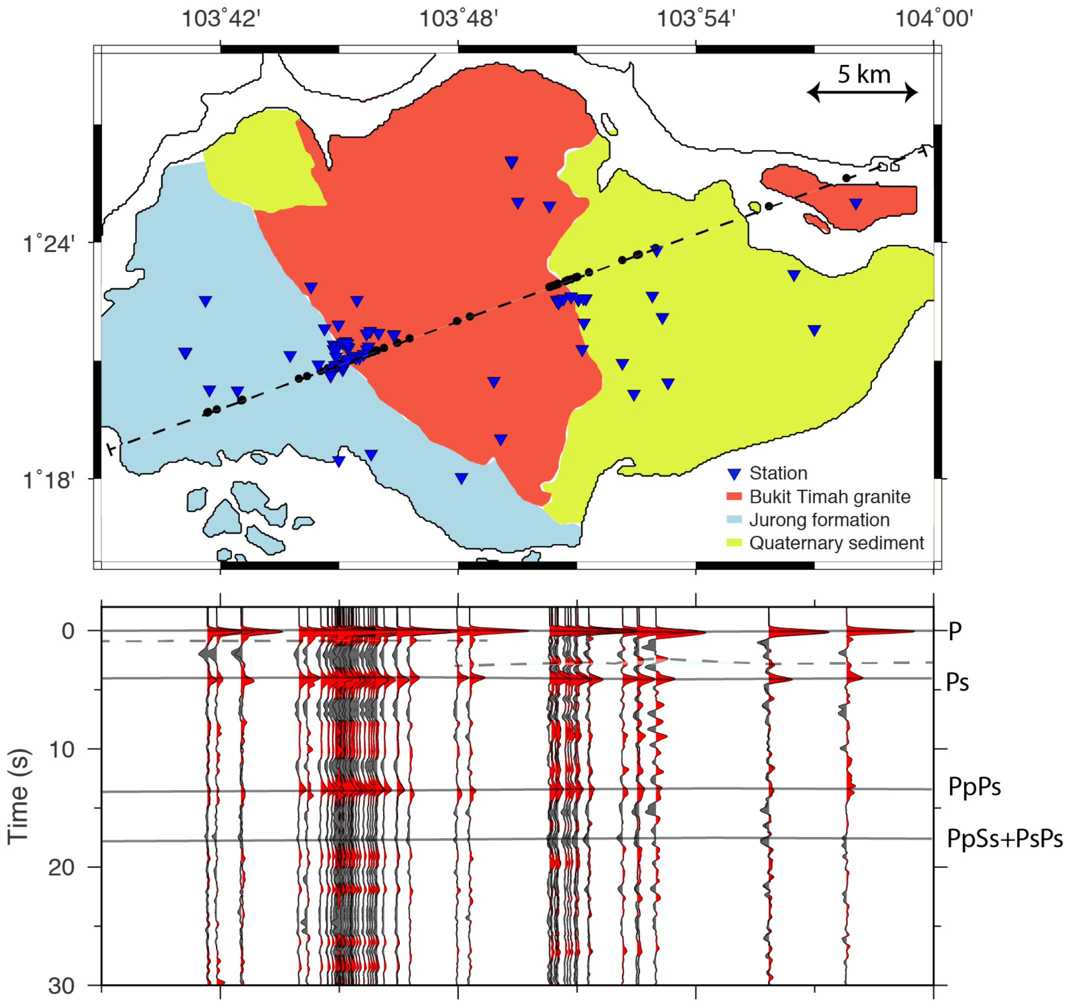

Figure 2. Receiver function profile across Singapore. Stations (blue triangles) within 7 km of the profile are projected on to the profile (black circles). Phase labels are based on predictions from a 30 km thick crust with an average P-wave velocity of 6 km/s and Vp/Vs of 1.78.

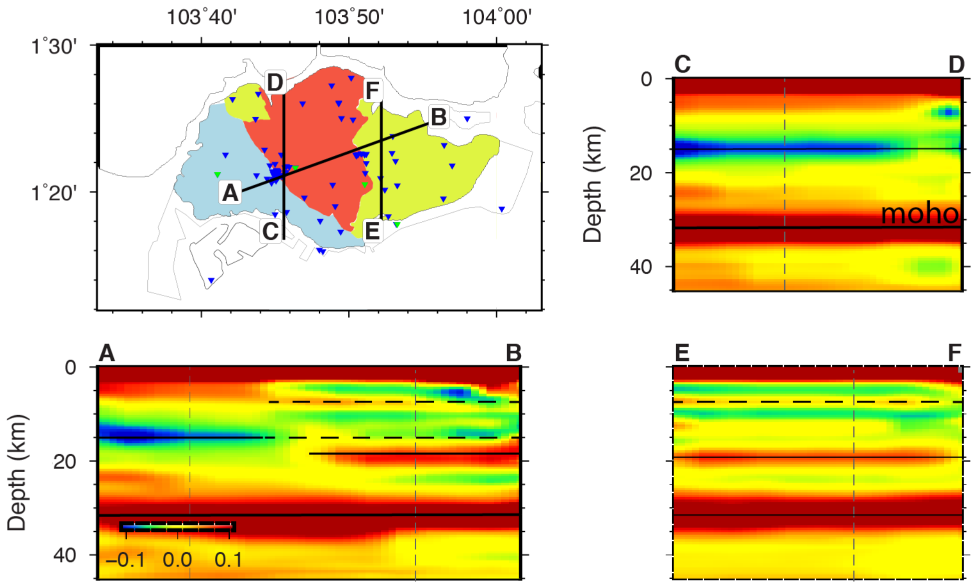

Figure 3. Common-conversion point images of the crust across Singapore.

band station in the centre of Singapore (Macpherson et al., 2013). After back-projection of all receiver functions, the crustal volume is divided into bins and all amplitudes within a bin are stacked, such that the amplitude of each bin represents the impedance contrast at that location.

Figure 3 shows the resulting CCP image at several profiles. The moho is a high amplitude peak at 32 km depth. Macpherson et al. (2013) proposed that the depth to the moho varied at a short wavelength across Singapore however we show that the moho depth is constant. There are significant intra-crustal variations from west to east across Singapore. The negative arrival in western Singapore corresponds to the top of a low velocity zone at 15 km depth. This trough appears to disappear towards the east, where it is replaced by a peak at 19 km depth, marking the top of a high velocity layer. In the east there is an additional low amplitude peak at 7 km depth. It is possible that this peak continues to the west but it is not clearly separated from the main P arrival. The CCP images show remarkably complex lateral variations over a distance of only 40 km.

The majority of teleseismic earthquakes occur to the east of Singapore and so imaging is dominated by energy arriving from the east (azimuths of 240 - 280° from source to receiver, Figure 1). Fortuitously, however, one suitable earthquake occurred in the Indian ocean during the nodal deployment and produced high quality receiver functions.

Seismic waves from the Indian ocean event travel to Singapore at an azimuth of 75°, illuminating the far western side of Singapore (Figure 4). This is particularly useful for investigating variations in crustal structure from the Jurong Group to the Bukit Timah granite, across the postulated Bukit Timah fault.

Figure 4 shows receiver function profiles generated in the three azimuths groups. The piercepoints of rays at the base of the crust are shown in Figure 4a for each azimuth group. Waves arriving from an azimuth of 75° penetrate the crust of the Jurong Group, while the other azimuths sample the crust below the Bukit Timah granite. The receiver functions from an azimuth of 75° are dramatically different from the other azimuth groups. A peak at 2 seconds due to an intra-crustal boundary appears, with sharp negative arrivals surrounding the peak. On the other hand the profiles from azimuths 240° and 280° show a relatively simple structure with one intra-crustal negative arrival as shown in Figure 2. The dramatic change in receiver functions depending on the crust that is sampled, indicates the crustal structure below the different geological units is very different. Therefore it follows that the Bukit Timah fault is an approximately vertically dipping fault running throughout the crust. The presence of a significant fault also agrees with geological information showing that the ages of the two units are very similar (Dodd et al., 2019; Oliver & Manka, 2014). This suggests that significant tectonic movement must have occurred in order for sedimentary rocks to be adjacent to a granite pluton that formed at the same time.

6 Discussion and Conclusions

We have generated robust receiver functions at high frequencies using a nodal array in a noisy urban environment. The method relies on 1) high receiver density allowing coherent signals to be identified and 2) man-made noise predominantly occurring at frequencies greater than 3 Hz. To create receiver function profiles across Singapore, we first de-noise the data by stacking. We stack both receiver functions from different earthquakes and receiver functions from nearby stations. We also show for the first time that a temporary nodal array can be used for receiver function imaging using the popular common conversion point method. The CCP method is a ray-based method and we suggest that future studies might profitably focus on wave-based migration methods (such as reverse time migration (Chen et al., 2005)), which may prove superior with high receiver density (Shang et al., 2017). In this study, we do not invert for seismic velocity, since

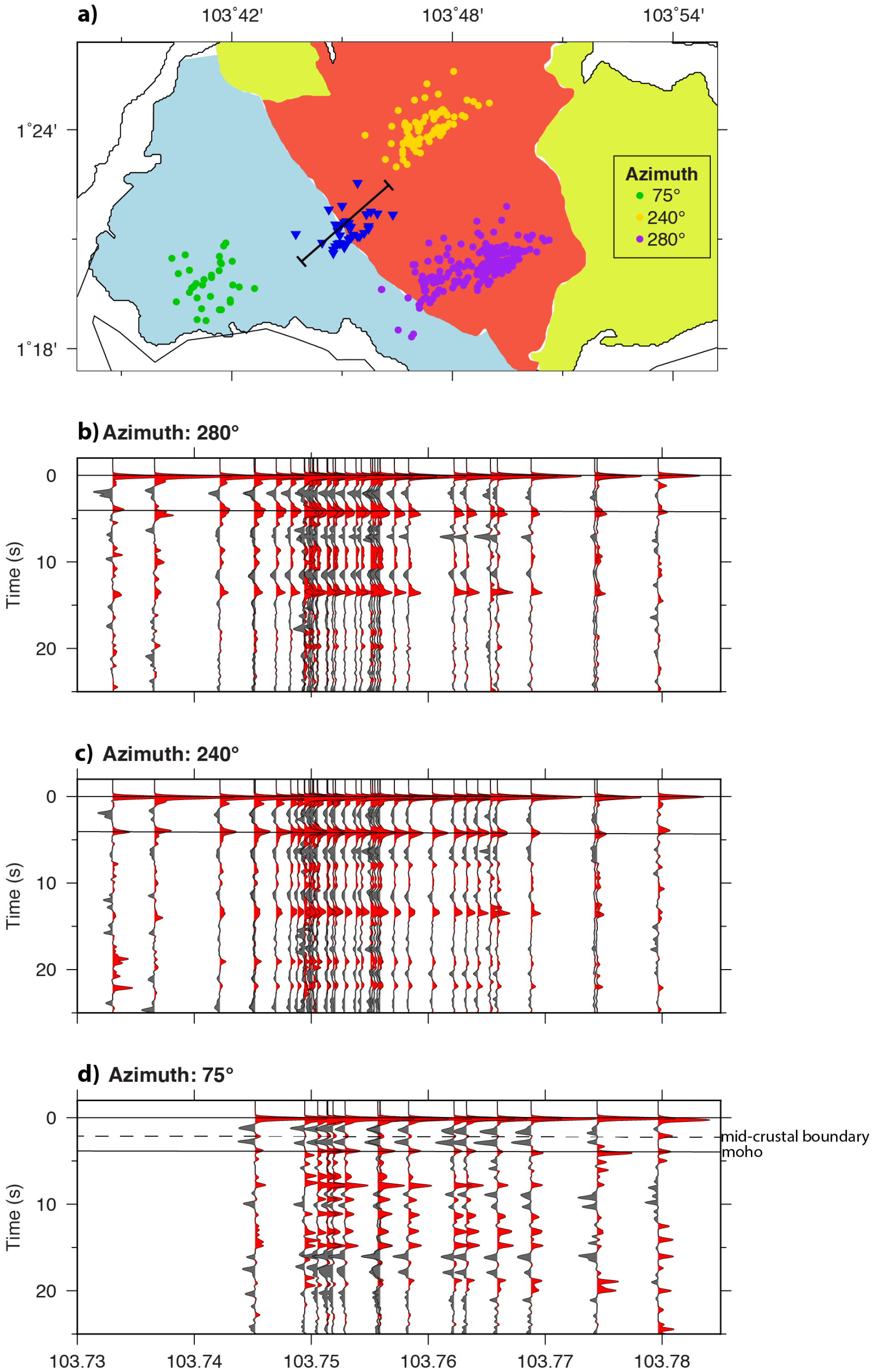

Figure 4. Azimuthal variations in receiver functions across Singapore. a) Map showing piercepoints where rays enter the base of the crust for three earthquakes from different azimuths. b) Receiver functions for seismic waves travelling at an azimuth of 280°. c) Receiver functions for seismic waves travelling at an azimuth of 240°. d) Receiver functions for seismic waves travelling at an azimuth of 75°.

receiver functions have low sensitivity to absolute seismic wave speed. Instead the receiver functions presented here will be combined with surface waves in a joint inversion for 3D velocity structure.

Our results indicate a complex crustal structure beneath Singapore, reflecting Singapore's complex geological history. In particular, azimuthal variations in receiver functions show distinct crustal structure below the Jurong Group and Bukit Timah granite, confirming the presence of the Bukit Timah fault. Old faults in this area can be reactivated by distant stress fields from surrounding subduction zones. Therefore geological faults in and close-by to Singapore pose a seismic hazard to this densely populated area and warrant further characterisation.

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