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BASEMENT STRUCTURE IN THE KATHMANDU VALLEY, NEPAL USING RECEIVER FUNCTION ANALYSIS

M. Shigefuji[(1)], N. Takai[(2)], S.M. Bijukchhen[(3)], M. Bhattarai[(4)], C. Timsina[(5)], S Singh[(6)], H. Miyake[(7)], K. Koketsu[(8)]

[(1)] *Assistant Professor, Kyushu University, Japan, shigeufji@arch.kyushu-u.ac.jp*
[(2)] *Associate Professor, Hokkaido University, Japan, tki@eng.hokudai.ac.jp*
[(3)] *Senior Lecturer, Khwopa Engineering College, Nepal, subegbij@khec.edu.np*
[(4)] *Researcher, National Seismological Centre, Nepal, bamdev2031@gmail.com*
[(5)] *Researcher, National Seismological Centre, Nepal, chintan1119@gmail.com*
[(6)] *Researcher, Department of Mines and Geology, Nepal, ssingh_15@hotmail.com*
[(7)] *Associate Professor, Earthquake Research Institute, University of Tokyo, Japan, hiroe@eri.u-tokyo.ac.jp*
[(8)] *Professor, Earthquake Research Institute, University of Tokyo, Japan, koketsu@eri.u-tokyo.ac.jp*

Abstract

The Kathmandu Valley in Nepal is filled with soft lake sediment of Plio-Pleistocene origin, more than 650 m thick in the central part of the valley. The diameter of the valley is about 25 km in length. The Himalayan continental collision zone of the Indian plate and the Eurasian plate has experienced devastating earthquakes in the past. For example, during the 1934 Nepal-Bihar earthquake (M_w 8.2) caused heavy damage in this valley, in spite of the 150 km epicentral distance. The cause of this heavy damage is thought to have been affected by its soft lake sediment. Now a day, the future great earthquakes in Nepal Himalaya have the potential to occur in the Central Seismic Gap of the Main Frontal Thrust. Therefore, we must examine the amplification characteristics of the valley and grasp the susceptible to the risks of strong ground motion at the next great earthquake.

In the valley, there are four permanent strong-motion observation stations that were collaborated between Hokkaido University and Tribhuvan University after 2011. After the 2015 Gorkha Nepal earthquake, we also carried out the four temporary stations for the aftershock observation over three months. Moreover, as part of a project for the integrated research on great earthquake and disaster mitigation in Nepal Himalaya of Science and Technology Research Partnership for Sustainable Development program supported by JST and JICA (FY 2016 - 2021, PI: Kazuki Koketsu, University of Tokyo, Counterpart: Department of Mines and Geology, Nepal), the strong motion observation network was initiated with ten strong-motion seismometers in the Kathmandu Valley from November 2016 to May 2018.

To grasp the site amplification characteristics, it is important to construct the velocity structure of the valley. In this study, in order to understand the basement topography of the valley and depth of the sediment, we apply the receiver function analysis to strong-motion records obtained from stations in the valley and validate the previous velocity structure model. First, we conducted using strong motion records at the seventeen stations. Since the estimated receiver functions clearly show the P-to-S converted wave across the boundary between the basement and soft sediment, we can examine the Ps-P time quantitatively. The Ps-P times are large differences in the range of 0.28 to 1.06 second in the sedimentary sites, this feature shows the complex basement topography of the valley. The time difference between the direct P- and P-to-S waves and the top of basement depth from the previous velocity structure model indicate mostly a linear relationship.

Keywords: Kathmandu Valley, Nepal; P-to-S receiver function; Basement depth

1. Introduction

The Kathmandu Valley in Nepal is filled with soft lake sediment of Plio-Pleistocene origin, more than 650 m thick in the central part of the valley [1] [2]. The diameter of the valley is about 25 km in length. The Himalayan continental collision zone of the Indian plate and the Eurasian plate has experienced devastating earthquakes in the past (Fig. 1). For example, during the 1934 Nepal-Bihar earthquake (M_w 8.2) heavy damage occurred in this valley [3], in spite of the 150 km epicentral distance. The cause of this heavy damage is thought to be the effect of its soft lake sediment. Now a day, the future great earthquakes in Nepal Himalaya have the potential to occur in the Central Seismic Gap of the Main Frontal Thrust [4]. Therefore, we must examine the amplification characteristics of the valley and grasp the susceptible to the risks of strong ground motion at the next great earthquake. The location in the seismically active region and the presence of thick sediments amplifying seismic waves have increased the seismic vulnerability of Kathmandu. Accounts of more than 20 devastating earthquakes occurring in or near Nepal Himalaya after 13th century [5] could be found in the history, the 2015 Gorkha Nepal earthquake (M_w 7.8) being the latest in the list.

To grasp the site amplification characteristics, it is important to construct the velocity structure of the valley. In this study, in order to understand the basement topography of the valley and depth of the sediment, we apply the receiver function analysis to strong-motion records obtained from stations in the valley. First, we conduct using strong-motion records of the 2015 Gorkha Nepal earthquake aftershocks at eight stations [6] [7], and strong-motion records by new strong-motion observation network at ten stations [8]. The large velocity contrast which lies at the boundary between basement rock and sediment affects the P-to-S (Ps), S-to-P (Sp) wave conversion strongly. Therefore, this time difference between direct P- and converted Ps- or Sp- waves have important information about the sediment depth. Since the estimated receiver functions clearly show the Ps wave across the boundary between basement rock and soft sediment, we can examine the difference of arrival time between the direct P- and Ps-waves (Ps-P time) quantitatively. The large Ps-P time differences in the sedimentary sites show the complex basement topography of the valley. Finally, we discuss the relationship between the Ps-P time and the basement topography of the Kathmandu Valley.

2. Velocity structures of the Kathmandu Valley

The Kathmandu valley is a tectonic basin filled with fluvio-lacustrine deposits and surrounded by hills on all sides. Bouguer anomaly [2] shows an undulating basement topography. The borehole loggings [9] [10] [11] have demonstrated a number of different layers and lenses formed due to varying depositional environments. The basin topography is highly undulated and there are several rocky hillocks that breach through the thick sediments to the surface as bedrock exposures. One of these exposures can be seen in Kirtipur (Fig. 2) where one of the accelerometers is installed as KTP.

Bijukchhen *et al*. [12] consulted available geological maps [1] [2], cross-sections, and borehole logging data [9] [10] [11] as the basis for initial models for the sediment sites. Strong-motion records of a medium-sized earthquake from eight accelerometers installed by Hokkaido University and Tribhuvan University [6] were used to construct a 1-D velocity structure model. These initial models were tuned by 1-D simulation using the propagator matrix method [13] and by comparing the observed horizontal-to-vertical spectral ratio with theoretical ones from the diffused field theory [14]. These models show high-velocity contrast at the basement depth, the sediment sites to have more than 155-440 m thick deposits resulting in significant wave amplification. Moreover, Bijukchhen [15] constructed a 3-D velocity structure model of the Kathmandu Valley based on the 1-D velocity structure models, geological maps, and geological cross-sections.

3. Strong motion observation

A collaboration between Hokkaido University, Japan, and Central Department of Geology (CDG), Tribhuvan University, Nepal, began in 2011 to study the strong-motion characteristics in the Kathmandu Valley [6]. Four strong-motion accelerometers were installed at KTP, TVU, PTN, and THM, in a west-to-east array (Fig. 2). The seismometers recorded a number of earthquakes including the M_w 7.8 Gorkha Nepal earthquake on 25 April 2015, and its subsequent aftershocks. Four more temporary stations (BKT, RNB, PPR, and KPN) were deployed for three months (8 May to 6 August 2015), after the 2015 Gorkha Nepal earthquake, to observe aftershock activity [7]. The installed instrument is a highly damped moving coil type accelerometer (Mitsutoyo JEP-6A3-2) with data loggers (Hakusan DATAMARK LS-8800) recording at a sampling rate of 100 Hz, and the time calibration is carried out using GPS. The KTP station lies in Kirtipur, west of Kathmandu, on a rock site. Other stations are on the sediment sites.

"Integrated Research on Great Earthquake and Disaster Mitigation in Nepal Himalaya" is a project of Science and Technology Research Partnership for Sustainable Development program supported by JST and JICA (SATREPS NERDiM, FY 2016 - 2021, Counterpart in Japan: University of Tokyo, Counterpart in Nepal: Department of Mines and Geology). As part of this project, to construct the source and velocity structure models for the ground motion prediction, the strong-motion observation network was initiated with ten strong-motion seismometers in the Kathmandu Valley from November 2016 to May 2018 [8]. The installed instrument is the network sensor CV-374A2 (Tokyo Sokushin) with the servo accelerometer (frequency range: DC~100 Hz). Due to long hours of a power outage in Kathmandu, the observation system has a UPS, down transformer, voltage stabilizer, and large external back-up battery. We installed the instrument to the north (JHR) and the east (SNG) rock site stations. The SGL station was installed in the area predicted to have the deepest sediment deposit. Others were installed in the marginal area of the valley; the BLJ station was installed in the heavily damaged area during the 2015 Gorkha Nepal earthquake, and the TKT station was installed near the Chandragiri fault. A list of the strong motion stations is shown in Table 1.

Fig. 3 shows a radial component record section during the medium-sized earthquake that occurred near the valley. We can understand that the rock site KTP shows the simple waveform and others have a long later phase clearly. The amplitude of the TVU station on the sub-basin is more than twice that of the closest station KTP.

Table 1 – List of the strong motion stations used for this study. The geology of each site is from Shrestha *et al*. (1998) [16] as shown in Fig. 2.

Code	Station name	Geology	Installation
KTP	Kirtipur	Hard rock	Sepember 2011 –
TVU	CDG, Tribhuvan University, Kirtipur	Slightly consolidated sediment	
PTN	Pulchwok Campus, Lalitpur	Slightly consolidated sediment	
THM	University Grants Commission, Thimi	Slightly consolidated sediment	
BKT	Bhaktapur	Slightly consolidated sediment	8 May 2015 – 6 August 2015
RNB	Ranibu, Lalitpur	Slightly consolidated sediment	
PPR	Panipokhari, Kathmandu	Slightly consolidated sediment	
KPN	Kapan, Kathmandu	Unconsolied sediment	
JHR	Jhor, Tokha	Hard rock	November 2016 –
BLJ	Balaju, Kathmandu	Slightly consolidated sediment	
TCH	Thecho	Slightly consolidated sediment	
SNK	Sankhu, Shankharapur	Slightly consolidated sediment	
KPN2	Kapan, Kathmandu	Hard rock	November 2017 –
KRP	Kharipati	Slightly consolidated sediment	
TKT	Thankot, Chandragiri	Unconsolied sediment	
SNG	Sanga	Hard rock	
SGL	Sinamangal, Kathmandu	Slightly consolidated sediment	
LMT	Lamatar	Unconsolied sediment	May 2018 –

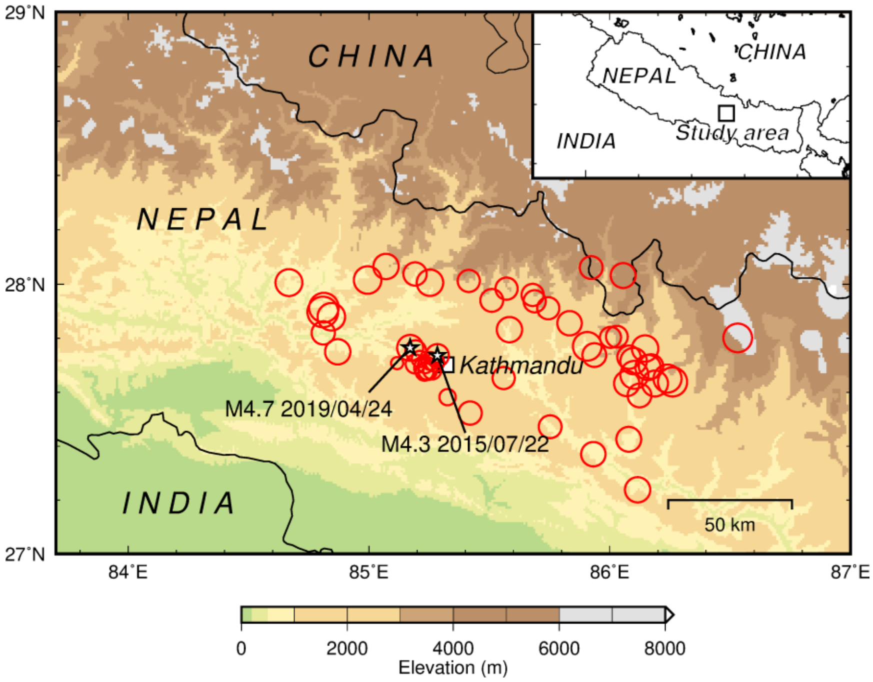

Fig.1 – Location map of the epicentres used for this study. The right inset shows the study area. Red circles and black stars indicate the epicentres.

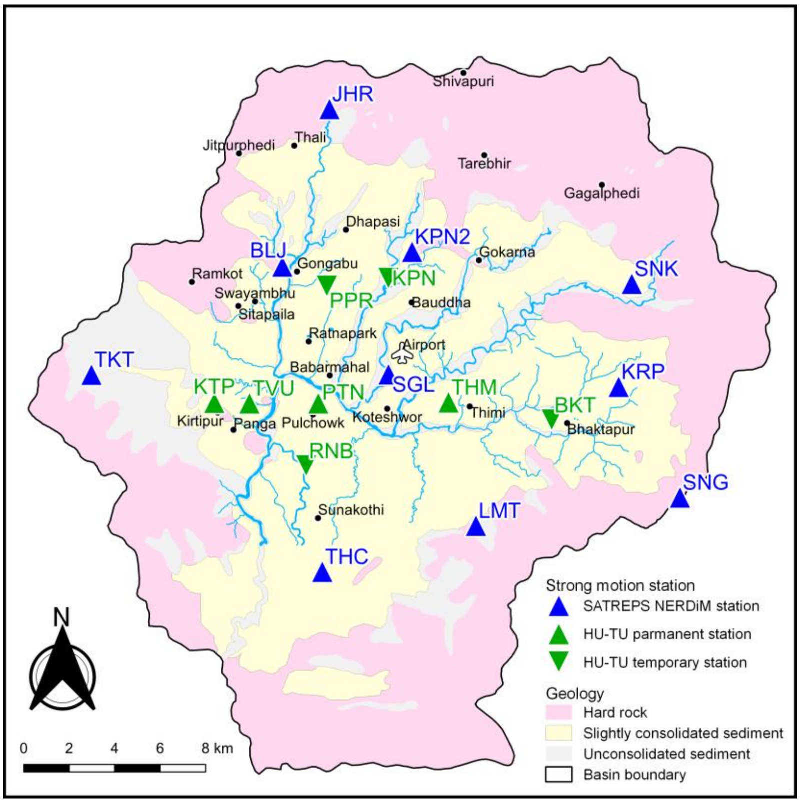

Fig. 2 – Location map of strong-motion observation stations. Blue triangles are the SATREPS NERDiM stations, green triangles are the Hokkaido University- Tribhuvan University (HU-TU) stations [6]. Geological formations are modified from Shrestha *et al*. (1998) [16].

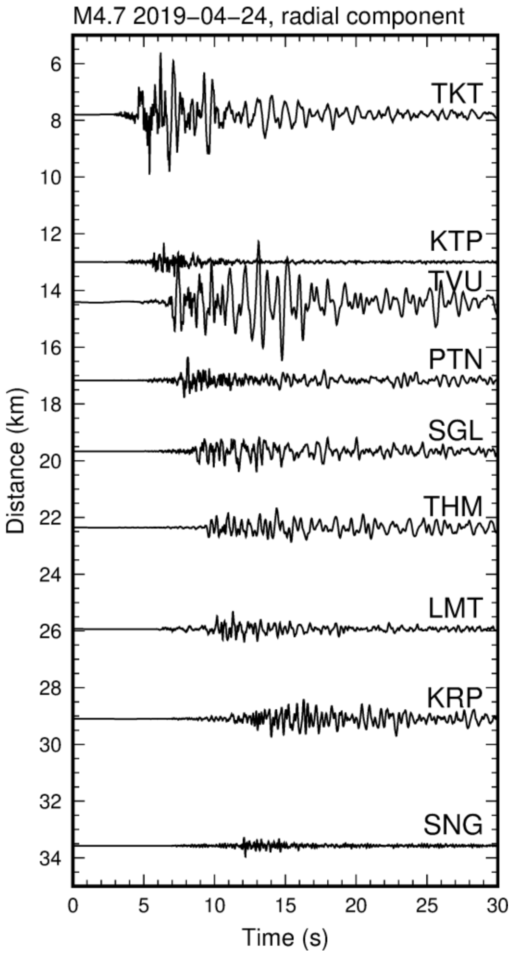

Fig. 3 –Record section of observed radial component velocity waveforms during the 24 April 2019 earthquake (mb 4.7, depth = 27 km). The epicentre is shown in Fig. 1.

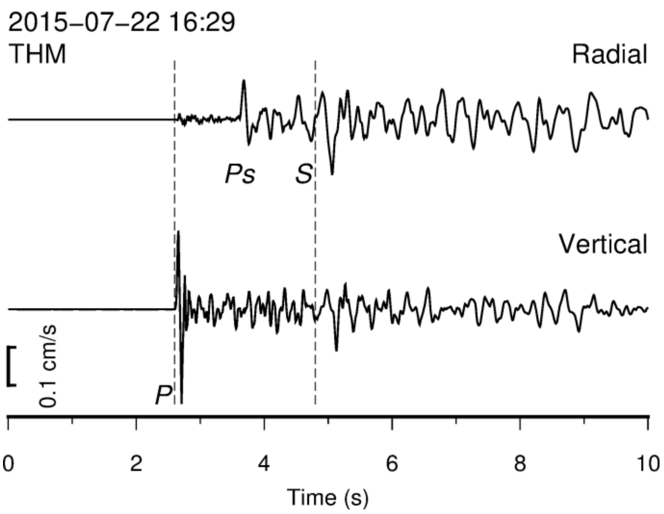

Fig. 4 – Observed radial and vertical component velocity waveforms of the THM station during the 22 July 2015 earthquake (*M* 4.3, depth = 7 km). The epicentre is shown in Fig. 1.

4. Method and data

The Ps-P time differences in the sedimentary sites show the complex basement topography of the valley. To examine the quantitative time difference, the receiver function analysis [17] [18] of strong-motion records are used frequently [19]. We applied this analysis to strong-motion records obtained from the stations in the valley and validate the previous velocity structure model of the Kathmandu Valley [15]. First, the horizontal components are rotated to the radial and transverse directions. the first 3.0 sec from the direct P-wave arrival time of strong-motion records are used, and then band-pass filtered with a frequency range from 1 to 10 Hz. The procedure of the receiver function analysis is based on Kobayashi *et al.* [19]. These receiver functions are stacked to form an average one.

Strong-motion records in the seventeen stations except for the KPN2 station during earthquakes with the magnitude from 2.3 to 6.0 are used in this study as shown in Fig. 1. The strong-motion records of the KPN2 station are not obtained sufficiently. We used the location of the epicentre determined by Ichiyanagi *et al.* [7], Adhikari *et al.* [20], Nepal Seismological Centre [21], and the United States Geological Survey [22]. Events used for this study occurred near the seismic fault of the 2015 Gorkha Nepal earthquake. Fig. 4 shows the radial and vertical component velocity waveforms in the THM station during the 22 July 2015 earthquake (M 4.3, depth = 7 km) that occurred near the Kathmandu Valley, as an example. The Ps-wave is shown clearly between the direct P- and S-waves in the radial component and the Ps-P time is approximately 1 second.

5. Result and Discussion

Fig. 5 shows the distribution of the basement topography and the result of the receiver function analysis for each section on the seventeen strong-motion stations. The peak times of the receiver functions almost correspond with the theoretical Ps-P times calculated from the 1-D velocity structure under each strong-motion station [15]. Therefore, these peak times indicate the time differences between the direct P-wave and Ps-wave converted at the basement-sediment boundary. Comparing between the undulation of basement topography and the Ps-P time difference in each section, both indicate a similar tendency. The observed Ps-P time of the KTP station is less, it is one evidence KTP being of the rock site. Those of the SGL and THM stations are approximately 1 second, the largest difference. We can understand that the Ps-P times have a large variation in the valley. This feature suggests complex basement topography of the valley.

Fig. 6 shows the relationship between the observed Ps-P time and the basement depth from Bijukchhen [15]. For most stations, these relationships indicate a linear relationship. However, the observed Ps-P time of the SGL, TKT, and SNK stations are not consistent with the related tendency. These stations are on the center and marginal part of the valley, not used by the construction of the velocity model [15].

6. Concluding remarks

We applied the strong-motion records obtained in the seventeen stations to the receiver function analysis and investigated the basement structure in the Kathmandu Valley. The observed Ps-P time indicates the time difference between the direct P-wave and Ps-wave converted at the sediment-basement boundary. We can understand that the Ps-P times have a large variety in the range of 0.03 to 1.06 second in the valley. This feature suggests complex basement topography of the valley. The Ps-P time difference and the top of basement depth from the previous velocity structure [15] mostly indicate a linear relationship.

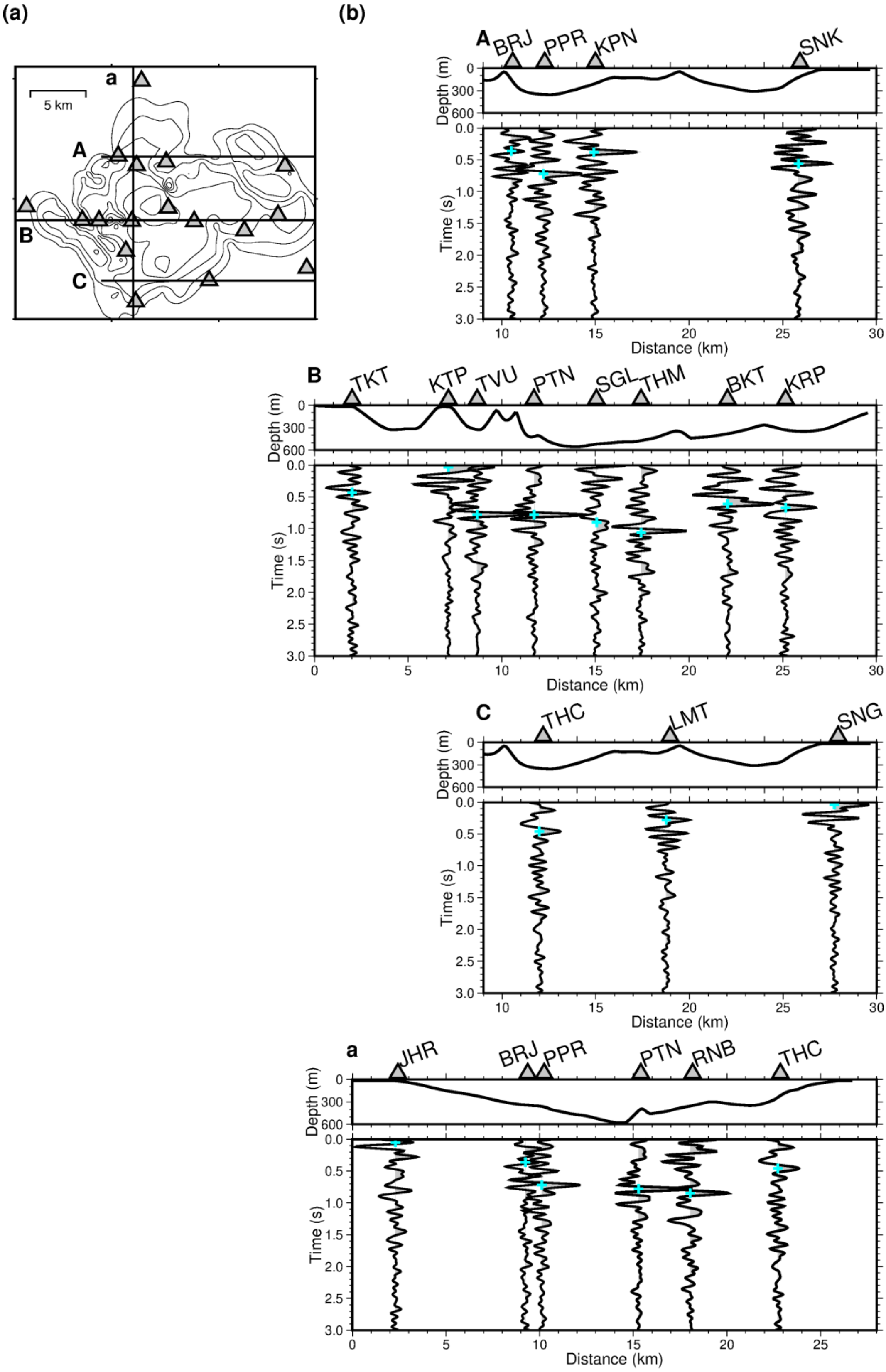

Fig. 5 – (a) Distribution map of the basement depth [15], the strong-motion stations, and cross-sections. (b) Vertical profile of the top of basement depth (upper) and receiver function of each cross-section (lower). The blue crosses mark shows the observed Ps-P times.

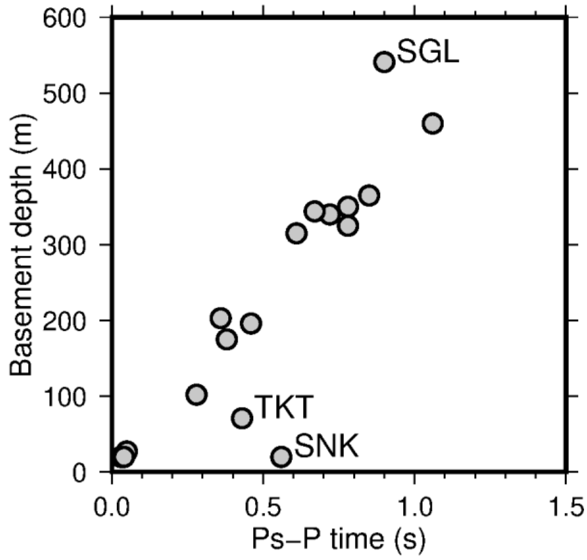

Fig. 6 – Relationship between the observed Ps-P time and the top of the basement depth from Bijukchhen [15].

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