

# Chapter 3

## The Crust and Upper Mantle Structure Beneath the Bangladesh and Its Effects on Seismic Hazard



Ritima Das, Utpal Saikia, and Gokul Kumar Saha

**Abstract** Bangladesh is one of the most densely populated and seismically active region of the world, which is situated on the easternmost part of the India-Eurasia collision zone. It lies at the junction of the three plates—the Indian plate, the Eurasian plate and the Burma plate. With a population over 160 million, the nation Bangladesh is located on a seismically active fold and thrust belt that forms the updip point of an active, oblique subduction zone plunging to the east beneath Myanmar on the eastern edge of the India-Eurasia collision zone. Approximately 15–20 km of sediments have been deposited here during past 55 million years. The process of sedimentation continues till today as the rivers Brahmaputra, Ganges and Meghna flow across the nation Bangladesh and formed the Ganges–Brahmaputra Delta (GBD), the largest delta in the world. The region is mainly an accretionary prism made up mostly of sediments from the cretaceous to the Eocene. Its location on the largest river delta in the world and proximity to the sea puts it at risk for tsunamis and the potential for rivers to overflow their banks in the case of an earthquake. Due to a scarcity of seismic data from Bangladesh, it is still difficult to comprehend the structure of the Bengal Basin and the tectonic forces, which are main sources of its deformation. Understanding the structure beneath Bangladesh is one of the important aspects in order to evaluate its vulnerability towards the earthquake hazard scenario. This study will present an improved 3-D shear wave velocity image of the crust and uppermost mantle beneath Bangladesh region. The shear velocities are obtained from the joint inversion of the receiver function and fundamental mode Rayleigh wave group velocities, which are calculated from the cross-correlation of ambient noise as well as earthquake seismogram. Our findings show that the crust and the

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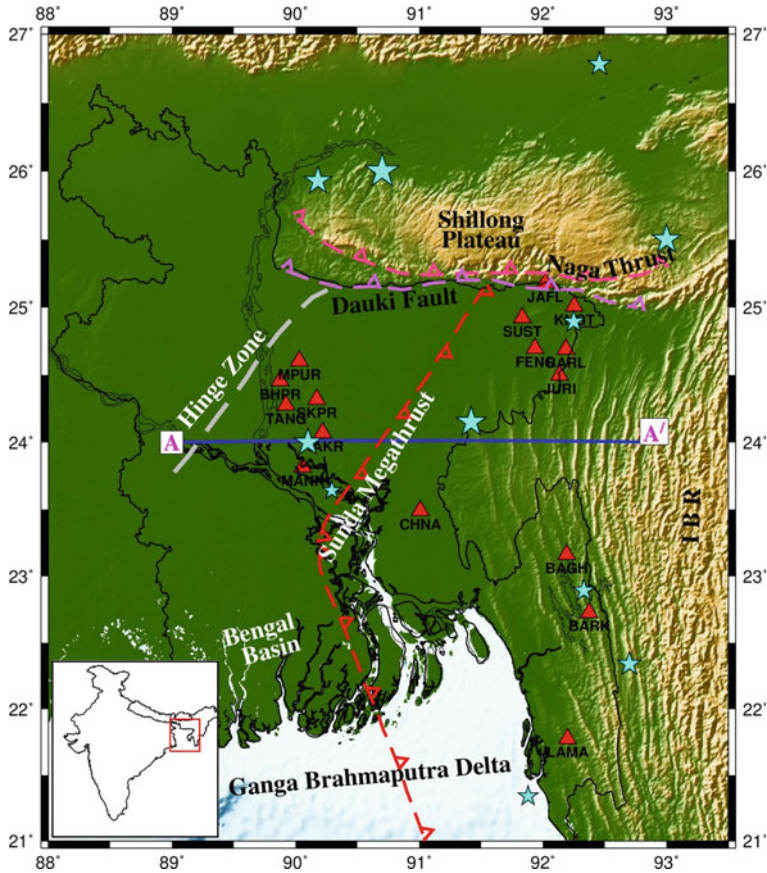
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upper mantle structure beneath Bangladesh region is highly varying. The shear wave velocities of the sediments have been observed up to a depth of ~15 km. We can clearly see the subduction pattern in terms of the velocity along the east–west profile from the Indian craton across the Ganga Brahmaputra Delta (GBD) underthrusting the Burma arc of south eastern Asian plate. The findings help us to understand the particular episode of subduction by placing important restrictions on the sedimentary and lithospheric features throughout the system.

**Keywords** Bangladesh · Bengal Basin · Velocity structure · Earthquake · Seismic hazard

### 3.1 Introduction

Bangladesh is seismically active due to the ongoing India-Asia collision to the north and the Indo-Burmese subduction to the east. It is surrounded by the Shillong Plateau in the north, Indo-Burma ranges in the east, Indian shield in the west and the Indian Ocean in the south. The rivers Brahmaputra, Ganges and Meghna run across the Bangladesh and form the largest delta in the world: The Ganga–Brahmaputra delta in the south of the nation Bangladesh. In the last 55 million years, for about 15–24 km of sediments have been deposited here (Curry 1994; Maurin and Rangin 2009; Singh et al. 2016). The Shillong Plateau is moving southward to the north at the intersection of the Himalaya and Burma Arcs and may signal the start of the Himalaya's forward jump. The Shillong Plateau has a history of vertical uplift dating back to the Cretaceous and is distinguished by a significant positive E-W trending isostatic anomaly. This is due to regional tectonic stresses from the Himalayan collision zone to the north and the Indo-Burma subduction zone to the east (Verma and Mukhopadhyay 1977). Bangladesh has a population of more than 160 million and is situated on a seismically active fold and thrust belt that serves as the updip point of an active, oblique subduction zone that plunges beneath Myanmar on the eastern side of the India-Eurasia collision zone. During the year 1869–1930, five earthquakes of big magnitude earthquakes (Cachar earthquake, 1869,  $m = 7.5$ ; Bengal Earthquake 1885,  $m = 7.0$ ; Great Indian earthquake 1897,  $m = 8.7$ ; Srimongal earthquake, 1918,  $m = 7.6$ ; (m: magnitudes in Richter scale) Dhubri Earthquake, 1930,  $m_s = 7.1$ ) (Akhter 2010; USGS catalogue) had been occurred in the surroundings of Bangladesh (Fig. 3.1), which had major affects in the region. All these earthquakes took place within 250 km distance from the city Dhaka of Bangladesh. Recently on April 28, 2021, another earthquake of magnitude  $m_w = 6.1$  (USGS catalogue) had been occurred in the Kapili fault of Assam which also affected the region. There are also records of moderate magnitude earthquakes (Fig. 3.1), which occurred in Bangladesh and affected the country. Few among them are May 1997 Sylhet earthquake ( $m = 5.6$ ), November 1997 Myanmar border earthquake ( $m_w = 6.1$ ) July 1999



**Fig. 3.1** Tectonic map of Bangladesh and its surrounding region. Red triangles are the seismic stations whose data are used for the study. The faults are marked with the dashed lines. Cyan colour stars are the earthquakes (as described in the text) which had major effects on the Bangladesh area. The size of the stars varies according to the magnitude of the earthquake

Moheshkhali Island earthquake ( $m = 5.1$ ), December 2001 Dhaka city earthquake ( $m = 4.5$ ), July 2003 Rangamati earthquake ( $m_w = 5.7$ ) (Akhter 2010; USGS catalogue). All these earthquakes resulted in loss of lives, collapse of the buildings and mud-walled houses, serious damage to the cyclone shelter column, brick masonry buildings etc. Despite having the spare records of these earthquakes, the 12–24 mm/year of convergent strain accumulation along with  $\sim 8$  mm/year of dextral shear beneath the Indo–Burman Ranges (Mallick et al. 2019) show the presence of seismic hazard in the region. A clear understanding of the internal structure of the Earth beneath the region is necessary for properly analysing this risk. The regional-scale seismic velocity structure beneath Bangladesh remains enigmatic despite the region’s complicated geology context and high degree of seismic hazards, largely because there are not sufficient local or regional seismic waveform measurements. In order to

better describe the structural settings beneath Bangladesh, we have performed a joint inversion scheme to acquire the shear wave velocity structure beneath the region.

## 3.2 Geological Background

Bangladesh that shares the geology of the Bengal Basin is situated in the northeastern region of the Indian Subcontinent, between the Indo-Myanmar Ranges to the east and the Indian Shield to the west. The region is encircled in the north with the Himalayan Foredeep, the Shillong Plateau and the Assam Basin (Roy and Chatterjee 2015; Najman et al. 2016). The south of the basin is opened into the Bengal Fan (Najman et al. 2012). Over the last 55 million years around ~15–20 km of sediments has been deposited by the Ganges–Brahmaputra and the Meghna Rivers which flows through the region and formed the largest delta in the world: the Ganges–Brahmaputra Delta (Alam 1989; Steckler et al. 2008; Singh et al. 2016). This delta is constructed with the deposition of fluvial and delta-plain sediments, including the Tipam Sandstone and Dupi Tila Formation (Johnson and Alam 1991). The source of these sediments is mainly drained from the world's largest orogenic system, the Himalayan Range, the closest areas like Shillong Plateau and the Chittagong-Myanmar fold and thrust belt (CMFB). These sediments created a massive sediment accumulation that is currently approaching the Indo-Myanmar Arc subduction zone by advancing the continental margin of the Indian subcontinent by about 400 km (Steckler et al. 2008). The Chittagong-Myanmar fold and thrust belt (CMFB) is a 250 km wide extend in the eastern part of Bangladesh. Over a horizontal distance of 250 km, the height of the CMFB steadily rises from west to east. It begins close to sea level and rises approximately 1,500 m within the Indo-Burman Ranges. Both the Shillong Plateau and the CFMB began to uplift during the end of Miocene, which is around ~5–8 Ma (Johnson and Alam 1991; Alam et al. 2003). The Shillong Plateau is a large, 2-km-high elevated area that is bordered to the south by the steeply descending, deeply ingrained Dauki fault (Johnson and Alam 1991). The GBD is located close to the syntaxis of the Himalayan and Burma arcs, two plate-convergence borders. The Indian plate is overridden by these arcs from the north and the east, which are convex in the direction of the Indian plate. With its large extending foredeeps and thrust-fold belts, India serves as the foreland of both the Himalayan and Burmese convergent borders. Since the Eocene, continents have been colliding along the Himalayan arc. As the Himalayan collision moved forward, it encircled Assam syntaxis and moved down the Burma Arc from north to south (Lee and Lawver 1995; Uddin and Lundberg 1999). The Himalayan and Burmese arc foredeeps show how the lithosphere beneath the subducting plates bent under their weight (Le Dain et al. 1984). On the eastern side of the GBD, the Burma Arc exhibits all the signs of a subduction zone, including a volcanic belt on the Burma overriding platelet up to 25° N, the latitude of the Shillong Plateau (Steckler et al. 2008).

### 3.3 Seismological Approach for Mapping the Internal Structure Beneath Bangladesh

We have used the method of joint inversion (Julia et al. 2000) of the Rayleigh wave group velocity dispersion along with the receiver functions for the construction of the models. For the surface wave dispersion, we have extracted the values from the surface wave tomography for the entire south Asia using ambient noise and earthquake (Saha et al. 2020, 2021). The receiver functions are constructed from the teleseismic earthquakes recorded in the stations as shown in Fig. 3.1.

#### 3.3.1 Data

In this study, we have used seismic data collected from 16 broadband seismic stations in and around Bangladesh. The data are downloaded from the IU, XI and Z6 network of Incorporated Institutions for Seismology (IRIS) database (Fig. 3.1). The data from the seismograph deployed during 2008–2010 have been used for this study. This data collection was utilised for the construction of the receiver functions. We have used a total of 257 good receiver functions computed from the 16 seismic stations data for this study. We have retrieved the surface wave dispersion values from the entire south Asia using ambient noise and earthquake (Saha et al. 2020, 2021).

#### 3.3.2 Surface Wave Dispersion

For the calculation of group velocity dispersion, we have used the method of multiple filter technique (MFT) developed by Dziewonski et al. (1969), which is later improved by Herrmann (1973), Bhattacharya (1983), Herrmann and Ammon (2004). Both the cross-correlation of data on ambient noise and the data on earthquakes have been used to compute the group velocity dispersions. The continuous vertical component seismograms are used to compute the cross-correlation (Bensen et al. 2008). A total of 18,552 paths recorded at 683 seismic stations have been used to calculate the cross-correlation of the ambient noise. The cross-correlated functions obtained for each pair of stations are then averaged to generate a symmetric signal and stacked to improve the signal to noise ratio (SNR). For the final selection of the data, we have used only those cross-correlation functions whose SNR is greater than 15 and interstation separation is equal to or  $>3$  times the wavelength (Lin et al. 2008). The group velocities were then determined by applying the multiple filter taper analysis to each noise correlation function. After that, from the 417 earthquakes (with magnitude  $> 5.5$ ) recorded at 209 seismic sites, we included group velocities along 3048 pathways across the area. We have selected regional earthquakes with depths ranging from 10 to 95 km that occurred between  $15^{\circ}$  S and  $40^{\circ}$  N and  $31^{\circ}$  to

130° E. The details of the data are published in Saha et al. (2020, 2021). We could able to construct the 2D group velocity maps from 5 to 70 s period averaged for every  $1^\circ \times 1^\circ$  of the study region by using the methodology of Barmin et al. (2001). Saha et al. (2021) give a detailed presentation of the method applied to these sets of data. The resolution test was carried out by creating synthetic data for every checkerboard model in a set that represents the group velocity structures of an imaginary Earth's group velocity structure, computing a solution model using the synthetic data, and comparing the solution velocity models to the synthetic earth models. The resolution of the ray paths used for this analysis for a given time period can be estimated by the distinctness with which the original pattern is reproduced in the inverted model. The cell size of  $1^\circ \times 1^\circ$  provides the maximum resolution of the data used in this study from 5 to 70 s period in the study region. Thus, we could get the fundamental mode Rayleigh wave group velocity maps which are well resolved at  $1^\circ \times 1^\circ$  by the data used in this study from 5 to 70 s period. The Rayleigh wave group velocities are measured for different frequencies. These frequencies are sensitive to different depths inside the Earth. For a layered Earth model, we can show the relationship between the Rayleigh wave group velocity measurements at different frequencies to the different depth in the Earth by means of the sensitivity kernel. The depth sensitivity increases with the increasing time periods. The 5 s period is sensitive to 5–10 km depth and with increasing time period the depth sensitivity increases to a sensitivity of 70 s period to about 130 km depth. The sensitivity kernel gets more flat with increasing time period, which implies of the larger depth averaging. Saha et al. (2021) show the depth sensitivity kernel of the fundamental mode Rayleigh wave group velocities at different time periods for this study region.

### 3.3.3 Receiver Function Analysis

The receiver function (RF) is a routinely used method to extract the information of the interior of the Earth. Here, we have used the iterative deconvolution algorithm (Ligorria and Ammon 1999) in time domain for computing the RFs. The RFs are computed with Gaussian width 1.6, which corresponds to the frequency  $\sim 0.8$  Hz. We have selected the earthquake data recorded for the epicentral distance  $30^\circ$  to  $95^\circ$  and with magnitude greater than 5.5 for the computation of the RFs. The use of the aforementioned distance ranges aids in preventing both complications at a distance larger than  $95^\circ$  brought on by the core-mantle boundary and multiple arrivals in the direct P-wave. Only those seismograms that have a clear P arrival are used which are filtered using a Butterworth high pass filter with a corner frequency of 0.02 Hz after being visually examined corresponding with these events. Using the Taup-Tool-kit (Crotwell et al. 1999), the P arrival on the seismogram is marked in relation to the IASP91 velocity model (Kennett and Engdahl 1991). In order to extract the radial and transverse components, the three component waveforms are then rotated into a great circle and cut 30 s before and 120 s after the predicted P onset. Then by iteratively deconvolving radial components from vertical components in the time domain, these

data are used to construct the receiver functions (Ligorra and Ammon 1999). For further analysis, we have kept only those RFs whose signal to noise ratio (SNR) is greater than 10 and the convolution misfit of the radial component signal power is greater than 80%. The SNR of the receiver function is evaluated using a least squares misfit approach on the original radial waveform. In the misfit criteria, original radial waveform is compared with newly constructed radial waveform.

### 3.3.4 *Joint Inversion of Surface Wave Dispersion and Receiver Function*

We have used the iterative linearised damped least square method by Julia et al. (2000) for the inversion. For this, we have jointly inverted the surface wave dispersion along with the receiver function to obtain the shear wave velocity structure beneath Bangladesh. The surface wave is sensitive to the absolute S-wave velocity at depth and receiver functions provide constraints on velocity contrast. Through their joint inversion, the complimentary properties of the two datasets are utilised to create a better velocity image (Julia et al. 2000; Bodin et al. 2012). The method states to minimise the following function  $S$

$$S = \frac{1-p}{N_r} \sum_{i=0}^{N_r} \left( \frac{O_{ri} - P_{ri}}{\sigma_{ri}} \right)^2 + \frac{p}{N_s} \sum_{j=0}^{N_s} \left( \frac{O_{sj} - P_{sj}}{\sigma_{sj}} \right)^2$$

where,  $N_r$ : Total number of receiver functions.

$N_s$ : Total number of surface wave dispersion.

$O_{ri}$ : Observed receiver function at time  $t_i$ .

$P_{ri}$ : Predicted receiver functions at time  $t_i$ .

$O_{sj}$ :  $j$ th observed surface wave dispersion.

$P_{sj}$ :  $j$ th predicted surface wave dispersion.

$\sigma_{ri}$ : the standard errors in receiver function data set.

$\sigma_{sj}$ : the standard errors in surface wave dispersion data set.

The influence parameter, or factor  $p$ , is an a priori value that modifies the impact of either data set on the minimisation process. The  $p$ 's value ranges from 0 to 1. We set  $p$  to 0.5, which gives the receiver function and dispersion curve fits equal weight. For the initial velocity model, we have considered a half space model with shear wave velocity 4.5 km/s ( $V_p/V_s = 1.73$  and density = 3.3 g/cc) up to a depth of 130 km. We generated the mean dispersion data in a  $1^\circ$  circular bin centred around the station using group velocity maps for the period of 5–70 s. Inversion of the averaged dispersion data is done along with each station's estimated stacked receiver function. The inversion has been performed for all the station of the region. With reference to (Christensen 1996; Rudnick and Gao 2013), the resulting velocity is described

as the upper crust having a corresponding shear velocity of 2.8–3.5 km/s, middle crust having a corresponding shear velocity of 3.5–3.8 km/s, and lower crust having a corresponding shear velocity of 3.8–4.1 km/s.

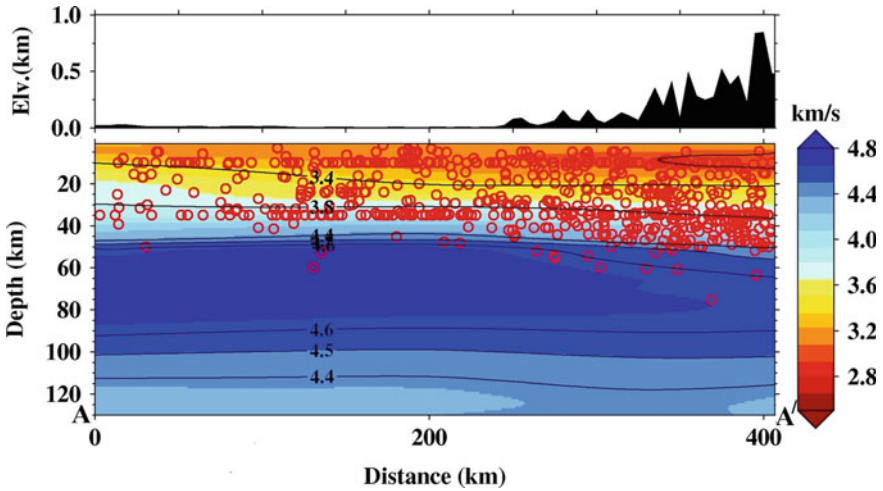
### 3.4 Seismic Hazard Scenario and the Velocity Structure Beneath Bangladesh

Tectonic strain can build up within and around the geological structures of Bangladesh. In the past, these structures have released enough energy to cause destructive earthquakes. The great Indian earthquake (1897,  $m = 8.7$ ) that occurred due to the vertical displacement of the Dauki fault located in the northernmost part of Bangladesh caused an extraordinary shaking of the ground. The Shillong Plateau got pop-up by roughly 20 m in just a few seconds as a result of the earthquake, and debris was blasted miles away from the epicentre. On January 26, 2001, a comparable powerful and exceptional earthquake with a magnitude of 7.5 struck Bhuj, which destroyed major urban areas in Gujarat and took the life of around 25,000 people. Such type of earthquakes is rare but the edges of the Indian peninsula could be severely damaged by this kind of earthquake. Bangladesh is located in the eastern extremity of the Indian peninsula and Kutch Basin located in the western extremity is a mirror image of the Bengal Basin. The eastern and western extremities of the regional geological structures from south to north postulate a geometrical symmetry that would be amenable to identical tectonic behaviour in terms of stress distribution. Keeping this in mind in light of its geological makeup, Bangladesh might be susceptible to large earthquakes. In the easternmost part of Bangladesh, the two tectonic plates (India Eurasia collision) have created a large, nearly flat earthquake-producing fault, which has an estimated seismic potential of Mw 8.2–9.0 earthquake (Steckler et al. 2016; Bürgi et al. 2021). This megathrust underlies the land surface on which over 160 million people reside. In some cases, barely 5 km separate occupied areas from the shallowest part of the megathrust (Bürgi et al. 2021). Bangladesh and the neighbouring nations (India and Myanmar) would suffer terrible consequences from a big earthquake on this system. The dense distribution of the population in the region makes it more vulnerable in terms of the seismic hazard scenario. The 2015 Gorkha Nepal earthquake ( $M = 7.8$ ) is one of such recent evidence, which demonstrate how bad its impact when an earthquake of such magnitude occurred in densely populated area. It illustrated the serious danger that powerful seismic events pose to society and emphasised the requirement for efficient measures to reduce the risk of earthquakes. Bürgi et al. (2021) mapped the geometry of the décollement below the eastern Bangladesh, which is ~9 km deep in northeast and southeast Bangladesh, but shallow ~5 km in the central-east part with an area of about ~150 × 450 km, which is capable of producing an 8.5 magnitude earthquake. Their study hypothesised that the heavier sediment loads in north and south Bangladesh have twisted the décollement and weighed down the earth's surface. The massive sediment deposit in Bangladesh



is also one of the peculiar reasons of chances of occurring a high-magnitude earthquake. According to recent research, the biggest earthquakes occur in subduction zones with deep sediment deposits (Oleskevich et al. 1999; Heuret et al. 2012).

Most of the previous geophysical studies do not contribute much to the crustal structure beneath the Bengal Basin. Many of the studies are either on the north or further northeast of the Shillong plateau. Regarding the composition of the crust that lies beneath the northern Bay of Bengal, two contrasting viewpoints are prevalent. The Rajmahal and Sylhet Traps lie beneath the onshore Bengal Basin, and the continent-ocean boundary (COB) that runs along that line shows the presence of oceanic crust close to the Bangladesh border (Talwani et al. 2016, 2017; Ismaiel et al. 2019). In contrast, the velocity structure of the northern Bay of Bengal from 19° N to 25° N of the Shillong Plateau (Sibuet et al. 2016, 2017) is suggestive of the continental crust that has thinned to a thickness of approximately 10–20 km due to the insertion of volcanic material in the form of sills and seaward-dipping reflectors (SDRs). In the Sylhet Basin, a continental basin located immediately south of the Shillong Plateau (Johnson and Nur Alam 1991), a thinned continental crust was detected onshore Bangladesh (Kaila et al. 1992) and reached a thickness of 30 km south of the Shillong Plateau (Mitra et al. 2006). Singh et al. (2016) observed thinner crust under the Bengal Basin, and the Shilling Plateau and Bengal Basin show no discernible lateral changes from north to south. They calculated the sedimentary thickness varying from ~3 km to ~17 km across Hinge zone using receiver function modelling. They also reported a thickened crust in the deep Bengal Basin, which is 16–19 km thick with higher velocity might be due to the Kerguelen plume, which was active close to the boundary at the period of rifting. Their study finds similar Moho depth under the Shillong plateau and the Bengal Basin. All the above studies are unable to give a clear picture beneath the Bangladesh, which is essential in order to understand the complete hazard scenario of the region. The location of the ocean/continent boundary is also unknown, despite the fact that the large sediment thickness suggests a thin crust. In order to better understand the variation of velocity anomalies as a function of depth, we have plotted the shear wave velocity obtained from our study of joint inversion of surface wave dispersion with the receiver function along a profile at 24° N latitude from west to east of Bangladesh (Fig. 3.2). The velocity profile shows a clear gradual increase of the sedimentary thickness ~5 km to ~18 km from west to east in Bangladesh. A comparatively high velocity crust has been observed beneath the Bangladesh region. We can observe the subducting structure from west to east at ~45 km depth. This is at the Indo Burma subduction zone where we can observe the high sedimentary deposits of around ~20 km. A large accretionary prism has grown due to subduction of the 20 km thick sediment prism (Steckler et al. 2008). The Bengal Basin is obliquely overthrust from the east by the Indo-Burmese subduction zone. The earthquakes that occurred during last 21 years from 2000 to 2021 in the region are also projected along the velocity profile (Fig. 3.2). The pattern of the earthquake occurrences clearly depicts the subduction structure beneath the region. This clearly shows the vulnerability of the region towards the occurrence of the earthquake. Overall, this study provides significant constraints on the sedimentary and lithospheric features present throughout the system, which aids



**Fig. 3.2** Absolute shear wave velocity variation in the vertical cross-sections along the profile at  $24^{\circ}$  N (Fig. 3.1). The earthquakes that occurred are projected along the profile. The information of the earthquakes are taken from the catalogue by International Seismological Centre (ISC) (<http://www.isc.ac.uk/iscbulletin/search/catalogue/>)

in our understanding of the specific event of subduction. Further investigation will be carried out to map the comprehensive structure beneath the entire Bengal Basin along with the Shillong Plateau.

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