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Lateral Moho variations and the geometry of the Main Himalayan Thrust beneath the Nepal Himalayan orogen revealed by teleseismic receiver functions

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SUMMARY

The lateral Moho variations and the geometry of the Main Himalayan Thrust under the Nepal Himalayan orogen are investigated to determine a new crustal model using a large number of high-quality receiver functions recorded by the HIMNT and HiCLIMB portable seismic networks. Our new model shows an evident and complicated lateral Moho depth variation of 8–16 km in the east–west direction, which is related to the surface tectonic features. These results suggest a non-uniformed crustal deformation, resulted from the splitting and/or tearing of the Indian plate during the northward subduction. Our migrated receiver function images illustrate a discernible ramp structure of the Main Himalayan Thrust with an abrupt downward bending close to the hypocentre of the 2015 Gorkha M_w 7.8 earthquake. The distribution of the aftershocks coincides with the present decollement structure. Integrated with previous magnetotelluric soundings and tomographic results, our results suggest that the ramp-shaped structure within the Main Himalayan Thrust could enhance stress concentration leading to the nucleation of the large earthquake. Our new crustal model provides new clues to the formation of the Himalayan orogen.

Key words: Receiver function; Nepal Himalayan orogen; Moho variations; Main Himalayan Thrust; the 2015 Gorkha earthquake.

1 INTRODUCTION

Since 50 Ma, the Tibetan plateau, with the highest topography on the Earth, has been undergoing the continuous deformation caused by certain possible dynamic mechanisms, such as rigid block extrusion (e.g. Tapponnier *et al.* 2001), crustal thickening (e.g. England & Houseman 1986) and/or crustal channel flow (e.g. Burchfiel *et al.* 1995; Royden *et al.* 1997, 2008). The Himalayan arc is widely acknowledged as one of the major zones for the absorption of the Tibetan deformation during the indentation of India into Eurasia (Powell & Conaghan 1973; Tapponnier *et al.* 1990; England & Houseman 1986; Yin & Harrison 2000).

The Nepal Himalayan region, situated in the central Himalayan arc, is generally divided into four major tectonic zones from the south to the north, that is, the Sub-Himalaya (SH), the Lesser Himalaya (LH), the Greater Himalaya (GH) and the Tethyan Himalaya (TH), which are separated by the Main Boundary Thrust (MBT),

the Main Central Thrust (MCT), the Southern Tibetan Detachment System (STDS), with the southern boundary abutting on the Main Frontal Thrust (MFT) and the northern border on the Indus-Tsangpo Suture Zone (ITSZ) (Figs 1 and 2; e.g. Gansser 1964; Le Fort 1975, 1986; Bollinger *et al.* 2004). The GPS measurements showed that the Nepal region had been accommodating the convergence at a rate of approximately 20 or even 40–50 mm yr⁻¹, due to the ongoing northward movement of the Indian plate relative to the stable Eurasian plate (e.g. Bilham *et al.* 1997; Larson *et al.* 1999; Wang *et al.* 2001), leading to the occurrence of multiple large earthquakes with magnitudes larger than 7.5, such as the 1100 Nepal M_w 8.5 earthquake, 1934 Bihar M_w 8.1 earthquake and 2015 Gorkha M_w 7.8 earthquake (Cattin & Avouac 2000; Sapkota *et al.* 2013; Srivastava *et al.* 2013; Sharma *et al.* 2017). Many geophysical and geological investigations (e.g. Li *et al.* 2008; Liang *et al.* 2011; Sapkota *et al.* 2013; Lei *et al.* 2014; Hubbard *et al.* 2016; Lei & Zhao 2016a; Zhou & Lei 2016) have been conducted surrounding this region

Figure 1. Seismic stations used in this study and tectonic map of the central and eastern Nepal Himalayan orogen. The inverted triangles and diamonds indicate seismic stations from the Hi-CLIMB and HIMNT temporary seismic networks respectively. The main tectonic units extracted from Hodges (2000) are shown as areas with different colours. Grey lines delineate the Nepal national border. The concentric-circle symbol denotes the capital city Kathmandu. Seismic station labelled with names are used in Figs 3 and 4. KK, Kathmandu Klippe; SH, Sub-Himalaya; LH, Lesser Himalaya; GH, Greater Himalaya; TH, Tethys Himalaya. MFT, Main Frontal Boundary; MBT, Main Boundary Thrust; STDS, Southern Tibetan Detachment System; ITSZ, Indus-Tsangpo Suture Zone.

Figure 2. Piercing points (brown crosses) of teleseismic rays at 50 km depth, calculated based on the modified IASP91 velocity model (Kennett & Engdahl 1991) shown in the inset map at the bottom left corner. The inverted triangles and diamonds indicate seismic stations used. The inset on the top left illustrates the epicentral locations of teleseismic events used in the *P*-wave receiver function analysis prior to (grey circles) and after (red dots) data processing, whereas that on the top right shows the study area on a larger scale. Abbreviations are the same as in Fig. 1.

recently, but the mechanisms behind those megathrusts in the Nepal region remain debatable. A detailed imaging in the longitudinal and latitudinal variations of crustal structures in the Nepal region could provide new insights into the formation and evolutionary dynamics of the Himalayan orogen as well as the possible mechanisms for the large earthquakes in the region.

Since the mid-Miocene, a series of south-vergent thrust faults have accommodated the shortening across the Himalayan range, gradually forming several distinguishable tectonostratigraphic units (Gansser 1964). These major thrust faults are believed to sole into the Main Himalayan Thrust (MHT) at depth, which serves as a decollement as well as a boundary that separates the Indian crust

below from the Himalayan crust above (e.g. Wobus *et al.* 2006). Disparity exists between how geologists and geophysicists perceive of the MHT geometry (e.g. Schutle-Pelkum *et al.* 2005; Wobus *et al.* 2006; Nabelek *et al.* 2009; Cannon & Murphy 2014). The detailed structure of the MHT decollement is still an open question. In addition, although it is widely accepted that the Indian crust has been subducting beneath the Himalayan orogen, resulting in a gradual deepening Moho discontinuity to ~ 70 km depth in the latitudinal direction (e.g. Kosarev *et al.* 1999; Kind *et al.* 2002; Schutle-Pelkum *et al.* 2005; Nabelek *et al.* 2009), the longitudinal variation of the Moho discontinuity beneath the Himalayan orogen has yet to be investigated more thoroughly.

In this paper, we employ several receiver function imaging techniques to investigate the Moho and MHT structures in the Nepal region. Special emphasis has been placed on the observation and interpretation of a complicated Moho variation in the longitudinal direction and the interpretation and analysis of the MHT geometry in the region.

2 DATA AND METHOD

2.1 Data

The data used in our study originate from a combination of two portable seismic experiments, HIMNT (Himalayan Nepal Tibet Seismic Experiment) and HiCLIMB (Himalayan-Tibetan Continental Lithosphere During Mountain Building) (Fig. 2). The HIMNT is an IRIS-PASSCAL temporary network consisting of 29 broadband seismometers deployed in eastern Nepal and southern Tibet between October 2001 and March 2003. The stations were installed in a 2-D grid with approximate station spacing of 50 km. Each station was equipped with a three-component Streckheisen STS2 broadband seismometer, and the data were continuously recorded at 40 or 50 samples s^{-1} . The HiCLIMB is an internationally collaborated seismic experiment that was in operation from September 2002 to August 2005. This experiment deployed a dense linear array that extended from the SH region to central Tibet with the average station spacing of 5 km (Nabelek *et al.* 2009). In this study, only 126 stations to the south of $30^{\circ}N$ are selected from the HiCLIMB experiment, which reside within the Nepal Himalayan zone, to image the crustal structure beneath the study region (Figs 1 and 2).

In order to obtain a sufficient number of receiver functions, we adopt two different criteria for these two experiments in selecting teleseismic events with epicentral distances ranging from 30° to 90° . For the HiCLIMB experiment, the magnitude of teleseismic events for the receiver function analysis is greater than 5.5, and a total number of 620 teleseismic events are used. For the HIMNT experiment, a minimal magnitude of teleseismic events is set to 5.0, considering its short time span of deployment, and a total number of 803 teleseismic events is adopted. Fig. 2 shows the distribution of events chosen. Most events are located in the western Pacific subduction zone, and some in the mid-oceanic ridges.

2.2 Method

Receiver functions are extracted using the standard data processing procedure, which can be summarized into data pre-processing, rotation, deconvolution and moveout correction. During data pre-processing, all the seismograms are cut 20 s prior to and 200 s after the theoretical arrival times of the direct P waves. We remove the instrument response, the linear trend and the mean value in the raw

data. The displacement of ground motion is recovered using mathematical convolution. All the traces are band-pass filtered from 0.01 to 10.0 Hz, where seismic energies in 0.1–1.0 Hz are fully reserved but that in 0.01–0.1 Hz and 1.0–10.0 Hz are attenuated using the first quarter cycle of a cosine function. The filtered seismic waveforms are then carefully inspected, and those with both clear P -wave onsets and high signal-to-noise ratios (larger than ~ 5.0) are kept. Here, the signal-to-noise ratio is defined as the ratio of the maximal amplitude of the first P -wave onset to the maximal amplitude within 5 s before the P -wave arrival. A total number of 7096 seismic waveforms have been visually selected for further processing.

After finishing pre-processing the data, all the selected seismic waveforms are rotated from their original Z–N–E component system into ray coordinate system L–Q–T based on event backazimuth and incident angle determined from the radial–vertical covariance matrix of the P -signal of original data (Vinnik 1977). We adopt the least-squares wavelet deconvolution technique proposed by Berkhout (1977) to retrieve the receiver functions, wherein the effects of rupture process and ray path below the converting interface are excluded. The yielded receiver functions mainly contain the amplitudes and delay times of both the P -to- S converted (P_s) waves and multiples generated at different depths of discontinuities. In order to eliminate the difference in the P_s arrival times due to the different epicentral distances and focal depths, the moveout correction has been performed before further imaging, where a reference slowness of 6.4 s deg^{-1} is used.

With the aim to shed light on the same subsurface structure from different angles of view and to enhance the robustness of our results and interpretation, we construct receiver function images beneath the region along different profiles using four different imaging techniques. They are (1) stacked receiver functions imaging beneath each station (e.g. Kind *et al.* 1995; Yuan *et al.* 1997; Gilligan *et al.* 2015), (2) stacked receiver functions in a bin of 20 km shifting every 10 km (or common-depth-point (CDP) stacking receiver functions) (e.g. Zhang *et al.* 2014), (3) backprojection migration or common-conversion-point (CCP) stacking (e.g. Kosarev *et al.* 1999) and (4) migration imaging along the Fresnel zone (e.g. Kind *et al.* 2002; Shi *et al.* 2015). For the former two techniques, we obtain the arithmetic mean of all the receiver functions at each station as well as within each bin containing the theoretical receiver functions piercing at different Moho depths to strengthen indistinct coherent signals and suppress incoherent scattering energies. For the latter two techniques, the amplitude vectors of each receiver function are backprojected and stacked along their own ray paths. Different techniques adopt different cell sizes. For the backprojection migration imaging, the cell is set to 1×1 km in the horizontal and vertical directions. All the amplitudes in a bin are stacked and normalized by the number of the traces in the bin, whereas the amplitudes of bins with no ray piercing through are assigned to be null. For the Fresnel-zone migration technique, we employ the size of the first Fresnel zone as the horizontal smoothing factor to generate the final image. The width of the Fresnel zone represents the minimal lateral resolution of the CCP stacking.

We have also evaluated the effects of different velocity models from previous studies (e.g. Kennett & Engdahl 1991; Schutle-Pelkum *et al.* 2005; Guo *et al.* 2009; Caldwell *et al.* 2013) on our final migration results (see Supporting Information Fig S1). Our test results demonstrate that under different velocity models, there exists no discrepancy in the pattern of the Moho variation as well as that of the shallower discontinuities above the Moho depth, given a fixed V_p/V_s ratio of 1.75 is chosen. As for the impact on the absolute value of the Moho depth, our tests exhibit that different P - or

S-wave velocity models with a fixed V_p/V_s ratio might lead to up to a ~ 2.5 -km-Moho variation for a crustal thickness of 80 km, which is in general agreement with the estimated influences by previous receiver function studies (e.g. Zhu & Kanamori 2000; Kind *et al.* 2002; Yuan *et al.* 2002; Caldwell *et al.* 2013). This is mainly due to the fact that the receiver function analysis uses the differential traveltimes between the P_s waves and the incident P -wave, and thus the estimations of the Moho depth from receiver function analysis are less sensitive to the absolute value of V_s or V_p (Zhu 2000; Kind *et al.* 2002; Yuan *et al.* 2002) compared with the V_p/V_s ratio. Nevertheless, assuming the ~ 2 per cent variation in each parameter, if considering possible variations in both V_p (or V_s) and V_p/V_s ratio, one might get about up to a ~ 5 per cent variation in the Moho depth as shown in the velocity test by Kind *et al.* (2002). This implies that it might correspond to a ~ 3 km error for a Moho depth of 60 km. Furthermore, due to the drastic thickness-varied crust and the very thick crust in the region, thus the actual error in the estimation of the Moho depth could be much larger.

In this study, we use a modified velocity model containing an 80-km-thick crust (Fig. 2) to ensure that the calculation of the P_s traveltimes is based on the crustal rather than mantle velocity. Prior to the migration imaging, we perform the elevation corrections for all the stations used in our study region so that the imaged discontinuity depths are all referred to the sea level.

3 RESULTS

3.1 Receiver function analysis beneath the stations

Fig. 3 shows examples of receiver functions for the stations BUNG, SAGA, H0380 and H0420. These receiver functions are obtained in the three different frequency bands, 0.03–0.5, 0.03–1.0 and 0.03–2.0 Hz. In Fig. 3, strong converted phases are visible in the first 10 s. Except for the station H0380, receiver functions recorded at the other three stations BUNG, SAGA and H0420 have the maximal positive amplitudes from 5 to 9 s, which represents the converted energy excited by the Moho discontinuity. For the station H0380, the maximal energy is detected before 2 s in the bands of 0.03–1.0 Hz and 0.03–2.0 Hz, but it becomes invisible in the band of 0.03–0.5 Hz where only long period (larger than 2 s) energies are allowed. Similar frequency-depend phenomenon can also be observed in the station H0420 where the shallower high amplitude energy is suppressed in the band of 0.03–0.5 Hz. All the receiver functions in the two shorter period bands have no significant differences, suggesting that most of the frequencies of converted energy are less than ~ 1.0 Hz. Another intriguing feature in Fig. 3 is that compared with the station SAGA situated within the ITSZ, the subsurface structures beneath the stations BUNG, H380 and H420 near the MBT, are much more complicated. Fig. 4 shows the receiver functions stacked in the backazimuthal bin at the four stations H1090, DINX, TUML and NBENS. For the station H1090, the arrival time of the maximal positive energy of receiver functions varies from 8 to 9.5 s apart from the sedimentary energy within the first 3 s (Fig. 4a), and there are visible differences between the amplitudes of summed waveforms impinging from both the north and the south in the backazimuth of the teleseismic events used (Fig. 4c). Beneath the station DINX (Figs 4b and d), two prominent double positive energies emerge at about 5 and 8 s, respectively, where the shallower positive amplitude could be interpreted as partial eclogitization of the lower crust (e.g. Kind *et al.* 2002; Schutle-Pelkum *et al.* 2005). For the stations TUML and NBENS, although there are azimuthal variations in the

binning stacked receiver function waveforms (Figs 4e and f), the summed receiver functions from both the north and the south in the backazimuth of the teleseismic events used roughly have no significant differences (Figs 4g and h).

3.2 Stacked receiver functions along the profiles

In order to reveal the features of different subsurface structures and Moho variations along the Himalayan arc and perpendicular to the collision zone, we plot the stacked receiver functions for each station along seven profiles, three along the Himalayan arc and four perpendicular to the collision zone (Fig. 5h). It can be seen that the energy pattern of P_s conversions from the Moho and shallower structure varies significantly. For the stacked receiver functions near the MBT, the energy from P_s conversions displays an exceptional complicated feature (Fig. 5c), indicating an intense disruption of the upper Indian crust as it is sheared and stacked to form the Himalayan orogen.

The Moho phase generally appears later in the north than that in the south (Figs 5a–c). Along the Nepal Himalayan orogen, the delay times of P_s conversion from the Moho differ by up to ~ 2 s (Fig. 5a), equivalent to an over-16-km variation in the Moho depth. Extremely strong P_s energies emerge within the first 2 s south of 27.4° N beneath the Nepal Himalayan transect (Fig. 5f), suggesting a thick sedimentary layer beneath the Himalayan foreland basin. For the two N–S profiles extending from $\sim 27^\circ$ to $\sim 29^\circ$ N, progressive deepening of the Moho with different dipping angles can be clearly observed (Figs 5f and g).

Due to the strong heterogeneity of the crustal structure beneath the Himalayan collision zone, receiver functions beneath the same station could also be azimuthally dependent, and thus simplified averaging the receiver functions based on the stations could lead to a highly complicated waveform containing information of discontinuities at different locations. In order to effectively investigate the continuous Moho variation and to enhance the reliability of the observed energy excited by the Moho discontinuity, we also stack receiver functions binned according to their piercing points at certain depths (Fig. 7). The CDP stacking technique could significantly suppress incoherent noises and render a more smoothly varied Moho geometry.

The image of binning stacked receiver functions illustrates a strong lateral variation along the major thrust zones (Figs 6a–c). An evident deepening of the Moho discontinuity to the centre of the profile along the MBT can be distinguished (Fig. 6c). Along the profile beneath the TH, a prominent feature of the doublet Moho energy is clearly visible in the section eastward to 86° E, whereas the Moho energy in the western 50 km part of this profile is diffusive (Fig. 6b). In the ITSZ, the Moho also demonstrates the most evidently lateral variation in all three profiles along the Nepal Himalayan orogen (Fig. 6c). Along the profiles of the Himalayan collision, no distinct Moho variations appear to emerge across the MFT or MBT (Figs 6d and e). A dipping Moho is clearly imaged along the profile EE', reaching an averaged delayed time of ~ 9 s to the north of 29° N (Fig. 6e). The steepening of the Moho becomes less pronounced in the eastern Nepal Himalayan orogen, but a clearer doublet Moho can be easily discerned (Fig. 6f).

3.3 Backprojection and Fresnel-zone migration imaging

Even though binning stacked receiver functions could provide a more continuous and explicit trend of the Moho variation along

Figure 3. Individual receiver functions in different frequency bands for four stations, BUNG, SAGA, H0380 and H0420, as shown in Fig. 1, located in different tectonic units. The upper bounds of the frequency bands are set to 2, 1 and 0.5 Hz, respectively, whereas the lower bound is set to 0.03 Hz. The coloured top panel shows the stacked receiver functions.

Figure 4. Azimuthally binned stacked receiver functions for the stations H1090 (a), DINX (b), TUML (e) and NBEWS (f) (stations are shown in Fig. 1) and the summed receiver functions impinging to the station from the north and the south (c, d, g and h). The data are stacked using a bin of 20° in the backazimuths but without overlapping between adjacent bins. Since most receiver functions calculated in a range of 0° – 180° in the backazimuth, only these receiver functions are displayed.

the profile, one inevitable shortcoming of stacking receiver functions according to their assumed P_s conversion depth is the muffling of highly incoherent energies excited at the discontinuities shallower than the Moho. In order to clearly observe the detailed crustal structure, we employ two independent imaging techniques, the backprojection migration and the Fresnel zone projection migration, to map the subsurface structure in the study region. First,

we apply the backprojection migration imaging, or commonly referred to as the CCP stacking technique, in which amplitudes are backprojected along ray paths and then accumulated and normalized in specified bins, and they are laterally smoothed over a certain area. A further imaging approach implemented is the backprojection along the range of the Fresnel zone, which defines the lower limit of seismic resolution. The radius of the Fresnel zone depends

Figure 5. (a–g) Binning stacked *P* receiver functions along seven profiles. Along each profile, only stations within a range of 20 km off the profile are selected. Positive amplitudes are denoted as red colour and negative amplitudes as blue. Black dotted lines are inferred tracks of the Moho. (h) Locations of profiles (yellow lines). Seismic stations used are indicated as triangles and diamonds. MFT, Main Frontal Boundary; MBT, Main Boundary Thrust; THZ, Tethyan Himalayan Zone; ITSZ, Indus-Tsangpo Suture Zone; CNHO, Central Nepal Himalayan Orogen; ENH, Eastern Nepal Himalaya.

on both the depth and wavelength, thus it gradually expands with depth.

Several interesting features can be clearly observed in the migration image (Fig. 7). The first one is that there exist two prominent positive converters along the entire E–W profiles beneath the TH at depths of ~40–50 km and ~55–65 km (Fig. 7b), suggesting a rather ubiquitous presence of the lower Indian crust conversion during the initial bending stage of the Indian lithosphere underthrusting beneath the Himalayan orogen. Similarly, previous results also showed high *P*-wave velocities (Schulte-Pelkum *et al.* 2005), high densities (Hetenyi *et al.* 2007) and low *V_p/V_s* ratios (Wittlinger *et al.* 2009) in the region, suggesting the presence of eclogitization within the Moho doublet layer beneath the GH, TH and Lhasa blocks. The positive converter at depths of ~15–20 km above the ~60-km-depth Moho to the north of the STDS might represent the onset of eclogitization when the Indian crust embarks upon the strong bending under the increasing resistance, which can be demonstrated by previous receiver function images (e.g. Schulte-Pelkum *et al.* 2005; Acton *et al.* 2011; Caldwell *et al.* 2013; Shi *et al.* 2015). Eclogites have been documented locally in the structural culminations under the Himalayan region or the north Himalayan gneiss domes. The rocks that contain the eclogites are probably of the GH affinity (Tonarini *et al.* 1993; O'Brien *et al.* 2001). These rocks were evidently metamorphosed during the Eocene time and subsequently exhumed from depths of up to ~100 km to the mid-crustal levels during the late Eocene–Oligocene time (Chemenda *et al.* 2000; O'Brien *et al.* 2001; Kohn & Parkinson 2002).

Although the shallower crustal structures above the Moho discontinuity along the ITSZ appear to be less complicated than those

along the MHT (Figs 7a and c), both the depth and pulse shape of Moho conversions along the ITSZ vary significantly, where the Moho converter around 86° E is broad and deep but becomes relatively narrower and shallower to the east of 86° E, implying a highly inhomogeneous crust-to-mantle transition beneath the orogenic suture zone (Fig. 7c).

There are evident differences in the steepening extents of the Moho depth along the profiles across the central Nepal Himalayan orogen and eastern Nepal Himalaya (Figs 7f and g), possibly implying that the Indian crust is not being subducted as a coherent unit, and during the subduction the Indian lithosphere could have encountered different resistances in the different areas, due to the strong lateral heterogeneities of the deep mantle (e.g. Huang & Zhao 2006; Li *et al.* 2008).

4 DISCUSSION

4.1 Comparison with previous studies

Our crustal structure is generally consistent with some previous results (e.g. Schulte-Pelkum *et al.* 2005; Nabelek *et al.* 2009) in the region. From south to north, across eastern Nepal Himalaya, both our model and the model of Schulte-Pelkum *et al.* (2005) show a dipping Moho as well as a doublet Moho beneath the THZ. Across the central Nepal Himalaya, both our model and the model of Nabelek *et al.* (2009) illustrate a similar pattern of the Moho variation. Nevertheless, there are also some significant differences between our

Figure 6. (a–g) CDP stacking of P receiver functions along the same profiles as shown in Fig. 5. For different profiles, different Moho depths from 45 to 70 km are adopted when calculating theoretical locations of piercing points. The receiver functions are projected to the corresponding profiles using bins of 20 km along and 40 km perpendicular to the profile but with a 10 km overlapping. Black dotted lines are inferred tracks of the Moho. (h) Locations of profiles. Piercing points of teleseismic rays are shown as crosses.

and previous studies. First, the dataset used in this study is the combination of two separate seismic networks, which not only provides a better coverage in the region, but also offers us an excellent opportunity to investigate the west–east Moho variations. Second, quality-control procedures of receiver functions adopted in this study are different from those in the previous work of Nabelek *et al.* (2009). In the study of Nabelek *et al.* (2009), the data were selected automatically, while in this study all receiver functions have been visually inspected and carefully selected with consideration of the signal-to-noise ratios, the degree of consistency when receiver functions are grouped backazimuthally and epicentrally under the same station, and the detection of abnormality of receiver functions before the P -wave arrival or after 12 s of P -onset. Last but not the least, pronounced contrasts can be noticed in terms of approaches to image the underlying shallower structure above Moho discontinuities. Nabelek *et al.* (2009) derived the final migrated image by combining the images of P_s conversions with images of migrated PpS and PsS , assuming that the multiples phases (PpS and PsS) could also represent a coherent conversion from a shallow structure. However, multiples could improperly interfere with converted phases due to their nature of complexity. In our study, we only employ P_s conversions migration for our final interpretation in view of the attested robustness of P_s receiver functions (e.g. Kosarev *et al.* 1999; Kind *et al.* 2002). As a consequence, the geometry of the MHT in our new model is rather different from the previous results in the region (e.g. Schult-Pelkum *et al.* 2005; Nabelek *et al.* 2009). Previous studies showed a smooth MHT geometry in the Nepal Himalayan orogen (e.g. Schult-Pelkum *et al.* 2005; Nabelek *et al.* 2009), but in this study an abrupt ramp structure of the MHT can be observed, quite

similar to the feature appeared in the other parts of Himalaya in the more recent studies (e.g. Acton *et al.* 2011; Caldwell *et al.* 2013). The image and detailed interpretation of the MHT can be seen in Section 4.4.

4.2 Lateral variation of the crustal thickness during the continental collision

Most of previous receiver function studies in the Himalayan orogen (e.g. Schult-Pelkum *et al.* 2005; Rai *et al.* 2006; Oreshin *et al.* 2008; Nabelek *et al.* 2009; Acton *et al.* 2011; Caldwell *et al.* 2013; Gilligan *et al.* 2015) focused on imaging how the Indian plate plunges beneath the Himalaya and Tibetan plateau mostly owing to the distribution of seismic stations. However, the laterally plunging geometry of the crust is of equal importance for understanding the formation and evolution of the Tibetan plateau. In this study, we illustrate the overall architecture of the Moho variations in the collision zone to reveal how the underthrusting crust responds to the formation of the Tibetan plateau using the Moho depths extracted from the CDP stacking technique mentioned in Section 3.2 (Fig. 8b).

Lateral Moho depth variations are clearly identifiable from ~ 8 km along profile CC', and ~ 13 km along profile BB' to ~ 16 km along profile AA' (Fig. 8a). The dipping angle varies from $\sim 27^\circ$ along profile FF' to $\sim 20^\circ$ along profile GG' (Fig. 8a). These results suggest that the subducting Indian plate has experienced different extents of deformation in different parts of the Nepal Himalayan orogen along the Himalayan arc as the Indian plate makes indentations northward beneath the Tibetan plateau.

Figure 7. (a–g) Backprojected (top) and Fresnel-zone (bottom) migration images in the depth domain along the profiles as shown in Figs 5 and 6. Topography (polygons) and stations (inverted triangles) are displayed on the top. Black dotted lines are inferred tracks of the Moho.

The non-uniform underthrusting may be caused by two plausible dynamic processes—tearing of the subducted Indian slab and complicated convergence during the continental collision. In the first scenario, if the accumulated strain goes beyond the strength of the plate, the slab might break into the segmentation along the internal weaknesses (Rosenbaum *et al.* 2008). Modification of the physical properties in the subducting slab and severely accumulated strain in the slab can provide a locus for incipient tears (Kennett & Furumura 2010). Based on the shear wave splitting measurements, Chen *et al.* (2014) suggested the possible tearing of the Indian lithosphere with the different subduction angles. This has been supported by the finite-frequency tomographic model of Liang *et al.* (2011) which

showed some high-velocity anomalies extending from the Moho to ~200 km depth along the GH.

For the second case, it has been long acknowledged that there exist two convergent mechanisms for the absorption of the Indian mantle lithosphere in the collision zone. One is the flat underthrusting of the Indian plate, proposed by Argand (1924) and demonstrated by many recent studies (e.g. Zhou & Murphy 2005; Huang & Zhao 2006; Li *et al.* 2008; Nabelek *et al.* 2009; Zhou & Lei 2016; Lei & Zhao 2016b), and the other is steep subduction, where the Indian lithosphere plate plunges steeply into the asthenosphere (e.g. Kosarev *et al.* 1999; Replumaz *et al.* 2010; Oreshin *et al.* 2008). Our finding of the lateral variations of the Moho discontinuity might contain

Figure 8. The Moho architecture beneath the Nepal Himalayan orogen. (a) Moho depth variations along profiles AA' to GG'. (b) Colour map of Moho variations beneath the Nepal Himalayan orogen. The star represents the epicentre of the 2015 Gorkha earthquake. The dotted grey lines delineate the major tectonic units as shown in Fig. 1. For the areas where there are no receiver function piercing points, the Moho depth is interpolated using curvature splines with a 0.8 tension factor.

these two convergent mechanisms of both flat underthrusting and steep subduction (e.g. Huang & Zhao 2006; Li *et al.* 2008). Shi *et al.* (2016) also observed the dramatic west–east changes of the crustal and upper-mantle structure in the central India–Tibet collision zone, as suggested by Lei & Zhao (2016a).

4.3 The Moho architecture under major geological units

This study shows that the Moho depth variations are related to the geological features on the surface (Fig. 9). Beneath the SH zone the Moho depth variations reaches ~4 km, from ~40 km depth in the west to ~44 km depth in the centre of the study region. Beneath the LH zone, the Moho dips smoothly from 83°E to 86.5°E in the central and western parts of our study region, whereas the dipping angle of the Moho becomes complicated in the eastern part, where the Moho depth reaches ~50 km eastward to 86°E in contrast to ~44 km in the west. Across the MCT or the STDS, no abrupt

steepening has been observed. Another rather interesting finding is that there are obvious differences in the Moho architecture from the west to the east beneath the TH zone. In the west, the Moho discontinuity changes sharply by up to 14 km from the south to the north, whereas in the east it changes gently, only by 8 km. Such a phenomenon was also observed by Zhao *et al.* (2010) and Acton *et al.* (2011) beneath the TH zone to the west of the region. This could be resulted from the different subduction angles of the Indian plate, the steep subduction between 85.5°E to 86.5°E and the flat underthrusting east of 87°E, consistent with the interpretations of previous studies (Kosarev *et al.* 1999; Tilmann *et al.* 2003; Li *et al.* 2008). Within the ITSZ, our results also show some significant variations in the Moho discontinuity, amounting to ~16 km along and ~10 km across the zone, which, apart from the possible cause of the slab tearing discussed above, could also be due to the hot material upwelling resulted from the large change in the subduction

Figure 9. Moho variation beneath major geological units in Nepal Himalayan orogen. The red star symbol represents the epicentre of the 2015 Gorkha earthquake. The red lines stand for the contours of Moho depth with an interval of 2 km. SH, Sub-Himalaya; LH, Lesser Himalaya; GH, Greater Himalaya; TH, Tethys Himalaya; ITSZ, Indus-Tsangpo Suture Zone.

angle of the Indian slab around the zone (Tilman *et al.* 2003). This requires further investigations.

4.4 The geometry of MHT

Since the early Pleistocene, $\sim 2 \text{ cm yr}^{-1}$ of convergence between the Indian and Eurasian plates has been absorbed across the central Himalaya (Bilham *et al.* 1997). Such convergence is commonly interpreted to be accommodated along the MHT, which reaches the MFT on the surface (Lavé & Avouac 2000). For the behaviour of the MHT, previous studies suggested that during the interseismic period, the downward dip fault is locked from the surface to a creeping ductile shear zone beneath the GH region (e.g. Avouac 2003). However, the morphology of the MHT interface beneath the continental collision zone remains controversial in the geosciences field (e.g. Schulte-Pelkum *et al.* 2005; Acton *et al.* 2011; Cannon & Murphy 2014; Coutand *et al.* 2014). Some researchers suggested a smoothly deepening MHT geometry (e.g. Schulte-Pelkum *et al.* 2005; Nabelek *et al.* 2009), whereas others indicated a steeper ramp linking gentler sections from the LH to the GH (e.g. Acton *et al.* 2011; Caldwell *et al.* 2013). To address this question, here we investigate the detailed structure of the MHT using a large number of receiver functions. In addition, to confirm which seismic converter is interpreted as the MHT, it requires the related lithologic structure juxtaposed across the MHT throughout the region.

It is commonly acknowledged that the MHT serves as a decollement containing a kilometre-thick layer of the Tertiary fluvial deposits (Srivastava & Mitra 1994; Robinson *et al.* 2006) and separates the overlying Proterozoic metasedimentary rocks (the LH sequence). Thus the MHT should be characterized by the lower seismic velocities. As observed in our receiver function migration imaging, a sharp velocity decrease at depth of $\sim 10 \text{ km}$ can be clearly visible between 27.6°N and 28.7°N (Fig. 10). At the same place, high conductivities have also been revealed by previous magnetotelluric studies (Lemonnier *et al.* 1999; Patro & Harinarayana 2009; Rawat *et al.* 2014). Here, this low-velocity and high-conductivity layer

can be interpreted as the MHT. The MHT appears to be flat south of $\sim 28^\circ \text{N}$, turns abruptly steeper beneath $\sim 28^\circ \text{N}$ and becomes flat again north of $\sim 28^\circ \text{N}$ (Fig. 10). Similar variation of the MHT structure, or a ramp structure, was also found by Lemonnier *et al.* (1999), Caldwell *et al.* (2013), Unsworth *et al.* (2005) and Rawat *et al.* (2014). The disruption of the flat MHT geometry could also be a sign of the acceleration of the thinning process of the Indian upper crust during the continental collision. In addition, the presence of free fluids around the lower corner of the ramp and the absence of propagating metamorphic fluids trapped below the MHT north of the ramp are proposed by Rawat *et al.* (2014). We therefore interpret the negative (blue) conversion as the MHT at the bottom of the ramp structure (from 28.0°N to 28.2°N) in our migration imaging, similar to the results of Caldwell *et al.* (2013).

Further north, the MHT separates the LH metasedimentary rocks from the Indian basement, thus the seismic signature of the MHT could switch to a positive 'red' converter instead of the 'blue' (negative converter)-over-red' pair of stripe. Therefore, a positive impedance contrast to the north of ramp is interpreted to represent the north part of the MHT decollement. Although the seismic signature of the MHT becomes invisible around 28.9°N , it appears again at $\sim 29.0^\circ \text{N}$ (Fig. 10). Further north, a second ramp structure is found near the ITSZ from $\sim 30 \text{ km}$ depth at $\sim 29.15^\circ \text{N}$ to $\sim 50 \text{ km}$ depth at $\sim 29.35^\circ \text{N}$. A similar feature of the MHT seismic structure has also been reported by Hauck *et al.* (1998) to the east of our profile using the seismic reflection method.

4.5 Relationship of the MHT to the 2015 Gorkha main shock and aftershocks

On April 25, 2015 the Gorkha M_w 7.8 earthquake shocked Nepal, resulting in an enormous death toll of 8786. Many studies have been made to understand the mechanism of the main shock (Avouac *et al.* 2015; Galetzka *et al.* 2015; Elliott *et al.* 2016; Hubbard *et al.* 2016). Here, we discuss the relationship of the large earthquake and

Figure 10. CCP stacking images using four different schemes along profile FF'. (a) Backprojected migration imaging with a bin size of 1 km. Amplitudes are normalized in fractions of the magnitude of the incident *P*-wave for each receiver function. (b) CCP stacking with a bin size of 1 km in the vertical direction and 5 km in the horizontal direction. (c) 15 km horizontally smoothed CCP stacking image. (d) Fresnel-zone migration image. The black thick solid line represents the possible MHT, whereas the dashed grey lines, MFT, MBT, MCT and STD are the same as shown in Fig. 1. The dashed grey line is our proposed concealed fault that is possibly related to the 2015 Gorkha earthquake. The panel on the top shows the topography as well as the surface tectonics as shown in Fig. 1. GT represents the Gorkha concealed thrust, a possible structure buried beneath the Kathmandu Klippe linking the surface structure to the ramp on the MHT.

its aftershocks with our present crustal structure. Fig. 10 superimposes the hypocentres of the 2015 Gorkha main shock and its 233 aftershocks on our receiver function migration images. These earthquakes are determined by Bai *et al.* (2016) using the HYPOSAT location method of Schweitzer (2001), and their uncertainties in focal depth could be larger than those (2.0 km) estimated by Wang *et al.* (2017) who used waveform data rather than just arrival times.

Most aftershocks occurred to the south of the main shock with a majority of focal depth less than 15 km, which are well matched with the flat geometry of the MHT south of 28°N. The southern edge of the aftershock zone is very close to the MBT. Pandey *et al.* (1995, 1999) also found that most earthquakes along the Himalayan orogen are distributed parallel to the MHT structure. The distribution of the Gorkha aftershocks seems to take an abrupt halt around the bending of this 'blue-over-red' pair of stripes. Further north, the main shock seems to be generated at a greater depth compared with the majority of its aftershocks (Avouac *et al.* 2015; Galetzka *et al.* 2015; Grandin *et al.* 2015; Elliott *et al.* 2016; Bai *et al.* 2016; Lay *et al.* 2017; Wang *et al.* 2017), and is located north to the lower corner of the ramp structure along the central Nepal Himalayan orogen profile (Fig. 10). As illustrated in Figs 10 and 11, the 2015 Gorkha earthquake seems to originate not directly at the bottom of the ramp structure, which might serve as a locked structure for the bursting of major earthquakes, but several kilometres north to the lower

corner of the ramp. This locale relationship between major event and ramp structure might be interpreted to be linked by a possible duplex structures in between (Fig. 11). Similar observations of the 'flat-ramp-flat' or 'ramp-flat-ramp' structure of the MHT have also been made in other geophysical and geological studies, especially after the 2015 Gorkha earthquake (e.g. Duputel *et al.* 2016, Wang *et al.* 2017; Hubbard *et al.* 2016). Such seismic structures could enhance stress concentration leading to the nucleation of the large earthquake. All these results suggest the close relationship between earthquakes and the MHT geometry in the region.

4.6 Thrusting behaviour beneath Nepal Himalaya

There are several well-known mechanisms for thrusting of the MHT structure, (1) passive overthrusting in which the MFT displacement absorbs most of the present shortening across the Himalaya (Lavé & Avouac 2000), (2) active out-of-sequence thrusting on the MCT, possibly resulting from or amplified by erosion at the range front (e.g. Harrison *et al.* 1997; Wobus *et al.* 2003, 2006), (3) duplexing mode that is resulted from the accretion from both the hanging wall and the footwall of the MHT around the ramp (Schelling & Arita 1991; Bollinger *et al.* 2006). Even though the MHT in our migration image could not directly tell us which mechanism takes effect,

Figure 11. Possible interpretation for the underlying crustal structures beneath the Nepal Himalayan orogen along profile FF'. The star and dots show the 2015 Gorkha main shock and aftershocks. SH, Sub-Himalaya; KK, Kathmandu klippe; LH, Lesser Himalaya; GH, Greater Himalaya; TH, Tethyan Himalaya; ITSZ, Indus-Tsangpo Suture Zone. The filled colours over the topography curve are coded as shown in Fig. 1.

integrated with the distribution of the main shock and aftershocks, our MHT structure can be well explained by the lithologic contrasts in the duplexing mode rather than the out-of-sequence thrusting or passive overthrusting mode (Fig. 11). Although some previous results did not show the ramp structure in the MHT (e.g. Schulte-Pelkum *et al.* 2005; Nabelek *et al.* 2009), recent results clearly demonstrate a steep bending structure within the MHT decollement (e.g. Acton *et al.* 2011; Caldwell *et al.* 2013) resembling the abrupt ramp (Figs 8, 10 and 11) in this study.

5 CONCLUSIONS

In this paper, we investigate the lateral Moho variation and the geometry of the MHT under the Nepal Himalayan orogen using a large number of receiver functions. The findings of our new crustal model could be summarized in the following aspects.

- (1) Evident lateral variations of the Moho discontinuity have been found perpendicular to the indentation of India into Eurasia, suggesting a possible tearing of the subducted Indian slab and/or a complicated convergent mechanism of the Indo-Eurasian collision zone.
- (2) Our results show that the Moho depth variations are related to the surface geological units. For example, along the ITSZ, the Moho depth varies by up to ~16 km, suggestive of hot material upwelling due to the sharp changes in the subduction angle there.
- (3) Our observations clearly reveal a ramp structure along the MHT as the decollement stretching from the MFT to southern Tibet. Such a flat–ramp–flat MHT structure could be caused by a duplexing mode of thrusting, which would be helpful for understanding the formation of Nepal Himalayan orogen and the mechanisms of the 2015 Gorkha earthquake and its aftershocks.

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SUPPORTING INFORMATION

Supplementary data are available at *GJI* online.

Figure S1. CCP stacking images using four different velocity models along profile FF' as shown in Figs 5 and 6. The velocity models of Guo *et al.* (2009), Caldwell *et al.* (2013), Schulte-Pelkum *et al.* (2005) and Kennett & Engdahl (1991) on the right are used to completely investigate the effects of velocity models on the CCP stacking images (on the left) in the Himalayan orogen. Note that the IASP91 velocity model (Kennett & Engdahl 1991) is modified to contain an 80-km thick crust for proper determination of the crustal discontinuity depths.

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