Review of earthquake activity and faulting structure in Nepal Himalaya

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ABSTRACT

The collision between the Indian and Eurasian plates formed the Himalaya orogenic belt (HOB) and highest plateau in the world. The HOB has experienced more than a dozen of devastating earthquakes with moment magnitudes (Mw) greater than 7.5 for more than 1000 years. In the central part, a Mw 7.8 earthquake occurred on 25th April 2015 at the Gorkha, Nepal area, caused more than 9000 fatalities and large amount of economic losses. This earthquake occurred on the Main Himalaya Thrust (MHT), the shallow portion of the convergence boundary between the Indian and Eurasian plates. In this article, we reviewed previous studies related to the geometry of the MHT and major earthquakes occurred on the HOB. Then we focused on the source area of the 2015 Gorkha earthquake to summarize the recent progress about the lateral variation of the MHT and the aftershock activity. We found that most aftershocks were located above the MHT, illuminating faulting structure in the hanging wall with dip angles that were steeper than the MHT. The deeper edge of the aftershock distribution marks the MHT, which exhibits clear lateral variation both along and across the geological strike of the Himalaya orogenic belt.

Key words: Himalayan orogenic belt, Main Himalayan Thrust, 2015 Mw7.8 Gorkha earthquake

INTRODUCTION

The collision between the Indian and Eurasian continental plates since 65-55 Ma formed the Himalaya orogenic belt (HOB) - the highest mountain range on the Earth (Kayal, 2001; Yin 2006; Meng et al., 2012; Li et al., 2015). The HOB extends from Nanga Parbat in the west to Namche Bharwa in the east with a length of ~2500 km and a width of ~250 km (Gansser, 1964). After the collision, the Indian continental lithosphere continued to underthrust northwards, resulting in large-scale inland subduction beneath the Tibetan plateau. The detailed study on its formation and evolution processes provide important constrains on the continental dynamics and various engineering constructions.

The convergence rate between the Indian and Eurasian plates is approximately 45 mm/yr, with about 20 mm/yr driving the uplift of the Himalaya orogenic belt (Lavé and Avouac, 2000; Ader et al., 2012; Castaldo et al., 2017). As a result, earthquakes are widespread along the HOB. Historical documents since the tenth century show evidence for great Himalayan earthquakes with a recurrence interval of about 800 years (Kumar et al., 2010; Bollinger et al., 2014). Since the past century, more than a dozen of earthquakes with Mw >7 occurred, including the 1505 Nepal earthquake (Mw 8.1), the 1905 Kangra-India earthquake (Mw 8.6), the 1934 Bihar-Nepal earthquake (Mw 8.1-8.2), and the 1950 Assam earthquake (Mw8.6) (Fig.1, 2 & Table1, Sapkota et al., 2013). These major earthquakes completely ruptured many parts of the HOB (Bilham, 2004; Bilham, 2019).

On 25 April 2015 the Mw 7.8 Gorkha earthquake occurred in the central part of the HOB, i.e., the Nepal Himalaya. This earthquake partially ruptured ~150 km by 80 km patch of the north-dipping MHT, propagated eastwards from the hypocenter, which is located ~80 km WNW of Kathmandu (Avouac et al., 2015; Ellott et al., 2016; Whipple et al., 2016; Gallen et al., 2017). By the end of 2018, more than 900 aftershocks with magnitudes greater than 3.5 were recorded, including the Mw7.3 Kodari earthquake that occurred on 12th May 2015 at the eastern edge of the rupture zone (Adhikari et al., 2015; Bai et al., 2016). The mainshock is a reverse faulting along the WNW-ESE direction, nearly perpendicular to the plate convergence direction. Landslides are triggered by the Mw7.8 and Mw 7.3 earthquakes at many places, especially to the north of the aftershock zone (Kargel et al., 2016; Roback et al., 2018).

Though the Gorkha earthquake has been extensively studied and linked to the structure of the MHT, there are still many issues on debate, including the location of aftershocks and the lateral variation of the MHT. In this study, we focus on the central segment of the HOB (Nepal Himalaya) and review the tectonic setting, the faulting structure, the historical large earthquakes, the 2015 Gorkha earthquake and its aftershocks. These pieces of information are essential for our understanding about the uplift of mountain range and the seismic hazards for the Himalayan area.

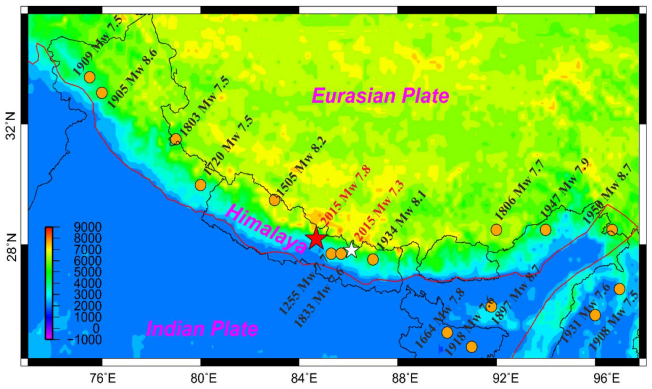

Fig. 1: Distribution of Mw>7 historical earthquakes along the HOB (Gupta, 1993; Pandey et al., 1995; Ambraseys and Douglas, 2004). Two stars show the Mw7.8 Gorkha earthquake and the Mw7.3 Kodari earthquake. Yellow dots show historical large earthquakes.

TECTONIC SETTING AND MAJOR THRUST SYSTEM

The HOB is classically divided into four tectonic units from south to north, including Sub-Himalaya, Lesser Himalaya, Higher Himalaya and Tethyan Himalaya (Gansser, 1964; Le Fort, 1986). They are separated by The Main Frontal Thrust (MFT), Main Boundary Thrust (MBT), Main Central Thrust (MCT) and South Tibet Detachment (STD) system (Fig. 3; Ni and Barazangi, 1984; Zhao and Nelson, 1993). These major faults converge beneath the Earth at the Main Himalaya Thrust (MHT), the detachment along which the Indian plate subducts beneath the Himalayan Mountains (Ni and Barazangi, 1984; Zhao and Nelson, 1993; Nabelek et al., 2009).

Major tectonic division

Sub-Himalaya Zone

The Sub-Himalaya zone or the Siwalik of Nepal is the youngest mountain chain. It extends from east to west along the southern part of the HOB and also named as Churia hills (Fig. 3; Upreti, 1999). It is delimited by the MFT to the south and MBT to the north. The Himalaya foreland basins consist of the Neogene fluvial sediments and mark the topographic front of the Himalaya (Baral et al., 2016). Groups of metasedimentary rocks of the Lesser Himalaya have been thrust southward over the Siwaliks rocks along the MBT covering a large part of the Churia (Siwalik) rocks (Upreti 1999). Based on the grain size distribution, this unit is further classified into three folds classification: Lower Siwalik (fine grain), Middle Siwalik (coarse grain) and Upper Siwalik (Conglomerate).

Lesser Himalaya

The lesser Himalaya is bordered to the north by the MCT and to the south by the MBT with a total width ranging from 60 to 80 km (Fig. 3). The geology of the lesser Himalaya is complicated due to the presence of different structures such as

Table 1: List of earthquakes with Mw>7 occurred since 1000. ID is the number of earthquake in origin time order. ëE is longitude and øN is latitude.

ID	Event Time mm/dd/year	ψ_N /°	λ_E /°	Magnitude (Ms)	Location	Source and commentary
1	June 7, 1255	27.7	85.3	7.7	Kathmandu	P & S
2	June 6, 1505	29.5	83.0	8.2	Lo Mustang	A & D
3	1664	25.0	90.0	7.8	N Bangla	A & D
4	Jul. 25, 1720	30.0	80.0	7.5	N Uttar- Pradesh	A & D
5	Sep. 1, 1803	31.5	79.0	7.5	Uttar- Pradesh	A & D
6	June 11, 1806	28.50	92.0	7.7	Samye	A & D
7	Aug. 26, 1833	27.70	85.7	7.6	Nepal	A & D
8	June12, 1897	25.9	91.8	8.7	Assam	G
9	April 4, 1905	33.0	76.0	8.6	Kangra valley	G
10	Dec. 12,1908	26.5	97.0	7.5	N.Burma	G
11	July 7, 1909	36.50	70.5	7.52	Hindu-khus	A & D
12	July 8,1918	24.5	91.0	7.6	Assam	G
13	Jan, 27, 1931	25.6	96.0	7.6	-	G
14	Jan, 15, 1934	27.55	87.09	8.11	Bihar-Nepal	A & D
15	July 29,1947	28.5	94.0	7.9	N.E. Assam	G
16	Aug. 15,1950	28.5	96.7	8.7	Assam	G

Note: Source and Commentary represents, G - (Gupta, 1993), A&D - (Ambraseys and Douglas, 2004), and P&S - (Pandey et al., 1995; Sapkota et al., 2013) respectively.

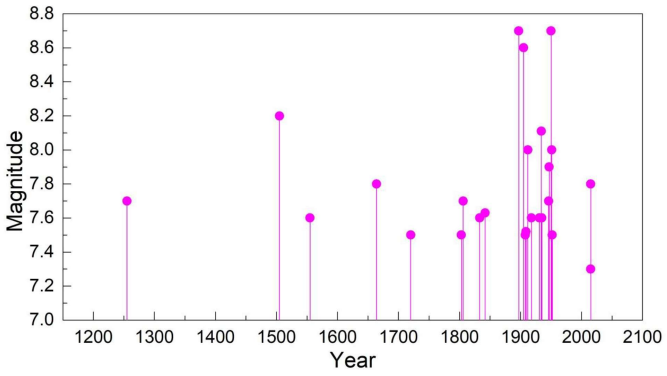

Fig. 2: Temporal distribution of historical large Himalayan Earthquake from 1200 to 2018 with magnitudes greater than 7 (Pandey and Molnar, 1988; Molnar and Pandey, 1989; Gupta, 1993; Pandey et al., 1995; Ambraseys, 2000; Monsalve et al., 2006; Shanker et al., 2012; Srivastava et al., 2013).

folding, faulting, nappe and klippe (Stocklin 1980). From east to west, the lesser Himalaya shows wide variations in stratigraphy and structure. Based on conventional geologic evidence and isotopic data (DeCelles et al., 2000; Neupane et al., 2017), the lesser Himalaya is classified into upper and lower units, which are separated by a major unconformity (Valdiya et al,. 1996; Upreti, 1999). Similar classification of the lesser Himalaya has been given in India (Kohn et al., 2010) and Bhutan (McQuarrie et al., 2008).

Higher Himalaya

The crystalline zone marks the Higher Himalaya, and it extends from MCT to the south and STD to the north along the entire length of the Himalaya (Fig. 3). It mainly consists of comprises high grade metamorphic rock and granitic genesis

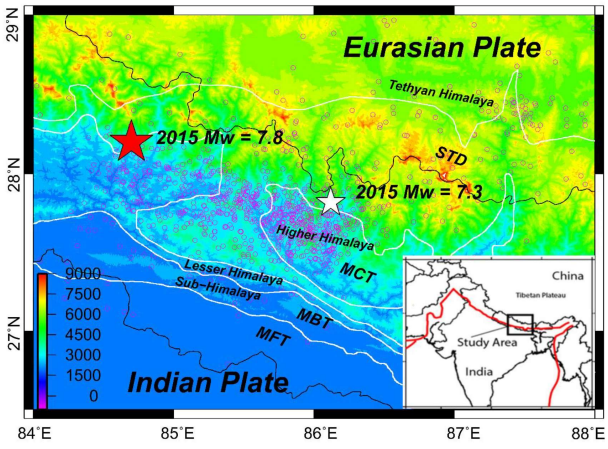

Fig. 3: Tectonic background and seismicity map of the aftershock zone of 2015 mainshock. The red star is the 2015 Mw 7.8 Gorkha earthquake and the white star is the Mw 7.3 Kodari earthquake. The white lines are major faults (Bai et al., 2016).

of pre-Cambrian age (Neupane et al. 2017). The major rock types are Kyanite-sillimanite bearing gneiss, schist, marble and granite (Upreti, 1999). It is also called as the higher Himalayan Crystalline Series (HHCS). It is further subdivided into four units in the ascending order: the Kyanite-sillimanite gneiss, the Pyroxenic gneiss and marble, the banded gneiss and the Augen gneisses (Bordet et al., 1972; Le Fort, 1975).

Tethys Himalaya

The Tethys Himalaya underlain the Higher Himalaya zone and extends to the Indus–Tsangpo Sutures Zone (ITS) to the north (Fig. 3). This zone is ~40 km wide and composed of fossiliferous sedimentary successions including shale, sandstone and limestone. The rocks of the Tibetan Tethys series consist of a thick and folded lower Paleozoic to lower Tertiary marine sedimentary succession. The rocks are considered to be deposited in a part of the Indian passive continental margin (Liu and Einsele 1994). These units are exposed in Thak Khola (Mustang), Manang and Dolpa areas, in central Himalaya (Colchen et al., 1986). A low-grade metamorphism can be observed adjacent to the thrust contact with the higher Himalaya whereas the rocks are Paleozoic to Cenozoic in age and make up to the hanging wall of the STD (Guillot, 1999).

Major thrust system

Main Frontal Thrust (MFT)

MFT is the youngest thrust fault in the HOB which can be traced along the southern part of separating the Indo-gangetic plain from the Siwalik group (Upreti, 1999). In the northern side of the MFT, the Central Churia thrust (CCT; Tokuoka et al., 1986) divides the Siwalik group into inner and outer Siwalik Group. The MFT is also named as Intra Churia thrust called Main Dun thrust (Jouanne et al., 1999) The emplacement of the MFT caused the tilting and folding of post- Siwalik sediments to the south of the MFT (e.g., Ratukhola section, Nepal) as well as the uplift for some parts of the Indo Gangetic Plain, marked by radial drainage patterns (e.g, south of Bhadrapur, eastern Nepal, Upreti, 1999).

Main Boundary Thrust (MBT)

Similar to the MFT, the MBT is also a continuous structure existing throughout the Himalaya range. It separates by unmetamorphosed Neogene to Quaternary Churia Group rocks to much older Pre-cambrian metasedimentary sequences and associated younger sedimentary rocks of the lesser Himalaya. The MBT was active in upper Miocene–Pliocene period (DeCelles et al., 2000). There are several geological effects engender by the MBT which can be observed along the Nepal Himalaya such as the large-scale slides, soil erosion and folded and faulted of strata.

Main Central Thrust (MCT)

The MCT is the oldest and first thrust which breaks the Indian crust, longitudinally appears in the Himalayan region (Le Fort, 1996). It was firstly activated at about 22 Ma and reactivated around 15 Ma and 6 Ma (Harrison et al., 1998). The MCT evolved both in time (early-middle Miocene) and space from a deep–level ductile shear zone to a shallow brittle thrust fault (Searle et al., 2008). It separates the highly crystalline units of metamorphosed rocks in higher Himalayan rocks from the less metamorphosed lesser Himalayan rocks (Heim and Gansser, 1939). The MCT is along the high–strain zone that frequently occurs along the base of the ductile shear zone and inverted metamorphic sequence. Due to the activation and re-activation of MCT, several small-scale geological structures were formed in the Higher Himalayan units (Upreti, 1999).

South Tibetan Detachment (STD)

The STD is a normal fault that runs 1500 km almost parallel to the HOB. It is a series of north dipping structures, accommodating top at the Tethyan sedimentary series to the North with respect to the underlying High Himalayan crystalline series in the south. The structure was active ~23-13 Ma and the total slip is > 34 km (Hodges et al., 1996; Godin et al., 2001). The collision of the STD stopped firstly in the west at ~17 Ma and then in the east at ~12 Ma, suggesting changes along the direction of the India-Eurasia convergence (Leloup et al., 2010).

LARGE EARTHQUAKES ALONG THE HOB

Historical documents since the 10th century show that the Himalaya frontal arc has experienced more than a dozen devastating earthquakes of Mw >7.5, which are related with the northward drifting of the Indian plate and the interaction with the Eurasian plate (Monsalve et al., 2006; Adhikari and Paudyal, 2014). During the last century, four strong earthquakes with Mw > 8 occurred in the HOB, including the Shillong plateau earthquake in 1897 (Mw 8.7), the Kangara earthquake in 1905 (M 8.5), the Bihar-Nepal border earthquake in 1934 (Mw 8.4) and the Assam earthquake in 1950 (Mw 8.7) (Thapa and Wang, 2013). Besides, large number of moderate earthquakes also occurred in the Himalaya region (Fig. 2).

Large historical earthquakes in Nepal Himalaya

On 6 June 1505, the Mw 8.2-8.8 Lo Mangthang Mustang earthquake occurred in the western region of the central Himalaya (Bilham and Ambraseys, 2005). This earthquake is located to the west of the rupture zone of the 2015 Gorkha earthquake. It is the one of the largest earthquakes in the Nepalese history (Malik et al., 2017). This earthquake was widely experienced in the Tibet, Nepal as well as Delhi and Agra in the Indo-Gangetic Plain (Malik et al., 2017).

On 26 August 1833, the Mw 7.5-7.9 earthquake struck Nepal and some parts of India (Chaulagain et al., 2018). The mainshock was led by two foreshocks just five hour before the mainshock which caused strong damage to the Kathmandu valley and its surrounding regions (Malik et al., 2017).

On 15 January 1934, the Mw 8.0-8.5 Bihar-Nepal earthquake occurred in eastern Nepal (Pandey and Molnar, 1988). This earthquake has rupture a fault section that overlaps with the fault rupture plane of the 2015 Gorkha earthquake (Goda et al., 2015). It caused widespread destruction in Bihar and Nepal area. This earthquake rupture the MFT with strong damage in Nepal and some part of India with ~10,000 fatalities (Malik et al., 2017).

2015 Mw7.8 Gorkha earthquake

On 25 April 2015, the Mw7.8 devastating earthquake struck central Nepal that affected more than 14 districts and killed ~9000 population with a huge economic loss (Adhikari et al., 2015). It was the worst natural disaster to strike Nepal since the 1934 Nepal Bihar earthquake. It occurred on the MHT, where the Indian plate under thrust beneath the Eurasian plate (Bai et al., 2016). The 2015 Gorkha earthquake occurred within a gap in historical seismicity which is surrounding by the several greater earthquake in central Himalaya (Fig. 1; Elliott et al,. 2016; Hui et al., 2017). Up to 25 April 2019, the Gorkha earthquake was followed by an intensive aftershock sequence including ~900 earthquakes of Mw>3.5 (Fig. 4). On 12th May 2015, the Mw 7.3 Kodari earthquake occurred ~ 140 km to the ESE of the Gorkha earthquake (Adhikari et al., 2015).

DISCUSSIONS

Aftershock activity of the 2015 Gorkha earthquake

The earthquake catalogs for the central HOB are insufficient as there are only limited number of seismic stations. The distribution of seismic activities in the HOB appears to be non-uniform as a function of time as well as space. Most of the aftershocks are concentered around the Mw7.3 Kodari earthquake. Locating earthquakes in the continental collision zone, especially for the focal depth is problematic because of the uncertainty in the local velocity structure and the limited number of local seismic observations.

It has been accepted that the 2015 Mw 7.8 Gorkha earthquake is located on the MHT. However, where the aftershocks are still on debate. They were relocated either on, above or below the MHT. Adhikari et al. (2015) and Bai et al. (2016) relocated the aftershock sequence based on local and regional seismic stations within Nepal and near the china-Nepal border. Most of the relocated aftershocks were located above the MHT in the hanging wall, illuminating faulting structure in the Himalayan prism. Hayes et al. (2015) and Wang and Wu (2017) relocated the hypocenters of relatively large aftershocks based on the teleseismic and regional dataset. They concluded that most of the aftershocks are located on the MHT and reveal

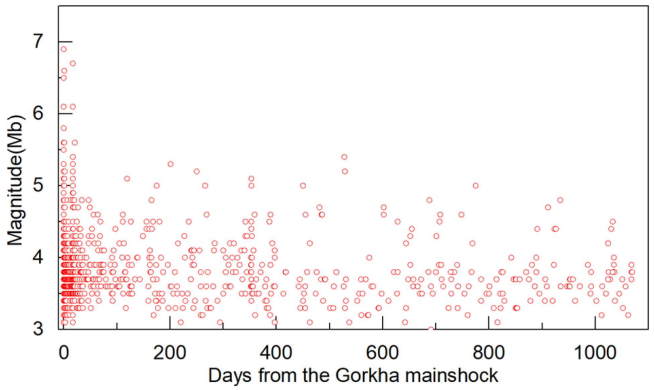

Fig. 4: Time versus magnitude for the 2015 Gorkha earthquake sequence. Data are taken from the International Seismological Center (ISC) catalog.

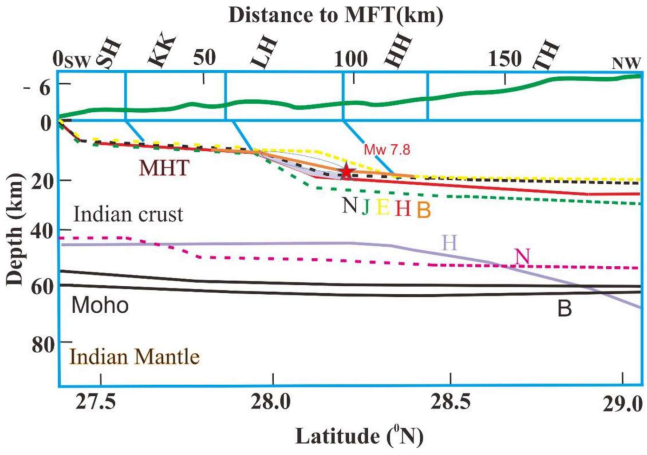

Fig. 5: Crustal structures beneath the Nepal Himalayan orogen. MHT and Moho from different literatures; N, H, E, J and B represent (Nabelek et al., 2009; Hubbard et al., 2015 Elliott et al., 2016; He et al., 2018; Bai et al., 2019) respectively. Red star shows the 2015 Gorkha mainshock. SH, KK, LH, HH, TH and ITSZ are Sub-Himalaya, Kathmandu Nappe, Lesser Himalaya, Higher Himalaya, Tethyan Himalaya and Indus-Tsangpo Suture Zone.

a ramp-?at geometry of the MHT. McNamara et al. 2017 analyzed the aftershocks based on regional seismic stations and InSAR and GPS data. Most of the aftershocks are located below the MHT as a representative example of earthquake-induced stress transformation of the subducting Indian lower crust (Jamtveit et al., 2018).

Geometry of the MHT

The MHT was firstly proposed by seismic observations (Ni and Barazangi, 1984), which suggested that the rupture of the Himalayan megathrust earthquakes may have started in the interpolate thrust zone. The MHT has played important roles on the revolution of the HOB. The change in elevation as well as the steep dip of the high topography is largely caused by geometry change of the MHT (Elliott et al., 2016; Taylor, 2016; Whipple et al., 2016). However, the morphology of the MHT remains controversial.

Avouac et al. (2015) uses a teleseismic waveforms and synthetic Aperture Rader imaginary after the 2015 Mw 7.8 Gorkha earthquake to study the geometry of the MHT. They suggest that the Mw 7.8 Gorkha earthquake unzipped the lower edge of the locked portion of the MHT. Hubbard et al. (2015) used surface geology to reconstruct the structural cross sections. They suggested a ramp-flat-ramp characteristic thrust structure across the strike, with a ramp beneath the lesser Himalaya (Caldwell et al., 2013; He et al., 2018). Wang et al. (2017) analyzed waveforms recorded by teleseismic seismic stations. They suggested a double-ramp geometry of the MHT with the flat portion beneath the lesser Himalaya (Nabelek et al., 2009; Schulte-Pelkum et al., 2005) and one ramp below the higher Himalaya (Avouac et al., 2015; Elliott et al., 2016) (Fig. 5).

CONCLUSIONS

The 2015 Mw 7.8 Gorkha earthquake has heightened concern for future large earthquakes along the Himalayan front (Bilham, 2015; Hand and Pulla, 2015). A large number of studies have linked earthquake activity to the faulting structure, mainshock rupture process, and velocity anomaly. The Mw 7.8 Gorkha mainshock initiated on the MHT. Most of our well-relocated aftershocks obtained from local seismic stations are shallower than the main shock and thus located above the MHT (Bai et al., 2016; Bai et al., 2019). In the source area, the geometry of the MHT exhibits clear lateral variations. As expected, the MHT deepens to the NNE parallel to the plate convergence direction as one moves from the foreland to the hinterland. In addition, a mid-crustal ramp has been imaged beneath the lesser Himalaya and higher Himalaya. Our study supports the idea that the Lesser Himalayan ramp exhibits a moderate dip on the MHT beneath the 2015 Gorkha earthquake area (Bai et al., 2019). Therefore, the MHT exhibits clear lateral variation both along and across the geologic strike of the HOB. It is important to understand the spatio-temporal variation of the seismicity and the lateral variation of the MHT geometry. They provide information for mitigation of earthquake disasters that affect the sustainable development for communities in multiple countries of the Himalayan maintain range.

ACKNOWLEDGEMENTS

This research is supported by the grant of the National Nature Science Foundation of China (No. 41761144076). We thank two anonymous reviewers for their constructive comments.

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