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Mio-Pliocene Tectonics and Exhumation Histories of the NW– and NE–Himalaya

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The collisional Himalayan orogen is commonly presented as largely laterally uniform from the NW– to NE–Himalaya, with almost similar geological and tectonic settings. Despite active continuous convergence and precipitation since many million years in the Himalaya, thermochronological/cooling age pattern, uplift and exhumation rates vary in different parts of NW– and NE–Himalaya as a function of structural positions such as dome/window/synform, klippen/nappe structures and thrusting/back-thrusting along different major faults. These surface structures appear to reflect the geometry and kinematics of the Main Himalayan Thrust (MHT) and duplex structures formed over the ramp of the MHT. These observations suggest that in this tectonically-active setting characterized by steep topography and intense storms, thermochronological/cooling age pattern and exhumation patterns do not mirror precipitation gradients or drive deformation on million-year timescales. Rather, exhumation patterns are controlled by local tectonics that is dictated by the subsurface geometry of the MHT and its associated structures.

Introduction

Subduction of the oceanic crust of the Indian plate under the Eurasian plate brought both the continents together with the continuous northward movement of the Indian plate resulting in continental collision at ca 55 Ma (Patriat and Achache, 1984; Garzanti et al., 1987). Continental collision resulted crustal shortening, rock uplift and erosion that shaped the Himalayan orogen (Fig. 1a). Crustal shortening was associated with the southward migration of deformational front from the Indus-Tsangpo Suture Zone (ITSZ) to coeval Main Central Thrust (MCT) and South Tibetan Detachment System (STDS) during 23 to 17 Ma (Burchfiel et al., 1992; Hodges

et al., 1996; Hodges, 2000; Searle and Godin, 2003) and then to Main Boundary Thrust (MBT) during 12 to 5 Ma (Meigs et al., 1995; DeCelles et al., 2001) and Main Frontal Thrust (MFT) during 4 Ma to present (Lavé and Avouac, 2000) (Fig. 1b). Synchronous deformation along the MCT and the STDS extruded the high-grade metamorphic rocks of the Higher Himalayan Crystalline (HHC) and thrust over the Lesser Himalayan meta-sedimentary (LHMS) zone. It was then followed by thrusting of the LHMS zone over the Sub-Himalaya along the MBT and then the Sub-Himalaya over the Indo-Gangetic alluvium along the MFT. Geophysical and structural data suggest that these structures merge at depth into a single mid-crustal décollement which was originally named as Main Detachment Thrust (Schelling and Arita, 1991) but later was called as the Main Himalayan Thrust (MHT) (Schulte-Pelkum et al., 2005; Zhao et al., 1993). It is described to absorb the bulk of the shortening accommodated across the central Himalaya (~20 mm/yr) during the Holocene (Avouac, 2003; Bilham et al., 1997; Lavé and Avouac, 2001; Wang et al., 2001). For understanding the mechanics of crustal shortening in the Himalayan orogen, the HHC has continuously stimulated geoscientists to search for new concepts and models. Most critically, the high-grade metamorphic rocks crop out along the HHC thus raising long-standing and lively-debated questions regarding the tectonic evolution and exhumation of the high-grade metamorphic rocks. The emplacement tectonics of the crystalline klippen/nappes over the LHMS zone, the development of Lesser Himalayan Duplex (LHD) over the ramp of the MHT and the geometry of the MHT have recently created interest among the geoscientists to understand the exhumation in the hanging and footwalls of the MCT.

The high elevation of the Himalayan collisional mountain belt is described due to the interaction and feedback relationship between tectonic processes that build the high Himalayan topography and the surface erosional processes such as fluvial incision, glaciers and mass wasting, which destroy it (Ahnert, 1970; Adams, 1980; Jamieson and Beaumont, 1988; Willet and Brandon, 2002). Foremost, we can believe in two competing processes in the rise of Himalayan topography: (i) past or present tectonic uplift and (ii) erosion and increased precipitation. This interaction and feedback between tectonics and erosion in orogens have been suspected since early studies of thrust tectonics (Chapple, 1978; Suppe, 1981; Davis et al., 1983; Dahlen,

Figure 1. (a) Topographic map of the Himalaya (topography based on the GTOPO30 digital elevation model, U.S., Geological Survey), (b) Simplified Geological map of the Himalaya. (Modified after Yin 2006 and Yin et al., 2010b) and (c) Tropical Rainfall Measurement Mission (TRMM)-derived rainfall variations for the study region (from Bookhagen and Burbank, 2006). The TRMM-based monsoon rainfall amounts are averaged from January 1998 to December 2005.

1984; Dahlen and Suppe, 1988) and is currently an extensive topic of research in the Himalaya (Beaumont et al., 1992, 2001; Willet, 1999). Our present knowledge of interaction and feedback between tectonics and exhumation that shaped the Himalayan orogen has largely been derived by low-temperature thermochronology (Copeland et al., 1991; Jain et al., 2000; Wobus et al., 2003, 2005; Vannay et al., 2004; Bollinger et al., 2004, 2006; Hodges et al., 2004; Thiede et al., 2004, 2005, 2009; Grujic et al., 2006; Blythe et al., 2007; Patel and Carter, 2009; Patel et al., 2011a, b; Deeken et al., 2011; Singh et al., 2012; Streule et al., 2012) and thermokinematic modeling (Robert et al., 2009; Herman et al., 2010) of the HHC and crystalline klippen over the LHMS zone in the core of the orogen. The rapid exhumation of the HHC in the hanging wall of the MCT is described by three models: (i) under plating along the MHT (Lavé and Avouac, 2001, Avouac, 2003; Bollinger et al., 2004, 2006), (ii) active out-of-sequence thrusting (Wobus et al., 2003; Hodges et al., 2004; Patel and Carter, 2009; Singh et al., 2012; Adlakha et al., 2013) and (iii) feedback relationship between erosion and precipitation/glaciation (Thiede et al., 2004, 2005; Streule et al., 2012). The slow but variable exhumation pattern of the crystalline klippe in the footwall of the MCT is described due to thrusting and back-thrusting (Patel et al., 2015; Singh and Patel, 2016).

Two most recent reviews by Adlakha et al. (2013a) and Thiede and Ehlers (2013) have observed large spatial and temporal variations in the Himalayan exhumation. Adlakha et al. (2013a) have correlated the surface structures with the thermochronological ages and suggested that local tectonics of the area is the main factor controlling the exhumation. Thiede and Ehlers (2013) remained focus over the temporal variations in exhumations and differentiated the patterns of denudations along the frontal ranges and northern higher elevation ranges over different span of time. However, these reviews have not considered the sub-surface structures that directly manifest over the surface and dictate the crustal denudations. Therefore, in this paper review on thermochronological studies from both the NW- and NE-Himalaya, has been made to understand the relationship between sub-surface geometry, surface structures and exhumation pattern (Fig. 1b). Plots of the thermochronological ages over the published cross-section across various transect have been examined to understand how sub-surficial deformation i.e. development of duplex over the MHT ramp or surface breaking fault emerging over the MHT influenced the patterns of thermochronological ages and hence the exhumation rates. This review is not only confined to the hangingwall of the MCT, i.e. within the HHC but also extends to the footwall of the MCT i.e. within the Lesser Himalayan Sequence (LHS). The present study compliments the earlier reviews to show the tectonic control over exhumation patterns in the NW- and NE-Himalaya.

Geology and Tectonics

The Himalaya stretches nearly 2500 km along the boundary between the Indian and Eurasian plates and its geological and tectonic setting is largely uniform from NW to NE (Figs. 1a, b). The Himalaya from NW to NE includes major lithotectonic units of the deformed northern edge of the Indian crust (DeCelles et al., 2016). From north to south these consist of the Tethyan Himalayan Sequence (THS), the Higher Himalayan Crystalline (HHC) and the Lesser Himalayan Sequence (LHS), followed by the Sub-Himalaya. The LHMS zone along with overthrust crystalline klippen/nappes rooted from the HHC

is called as the LHS. These lithotectonic units are similar in both NW- and NE-Himalaya. A series of south-vergent thrusts generally define boundaries between these major units (Gansser, 1964). These structures are interpreted to sole into the MHT at depth. The MCT placed the Paleo-to-Neoproterozoic HHC of high-grade metamorphic core over the Paleoproterozoic LHMS (Hubbard and Harrison, 1989) of low- to medium-grade rocks. Farther south, the MBT placed the LHS over the foreland basin sediments of the Sub-Himalaya (Huyghe et al., 2005). The Sub-Himalayan Cenozoic belt contains marine and continental sedimentary rocks, eroded from the Himalaya and then thrust over the Indo-Gangetic Plain (Lavé and Avouac, 2001; Patel and Kumar, 2003; Najman et al., 2009).

In spite of similar lithotectonic units in all the sections of the Himalaya, there is significant difference in the geological structures, topography, precipitation rate and convergence rates between the NW- and NE-Himalaya. These geological structures are the surficial manifestations of the sub-surface structural deformations along the Main Himalayan Thrust (MHT) ramp, leading to the development of duplex or out-of-sequence fault geometry. In this study, published cross-sections and sub-surface geometry of the MHT have been used to correlate exhumation patterns in cross-sections across the NW- and NE-Himalaya.

NW-Himalaya

The NW-Himalaya represents the segment of the Himalayan orogen between 66° to 81°E (Fig. 1b), and includes Salt Range of Pakistan, Kashmir, Zaskar, Spiti, Himachal, Garhwal and Kumaun regions. Here, we have reviewed the geological and tectonic setting, topography and precipitation of the LHS and the HHC zones, as most of exhumation studies concentrate in these zones.

Different studies in the NW-Himalaya show that the outcrop pattern of the HHC and the LHS zones vary strongly along the strike from Kumaun-Garhwal regions to Himachal and Kashmir regions (Fig. 2a). The HHC zone is narrow in the Kumaun-Garhwal regions than the Himachal and Kashmir regions. On the other hand, the LHMS zone is wider in the Kumaun-Garhwal regions than the Himachal and Kashmir regions. This along-strike variation is described due to the presence or absence of a lid of the HHC rocks that have overthrust the LHMS zone up to 150 km southward of the general trace of the MCT (Fig. 1b). The HHC forms a series of prominent klippen within the LHMS zone in the Kumaun-Garhwal regions such as Chiplakot, Askot, Almora, Bajinath, Lansdown, Purola Crystalline Belt, while windows of the LHMS zone form within the HHC zone such as Larji-Kullu-Rampur (LKR) Window and Kishtwar Window (KW) in the Himachal-Kashmir regions (Fig. 2a). This type of tectonic setting in Kashmir-Himachal and Kumaun-Garhwal regions is described due to regional folding of the overlying HHC and underlying LHMS zones into antiform and synform structures (Valdiya, 1980; Srivastava and Mitra, 1994; Steck, 2003; Vannay et al., 2004; Célérier et al., 2009). Some of the antiform structures are present as dome structures such as Suru and Chisoti domes in Zaskar region. Erosion of the crest zones of the some antiforms has cropped out the underlying LHMS rocks as windows in the Himachal-Kashmir regions while uneroded remnant of the overlying crystalline rocks in the synform are present as klippen in the Garhwal-Kumaun regions. The HHC zone in the north of the LHMS zone in Garhwal-Kumaun regions is composed of two distinct lithotectonic units (Valdiya, 1980; Srivastava and Mitra, 1994; Ahmad et al., 2000). The northern unit is the Vaikrita Group of

Figure 2. Geological map of the (a) NW-Himalayan region. Modified after Valdiya (1980), Jain and Patel (1999) and Jain et al. (2000). Low-temperature thermochronological data: 1. Kumar et al. (1995); Sorkhabi et al. (1997). 2. Kumar et al. (1995). 3. Schlup et al. (2003). 4. Lal et al. (1999) and Walia et al. (2008). 5. Vannay et al. (2004). 6. Jain et al. (2000). 7. Thiede et al. (2004, 2005, 2009, 2017). 8. Sorkhabi et al. (1996) and Searle et al. (1999). 9. Patel and Carter (2009) and Bojar et al. (2005). 10. Singh et al. (2012). 11. Patel et al. (2007). 12. Patel et al. (2011). 13. Patel et al. (2015) and Singh and Patel (2016). 14. Adlakha et al. (2013). 15. Deeken et al. (2011). (b) NE-Himalayan region. Compiled from Kumar (1997), Grujic et al. (2006), Singh and Jain (2007) Yin et al. (2010), Coutand et al. (2014), and DeCelles et al. (2016), showing tectonic setting of the NW- and NE- Himalaya in the overall lithostrati-graphic framework of the region. Low-temperature thermochronological data: 1. Grujic et al. (2006), Coutand et al. (2014). 2. Adlakha et al. (2013) and DeCelles et al. (2016). 3. Adlakha et al. (2019). 4. Salvi et al. (2017). The areas of study of thermochronological ages on samples collected from different locations from the NW- and NE-Himalaya are shown on boxes. STDS: South Tibetan Detachment System. ZT: Zimithang Thrust. VT: Vaikrita Thrust. MCT: Main Central Thrust. MT: Munsiri Thrust. BDT: Bomdila Thrust. BT: Bame Thrust. MBT: Main Boundary Thrust. HHC: Higher Himalayan Crystallines.

Neoproterozoic age which is comprised of a thick sequence of amphibolite facies metamorphics to migmatite gneisses. It is bounded by the Vaikrita Thrust (VT) at its base and the STDS at the top. Beneath the VT, the lower unit is the Paleoproterozoic Munsiri Formation, predominantly composed of amphibolite facies augen gneiss, and bounded at its base by the Munsiri Thrust (MT). The Munsiri Formation is locally known as the MCT zone (Metcalf, 1993; Searle et al., 1999).

The LHMS rocks in the Kashmir and Himachal Himalaya, exposed within the HHC as the LKR Window and KW, are interpreted as antiformally-stacked duplex (DiPietro and Pogue, 2004; Yin, 2006;

Searle et al., 2007). The MHT acts as the basal décollement and the MCT represents the roof thrust of the duplex. Rocks from within the windows thus represent structurally deeper levels than rocks above the MCT. At the northern end of the HHC, it is bounded by the Zaskar Shear Zone (ZSZ)/STDS carrying THS (Patel et al., 1993; DiPietro and Pogue, 2004; Searle et al., 2007; Searle and Godin, 2003; Yin, 2006).

The LHMS zone in the Kumaun-Garhwal regions forms a complex structural duplex with several major internal thrusts (Srivastava and Mitra, 1994; Célérier et al., 2009). These indicate a forward propagating sequence that initiated after cessation of activity

on the MCT. Thrusts in the internal LHMS zone were active between ~12 and 15 Ma (DeCelles et al., 2001; Robinson et al., 2006) and the LHD was built since ~12–10 Ma (DeCelles et al., 2001; Huyghe et al., 2001; Robinson et al., 2006).

NE-Himalaya

The NE-Himalaya covers about ~560 km of the easternmost part of the Himalaya and extends from the eastern boarder of Bhutan to the Dibang and Lohit valleys in the east (Singh and Chowdhary, 1990; Singh, 1993; Acharyya, 1998; Burg et al., 1998; Ding et al., 2001; Zeitler et al., 2001; Singh and Jain, 2007) (Fig. 2b). The HHC and the LHMS tectonic structures are similar to the NW-Himalaya, but major structural variations are observed along the strike such as large-scale (tens of km) orogen perpendicular and parallel tectonic window/domes, klippen, and out-of-sequence thrusts. The Malda-Kishanganj fault at 88°E longitude is identified as a boundary coinciding with structural changes within the Himalaya (Clark and Bilham, 2008). Number of tectonic windows and re-entrants are dramatically reduced east of this boundary while klippen of the THS bounded by the STDS suddenly appear. Both the STDS and the MCT are located at least 100 km further south than observed in the west (Grujic et al., 2002; Clark and Bilham, 2008). All klippen of the THS occur in the cores of open, upright syncline with variable axial orientation (Grujic et al., 2002). The LHMS in the Arunachal Himalaya is confined to a narrow width but the LHMS rocks also crop out in the windows/half windows structures within the HHC. Such windows/half windows structures are Kuru Chu half window in Bhutan (Grujic et al., 2002; Long et al., 2011), Lum La window in the western Arunachal region (Yin et al., 2010), and the Menga (MeW) and the Nacho (NaW) Windows in eastern Arunachal region (Singh and Jain, 2007). The emplaced HHC rocks over the LHMS in the central Arunachal region have been folded into antiform and synform structures. The crest of the antiforms has been eroded leading to the exposition of LHMS rocks as windows while the synformal part has been left as nappes (Singh and Jain, 2007; Adlakha et al., 2018).

In the easternmost part of the Arunachal Himalaya, the Siang window is the largest of the all Himalayan window (Acharyya, 1998). The Himalayan windows have the LHMS duplex forming their core with the MCT as the roof thrust. The Siang window is unique that it possesses a core made up of a complex duplex of Cenozoic metasediments and metavolcanics with the MBT and MCT thrust sheets as its roof thrusts (Acharyya, 1998; Acharyya and Sengupta, 1998; Acharyya, 2007). Initiation and amplification of the Siang antiform have been described due to folding of the emplaced MBT thrust sheet. Acharyya (1998) and Acharyya and Sengupta (1998) suggested that the duplexing below the MCT and MBT thrust sheets caused the half dome structure (Salvi et al., 2017).

Topography and Precipitation

Topographic profiles across the Himalaya show marked variations in elevation ranging from ~400 m at the mountain front to around 1000 m in the Siwalik hills to ~1200 m in the LHMS and >3000 m within the HHC. However, there is strong difference in topography pattern between the NW-Himalaya (Figs. 3a, e; 4a, d, g) and the NE-Himalaya (Figs. 5a, d; 6a, d). The orography of the NW-Himalaya pick up at two zones: first in the south between MFT and the MBT and then above the MCT (Bookhagen and Burbank, 2010) (Figs. 3a,

e; 4a, d, g). Thus, there exists a physiographic transition zone in the south of the MCT. The transition zone is described to locate above the deep crustal ramp of the MHT (Seeber and Gornitz, 1983; Lavé and Avouac, 2001; Duncan et al., 2003; Wobus et al., 2003; Robert et al., 2011).

The topography is very different in the NE-Himalaya (Bookhagen and Burbank, 2010), and rises steeply at MFT zone and then straight to slightly convex-tapered (Figs. 5a, d; 6a, d). The rise to the high peaks in the NE-Himalaya is much more gradual than the NW-Himalaya. A single orographic break in NE-Himalaya is located at the MFT.

The orographic breaks of the NW-Himalaya make two belts of focused precipitation and these extend longitudinally from the NW-Himalaya (Uttarakhand) to the Central (Nepal) Himalaya (Fig. 1c). In the Kashmir and Himachal Himalaya, the orographic breaks are the Pir Panjal and Dhauladhar range respectively, located very close to the MBT. These orographic breaks make a wide belt of precipitation at the MBT-MCT zone in the front of the mountain.

The orographic break in the NE-Himalaya makes a single belt of focused precipitation at the MFT (Fig. 1c). A ~400 km long and ~1600 m high Shillong Plateau in front of the NE-Himalaya creates another orographic barrier for precipitation to the south of the Shillong Plateau, which strongly influences rainfall across the NE-Himalaya. It reduces mean annual precipitation in the rain shadow to half of that observed in neighboring regions (Biswas et al., 2007; Bookhagen and Burbank, 2010; Grujic et al., 2006; Adlakha et al., 2013). In spite of its influence, precipitation markedly changes from NW-to NE-Himalaya and shows an increasing trend from ~1500 mm/a in the NW-Himalaya to >3000 mm/a in the NE-Himalaya. The Indian Summer monsoon which is responsible for maximum precipitation in the Himalaya (Bookhagen and Burbank, 2010) was established by late Miocene (12–8 Ma) (An et al., 2001; Dettman et al., 2001, 2003; Molnar et al., 1993) or possibly much earlier (e.g., Clift et al., 2008; Guo et al., 2002; Sun and Wang, 2005; Srivastava et al., 2013). Although past intensified monsoon phases might have delivered more precipitation deeper into higher elevation regions (Bookhagen et al., 2005a, b), as long as the orography remained unchanged, variations in monsoon strength would not change the location of the major peak in rainfall at the Himalayan range front or the strong east-west precipitation gradient (Bookhagen and Burbank, 2010; Grujic et al., 2006).

Thermochronology and Exhumation

Approach

A number of thermochronological studies from the NW- and NE-Himalaya have been carried out by many workers since last two decades. Systematic study of the thermochronological data from both regions can reveal first-order patterns of differential rock uplift and exhumation that are difficult to observe, otherwise. Furthermore, spatial-temporal variation in exhumation histories of the NW- and NE-Himalaya can also be estimated and analyzed via thermochronological analysis. We relooked at ~800 published apatite fission track (AFT), zircon fission track (ZFT), ⁴⁰Ar/³⁹Ar (white mica/biotite) and apatite U-Th/He (AHe) and zircon U-Th/He (ZHe) from the HHC and the Crystalline klippen/nappes from both the NW-Himalaya (Kumar et al., 1995; Sorkhabi et al., 1996; Sorkhabi et al., 1997; Lal et al., 1999; Jain et al., 2000; Thiede et al., 2004; 2005;

Figure 3. (a) Topography and precipitation swath across the Kishtwar window, Kashmir Himalaya. Blue line indicates TRMM-derived rainfall. Black line shows mean elevation. After Gavillot *et al.* (2018). (b) Plot of AHe, ZHe ages (Gavillot *et al.*, 2018). Cited AFT and ZFT ages for the Kishtwar window and the HHC Himalaya (Kumar *et al.*, 1995). (c) Simplified SW-NE regional geological cross-section across the Kishtwar window, Kashmir Himalaya (Gavillot *et al.*, 2018). (d) AFT cooling ages from the Suru dome to the STDS, Zaskar, Kashmir Himalaya (Kumar *et al.*, 1995). (e) Topography and precipitation swath across the LKR window, Himachal Himalaya. Blue line indicates TRMM-derived rainfall and black line shows mean elevation. After Thiede *et al.* (2004). (f) AFT cooling ages along the Sutlej River (Thiede *et al.*, 2004). (g) Simplified SW-NE regional geological cross section across the Simla klippe-LKR window, Himachal Himalaya. After Thiede *et al.* (2004). (h) Simplified geological cross-section and distribution of cooling ages along the Sutlej Valley. After Vannay *et al.* (2004) and Thiede *et al.* (2005).

Vinnay *et al.*, 2004; Bojar *et al.*, 2005; Walia *et al.*, 2008; Célérier *et al.*, 2009a, b; Patel and Carter, 2009; Thiede *et al.*, 2009; Patel *et al.*, 2007, 2011a, b, 2015; Schlup *et al.*, 2011; Deeken *et al.*, 2011; Singh *et al.*, 2012; Adlakha *et al.*, 2013b; Thiede and Ehlers, 2013; Singh and Patel, 2016; Gavillot *et al.*, 2017; Thiede *et al.*, 2017) and NE-Himalaya (Grujic *et al.*, 2006; Long *et al.*, 2012; Adlakha *et al.*, 2013c, 2018; Coutand *et al.*, 2014; McQuarrie *et al.*, 2014; Adams *et al.*, 2015; DeCelles *et al.*, 2016; Salvi *et al.*, 2017) to highlight along-strike changes in the exhumation pattern and ultimately variation in tectonics. These thermochronological data depict cooling of rocks

from ~400°C isotherm to the surface. Methods used are (i) a compilation of all published AFT, ZFT, AHe, ZHe, $^{40}\text{Ar}/^{39}\text{Ar}$ ages, (ii) estimating exhumation rate using 1-D modeling with AGE2EDOT programme (Brandon *et al.*, 1998; Ehlers *et al.*, 2005). Available AFT, ZFT, AHe, ZHe and $^{40}\text{Ar}/^{39}\text{Ar}$ -Muscovite cooling ages in the NW- and NE-Himalaya have been used to calculate average-exhumation rates by applying 1D-AGE2EDOT thermal model (for AFT, ZFT, U-Th/He and $^{40}\text{Ar}/^{39}\text{Ar}$ -Muscovite cooling ages) (Brandon *et al.*, 1998; Ehlers *et al.*, 2005) and through standard cooling rate/geothermal gradient method by taking an appropriate closure temperatures of ~135°C for AFT, ~240°C for ZFT (Brandon *et al.*, 1998), ~180°C for ZHe, ~65°C for AHe (Reiners, 2005) and ~300°C for K-Ar biotite (Purdy and Jäger, 1976; Wagner *et al.*, 1977; Dodson, 1981) and ~350°C for $^{40}\text{Ar}/^{39}\text{Ar}$ -Muscovite (McDougall and Harrison, 1998; Hodges, 2003), and (iii) estimating transient exhumation rate for each thermochronometer system of both the NW- and NE-Himalayan regions. Temporal-transient exhumation rates are calculated using the approach of Thiede *et al.* (2009). The 1D model is based on the solutions of steady-state advection and diffusion equations and rely on reasonable values of material properties. The reason for not employing more complex two-or-three-dimensional models is the thermokinematic modeling study of Whipp *et al.* (2007) who established that the thermal field in rapidly eroding orogens like “the Himalaya”, is mainly controlled by the vertical advection and conduction. The range of cooling ages with mean age of respective mineral clocks available in

different sector of the NW- and NE-Himalaya and estimated average exhumation and temporal-transient exhumation rates are shown in Table 1.

Thermochronological age / Exhumation versus Precipitation

NW-Himalaya: Thermochronological age pattern in different sectors of the Himalaya has been observed in age vs distance plots along different traverses across the HHC and the LHS (Figs. 3, 4). The

Figure 4. (a) Topography and precipitation swath across the Chamba region, Himachal Himalaya. Blue line indicates TRMM-derived rainfall and black line shows mean elevation. After Bookhagen and Burbank (2006, 2010) and Deeken et al. (2011). (b) Plot of ZFT, ZHe, AFT and AHe ages. After Deeken et al. (2011), and cited AFT and ZFT ages for the Kishwar window and the HHC Himalaya. After Deeken et al. (2011) and Adlakha et al. (2013). (c) Simplified geological cross-section of Chamba. Modified from Robyr et al. (2006) and Deeken et al. (2011). (d) & (g) Topography and precipitation swath across the Kumaun and Garhwal region respectively, Uttarakhnad Himalaya. Blue lines indicate TRMM-derived rainfall, and black lines show mean elevation and red lines show relief of the area. After Bookhagen and Burbank (2006, 2010). (e) & (h) AFT and ZFT cooling ages across the Kumaun and Garhwal region, respectively (Patel and Carter, 2009; Patel et al., 2011; 2015; Singh et al., 2012; Singh and Patel, 2016). (f) & (i) Simplified geological cross-section across the Kumaun and Garhwal region, respectively. Modified after Srivastava and Mitra (1994) and Célérier et al. (2009).

regions of Suru-Doda, Chenab-Bhot and Sutlej valleys are characterized by dome/window structures such as Suru dome, KW and LKR Window respectively (Fig. 2) (Kundig, 1989; Thakur, 1992; Kumar et al., 1995; Jain et al., 2000). The MCT/Munsiari Thrust (MT) and Vaikrita Thrust (VT) and klippen such as Almora, Baijnath, Askot and Chiplakot Crystalline Belt (CCB) are the important structures in the Garhwal-Kumaun regions (Valdiya, 1980; Srivastava and Mitra, 1994). In Kashmir and Himachal Himalaya most of plots are across dome/window structures and some are across the major fault structures such as the STDS, MCT and MBT. Age patterns in Uttarakhand are studied across major structures such as the MCT and klippen zones. These plots across different sectors in the NW-Himalaya clearly indicate that there is hardly any correlation between age and mean annual rainfall (Figs. 3 and 4). The KW and LKR window are located in two different precipitation zones. The KW region receives less rain fall (<2m/yr) than the LKR window (2.5-3.5 m/yr). In spite of different precipitation, both the windows have been undergoing exhumation at almost same rate (1.28-1.30mm/yr) (Fig. 7a). In other cases of two adjacent regions i.e. Kumaun and Garhwal, although share similar precipitation pattern, there is significant difference in thermochronological age patterns and exhumation rates (Figs. 4d, e, g,h) (Patel and Carter, 2009).

NE-Himalaya: One of the uniqueness about the NE-Himalaya is that the Shillong Plateau strongly influences the rainfall across the Eastern Himalaya by reducing mean annual precipitation in the rain shadow (5 m/yr) to nearly half of that observed in neighboring regions

(9 m/yr) (Biswas et al., 2007; Bookhagen and Burbank, 2010; Grujic et al., 2006). The zone of maximum precipitation (>3 m/yr) in NE-Himalaya is located in front of the Himalaya along the MBT-MFT zone, while low precipitation zone (<2 m/yr) is marked in the hinterland. Thermochronological studies from the HHC and the LHS zones in Bhutan and Arunachal Himalaya are available where precipitation is low and not varying from eastern Bhutan to western Arunachal. Thermochronological pattern does not show any correlation with precipitation pattern. In spite of similar precipitation pattern in the HHC zone of the eastern Bhutan and western Arunachal, there is significant variation in the exhumation rates between them (Figs. 5d; 6a, b). In both the Bhutan and Arunachal Himalaya, footwall zone of the MCT, i.e. LHS zone receives more annual rainfall than the hanging wall zone, i.e. HHC zone but is characterized by young thermochronological ages than the LHS zone. It is also estimated that the HHC zone is exhuming rapidly than the LHS zone (Fig. 7b).

Regionally, NE-Himalaya is receiving more annual rainfall than the NW-Himalaya; runoff from the Brahmaputra catchment is at least twice as high as that of the Ganga and up to ten times than the Indus (Baillie and Norbu, 2004). It means that the NE-Himalaya should exhume much faster than the NW-Himalaya, but it is not so. The exhumation pattern in the HHC zone of the entire Himalaya except eastern Bhutan and Zaskar Himalaya is almost identical.

Based on these observations, it can be inferred that precipitation is not a leading factor to influence the exhumation of the rocks of the Himalaya.

Figure 5. North-south distribution of cooling ages along (a) western and (d) eastern Bhutan. Topographic profile for each transects is represented by bold black line and mean annual precipitation distribution represented by the bold blue line. Location of the main tectonic boundaries are represented by vertical dotted lines. Instantaneous (red line) and long-term (colored dots) exhumation rates from (b) western and (e) eastern Bhutan; each dot represents the long-term exhumation value returned by each sample. Geometry of the MHT (c) western and (f) eastern Bhutan. After Coutand et al.(2014).

Figure 6. (a) Topography and precipitation swath across the western Arunachal Himalaya. Blue line indicates TRMM-derived rainfall and black line show mean elevation. After Bookhagen and Burbank (2006, 2010). (b) Cooling age data and model-predicted cooling ages (lines) are plotted vs. distance along the sample transect in western Arunachal Himalaya. After Adlakha et al. (2013). (c) Regional geological cross section across western Arunachal Himalaya (DeCelles et al., 2016). (d) Topography and precipitation swath across central Arunachal Himalaya. Blue line indicates TRMM-derived rainfall and black line shows mean elevation. After Bookhagen and Burbank (2006, 2010). (e) Variation in AFT ages within the HHC klippe with respect to the MCT, and distance, and plot of exhumation rates of each sample locations. (f) Regional geological cross-section across the HHC klippe in central Arunachal Himalaya (Adlakha et al., 2018). (g) Mean topography (solid black line), relief (grey zone) and precipitation variation (dotted blue line) across a 10-km topographic swath from Pasighat to NE of Tuting (Salvi et al., 2017). (h) Distance vs AFT cooling ages plot along the hinge of the Siang Antiform from Pasighat to NE of Tuting (Salvi et al., 2017). (i) Distance vs cooling ages (AFT and ZHe) plot along SW-NE traverse from Along across the Siang Antiform.

Tectonic control on exhumation

Thermochronological pattern from the Kashmir and Himachal Himalaya can be explained by out-of-sequence thrusting driven by climate-enhanced erosion (Jain et al., 2000; Hodges et al., 2004;

Hodges et al., 2004; Thiede et al., 2004, 2005; Wobus et al., 2003; Wobus et al., 2005; Grujic et al., 2006; Huntington and Hodges, 2006; Deeken et al., 2011) and by overthrusting, duplex development and movement across a mid-crustal ramp on the MHT (Bollinger et al., 2006; Brewer and Burbank, 2006; Whipp et al., 2007; Herman et al.,

2010; Robert et al., 2009; van der Beek et al., 2016). Here, we assess the coupling between tectonics and exhumation across the NW–Himalaya and NE–Himalaya by comparing thermochronological pattern with the structural data (Figs 3–7). It is noticed that development of dome/window and nappe/klippe structures, and reactivation of the MCT zone (MT and VT) as out-of-sequence thrusting have taken leading role in exhumation of the NW– and NE–Himalaya.

Dome/Window/Fold controlled exhumation

NW–Himalaya: Regions of young thermochronological ages and high exhumation rates correspond with windows and dome structures in the Kashmir and Himachal Himalaya.

Suru Dome: The thermochronological age pattern is compatible with development of the Suru dome. The core of the dome is characterized by young AFT ages range between 4.90 ± 0.26 and 5.57 ± 0.55 Ma with mean age 5.24 Ma and outside core, ages range between 3.75 ± 0.32 and 8.07 ± 0.71 Ma with mean age of 6.25 Ma (Kumar et al., 1995) (Table 1, Fig. 3d). Plot of age vs distance shows that the ages outside core increase linearly northward away from the core of dome (Fig. 3d). The ZFT ages out of the core ranging between 12.92 ± 0.64 to 13.79 ± 0.63 Ma also show similar linear trend as AFT ages.

Temporal-exhumation rates between ~15 and 5 Ma and since ~5 Ma to present within the core are 0.72 mm/yr and ~0.55 mm/yr, respectively, while outside the core, the rates are ~0.46 to 0.56 mm/yr and 0.48 mm/yr, respectively (Fig. 7). It appears that development of Suru dome has been continuing since ~15 Ma and influencing exhumation pattern in Zaskar region.

Kishtwar Window (KW): Young AFT ages range between 1.01 ± 0.15 and 3.23 ± 0.45 Ma correspond to window, while ages range between 2.13 ± 0.14 and 11.0 ± 0.30 Ma in the overlying HHC thrust sheet structurally above the window (Kumar et al., 1995). The AFT ages from this region are comparatively younger than the Suru dome. Age vs distance plot shows curvilinear trend with concave upward with crest zone is located above the window zone (Fig. 3b). The oldest age is found along the STDS zone which is the dry region of Jammu and Kashmir. ZFT (range between 6.17 ± 0.57 and 12.26 ± 0.67 Ma) and K–Ar Biotite (range between 13.7 ± 0.3 and 24.9 ± 0.6 Ma) ages (Kumar et al., 1995; Sorkhabi et al., 1997) also show similar pattern as the AFT ages within the HHC, i.e. becoming older due NE (Fig. 3b).

Since 2.3 Ma, the window zone is exhuming at rate 1.3 mm/yr while outside window zone the HHC is exhuming at rate 0.65 mm/yr since 5 Ma. The HHC to the south and north of the window was exhuming at rate 0.41 mm/yr during 18 and 9 Ma and then it accelerated to 0.84 mm/yr during 9 and 5 Ma. Thus, the thermochronological age pattern across the hinterland demonstrates that younger ages and higher exhumation rate characterize the core of the window structural culmination, which contrasts from structurally bounding higher thrust sheets. It appears that probably 9 Ma was time during which the window structural culmination started. It has been inferred that duplex development due to horse emplacement above the MHT at depth controls the locus of exhumation associated with the KW (DiPietro and Pogue, 2004; Yin, 2006; Searle et al., 2007). Horse emplacement at depth produces localized regions of relatively high uplift rates (Boyer and Elliott, 1982; Molnar and Lyon-Caen, 1988), a mechanism invoked to explain young cooling ages.

Larji-Kullu-Rampur (LKR) Window: Age vs distance plots (Figs. 3f, h) show curvilinear trend with younger ages within the window and gradually older ages within the overlying HHC. The age pattern across LKR Window is similar to the KW.

At the time of emplacement of the HHC i.e. during ~23–19 Ma, the emplaced HHC sheet was exhuming at rates >3 mm/yr. Between ~19–13 Ma, the exhumation of the HHC receded to one sixth from previous rate and exhumed at ~0.5–0.7 mm/yr. At ~13 Ma, growth of the LKR dome began and was exhuming at ~3 mm/yr. It continued till 4 Ma. During this ~13 to 4 Ma, the overlying HHC rocks, surrounding the dome, were exhuming slowly at ~0.5 mm/yr. This peak period of rapid exhumation of the LKR window was followed by a time between ~4 Ma till present during which both the window and the overlying HHC started exhuming at rate ~1–2 mm/yr. Rapid exhumation of the LKR window since 13 Ma is described due to continuous development of the Lesser Himalayan Duplex (LHD) (DeCelles et al., 2001). Duplex development at depth produced localized regions of relatively high uplift/topography, a mechanism that explains young cooling ages.

NE–Himalaya

Synformal Nappe near Tamen along Kurung River: AFT ages range between 5.0 ± 0.8 and 14.4 ± 1.3 Ma across synformal nappe of the HHC that emplaced over the LHMS zone in Central Arunachal Himalaya (Fig. 2b; Adlakha et al., 2019). The age pattern shows folded convex upward linear pattern (Fig. 6e). The AFT cooling ages are younging on both the northern (6 Ma) and southern (5 Ma) flanks of the synform near the MCT, while oldest age (14 Ma) is confined in the core of synform. Exhumation rates calculated from these cooling ages vary from 0.25 ± 0.12 to 0.69 ± 0.25 mm/yr with slow exhumation in the core of the synform and rapid exhumation towards northern (south-dipping MCT) and southern (north-dipping MCT) flanks of the synform. The close mimicking of a shallow crustal exhumation pattern with the synform suggests a strong control of its development on the exhumation path of the rocks. The fast cooling in the flank domains of the synform in the present example can only be explained by synchronous reactivation of the MCT as out-of-sequence thrusting on the southern flank and back-thrusting on the northern flank. It points towards tectonics–exhumation linkage in the central Arunachal Himalaya. The AFT age pattern in central Arunachal Himalaya does not match with the pattern of precipitation, which suggests an absence of climate-driven tectonic deformation via focused erosion.

Siang Antiform along Siang River: AFT and U–Th/He zircon (ZHe) ages from the Siang valley highlight the unique spatial erosion along the axial regions of the Siang antiform. All the ZHe and AFT cooling ages from the region range between ~14 and 9 Ma, and 2.4 Ma to present, respectively (Salvi et al., 2017). A northernmost ZHe age is distinctly younger (~3.8 Ma). Northward younging trend of the AFT ages reveals rapid cooling/exhumation in the northernmost part of Siang Valley. Salvi et al., (2017) described a phase of relatively slow cooling (5 – $11^\circ\text{C}/\text{Ma}$) between ~14 and ~1.5 Ma followed by a period of rapid cooling (40 – $100^\circ\text{C}/\text{Ma}$) post~1.5 Ma. Spatially coincident of zone of rapid cooling/exhumation, steep slopes, higher fluvial incision potential and heavy precipitation has been described as a balance between rapid rock uplift and erosion in the upper Siang Valley (Figs. 6g, h; Salvi et al., 2017). Rapid cooling/exhumation on the northern side of Siang Antiform marks the

Table 1: Cooling ages and Exhumation Rates from NW- and NE Himalayas

Geographic Zone	Tectonic Zone	Dating Method (No. of samples)	Age (Ma)		Exhumation Rates (mma-1)						
			Range	Mean	Min	Max	Mean	Duration (Ma)	Corrected (Ma)	Δt	
Kashmir Region (NW-Himalaya)											
Suru –Doda Valleys (Kumar et al., 1995; Sorkhabi et al., 1997)	Higher Himalayan Crystalline (outside the core of dome)	AFT (15)	3.75±0.32 - 8.07±0.71	6.25	0.36	0.74	0.48	6.25	0.48±0.10	6.25-0	
		ZFT (4)	12.92±0.64 - 13.79±0.63	13.37	0.46	0.49	0.47	7.12	0.46±0.02	13.37-6.25	
		K-Ar Biotite	19.97±0.45	19.97	0.50	0.50	0.50	6.6	0.56	19.97-13.37	
	Higher Himalayan Crystalline (core of dome)	AFT (2)	4.90±0.26 - 5.57±0.55	5.24	0.52	0.59	0.55	5.24	0.55±0.04	5.24-0	
K-Ar (1) Biotite		~15.15±0.34									
Chenab-Bhot Nala Valley (Kumar et al.,1995; Sorkhabi et al., 1997; Gavillot et al., 2017)	Higher Himalayan Crystalline	AFT (43)	2.13±0.14 - 11.0±0.30	4.85	0.27	1.19	0.65	4.85	0.65±0.19	4.85-0	
		ZFT (8)	6.17±0.57 - 12.26±0.67	8.58	0.50	0.93	0.73	3.73	0.84±0.15	8.58-4.85	
		K-Ar (9) Biotite	13.7±0.3 - 24.9±0.6	18.39	0.40	0.73	0.56	9.81	0.41	18.39-8.58	
	Lesser Himalayan Crystalline (Kishtwar window) zone	AFT (4)	1.01±0.15 - 3.23±0.45	2.33	0.84	2.12	1.28	2.33	1.28±0.53	2.33-0	
		Kashmir-Chamba Nappe including Haimanta Fm. (between MBT and MCT)	AHe (4)	5.1± 2.1 - 21.1 ± 6.7						0.1–0.2	
			ZHe (4)	13.3 ± 5.6 - 22.5 ± 3.9							
Himachal Region (NW-Himalaya)											
Around Larji-Kullu-Rampur Window (Kumar et al., 1995; Lal et al., 1999; Jain et al., 2000; Schlup et al., 2003, 2011; Thiede et al., 2004, 2005, 2009; Vannay et al., 2004; Deeken et al., 2011)	Higher Himalayan Crystalline	AFT (79)	0.6±0.2 - 3.6±0.5	1.86	0.9	3.7	1.52	2	1.5±0.5	2.0-0	
		ZFT (11)	6.1±0.2 - 19.9±0.5	13.4	0.5	0.8	0.55	11	0.4±0.1	13-2	
		⁴⁰ Ar/ ³⁹ Ar Mus. (38)	9.7±0.2 - 22.3±0.5	18.5	0.4	0.8	0.63	6	0.8±0.1	19-13	
		Peak Meta.	23	-	-	-	1.30	4	4.5±0.2	23-19	
	Lesser Himalayan Crystallines (Larji-Kulu Rampur Window)	AFT (21)	0.6±0.2 - 3.6±0.5	1.86	0.9	3.7	1.52	0.54	1.5±0.5	2.0-0	
		ZFT (12)	1.4-4.8	2.3	1	3	2.4	0.65	3.2±0.7	4-2	
		⁴⁰ Ar/ ³⁹ Ar Mus (14)	4.4-14.9	6.2	1.8	2.9	1.75	0.40	2.0±0.4	6-4	
		Peak Meta.	11.0	-	-	-	2.73	-	3.9±0.5	11-6	
Dhauladhar - PirPanjal Ranges to Gianbul Dome	Haimanta	AFT (22)	1.7 ± 0.3 - 9.3 ±0.9						0.3-0.9	~15-0	
		ZHe (21)	6.3 ±0.6 - 18.1 ± 1.8								
(Lal et al., 1999; Walia et al., 2008; Deeken et al., 2011, Adlakha et al, 2013; Thiede et al., 2017)	Higher Himalayan Crystalline	AFT (27)	1.9 ±0.4 - 8.7 ± 0.5						0.8-1.9	~4-0	
		ZHe (16)	3.0 ± 0.2 - 15.3± 1.5								
		ZFT (26)	3.9± 0.8 - 21.1 ± 2.2								

Table 1: Contd....

Geographic Zone	Tectonic Zone	Dating Method (No. of samples)	Age (Ma) Range	Mean	Exhumation Rates (mma-1)					
					Min	Max	Mean	Duration (Ma)	Corrected (Ma)	Δt
Garhwal Region(Uttarakhand) (NW-Himalaya)										
Pindari-Dhauliganga-Bhagirathi Valleys (Sorkhabi et al., 1996; Patel and Carter, 2009; Singh et al., 2012)	Higher Himalayan	AFT (34)	0.9±0.3 to 4.2±0.7	2.16	1.25	1.60	1.42	2.16	1.42	~2-0
	Crystalline	ZFT (19)	2.3 ± 0.3 to 11.7	6.77	1.05	1.41	1.23	4.61	1.14	~7-2
		⁴⁰ Ar/ ³⁹ Ar (23)	5.7 to 22.2	14.63	0.50	0.80	0.65	7.86	0.17	~14-7
Kumaon Region(Uttarakhand) (NW-Himalaya)										
Kaliganga-Darma-Goriganga valleys (Bojar et a, 2005; Patel and Carter, 2009; C��l��rier et al., 2009; Patel et al., 2011)	Higher Himalayan	AHe (4)	0.3 to 0.58	0.4	3.62	4.25	3.93	0.4	3.93	~0.5-0
	Crystalline	AFT (45)	0.3 to 2.9	1.34	2.15	2.70	2.42	0.94	1.77	~1-0.5
		ZFT (17)	0.9-5.2	2.57	1.83	2.38	2.10	1.23	1.75	~2.5-1
		⁴⁰ Ar/ ³⁹ Ar (1)	10.3	10.3	0.5	0.8	0.65	7.66	0.16	~10-2.5
Almora klippen (Patel et.al., 2015, Singh and Patel, 2016)	North Almora Thrust (NAT)–Kasun Thrust (KT)	AFT (05)	7.0–13.2	10.8	0.25	0.45	0.35	10.8	0.35±0.1	10.8-0
		ZFT (02)	13.9–16.8	15.4	0.30	0.55	0.42	4.6	0.58±0.1	15.4-10.8
		Ar–Ar (02)	18.2–19.8	19.0	0.25	0.45	0.35	4.4	0.11	19.0-15.4
	Kasun Thrust (KT)–South Almora Thrust (SAT)	AFT (11)	3.7–13.2	8.5	0.45	0.65	0.55	8.5	0.52±0.1	8.5-0
		ZFT (07)	13.4–21.4	18.2	0.3	0.55	0.42	9.7	0.31±0.1	18.2-8.5
		Ar–Ar (02)	22.8–25.7	24.2	0.25	0.45	0.35	4.6	0.06	24.2-18.2
Baijnath Klippe (Singh et al., 2012)	Baijnath Klippe	AFT (03)	4.7 ± 0.5 – 6.6 ± 0.8	5.4					0.5 – 0.6	5.4 - 0
Chiplakot Crystalline Belt (CCB) (Patel et al., 2007)	Chiplakot Crystalline Belt (CCB)	AFT (09)	7.6 ± 0.6 – 17.9± 0.9	12.23					0.25 – 0.38	12.23 - 0
Bhutan (NE-Himalaya)										
Western Bhutan (Grujic et al., 2006; Coutand et al., 2014; McQuarrie et al., 2014; Adams et al., 2015)	Higher Himalayan Crystalline + Paro window	AHe (31)	2.6± 0.3 - 6.8± 0.3						1.0–1.8	2.5 - 0
		AFT (42)	2.4 ± 0.3 - 8.4 ± 1.4							
		ZHe (18)	3.24 ±0.2 - 10.44±0.6							
		ZFT (10)	7.9± 1.1 - 13.5 ± 1.6							
Eastern Bhutan (Grujic et al., 2006; Long et al., 2012; Coutand et al., 2013)	Higher Himalayan Crystalline	AHe (10)	2.9± 0.5 - 5.5 ±1.1						HHC 0.55-0.85	HHC ~4-0
		AFT (34)	3.0 ± 0.7 – 8.6 ± 0.8						0.6-1.3	~7-4
	Lesser Himalayan Duplex	ZHe (29)	4.05 ± 0.1 – 11.6 ± 0.3						1.4-1.8	~12-7
		ZFT (03)	7.9 ± 1.3 -17.5 ± 0.7						LHD 0.8-0.9	LHD 7-0

Table 1: Contd....

Geographic Zone	Tectonic Zone	Dating Method (No. of samples)	Age (Ma) Range	Mean	Exhumation Rates (mma-1)					
					Min	Max	Mean	Duration (Ma)	Corrected (Ma)	Δt
									1.3-2.6	13-7
									0.2-0.25	23-13
Arunachal (NE-Himalaya)										
Western Arunachal (Adlakha et al., 2013; DeCelles et al., 2016)	Higher Himalayan Crystalline	AFT (28)	1.3±0.1 - 2.9±0.3	2.1	0.92	1.69	1.27	2.1	1.27±0.2	2.1-0
		ZFT (07)	4.5±0.5 - 8.9±1.3	7.04	0.68	1.19	0.85	4.94	0.67±0.2	7.04-2.1
		⁴⁰ Ar/ ³⁹ Ar	8.0-12.2	10.44	0.97	1.03	1.03	3.4	1.40±0.1	10.44-7.04
	Lesser Himalayan Sequence	AFT (11)	5.7±0.6 - 13.3±1.4	8.1	0.23	0.50	0.38	8.1	0.38±0.1	8.1-0
		ZFT (07)	10.9±0.6 - 14.1±1.1	12.17	0.44	0.60	0.51	4.07	0.77±0.1	12.17-8.1
Central Arunachal (Adlakha et al., 2018)	Higher Himalayan Crystalline (Nappe)	AFT (07)	5.0 ± 0.8 -14.4±1.3						0.2 - 0.68	
Eastern Arunachal (Salvi et al., 2017)	Upper Siang Valley	AFT (11)	0.6 ± 0.2 – 2.5 ±0.3	1.6						
		ZHe (09)	3.8 ± 0.2 - 14.0 ± 0.9	10.44						

Notes: ^aUnit, morphotectonic unit; Range, it is of obtained cooling age population; Mean, arithmetic mean; $E_2 = [(E_0 t_0) - (E_1 t_1)](t_0 - t_1)^{-1}$; $E_3 = [(E_0 t_0) - (E_1 t_1) - (E_2 t_2)](t_0 - t_1 - t_2)^{-1}$; HHC: Higher Himalayan Crystallines; LHC, Lesser Himalayan Crystallines. Since, the exhumation is dominated by erosional advection, the 1D modelling is based on geothermal gradient values in range 25 - 45°C km⁻¹ (Whipp et al., 2007; Patel and Carter, 2009) and closure temperature of 135°C corresponds to Apatite FT ages, 240° to Zircon FT ages (Brandon et al., 1998) and ~ 350°C for ⁴⁰Ar/³⁹Ar-Muscovite (McDougall et al., 1998; Hodges, 2003). Thermal conductivity, we use values range between 2.0 and 3.6 W m⁻¹ K⁻¹ (Ray et al., 2007; Thiede et al., 2009) and heat production with values ranging between 0.8 and 3.0 μ W m⁻³ for the HHC (England et al., 1992; Roy and Rao, 2000). Thermal diffusivity value range of 29-50 Km² Ma⁻¹ are used (Patel and Carter, 2009). Surface temperature of 10°C is used.

southwestern limit of the rapid uplift related to the growth of the Namche Barwa antiform.

Plot of the AFT and ZHe cooling ages vs distance across the Siang Antiform shows a horizontal linear trend of the ZHe ages across the antiform whereas AFT ages show a concave upward trend (Fig. 6i). It reveals that the formation of the Siang antiform is younger than ZHe ages (~12 Ma) and the antiform started developing post ~1.5 Ma (AFT age). Development of antiform exposed the hinge zone for rapid exhumation while limbs zone of the antiform reveals slow exhumation away from it. Uniform ZHe cooling ages of ~12 Ma across the antiform represents the time of emplacement of the LHMS along the MBT over the Sub-Himalayan rocks.

Thrust influenced exhumation

NW-Himalaya: Several thermochronological studies have been carried out in different sectors of the NW-Himalaya such as Kashmir, Himachal, Garhwal and Kumaun, and Bhutan and Arunachal in the NE-Himalaya (Fig. 2). Thermochronological data are confined in the hanging wall of major thrusts such as the MBT and the MCT and across the Almora klippe.

Kashmir and Himachal Himalaya: AHe and ZHe cooling ages are available across folds and faults in the foreland basin of the Sub-Himalayan belt and from thrust sheets in the hinterland of the Pir

Panjal Range in the Kashmir Himalaya (Figs. 2, 3b) (Gavillot et al., 2018). In the foreland, reset young AHe cooling ages (<4 Ma; Fig. 3b) and high exhumation rates (≥ 1 mm/yr) are described as thrust-related exhumation on structures within the Sub-Himalaya (Figs. 3b, c). Coeval thrusting across multiple faults in the Kashmir Sub-Himalaya explains the regional upper-plate exhumation and demonstrates that it was established since ~4 Ma. In the Kashmir Himalayan hinterland along the Pir Panjal Range, AHe data yield older cooling age (>5.1 Ma) and lower exhumation rate (<0.2 mm/yr) across the MBT and the MCT (Fig. 3b). Hinterland and foreland ZHe age data reveals a similar cluster in cooling ages (14–23 Ma) associated with exhumation and erosion on the MCT. It has been described that the active deformation front indicates that duplex growth is responsible for the KW. Decoupling of precipitation and Late Cenozoic cooling and exhumation in the Kashmir Himalaya suggests that climate is not the primary driver of deformation. Rather these new data indicate that the exhumation pattern since 4 Ma primarily reflects changes in structural architecture and spatial variability in the distribution of shortening.

Along 100 km long orogen perpendicular traverse across Chamba in Himachal, several AFT and ZHe ages (Table 1) yielded distinct variation in age distributions and long-term exhumation rates between the highly precipitated frontal range and the low precipitated orogen interior (Deeken et al., 2011). In this region, young AFT cooling ages (<3 Ma) and high exhumation rates (0.8 to 1.9 mm/yr) correspond to

Figure 7. Regional distribution of calculated AFT exhumation rates in different sectors of the Himalaya estimated by different workers: (a) NW-Himalaya and (b) NE-Himalaya.

the southwestern flank of the Dhauladhar Range (Figs. 4a-c; 7a). Therange is bounded by the MBT and the MCT, but the Chamba nappe is not folded above a structural culmination in hanging wall of the MCT (Robyr et al., 2006) as observed in the KW or the LKR window along strike to the southeast (Fig.2). In contrast, AFT and ZHe ages within the orogen interior are older (4–9 and 7–18 Ma, respectively) and yield lower mean exhumation rates (0.3–0.9 mm/yr). Adlakha et al. (2013) determined AFT and ZFT ages in the frontal part of the Dhauladhar range, where Deeken et al. (2011) determined similar AFT ages. The ZFT ages range between 10.4 ± 1.4 and 21.1 ± 2.2 Ma. Two data sets were used in describing the cease of activity along the MCT/Panjali Thrust at ~ 15 Ma and development of the MBT at ~10 Ma (Adlakha et al., 2013). Activities along the MBT and the MCT tilted the topography which controlled the exhumation pattern of the frontal part of the Chamba during Middle to Late Miocene (Adlakha et al., 2013; Gillvot et al., 2018).

Jain et al. (2000) have determined AFT and ZFT ages in the HHC along the Sutlej valley, Himachal Pradesh and identified two distinct clusters of the AFT ages. Cluster of older AFT ages (4.9 ± 0.2 Ma) is confined to the footwall of the Chaura thrust, while young AFT ages (1.49 ± 0.07 Ma) lie in its hanging wall. It has been estimated that the hanging wall has been exhuming at 2.01 ± 0.35 mm/yr since 1.49 Ma while the foot wall is exhuming at 0.61 ± 0.10 mm/yr since 4.9 Ma. In the north of Chaura thrust, the hanging wall of the VT has been exhuming at 2.29 ± 0.66 mm/yr since 1.31 ± 0.22 Ma. These observations indicate that activity along the Chaura thrust and VT has been influencing the exhumation pattern of the HHC along the Sutlej valley.

Such strong variability in along-strike exhumation between the Kashmir and Himachal is recently described due to lateral geometric variations in the MHT (Thiede et al., 2017; Gillvot et al. 2018).

Uttarakhand Himalaya (Garhwal Region): In the Garhwal region FT and mica $^{40}\text{Ar}/^{39}\text{Ar}$ ages are available along the Dhauliganga (Patel and Carter, 2009) and Pindari (Singh et al., 2012) Rivers, and Gangotri (Sorkhabi et al., 1996) region (Table 1). FT data from the Dhauliganga section show systematic changes in age (individual AFT ages range from 0.9 ± 0.3 to 3.6 ± 0.5 Ma, $r^2=0.82$) that record faster exhumation across a zone that extends from the MCT/MT to north of the VT. AFT ages along the Pindari River range between 0.3 ± 0.1 and 4.2 ± 0.7 Ma in the HHC and LHMS zone and between 4.7 ± 0.5 and 6.6 ± 0.8 Ma in the Baijnath klippe. Linear but southward inclined trend and distinct jump in AFT age trend across the VT along the Pindari valley in the NW–Himalaya has been described due to progressive late thrust movement (Singh et al., 2012). The progressive increase in time difference between the AFT and ZFT ages with distance towards north of the VT shows that exhumation has been faster near the region of the MCT/MT and VT (Patel and Carter, 2009; Patel et al., 2011; Singh et al., 2012). Cooling ages from the Gangotri region has been described through two pulses of rapid exhumation: one pulse is due to detaching of cover rocks along the Martoli Normal Fault (STDS) during the Early Miocene and second pulse is described due to erosion of tectonically uplift topography during Late Pliocene–Quaternary period (Sorkhabi et al., 1996).

Kumaun Himalaya: Thermochronological studies using AHe, AFT and ZFT in the HHC and the Almora klippe of the Kumaun region reveal that the AFT ages from the HHC region show a stepwise change

across the VT (Table 1). Footwall and hanging wall samples yield weighted mean AFT age of 1.6 ± 0.1 Ma and 0.7 ± 0.04 Ma, respectively. It suggests Quaternary thrust sense displacement along the VT. A constant ZFT age of 1.8 ± 0.4 Ma across both the footwall and hanging walls shows the 0.9 Ma difference in the AFT ages. It is described due to movement on the VT that initiated soon after ~1.8 Ma. The clear tectonic signal in the Kumaun region is described due to lack of complete adjustment of climate erosion to tectonic perturbation of the region (Patel and Carter, 2009). Further, zero slope line of ages with respect to distance from the thrust zone indicates a balance between the tectonic uplift and erosion since at least Plio–Quaternary time in the Kumaun Himalaya (Patel et al., 2011; and references therein). No variation of the FT ages with respect to elevation in the Kumaun Himalaya shows uplift and exhumation histories as a single block since at least 2 Ma.

The AFT ages from the crystalline klippen (Almora klippe and the CCB) over the LHMS zone are older (>5 Ma) than the HHC zone (<3 Ma). In spite of no major difference in precipitation between the HHC and the LHMS zone in the Kumaun Himalaya, a remarkable difference in ages and exhumation rates between them reflect that there is a major tectonic break i.e. the MCT along which its hanging wall has uplifted while in its footwall the LHS has not relatively moved up. The broken and jump of age patterns across faults within the Almora klippe and the CCB (Figs. 4e, h) are interpreted due to growth of imbricate structures along with the MBT in the outer LHS and reactivation of inner LHS duplex. These growths of LHS duplex and imbricate structures along the MBT are described due to movement along the MHT. The slip along the MHT fed some fraction of slip along individual thrust in the duplex. It has resulted in reactivation of the older faults within the overlying rocks including the Almora klippe, Ramgarh thrust sheet and the CCB (Patel et al., 2007; Patel et al., 2015).

NE–Himalaya: Thermochronological cooling ages from the NE–Himalaya have been analyzed from three regions namely the Bhutan Himalaya, Western and Eastern Arunachal Himalaya (Fig. 2).

Bhutan Himalaya: In Bhutan Himalaya, ZFT, ZHe, AFT and AHe thermochronological ages and exhumation rates have been studied along two longitudinal regions namely the western Bhutan and the eastern Bhutan Himalaya (Grujic et al., 2006; Coutand et al., 2014). Ranges of age of different systems are given in Table 1.

Grujic et al (2006) determined the AFT ages between 1.4 ± 0.6 and 6.7 ± 0.8 Ma in the western Bhutan Himalaya and between 3.0 ± 0.7 and 8.6 ± 0.8 Ma in the eastern Bhutan Himalaya. However, most of the ages in the west are between 1.5 and 4 Ma. This range is very similar to the one observed in the NW–Himalaya. The mean AFT age of 2.55 ± 0.15 Ma provides mean long-term exhumation rate of 1.0–1.8 mm/yr. The mean AFT age in the eastern Bhutan is 5.08 ± 0.09 Ma that yields a long-term exhumation rate of 0.55 to 0.85 mm/yr. (Grujic et al., 2006). This range of AFT ages is comparatively older than other parts of the HHC in the western Bhutan and NW–Himalaya. This variation of AFT ages and exhumation rates is described due to anomalous behavior of the Shillong Plateau as an orographic barrier that has reduced precipitation in interior of the Himalayan orogen of the eastern Bhutan and hence lowered erosion rates (Grujic et al., 2006; Biswas et al., 2007). Based on this observation, Grujic et al. (2006) demonstrated that the exhumation variation in the Bhutan

Himalaya is a climatically driven erosion-rate variation on the scale of eastern Himalaya, a change that, in turn, likely influences region's recent tectonic evolution.

Later, Coutand et al. (2014) determined new AHe, ZHe, AFT and ZFT ages from both western and eastern Bhutan Himalaya and McQuarrie et al. (2014) determined new ZHe and MAr ages from western Bhutan Himalaya (Table 1). Age vs distance plots of both western and eastern Bhutan show similar patterns from south to north; ages become older from the MBT to and across the MCT. Age patterns then progressively young up to Jomolhari in western Bhutan and upto Lhuntse in the eastern Bhutan. The age patterns in the north of these locations again become older northward in both the western and eastern Bhutan (Figs. 5a,d). They observed that age patterns do not spatially coincide with surface trace of the MCT or any major faults, hence are not controlled by the activity of the MCT. Grujic et al. (2006) therefore described the different age patterns between the western and eastern Bhutan due to precipitation gradient between them. On the basis of 3-D thermokinematic modeling, Coutand et al. (2014) described that these age patterns are compatible with a strong tectonic influence, involving a variably-dipping MHT geometry between the western and the eastern Bhutan Himalaya and steady-state topography. The erosion rates remained constant in western Bhutan over the last ~10Ma, while significant decrease occurred at ~6Ma in eastern Bhutan, which is described due to convergence partitioning into uplift of the Shillong Plateau.

Western Arunachal Himalaya: AFT and ZFT ages in western Arunachal Himalaya across the HHC range from 1.4 ± 0.2 to 2.9 ± 0.3 Ma with mean ~2.1 Ma, while ZFT ages range from 4.5 ± 0.5 to 8.9 ± 1.3 Ma with a cluster at ~7 Ma (Table 1) (Adlakha, et al., 2013). The AFT ages in the LHS range from 5.6 ± 0.6 to 12.4 ± 1.3 Ma (mean ~7.9 Ma) and the ZFT ages from 10.9 ± 0.6 to 14.1 ± 1.1 Ma (mean ~12.5 Ma). Adlakha et al. (2013) expected that the AFT ages in the HHC of the western Arunachal Himalaya should be similar to the previously published ages (3.0 ± 0.7 and 8.6 ± 0.8 Ma with weighted mean 5.08 ± 0.09 Ma from neighboring Bhutan Himalaya (Grujic et al., 2006), since these regions fall in the same rain shadow of the Shillong Plateau. Instead, AFT age as young as 1.3 ± 0.2 Ma and ZFT age as young as 4.5 ± 1.0 Ma (2σ) demonstrate that spatial gradients in precipitation do not correlate with variations in long-term erosion and crustal strain as predicted by geodynamic models. Thermokinematic modeling of these data suggests that local exhumation patterns reflect gradients in rock uplift dictated by fault kinematics along the MCT in this rapidly deforming area (Fig. 6b), despite a dramatic precipitation gradient (Adlakha et al., 2013). In the HHC zone of western Arunachal and western Bhutan, exhumation rates vary between ~0.9 and 1.8 mm/yr and in eastern Bhutan Himalaya these are between ~0.6 and 0.9 mm/yr. As observed in other segments of the Himalaya, a zone of rapid exhumation in Arunachal Himalaya can be recognized extending from the MCT in the south to Zimithang Thrust (ZT) in the north. The following arguments also support the tectonics as the primary cause.

- (i) There are no evidences that tectonic activity in the Himalayan region has diminished or convergence of the Indian plate has receded during late Pliocene–Quaternary. Plate motion models (DeMets et al., 1994), geologic observations (Kondo et al., 2008; Kumar et al., 2006; Lavé and Avouac, 2000; Lavé et al., 2005; Wesnousky et al., 1999; Yule et al., 2006), and GPS measurements (Bilham et al., 1997; Wang et al.,

2001; Jade et al., 2007; Mukul et al., 2009) indicate that current convergence between the Indian and Eurasian plates is between ~40 and 50 mm/yr; out of about 10 and 20 mm/yr of convergence is taken up by thrust motion along the Himalayan Arc.

- (ii) Active faulting (Nakata, 1989; Yeats et al., 1992, Valdiya, 1993; Yin et al., 2010), and seismicity (Joshi and Patel, 1997; Patel and Kumar, 2003; Meyer et al., 2006) in the Himalaya as well as present-day seismotectonic activities in Tibet (Molnar and Tapponnier, 1978) indicate that continuous feeding of tectonic forces have shaped the Himalayan orogen. Brittle faults in different zones of the Himalaya indicate recent tectonic activities in the Himalaya.

Discussions

The Himalayan range is commonly presented as largely laterally uniform from NW–Himalaya to NE–Himalaya. However, geological structures, topography, precipitation rates, convergence rates, and low-temperature thermochronological ages all vary significantly along strike. Various hypotheses have been proposed regarding the exhumation of the HHC, based on thermochronological studies. One group of literatures says that topographic break from low to high relief and mean elevation are caused by focuses orographic precipitation (Hodges et al., 2001, 2004; Bookhagen and Burbank, 2006, 2010; Wobus et al., 2006). Since erosional efficiency is linked to precipitation (Whipple and Tucker, 1999; Whipple and Meade, 2004, 2006), it is described as the controlling factor for exhumation of the Himalaya (Thiede et al., 2004, 2005; Grujic et al., 2006; Deeken et al., 2011). Another group of literatures argues that out-of-sequence thrusting explains exhumation pattern across the MCT (Jain et al., 2000; Wobus et al., 2003; Hodges et al., 2004; Wobus et al., 2005; Huntington and Hodges, 2006; Patel and Carter, 2009; Patel et al., 2011a, b; Singh et al., 2012; Adlakha et al., 2013). Others describe that overthrusting, duplex formation, and translation across a mid-crustal ramp on the MHT explain the same exhumation pattern (Bollinger et al., 2006; Brewer and Burbank, 2006; Whipp et al., 2007; Robert et al., 2009, 2011; Herman et al., 2010; Coutand et al., 2014; van der Beek et al., 2016; Gavillot et al., 2018). We re-assess the coupling or decoupling between climate and tectonic forcing on the exhumation pattern across the NW–and NE–Himalaya by comparing (i) thermochronometric ages with topographic and precipitation data across the structural transect, and (ii) neighboring tectonics with thermochronometric data.

Precipitation data from the Himalaya (Bookhagen and Burbank, 2006), topographic indices (relief and elevation), thermochronological ages, and structural cross-section (Figs. 3–6) in different sectors of the Himalaya have been compared. Regions of young thermochronological ages (<3 Ma) and high exhumation rates (≥ 1 mm/yr) correspond with active structures in the Sub-Himalaya, tectonics along the MCT and its hanging wall, windows and dome structures within the HHC (Figs. 2, 3). Precipitation reaches peak values (~4 m/yr) in frontal parts of the orogen, i.e. along the MFT–MBT–MCT zones in Kashmir and Himachal, and drops steadily northward to ~1 m/yr across the HHC (Fig. 3). At the position of the KW, precipitation is ~1.5 m/yr or less than half of the annual precipitation over the Sub-Himalaya (Fig. 3). In spite of contrasting annual precipitation between Sub-Himalaya and KW, rocks of both regions are associated with young cooling ages with exhumation rate

≥ 1 mm/yr. Thus, although the frontal part of the Himalaya represents a clear barrier that focuses orographic precipitation, cooling ages vary as a function of structural position within the Himalayan orogen and are independent of precipitation.

Along strike to the southeast, i.e. in the central parts of Himachal Himalaya, young AFT cooling ages (< 3 Ma) and high exhumation rates (> 1 mm/year) correspond with the southwestern flank of the

Dhauladhar Range (Fig. 3). The range is bounded by the MBT and the MCT, but the Chamba nappe in the hanging wall of the MCT does not fold to any doming structures as the KW along strike to the northwest or the KLR window along strike to the southeast (Robyr et al., 2006). Increasing trend of cooling ages towards the hinterland from the Dhauladhar range represents decreasing of exhumation toward the hinterland. This spatial variation in exhumation pattern

Figure 8. Geometry of the Main Himalayan Thrust (MHT) along different sectors of the NW-Himalaya and NE-Himalaya. (a) Kashmir. After Gavillot et al. (2018). (b) Himachal-Chamba. After Deeken et al. (2011). (c) Himachal: Laji-Kullu-Rampur Window. After Vanney et al., (2004); Deeken et al. (2011). (d) Uttarakhand Garhwal. Srivastava and Mitra (1994); Caldwell et al. (2013); Kanaujia et al. (2016). (e) Uttarakhand Kumaun. After Srivastava and Mitra (1994). (f) Western Bhutan. (g) Eastern Bhutan. After Coutand et al. (2014). (h) Western Arunachal Pradesh. After DeCelles et al. (2106).

has been described due to structurally-driven orogenic growth along the MHT driving upper plate exhumation and tilting of the MBT and MCT thrust sheets (Adlakha et al., 2013; Gillvot et al., 2018). Along strike to the southeast, the cooling ages and exhumation pattern are very similar to the Kashmir Himalaya. Along a traverse from Mandi in the southwest across the LKR window to Akpa in the northeast, exhumation rate is $>1\text{ mm/yr}$ near the frontal part of the orogen i.e. at Mandi and at LKR window but the HHC rocks between these two regions and region in the northeast of the LKR window are exhuming at rate $<1\text{ mm/yr}$. This pattern of exhumation mimics the structural pattern and can be described due to function of structural position of the MBT and the LKR window.

Along the strike to further southeast in Garhwal–Kumaun region, peak precipitation zone, reaching to $>3\text{ m/yr}$, is confined south of the MCT zone and then it drops to $<2\text{ m/yr}$ towards north of the MCT zone. In spite of similar precipitation pattern in both Garhwal and Kumaun regions, the Garhwal region shows gradual increase in age trend from the MCT towards the STDS while it is zero increasing trends, i.e. horizontal in the Kumaun region. The mean exhumation rate is 1.42 mm/yr in the Garhwal region and is 3.93 mm/yr in the Kumaun region. In the footwall of the MCT within the Almora and Baijnath klippen, and within the CCB, the exhumation rates are varying between 0.3 and 0.6 mm/yr . This differential exhumation history in these regions is attributed to local tectonically-driven uplift in the region since $\sim 2\text{ Ma}$ (Patel and Carter, 2009).

The Bhutan and Arunachal Himalayas are located in the wettest eastern parts of the Himalaya, where peak precipitation is 5 to 6 m/y and 2 to 3 m/yr in the NW–Himalaya. In spite of this variation, there is no major difference in exhumation rates of the HHC between the NW– and NE–Himalaya (Fig. 7a, b). As the thermochronological ages do not spatially correlate with surface traces of major faults in the Bhutan Himalaya, it has been correlated with the geometry of the underlying MHT.

It has been recently described that thermochronological age pattern has compatibility with strong tectonic influence, involving a variable–dipping MHT geometry (Fig. 8). Duplex development due to horse emplacement above the MHT at depth controls the locus of exhumation. Horse emplacement at depth produces localized regions of relatively high uplift rates (Boyer and Elliott, 1982; Molnar and Lyon-Caen, 1988). It is a mechanism that explains young cooling ages and fault-related exhumation across structural culminations in the Nepalese hinterland (Bollinger et al., 2006; Brewer and Burbank, 2006; Robert et al., 2009; Herman et al., 2010) and in the Sikkim Himalaya hinterland (Abrahami et al., 2016; Landry et al., 2016).

Conclusions

Despite active convergence and a dramatic precipitation gradient that has persisted for millions of years in the Himalaya, long-term erosion in both NW– and NE–Himalaya appears to reflect patterns of rock uplift dictated by the geometry and kinematics of the MHT and duplex structures formed over the ramp of the MHT. These observations suggest that in this tectonically active setting, characterized by steep topography and intense storms, erosion patterns do not mirror precipitation gradients or drive deformation on million-year timescales, but are themselves controlled by active tectonic boundary conditions and dome/window/synform structures.

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