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Large spatial and temporal variations in Himalayan denudation

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ABSTRACT

In the last decade growing interest has emerged in quantifying the spatial and temporal variations in mountain building. Until recently, insufficient data have been available to attempt such a task at the scale of large orogens such as the Himalaya. The Himalaya accommodates ongoing convergence between India and Eurasia and is a focal point for studying orogen evolution and hypothesized interactions between tectonics and climate. Here we integrate 1126 published bedrock mineral cooling ages with a transient 1D Monte-Carlo thermal–kinematic erosion model to quantify the denudation histories along ~2700 km of the Himalaya. The model free parameter is a temporally variable denudation rate from 50 Ma to present. Thermophysical material properties and boundary conditions were tuned to individual study areas. Monte-Carlo simulations were conducted to identify the range of denudation histories that can reproduce the observed cooling ages. Results indicate large temporal and spatial variations in denudation and these are resolvable across different tectonic units of the Himalaya. More specifically, across >1000 km of the southern Greater Himalaya denudation rates were highest (~1.5–3 mm/yr) between ~10 and 2 Ma and lower (0.5–2.6 mm/yr) over the last 2 My. These differences are best determined in the NW-Himalaya. In contrast to this, across the ~2500 km length of the northern Greater Himalaya denudation rates vary over length scales of ~300–1700 km. Slower denudation (<1 mm/yr) occurred between 10 and 4 Ma followed by a large increase (1.2–2.6 mm/yr) in the last ~4 Ma. We find that only the southern Greater Himalayan Sequence clearly supports a continuous co-evolution of tectonics, climate and denudation. Results from the higher elevation northern Greater Himalaya suggest either tectonic driven variations in denudation due to a ramp-flat geometry in the main décollement and/or recent glacially enhanced denudation.

1. Introduction

The degree to which variations in deformation and climate have influenced the formation of the Himalaya over geologic time scales remains heavily debated (e.g., Beaumont et al., 2001; Burbank et al., 2003; Clift et al., 2008; Herman et al., 2010; Robert et al., 2011). The deformation history of the Himalayan–Tibetan orogen is controlled by a north dipping, southward propagating, crustal-scale thrust sequence and has broadly been constrained from units exposed across the range front (Gansser, 1964; Fuchs, 1981; Hodges, 2000; Yin and Harrison, 2000; Yin, 2006). Since the Oligo-Miocene the accommodation of convergence and style of deformation within the Himalayan orogenic wedge has been described as the result of crustal-scale shear zones underlying the Himalaya. These shear zones include the Main Central Thrust (MCT) that was active in at least the Early to Middle Miocene, followed by the Main Himalaya Thrust (MHT) active until the present (Hodges, 2000; Yin and Harrison, 2000; Yin, 2006). These shear zones resulted in rock-uplift and exhumation along major fault systems, such as the Southern Tibetan Detachment system (STD) and in extensive crustal shortening, along the Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT). A large number of thermochronology studies have been conducted across the Himalaya in the past decades (e.g. see Table 1) and typically focus on rock exhumation histories from specific geographic areas (e.g. along major transverse rivers). In this study, we present a compilation of these data and quantification of the denudation histories that could produce these ages from thermal–kinematic modeling.

Previous Himalayan studies have documented significant variations in the structural architecture, deformation and climate history. Numerous balanced geological cross sections document the structure of the Himalaya and suggest scenarios for its kinematic history (e.g., Schelling and Arita, 1991; Srivastava and Mitra, 1994; DeCelles et al., 2002; Pearson and DeCelles, 2005; Robinson et al., 2006; Long et al., 2011). Despite significant lateral variations observed in these cross sections, they suggest that the general evolution of the Himalaya has been similar from west to

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Table 1
Summary of Mean Age±1σ of published data used in this study.

Geographic region (see Fig. 1)	Apatite fission track	Zircon fission track	(^{40}Ar/^{39}Ar)-white mica
A1—NW-Pakistan	(AFT)	(ZFT)	(^{40}Ar/^{39}Ar)
Tethyan metamorphic rocks	Zeitler (1985)	Zeitler (1985)	
Haimanta affinity	Mean Age±1σ	Mean Age±1σ	
Kohistan arc complex	15.2±4.0 (n=23)	33.9±17.6 (n=51)	
A2—Nanga Parbat	(AFT)	(ZFT)	(^{40}Ar/^{39}Ar)
GHS	Zeitler (1985)	Zeitler (1985)	
Mean Age±1σ	1.9±1.6 (n=9)	2.4±1.3 (n=7)	
A3—NE-Pakistan	(AFT)	(ZFT)	(^{40}Ar/^{39}Ar)
Ladakh arc complex	Foster et al. (1994)	Zeitler (1985)	
	Zeitler (1985)	Foster et al. (1994)	
	van der Beek et al. (2009)		
Mean Age±1σ	8.2±2.6 (n=22)	16.5±5.4 (n=13)	
B1—Chenap	(AFT)	(ZFT)	(^{40}Ar/^{39}Ar)
Tethyan Himalaya	Kumar et al. (1995)	Kumar et al. (1995)	
	Kirstein et al. (2006)		
Mean Age±1σ	6.4±1.1 (n=7)	12.7±1.0 (n=7)	
GHS-N	Kumar et al. (1995)	Kumar et al. (1995)	Searle et al. (1992)
Mean Age±1σ	3.6±1.1 (n=15)	7.6 ±1.5 (n=6)	19.3±4.0 (n=6)
GHS-S	Kumar et al. (1995)	Kumar et al. (1995)	
Mean Age±1σ	2.3±0.5 (n=1)	7.1±0.9	
Lesser Himalaya	Kumar et al. (1995)		
Mean Age±1σ	4.5±1.2 (n=6)		
B2—Beas	(AFT)	(ZFT)	(^{40}Ar/^{39}Ar)
Tethyan Himalaya	Schlup (2003)	Schlup (2003)	Dezes et al. (1999)
	Schlup et al. (2003)	Schlup et al. (2003)	Walker et al. (1999)
			Schlup et al. (2003)
Mean Age±1σ	16.0±8.9 (n=18)	34.5±8.7 (n=20)	20.4±0.9 (n=12)
			(Zanskar Shear Zone)
GHS-N	Schlup (2003)	Schlup (2003)	Schlup (2003)
	Schlup et al. (2003)		
Mean Age±1σ	1.8±0.6 (n=7)	12.3±4.4 (n=6)	20.1±2.1 (n=5)
Lesser Himalaya		Lal et al. (1999)	
		Schlup (2003)	
Mean Age±1σ		9.7±1.3 (n=4)	
B3—Sutlej	(AFT)	(ZFT)	(^{40}Ar/^{39}Ar)
Tethyan Himalaya-Dome	Thiede et al. (2006)		Thiede et al. (2006)
			Hintersberger et al. (2010)
Mean Age±1σ	4.3±2.6 (n=13)		15.1±1.0 (n=4)
Tethyan Himalaya	Vannay et al. (2004)	Vannay et al. (2004)	Vannay et al. (2004)
	Thiede et al. (2006)		Wiesmayr and Grasemann (2002)
Mean Age±1σ	3.7±0.9 (n=8)	14.8±1.1 (n=5)	21.2±10.9 (n=6)
GHS-N	Vannay et al. (2004)		Vannay et al. (2004)
	Thiede et al. (2004)		Thiede et al. (2005)
	Thiede et al. (2005)		
	Thiede et al., 2009		
Age (3km)±m. Er.	2.9±0.5 (n=15)		
Mean Age±1σ	2.6±1.1 (n=15)	16.0±1.0	
GHS-S	Jain et al. (2000)	Jain et al. (2000)	Vannay et al. (2004)
	Vannay et al. (2004)	Vannay et al. (2004)	Thiede et al. (2005)
	Thiede et al. (2004)		
	Thiede et al. (2005)		
Age (3km)±m. Er.	1.7±0.3 (n=19)		
Mean Age±1σ	1.6±0.7 (n=19)	2.3±0.6 (n=8)	5.2±1.0 (n=10)
Lesser Himalaya	Vannay et al. (2004)	Vannay et al. (2004)	
	Thiede et al. (2004)		
	Thiede et al. (2005)		
	Thiede et al. (2009)		
Mean Age±1σ	5.0±2.6 (n=12)	11.5±0.6 (n=6)	
B4—Bhagarathi, Dhauliganga	(AFT)	(ZFT)	(^{40}Ar/^{39}Ar)
Tethyan Himalaya-South	Sorkhabi et al. (1996)	Searle et al. (1999)	
	Searle et al. (1999)		
Age (3km)±m. Er.	1.6±0.3 (n=17)		
Mean Age±1σ	2.1±0.5 (n=18)	8.8±1.2 (n=1)	
GHS-N	Patel and Carter (2009)	Patel and Carter (2009)	Metcalfe, 1993
	Thiede et al. (2009)		Sorkhabi et al. (1996)
Age (3km)±m. Er.	1.9±0.3 (n=6)		