

A MULTI-GEOCHRONOLOGIC APPROACH TO IDENTIFY THE FOCUS OF EROSION IN
THE KOSI BASIN, NEPAL

by
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A thesis submitted in partial fulfillment
of the requirements for the degree

of
Master of Science
in
Earth Science

MONTANA STATE UNIVERSITY
Bozeman, Montana

May 2025

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DEDICATION

I dedicate this thesis to my grandfather, Dr. Eugene Rasmusson. My grandfather was a pioneering earth scientist in the field of meteorology, with a decades long career primarily studying El Niño Southern Oscillation. He was deeply dedicated to the pursuit of knowledge and from a young age instilled in all of us and the value of education. In his passing, he was remembered as “[fostering] a strong sense of community among his peers in the geosciences: in particular, [by] the sharing of ideas, the culture of working cooperatively for the benefit of society rather than merely for personal gain, and the cultivation of the next generation of scientists.” It makes me very proud to have followed in his footsteps as part of that next generation.

ACKNOWLEDGEMENTS

This work was supported by NSF-EAR-NERC Award #2026870 to D.A. Orme. We are grateful for the organizational skills and friendship of Bhairab Satula in facilitating field work in Nepal. We thank Victor Valenica at ZirChron LLC for mineral separation and are grateful for Jim Metcalf at the CU TRaILS lab for his work on zircon (U-Th)/He analyses. We thank the staff at The University of Arizona Laserchron center for their work on zircon U-Pb analyses (NSF-EAR 2050246).

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ABSTRACT

The Himalayan orogen represents a convergent tectonic setting in which two continental tectonic plates collided, forcing material upwards and forming a chain of high elevation peaks. This setting is also host to the Indian Summer Monsoon, which hammers the region with heavy seasonal rainfall. The respective roles of tectonics and climate in shaping this dramatic landscape remain a subject of debate. Our research approaches this gap in understanding by investigating sediment routing in Nepal's Kosi basin. The Kosi watershed is a well-suited basin to study this phenomenon, as it captures many of the key geologic structures and climatic conditions that are characteristic of the region.

We sampled modern rivers to understand the sediment profile in the Kosi basin. We then utilized two radioactive dating methods to fingerprint sediment grains and understand their origin in the watershed. Detrital zircon U-Pb geochronology dates when a crystal formed and utilizes large sample sizes to match detrital age spectra to known bedrock profiles. Alternatively, (U-Th)/He low-temperature thermochronology dates when an individual zircon grain cooled to the surface. These detrital cooling dates are in turn matched to areas known to have cooled at similar times. We applied both methods to our modern river samples. Using our new geochronological and thermochronological datasets, we completed two statistical analyses to pinpoint accelerated areas of erosion: inverse monte-carlo mixture modeling and multi-dimensional scaling nearest-neighbor analysis.

Our results suggest that each major geologic unit and sub-basin in the watershed contributes to the sediment load in the Kosi River to some extent. Furthermore, U-Pb mixing model results and young helium cooling ages both highlight an over representation of grains in the center of the watershed, by latitude. Integrating our datasets, these results suggest that erosion is focused north of the dominant precipitation band and south of the largest glacial cover. We propose that these findings support a model of landscape evolution in which structural geometry at depth, specifically duplexing along a midcrustal ramp, plays a critical role in shaping surface topography.

CHAPTER ONE

INTRODUCTION

Host to the highest topography on Earth, the Himalayan orogen has remained a hot spot of geologic research for over one hundred years (e.g., Argand, 1924). Much of this research has been fueled by debate over the respective roles and interplay of tectonics and climate in shaping the landscape (e.g., Beaumont et al., 1992; Molnar & England, 1990; Whipple, 2009). One approach to evaluate this landscape evolution is to consider the movement of sediment throughout watersheds within the orogen by processes of erosion, sediment routing, and deposition (e.g., Blum & Pecha, 2014; Gehrels, 2014; Huntington & Hodges, 2006; Ibañez-Mejia et al., 2018; Olen et al., 2015; Sundell & Saylor, 2017). This can be done by characterizing the age and thermal history of modern river sediments in the streams that drain the Himalaya, to understand from where material is eroding (e.g., Gemignani et al., 2018; Ruhl & Hodges, 2005).

The Kosi River, which centers around the Sagarmatha (Mt. Everest) massif, is a tributary to the Ganges-Brahmaputra source-to-sink sediment routing system (Figure 1a). The Kosi basin captures each of the main lithotectonic sequences and fault structures which exist along strike in the Nepalese Himalaya (Figure 1b; Kapp & DeCelles, 2019; Yin & Harrison, 2000). Sediment provenance work in this basin benefits from extensive literature characterizing the bedrock geochronology and low-temperature thermochronology, which present usable data suites to compare to modern river profiles (e.g., Gehrels et al., 2011; Van Der Beek & Schildgen, 2022; Whipple et al., 2023). Furthermore, this basin features a topographic gradient and precipitation patterns which are present along strike (Whipple et al., 2023). Considering these geologic, structural, geomorphological, and climatic conditions—as well as the robust bedrock

characterization available—we propose that the Kosi basin offers an excellent natural laboratory for testing the relationship between tectonics and climate in the frontal Himalaya.

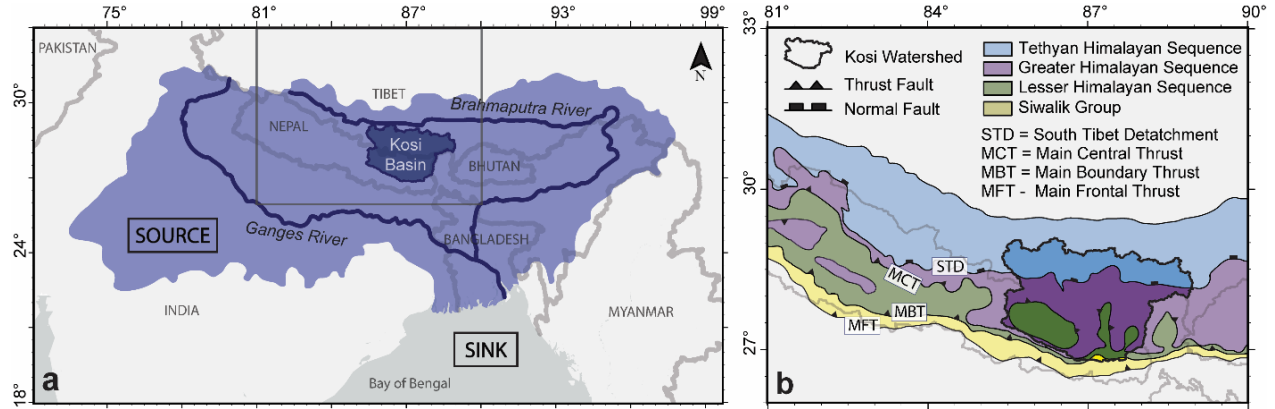


Figure 1. (a) Ganges-Brahmaputra source-to-sink sediment routing system. The area that drains to the Bay of Bengal is blue. The Kosi River watershed is a sub-basin within the larger system, draining eastern Nepal and parts of southern Tibet. Modified from Nicholls et al. (2018). (b) The Kosi basin shown in the context of the regional geology of Nepal. The basin is composed of bedrock from the Tethyan Himalayan Sequence, the Greater Himalayan Sequence, and the Lesser Himalayan Sequence. Modified from DeCelles et al. (2020).

We leverage the strengths of both U-Pb geochronology and (U-Th)/He low-temperature thermochronology to more confidently highlight the spatial focus of erosion in the basin. Detrital zircon U-Pb geochronology benefits from its ability to broadly characterize the geochronometry of large and often inaccessible regions challenged by physical and logistical barriers via modern rivers (e.g., Link et al., 2023). Alternatively, the application of low-temperature thermochronology as a provenance tool can provide valuable insight to mid-crustal and near surface processes but is traditionally constrained by small sample sizes and requiring direct age-elevation cooling relationships (e.g., Ruhl & Hodges, 2005; Stock et al., 2006). We test the limits of using low-temperature thermochronology as a sediment router in a larger, more structurally complex setting. We find that these data are especially useful when paired with a secondary

routing metric, such as detrital zircon geochronology, highlighting the utility of a multi-method approach within other locales globally. In this study, we present a multi-geochronologic analysis of sediment routing in Nepal's Kosi watershed to isolate the dominant sediment source region and investigate the respective roles of climate and tectonics in driving landscape evolution.

CHAPTER TWO

GEOLOGIC SETTING

Regional Geology

Nepal's geology is broadly characterized as a series strike-parallel tectonostratigraphic packages that are bounded by regional scale fault systems. Each fault is representative of a zone of deformation with localized complexities, and different regions include various windows and klippen, creating prominent local heterogeneities. The three geologic packages that make up the bulk of the Nepalese Himalaya are the Tethyan Himalayan Sequence (THS), the Greater Himalayan Sequence (GHS), and the Lesser Himalayan Sequence (LHS) (Yin & Harrison, 2000). The northernmost THS is bounded to the north by the Great Counter Thrust and by the South Tibet Detachment (STD) to the south (Kapp & DeCelles, 2019). The STD is a low-angle normal fault system that was last active as recently as mid-Miocene time (Hodges et al., 1998; Murphy & Harrison, 1999; Orme et al., 2015). This sequence is primarily composed of early Paleozoic to late Precambrian siliciclastic and carbonate sedimentary and metasedimentary rocks (Nakajima et al., 2022; Yin & Harrison, 2000). The Greater Himalayan Sequence is bounded to the north by the STD and to the south by the Main Central Thrust (MCT). The GHS features early Cambrian to late Proterozoic sillimanite grade schists, gneisses, and migmatites, which are generally the highest grade metamorphic rocks in Nepal (Nakajima et al., 2022; Olen et al., 2015; Parrish & Hodges, 1996). In both the THS and GHS, there exists a series of leucogranite plutons, dikes, and sills of Miocene-Eocene age (~15-45 Ma) (Cao et al., 2022; Godin et al., 2001; Hodges, 2000; Lavé & Avouac, 2001). These intrusions are associated with

decompression melting of GHS rocks during MCT thrusting and STD normal faulting (Sherpa et al., 2024).

The southernmost tectonic package is the LHS, bounded by the MCT to the north and the Main Boundary Thrust (MBT) to the south. LHS rocks are primarily composed of Precambrian clastic sediments and metasedimentary rocks, intruded by granitic augen gneisses (Sherpa et al., 2024; Yin & Harrison, 2000). Within the LHS runs the Ramgarh Thrust System. Although thin, this fault system is laterally extensive across all of Nepal, placing greenschist grade rocks on top of less metamorphosed LHS rocks (DeCelles et al., 2001). South of the MBT is the Siwalik Group. This group is more than 5,000 m thick and runs along the full extent of the Nepalese Himalaya, representing former foreland basin deposition. The sediments filling this basin were primarily deposited by southward flowing rivers, commonly in the form of large alluvial fans and fluvial systems (DeCelles et al., 1998; Parkash et al., 1980). The Siwalik group is bounded by the Main Frontal Thrust (MFT) to the south. South of this thrust system in Nepal is dominantly Quaternary sediments.

Most structural models of the Himalayan orogen propose that these four major surface-breaking faults connect to a single detachment at depth, the Main Himalayan Thrust (MHT). While the MFT, MBT, MCT, and STD are generally well-defined in the literature, there is more debate on the geometry and location of the Main Himalayan Thrust. The 2015 M_w 7.8 Gorka earthquake in Kathmandu provided valuable data in characterizing this ramp thrust geometry (e.g., Elliott et al., 2016; Hubbard et al., 2016; Whipple et al., 2016). Current models of Main Himalayan Thrust geometry place the ramp structure between 50 – 110 km north of the MFT in the central Himalaya, where this earthquake was located (Elliott et al., 2016; Hubbard et al.,

2016; Johnston et al., 2020; Whipple et al., 2016). Many studies have argued that the location of the Main Himalayan Thrust ramp plays a significant role in defining the dominant band of erosion along the orogenic front (e.g., Burbank et al., 2003; Dal Zilio et al., 2019; Elliott et al., 2016; Godard et al., 2014; Grandin et al., 2012; Johnston et al., 2020).

The Kosi region features each of the main lithotectonic units and major fault systems noted above (Figure 2a). Within the watershed, there are three notable tectonic windows in which LHS rocks are exposed within the GHS. From west to east, these windows are the Okhaldhunga Window, the Arun Window, and the Taplejung Window (Dhital, 2015). The Okhaldhunga Window is the largest window in Nepal and is occupied by the Great Midland Antiform (Dhital, 2015; Sherpa et al., 2024). There are added complexities to the bedrock makeup in the Tibetan area of the watershed. To the north, there are small slivers of North Himalayan Cretaceous sediments and the rocks of the India-Asia suture zone, including the pre-collisional early Paleogene-Cretaceous subduction complex. Within the GHS & THS, there are a series of Miocene-Eocene leucogranites (Cao et al., 2022; Kapp & DeCelles, 2019). Other structures within the watershed include N-S trending extensional faults, most notably the Ama Drime Massif in the northeast region of the Kosi basin (e.g., Jessup et al., 2008; Figure 3a).

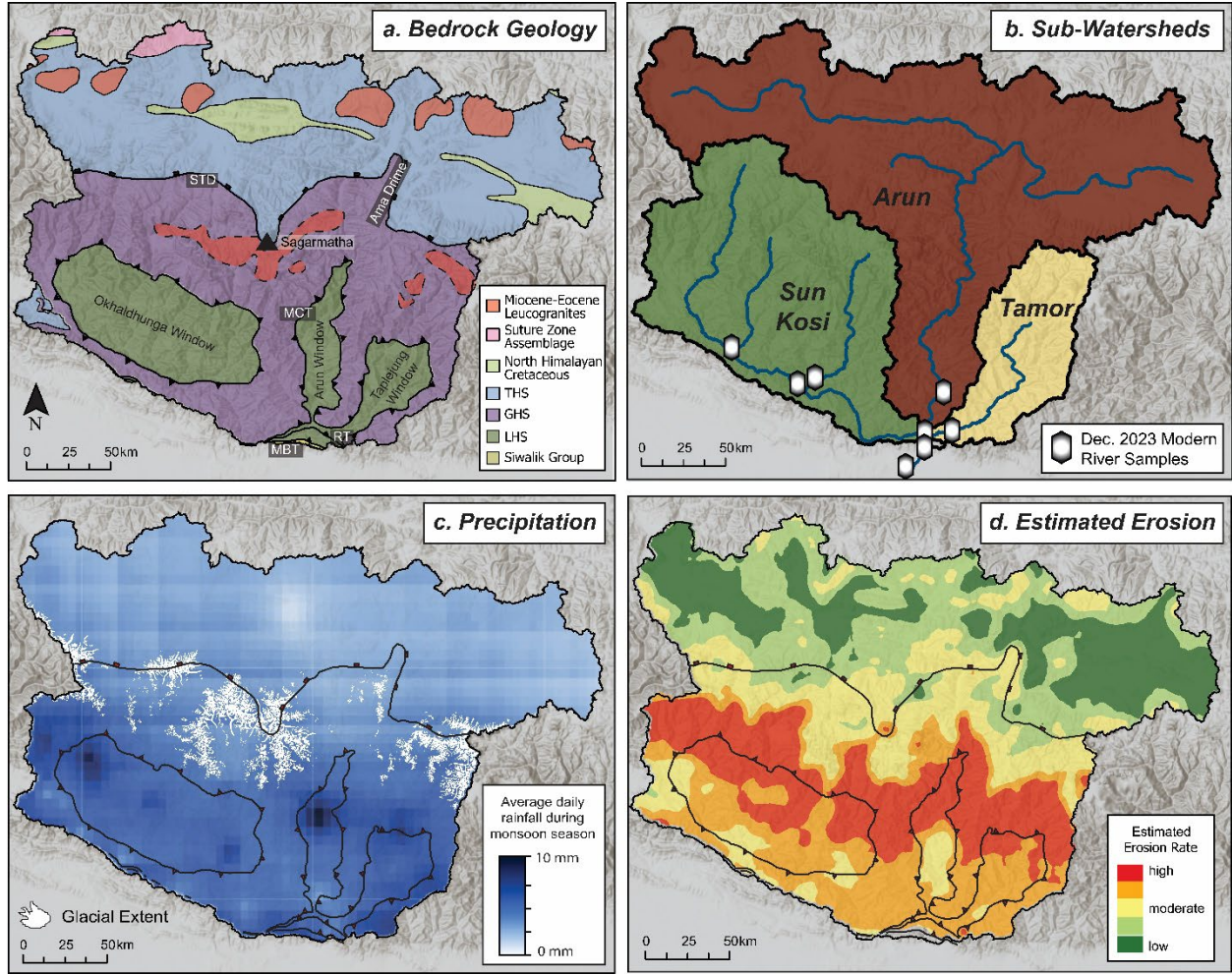


Figure 2. (a) Geologic map of the Kosi basin. Modified from Cao et al. (2022), DeCelles et al. (2020); Hodges (2000); Kapp & DeCelles (2019); Searle & Cottle (2024) (b) Sub-Watersheds for the three main tributaries to the Kosi River: the Sun Kosi, the Arun, and the Tamor (c) Current glacial extent and average Rainfall during monsoon season in mm/day. Precipitation data does not include snowfall. Precipitation data from CHIRPS (Climate Hazards group Infrared Precipitation with Stations; Funk et al., 2015); Glacial extent from GLIMS (Global Land Ice Measurement from Space; GLIMS Consortium, 2005) (d) Estimated erosion rate computed from a grid of discharge-based channel steepness, k_{snQ} (Whipple et al., 2023). Categorized from low (green) to high (red) for visual distinction: low (0-25 m/My), moderate-low (25-45 m/My), moderate (45-165 m/My), moderate-high (165-270 m/My), high (>270 m/My).

Regional Climate and Geomorphology

The Himalayan foreland receives heavy, seasonal rainfall from the Indian summer monsoon (e.g., Bookhagen & Burbank, 2010; Gupta & Tandon, 2020; Olen et al., 2015). Although precipitation is greatly concentrated between the months of June throughout September, mean annual rainfall can locally exceed 5 m per year (Olen et al., 2015). The effects of the monsoon are generally heightened in closer proximity to the Bay of Bengal, resulting in high precipitation rates in the Kosi watershed. The northern, high elevation regions of the watershed are arid, receiving minimal precipitation in the form of rainfall (<250 mm/yr; Figure 3c; Bookhagen & Burbank, 2010).

The timing of initiation and intensification of the Indian summer monsoon remains debated. A variety of climate proxies suggest initiation from between 55 Ma to 7.5 Ma, with most interpretations suggesting the monsoon to be established by ~24 Ma and intensified between 13 to 8 Ma (Gupta & Tandon, 2020). This initiation has been interpreted to be driven by both global climatic and tectonic factors, including establishment of modern wind regimes, presence of a permanent Antarctic ice sheet, and the final closure of the Tethyan seaway (Clift & Webb, 2019; Kennett, 1977; Lawver & Gahagan, 1998). It is suggested that the monsoon began to weaken ~5 Ma to gradually reach modern conditions (Sanyal et al., 2004). Arguments have also been made for a more recent intensification of the monsoon, from ~ 2.5–0.9 Ma, as evidenced by increased sedimentation rates (Huntington et al., 2006).

Across strike, there is a sharp topographic transition separating the foothills of the low Himalaya and the rugged high Himalaya, which hosts famous 8,000 m peaks like Sagarmatha and Makalu. This transition has traditionally been referred to in the literature as “Physiographic

Transition 2” (PT2; Hodges et al., 2001), and more recently defined as the “High Himalaya Topographic Front” (HHTF; Whipple et al., 2023), considering the absence of low Himalaya physiography across the full extent of the orogen. This topographic front is well-documented to be associated with high erosion and rock exhumation rates (e.g., Burbank et al., 2003; Huntington et al., 2006; Olen et al., 2015). For example, in this zone in the Arun valley, apparent denudation rates reach ~5 mm/yr, accounting for landsliding (Olen et al., 2015). This erosion regime is more variable in both rates and processes when compared to the low and high Himalaya (Olen et al., 2015).

Three main tributaries combine to form the Kosi River, all meeting at one major confluence approximately 15 km northwest of the city of Dharan, Nepal (Figure 2b). From west to east these rivers are the Sun Kosi, the Arun, and the Tamor. Each river is broadly located along a major tectonic window, as all three rivers expose lesser Himalayan rocks (Dhital, 2015). River profiles vary slightly among the three tributary rivers, reflective of their spatial relationship to the underlying landscape and geologic structures. The Arun River, with a significant portion reaching to the Tibetan Plateau, hosts two large slope breaks (Olen et al., 2015). These knickpoints are seemingly associated with the location of the STD (Olen et al., 2015; Sonam & Jain, 2018). Neither the Sun Kosi River nor the Tamor River express any obvious knickpoints in river profile (Sonam & Jain, 2018). Han et al. (2024) further attribute the steep nature of the Arun River as a response to a recent (~89 ka) increase in stream power through processes of “river piracy.” All three tributaries have the highest stream power values when carving through the higher Himalaya. The Arun and Tamor rivers have maximum stream power values between

40,000 to 130,000 W/m, while the Sun Kosi shows a bimodal peak in stream power, reaching a highest total between 25,000 – 40,000 W/m (Sonam & Jain, 2018).

Glacial coverage is widespread at high elevations in the Kosi basin, composing a total area of $3,225 \pm 90.3 \text{ km}^2$ according to remote-sensing investigations from 2009 (Shangguan et al., 2014). However, the Kosi basin additionally exhibited one of the fastest rates of glacial retreat in the orogen from 1976-2009 (Shangguan et al., 2014). This retreat is expected to continue, with models estimating between 65-85% decrease in area by 2100 (Khadka et al., 2020). While glacial erosion is known to be a prominent player in contributing to denudation in mountain settings, it remains difficult to quantify (Godard et al., 2012; Olen et al., 2015). In a study of the Marysandi drainage, west of the Kosi watershed, Godard et al. (2012) find significant spatial variation in estimates of glacial erosion rate even within the same catchment, with their upper estimates suggesting an average glacial erosion rate of 5 mm/year in the High Himalaya. All three sub-watersheds in the Kosi basin capture glaciated high peaks where these erosive forces may be at play, with the most glacial coverage found in the Dudh Kosi watershed and the Tethyan portions of the Arun watershed.

Known Kosi Bedrock Ages

This project benefits from a large quantity of previous studies that have analyzed regional bedrock to determine crystallization and lower temperature cooling ages. We compare the published cooling and crystallization age data to our modern river samples.

U-Pb Geochronology

Bedrock U-Pb geochronological ages for this study are grouped by major lithotectonic unit and compiled by Gehrels et al. (2011). These ages are reported as composite distributions for THS & upper LHS, GHS, and lower LHS, and are compiled from published U-Pb geochronological datasets across the Himalayan orogen. THS strata are combined with upper LHS strata due to stratigraphic correlation between units (Gehrels et al. 2011). These strata show strong similarity from the Cretaceous through the Cambrian. Dominant age ranges include 480 - 570 Ma, 750 - 1200 Ma, and 2430 - 2560 Ma (Figure 3b; Gehrels et al., 2011). GHS strata show relative peaks at 800 - 1200 Ma, 1600 – 1900 Ma, and 2400 - 2700 Ma. About half of the samples included in this compilation also contain 540–750 Ma grains. The lower LHS strata are consistently older, reporting dominant ages between 1700 - 2000 Ma and 2400 - 2800 Ma.

As noted, within the THS and GHS are young leucogranite bodies, likely formed via decompression melting during MCT thrusting and STD extension (Hodges, 2000; Sherpa et al., 2024). U-Pb ages of leucogranites in the GHS range from 12 – 23 Ma (Cao et al., 2022; Hodges, 2000). THS leucogranites are generally older, ranging from 33 – 45 Ma, with ages >38 Ma overlapping with the tail-end of Gangdese magmatic arc magmatism in southern Tibet (Cao et al., 2022; Kapp & DeCelles, 2019).

Low-Temperature Thermochronology

Numerous studies have applied low-temperature thermochronology to bedrock within the Kosi basin with the goal of quantifying rates of exhumation (e.g., Jessup et al., 2008; Nakajima et al., 2022; Streule et al., 2012; Wang et al., 2010). These studies use a range of thermochronometric systems including apatite fission track, apatite helium, zircon fission track,

and zircon helium. Zircon low-temperature work (fission track and (U-Th)/He) is the most abundant and offers the most spatial coverage across the basin.

Owing to the documented high rates of exhumation within this region (e.g., Long et al., 2012), we elected to combine both zircon fission track (ZFT) and zircon (U-Th)/He (ZHe) ages to increase the size and spatial resolution of our bedrock dataset, despite the resulting broader range in closure temperature (Figure 3a). ZFT has a closure temperature range of $\sim 180 - 350^{\circ}\text{C}$ and ZHe has closure temperature falling between $\sim 140 - 200^{\circ}\text{C}$ (Guenther et al., 2013; Reiners et al., 2004; Yamada et al., 1995). From south to north, there is an initial general decrease in cooling age towards the center of the watershed, followed by an increase in age as you move northward across the STD. Ages are broadly latitudinally consistent in the southern portion of the watershed, but show variation to the north, specifically with younger cooling ages suggesting more recent extension and exhumation in the Ama Drime region (Jessup et al., 2008; McDermott, 2012).

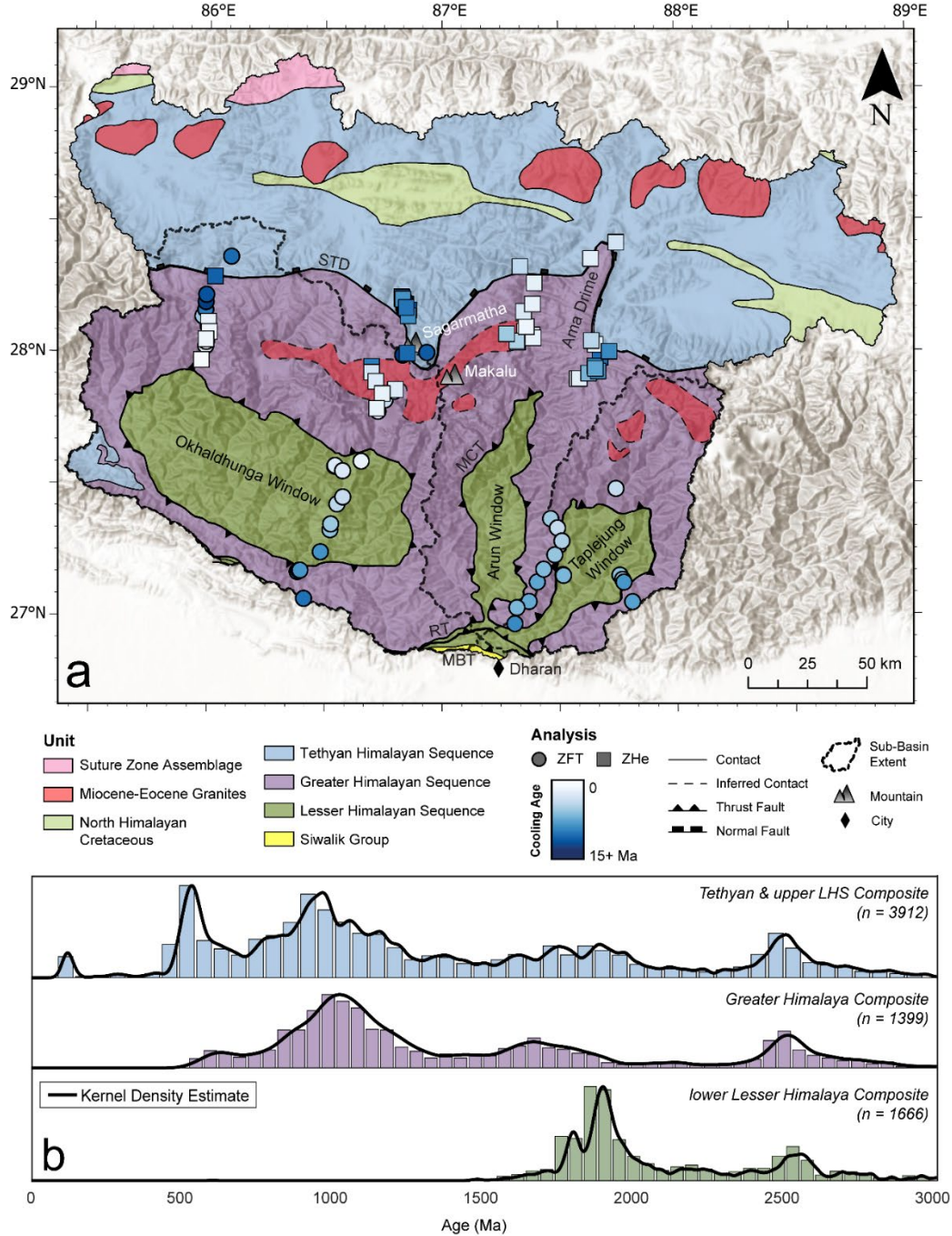


Figure 3. (a) Published mean ages of zircon low-temperature thermochronological data in the Kosi region, shown in reference to the major tectonic units and rivers. Geologic map modified from Cao et al. (2022); Hodges (2000); Kapp & DeCelles (2019); Searle & Cottle (2024); Sherpa et al., (2022). See text for definition of acronyms. (b) Normalized probability plots for the Tethyan strata and upper Lesser Himalayan strata, Greater Himalayan strata, and lower Lesser Himalayan strata (Gehrels, 2011).

The oldest bedrock cooling ages to the south are 12.7 Ma (ZFT mean age; Nakajima et al., 2020). The youngest ages are broadly found in the middle of the watershed, by latitude, with a youngest reported age of 1.415 ± 0.049 Ma (ZHe mean age; McDermott et al., 2013). Cooling ages increase again when moving across the STD into the northernmost recorded ages in the watershed. For example, Orme et al. (2015) find ZHe ages of 17 Ma (± 0.3 ; single-grain) in the Rongbuk Valley north of Sagarmatha. While thermochronological ages show broad consistency along strike (e.g., Whipple et al., 2023), there are also localized differences. This bedrock dataset emphasizes the many heterogeneities in cooling age in an area this structurally complex. Furthermore, it highlights that many of these complexities may not be shown by the resolution of our existing thermochronological dataset, as we are reliant on where past projects have been focused.

CHAPTER THREE

METHODS

Methods Overview

To investigate sediment routing in the Kosi basin, our team sampled modern river sands from each of the major tributaries within the watershed. We characterized detrital zircon extracted from bulk sediment samples using U-Pb geochronology and (U-Th)/He low-temperature thermochronology. We compare these cooling and crystallization ages to published bedrock dates and cross-comparison with other sediment samples (Gehrels, 2014). The application of low-temperature thermochronology to decipher the provenance of sediment in modern river systems remains less extensive (e.g., Carrapa et al., 2017), and is often applied to small drainage basins with direct cooling age-elevation relationships (e.g., Ruhl & Hodges, 2005; Stock et al., 2006). Therefore, we pair geochronology with low-temperature thermochronology to take advantage of the strengths of each method and provide an integrated dataset to better match detrital grains to their original host rock (e.g., Peyton & Carrapa, 2013).

Zircon U-Pb geochronology through laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) is based on three different decay systems: $^{238}\text{U}/^{206}\text{Pb}$, $^{235}\text{U}/^{207}\text{Pb}$, and $^{232}\text{Th}/^{208}\text{Pb}$ (Gehrels, 2014), each of which provides an independent crystallization age of the zircon mineral. In turn, a fourth date is generated through the combination of two decay schemes, producing a $^{206}\text{Pb}/^{207}\text{Pb}$ date. Based on the respective decay constants of each system, $^{238}\text{U}/^{206}\text{Pb}$ ages are used for < 1200 Ma ages and $^{206}\text{Pb}/^{207}\text{Pb}$ ages are used for > 1200 Ma ages (Gehrels et al., 2008). Crystallization ages are obtained via LA-ICP-MS to excavate and quickly analyze

crystal material (Gehrels, 2014) allowing for datasets of at least 300 grains per sample (Pullen et al., 2014).

Low-temperature thermochronology constrains when rocks cool toward Earth's surface, generally by processes of erosion or tectonically driven exhumation (Reiners et al., 2004; Reiners & Brandon, 2006). This method uses a mineral's closure temperature, defined as the range of temperatures within which the daughter product is retained in a crystal (Dodson, 1973). Zircon (U-Th)/He low-temperature thermochronology uses the same U-Th-Pb decay scheme as U-Pb geochronology, which generates ^4He atoms via alpha decay along their decay chain to their final Pb daughter products (Flowers et al., 2023). ZHe has a low closure temperature between $\sim 140\text{--}200^\circ\text{C}$ (Guenther et al., 2013; Reiners et al., 2004), making it sensitive to near-surface processes, especially in rapidly exhuming landscapes such as the Himalaya (e.g., Colleps et al., 2018; Long et al., 2012).

Sample Collection and Laboratory Processes

We collected 10 modern river samples: eight from tributaries that feed the Kosi River and two post-confluence samples from the Kosi River (NP23-01, NP23-06; Figure 4). Four samples were collected from the Sun Kosi system (NP23-05 Sun Kosi, NP 23-08 Dudh Kosi, NP23-09 Sun Kosi, and NP23-10 Tama Kosi). Two samples were collected from the Arun River (NP23-03, NP23-04) and two samples from the Tamor River (NP23-02, NP23-07). Bulk sediment samples were separated by ZirChron LLC to isolate zircon grains using standard mineral separation processes (e.g., Gehrels, 2008). From these separated samples, we analyzed 10 individual grains per sample for (U-Th)/He cooling ages and approximately 300 grains per sample for U-Pb crystallization ages.

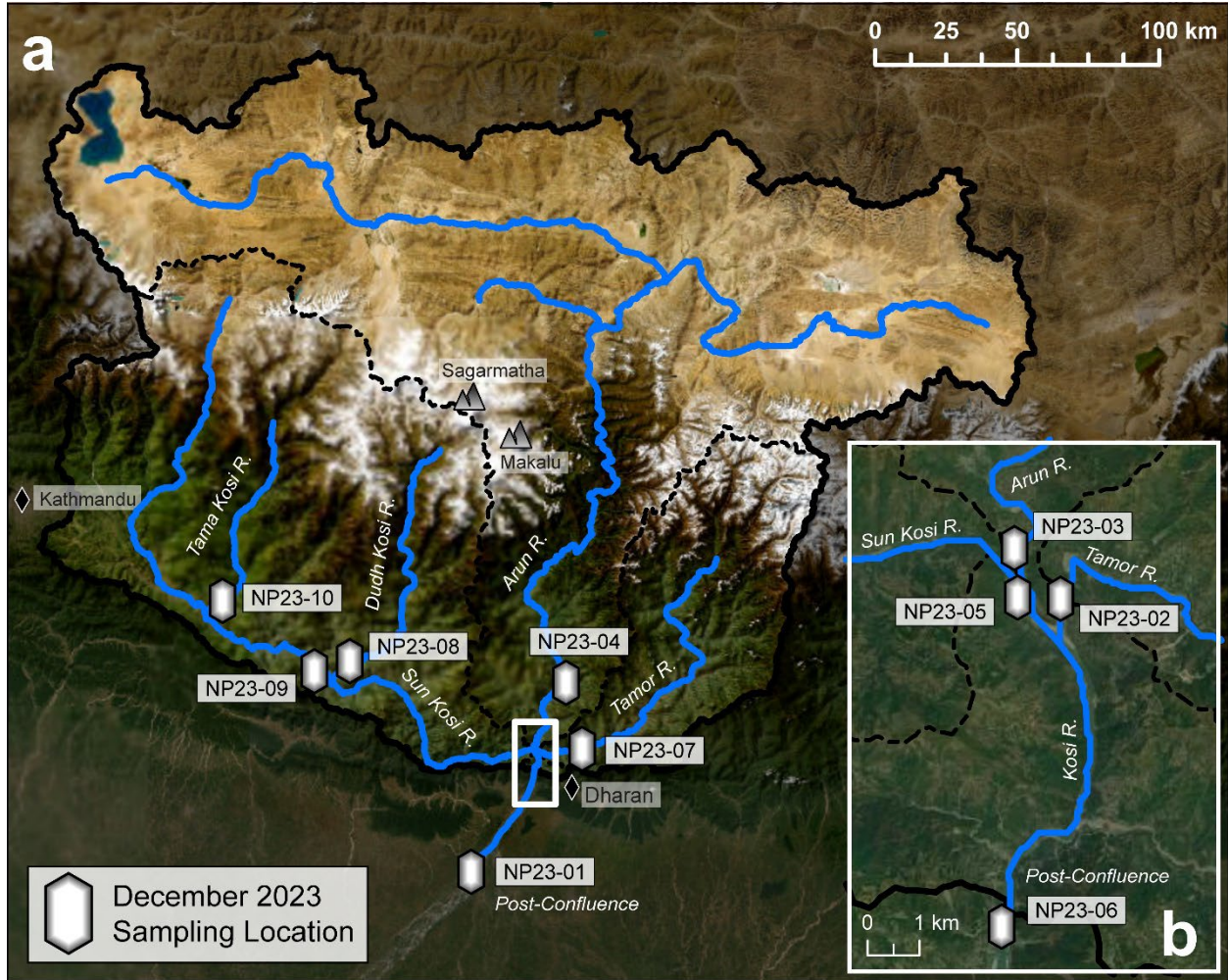


Figure 4. (a) Sampling locations of modern river sands analyzed in this study at the watershed scale. (b) Inset showing sampling locations immediately pre- and post-confluence of major tributaries.

Table 1. Collected sample locations.

Sample Name	Tributary	Latitude	Longitude	Elevation (m)
NP23-01	Post-Confluence Kosi	26.54079	86.96038	80
NP23-02	Tamor	26.91678	87.16207	150
NP23-03	Arun	26.92559	87.15314	130
NP23-04	Arun	27.13897	87.2646	240

Table 1 Continued.

Sample Name	Tributary	Latitude	Longitude	Elevation (m)
NP23-05	Sun Kosi	26.917	87.15376	128
NP23-06	Post-Confluence Kosi	26.8598	87.15057	117
NP23-07	Tamor	26.92869	87.32131	253
NP23-08	Dudh Kosi	27.16677	86.45836	346
NP23-09	Sun Kosi	27.17466	86.3997	361
NP23_10	Tama Kosi	27.27222	85.99639	469

We analyzed 9 of 10 bulk samples for detrital zircon U-Pb age spectra, excluding NP23-07 due to proximity to sample NP23-02 along the Tamor River. U-Pb crystallization ages were obtained at The University of Arizona LaserChron Center, following their standard laboratory procedures (Gehrels et al., 2008). The number of grains analyzed per sample ranged from 147 grains (NP23-04) to 530 grains (NP23-01) with > 300 grains analyzed for 7 of 9 samples to properly characterize the age distributions and relative abundance of age peaks (Supplemental Table 2).

To obtain (U-Th)/He low-temperature cooling ages, we followed standard laboratory procedures of grain selection, helium degassing, crystal dissolution, and data reduction (Flowers et al., 2023). Individual grains were selected and packed in Nb packets at the Montana State University Tectonic Sedimentary and Thermochronology laboratory. Picked grains were prioritized to be inclusion-free, euhedral, and clear. Helium degassing, crystal dissolution, and data reduction occurred at the University of Colorado TRaIL lab from July-September 2024,

following their standard laboratory procedures. We analyzed 10 zircon grains per sample for (U-Th)/He low-temperature thermochronology, except for NP23-01, due to low zircon yield. However, we analyzed 20 grains from NP23-06 to maintain a 20 grain post-confluence sample size, resulting in a dataset of 100 ZHe cooling ages.

Statistical Analyses

We performed multidimensional scaling (MDS) analysis on each of the U-Pb and ZHe datasets to visualize the (dis)similarity among detrital zircon age distributions. This method maps samples as points in Cartesian space by transforming sample dissimilarity into Euclidian distance (Vermeesch, 2013). More alike samples plot closer to each other, with greater distances between points representing greater sample dissimilarity. We used the MATLAB-based program, DZmds, to produce these maps (Saylor et al., 2017). Also included on the MDS maps are arrows to denote the nearest-neighbor distribution to each sample. We use the cross-correlation metric for U-Pb datasets and the Kuiper test for ZHe datasets. The cross-correlation coefficient represents the R^2 value of a crossplot of finite mixture distribution quantiles. The Kuiper test V-statistic is calculated by summing the maximum distance between two CDFs (Sundell & Saylor, 2017).

To further characterize the relationship between samples, we ran a series of Inverse Monte Carlo mixture models. The goal of this analysis is to statistically compare river sands to their sources, using the MATLAB-based program, DZmix (Sundell & Saylor, 2017). This model compares one mixed sample to multiple potential source samples and reports best-fit percent contributions from each source.

We completed six MDS analyses and six mixture models. U-Pb analyses use the composite post-confluence age distribution (combined NP23-01 & NP23-06) to represent the

post-confluence sediment profile. ZHe analyses use the twenty grains dated from NP23-06 to represent the post-confluence sediment profile (NP23-06). A breakdown of the model parameterizations is as follows, in which each listed parameterization represents an MDS and mixture analysis:

1. U-Pb: NP23 post-confluence composite compared to NP23 modern river sands, by sample
2. U-Pb: NP23 post-confluence composite compared to NP23 modern river sands, by watershed
3. U-Pb: NP23 post-confluence composite compared to known bedrock age distributions by lithotectonic unit (Gehrels et al., 2011)
4. ZHe: NP23 post-confluence sample compared to NP23 modern river sands, by sample
5. ZHe: NP23 post-confluence sample compared to NP23 modern river sands, by watershed
6. ZHe: NP23 post-confluence sample compared to known bedrock cooling ages, by watershed

Noting the small sample sizes incorporated into these models from our thermochronological data, we consider our helium model results with caution. While mixture model results offer additional quantitative insight on potential sediment sourcing, especially when paired with MDS analyses, we are conservative in our interpretations and consider the results in proper geologic context.

CHAPTER FOUR

RESULTS

New data include U-Pb geochronological age distributions for 9 of 10 detrital samples and (U-Th)/He thermochronological ages for 9 of 10 detrital samples (Figure 5). We present these profiles by sample, sub-watershed, and for the full Kosi basin. We report MDS analyses and mixture model results for each of the six scenarios described above.

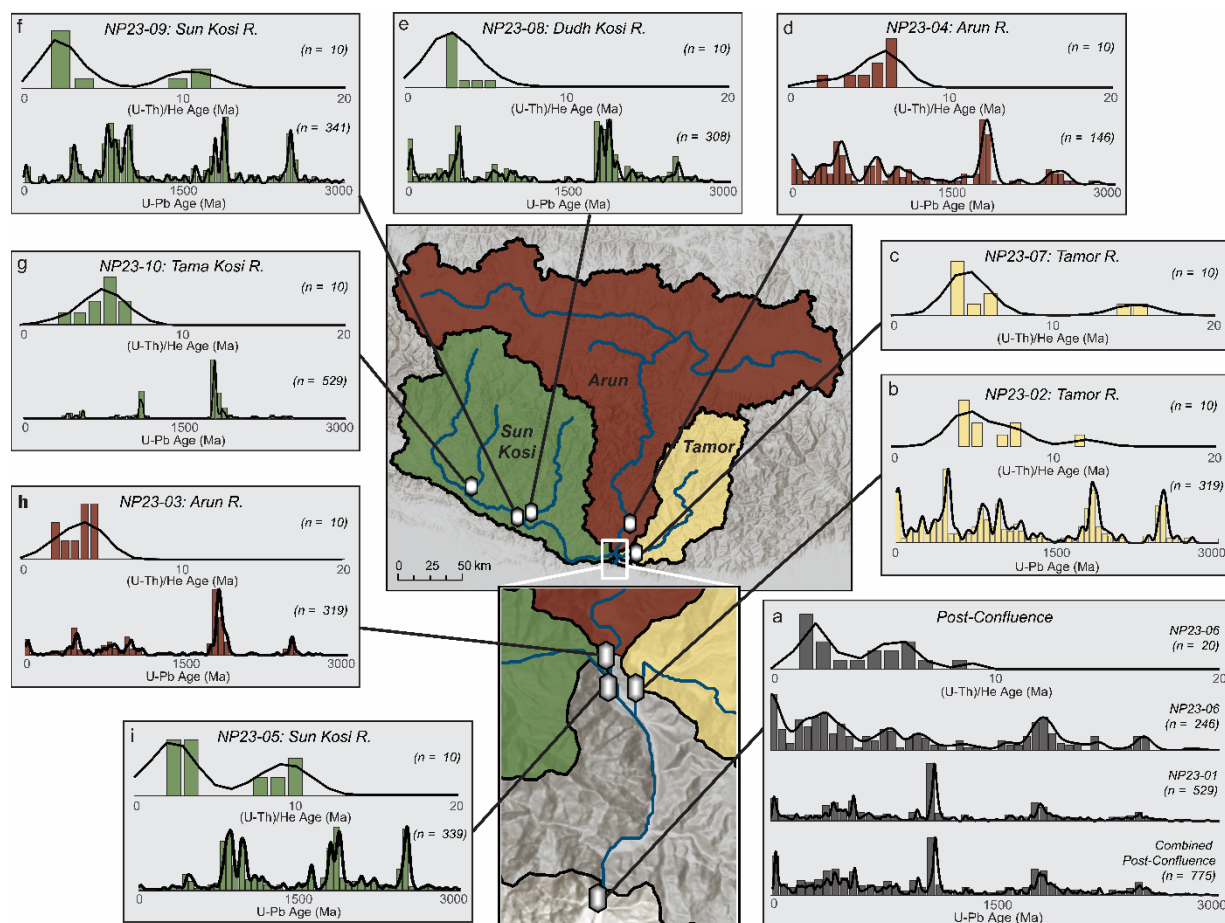


Figure 5. U-Pb Geochronological data and (U-Th)/He Thermochronological data by sample location. (a) Post-confluence (b) NP23-02: Lower Tamor (c) NP23-07: Upper Tamor (d) NP23-04: Upper Arun (e) NP23-08: Dudh Kosi (f) NP23-09: Upper Sun Kosi (g) NP23-10: Tama Kosi (h) NP23-03: Lower Arun (i) NP23-05: Lower Sun Kosi.

U-Pb Geochronology of Modern River Sands

U-Pb spectra of detrital samples reflect known bedrock ages in the Kosi watershed (Fig 6; Supplementary Table 1). We elect to combine both of our post-confluence samples into one composite sample of 775 grains, due to consistent presence of age peaks and similar results from K-S test statistics. This composite sample has prominent age ranges 20 – 50 Ma, 400 – 430 Ma, 540 – 570 Ma, 1070 – 1120 Ma, 1790 – 1830 Ma, and 2450 – 2480 Ma (Fig. 6). Paleozoic and Proterozoic age peaks correlate to known dates from major lithotectonic units (Gehrels et al., 2011), and the youngest 20 – 50 Ma age peak correlates with leucogranites in the GHS and THS. The dominant age peak of the post-confluence sample is 1070 – 1120 Ma, which is likely reflective of ages from the GHS (800 – 1200 Ma) or THS / upper LHS (750 – 1200 Ma).

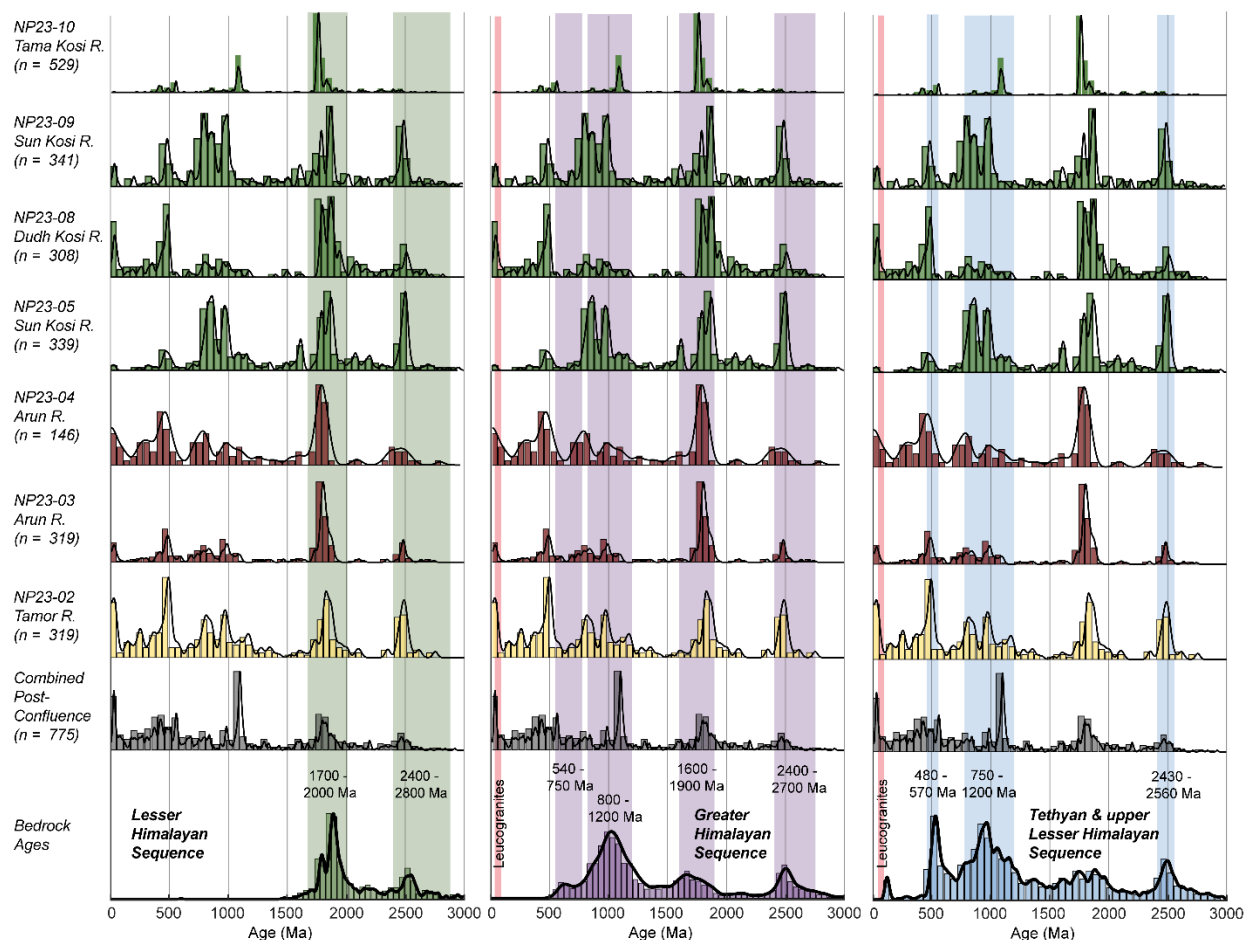


Figure 6. Detrital zircon U-Pb age spectra by sample compared to bedrock ages, with known age peaks by unit highlighted (Gehrels et al., 2011).

Geochronologic ages are largely consistent between samples, with variation in the relative proportionality of ages (Table 1). The most consistent age range among samples is 1600 – 2000 Ma, which is the dominant age range in six of eight samples and is present in all samples. Each sample contains young grains <50 Ma, forming a relative mode in five of eight samples. The abundance and age range of these young grains varies by sample, with the dominant age range between 15 - 35Ma, and a scattering of grains between 40-50 Ma (Table 2).

Table 2. Prominent U-Pb age ranges present in each detrital sample. Included is their relative abundance (compared to other age ranges within the same distribution) and overlapping age ranges within bedrock age composite distributions (Gehrels et al., 2011).

Sample	Dominant Age Range	Relative Ranking in Abundance	Overlapping Bedrock Age Ranges
Post-Confluence Composite	15 - 50 Ma	2	Leucogranite intrusions
	400 - 430 Ma	4	n / a
	540 - 570 Ma	5	480 – 570 (THS/uLHS), 540 – 750 (GHS)
	1070 - 1120 Ma	1	750 – 1200 (THS/uLHS), 800 – 1200 (GHS)
	1790 - 1830 Ma	3	1700 – 2000 (LHS)
	2450 - 2480 Ma	6	2400 – 2800 (all bedrock units)
Lower Tamor (NP23-02)	16 - 30 Ma	3	Leucogranite intrusions
	470 - 510 Ma	1	480 – 570 (THS/uLHS)
	790 - 820 Ma	6	750 – 1200 (THS/uLHS), 800 – 1200 (GHS)
	950 - 1000 Ma	5	750 – 1200 (THS/uLHS), 800 – 1200 (GHS)
	1820 - 1880 Ma	2	1700 – 2000 (LHS)
	2450 - 2520 Ma	4	2400 – 2800 (all bedrock units)
Lower Arun (NP23-03)	15 - 35 Ma	4	Leucogranite intrusions
	470 - 510 Ma	2	480 – 570 (THS/uLHS)
	780 - 830 Ma	6	750 – 1200 (THS/uLHS), 800 – 1200 (GHS)
	960 - 1000 Ma	3	750 – 1200 (THS/uLHS), 800 – 1200 (GHS)
	1760 - 1830 Ma	1	1700 – 2000 (LHS)
	2460 - 2510	5	2400 – 2800 (all bedrock units)
Upper Arun (NP23-04)	15 - 35 Ma	3	Leucogranite intrusions
	450 - 500 Ma	2	480 – 570 (THS/uLHS)
	820 - 860 Ma	4	750 – 1200 (THS/uLHS), 800 – 1200 (GHS)
	1760 - 1840	1	1700 – 2000 (LHS)
	2460 - 2510 Ma	5	2400 – 2800 (all bedrock units)
Lower Sun Kosi (NP23-05)	17 - 29 Ma	6	Leucogranite intrusions
	450 - 500 Ma	5	480 – 570 (THS/uLHS)
	820 - 880 Ma	3	750 – 1200 (THS/uLHS), 800 – 1200 (GHS)
	1600 - 1630 Ma	4	1600 – 1900 (GHS)
	1800 - 1900 Ma	1	1700 – 2000 (LHS)
	2430 - 2530 Ma	2	2400 – 2800 (all bedrock units)
Dudh Kosi (NP23-08)	13 - 50 Ma	3	Leucogranite intrusions
	430 - 500 Ma	2	480 – 570 (THS/uLHS)
	780 - 1000 Ma	5	750 – 1200 (THS/uLHS), 800 – 1200 (GHS)
	1760 - 1860 Ma	1	1700 – 2000 (LHS)
	2480 - 2700 Ma	4	2400 – 2800 (all bedrock units)

Table 2 Continued.

Sample	Dominant Age Range	Relative Ranking in Abundance	Overlapping Bedrock Age Ranges
Upper Sun Kosi (NP23-09)	15 - 35 Ma	6	Leucogranite intrusions
	460 - 500 Ma	5	480 – 570 (THS/uLHS)
	760 - 810 Ma	3	750 – 1200 (THS/uLHS), 800 – 1200 (GHS)
	860 - 1000 Ma	2	750 – 1200 (THS/uLHS), 800 – 1200 (GHS)
	1850 - 1900 Ma	1	1700 – 2000 (LHS)
	2460 - 2520 Ma	4	2400 – 2800 (all bedrock units)
Tama Kosi (NP23-10)	480 - 570 Ma	3	480 – 570 (THS/uLHS)
	1070 - 1150 Ma	2	800 – 1200 (GHS)
	1750 - 1880 Ma	1	1700 – 2000 (LHS), 1600 – 1900 (GHS)

Additionally, we combine sample age spectra by watershed to create composite age spectra by major tributary. With these groupings, both the post-confluence and Tamor signals remain the same with no required new composite for either distribution. The Arun composite sample closely resembles both individual Arun sample distributions, with a dominant age range from 1600 – 2000 Ma. Individual Sun Kosi watershed sample distributions are more variable when compared to each other. Most notably, distributions sampling the main stem of the Sun Kosi, NP23-05 and NP23-09, have prominent age ranges from ~750 – 1200 Ma, which are absent from the two Sun Kosi tributary samples (Dudh Kosi R. and Tama Kosi R.). The composite age distribution for the Sun Kosi watershed reflects this age range but offers a reminder of the variability in sediment profile throughout the watershed.

Low-Temperature Thermochronology of Modern River Sands

All 100 grains selected and analyzed for zircon (U-Th)/He thermochronology returned an accepted cooling age (Figure 7). These ages range from 1.2 ± 0.0 to 15.9 ± 0.4 Ma, except for

one grain from the upper Arun sample that returned an age of 55 ± 0.7 Ma. Data show potentially two young age ranges, from 1.5 – 3.0 Ma and 4.5 – 7.0 Ma, with 76% of ages being less than 6 Ma. The median age is 4.4 Ma.

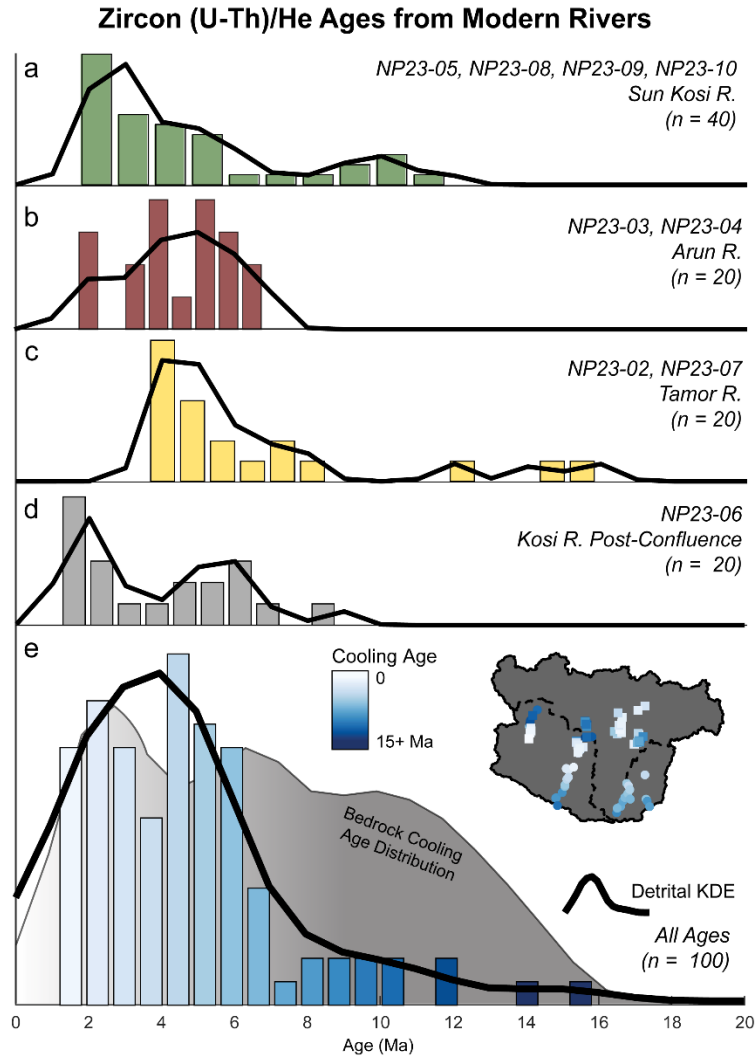


Figure 7. Low-temperature thermochronological age distributions by watershed. Singular 55 Ma grain from the Arun sample is removed for visualization purposes. (a) ZHe ages from Sun Kosi watershed samples (b) ZHe ages from Arun watershed samples (c) ZHe ages from Tamor watershed samples (d) ZHe ages from post-confluence sample (e) All detrital ZHe ages from this study. Histogram and bold KDE represent detrital grains, compared to bedrock ZHe & ZFT combined age distribution in gray gradient. Inset watershed shows locations of bedrock ages.

To better understand detrital ZHe ages throughout the Kosi basin, we grouped ages by sub-watershed in addition to the full detrital age distribution (Table 3). Median ages by watershed are similar to each other and the overall distribution, ranging from 3.7 to 5.0 Ma. The youngest sub-population of ages is in the post-confluence sample, with seven grains younger than 2.0 Ma and a median age of 3.4 Ma. The age distribution from the Arun River appears to be unimodal, while Sun Kosi and Tamor age distributions are potentially multi-modal, with dominant ranges from 1.7 – 5.0 Ma and 7.0 - 12 Ma (Sun Kosi) and from 3.6 – 6.0 Ma and 12 – 16 Ma (Tamor).

Table 3. (U-Th)/He age ranges for each watershed, the post-confluence sample, and combined age distribution of all ages.

Composite Sample	Number of Grains	Ages Present	Median Age
Sun Kosi Watershed	40	$1.7 \pm 0.0 - 11.8 \pm 0.2$ Ma	3.7 Ma
Arun Watershed	20	$1.7 \pm 0.0 - 6.8 \pm 0.0$ Ma, with singular 55 ± 0.7 Ma outlier	4.9 Ma
Tamor Watershed	20	$3.6 \pm 0.0 - 15.9 \pm 0.4$ Ma	5.0 Ma
Post-Confluence	20	$1.2 \pm 0.0 - 8.8 \pm 0.4$ Ma	3.4 Ma
All Grains	100	1.2 ± 0.0 to 15.9 ± 0.4 Ma, with singular 55 ± 0.7 Ma outlier	4.4 Ma

There is some variability between samples within the same sub-watershed (Figure 5). Of the Sun Kosi samples, there is variation between samples taken from the main stem of the Sun Kosi and its tributaries. NP23-05 and NP23-09, both sampled from the main Sun Kosi River, show slight bimodality, with modes around ~2 Ma and ~10 Ma. NP23-08 (Dudh Kosi River) and

NP23-10 (Tama Kosi River) report younger and more similar distributions, with modes around ~3 Ma and ~4 Ma, respectively. The upper Arun sample (NP23-04) is significantly older than the lower Arun sample (NP23-03). Most ages from the upper Arun fall between 4.9 – 6.8 Ma, while all ages from the lower sample are younger than 5.0 Ma. Both Tamor samples show similar ages, the only difference being a slightly more pronounced older age range (~13 – 16 Ma) for the upper sample. All individual ages by sample are reported in Supplementary Table 2.

Zircon (U-Th)/He ages in the bedrock range from 1.4 to 17.0 Ma (Figure 3, Table 3). Ranges vary by tributary. Broadly, bedrock data show a similar range in age to our detrital datasets for each tributary and for the entire Kosi basin. However, the relative proportionality of ages within this range is skewed differently, with modern river detrital samples reporting younger median ages for each tributary and the full basin when compared to the associated bedrock ages.

Table 4. (U-Th)/He bedrock age ranges for each watershed and combined age distribution of all ages.

Composite Sample	Number of Ages	Ages Present	Median Age
Sun Kosi Watershed	38	$1.415 \pm 0.25 - 16.1 \pm 0.95$ Ma	5.2 Ma
Arun Watershed	46	$2.24 \pm 0.06 - 17.0 \pm 0.36$ Ma	8.5 Ma
Tamor Watershed	17	$5.4 \pm 0.3 - 11.6 \pm 0.5$ Ma	7.9 Ma
Full Watershed	101	$1.415 \pm 0.02 - 17.0 \pm 0.36$ Ma	7.6 Ma

Statistical Analyses: MDS Nearest Neighbor and Mixture Model Results

We conducted three MDS nearest-neighbor analyses (Figure 8a-c) and three mixture models (Figure 8d-e) using our detrital zircon U-Pb data. Stress values range from 0.076 to 0.231, falling between good and poor (Kruskal, 1964). Regarding detrital U-Pb age distributions by sample, the most similar samples to the post-confluence composite are the Tamor (NP23-02) and the upper Arun (NP23-04). The most similar samples to each other are the upper and lower Sun Kosi samples. The nearest neighbor watershed composite to the post-confluence sample is the Tamor, while the most similar distributions to each other by watershed are the Arun and Sun Kosi composites. The most similar bedrock age spectra to the post-confluence composite is the THS / upper LHS, which is very closely related to the GHS.

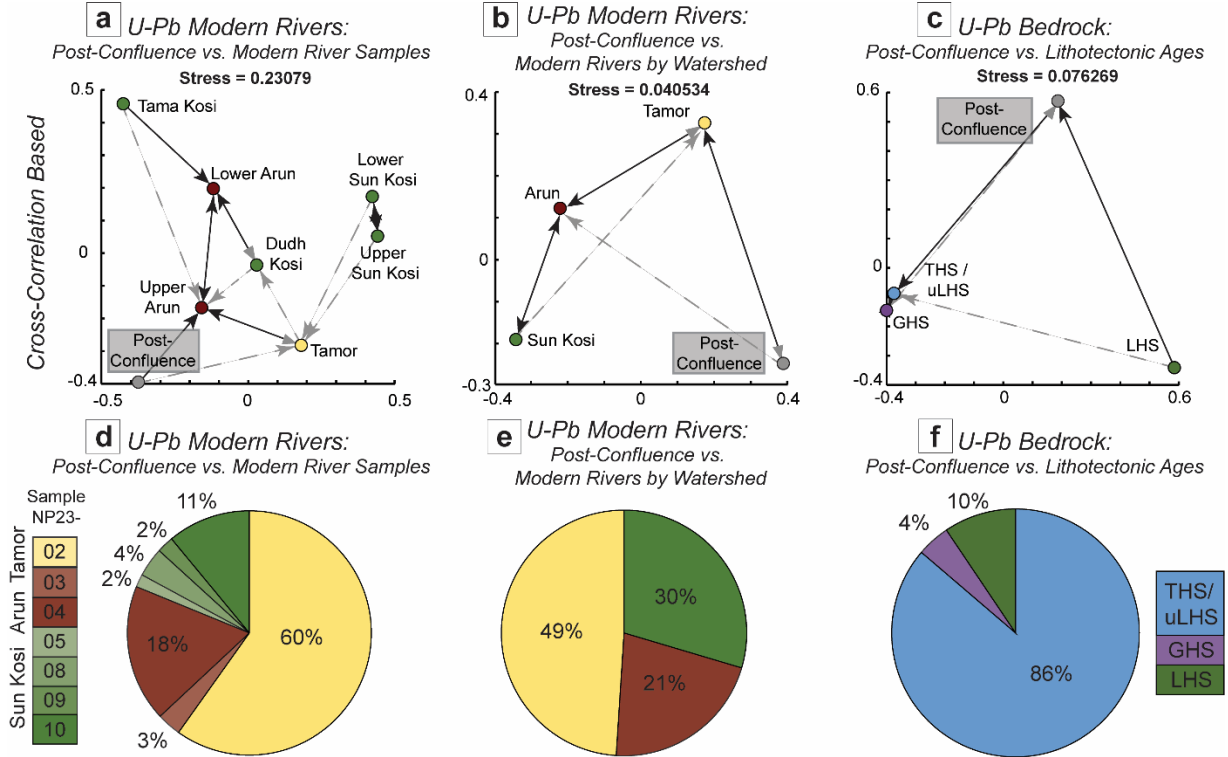


Figure 8. MDS analyses (a-c) and mixture model results (d-f) for U-Pb data (Supplementary Table 3). Arrowheads point from each datapoint towards their first-nearest and second-nearest neighbors in solid black and dashed gray, respectively (a) Comparison of post-confluence U-Pb age distribution to all other individual modern river samples (b) Comparison of post-confluence U-Pb age distribution to composite U-Pb river sand distributions grouped by tributary watershed (c) Comparison of post-confluence U-Pb age distribution to composite U-Pb distributions by lithotectonic unit (Gehrels et al., 2011) (d) Mixture model results of post-confluence U-Pb age distribution compared to individual modern river samples (e) Mixture model results of post-confluence U-Pb age distribution compared to composite U-Pb river sand distributions grouped by tributary watershed (f) Mixture model results of post-confluence U-Pb age distribution compared to composite U-Pb distributions by lithotectonic unit (Gehrels et al., 2011).

Mixture model results by sample show the Tamor sample (NP23-02) to be the largest contributor (60%) to the post-confluence region. By watershed, the Tamor remains the largest contributor (49%). Bedrock mixture models, using composite distributions for the LHS, GHS, and THS/upper LHS as source populations, show the greatest contribution from the Tethyan & upper Lesser Himalayan Sequence (86%). As noted previously, each detrital sample also contains

ages from 15 – 50 Ma, with most dates from this age range between 15-35 Ma. This age range was not included in the bedrock age composites, nor therefore as a source population in our mixture models that are based on major lithotectonic units. However, we identify this age range to likely be reflective of Eocene-Miocene age leucogranites intruding into the GHS or THS.

We additionally conducted three MDS nearest-neighbor analyses (Figure 9a-c) and three mixture models (Figure 9d-f) using our detrital ZHe data. Stress values range from 0.022 to 0.199, falling between excellent and fair (Kruskal, 1964). MDS analysis for ZHe data shows the most similar sample to the post-confluence to be the upper Sun Kosi, followed by the lower Arun (Figure 9a-c). The most similar samples to each other are the upper Tamor and Tama Kosi. By watershed, the most similar composite to the post-confluence is the Sun Kosi, followed by the Arun, then the Tamor. Using bedrock ZHe ages, the most similar distribution to the post-confluence is again the Sun Kosi.

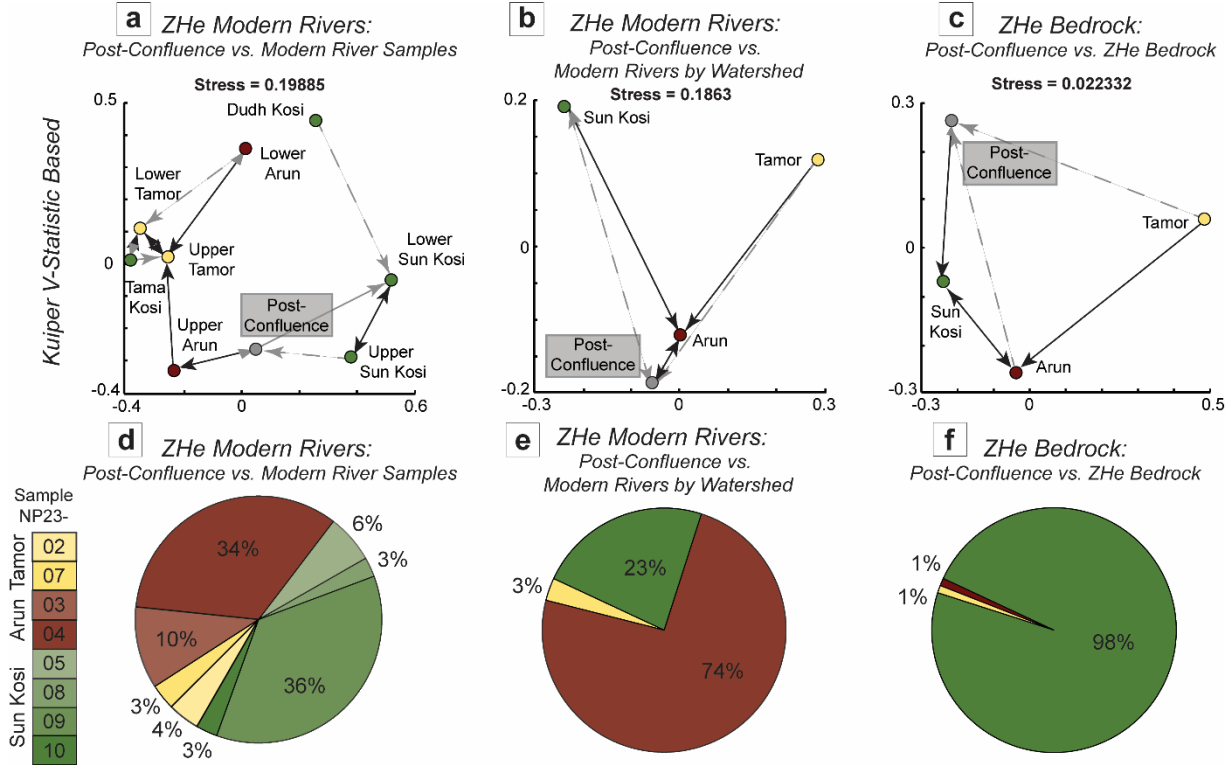


Figure 9. MDS analyses (a-c) and mixture model results (d-f) for ZHe data (Supplementary Table 4). Arrowheads point from each datapoint towards their first-nearest and second-nearest neighbors in solid black and dashed gray, respectively (a) Comparison of post-confluence ZHe age distribution to all other individual modern river samples (b) Comparison of post-confluence ZHe age distribution to composite ZHe river sand distributions grouped by tributary watershed (c) Comparison of post-confluence ZHe age distribution to composite ZHe distributions by watershed (d) Mixture model results of post-confluence ZHe age distribution compared to individual modern river samples (e) Mixture model results of post-confluence ZHe age distribution compared to composite ZHe sand distributions grouped by tributary watershed (f) Mixture model results of post-confluence ZHe age distribution compared to composite ZHe distributions by watershed.

We use the Kuiper V-statistic to determine source contributions in our detrital ZHe dataset (Figure 9d-f). Mixture model results by sample show the Upper Sun Kosi (NP23-09) to be the largest contributor (36%), followed by the Upper Arun (NP34-04; 33%). When we run the mixing model by watershed, the Arun is the dominant contributor (74%), followed by the Sun Kosi (23%), and the Tamor (3%). This contrasts mixing results from our geochronological

dataset, which suggest the dominant contributor to be the Tamor. The final mixture model compares the combined post-confluence detrital sample to the known bedrock cooling ages by tributary watershed. This model shows a very dominant signal from the Sun Kosi, contributing 98%, compared to 1% by each the Tamor and the Arun. Again, this contrasts results from our geochronological dataset and compared to our detrital thermochronological dataset.

CHAPTER FIVE

DISCUSSION

Geochronological Insights

We draw three primary insights when interpreting our geochronological data in isolation. First, the age ranges present support the conclusion that sediment is being sourced to some extent from all major lithotectonic sequences (Figure 6). Second, mixture models using tributary populations as potential sources show similar contributions from each river, supporting the conclusion that sediment is also being sourced from all tributaries. Third, these data suggest the dominant sediment source to be from the upper LHS and GHS.

While evidence for the presence of detritus from all lithotectonic packages is found in the post-confluence composite, the dominant age range in this sample is 1070 – 1120 Ma. This age range is notably not present in the lower LHS composite, suggesting it is not the strongest contributor, despite occupying a large area of the lower latitude regions. Mixture models using lithotectonic packages as potential sources show a dominant signal from the THS/upper LHS. The THS and the upper LHS are indistinguishable stratigraphically and geochronologically (Gehrels et al., 2011). However, because we see evidence of these ages in the Tamor sample, which does not tap the THS, and we see the Tamor and Sun Kosi signals in the post-confluence composite, we infer that these ages are derived from the upper LHS.

Furthermore, the presence of ~15-35 Ma age grains in all samples is indicative of erosion of mid-Miocene leucogranites found within the GHS (Godin et al., 2001; Hodges, 2000; Lavé & Avouac, 2001). This is supported by the U/Th ratios of these grains that are elevated (~75-300)

compared to older zircons (<50) (Supplementary Material 1). In addition, the relative lack of these age grains from the Tama Kosi (NP23-10) and Sun Kosi (NP23-05), with one and seven grains, respectively, reflects that these river systems do not erode into large, mapped leucogranitic intrusions (Figure 3a). By contrast, the Dudh Kosi (NP23-08) has 20 grains <50 Ma, reflecting the presence of leucogranites within its headwaters (Figure 3a). With these inferences in mind, we interpret our geochronological dataset to support a region of dominant erosion in the upper LHS and GHS portions of the watershed.

We acknowledge the limitations and potential caveats of these interpretations, which may stem from our decision to choose to combine both post confluence samples into one composite sample. Figure 5 shows that while these samples include the same age ranges, the relative abundance varies. More specifically, NP23-01, sampled farther down in the watershed, shows a very prevalent peak at 1070 - 1120 Ma, which is subdued in the upper post-confluence sample. We are surprised by this difference as no major tributaries drain into the Kosi between sampling locations. This may reflect the effects of sampling location, as our lower sample was gathered from the floodplain and our upper sample taken from an active riverbank (e.g., Ibañez-Mejia et al. 2018). However, results from MDS analysis and mixture models between each post-confluence sample remain consistent, so we elect to combine samples for the benefit of a larger-n composite.

Thermochronological Insights

Thermochronological results suggest a dominant detrital signal from rocks with the youngest bedrock cooling ages in the watershed. This is evidenced by the abundance of younger cooling ages in modern river sands relative to the known bedrock ages, with a median age for

rivers that is 2.8 million years younger (4.4 Ma compared to 7.6 Ma). We visually correlate this range of young ages, <6 Ma, to the center of the watershed by latitude. This places the dominant band of erosion near the High Himalaya Topographic Front, just north of the MCT and broadly in agreement with Johnston et al. (2020).

The ~ 55 Ma ZHe grain found in our upper Arun sample (NP23-04) is anomalous compared to the other 99 grains analyzed. We interpret this age to suggest sediment input from southern Tibet, as this is an age found within Gangdese Range (e.g., Chapman & Kapp, 2017; Heri et al., 2015; Huang et al., 2017). With headwaters located in southern Tibet, the Arun watershed contains abundant pre-Miocene leucogranites that intrude the Tethyan Himalaya (Cao et al., 2022) and recycled Gangdese batholith grains (e.g., high flux age ranges of ~ 38 -70 and 100-140 Ma) found within the suture zone assemblages (Figure 3a; Metcalf & Kapp, 2019; Orme et al., 2015). Our U-Pb age populations from the Arun (NP23-03, -04) contain a scattering ($n = 7/465$) of grains between 25 Ma and 37 Ma with elevated U/Th that support derivation from the Tethyan Himalaya leucogranites (Supplementary Table 8). In addition, these samples contain several grains ($n = 10/465$) with U-Pb ages between 44 Ma and 140 Ma with U/Th ratios <50 , which may be derived from the suture zone assemblages (Supplementary Table 8). Collectively, we propose that the presence of these grains suggests some Tibetan signal is still present in the Arun by the point of sampling. However, we argue that these grains make up a minor input to the sediment load, due to an absence of additional >15 Ma dates in our detrital sample, which are found in this same region of Tibet.

Our detrital ZHe dataset also allows us to evaluate the merits of using this method as a provenance indicator. We find that statistical interpretations of our thermochronological dataset

are limited by two main factors: spatial bias and small sample size. This study has the benefit of being conducted in one of the most well-researched basins in the world yet remains biased by bedrock data availability. Geologic studies by nature tend to be conducted in areas of geologic interest, likely biasing these data to overrepresent areas with unique cooling signatures. For example, the Arun bedrock dataset includes a large portion of bedrock ages studying recent exhumation by Tibetan normal faults (e.g., Jessup et al., 2008; McDermott, 2012). Bedrock data in the Sun Kosi region, alternatively, are largely sourced from consistent N-S traverses, offering a more uniform understanding of cooling age along strike (e.g., Nakajima et al., 2020; Wang et al., 2010). We suggest that this inconsistency is likely responsible for the dramatic skew in favor of contribution by the Sun Kosi (98%), when conducting a mixture model using ZHe bedrock data.

As a further limitation, low-temperature thermochronological analysis is an expensive and time-consuming method. We find that this small-n dataset allows for qualitative analysis but is limited in quantitative analysis as mixture models are most robust with a large-n dataset (Sundell & Saylor, 2017). Our mixture model results highlight the potential issues that arise using a small-n dataset. For example, we frequently see a greater contribution from upstream samples relative to downstream samples (e.g., greater contribution from the upper Sun Kosi sample compared to the lower Sun Kosi). This proves illogical considering the upstream signal should be integrated in the downstream sample and there are no known changes in zircon fertility of the bedrock between sampling locations (e.g. Amidon et al., 2005). We take these results to caution against using absolute mixing values from quantitative analysis. However, we argue there is still value in considering the qualitative takeaways from these mixture models.

Benefits of a Multi-Proxy Approach

Our results show that by considering dating metric results together, we are able to better constrain the dominant region of erosion in a structurally complex basin. Both approaches of using zircon U-Pb geochronology and (U-Th)/He thermochronology present the same broad conclusions, that sediment in the Kosi basin is dominantly sourced from the central basin, primarily deriving from the upper LHS and GHS. This focus correlates with models of highest erosion rates (e.g., Whipple et al., 2023; Figure 2D).

Disagreement with Climatically Driven Landscape Evolution

Integrating our datasets, we interpret the focus of erosion within the Kosi watershed to be from the upper LHS to lower GHS (Figure 10). This region is north of the heaviest precipitation band and south of the most glaciated areas (Figure 10a; Funk et al. 2015; GLIMS Consortium, 2005). We argue that if present-day landscape change was driven exclusively by climatic factors, our detrital sediment signal would be reflective of geochronologic and thermochronologic ages that are characteristic of the bedrock in one or both of these regions. Figure 10a highlights the spatial disagreement between precipitation, glaciation, and detrital sediment signal. This discrepancy emphasizes the need for some additional driver beyond climate to be influencing landscape evolution in the basin.

Structural Implications

We argue that our identified dominant erosion band coincides with inferred structures at depth, interpreting our results to support a model of landscape evolution in the Kosi basin in which the Main Himalayan Thrust at depth plays a role in shaping the topographic landscape

(Figure 10b). Using a similar method along strike in central Nepal, Johnston et al. (2020) find peak erosion in the Marsyandi basin to also be located just north of the MCT and overlapping with proposed locations of the Main Himalayan Thrust ramp. When comparing this dominant erosive signal to studies constraining ramp geometry at depth (e.g., Hubbard et al., 2016; Elliot et al., 2016), they conclude that significant duplexing on a midcrustal ramp 80 – 100 km north of the MFT is required to fit their data to these geometries. We interpret our data to support a similar tectonic geometry signal across strike due to consistency in dominant erosion across all three sub-basins in the Kosi watershed.

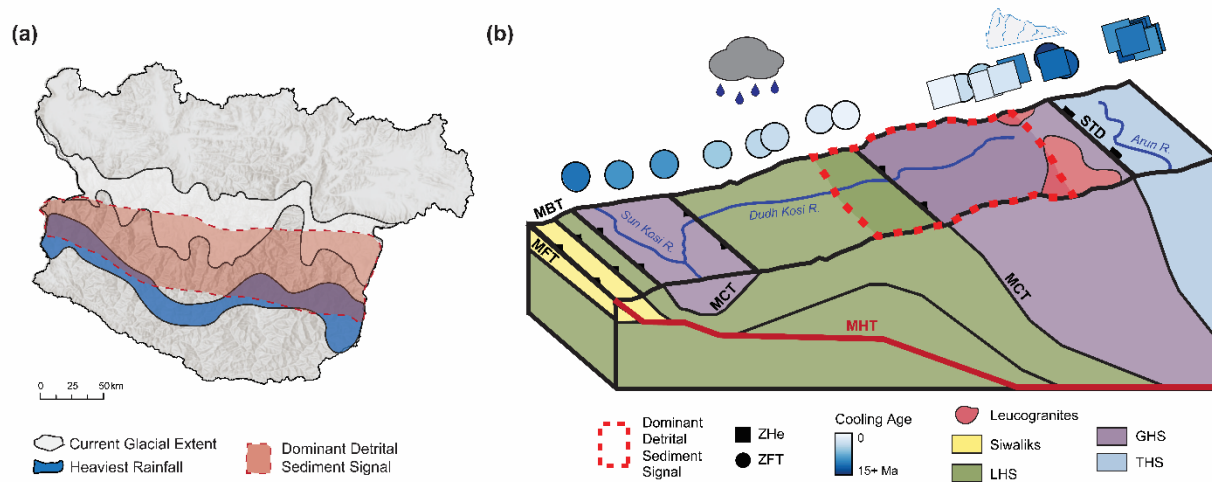


Figure 10. (a) Generalized tracing of dominant sediment signal from this study compared to band of heaviest rainfall and current glacial extent (Funk et al., 2015; GLIMS Consortium, 2005) (b) Schematic cross-section highlighting location of dominant sediment signal in reference to surface geology, structure, and climatic signals. Structure at depth modified from Hubbard et al. (2016). Thermochronological symbols represent bedrock ages along Dudh Kosi river profile within ~50 km (Figure 3). Raincloud represents approximate latitude of highest precipitation and glacial graphic represents approximate latitude of glaciation.

This interpretation further agrees with the other studies along strike investigating geometric structure at depth, which emphasize the need for internal deformation to explain surface

observations of topography and thermochronometry (e.g., Johnston et al., 2020; McQuarrie et al., 2014; Sherpa et al., 2024; K. X. Whipple et al., 2016). For our schematic cross-section (Figure 10b), we incorporate a cross-section proposed by Hubbard et al. (2016) in light of the 2015 Gorkha earthquake. This model includes a series of three deep ramps within the MHT, producing an imbricated duplex. Our interpreted region of dominant sedimentation falls above of this ramp structure at depth, supporting this model.

Our results further agree with the peak erosive band proposed for the Arun watershed by Olen et al. (2015). This study, using ^{10}Be to determine denudation rates, also argues for a strong tectonic forcing signal, in agreement with studies such as Godard et al. (2012) and Burbank et al. (2003), citing similar denudation patterns in the Arun valley and in studies where denudation rates are fit to tectonic drivers (Olen et al., 2015). Importantly, however, Olen et al. (2015) also acknowledge the limitations of their detrital dataset, specifically in the inability to rule out climatic influences such as glaciation and localized landslides. The resolution of our data also does not allow us to tease out these signals. One could possibly test for the influence of glacial or recent rock erosion by focusing the study area closer to these processes in the higher elevations of the Himalaya or by sampling before and after significant landslide events. In addition, Olen et al. (2015) note the possibility of a diluted Tibetan signal due to the washing out of larger grains (e.g., $>2\text{ mm}$) analyzed in their detrital dataset by the point of sampling. This limitation is also possible in our dataset, especially in consideration of the presence of a singular ZHe 55 Ma grain and multiple Eocene age zircons, which we interpret to be a Tibetan signal. However, in agreement with this study, we ultimately argue that our detrital data is broadly representative of

the sediment profile in the Kosi River, thus providing a useful tool for investigating landscape evolution in this system.

CHAPTER SIX

CONCLUSION

By combining geochronological and thermochronological methods, we are able to better isolate the dominant detrital sediment signal in the Kosi basin. This signal supports the hypothesis that tectonics, not exclusively climatic factors, continue to play a key role in shaping the landscape in the region. While our data does not explicitly allow for distinction of a particular tectonic model, nor does it rule out the role of high slope topography, it supports a model in which duplexing along a midcrustal ramp at depth continues to provide rock to be eroded at the surface, in agreement with studies advocating for a prominent tectonic forcer in landscape evolution (e.g., Godard et al., 2012; Johnston et al., 2020).

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APPENDICES

APPENDIX A

U-PB AGES

(THIS DATA CAN BE FOUND IN SUPPLEMENTAL MATERIAL TAB 2)

APPENDIX B

ZHE AGES

(THIS DATA CAN BE FOUND IN SUPPLEMENTAL MATERIAL TAB 3)

APPENDIX C

U-PB CROSS-CORRELATION RESULTS

(THIS DATA CAN BE FOUND IN SUPPLEMENTAL MATERIAL TAB 4)

APPENDIX D

ZHE KUIPER V-STATISTIC RESULTS

(THIS DATA CAN BE FOUND IN SUPPLEMENTAL MATERIAL TAB 5)

APPENDIX E

ZHE BEDROCK COMPILATION

(THIS DATA CAN BE FOUND IN SUPPLEMENTAL MATERIAL TAB 6)

APPENDIX F

U-TH RATIOS FROM ARUN SAMPLES

(THIS DATA CAN BE FOUND IN SUPPLEMENTAL MATERIAL TAB 7)