AGU ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2021GL095008

Climate as the Great Equalizer of Continental-Scale Erosion

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Key Points:

- Despite the magnitude of the India-Asia collision, erosion throughout Central Asia reflects Phanerozoic tectonics
- Regions of "old" erosion are preserved in more arid areas, whereas more recent erosion is concentrated in areas of high precipitation
- Tectonic mechanisms are required to initiate erosion; however, climate modulates the magnitude of erosion

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Jepson, G., Carrapa, B., Gillespie, J., Feng, R., DeCelles, P. G., Kapp, P., et al. (2021). Climate as the great equalizer of continental-scale erosion. *Geophysical Research Letters*, *48*, e2021GL095008. https://doi.org/10.1029/2021GL095008

Received 30 JUN 2021
Accepted 5 OCT 2021

Abstract

Central Asia hosts the most extensive and highest topography on Earth, which is the result of the feedbacks among rock uplift, atmospheric circulation and moisture transport, and erosion. Here, we analyze 2,511 published low-temperature thermochronometric ages as a proxy of the regional-scale erosion of Central Asia. We compare these ages to tectonic and climate proxies, and state-of-the-art paleoclimate simulations to constrain the influences of climate and tectonics on the topographic architecture of Central Asia. We observe a first-order relationship between younger cooling ages in areas of high precipitation and older ages (Mesozoic) in areas that have been sheltered from precipitation, despite high strain rates. Thus, we suggest that climate enhances erosion in areas where rock uplift produces significant orographic gradients, whereas in the continental interior, areas which are tectonically active but have been sheltered from significant precipitation record older ages and a longer erosional history.

Plain Language Summary

Modern topography represents the product of the relationships among climate, tectonics, and erosion through time. Central Asia is one of the most topographically diverse regions on Earth. However, the relative role of tectonics versus climate on erosion of continental Asia remains one of the major debates in Earth sciences. One way to investigate this is through the analysis of erosional proxies. In this study, we present the first regional-scale analysis of thermochronometric ages from Central Asia as a proxy of erosion. We compare these data to tectonic processes, climate proxies, and state-of-the-art paleoclimate simulations in order to constrain the relative influences of climate and tectonics on the topographic architecture and erosion of Central Asia. There is a first-order relationship between more recent erosion and active tectonic boundaries. However, more recent erosion is also associated with areas of high precipitation, whereas areas that have been sheltered from significant precipitation retain a signal of older erosional events. Thus, we suggest that climate plays a key role in enhancing erosion in areas with developed topography and high precipitation, whereas areas which experienced sustained aridity record less erosion and preserve a record of older erosion.

1. Introduction

Changes in continental erosion through geological time can be interpreted in terms of changing climate and tectonics (Willett, 1999). Central Asia lies at the nexus of the Earth's most significant plate tectonic boundary and climate systems, the South Asia-East Asia monsoons and the northern hemispheric belt of the westerlies (Caves et al., 2015; Quade et al., 1989). The ongoing collision of India with Asia since the early Cenozoic coupled with vigorous precipitation produced Earth's highest mountains, largest topographic plateau, thickest crust, and greatest erosional efflux to the global ocean. From our understanding of plate tectonics, we would expect the Central Asian erosional history to record a Cenozoic signal of the India-Asia collisional deformation (Molnar & Tapponnier, 1975).

Assessment of tectonic or climate controls on erosion is complicated by the coupled tectonic-climatic evolution of the region. Some have suggested a climatic control on erosion and tectonics (Beaumont et al., 2001; Herman et al., 2013; Whipple, 2009), whereas others have invoked a primary tectonic control on erosion (Burbank, 2005; Burbank et al., 2003; Copeland et al., 2015; Wobus et al., 2005). Investigation of

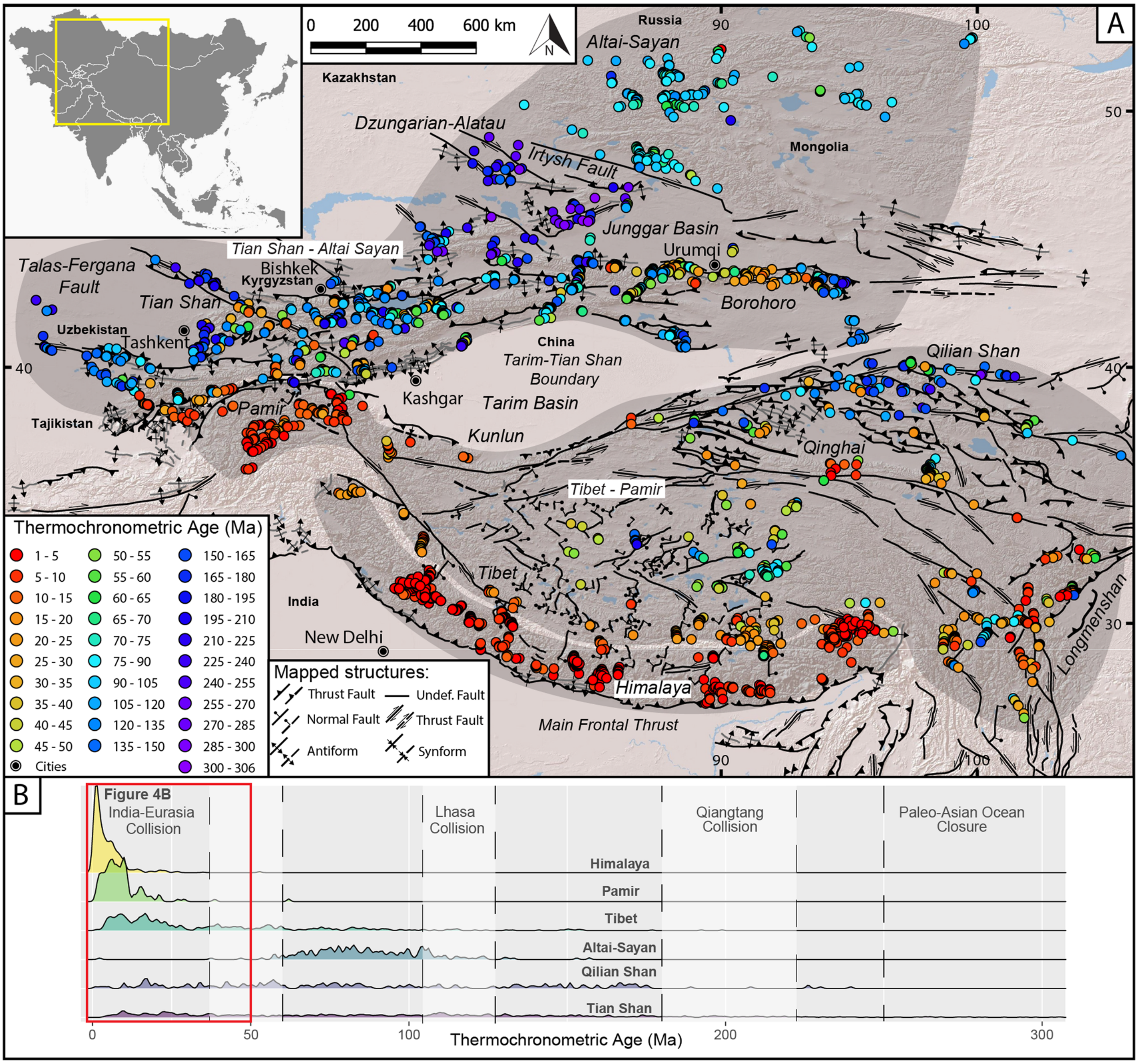

Figure 1. (a) Map of Central Asia detailing all low-temperature thermochronometric ages used in this study (apatite fission-track, apatite, and zircon (U-Th-Sm)/He). Table of individual ages and their associated metadata can be found in Tables S1–S2 in the Supporting Information S1. Structures are from Styron et al. (2010). Shading outlines the three regional subdivisions: Tian Shan-Altai Sayan; Tibet-Pamir; and the Himalaya. (b) Kernel density estimates of thermochronometric age in comparison to major tectonic events.

the exhumation history of Central Asia presents an outstanding opportunity to address the question: "What controls continental-scale erosion?" In this study, we use low-temperature thermochronology as a proxy for erosion. Combined zircon and apatite U-Th-Sm/Helium (ZHe, AHe) and apatite fission-track (AFT) thermochronology document cooling through the ~190–40°C closure temperature (T_C), which can be used as a proxy for erosion associated with upper crustal deformation and/or climate (e.g., Braun et al., 2006). Although we recognize the limitations of this assumption, we posit that at the continental scale erosion is the prevalent process controlling rock exhumation and cooling in regions dominated by upper-crustal shortening. We assess the extent of erosion across an area of $\sim 11.7 \times 10^6$ km^2 of Central Asia since the late Paleozoic by compiling 2,269 (AFT), 133 (AHe), and 109 (ZHe) ages from three topographic regions: (a) the Tian Shan-Altai Sayan, (b) the Tibet-Pamir Plateau, and (3) the Himalaya (Figure 1, Tables S1 and S2 in the Supporting Information S1).

The topography of Central Asia is the result of surface uplift processes related to the collage of orogenic belts which formed over the last *ca*. 300 Ma (De Grave et al., 2007; England & Searle, 1986; Hendrix et al., 1992; Sobel et al., 2003; Weller et al., 2015; Xiao et al., 2013). Surface uplift is the product of rock uplift minus erosion (*sensu* England & Molnar, 1990). Therefore, constraining the relative influences of climate and tectonic processes on erosion will provide key insights into the underlying control on surface uplift.

To elucidate relative contributions of climate and tectonics to the distribution of erosion in Central Asia we compare our data set to geodetic strain (Figure S1 in the Supporting Information S1, Kreemer et al., 2014) and proximity to major tectonic boundaries (Thiede & Ehlers, 2013), and modern- and paleo-precipitation (Figures 2–4, Dee et al., 2011; Caves Rugenstein & Chamberlain, 2018; Feng et al., 2020; Tabor et al., 2016; Zhu, Poulsen, & Tierney, 2019). We find that mid-to late Cenozoic cooling ages are confined to the southern, western, and eastern margins of the Tibetan-Pamir Plateau, which is vulnerable to aggressive erosion by orographic barrier precipitation associated with the Westerlies and the East Asian and South Asian monsoons (Clift & Webb, 2019; Farnsworth et al., 2019). Cooling ages typical of India-Asia collision time (*ca*. 45–60 Ma) are limited throughout the interior of Asia (<7%; Figure 1). Whereas, the interior of Central Asia, which is seismically active (Figure S2 in the Supporting Information S1) and preserves considerable topographic relief and elevation, records much older cooling ages. Our study suggests that, although rock uplift provides the first-order control on the locus of continental erosion by producing surface uplift and orography, the global atmospheric circulation and moisture transport patterns ultimately regulate the magnitude of erosion.

1.1. Tectonics of Central Asia

The Eurasian continent formed due to closure of the Turkestan ocean during the Late Carboniferous- Permian, which initiated northward subduction of Tethyan oceanic plates beneath the southern Eurasian continent (Xiao et al., 2013). Successive closure of multiple generations of Tethyan oceans caused peri-Gondwanan fragments to collide with the Eurasian margin (De Grave et al., 2007). These events were dominated by collision of the Qiangtang block during the Late Triassic–Early Jurassic, the Lhasa block during the Late Jurassic–Early Cretaceous, and the Karakoram and Kohistan-Ladakh arcs during the Late Cretaceous (Hendrix et al., 1992; Kapp & DeCelles, 2019; Yin and Harrison, 2000; Şengör 1984).

Final closure of the Neo-Tethyan Ocean resulted in collision of the Indian continent with southern Eurasia during the Cenozoic. Exact timing and mechanisms of the collision are intensely debated with a single-stage *ca*. 58 Ma collision and multi-stage *ca*. 58 Ma and *ca*. 45 Ma collision hypotheses gaining prominence (DeCelles et al., 2014; Kapp & DeCelles, 2019; Garzanti et al., 1987, and references therein). During the Eocene-Oligocene widespread shortening occurred in the northern Himalaya (e.g., Hodges 2000; Najman et al., 2005; Ratschbacher et al., 1994; Searle et al., 1988) contemporaneous with shortening and volcanism in central Tibet (Ding et al., 2003; Kapp et al., 2005). East-West extension initiated across the northern Himalaya and southern Tibet during the mid-Miocene and continues today (Armijo et al., 1986; Burke et al., 2021; Garzione et al., 2000; Styron et al., 2015). Northern Himalayan gneiss domes were also exhumed during mid-Miocene time (Jessup et al., 2019; Lee et al., 2000). Thrusting was active in the Himalaya during the Miocene with internal duplexing developing at 11-5 Ma and initiation of the Main Boundary Thrust (Figure 1) at 5 Ma (DeCelles et al., 2020, and references therein). Shortening along the northeastern margin of the Tibetan Plateau has been semi-continuous from the Eocene to present (Lease, 2014; Yin et al., 2008; Zuza et al., 2019).

The Tian Shan experienced localized uplift and erosion during the Cretaceous-Paleocene (Dumitru et al., 2001; Jolivet et al., 2010) and a major phase of structural reactivation and associated exhumation beginning at *ca*. 24 Ma (Hendrix et al., 1994; Sobel, Chen et al., 2006; Sobel, Oskin et al., 2006) and intensifying in the Miocene (Bullen et al., 2001; Glorie et al., 2011). At present day, shallow crustal seismicity is widespread throughout the study region; intermediate-depth mantle seismicity is limited to the Hindu-Kush and the northern edge of the Pamir (Figure S2 in the Supporting Information S1). Therefore, deformation has been widely distributed across Asia throughout the ongoing India- Asia collision (Meade, 2007).

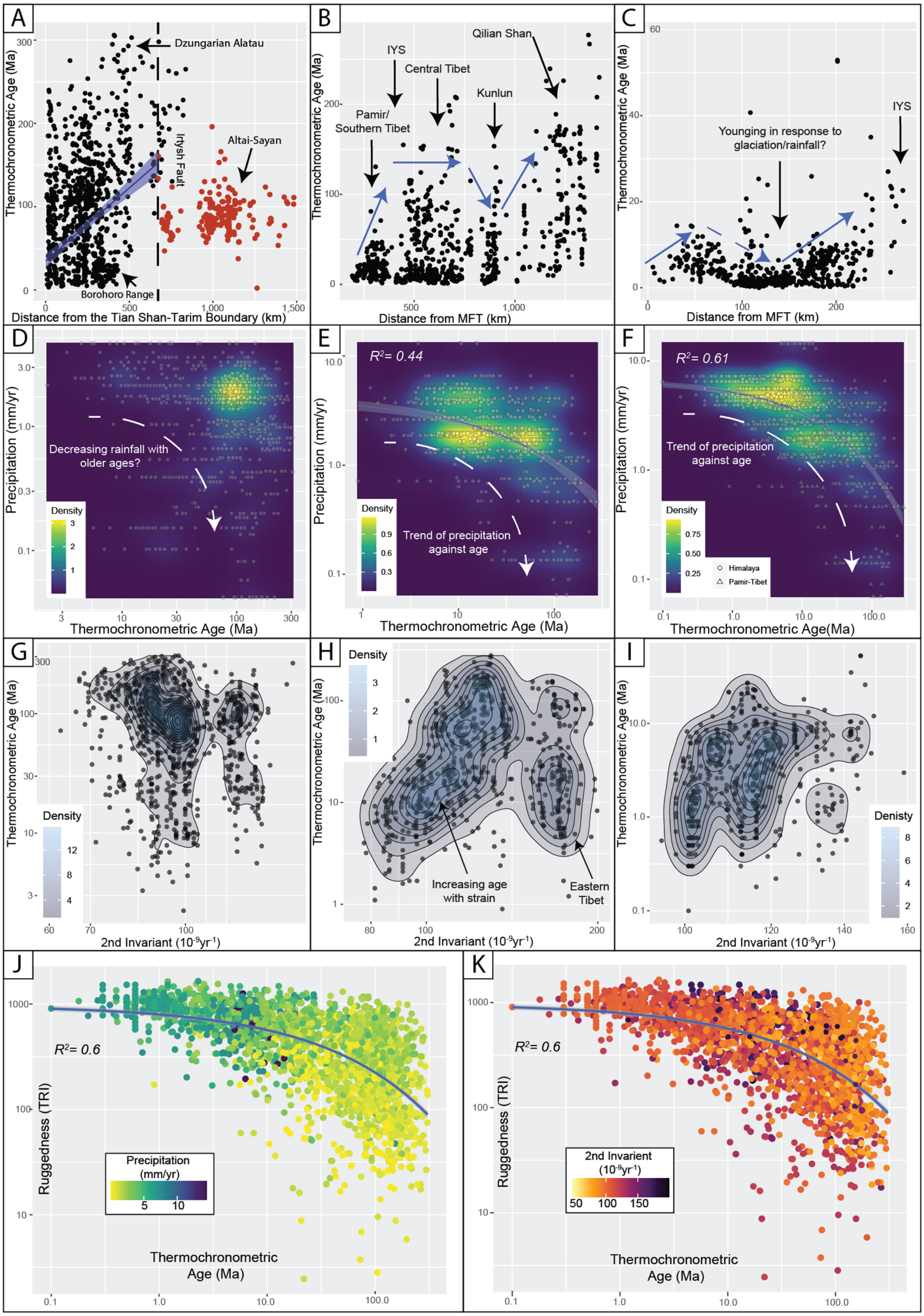
A
Dzungarian Alatau
Altai-Sayan
Irtysh Fault
Borohoro Range
Thermochronometric Age (Ma)
Distance from the Tian Shan-Tarim Boundary (km)
B
IYS
Central Tibet
Qilian Shan
Kunlun
Pamir/ Southern Tibet
Distance from MFT (km)
C
IYS
Younging in response to glaciation/rainfall?
Distance from MFT (km)
D
Decreasing rainfall with older ages?
Precipitation (mm/yr)
Density
E
R²= 0.44
Trend of precipitation against age
F
R²= 0.61
Trend of precipitation against age
Himalaya
Pamir-Tibet
G
H
Increasing age with strain
Eastern Tibet
I
Denisty
2nd Invariant (10⁻⁹yr⁻¹)
J
R²= 0.6
Precipitation (mm/yr)
Ruggedness (TRI)
Thermochronometric Age (Ma)
K
2nd Invarient (10⁻⁹yr⁻¹)

Figure 2.

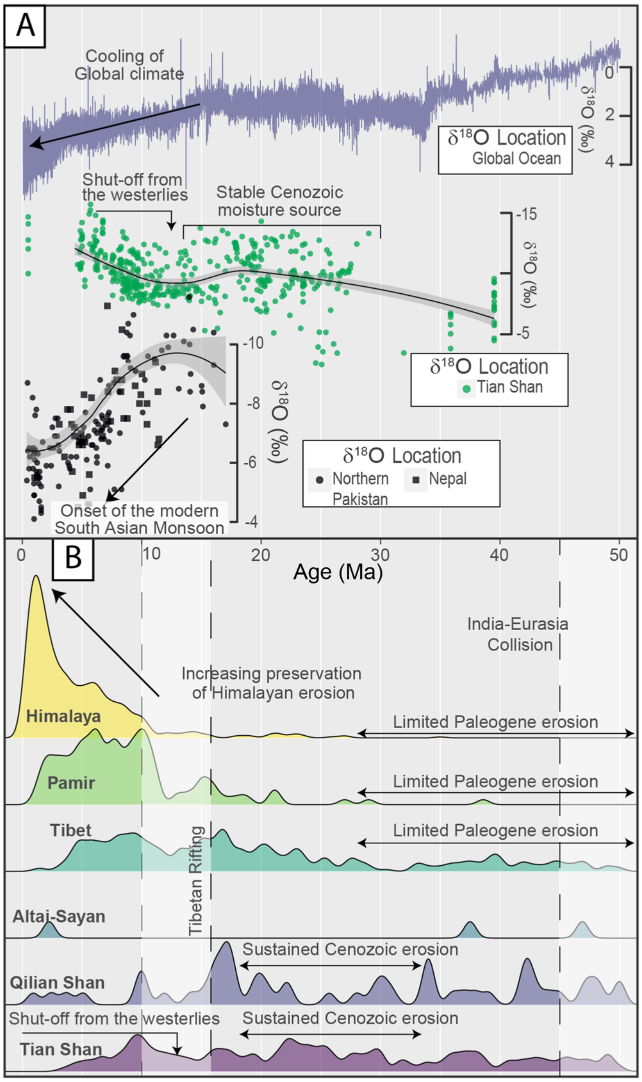

Figure 3. (a) δO^{18} isotopes from pedogenic carbonates from Northern Pakistan and Nepal (Behrensmeyer et al., 2007; Quade & Cerling, 1995; Quade et al., 1989) and the Tian Shan (Caves Rugenstein & Chamberlain, 2018, and references therein), the global oceanic δO^{18} isotope record from (Zachos et al., 2001). (b) A kernel density estimate of thermochronometric age <50 Ma till present.

2. Methods

Apatite fission-track thermochronology constrains the cooling through a temperature window between ~120-60°C. Apatite and zircon (U-Th-Sm)/He thermochronology constrain cooling through the 80–40°C window and ~190–170°C, respectively (Braun et al., 2006, and references therein). When combined these techniques provide constraints on upper-crustal processes. Data from this study were compiled from 126 peer-reviewed publications (for a complete list of samples, ages, coordinates, and references refer to Tables S1 and S2 in the Supporting Information S1 and Figure 1). The thermochronometric ages were analyzed with respect to relative proximity to regional-scale structures (Figures 1 and 2), relief, and strain (Braun, 2002; Ehlers, 2005; Kreemer et al., 2014; Riley et al., 1999).

To evaluate potential paleoclimate conditions, fully coupled, state-of-the-art model simulations for the late Cretaceous, Early Eocene, and Pliocene were employed (Text S1 in the Supporting Information S1, Feng et al., 2020; Tabor et al., 2016; Zhu et al., 2019). Finally, the global Cenozoic climate cooling trend and the onset of the South Asian Monsoon are frequently asserted to be drivers of increased global erosion (Grujic et al., 2006; Herman et al., 2013). In order to explore this hypothesis, our data set has been compared to precipitation (mm/yr) from ERA-Interim (Figure S3 in the Supporting Information S1, Dee et al., 2011).

3. Results/Discussion

We will focus on long wavelength (~100 km) topography to assess the relationship between rock uplift and erosion. In this analysis, we use geodetic strain rate and distance to major tectonic boundary as proxies for rock uplift (Kreemer et al., 2014; Thiede & Ehlers, 2013), modern global precipitation as a proxy for climate (Dee et al., 2011), and ruggedness as a proxy for relief (Riley et al., 1999). While comparing modern proxies to paleo-erosion has limitations, if a relationship between a given proxy and erosion existed in the past, a similar relationship should be generally evident in the modern. Therefore, if erosion is primarily controlled by orography and moisture transport patterns, then we should expect thermochronometric age to vary in response to modern and paleo-climate proxies and relief. Alternatively, if erosion is primarily controlled by variations in rock uplift that drive steepness of topography then we would expect thermochronometric age to vary with respect to strain rate and distance to structure (Figure 2).

3.1. Relationships Among Tectonics, Cooling Ages, and Erosion

There are first order correlations between thermochronometric age and long-wavelength structural features corresponding to paleo-ocean closures (Figures 1 and 2, Figures S4–S9 in the Supporting Information S1). The exhumation and geometry of the Tian Shan have been attributed to Cenozoic India-Eurasia collision (De Grave et al., 2007; Molnar & Tapponnier, 1975). However, abundant Jurassic and Cretaceous cooling

Figure 2. Plots comparing distance from major tectonic boundary (km) for (a) the Tian Shan-Altai Sayan, (b) the Tibet-Pamir, and (c) the Himalaya. Log-log 2D kernel density estimates displaying annual mean rainfall (Figure S3 in the Supporting Information S1, mm/day, Dee et al., 2011) for (d) the Tian Shan-Altai Sayan, (e) the Tibet-Pamir, and (f) the Himalaya and Tibet-Pamir combined. Log-log contour plots comparing thermochronometric age against the second invariant of strain rate (Kreemer et al., 2014) for (g) the Tian Shan-Altai Sayan, (h) the Tibet- Pamir, and (i) the Himalaya. MTF is the Main Frontal Thrust and IYS is the Indus-Yarlung Suture. Log-log plots of combined thermochronometric ages against topographic ruggedness index (TRI, after Riley et al., 1999) colored by (j) precipitation and (k) strain.

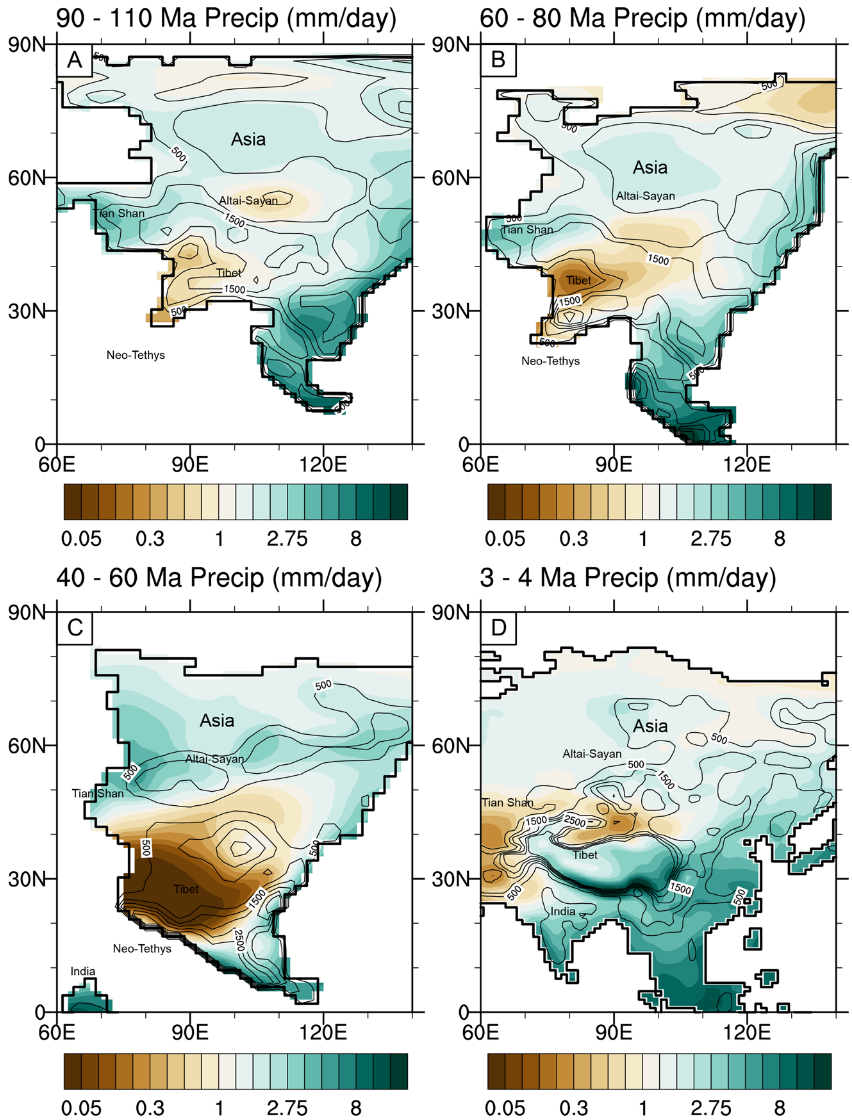

Figure 4. Community Earth System Model-simulated annual mean paleo-precipitation (shading; mm per day) for the (a) mid-Cretaceous, (b) late Cretaceous, (c) early Paleogene, and (d) Pliocene. Contours are surface elevation (meters) used in each simulation.

ages suggest that large parts of the Tian Shan experienced significant erosion prior to the Cenozoic and that the India-Eurasia collision did not strongly rejuvenate exhumation despite high geodetic strain rates (Figure 2, De Grave et al., 2007; Jolivet et al., 2001).

The Tibetan Plateau and Pamir Mountains are characterized by the thickest continental crust on Earth (Schneider et al., 2013, 2019). Thermochronometric ages from Tibet show younger cooling and erosion (<30 Ma) closer to the India-Eurasia collisional margin in the southern Tibetan Plateau, Longmenshan, and near localized late Cenozoic rifts and extensional gneiss domes. In central Tibet, prevailing Jurassic- Cretaceous thermochronometric ages can be explained by the Mesozoic Lhasa-Qiangtang collision; early Cenozoic ages are limited (Figures 1 and 2, Rohrmann et al., 2012). Thermochronometric ages show decrease northward from central Tibet toward the southern margin of the Tarim basin (~120–10 Ma, Kunlun, Figure 2b), attributed to the northward growth of the Tibetan Plateau (Law and Allen, 2020). Extensive Miocene ages in the Pamir are due to tectonic exhumation associated with extensional gneiss domes coupled with orographic barrier precipitation-enhanced erosion associated with the westerly belt (Carrapa et al., 2014; Käßner et al., 2017; Wang et al., 2020; Worthington et al., 2020). In southern Tibet, the predominance of

Miocene ages has been attributed to focused erosion in response to Indian slab breakoff followed by northward underthrusting of Indian lithosphere, mid-crustal duplexing, and the onset of east-west extension (i.e., Indus-Yarlung fluvial system, Figure 2, Carrapa et al., 2014; Laskowski et al., 2018; Leary et al., 2016; Lee & Whitehouse, 2007; Styron et al., 2015; Webb et al., 2017). Older thermochronometric age correlate with higher geodetic strain rates (Figure 2h) except for eastern Tibet, where high-strain is coupled with the East Asian monsoon (e.g., Farnsworth et al., 2019).

The Himalaya and Longmenshan define the southern and eastern margins of the Tibetan Plateau, respectively, and are characterized by late Cenozoic thermochronometric ages and high strain rates (Figures 1 and 2). Climatic and tectonic drivers are invoked for the rapid erosion rates observed in the Himalaya, with ongoing discussion on which is the primary influence on current topography (Grujic et al., 2006; Thiede & Ehlers, 2013; Zeitler et al., 2014). Himalayan thermochronometric ages increase with distance and higher strain from the Main Frontal Thrust, young ~100–150 km away from the active orogenic front, before returning to older ages in the Tethyan (northern) Himalaya (Figures 2c–2i). These results suggest that although erosion covaries with tectonic structure, the distribution of erosion is independent of strain rate alone (Figures 2g–2i).

3.2. Relationships Among Climate, Cooling Ages, and Erosion

Despite the thousands of kilometers of intercontinental convergence during the Cenozoic India-Asia collision (Figure 2, England & Houseman, 1986; Molnar & Tapponnier, 1975), much of the Central Asian interior yields pre-Cenozoic thermochronometric ages. As a result, climate has long been recognized as a major contributor to continental erosion and relief (Molnar & England, 1990; Reiners et al., 2003).

We observe a general relationship between older thermochronometric age and lower modern precipitation (Figures 2d–2f). The Tian Shan-Altai Sayan displays a greater range between ages and associated precipitation (Figure 2d). Paleozoic-Mesozoic cooling ages are associated with low precipitation, which suggests limited erosion during the Cenozoic (Figure 2). The Pamir acted as an effective orographic barrier against the westerlies since the late Oligocene, indicated by a west to east decrease in the magnitude of Miocene erosion across the Pamir (Carrapa et al., 2014; Kent-Corson et al., 2009; Wang et al., 2020). Similarly, older ages are preserved in regions with low precipitation in the Tibetan Plateau interior, whereas younger ages correlated with regions of higher precipitation associated with the Asian monsoons (Figure 2e). In the Himalaya, the trend between thermochronometric ages and precipitation can be interpreted as the result of progressive rock uplift related to the southward development of the fold-thrust belt coupled with orographic barrier climate-enhanced erosion of high Himalayan topography (Figure 2f and Burbank et al., 2003; Thiede et al., 2004; Grujic et al., 2006; Streule et al., 2012; Thiede & Ehlers, 2013; Carrapa et al., 2016; DeCelles et al., 2020). However, this first-order observation breaks down in regions that experienced significant, mostly Miocene and younger, tectonic exhumation by normal faulting (i.e., the Pamir gneiss domes or orogen-parallel extension systems in southern Tibet and the northern Himalaya, Kapp & DeCelles, 2019; Leary et al., 2016; Murphy et al., 2000; Robinson et al., 2004; Webb et al., 2017); in regions where reliability of published data remains disputed (i.e., the Borohoro range, Gillespie et al., 2017), or where low-relief landscapes are preserved (i.e., eastern Tibet, Figure 1, Clark et al., 2005).

The covariance between climate proxies and thermochronometric age suggests that rock uplift alone cannot explain the distribution of continental-scale erosion. The influence of climate on erosion is best displayed in Figures 2j and 2k which compares ruggedness (a measure of surface relief, Riley et al., 1999) and all Central Asian thermochronometric data. Younger thermochronometric ages (increased erosion) correlate with higher ruggedness and increased precipitation (Figure 2j), whereas strain rate varies independently (Figure 2k). The invariance of strain rate with thermochronometric age supports the hypothesis that rock uplift and associated erosion is reduced by lithostatic loading which then causes deformation to migrate (e.g., Hilley et al., 2005; Willett, 1999). Therefore, we suggest that although there is a coupled relationship between climate and tectonics, at the continental scale the magnitude and distribution of erosion are more dependent on the magnitude of precipitation.

3.3. Paleoclimate and Erosion

Shifts in climate are invoked as a means for increased erosion (Herman et al., 2013; Thiede et al., 2004, 2009; Willett, 1999). Large scale climatic fluctuations have occurred in tandem with rock uplift (tectonic) events in Central Asia since the mid-Cretaceous (Figure 3). Across the Late Cretaceous greenhouse climate, global mean sea surface temperature (SST) decreased substantially (O'Brien et al., 2017; Tabor et al., 2016). Global cooling ceased following the end of the Cretaceous, with proxy records indicating warming (Hansen et al., 2013; Zachos et al., 2001). Starting from the late Eocene, global climate displayed another long-term cooling trend of prolonged cooling and high frequency variations including glacial advance and retreat and carbon cycle excursions (Westerhold et al., 2020). The South Asian Monsoon since the late Miocene (~10.7 Ma), coincident with a global cooling trend and more seasonal climate starting at ~8 Ma, are recorded by δO^{18} isotopes in pedogenic carbonate nodules across Northern Pakistan and Nepal (Behrensmeyer et al., 2007; Dettman et al., 2001; Quade et al., 1989; Zachos et al., 2001).

There is a strong erosional signal at 11–10 Ma in the Himalaya, contemporaneous with the onset of the modern South Asian Monsoon (Dettman et al., 2001; Quade et al., 1997) and internal duplexing (rock uplift, DeCelles et al., 2020, and references therein). The correlation between South Asian Monsoon development and Mio-Pliocene cooling ages in the Himalaya today and between aridity and older ages observed in Tibet and other regions sheltered from precipitation suggests that the feedback among rock uplift, precipitation, and climate can be extrapolated back in time (e.g., Sobel et al., 2003). To elucidate the impact of paleoclimate on erosion, we leverage existing paleoclimate simulations using the Community Earth System Model (CESM), which implement time-appropriate geological boundary conditions and well-reproduce the large-scale climate features in proxy records (Feng et al., 2020; Tabor et al., 2016; Zhu et al., 2019). Paleo-precipitation was simulated for Eurasia over four key time intervals from the Cretaceous to the Pliocene (Figure 4). These models show that: (a) The Tian Shan-Altai Sayan experienced higher precipitation in the mid Cretaceous and relatively lower precipitation from Late Cretaceous to present (>1 mm/day); (b) the Tibet-Pamir region was extremely arid during the Late Cretaceous with a slight increase in precipitation in the Neogene simulation, especially in the western and northern regions (<0.5 mm/day), and (c) the Himalaya has remained relatively wet (>2.75 mm/day) since the Pliocene (Figure 4). However, paleoclimate simulations are approximations. Here, we explore the larger scale patterns of hydroclimate response in Central Asia as paleo elevation uncertainties and limited model resolution preclude a more detailed assessment.

3.4. Climate and Tectonic Coupling Since the Mesozoic

Our study suggests that the absence of early Cenozoic cooling ages in most of Central Asia is a result of a drier climate due to its subtropical location and continentality, which limited erosion (Figure 4, Montgomery et al., 2001). We observe a lag between thermochronometric ages and the timing of major tectonic events (rock uplift) across Central Asia (Figure 1b). As these tectonic events resulted in the closure of a major paleo-seaway along the southern margin of Eurasia (Figure S4 in the Supporting Information S1) their closure produced rock uplift which sheltered the interior of the continent from moisture via orographic barriers (e.g., Tapponnier et al., 1990), thus contributing to aridity and continentality. A similar relationship is invoked by Sobel et al. (2003), where orographic barriers control the formation of major internally drained basins within Central Asia (e.g., the Qaidam and Tarim basins, Figure 1). This process minimizes relief via basin aggradation behind uplifts which reduce slope development, thus providing an additional mechanism for suppressing erosion in the continental interior. Further, Sobel et al. (2003) demonstrate that precipitation plays a controlling factor on bedrock erodibility and in-turn continental scale erosion. This model is consistent with paleo-precipitation models of Central Asia since the Late Cretaceous, which show regions with older thermochronometric ages in the Eurasian interior (e.g., Qilian Shan and central Tibet) associated with stable climate and limited rainfall (Figures 1a and 4, Caves Rugenstein & Chamberlain, 2018; Macaulay et al., 2016). Thus, the relationship among modern precipitation, Mio-Pliocene climate cooling, and erosion can be extrapolated into the Mesozoic where shifts in paleoclimate correlated with changes in erosion (Figure 4).

Our study corroborates the concept that tectonics is a pre-condition for generating rock uplift, which is subsequently impacted by erosion through orographic barrier precipitation (Figures 3 and 4, Boos & Kuang, 2010). Climate models and δO^{18} isotopes in the Tian Shan-Altai Sayan show a stable climate since the Eo-Oligocene, which is correlated with sustained erosion (Figures 3 and 4, Macaulay et al., 2016). In Tibet, increasing aridity toward the modern has limited erosion and preserved older tectonic-exhumation signals (Figure 4). Thus, throughout the Mesozoic-Cenozoic, tectonics generated significant topography as a function of rock (and surface) uplift, which focused erosion along the margin of major orogenic systems via orographic processes and in turn sheltered the interior from precipitation, enhancing aridity, suppressing erosion, and preserving older surface uplift events.

The relationships among tectonics, climate, and erosion are emphasized between the Himalaya and Tibet. In central Tibet, limited Paleogene ages (60–45 Ma) transition into Neogene ages along its southern margin, suggesting widespread aridity, coupled with low relief and internal drainage, persisted in the orogenic interior since the Cretaceous (Figures 1 and 2, Lippert et al., 2014; Rohrmann et al., 2012; Sobel et al., 2003). The eroding margin shifted southward during the Cenozoic as a response to growth of the Himalayan thrust belt (Hodges, 2000; Molnar et al., 2010), concentrating precipitation and erosion away from southern Tibet onto the newly formed Himalayan front (Grujic et al., 2006). Continuous, sustained erosion of the frontal part of the Himalaya throughout the Cenozoic contributed to the modern distribution of cooling ages along the southern margin of Asia. Our analysis suggests that while wetter climates enhance erosion, the drying of the climate and continentality plays a key role in the preservation of older erosional events. The paucity of Paleogene ages across the Himalaya is likely an artifact due to sparse data from the Tethyan Himalaya coupled with a relatively dry climate suppressing Paleogene erosion (Figure 4).

4. Conclusions

Our study shows that thermochronometric ages in Central Asia are the product of tectonics and rock uplift which affects global atmospheric circulation and moisture transport patterns, which in turn influences the spatial distribution of orography and erosion. The variable distribution of thermochronometric ages observed in the Tian Shan and Altai-Sayan indicates punctuated deformation events concentrating erosion throughout the Mesozoic and Cenozoic, particularly in response to the Qiangtang and Lhasa collisions, with the resulting ages being preserved due to low relief and shielding from high-precipitation via orographic barriers. Thermochronometric ages in the Pamir, Himalaya, and Tibet get progressively older away from major tectonic boundaries. The Tibetan Plateau interior preserves older ages because it was uplifted above sea-level during the Qiantang and Lhasa collisions and became dry and/or formed low topographic relief, thus becoming erosionally stable by the Eocene-Oligocene. Growth of the Himalaya and Pamir concentrated precipitation toward their high-rainfall margins leading to increased erosion. Through our thermochronometric analysis across Central Asia as a proxy for erosion, this study provides evidence for a coupled tectonics-climate control on erosion at the continental scale, where tectonics and rock uplift create topographic relief upon which climate controls the spatial distribution of erosion. This record stretches back into the Mesozoic, with paleoclimate proxies and modeling supporting a climate control on the distribution of erosion and cooling ages. Our study shows that rock uplift coupled with a vigorous, e.g., monsoon-like, climate amplifies the record of erosion and tectonics in the frontal part of the Himalaya, whereas drier paleoclimates help to preserve an erosional signal related to older tectonic processes and associated surface uplift events, even in extremely rugged, glaciated, and high strain rate orogenic belts like the Tian Shan. However, processes such as localized fault movement, glacial and fluvial systems, and rheology remain fundamental controls on the distribution of erosion and should not be discounted.

Acknowledgments
Kaustubh Thirumalai, Jay Quade, and Sarah George are thanked for their helpful discussions. Marcus Lovferstrom is acknowledged for procurement and formatting of the ERA-interim data. Paul Kapp acknowledges NSF grant OISE 1545859. Ran Feng acknowledges NSF grant NSF-1814029. Peter DeCelles acknowledges NSF-Tectonics program EAR1763432. Editor Lucy Flesch and reviewers George Hilley, Yang Wang and Rasmus Thiede are thanked for their insightful comments which improved this manuscript.

Data Availability Statement

Data and figures supporting the conclusions presented here is available on the University of Arizona's Research Data Repository (https://doi.org/10.25422/azu.data.14298227).

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