

Introduction to the special issue “Tibetan tectonics and its effect on the long-term evolution of climate, vegetation and environment”

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Abstract

The long-term evolution of the Tibetan Plateau significantly influenced Asian climate, nearby ocean physics and chemistry, and terrestrial biodiversity. This range of impacts has attracted research attention from a correspondingly broad range of disciplines, providing important new insights into prolonged and emerging debates concerning the Himalayan–Tibetan morphotectonic evolution and its impacts on the long-term evolution of climate, biodiversity, and the environment on regional to global scales. To communicate the latest advances on this coupled tectonic, climatic and biological system, we have launched a special virtual issue in *Terra Nova* and solicited submissions of 20 papers in total. The papers cover a wide range of topics that fall in the following, partially overlapping, categories: pre-India–Asia collision tectonic configuration; post-collision deformation; sedimentary system: source to sink studies, climatic forcing, and river incision; and climatic and biospheric influence of the Tibetan Plateau.

OVERVIEW

The Tibetan Plateau has long served as a superb natural laboratory for testing competing geodynamic models and investigating the ongoing debate on the interactions between tectonic and climate evolution (Molnar, 2005; Molnar et al., 2010; Prell & Kutzbach, 1992; Ruddiman & Kutzbach, 1989; Ruddiman et al., 1997). The Tibetan Plateau, standing at >4 km above sea level and covering an area

of 2.5×10^6 km² (Figure 1), results from the closure of a series of Phanerozoic ocean basins and subsequent collisions of continental blocks that culminated with the India–Asia collision at ca. 50–60 Ma (Kapp & DeCelles, 2019; Yin & Harrison, 2000). Thus, the rock record on the plateau and surrounding regions documents geodynamic and surface processes during progressive continental convergence. The long-term tectonic evolution of the Tibetan Plateau has been actively interacting with other processes at the Earth's

surface, including profound changes in Asian climate, ocean circulation and chemistry, and terrestrial biodiversity (Figure 2). This range of interactions and impacts has attracted research attention from a correspondingly broad range of disciplines, providing important new insights into prolonged and emerging debates concerning the Himalayan–Tibetan morphotectonic evolution and its impacts on the long-term evolution of climate, biodiversity, and the environment on regional to global scales. The Tibetan Plateau's evolution is an important analogue for studies of other modern and ancient orogenic plateaus.

To communicate the latest advances on this coupled tectonic, climatic, and biological system, we have launched a special virtual issue in Terra Nova and solicited submissions of 20 papers in total. The papers cover a wide range of topics that fall in the following, partially overlapping, categories: (a) Pre-India–Asia collision tectonic configuration (Liu, Liu, et al., 2021; Zhang, Liu, et al., 2021); (b) post-collision deformation that are subdivided into three sub-categories, including (1) Himalayan geology (Fu et al., 2020; Liu, Wang, et al., 2021; Xu et al., 2021), (2) intracontinental deformation (Pan et al., 2021; Pang et al., 2021; Pei et al., 2021; Wang, Replumaz, et al., 2022; Zhang, Zhang, et al., 2021), and (3) exhumation and topographic evolution (He et al., 2020; Ma et al., 2021; Wang, Wang, et al., 2021; Zhang, Li, et al., 2021); (c) sedimentary system: source to sink studies, climatic forcing, and river incision (Feng et al., 2021; Wen et al., 2022; Yang et al., 2021; Zhang, Daly, et al., 2021); and (d) climatic and biospheric influence of the Tibetan Plateau (Averyanova et al., 2021). Research locations of this special issue are distributed across the plateau, spanning from the frontal Himalayas in the south to the Qilian Shan and Tian Shan ranges in the north, and extending into the continental interior (e.g. Kazakhstan) (Figure 1). Diverse research methods have been used, ranging from field structural geology, petrology, palaeontology, geomorphology, mineralogy, geochemistry, geochronology, low temperature thermochronology and 3D numerical modelling. Several results also highlight the recent trend of conducting collaborative efforts in Tibetan Plateau research as an excellent example for understanding multi-sphere interactions.

1 | PRE-INDIA–ASIA COLLISION TECTONIC CONFIGURATION

In geodynamic models, the tectonic configuration before the terminal India–Asia collision plays a key role in focusing the deformation and is a key factor to understand the Cenozoic geological and topographic evolution of the Himalaya–Tibetan Plateau (Kapp & DeCelles, 2019; van Hinsbergen et al., 2011; Yin & Harrison, 2000). In this category I, two contributions study the Triassic and Jurassic oceanic remnants respectively (Liu, Liu, et al., 2021; Zhang, Liu, et al., 2021). Based on field observations, petrological and geochronological results derived from mafic intrusions in a tectonic mélange in the western Indus–Tsangpo suture zone (ITSZ), Liu, Liu, et al. (2021) interpret the initiation of the Neo-Tethys Ocean that they trace back to the middle Triassic. In the second study, Zhang,

Significance Statement

This is an introduction to the virtual issue that published 20 papers concerning the Tibetan tectonics and its effect on the long-term evolution of climate, vegetation, and environment. The tectonic impacts and interactions have attracted research attention from a correspondingly broad range of disciplines. Here we highlight major interactive paths among tectonics, climate, topography, and terrestrial biodiversity, especially those related to the major findings of papers published in this special issue.

Liu, et al. (2021) constrain the amalgamation of an oceanic plateau to the continent by applying mineralogical and geochemistry analysis to the cumulates of the Pengco Complex along the Bangong–Nujiang Suture between the Lhasa and Qiangtang terranes in central Tibet.

2 | POST-COLLISIONAL DEFORMATION

There are 13 papers that are collected in the most extensive category II of post-collision deformation. These studies are further divided based on their characterization of the Cenozoic geological history of the Himalaya–Tibetan Plateau from the following three aspects: (a) Himalayan geology, (b) intracontinental deformation in the plateau hinterland, and (c) exhumation and topographic evolution.

2.1 | Himalayan Geology

The Himalaya fold–thrust belt is a key factor in re-constructing geodynamic and monsoonal climate models for the Plateau (Beaumont et al., 2001; Boos & Kuang, 2010; Ding et al., 2017). Three papers fall into the sub-category of Himalayan geology. Xu et al. (2021) present a new structural and geochronological dataset for the Greater Himalayan Sequence in the Annapurna range of central Nepal and suggest that the Himalayas may have experienced a phase of ~31 to 21 Ma exhumation recorded in the Great Himalayan sequence, accommodated by general shear and anatexis beneath the Kalopani shear zone. Fu et al. (2020) present a new structural and zircon U/Pb geochronological study from the Cuonadong Dome that developed in Tethyan Himalayan sedimentary sequence (THS), north of the South Tibetan detachment system (STDS). Their results suggest a ca. 32 Ma hinterland-ward shear of the South Tibetan detachment system and lithosphere delamination. Liu, Wang, et al. (2021) report the first discovery of mantle-derived ultrapotassic rocks (a ca. 13 Ma lamprophyre dike) in the Himalayas. Geochemical evidence suggests that the ultrapotassic melt was derived from the subcontinental lithospheric mantle of the Indian plate, indicating middle Miocene mantle unrooting and asthenospheric upwelling in the Himalayan orogen.

2.2 | Intracontinental deformation

The kinematic history of the northern margins of the plateau (including Qilian Shan and Tian Shan) and the evolution of large-scale strike-slip faults (e.g. the Altyn Tagh, East Kunlun and Haiyuan faults) offer an excellent opportunity for investigating the far-field effects and strain accommodation related to the India–Asia collision. Five papers under this category characterize intracontinental deformation using methods ranging from modern Global Position System (GPS) observations and focal mechanism, late Quaternary faulting rates, to structural analysis of seismic reflection profiles and numerical modelling.

1. The study of Wang, Replumaz, et al. (2022) delineate the limit of Indian underthrusting beneath the Tibetan Plateau and proposed a new model to accommodate the mechanical processes of extension in the plateau. The study shows that the termination of the rifts in southern Tibet, south of the Karakorum–Jiali fault zone (KJFZ), does not correspond to the underthrusting Indian lower lithosphere. They suggest that E–W extension south of the KJFZ coincides with the divergent thrusting along the curved Himalayan arc and the extension north of the KJFZ in the western Qiangtang terrane that are associated with the rigid extrusion of the eastern Qiangtang block along the Xianshuihe fault.
2. Four papers have specific focus on the northeastern Tibetan Plateau and beyond (Figure 1). Using updated GPS velocity field and focal mechanism solutions, Pan et al. (2021) conduct kinematic block modelling to derive how strain is partitioned across a wide area extending from the East Kunlun range in the south to the Haiyuan in the north. The model shows a first-order pattern characterized by strain transfer from the strike-slip to shortening from west to east. Based on the interpretations of a set of high-resolution seismic reflection profiles, Zhang, Zhang, et al. (2021) study the termination of the Altyn Tagh fault by constraining its slip history and the transition from slip motion to shortening. The numerical modelling study of Pei et al. (2021) investigates the

arcuate structure and relates the formation of arcuate structure to lateral heterogeneities related to pre-existing strong blocks and varying sediment strata thickness and fault geometry. Su et al. (2022) utilize geomorphological methods to reveal the activity of the Qinghai Nanshan blind thrust. This study suggests that secondary faulting within the northeastern Tibetan Plateau may play a key role in regulating Cenozoic regional crustal deformation.

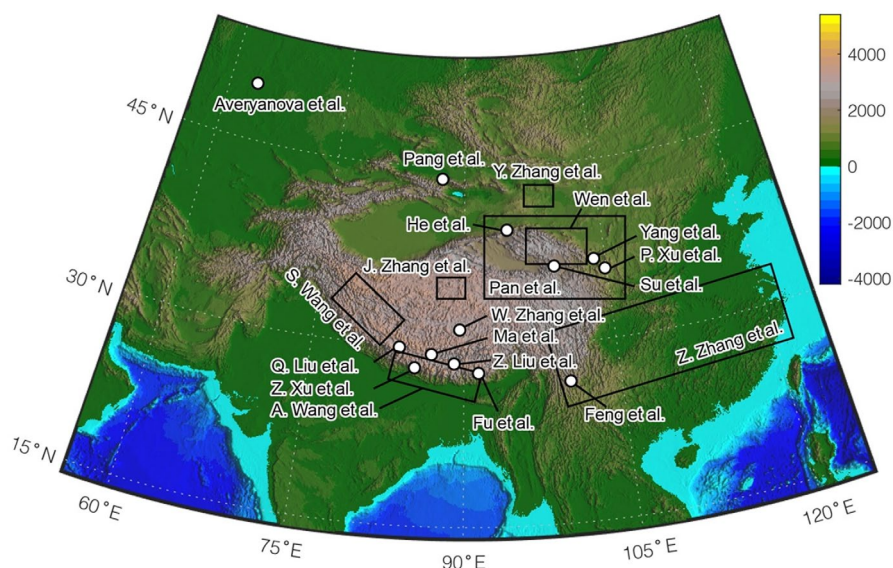
3. The Tianshan is located >2000 km away from Indus–Tsangpo suture zone where the Indian and Asian continents first collided, but it has accommodated a substantial portion of India–Asia convergence. By applying optically stimulated luminescence (OSL) dating to offset geomorphic features, Pang et al. (2021) map a lateral variation in the late Quaternary folding and thrusting of the Banfanggou fault (BF) in the southern Chaiwopu Basin, northern margin of Chinese Tian Shan foreland. The study bears societal implications, by providing estimates of relatively high seismic risk in the southern Chaiwopu Basin.

2.3 | Exhumation and topographic evolution

Topographic construction results from the competition between rock uplift driven by deep processes and removal by surficial erosional processes that are regulated by vegetation and climate (paths 1, 6 and 10 in Figure 2). Topographic changes feedback by changing gravitational potential, relief, the position of drainage divides, etc. (paths 2 and 5 in Figure 2). There are five contributions in this issue under the sub-category of exhumation and topographic evolution that reveal the exhumation history and their controlling factors, such as far-field collisional effects and underthrusting.

1. Two papers discuss early Cenozoic exhumation across the Tibetan Plateau, which highlights the far-field effects of the India–Asia collision. At the northeastern margin, He et al. (2020) use detrital apatite fission track analysis to constrain the early Cenozoic

FIGURE 1 Digital elevation model (DEM) of the Tibetan plateau and surrounding regions, on which locations of publications of this special issue are compiled



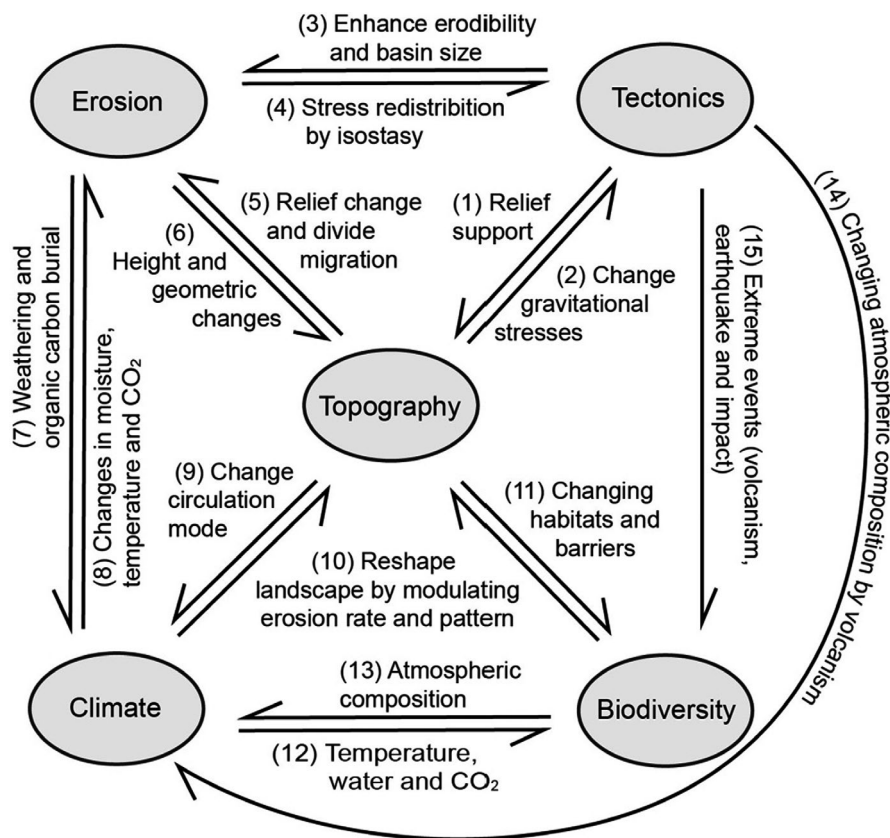


FIGURE 2 Interactions among tectonics, erosion, topography, climate and biodiversity. Potential interactions are listed on the arrows. Several of these interactive paths are showcased in the papers of this special virtual issue

exhumation history at 60–50 Ma, which is coeval to the India–Asia collision. In another fission track analysis study in North-Central Tibetan Plateau, Zhang, Li, et al. (2021) show the evidence supporting the construction of high topography in the Qiangtang during the Eocene–Oligocene. Additionally, the study also reveals an early stage of rapid cooling in the early Cretaceous, which supports models of a relict pre-Cenozoic thickened crust.

- Two papers discuss the role of underthrusting in controlling exhumation and topography. Using apatite and zircon U–Th/He thermochronology, Ma et al. (2021) reconstruct the spatial and temporal exhumation history in the Xigaze arc—a feature that relates to the closure of the Neo-Tethys and the subsequent India–Asia collision. They find a younging trend in exhumation and relate it to the underthrusting of the Indian plate, supporting a tectonic control on surficial processes (paths 1 and 3 in Figure 2). The other contribution by Wang, Wang, et al. (2021) uses an integrated approach by analysing bedrock channels and valley hillslopes in the Himalayas with a process-based model. Their study offers an example of the close relationship between active tectonics, extreme climate and surficial denudation.

3 | SEDIMENTARY SYSTEM: FROM SOURCE TO SINK, CLIMATIC FACTORS, RIVER INCISION

Sedimentary rocks archive histories of mountain uplift, interactions with the climate and factors influencing the potential of accretion (An

et al., 2001; Whipple, 2009; Zhang et al., 2001). Four contributions that we collected under category III (Sedimentary system: from source to sink, climatic factor and river incision) characterize the production, transport, preservation and factors controlling the sediment archive.

- The evolution of Yangtze River has been the subject of much debate focusing on the timing and mode of connection of its upper and lower courses (e.g. Sun et al., 2021; Zheng et al., 2020 and references therein). Feng et al. (2021) perform a provenance study using detrital zircon U–Pb analysis in the Jianchuan Basin and show that the sediment sources of the Jianchuan changed from a remote source via the upper Yangtze to a local source at late Eocene time (prior to ~36 Ma), which is consistent with lithology changes. They further infer that this late Eocene drainage change was one of the responses to coeval topographic uplift in the southeastern Tibetan Plateau. Along the upper, middle and lower courses of the Yangtze River, Zhang, Daly, et al. (2021) use lead (Pb) isotopic analysis on potassium feldspar crystals to address the debate concerning the relative contribution to sediment production from the steep, tectonically active highlands or the gently sloping lowlands. They find that sediments in the Yangtze trunk are mostly sourced from the upper Yangtze tributaries draining the southeastern Tibetan Plateau, highlighting the dominant role of the tectonically active highlands in sediment production.
- Chemical and physical weathering have long been recognized as a key mechanism that regulates the climate by impacting the global carbon cycle through organic carbon burial and weathering processes that either consume or release CO₂, depending on the

composition of the parent rock (path 7 in Figure 2). The Tibetan Plateau contributes heavily to chemical weathering and was argued to initiated the prologue of Cenozoic global cooling (Raymo & Ruddiman, 1992; Ruddiman et al., 1997; Zachos et al., 2001). Yang et al. (2021) use geochemical tracer of the Th/Sc ratio to study the production and transport of aeolian sediments in central Asia and contribute to the topic of weathering by investigating the relation between uplift of the Tianshan–Altay and Qilian Shan and the production of aeolian sediments.

3. Tectonic uplift, river incision and climatic variations are often intertwined and their relative importance in driving the geomorphic evolution of the plateau and its margins remain difficult to appreciate (see the interactions among tectonics erosion, climate and topography in Figure 2). By dating terrace sediments by optically stimulated luminescence (OSL), Wen et al. (2022) report results from a case study in the Liyuan He (Liyuan River) in the Northeast Tibetan Plateau, investigating the competing role of climate vs. tectonic uplift in shaping the Plateau.

4 | CLIMATIC AND BIOSPHERIC INFLUENCE OF THE TIBETAN PLATEAU

The past few years have witnessed an increase in the quantity, quality and diversity of observations and significant advances in our understanding of the evolution of the biosphere and its relation to the Tibetan Plateau uplift and incision (Barbolini et al., 2021; Spicer et al., 2020; Xing & Ree, 2017). Rapidly evolving topography and climate have greatly influenced the biosphere (Rahbek et al., 2019) (paths 11 and 12 in Figure 2), inducing, for example, the rich biodiversity characterizing the southeastern Tibetan Plateau (Xing & Ree, 2017). In this special issue, a contribution focuses on the evolution of vegetation in central Asian. Averyanova et al. (2021) present an early Oligocene palaeobotanical dataset from Kazakhstan, confirming the climatic and biospheric effects of the closure of the Paratethys and the uplift of the Tibetan Plateau and suggesting a cooler climate with enhanced seasonality in precipitation and temperatures.

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DATA AVAILABILITY STATEMENT

The data used in the article are available at the cited sources.

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