# Dynamic processes at the ends of collisional mountain chains

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**Understanding of the relationships between tectonic deformation and exhumation in the Himalaya remains incomplete, especially at the ends of the chain.**

The highest, most dramatic mountain systems on Earth developed through collisions between tectonic plates. These systems, or orogens, also feature our planet's highest rates of bedrock exhumation through processes ranging from fluvial and glacial erosion to normal faulting. A major topic of earth science research over the past 25 years has been how the tectonic processes that build mountains and the erosional and extensional processes that tear them down interact to shape the evolution of orogenic systems.

The cores of orogenic systems include large tracts of rocks metamorphosed at great depth (tens to over 100 kilometers) exhumed to the surface where we see them today. Only two earth processes can accomplish this exhumation: normal faulting and erosion. Erosion by flowing water or glacial ice is an especially efficient agent of exhumation in regions of high precipitation and high topographic relief. Normal faults that cut downward to middle and lower levels of Earth's crust can also strip overlying upper crust from the footwalls of these structures, a process referred to here as tectonic exhumation (*1*). Most deeply rooted normal faults responsible for major bedrock exhumation are found in extensional landscapes like the Basin and Range Province of North America, but such structures are also well documented in the Himalayan orogenic system (*2*). Built by the ongoing collision between the Indian and Eurasian plates, which began more than 50 million years ago, the Himalayan system stretches over 2500 km in a great arc from the Nanga Parbat in Pakistan (8126 m) to Namche Barwa (7782 m) in eastern Tibet. The Himalayan ranges are among the best places to study the relative importance of tectonic and erosional exhumation on mountain system evolution because they display abundant evidence that both processes have been highly influential over at least the past 25 million years.

In a recent *Science Advances* paper (*3*), Guevara *et al.* address the relative importance of tectonics and erosion in creating Himalayan landscapes. Their findings are based on metamorphic and igneous rocks from the deeply and rapidly exhumed core of the Nanga Parbat massif. Both Nanga Parbat and Namche Barwa coincide spatially with tight structural bends at either end of the Himalaya. These bends—referred to as orogenic syntaxes—mark the edges of the Indian plate as it collides with Asia. Compared to the rest of the Himalaya, the syntaxes are structurally complex, featuring broad, concave-upward (antiformal) structures surrounded on three sides by an array of steeply dipping thrust, normal, and strike-slip faults (*4*).

The syntaxes also feature some of the greatest topographic relief on Earth. For example, Nanga Parbat stands 7 km above the adjacent Indus River valley. Erosion rates now and in the recent past are extremely high at the syntaxes, more so than elsewhere along the Himalayan chain. This combination of rapid rock uplift, surface uplift, and bedrock exhumation is concentrated over a narrow geographic region around both Nanga Parbat and Namche Barwa. Similarities between the syntaxes suggest a common geologic origin, but there is a remarkable lack of consensus in the geoscience community about what that origin might be. Members of the community favor either that (i) the syntaxes developed largely as a consequence of the tectonic forces responsible for the complex fold and fault structures associated with them or (ii) development of the syntaxes was driven by the intertwined effects of tectonic deformation and extreme glacial and fluvial erosion spatially focused in the area of the two massifs.

Guevara *et al.* present models based on new geochronologic and petrologic data, leading them to conclude that rocks at Nanga Parbat experienced an extremely rapid (9 to 13 mm/year) pulse of exhumation over the past million years after fast but somewhat less extreme exhumation (2 to 5 mm/year) over the preceding several million years. The authors interpret the very rapid, localized, and recent exhumation event as structurally controlled and related either to a stiffening and tight flexure of the Indian plate at the syntaxis (*5*) or to lateral influx of hotter, more buoyant material from below associated with orogen-parallel crustal flow (*6*). Noting that their findings are remarkably similar to previous findings by others for the Namche Barwa syntaxis [e.g., (*7*)], Guevara *et al.*—like previous researchers—argue for a similar interpretation of that feature.

Although tectonic forces must have played an important role in the uplift of rocks found within the core of the Nanga Parbat syntaxis as Guevara and colleagues infer, neither flexural bending nor crustal flow would have directly resulted in exhumation of the rocks they studied. Some combination of erosional or tectonic exhumation would have been required. It is possible that surface relief resulting from flexural bending or crustal flow triggered sufficiently rapid erosion alone to expose the syntaxis core. Normal faulting may also have played a major role; at least one normal fault is among the structures that frame the syntaxis (*4*, *8*), and its geometry is such that slip on it would have brought rocks in the core nearer to the surface.

Regardless of the exact mechanisms, an outstanding question is how closely intertwined erosional and tectonic processes have been during syntaxis development. To some researchers, the syntaxes can be

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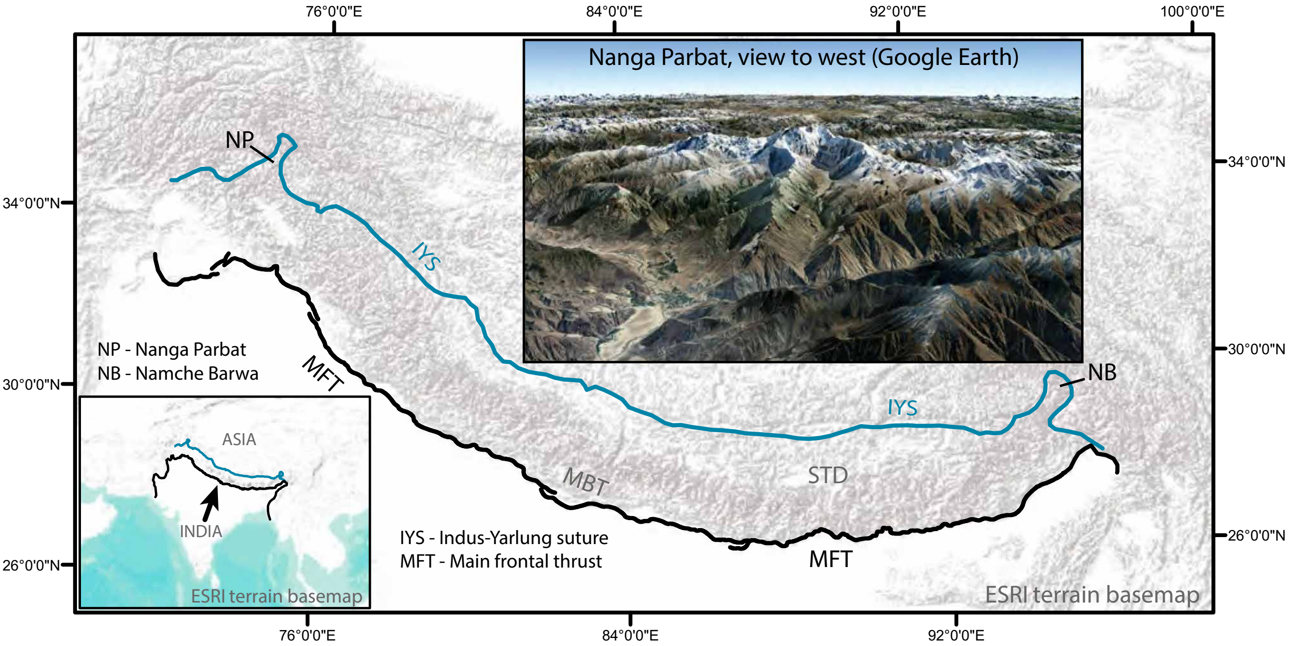


**Fig. 1. Shaded relief map of the Himalayan region showing the locations of Nanga Parbat and Namche Barwa.** The Himalayan orogenic system is bound to the north and south by the Indus-Yarlung suture and Main Frontal thrust. Insets show the Himalaya in the context of South Asia and a perspective view of Nanga Parbat from Google Earth (accessed July 2022). Credit: K.X. Whipple, ESRI basemap, Google Earth rendered image (Maxar Technologies CNES/Airbus)

thought of as "tectonic aneurysms," where tectonics and climatically driven erosion are closely connected through an intricate feedback loop as shown by Koons and colleagues (*9*), implying that development of the architecture we see today requires important contributions from both with continuous coordination between them. Others, like Guevara *et al.* and Wang *et al.* (*10*), have argued that tectonic forces alone are responsible for rapid rock uplift, with little or no coupling to climate and erosion. Fully evaluating these competing perspectives will require further research aimed at careful and precise reconstruction of the tempo of both faulting and erosion at Nanga Parbat and Namche Barwa over the past million years.

Another larger-scale question is why, though the syntaxes are 2000 km apart geographically, are their recent structural and erosional histories similar but distinctive from the rest of the orogenic system? Is it plausible that these similarities are evidence of large-scale geologic teleconnections in orogenic systems? These teleconnections would be similar to the atmospheric teleconnections that help us understand how Earth's climate works. And, if so, how might geologic and atmospheric teleconnections influence one another? Such questions argue for the importance of coordinated, interdisciplinary study of orogenic systems as a central element of earth system science.

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10.1126/sciadv.ade6607