

Climate and the evolution of Mountains

*New studies of the Himalaya
and the Tibetan Plateau
suggest a deep relation between
climate and tectonics*
By Kip Hodges

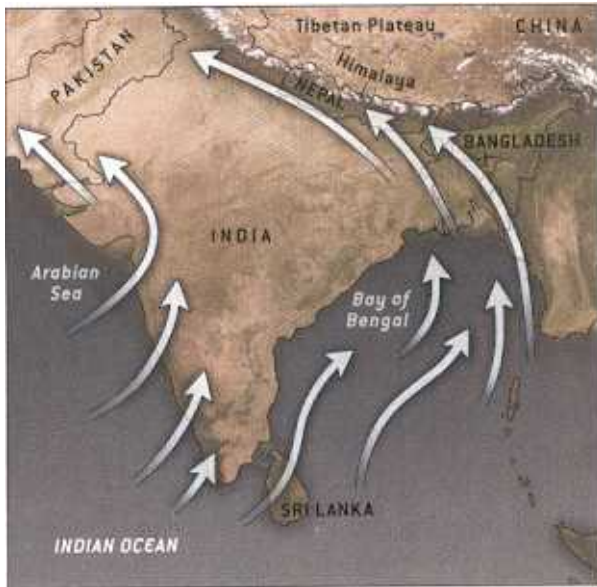
Six years ago I learned an important lesson about mountains and weather—from a farmer's horse. I was studying the geology of the ancient Kingdom of Mustang, now part of Nepal. Mustang lies high on the edge of the Tibetan Plateau, at the headwaters of the remarkable Kali Gandaki River, which carves a deep valley between the 8,000-meter-high peaks of Annapurna I and Dhaulagiri as it descends south to the Himalayan foothills. The farmer told me that the horse was perfectly good anytime for riding around on the plateau. But he mysteriously warned that if I were riding into the valley the horse would be good only in the morning.

I didn't understand his meaning until just after noon, when in a narrow part of the valley the horse and I found ourselves facing into a gale-force wind that seemed to come out of nowhere. As the winds intensified, the horse went slower and slower until it finally stopped, shook its head and turned around. No amount of prodding would get it to head into the wind with me on its back. As I dismounted and dragged it to the valley by its bridle, the thought occurred to me that this horse might know more about the weather patterns of the Himalaya than I did.

The winds of the Kali Gandaki Valley—some of the strongest upvalley winds on the planet, regularly reaching speeds of a steady 20 meters per second (just under 45 miles per hour)—are almost a daily occurrence. Air in the valley heats up after sunrise and rolls up from the valley as the day progresses. The predictable Kali Gandaki winds are just a local example of how climate can be affected by mountainous topography.

In turn, climate significantly influences the shape of the earth's surface. Wind, cold, heat, rain and ice all act as sculptors, and geologists have long studied the





MOIST AIR CURRENTS (white arrows) from the Indian Ocean drive the annual monsoons that occur during summer in India. When air masses tracking farther to the east flow over the Bay of Bengal, they pick up additional moisture, causing tropical depressions to form. Unable to climb high enough to pass over the Himalaya, the storms pound the land in their path; in places, as much rain falls as in a full year in the Amazon rain forest.

relation between climate and surface topography. But new research points to an unexpected, literally deep relation between climate and the evolution of mountain systems. Nowhere is this link better illustrated than in the intimate connection between the Indian monsoon and the continuing evolution of the Himalaya.

Monsoon Machinations

ONE OF THE MOST dramatic weather phenomena on earth, the annual Indian monsoon arises because springtime air temperatures rise rapidly over the Indian subcontinent but more slowly over the Indian Ocean. As a consequence, south-

westerly winds bring a landward flow of moisture. Near Sri Lanka, some of the moisture-laden air begins to track northward across southern and western India while some heads eastward into the Bay of Bengal [see illustration above].

The eastward-tracking air mass picks up additional moisture from the bay, promoting the formation of a series of tropical depressions off the northeast coast of the subcontinent. These storms— attracted by a low-pressure trough that develops in northern India, along the southern flank of the mountains—race northward across Bangladesh and India. Finally, they strike the Himalaya.

The storms are then deflected west-

ward, bringing on a monsoon season that begins in early June in northeastern India and Bangladesh, mid-June in Nepal, and late June in western India. Convection cells of moisture-laden air continually rise, like the hotter soup at the bottom of a pot bubbling to the surface, in a vain attempt to breach the wall of the Himalaya. As the air rises in these cells, the moisture condenses, resulting in torrential rain.

Meteorological stations in the Himalaya typically measure meters of rainfall every monsoon season (which can exceed the annual totals in much of the Amazon rain forest), concentrated in the Himalayan foothills at elevations between about 1,000 and 3,500 meters. Little precipitation makes it over the crests of the Himalayan ranges and onto the Tibetan Plateau, and so the climatic contrast across the Himalaya is extreme. In some regions, a traveler can pass from tropical forests, through rugged alpine terrain, and into high-altitude desert in less than 200 kilometers.

Obviously, the Himalaya, standing guard on the Tibetan Plateau, influence regional climate. But it turns out that climate can affect what goes on deep underneath the surface. How is such an effect possible? The answer has emerged from taking the understanding of how mountain ranges are built and adding new insights into how they interact with their surroundings. This synthesis builds on extensive research into several different geologic forces that control the formation and continual reshaping of mountains.

Mountain Building 101

THE TIBETAN PLATEAU and the Himalayan ranges are collectively known to earth scientists as the Himalayan-Tibetan orogenic system (after *oros*, Greek for “mountain,” and *genic*, meaning “producing”). This region includes the 100 tallest mountains on the planet. The plateau, which is roughly equivalent in surface area to the Iberian Peninsula, has an average elevation higher than all but eight of the mountains found in the U.S. and Canada.

The theory of plate tectonics gives a

Overview/Climate's Deep Impact

- Although the power of climate to sculpt the earth's surface has long been recognized, new research shows that climate may also influence geologic activity deep underground and play a role in the deformational history of mountain systems.
- An example of the climate-geology relation can be found in the feedback mechanism between the Himalaya and the annual Indian monsoon. Heavy rains erode the south flank of the Himalaya. And the erosion, recent evidence suggests, may cause a slow, steady flow of deep crustal material from underneath the southern Tibetan Plateau to the range front, rebuilding it, to more efficiently intercept the monsoon.
- Rapid and recent uplift of the terrain that receives the rains supports the idea of the flow of deep crustal material to the range front. Evidence for such uplift includes geodetic data as well as unusually steep topography and stream channels across the range front. High erosion rates, verified by thermochronologic studies, also support this scenario.

partial explanation of how these landforms arose. The earth's great mountain ranges mark regions where sections of the broken, rigid outer skin of the planet, known as lithospheric plates, are currently colliding or have done so in the past. The Himalaya were born when the Indian plate, drifting northward from the Mesozoic supercontinent of Gondwana, slammed into the Eurasian plate about 45 million years ago. A freight train or oil tanker may require many minutes to stop once the brakes are applied—the inertia of the Indian plate was so great that even today it continues to converge with the Eurasian plate at a rate of about four centimeters a year.

The advancing Indian plate, acting as what physicists would call a rigid indenter, has continually forced part of the Eurasian lithosphere out of its way. As Paul Tapponnier and Peter Molnar suggested in the 1970s when they were at the Massachusetts Institute of Technology, the indenter has apparently pushed relatively rigid blocks of lithosphere, separated from one another by curved faults, eastward toward Southeast Asia [see “The Collision between India and Eurasia,” by P. Molnar and P. Tapponnier; *SCIENTIFIC AMERICAN*, April 1977].

Another consequence of plate collision was shortening and thickening of the earth's crust (the top layer of the lithosphere). The average thickness of continental crust is about 30 kilometers. At mountain ranges, however, the crust can be much thicker. And the Himalayan-Tibetan orogenic system boasts the thickest crust on the planet—more than 70 kilometers in some places. The correlation between the thickest crust and the highest mountains is a manifestation of Archimedes' principle—an object immersed in a fluid is buoyed up by a force equivalent to the weight of the fluid it displaces. Just as a thick iceberg floats higher than a thinner iceberg because it displaces more of the denser seawater, a region of anomalously thick crust, such as the Himalayan-Tibetan orogenic system, “floats” higher in the underlying, denser mantle than do adjacent regions with thinner crust.

Energy Flow and Mountain Building

CRASHING PLATES help to explain the genesis of mountain ranges. But other processes, involving energy transfer, also influence mountain evolution. The great insight—and surprise—of the past few years is that monsoon rainfall appears to influence the way that energy transfer takes place at depth within the Himalayan-Tibetan system.

From the perspective of basic physics, an orogenic system is a storehouse of energy, akin to a reservoir behind a hydroelectric power plant. By impeding the flow of a river, a hydroelectric dam converts kinetic energy into gravitational potential energy stored in the form of a deep lake. Because of the elevation of the lake's surface compared with the river level downstream, a major difference in potential energy exists across a dam. Given the chance, the reservoir will rapidly dissipate its excess potential energy in an attempt to reestablish equi-

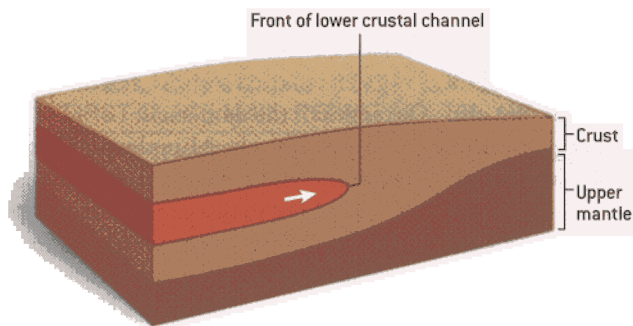
librium with its surroundings—it will burst the dam. The only thing preventing this catastrophic action is the strength of the dam itself.

Similarly, the Himalayan-Tibetan orogenic system has a natural tendency to spread out to dissipate the excess potential energy it has by virtue of the difference between its crust thickness and that of the adjacent lowlands.

The rigid upper crust, broken into blocks by large faults, flows like sand. At deeper levels of the crust, where temperatures and pressures are much higher, the rock instead flows like toothpaste being squeezed through a tube. Theoretical models and field observations show that such deep crustal fluid channels may persist for millions of years. And given the opportunity to dissipate potential energy, these channels will slowly spread. Recent work by my M.I.T. colleagues Marin Clark and Leigh Royden supports the idea that the gentle, steady decline in elevation from the Ti-



MONSOONS' EFFECTS on the surface are clearly visible in this satellite image of the Indian subcontinent. South of the Himalaya, the torrential rains promote the growth of vegetation, giving the area its green hue. North of the wall of mountains that intercepts the monsoon, the Tibetan plateau is relatively dry. White areas are snow-covered.



LATERAL FLOW of fluid lower crustal material underneath Tibet is theorized by some geologists. The flow would dissipate excess gravitational potential energy in the plateau region.

betan Plateau to the southeast was caused by outward flow of Tibetan lower crust [see illustration below] far under the eastern margin of the plateau.

In an exciting recent development, however, evidence has been found that suggests that the lower crust underneath Tibet is also flowing southward, directly toward the Himalayan mountain front. To begin to understand why, remember that water in a reservoir naturally flows preferentially to any crack in the dam. Similarly, the lower crustal channel might be expected to flow most readily in the direction of least resistance, toward the Himalayan range front, where surface erosion—driven by monsoon rainfall—is most active.

This crustal flow serves as a linchpin for emerging theories about the monsoon-mountain relation. As the rains relentlessly drive erosion along the Himalayan range front, the southern margin of the Tibetan Plateau should migrate northward. Instead, evidence suggests, the material removed by erosion is replenished by material in the lower crustal channel flowing southward and toward the surface. And to close the feedback loop, the erosion of the range front is what attracts the channel toward the surface in the first place.

Dissecting the Flow

THIS INTERPRETATION has its roots in the study of major faults in the Himalaya. Most major faults in mountainous regions are thrust faults, the kind that typically develop during plate collisions. Those of us who have shoveled away New England snowstorms are all too familiar with thrust fault features: the shingled sheets of crusty snow that build up in front of our shovels are separated

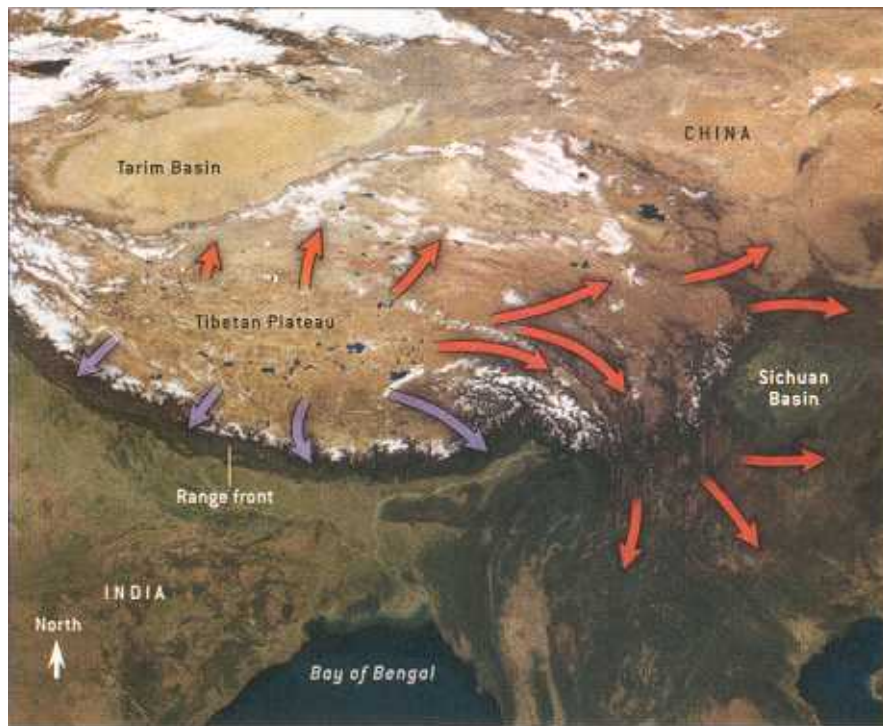
by fractures analogous to thrust faults. North-south vertical cross sections through the Himalaya show an architecture that is dominated by the Main Central, the Main Boundary and the Main Frontal thrust fault systems, all of which merge at depth to become what is known as the Himalayan Sole (as in “bottom”) thrust [see illustration on opposite page]. Material above these faults is moving southward, carried by the conveyor belt of the thrust, relative to the material below.

Some 20 years ago, however, a research team at M.I.T. (I was a junior member then), along with investigators

from other institutions, identified a second type of fault system in the Himalaya, which radically changed our view of continent-continent collisional mountain building. Lying near the crest of the Himalayan ranges, the South Tibetan fault system is characterized by faults with geometries similar to those of the thrust faults but with an opposite “shear sense”: rocks above faults in this system have moved northward relative to the rocks below.

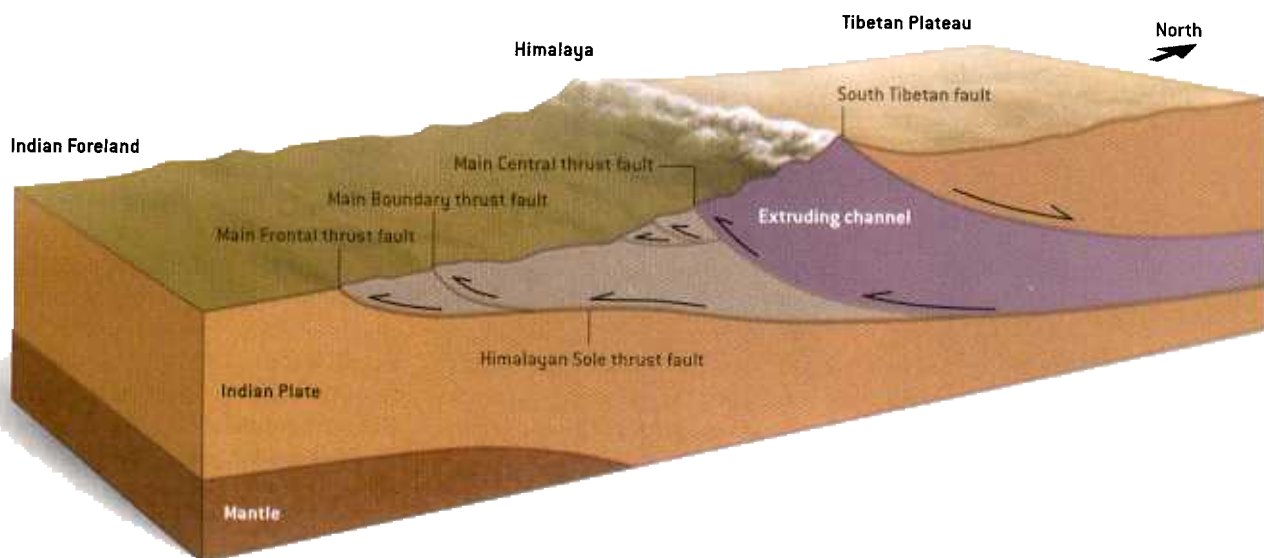
Such fault systems, which are known as detachment systems, are common in zones where the crust spreads and thins. Examples include mid-ocean ridges and the Basin and Range province of North America, which covers the area between the Colorado Plateau and the Sierra Nevada. But major detachment systems were not thought to occur in places where tectonic plates collide head-on until the South Tibetan system was discovered.

Attempts to incorporate the detachment system into the overall dynamics of the Himalayan-Tibetan orogenic sys-



FLOWING CHANNEL in many regions (indicated by orange arrows on the satellite image above) does not breach the surface but simply inflates the crust as it moves away from the plateau interior (as shown in cross-sectional diagram at top). But in regions where intense monsoon rainfall causes rapid erosion (indicated by purple arrows), the channel may be drawn to the surface (cross-sectional diagram on opposite page).

JEN CHRISTIANSEN; SOURCE: "A SYNTHESIS OF THE CHANNEL FLOW-EXTRUSION HYPOTHESIS AS DEVELOPED FOR THE HIMALAYAN-TIBETAN OROGENIC SYSTEM," BY K. V. HODGES, IN CHANNEL FLOW, DUCTILE EXTRUSION, AND EXPLANATION OF LOWER-MIDDLE CRUST IN CONTINENTAL COLLISION ZONES, EDITED BY R. L. LAW, M. SEARLE AND L. GODIN, GEOLOGICAL SOCIETY SPECIAL PUBLICATION, LONDON, [IN PRESS] [OP]; JEN CHRISTIANSEN; SOURCE: KIP HODGES; THE VISIBLE EARTH/NASA. (Bottom)



tem have led us to theorize that the flow of ductile lower crust continuously replenishes the range front of the Himalaya: material between the Main Frontal thrust and the South Tibetan fault system, especially the rocks above the Main Central thrust, moves southward relative to the material both above the South Tibetan fault system and below the Himalayan Sole thrust. This southward extruding zone is thought to represent the ductile lower crustal channel of Tibet as it grinds its way to the surface.

Evidence indicates that both the South Tibetan fault system and the Main Central thrust system were active during the Early Miocene epoch, between about 16 million and 22 million years ago. In the late 1980s my M.I.T. colleagues Clark Burchfiel and Leigh Royden and I proposed a simple model in which coordinated slip on these fault systems during the Early Miocene led to southward movement of the channel of rocks between the two fault systems. In our view, this process was driven by the pressure differential between the rising Tibetan Plateau and India.

Since then, several research teams have refined this so-called extrusion model. Djordje Grujic, then at the Swiss Federal Institute of Technology in Zurich, and his colleagues showed that strain patterns in rocks within and between the two fault systems were consis-

SHINGLING EFFECTS occur when tectonic plates collide and create thrust faults. Such shingling—the result of the India-Asia plate collision—has occurred in the Himalaya. Faults of a second type are found near the crest of the Himalaya, dipping northward below the Tibetan Plateau. Constituting what is known as the South Tibetan fault system, these faults share geometric similarities with the thrust faults, but rocks slip along this system in the opposite direction. This fault system may also mark the top of the fluid lower crustal channel below Tibet. New evidence suggests that northward slip along the South Tibetan fault system and simultaneous southward slip along the southern faults permit the southward extrusion of this channel toward the Himalayan range front. (Tan regions are moving north. Purple and gray regions are moving south.)

tent with ductile deformation, analogous to the flow of fluid in a pipe. And the late K. Douglas Nelson, then at Syracuse University, hypothesized that a fluid lower crust might have existed underneath Tibet as far back as the Early Miocene—and that the rock now exposed at the earth's surface between the South Tibetan and Main Central thrust systems may represent the ductile lower crustal channel that became more rigid as it reached the surface.

Most variants of the channel extrusion model [see illustration above] have focused on the Miocene evolution of the Himalayan-Tibetan system, but evi-

dence is mounting that the extrusion process is ongoing. Several research groups have used geologic chronometers—based on the radioactive decay of elements in minerals that crystallized during deformational events—to establish a better understanding of the movement histories of major Himalayan fault systems. The results show that faulting has occurred near or just south of the surface traces of the Main Central thrust and South Tibetan fault systems at various times over the past 20 million years. And the most recent deformation is extremely young, by geologic standards: my group's research indicates

THE AUTHOR

KIP HODGES investigates the development and evolution of mountain systems, integrating theoretical and laboratory methods with field studies. When he wrote this article, he had been a professor in the department of earth, atmospheric and planetary sciences at the Massachusetts Institute of Technology for 23 years. In July he became founding director of the new School of Earth and Space Exploration at Arizona State University (thus ending his snow shoveling experiments). He has an undergraduate degree in geology from the University of North Carolina at Chapel Hill and a Ph.D. in geology from M.I.T. Although much of his work has focused on the Himalaya and the Tibetan Plateau, he also has done tectonic research in Scandinavia, polar East Greenland, Ireland, the western U.S., Baja California and the Peruvian Andes. The North Carolina native is editor of *Tectonics* and is on the editorial board of *Contributions to Mineralogy and Petrology*. An avid recreational diver, Hodges spends as much time as possible below the waves, gaining new perspectives on our overwater world.

that structures that could have acted as boundaries of an extruding channel have been active in central Nepal in the past few thousand years. Extrusion of the channel may even be happening today.

Extrusion and Landscape Evolution

IF CHANNEL EXTRUSION has played an important part in remodeling the Himalaya, evidence for unusually rapid uplift of the earth's surface in the zone

between the surface traces of the fault systems should exist. Indeed, precise measurements made with traditional surveying equipment and Global Positioning System satellites over the past 30 years indicate that this zone is rising at a rate of a few millimeters a year relative to the region south of the surface trace of the Main Central thrust system.

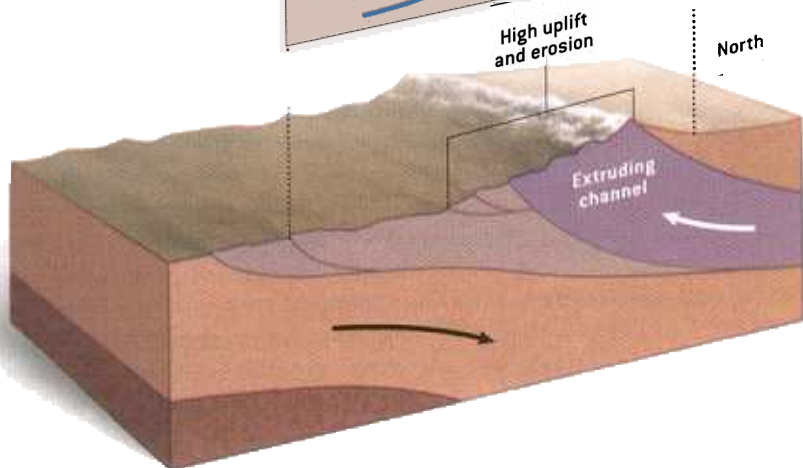
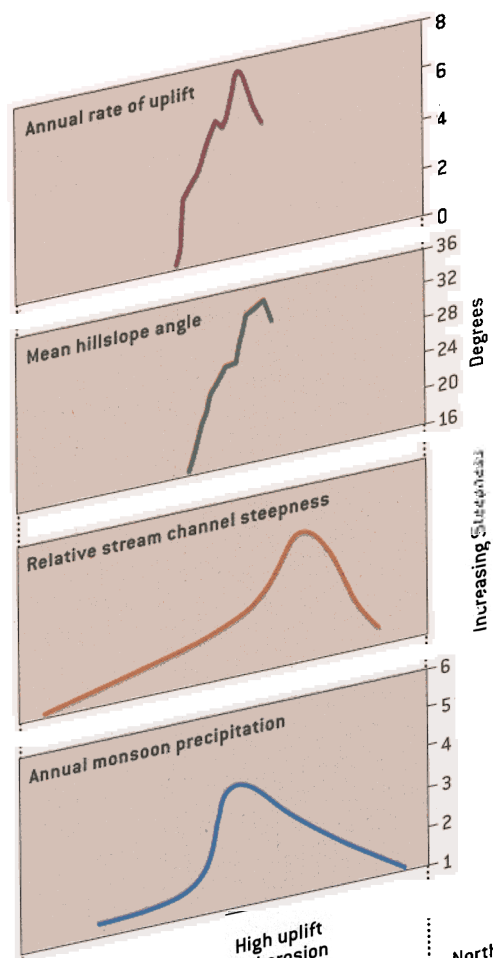
Additional evidence for rapid uplift comes from the landscape itself. In mountain systems, rapid uplift is usually correlated with high topographic

relief—a large change in elevation over a short horizontal distance—and steep river gradients. Stream profiles are in fact excessively steep across the Himalayan range front in Nepal where the streams cross the zone of proposed extrusion. Analysis of the topography across the front also shows unusually high relief there. But an important question is whether or not this phase of rapid uplift is simply a recent development over the past few decades or has persisted over geologic timescales.

We know that erosion occurs in response to the monsoon today. But various techniques can provide estimates of erosion rates over long periods. And by knowing the history of erosion of the range front, we can get a good sense of the pace of uplift. One of the most powerful methods of estimating erosion rates in orogenic systems is based on the natural production of what are known as cosmogenic nuclides (isotopes produced by cosmic rays) in surface rock exposures. The concentration of cosmogenic nuclides, such as beryllium 10 and aluminum 26, in surface samples is proportional to the elapsed time since exposure. My M.I.T. colleagues Cameron Wobus and Kelin Whipple and I, working with Arjun Heimsath of Dartmouth College, have used this technique in central Nepal to demonstrate a more than threefold increase in erosion rate in the zone of proposed extrusion relative to the region farther south over millennial timescales.

Different methods can be used to explore erosion patterns on even longer timescales. Most people are familiar with the isotopic "clocks" used to determine the age of geologic or biologic materials. (A favorite example is dating based on the isotope carbon 14.) But not all geologic chronometers measure the crystallization age of a rock sample. Some instead indicate the time when a rock that initially crystallized at a high temperature deep underground cooled through a narrow temperature range as erosion allowed the sample to reach the earth's surface. By applying such thermochronometers to samples collected from the Himalayan front in the Annapurna range of central Nepal, my col-

RAPID UPLIFT of the earth's surface between the Main Central thrust and the South Tibetan fault systems is supported by several lines of evidence, which are depicted in the top three graphs at the right. Each graph shows the south-north variations in characteristics of the region directly under the plot. The coincidence of a substantial increase in precipitation over the zone of unusually rapid uplift—and the zone between the Main Central thrust and South Tibetan fault systems—strongly implies a fundamental relation between local climate and deformation.

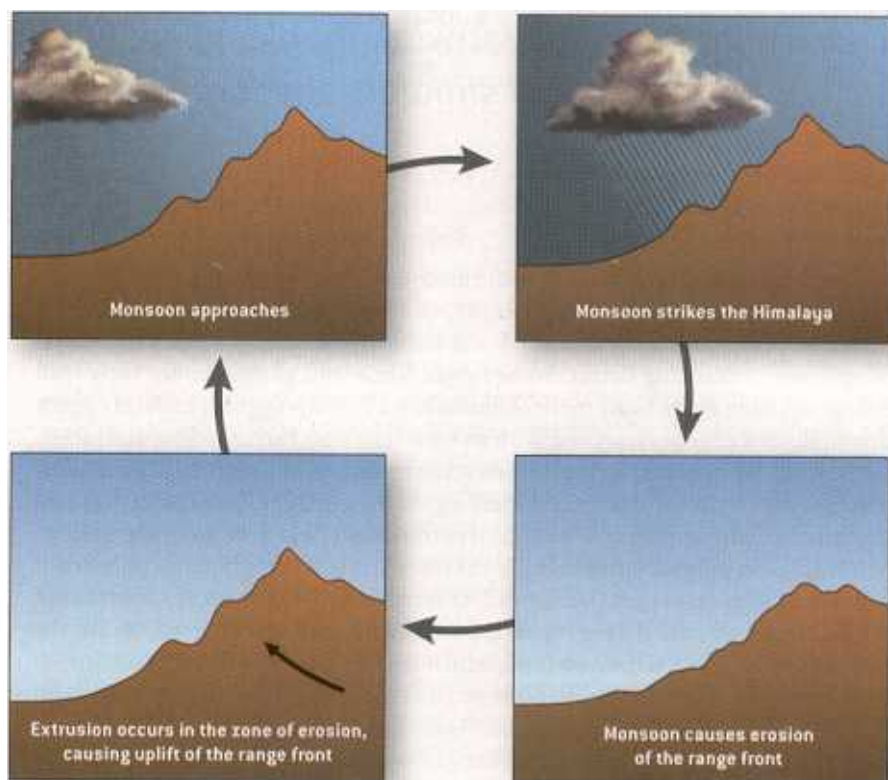


league Ann Blythe of the University of Southern California and my student Kate Huntington of M.I.T. have shown that erosion has increased in the zone of proposed extrusion for at least the past few million years. Collectively, the evidence from landscape studies, cosmogenic nuclides and thermochronometry supports the idea of rapid uplift sustained over very long periods.

Running water and flowing glacial ice are recognized as principal agents of physical erosion. Higher rates of precipitation, such as those associated with monsoons, would lead to higher rates of erosion along the Himalayan range front. If the proposed feedback loop between range front erosion and southward extrusion of the crustal channel is viable, we would expect the pattern of high monsoon precipitation to coincide with the pattern of sustained surface uplift. Several groups are defining these precipitation patterns using data collected from remote sensing satellites and networks of weather stations.

For example, Ana Barros of Duke University has been leading a multi-institutional study aimed at defining monsoon precipitation patterns in the Annapurna range since 1999. The results in fact indicate that monsoon rainfall is highest in the zone of rapid erosion and uplift defined by other studies. More important, the broad correspondence of the region of high monsoon precipitation to the zone of proposed extrusion is consistent with the hypothesis that the channel extrusion is caused by range-front erosion in response to the Indian monsoon. The extrusion activated by rapid erosion does indeed appear to build the wall that intercepts the monsoon on its northward trek. Intense rainfall along the front leads to the increased erosion that activates extrusion, thereby completing the loop.

Theoretical models confirm that such relations are to be expected in evolving orogenic systems. Chris Beaumont and his colleagues at Dalhousie University in Halifax, Nova Scotia, have been using such models to explore the possible impact of erosion on systems with mechanically weak lower crustal



FEEDBACK LOOP between monsoons and the Himalaya is shown here in simplified form. The summer monsoons track northward but are blocked by the ramparts of the Himalaya and drop enormous amounts of rain. The rain causes erosion, enabling the fluid lower crust of Tibet to extrude toward the range front. One effect of this extrusion is uplift, which counterbalances the tendency of rapid erosion to tear down the range front. By maintaining a steep range front, the extrusion process focuses monsoon rainfall, perpetuating the cycle.

channels. With a model constructed to represent the essential physics of the Himalayan-Tibetan system in the Miocene, they have shown that a weak lower crustal channel propagates (or “tunnels”) laterally in regions with low surface erosion but toward the surface in regions of high erosion—such as the modern Himalayan range front.

The existence of feedbacks between climatic and geologic deformational processes is a novel concept. Research-

ers who have been concerned only with their specific discipline—for example, tectonics—find themselves in a more exciting and more deeply interconnected world. Just as solid-earth scientists, atmospheric scientists and hydrologists are already joining forces in this effort, we should soon see the integration of biological studies into the “new” tectonics—if climate can influence the growth of mountain ranges, perhaps ecosystems can as well. ■

MORE TO EXPLORE

Himalayan Tectonics Explained by Extrusion of a Low-Viscosity Crustal Channel Coupled to Focused Surface Denudation. C. Beaumont et al. in *Nature*, Vol. 414, pages 738–742; December 13, 2001.

Southward Extrusion of Tibetan Crust and Its Effect on Himalayan Tectonics. K. V. Hodges et al. in *Tectonics*, Vol. 20, No. 6, pages 799–809; 2001.

Has Focused Denudation Sustained Active Thrusting at the Himalayan Topographic Front? Cameron W. Wobus et al. in *Geology*, Vol. 31, No. 10, pages 861–864; October 2003.

Monitoring the Monsoon in the Himalayas: Observations in Central Nepal, June 2001. Ana P. Barros and Timothy J. Lang in *Monthly Weather Review*, Vol. 131, No. 7, pages 1408–1427; 2003.

Quaternary Deformation, River Steepening, and Heavy Precipitation at the Front of the Higher Himalayan Ranges. Kip V. Hodges et al. in *Earth and Planetary Science Letters*, Vol. 220, pages 379–389; 2004.