[Note to KVH: what specifically were you studying there?]

Six years ago I learned an important lesson about mountains and weather—from a 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. I had hired the horse from a local farmer to make a fast trip down into the valley. 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 discounted the warning and was attempting to get to the river valley on the horse when fierce winds started to develop. 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 back 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.

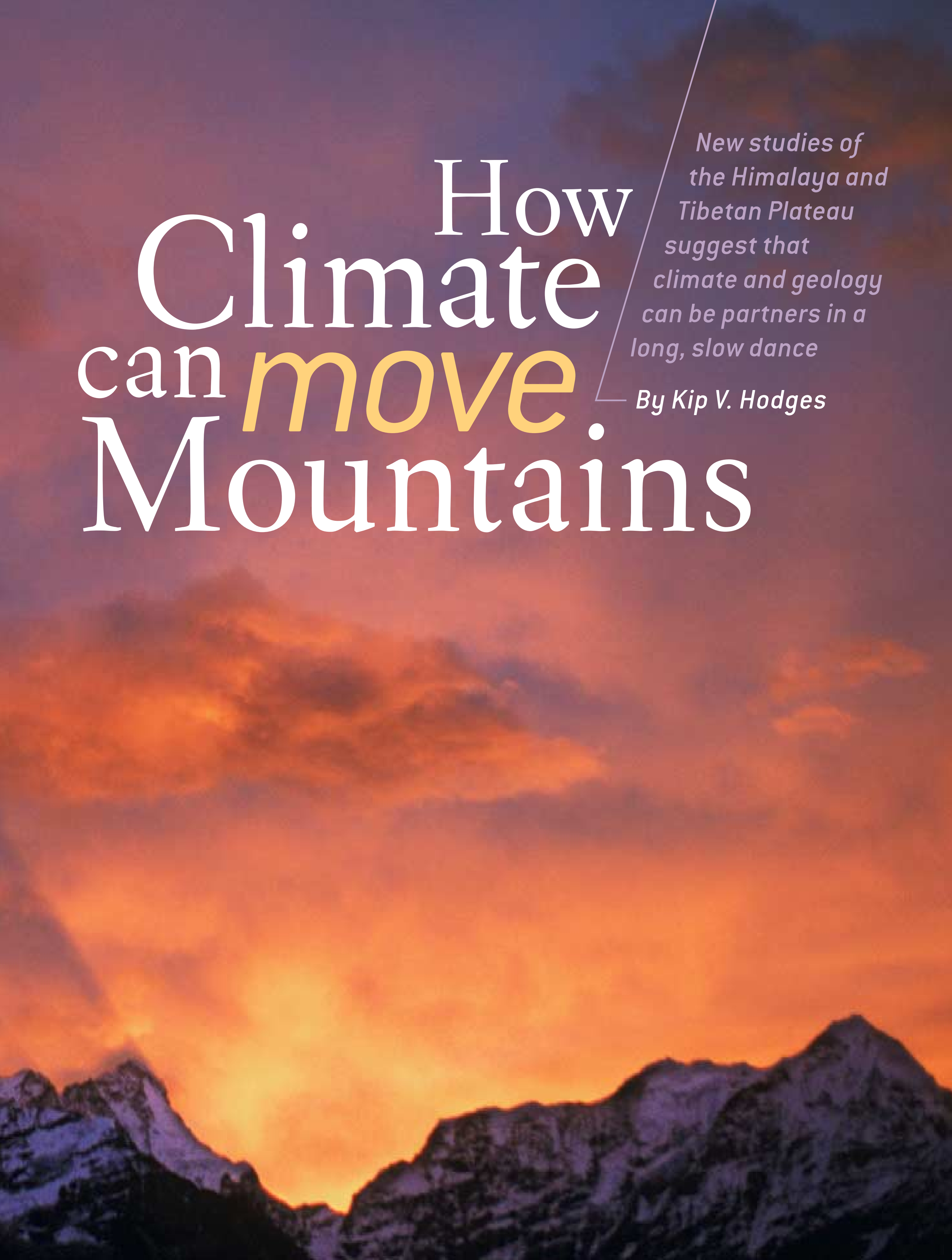
I soon discovered that the winds of the Kali Gandaki Valley—some of the strongest upvalley winds on the planet, regularly reaching speeds of a steady 20 meters per second (just under 45 miles per hour)—are almost a daily occurrence. Air in the valley heats up after sunrise and rolls up from the valley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

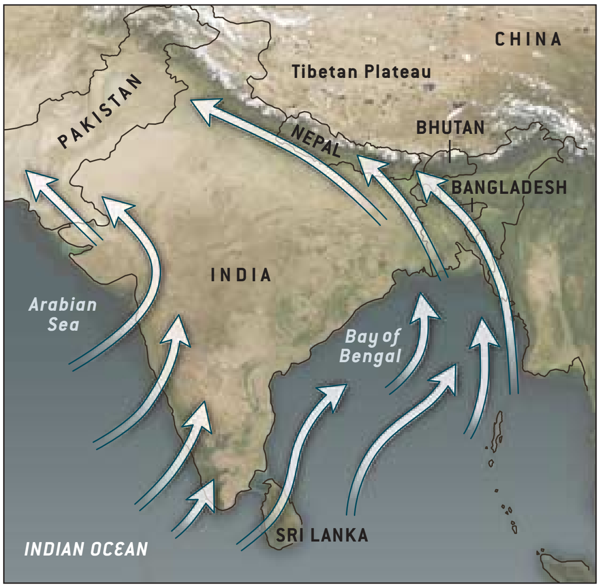
THE HIMALAYA at sunrise

How Climate can *move* Mountains

New studies of the Himalaya and Tibetan Plateau suggest that climate and geology can be partners in a long, slow dance

By Kip V. Hodges





AIR CURRENTS (*white arrows*) passing over the Bay of Bengal drive the annual monsoons that occur during summer in India. When already wet ocean air flows over the bay, the air picks up additional moisture, causing tropical depressions to form. Unable to climb high enough to pass over the Himalaya Mountains, the storms pound the land in their path with as much rain as falls in a full year in the Amazon rain forest.

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 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, southwesterly 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 into the Bay of Bengal, to India's east [*see illustration above*].

The Bengal 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 just north of India, along the southern flank of the mountains—are then pushed a bit north by the Coriolis effect of the rotating earth and race northwestward across Bangladesh and India. Finally, they hit the Himalaya.

The storms move westward, with the monsoon season thus beginning 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 still more torrential rain.

Meteorological stations in the Himalaya typically measure meters of rainfall every monsoon season (which can equal the annual totals in the Amazon rain forest), most concentrated in the Himalayan foothills at elevations between about 1000 and 3500 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 subsequent, continual reshaping of mountains.

Overview/*Evolution of Mountains*

- 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 internal evolution of mountain systems.
- An example of the climate-geology relation can be found in the feedback mechanism of the Himalaya mountain range and the annual Indian monsoon. The heavy rains erode the south wall of the Himalaya, which, recent evidence indicates, sets up a slow, steady flow of fresh crustal material to the wall, rebuilding it and thus continually intercepting the monsoon.
- Rapid and recent uplift of the land that receives the rains supports the idea of the flow of internal material to the wall face. Evidence for such uplift includes satellite data, unusually steep topography and stream channels. High erosion rates, verified by isotope analysis and temperature histories, also support this uplift scenario.

Mountain Building 101

THE TIBETAN PLATEAU and the Himalayan ranges are collectively known to earth scientists as the Himalayan-Tibetan orogenic system, or orogen (after *oros*, Greek for "mountain," and *genic*, meaning "producing"). This region includes the top 100 tallest mountains on the planet. The plateau, which is roughly equivalent in surface area to the Ibe-

CREDIT (*preceding pages*); CREDIT (*top*) rian Peninsula, has a higher average elevation than all but eight mountains in the U.S. and Canada.

The theory of plate tectonics gives a partial explanation of how these land forms 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 Tapponier 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 the plate collisions was the shortening and thickening of the earth's crust (the rigid top layer of the lithosphere)—think of the front end of a car after a crash. The average thickness of continental crust is about 30 kilometers. At mountain ranges, however, the crust can be much thicker. And the Himalayan-Tibetan orogen boasts the thickest crust on the planet—more than 70 kilometers in some places. The correlation between the thickest crust and the highest mountains on the planet 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 orogen, "floats" higher in the underlying, denser mantle than do adjacent regions with thinner crust.

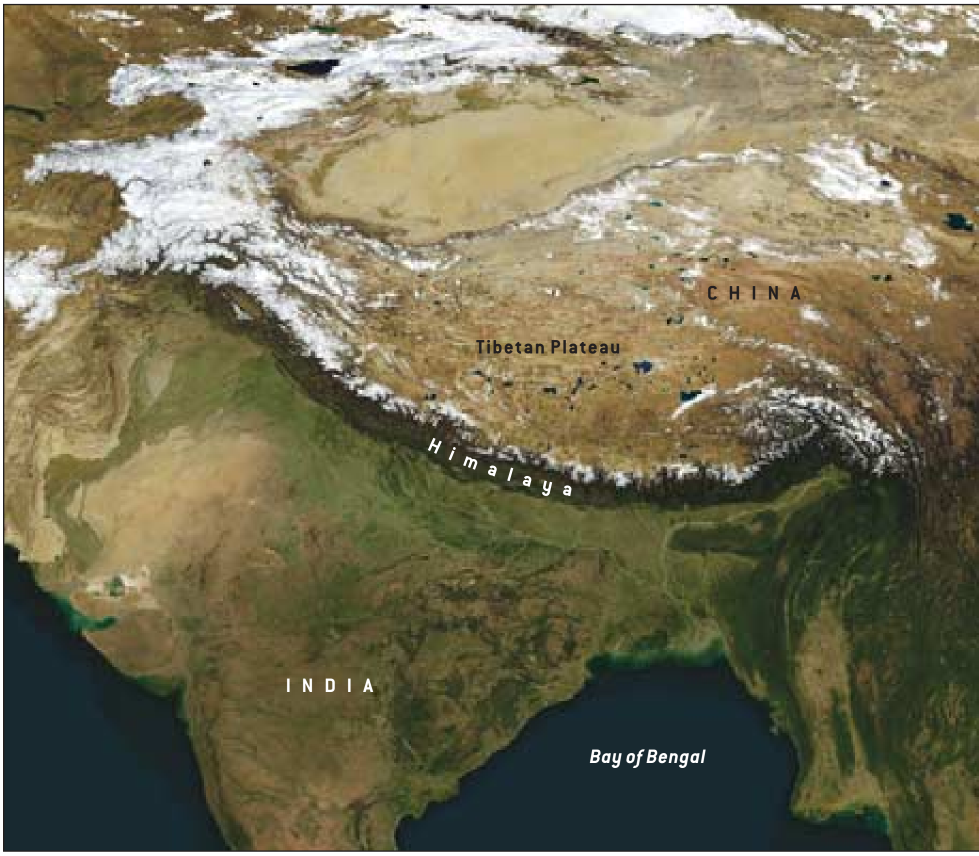
Energy Flow and Mountain Building

CRASHING PLATES help to explain the genesis of mountain ranges. But other processes, involving energy transfer, also influence the mountains over time. The great insight—and surprise—of the past few years is that monsoons, which arise because wet air masses are blocked by the mountains, in turn influence the energy flow deep below the surface. The rains thus continually shape the mountains—not only from above but also from within.

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 potential energy in an attempt to reestablish equilibrium 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 potential energy it has by virtue of the difference between its crust thickness and that of the adjacent lowlands.

The crust may flow like sand, with large blocks acting like sand grains. In addition, some regions of rock deep under the mountains can be pressure-cooked to high temperatures. The crust may thus actually begin to behave like tooth-



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 the green hue. North of the wall of mountains that intercepts the monsoon, the Tibetan plateau is dry. White areas are snow-covered.

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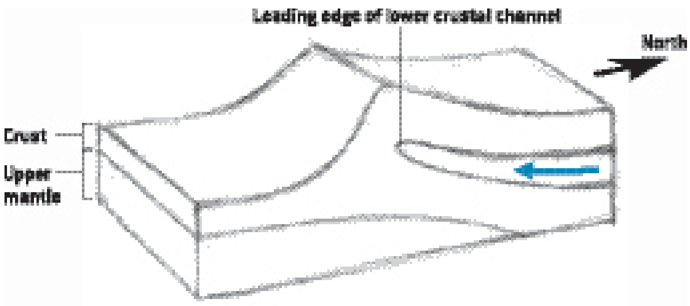
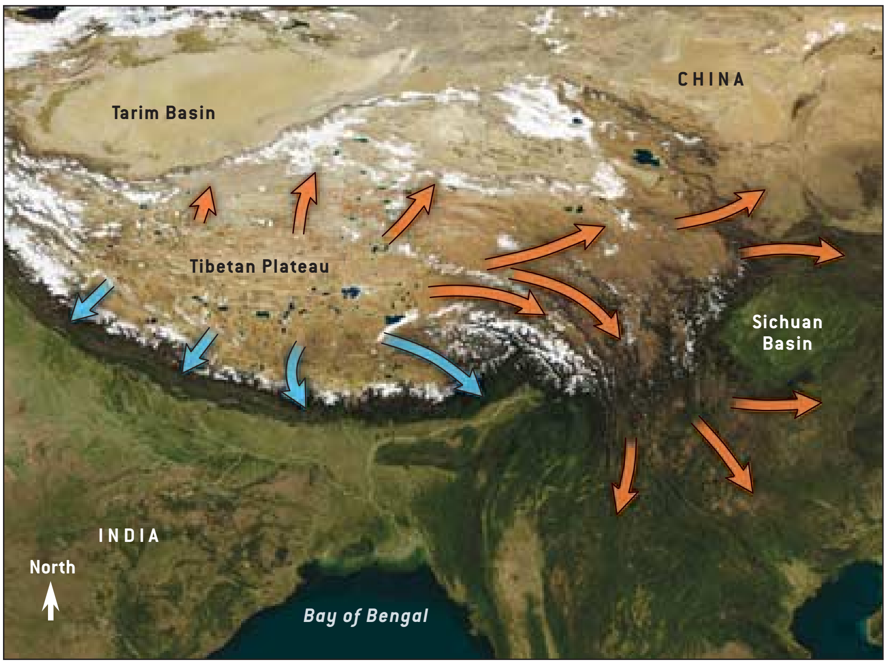
PASTY FLOW of underground geologic material (*blue arrows*) heads toward the south face of the Himalaya, drawn there by erosion at the surface. Enormous subterranean pressure forces additional crustal flow to the north, east and southeast (*orange arrows*), where naturally occurring structural weaknesses allow the soft crust to burrow. But only the rock that flows to the Himalayan wall ever reaches the surface.





paste being squeezed through a tube. Theoretical models and field observations show that such "paste" regions may persist for millions of years. And given the opportunity to dissipate potential energy, the pasty region 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 Tibetan Plateau to the southeast was caused by the outward "pasty" flow of Tibetan lower crust [*see illustration at left*], far below the mountain range. Water in a reservoir naturally flows preferentially to any crack in the dam. Similarly, the pasty crust flows under the Himalaya in the direction of least resistance, toward the section of the surface eroded by heavy rains—the southern face of the Himalaya. This crustal flow thus serves as the lynchpin of the monsoon-mountain relation. The rains should relentlessly erode away the mountain, and eventually breach the wall, reaching the dry plateau. But the flow of the lower crust constantly transports fresh material to the wall face, replenishing it. And, to close the circle, the erosion caused by the rains is the process that allows the crust the opportunity to flow to the face of the mountain range in the first place. The monsoon-mountain system is chasing its own tail.

Dissecting the Flow

THE PICTURE of the mountain's complex evolution started with an analysis of its faults, the cracks in the lithosphere along which plates slide past one another. Most major faults in mountainous regions are thrust faults, the kind typically seen during plate collisions. Those of us who shovel 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 [*see illustration on opposite page*]. 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 systems, all of which merge at depth to become what is known as the Himalayan sole (as in "bottom") thrust. Material above these faults is moving southward, carried by the conveyer belt of the thrust, relative to the material in the northward-moving Indian plate 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 Himala-

THE AUTHOR

KIP V. HODGES investigates the development and evolution of mountain systems, integrating theoretical and laboratory methods with field studies. When he wrote this article, he was a member of the geology department at the Massachusetts Institute of Technology, where he spent 23 years. In June he become founding director of the new School of Earth and Space Exploration at Arizona State University. 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.* Hodges is an avid recreational diver, often to be found in the waters off the island of Roatan in Honduras.

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ya, which greatly resolved our picture of 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 the fault have moved northward relative to the rocks below.

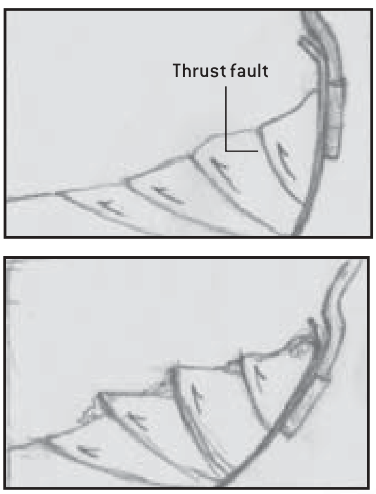
Such fault systems, known as detachment systems, are common in zones where the crust spreads and thins. Examples include mid-ocean ridges and the entire basin and range province of North America, which covers the area between the Colorado plateau and the Sierra Nevada Mountains. But major detachment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

The attempt to incorporate the detachment system into the overall dynamics of the Himalaya-Tibetan orogen led to the conclusion that the flow of pasty crust continuously replenishes the south face of the Himalaya: material south of the main central thrust system moves south, while everything north of the South Tibetan thrust system travels north; in between, the paste patiently grinds its way to the surface.

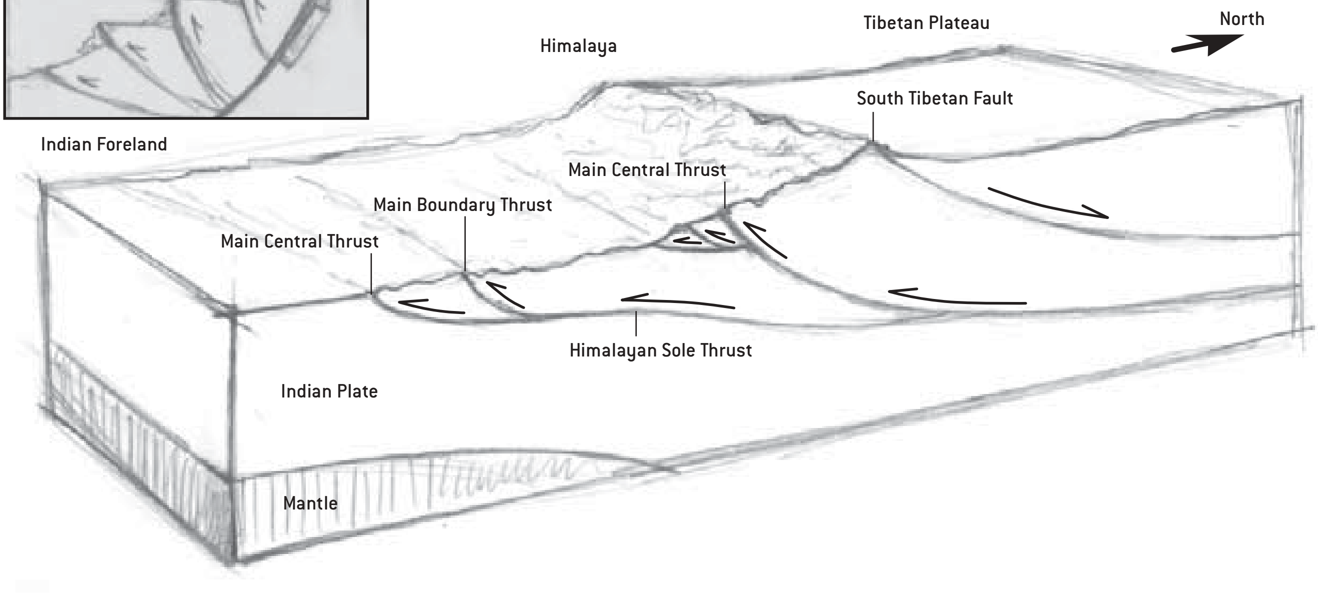
Evidence indicates that both the South Tibetan fault system and the main central thrust system were active during the Early Miocene epoch, between about 16 million and 22 million years ago. A simple model in which both systems are slipping simultaneously has the rocks between the two systems moving southward, toward India, relative to the rocks above and below. In the late 1980s and early 1990s, my M.I.T. colleagues Clark Burchfiel and Royden and I proposed that the southward motion occurred because the rocks in that zone were forced in that direction by the pressure differential between the rising Tibetan Plateau and India.

Since then, several research teams have refined this so-called extrusion model. Dordje Grujic, then at the Swiss Federal Institute of Technology in Zürich, and his colleagues showed that strain patterns in rocks within and between the two fault systems were consistent with ductile deformation, analogous to the flow of fluid in a pipe. And the late Douglas Nelson, when at Syracuse University, and others hypothesized that a fluid lower crust would 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 is simply the remains of the part of the ductile lower crustal channel that reached the surface and solidified, once free of the tremendous pressures that were keeping it soft.

Most variants of the channel extrusion model [*see illustration below*] have focused on the Miocene evolution of the Himalayan-Tibetan system, but evidence is mounting that the extrusion



SHINGLING EFFECT commonly seen when shoveling snow (*top images*) also occurs when tectonic plate collisions create thrust faults, hidden cracks in the crust along which one chunk of land rises up past another. Such shingled regions (*tan color TK in cross section below*)—the result of the India-Asia plate collision—have been found under the central Himalaya and the Tibetan plateau. Evidence now indicates that the crust in what has been called an extrusion channel between two of the faults—the South Tibetan and the main central thrust—apparently flows like paste toward the Himalaya's southern face, ultimately reaching the surface and rebuilding the mountain wall. Half arrows indicate the direction in which the rock is moving.



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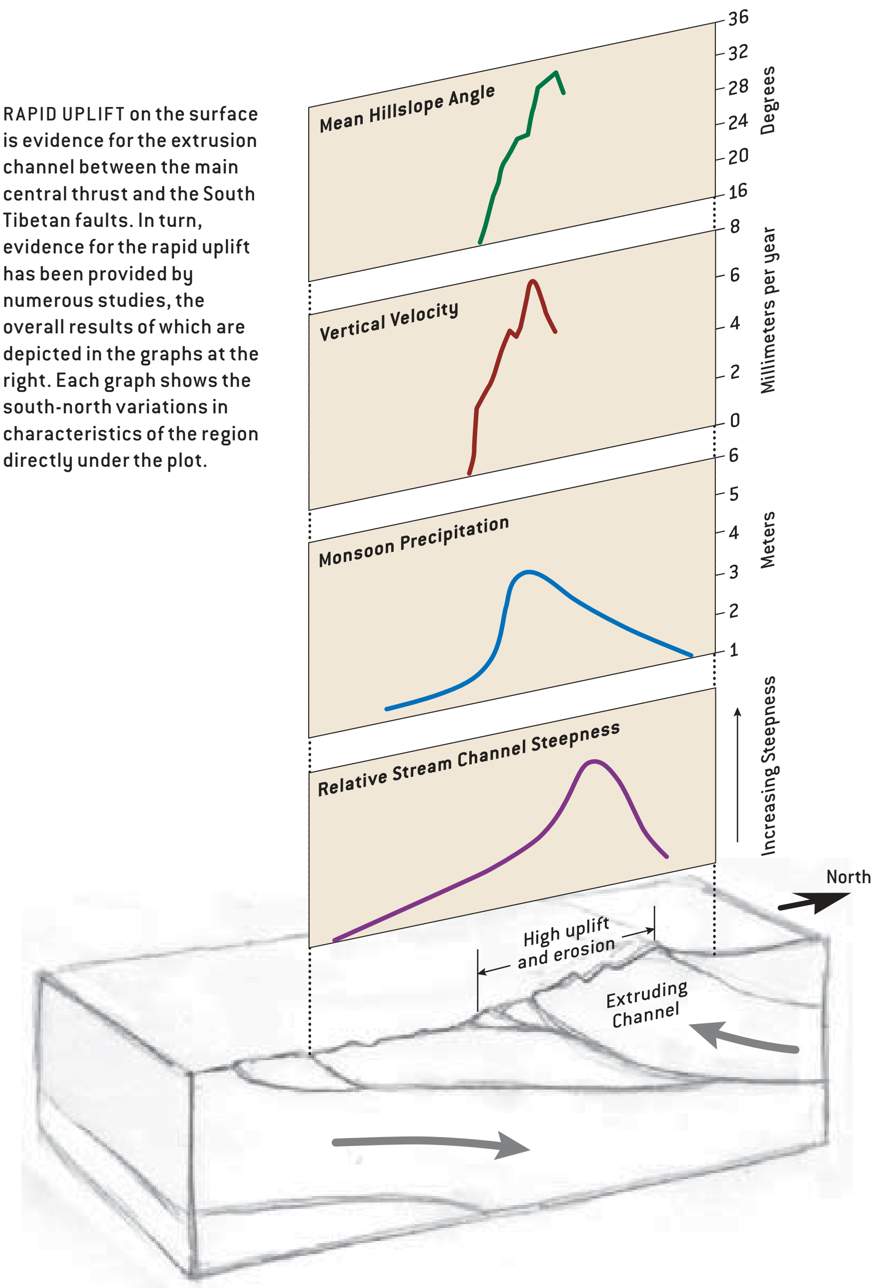
process is ongoing. Several research groups have used geologic chronometers—based on the radioactive decay of elements in minerals that crystallized following deformation of the earth's surface from plate collisions—to establish a better understanding of the movement histories of major Himalayan fault systems. The results show that faulting has occurred near or just south of the surface traces of the Miocene 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 M.I.T. group's research indicates 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 in the lower crust 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 exterior traces of the fault systems should exist. The uplift would be particularly rapid because extrusion brings new material to the surface far faster than would the slow, steady changes brought about by the ongoing collision of tectonic plates. One line of evidence for quick uplift comes from earth-surface data indicating that between 1977 and 1995 the land surface within the proposed zone of extrusion has been rising at a rate of a few millimeters a year relative to the region south of the zone. Measurable changes within a single human generation indicate that the process not only exists but is ongoing.

Additional evidence may be found in 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 front in Nepal where the streams cross the zone of proposed extrusion. Analysis of the topography across the front also shows unusually high relief here. Rapid uplift increases the gradient of rivers flowing across the landscape—the higher the gradient, the faster the flow of water. And the faster the flow, the faster it cuts into the rock, enhancing erosion. Therefore, spatial variations in erosion rate are markers of the rate of uplift.

One of the most powerful methods of estimating erosion rates at the millennial timescale in mountain systems is based on the natural production of what are known as cosmogenic nuclides (isotopes produced by cosmic rays) in bedrock surfaces, exposed rock that was once deeply buried. The concentration of cosmogenic nuclides, such as beryllium 10 and aluminum 26, in bedrock surface samples are proportional to the elapsed time since exposure. Cameron Wobus of M.I.T., working with Arjun Heimsath of Dartmouth College, has used this technique in central Nepal to demonstrate a three-fold increase in erosion rate in the zone of proposed extrusion relative to the region farther south **[Note to KVH: over how long a time period?]** The evidence does indeed point to rapid uplift.



RAPID UPLIFT on the surface is evidence for the extrusion channel between the main central thrust and the South Tibetan faults. In turn, evidence for the rapid uplift has been provided by numerous studies, the overall results of which are depicted in the graphs at the right. Each graph shows the south-north variations in characteristics of the region directly under the plot.

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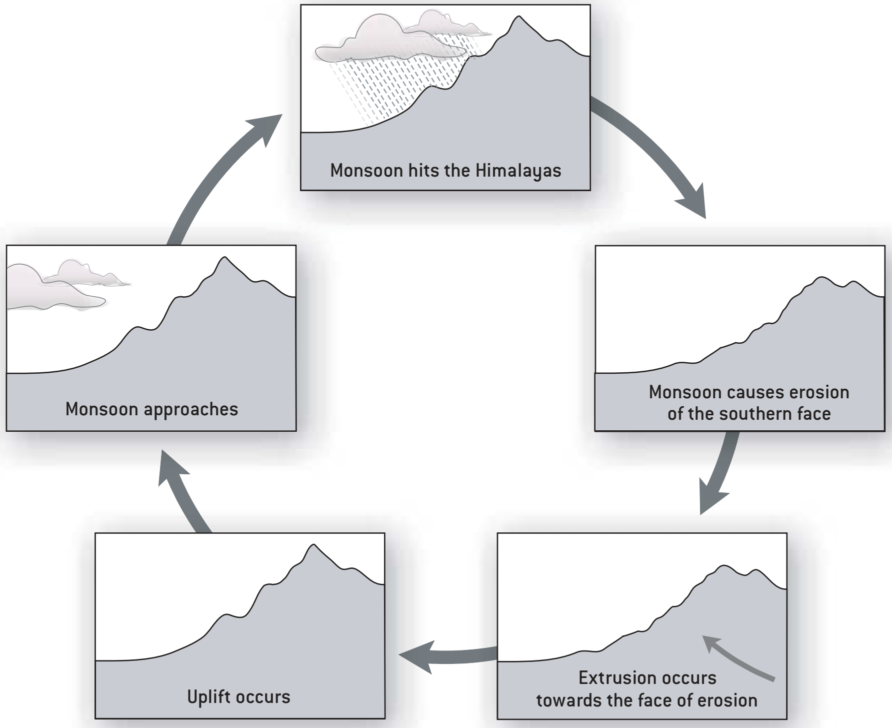
Different methods can be used to explore earlier erosion patterns. Some geologic chronometers do not yield the crystallization age of minerals but rather the time at which they merely experienced a small decrease in temperature. [**Note to KVH: what temp range are we talking about?**] Temperatures increase with depth; more recent cooling dates thus point to a given sample's more recent exhumation because of erosion. By applying such thermochronometers to samples collected from the Himalayan front in the Annapurna Range of central Nepal, my colleague Ann Blythe of the University of Southern California and our M.I.T. group have shown that erosion has increased in the zone of proposed extrusion for at least the past few million years. Again, the evidence supports the idea of rapid uplift.

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 also be expected to contribute to the significant erosion in mountainous terrain that would lead to the flow of crust to the face of the range. Several groups are examining these questions along the Himalayan front 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 do indeed indicate that monsoon rainfall is highest in the zone of rapid erosion and uplift defined by other studies. More important, the 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 driven by the Indian monsoon. The extrusion activated by rapid erosion does indeed appear to build the wall that intercepts the monsoon on its northward trek. The rain then falls here, leading to the increased erosion that activates extrusion, thereby completing the loop.

Chris Beaumont and his colleagues at Dalhousie University in Halifax, Nova Scotia, have constructed a model that represents the essential physics of the Himalayan-Tibetan system in Miocene time. They have shown that a lower crustal channel slowly and aimlessly spreads out in all directions when in regions with low surface erosion but flows directly toward regions of high surface erosion—like the modern Himalayan range front.

The existence of feedbacks between climatic and geologic deformational processes is a novel concept. Researchers 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 ecological studies into the "new" tectonics—if climate can move mountains, perhaps earthworms can as well. SA



FEEDBACK LOOP between monsoons and the Himalaya is shown here in simplified form. The summer monsoons attempt to travel north past the Himalaya but hit the mountain, dropping enormous amounts of rain (*top*). The rain causes erosion, and the eroded surface attracts the soft crust, deep underground, which flows toward the mountain face. The underground material reaches the eroded surface, causing rapid uplift. And the rapid uplift allows the rebuilt mountain wall to intercept the monsoon, thus perpetuating the cycle.

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.

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