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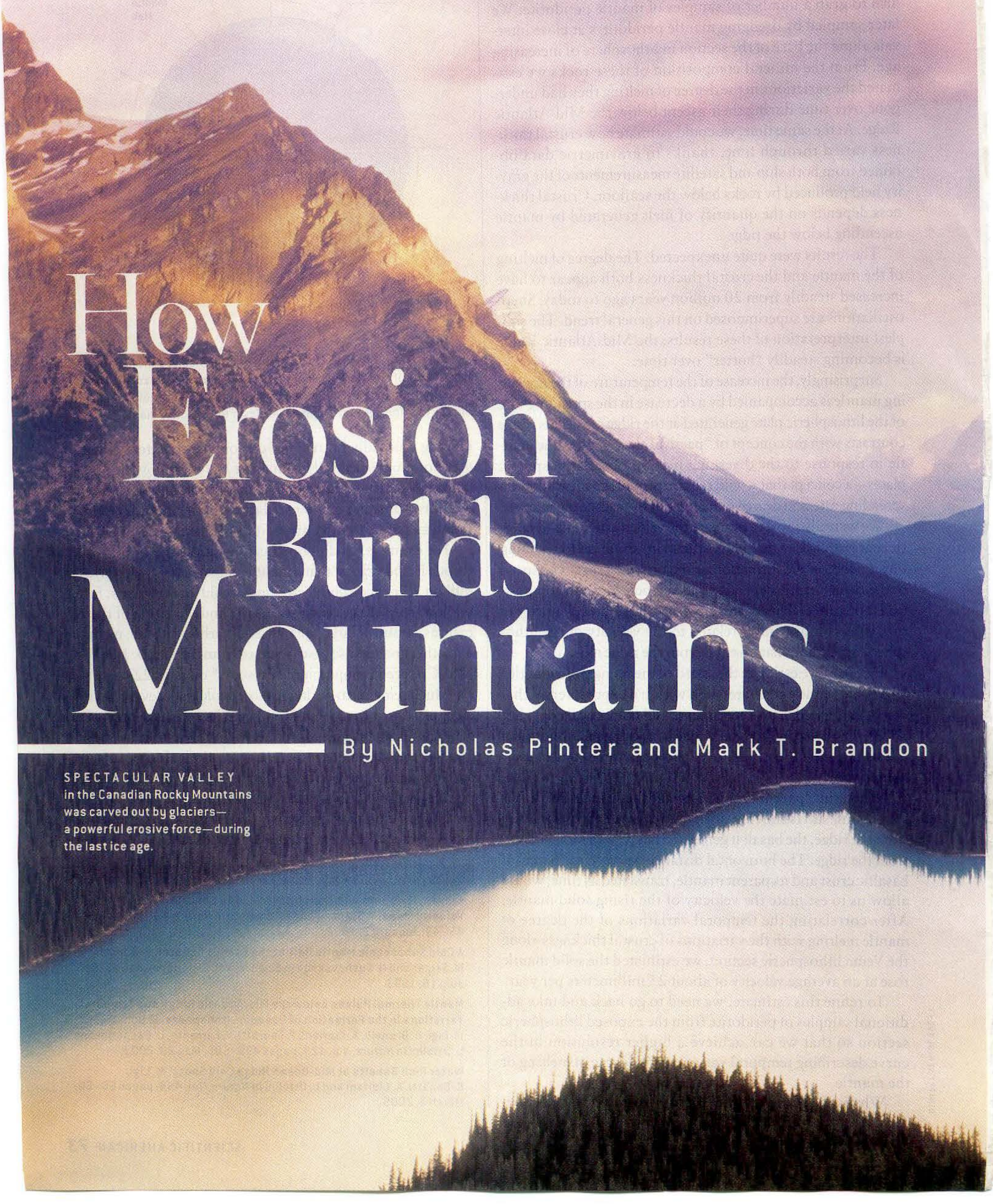
How Erosion Builds Mountains

By Nicholas Pinter and Mark T. Brandon



SPECTACULAR VALLEY in the Canadian Rocky Mountains was carved out by glaciers—a powerful erosive force—during the last ice age.

During the dives, we had used the *Nautile*'s mechanical arm to grab a number of samples of mantle peridotite. We later sampled by dredging mantle peridotites at close intervals along the base of the section in lithosphere of increasing age. From the mineral composition of these rocks we estimated the variations in the degree of melting they had undergone over time during their ascent below the Mid-Atlantic Ridge. At the same time, we could estimate how crustal thickness varied through time, thanks to gravimetric data obtained from both ship and satellite measurements of the gravity field produced by rocks below the seafloor. Crustal thickness depends on the quantity of melt generated by mantle ascending below the ridge.

The results were quite unexpected. The degree of melting of the mantle and the crustal thickness both appear to have increased steadily from 20 million years ago to today. Small oscillations are superimposed on this general trend. The simplest interpretation of these results: the Mid-Atlantic Ridge is becoming steadily "hotter" over time.

Surprisingly, the increase of the temperature of the upwelling mantle is accompanied by a decrease in the spreading rate of the lithospheric plate generated at the ridge axis. This result contrasts with the concept of "passive" upwelling of the mantle in response to the diverging motion of the lithospheric plates—a concept that would require proportionality between spreading rate and degree of melting of the ascending mantle.

We were also able to estimate the velocity of the solid mantle that rises below the ridge, crucial information for refining our models on the formation of the oceanic crust. The speed of the rising mantle depends on its temperature and composition (both affect density and viscosity) and on the diameter of the rising column and is related to the velocity of the lithospheric spreading that diverges from the ridge axis.

How can we estimate the speed of the rising solid mantle? The rising mantle generates melt within a depth interval that can be estimated from experiments and theoretical considerations. The melt fraction rises rapidly, cooling and solidifying as basalt in the crust, while its parent mantle continues to ascend slowly.

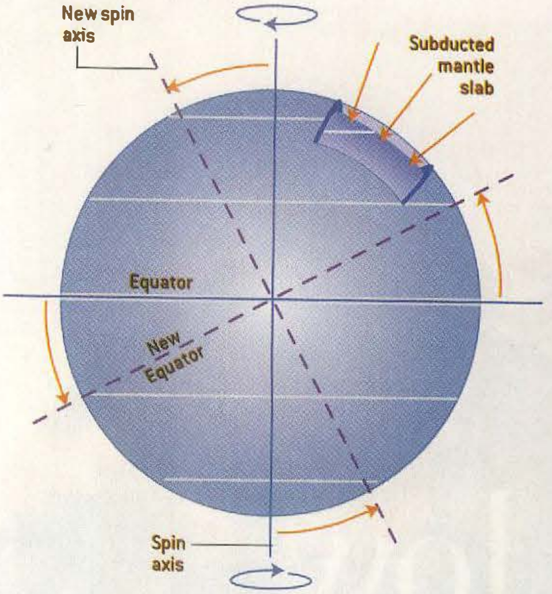
When the "parent" mantle peridotite reaches the lithosphere and starts moving horizontally with the plate away from the ridge, the basalt it generated has moved farther away from the ridge. The horizontal distance between the parcel of basaltic crust and its parent mantle, translated as time, would allow us to estimate the velocity of the rising solid mantle. After correlating the temporal variations of the degree of mantle melting with the variations of crustal thickness along the Vema lithospheric section, we estimated the solid mantle rose at an average velocity of about 25 millimeters per year.

To refine this estimate, we need to go back and take additional samples of peridotite from the exposed lithospheric section so that we can achieve a higher resolution in the curve describing temporal variations of degree of melting of the mantle.

Why is the Mid-Atlantic Ridge north of the equator becoming gradually hotter? We can only speculate. Perhaps a wave of plume-derived hot mantle has been flowing southward toward the equator since a few tens of million years ago. We have hints that major oscillations in the intensity of mid-ocean ridge activity occurred in the distant past.

For example, studies by Roger Larson of the University of Rhode Island suggest that a mantle "superplume" roughly 100 million years ago caused swelling of mid-ocean ridges, faster seafloor spreading, rising sea levels, and warming of the climate as a result of larger quantities of carbon dioxide, methane and other greenhouse gases released from the mantle [see "The Mid-Cretaceous Superplume Episode," on page 22].

Much remains to be done before geologists develop a complete picture of mantle dynamics and its influence on surface geology. Debate persists as to the origins of mantle convection and whether it extends into the lower mantle. Indeed, symposia that include theoreticians, geophysicists, geochemists and petrologists invariably yield heated discussions and much dissent. On one point there is unanimity: Earth's mantle is very much alive and is an exciting region to study. SA



SHIFTING OF EARTH'S AXIS can be influenced by the sinking of cold, dense slabs of mantle. Such sinking occurs in subduction zones, such as those surrounding the Pacific Ocean. Earth's axis of rotation would tend to shift so that the equator would move closer to the dense slabs.

DIMITRY SCHIDLOVSKY

MORE TO EXPLORE

Ridges, Hotspots and Their Interaction as Observed in Seismic Velocity Maps. Y. S. Zhang and T. Tanimoto in *Nature*, Vol. 355, pages 45–49; January 2, 1992.

A Cold Suboceanic Mantle Belt at the Earth's Equator. E. Bonatti, M. Seyler and N. Sushevskaya in *Science*, Vol. 261, pages 315–320; July 16, 1993.

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Water Rich Basalts at Mid-Ocean Ridge Cold Spots. M. Ligi, E. Bonatti, A. Cipriani and L. Ottolini in *Nature*, Vol. 434, pages 66–69; March 3, 2005.

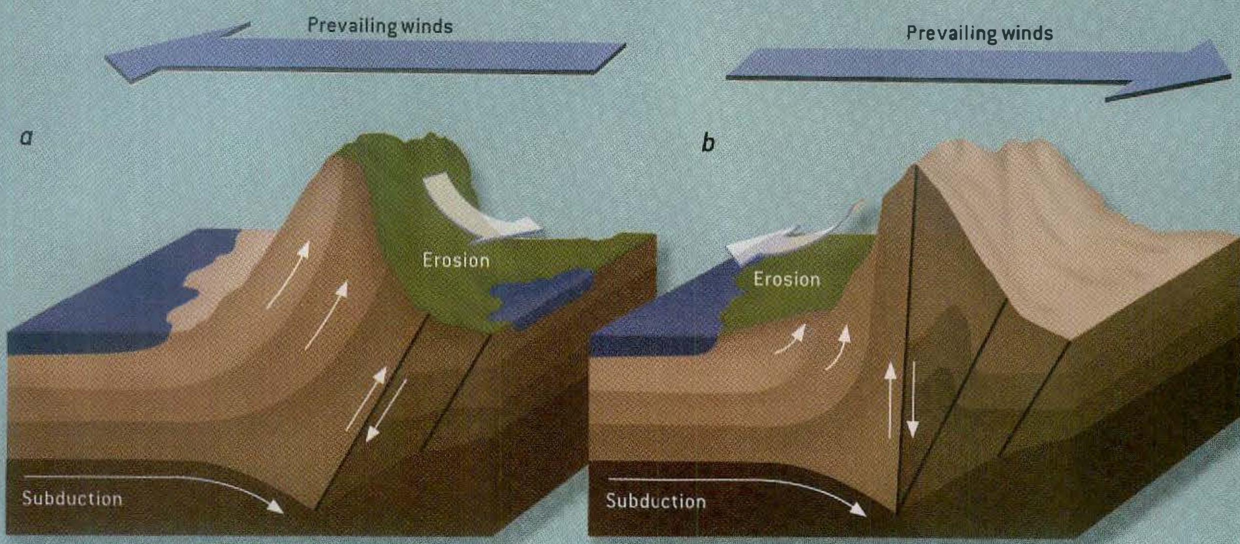
An understanding of how tectonic, erosional and climatic forces interact to shape mountains permits clearer insights into Earth's history

Mountains have evoked awe and inspired artists and adventurers throughout human existence. Recent research has led to important new insights into how these most magnificent of Earth's formations came to be. Mountains are created and shaped, it appears, not only by the movements of the vast tectonic plates that make up Earth's exterior but also by climate and erosion. In particular, the interactions between tectonic, climatic and erosional processes exert strong control over the shape and maximum height of mountains as well as the amount of time necessary to build—or destroy—a mountain range. Paradoxically, the shaping of mountains seems to depend as much on the destructive forces of erosion as on the constructive power of tectonics. In fact, after 100 years of viewing erosion as the weak sibling of tectonics, many geologists now believe erosion actually may be the strong one in the family. In the words of one research group, "Savor the irony should mountains owe their [muscles] to the drumbeat of tiny raindrops."

Because of the importance of mountain building in the evolution of Earth, these findings have significant implications for earth science. To a geologist, Earth's plains, canyons and, especially, mountains reveal the outline of the planet's development over hundreds of millions of years. In this sprawling history, mountains indicate where events in or just below Earth's crust, such as the collisions of the tectonic plates, have thrust this surface layer skyward. Thus, mountains are the most visible manifestation of the powerful tectonic forces at work and the vast time spans over which those forces have operated.

RICHARD SISK *Panoramic Images*

TURNING WIND INTO RAIN



OROGRAPHY is the phenomenon in which mountains lift the air currents flowing over them, increasing precipitation over the crest and windward slopes of the range. In a mountain range near an ocean, for example, when the prevailing winds blow offshore, opposite to the direction of subduction (*a*), erosion is concentrated on the inland side of the range, exposing the deepest, most deformed rocks in that area.

When the wind is in the same direction as subduction (*b*), erosion denudes the coastal side of the range, literally pulling buried rocks toward the surface. In this case, the inland side of the mountain range lies in an arid "rain shadow," such as the desert east of the Sierra Nevada (*photograph*).

The effort to understand mountain building has a long history. One of the first comprehensive models of how mountains evolve over time was the Geographic Cycle, published in 1899. This model proposed a hypothetical life cycle for mountain ranges, from a violent birth caused by a brief but powerful spasm of tectonic uplift to a gradual slide into "old age" caused by slow but persistent erosion. The beauty and logic of the Geographic Cycle persuaded nearly a century of geologists to overlook its overwhelming limitations.

In the 1960s the plate tectonics revolution explained how mountain building is driven by the horizontal movements of vast blocks of the lithosphere—the relatively cool and brittle part of Earth's exterior. According to this broad framework, internal heat energy shapes the planet's surface by compressing, heating and breaking the lithosphere, which varies in thickness from 100 kilometers or less below the oceans to 200 kilometers or more below the continents. The lithosphere is not a solid shell but is subdivided into dozens of plates. Driven by heat from below, these plates move with respect to one another, accounting for most of our world's familiar surface features and phenomena, such as earthquakes, ocean basins and mountains.

Earth scientists have by no means discarded plate tectonics as a force in mountain building. Over the past few decades, however, they have come to the conclusion that mountains are best described not as the result of tectonics alone but rather as the products of a system that encompasses erosional and climatic processes in addition to tectonic ones and that has many complex linkages and feedbacks among those three components.

THE ROLE OF TECTONICS

PLATE TECTONICS still provides the basic framework that accounts for the distribution of mountains across Earth's surface. Mountain building is still explained as the addition of mass, heat or some combination of the two to an area of Earth's crust (the crust is the upper part of the lithosphere). Thicker or hotter crust rises upward, forming mountains, because the crust is essentially floating on the mantle under it, and crust that is either thicker or hotter (less dense) floats higher. Plate tectonics contributes to the thickening of the crust by either lateral convergence between adjacent plates or through the upward flow of heat and magma (molten rock).

Convergence of tectonic plates generally occurs in one of two ways. One plate may slide down, or subduct, below the other, into the mantle. At a subduction zone boundary, the

upper plate is thickened as a result of the compression and from magma being added by the melting of the descending plate. Many mountains, including almost all the ranges that surround the Pacific Ocean in a geologically active area known as the ring of fire, formed by subduction. With continental collision, on the other hand, neither plate subducts into the mantle, and therefore all the mass added as a result of the collision contributes to the building of mountains. Such collisions have created some spectacular topography, such as the Tibetan Plateau and the Himalayas, the mountain range that includes the world's 10 highest peaks.

The flow of magma and heat to Earth's crust—during volcanic activity, for example—can also drive mountain building. Earth's longest mountain chains—the mid-ocean ridges—are the result of magma welling up as adjacent plates move apart, forming new crust under the ocean. These ridges run through the Atlantic, eastern Pacific and Indian oceans like the seam on a baseball; the Mid-Atlantic Ridge alone is more than 15,000 kilometers long, rising as much as 4,000 meters above the surrounding abyssal plains of the ocean floor. On land, heat associated with the flow of magma can also help uplift large areas by making the lithosphere less dense and more buoyant on the underlying mantle.

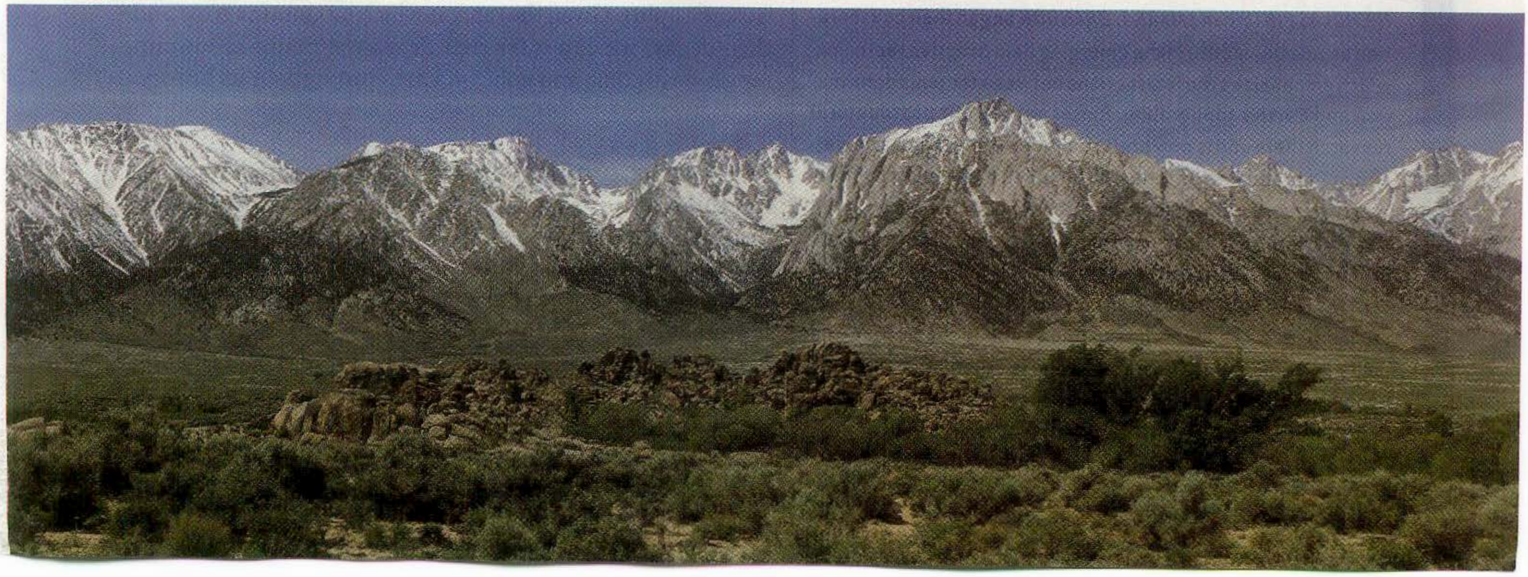
CLIMATE AND EROSION

THE EMERGING, SYSTEM-ORIENTED VIEW of mountain building adds to these tectonic phenomena the often closely intertwined effects of erosion and climate. Erosion includes the disaggregation of bedrock, the stripping away of sediment from slopes and the transport of the sediment by rivers. The mix of erosional agents active on a particular landscape—gravity, water, wind and glacial ice—depends on the local climate, the steepness of the topography and the types of rock at or near the surface.

Climate is inextricably linked with erosion because it affects the average rate of material loss across a landscape. In general, wetter conditions favor faster rates of erosion; however, more moisture also promotes the growth of vegetation, which helps to "armor" the surface. Mountains in polar latitudes are the least vulnerable to erosion, partly because of the aridity of cold climates and partly because continental ice sheets such as those on Greenland and Antarctica commonly are frozen to the underlying rock and cause little erosion. In contrast, mountain glaciers such as those of the European Alps and the Sierra Nevada in California aggressively attack the subsurface rock, so that this type of glacier may be Earth's most potent erosional agent.

There are many other links among erosion, climate and topography. For example, mountains lift the winds that flow over them, causing increased precipitation on the range's windward slopes, intensifying erosion as a result. Known as orography, this effect is also responsible for the "rain shadow" that creates deserts on the leeward sides of many mountain ranges [*see photograph on opposite page*]. Elevation can also affect erosion, because average temperature decreases with altitude, so that higher peaks are less likely to be protected by vegetation and more likely to be eroded by glaciers. In temperate regions the rate of erosion is proportional to the average steepness of the topography, apparently because gravity- and water-driven processes are more effective on steeper slopes. Taken together, all these facts suggest that mountains evolve their own climates as they grow—becoming typically wetter, colder and characterized by more intense erosion.

The links described above demonstrate that mountain ranges are best viewed as a system. To understand the behavior of any such system, it is necessary to identify both its components and the interactions among those components. Because these interactions are so important, simple system inputs can lead to surprisingly complex outputs. Such complexities include feedback—stabilizing or destabilizing links between component processes. In the simple example we have outlined, the system is forced by tectonic collision, which adds mass to the mountain belt, and the response is an increase in the average height of the mountain range. As the mountains grow taller, erosion increases, reducing the growth rate. This example illustrates negative feedback, in which continued positive forcing of a system leads to a progressively reduced response. In contrast, positive feedback has the opposite effect, accelerating any change in a system. The creation of a rain shadow is an example of positive feedback; erosion is inhibited, allowing a mountain range to continue its rapid growth. The rain shadow north of the Himalayas



MEGAN O'DEA; SOURCE: SEAN WILLETT, CHRISTOPHER BEAUMONT AND PHILIPPE FULLSACK IN *GEOLOGY*, VOL. 21, NO. 4; APRIL 1993 [*illustration*]; GERALD FRENCH *Panoramic Images* [*photograph*]

has contributed to the formation of the high-standing Tibetan Plateau [*see box on pages 80 and 81*].

The concept of feedback is at the heart of the new understanding of how mountains are built—and even how mountain building affects the Earth system as a whole. Numerous different types of feedback have been recognized or postulated. Among the most unexpected insights that have accrued from these discoveries is the realization that several important feedbacks enable surface processes, such as climate and erosion, to influence profoundly tectonic processes deep below the surface (and vice versa).

ISOSTASY IS KEY

ONE IMPORTANT FEEDBACK occurs through the phenomenon known as isostasy, which refers to the buoyancy of Earth's crust as it floats on the denser, fluidlike mantle below it. A mountain range, like any physical structure, must be supported, and it turns out that this support comes mainly from the strength of the crust and from isostasy. Under the soaring peaks of every mountain range is a buoyant "root" of crust that penetrates into the mantle. Icebergs offer a useful analogy: because ice is about 90 percent as dense as water, a given mass of ice above the water is supported by nine times that mass underneath the waterline. Continental crust is about 80 to 85 percent as dense as the mantle beneath, enabling crustal roots tens of kilometers deep to support mountains several kilometers high.

Isostasy is the key mechanism that links a mountain's tectonic, or internal, evolution to its geomorphic, or external, development. When erosion at the surface removes mass, isostasy responds by lifting the entire mountain range up to replace about 80 percent of the mass removed. This uplift explains a number of phenomena that were puzzling before researchers fully appreciated the role of feedback in mountain building.

For example, high-precision surveys along the eastern margin of the U.S. have revealed that the land is rising at rates of a few millimeters to a few centimeters a century. This was puzzling because the Appalachian Mountains lie in the interior of the North American plate, where there is

HIMALAYAS and Tibetan Plateau are visible in this satellite image as the mostly white areas north and east of India—towering manifestations of an ongoing collision that started 50 million years ago, when the Indian tectonic plate, moving north, began plowing into the Eurasian plate. The collision's most visible result is the high, flat topography of Tibet. In contrast, the Himalayas—the high snowcapped range along the southern margin of the plateau—comprise just a small fraction of the area created by this collision.

TOM VAN SANT *Geosphere Project*

no convergent plate boundary to account for the uplift. Some geologists suggested that the survey results must therefore have been in error. Given our new understanding, however, some or all of the measured uplift may be the isostatic response to erosion, especially in the high-relief areas of the Appalachians. Erosion that is concentrated at the bottom of river valleys may be especially significant because it can lift mountain peaks to elevations *higher* than the elevations before erosion started. This is possible because the removal of mass is localized (in the valleys), but the isostatic response lifts the entire mountain block, including both valleys and peaks.

Although isostasy can prop them up for many millions of years, landscapes without tectonic uplift do eventually succumb to erosion. Several studies have suggested that large areas of Australia are good examples of very old, decaying landscapes. These areas, which have not experienced tectonic uplift for hundreds of millions of years, are at most a few hundred meters above sea level. Their rates of surface uplift seem to be consistent with only isostatic response to erosion. In such tectonically active mountains as the Himalayas and the European Alps, measured uplift reflects a combination of tectonic driving forces and erosionally driven isostatic uplift. Given the rates at which mountains grow and then decay, we can infer that dozens of major mountain ranges have come and gone on Earth throughout its history.

UNUSUAL TECTONIC TIMES?

THE CONSTRUCTION OF MOUNTAINS, including ancient mountains that were built and eroded away in the distant past, can leave a variety of marks in the geologic record, such as those from lava flows, intrusion of magma, the exposure of once deeply buried rocks, as well as copious sediment deposited in lowland basins and the fossils of plants known to thrive only at high altitudes. By studying such indicators from many different periods, geologists can make inferences about the extent of mountain building on

THE AUTHORS

NICHOLAS PINTER and *MARK T. BRANDON* began their collaboration at Yale University in the emerging field of active tectonics, which emphasizes the interactions between tectonic deformation and Earth's topography. Pinter carried out postdoctoral research there and is now professor at Southern Illinois University at Carbondale. His research includes a focus on the topographic expression of tectonic processes and has involved work in California, South America and the peri-Adriatic region. Brandon is professor of structural geology and tectonics at Yale. His research is focused on understanding the interrelation between tectonic uplift and erosion at subduction zones and collisional mountain ranges. Areas he is studying include the Apennines, the Alps, the southern Andes, Crete and the Coast Ranges of the western U.S.

Earth at different times, thereby gaining insights into the planet's development.

Various geologists have looked at the relative abundance of sediment, magmatic activity and other potential indicators of mountain building and concluded that the past 40 million years represents an anomalous surge of tectonic activity and mountain building. This same geologic period, however, also saw a major climate shift on Earth, a global cooling that transformed Greenland and Antarctica from temperate, vegetated lands to permanent ice sheets and that culminated in the glaciers that covered North America and Europe during the past two million years. Given this evidence, two opposing theories have been proposed to explain mountain building and climate over the past 40 million years: either the surge of mountain building caused the global climate shift, or the climate shift caused the surge of mountain building.

The first of these two theories asserts that long-term cooling was caused by a surge in mountain building around the globe. For example, glaciers tend to be self-perpetuating: once established, they increase the reflectivity, or albedo, of the surface, thus lowering temperatures and allowing more ice to form. Widespread uplift of large mountain masses in the past 40 million years could have increased the area of Earth covered by mountain glaciers, which would have increased the albedo of the planet. Atmospheric carbon dioxide may have been another important feedback agent. One interpretation states that mountain building can alter the global distribution of rain and snowfall, increasing the pace at which rock is broken down by dissolution and chemical reactions. According to this hypothesis, accelerated chemical weathering removed carbon dioxide from the atmosphere, reducing the greenhouse effect and thereby leading to a cooler global climate.

The second theory about mountain building and climate contends that climate change was really the more powerful of those two forces during the past 40 million years. This theory proposes that climate change has actually produced many of the profound geologic changes that are usually attributed to accelerated mountain growth. Global cooling may have been driven by continental drift, which changed the distribution of land and ocean area with respect to latitude as well as the pattern of ocean currents, which are major mechanisms by which Earth equilibrates the heat imbalance between the equator and the poles [see "Chaotic Climate," by Wallace S. Broecker; SCIENTIFIC AMERICAN, November 1995]. How could these climate changes mimic mountain building? Through isostatic uplift. According to this interpretation, global cooling intensified erosion in many mountain ranges. Stepped-up erosion, particularly in the bottom of river and glacial valleys, resulted in increased uplift of mountain summits as isostasy compensated for the removal of mountain mass by erosion.

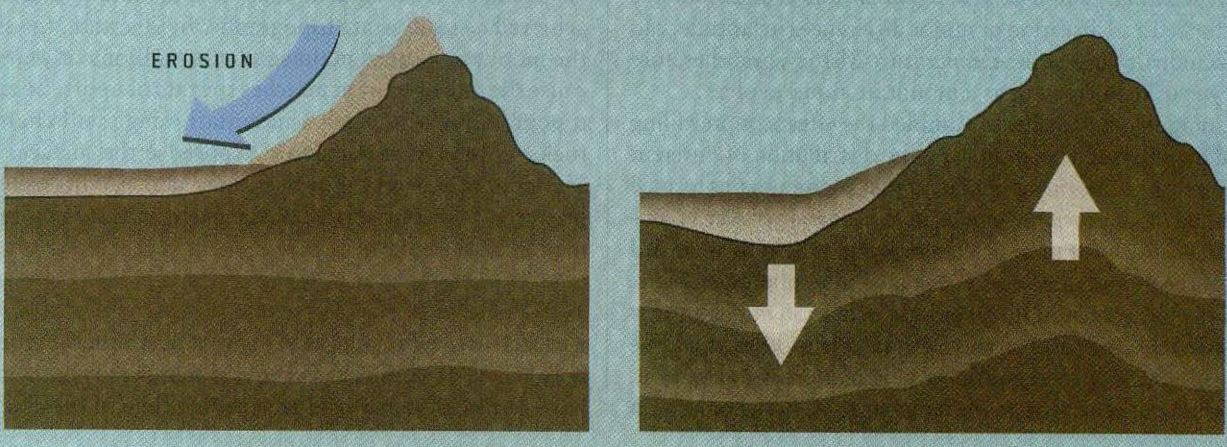
The cause-and-effect ambiguity between global climate and mountain building has been billed as a geologic paradox to rival the "chicken and egg" question, but such circularity is common in feedback-rich systems. Geologists may not currently know what initiated the changes in climate and topography that have occurred in the past 40 million years, but they now understand that the many kinds of feedback in this system are capable of amplifying any change and that tectonics, climate and erosion must have acted together in creating the geologic evidence that we find today.

EROSION'S PULL

RECOGNITION OF THE MANY TYPES of feedback in the mountain-building system reveals that erosion not only participates in shaping mountains but also guides tectonic processes deep within the crust. The ultimate limiting force to mountain growth is gravity. Thus, erosion, by reducing the weight of the mountain range, actually accelerates tectonic processes beneath the mountains. For this reason, erosional processes can be viewed as "sucking" crust into mountain

WHEN MOUNTAINS FLOAT ON MANTLE

ISOSTATIC UPLIFT occurs as a result of the buoyancy of a mountain on the more dense, fluidlike mantle (*not shown*) on which it "floats." Erosion causes the crust to rise up, whereas deposition of the resulting sediment in the basin area weighs the crust downward.



MEGAN O'DEA

THE HIMALAYAS AND THE APPALACHIANS

TWO OF EARTH'S grandest mountain ranges are the Himalayas and the Appalachians. Both were built by continental collisions, but the two ranges are about as different as mountains can be. Their comparison illustrates well the key principles of the new, system-oriented view of mountain building.

Stretching 2,500 kilometers across northern India and southern Tibet, the Himalayas are the king of Earth's mountain ranges. In this range stand many of the world's highest peaks, including Mount Everest, the tallest at 8,848 meters. Together with the Tibetan Plateau, to the north of the range in southwest China, the Himalayas contain the globe's greatest total mountain mass. It has even been suggested that this mountain belt is the largest high-elevation mass that Earth has seen in the past billion years. In spite of this range, the landscape atop the Tibetan Plateau is surprisingly flat. The plateau is Earth's largest expanse of land above 5,000 meters—a region approximately half the area of the continental U.S., most of it at least 600 meters higher than Mount Whitney, the highest single point in the continental U.S.

All this dramatic and varied topography developed during the past 50 million years, as a result of the collision between the Indian and the Eurasian tectonic plates. The collision began to squeeze both India and Tibet, activating a series of crustal-scale contractional faults that thrust part of the Indian continent underneath southern Asia. The northward velocity of India before the collision was 15 to 20 centimeters a year, and the velocity afterward was about five. Such deceleration of an entire continent is less surprising than the fact that India has continued to plow into and through southern Asia at about five centimeters

APPALACHIANS AND HIMALAYAS were formed by the same set of geologic processes, but roughly 250 million years apart. Many more years of erosion have given the older Appalachians (*left*) a less rugged appearance than the Himalayas (*right*), which are still being uplifted by strong tectonic forces.

a year for the past 40 million to 50 million years. India has advanced 2,000 kilometers into the Eurasian plate, give or take 800 kilometers, roughly doubling the thickness of the crust, uplifting the Himalayas and the Tibetan Plateau and pressing huge areas of Indochina and eastern China out to the east and southeast.

Construction of the Himalayas and the Tibetan Plateau

ranges and up toward the surface. And in this manner, erosion leaves a distinct fingerprint on the rocks and on the pattern of crustal deformation in and under mountains.

The type of rock at the surface of a mountain is determined, in part, by the local climate and by the rate and pattern of erosion. In this way, erosion influences both the topography and the composition and structure of mountains. Metamorphism of rocks (changes as a result of heating and pressure) and the creation of many rock-forming minerals are governed by the pressure and temperature profile within the crust. Seemingly small details of climate and erosion, such as wind speed and direction or minor differences in latitude, can profoundly influence the temperature history, and therefore the type of rock created, as a mountain range evolves.

Computer models have examined the effects of prevailing wind direction and orography on the distribution of different metamorphic zones in mountain ranges. For mountains formed by subduction, prevailing winds in the same direction as subduction cause most of the precipitation to fall on the seaward side of the mountain range, which faces the subducting plate.

This phenomenon intensifies deformation and exhumation of rocks from deep in the crust. If, on the other hand, the prevailing winds are in the opposite direction as subduction, erosion is concentrated on the landward side of the mountain range, so that deformation is relatively uniform throughout the range and deep exhumation is limited to the interior, or continental, side of the range. One study of the eroded cores of several ancient mountain ranges revealed that the fingerprint of orography and wind direction remains clear, in the distribution of rocks sucked into the range by climatically driven erosion, up to two billion years after the ranges had become tectonically inactive.

With growing evidence that tectonic uplift and erosion can occur over similar timescales and at similar rates, many researchers have concluded that some mountain ranges have achieved a steady-state topography. In this state, the size of the mountains can remain stable for millions of years, because the rate of erosion matches the rate of uplift. Localized topography within such a mountain range will change as rocks of different strength are exposed at the surface. Average mountain height, however, may undergo little change, because of the long-term balance between tectonics and climate-driven erosion.

THREE STAGES

ALTHOUGH RELATIVELY FEW of Earth's mountains are now believed to be in perfect equilibrium, many of them may have achieved such a balance at some time in their history.

CLYDE H. SMITH Peter Arnold, Inc.

illustrates many of the principles of feedback-rich mountain building. For example, uplift of the plateau apparently triggered a climatic change around eight million years ago, which dramatically strengthened the Asian monsoon, the pattern of intense seasonal rainfall across southern Asia. The monsoon pattern sharply intensified erosion in the Himalayas, increasing the flux of sediment from the Indus and Bengal rivers by factors as high as 13. The strengthening of the Asian monsoon apparently caused a surge of uplift in the Himalayas, as the isostasy (buoyancy) of the crust responded to the intensified erosion in the region. Meanwhile the interior of the Tibetan Plateau evolved much more slowly because it lies in the rain shadow of the Himalayas and because the major rivers have not yet eroded their way into it.

Although the present-day Appalachians are less spectacular than the Himalayas, they were created by the same tectonic processes and are now being shaped by the same system feedback. The primary difference is age: the Himalayas are about 50 million years old, whereas the main uplift of the Appalachians culminated 250 million to 350 million years ago.

Geologically, the eastern coast of North America is the quiet side of the continent today. Before 200 million years ago, however, it was a hotbed of mountain building. During the previous several hundred million years, the predecessor to the Atlantic Ocean (called the Iapetus Ocean) was subducting underneath eastern North America. As the Iapetus gradually closed, at least three smaller landmasses, probably island arcs analogous to present-day Japan, slammed into the continent. Later, the mountain-building process culminated with the collision of Africa and the eastern U.S. The early Appalachians that resulted from these collisions are estimated to have been 250 to 350 kilometers wide, with average elevations of 3,500 to 4,500 meters and isolated peaks perhaps much higher. One study suggests that during the past 270 million years, erosion has stripped between 4,500 and 7,500 meters of material from the surface of the Appalachians. (This fact does not mean that the mountains were once 4,500 to 7,500 meters higher; isostatic uplift, as is explained in the main article, has continually pushed the roots of mountains upward in response to erosion at the surface.) Over the past 200 million years, as North America rifted away from Africa and the Atlantic Ocean began to open, secondary events may have triggered minor episodes of uplift, but erosion has been the dominant process shaping the mountain range. *—N.P. and M.T.B.*

Mountain ranges, it appears, often go through three distinct phases. The first, formative stage begins with the converging of plates or some other tectonic event that thickens crust and causes topography to rise. During this stage, rates of uplift exceed those of erosion. Erosion rates increase dramatically, however, as elevations and relief increase. Depending on the size of the range and the local climate, uplift may persist until erosion rates or the strength of the crust limits the average elevation of the range from increasing any more. This is the second stage, a steady state that may continue as long as the rates of uplift and erosion remain equal. When uplift diminishes, erosion begins to dominate and the final stage begins. In this final stage, the average elevation of the mountain range begins a long, slow decline. The cycle may be interrupted or complicated at any stage by tectonic or climatic events as well as the feedback among those processes and erosion.

The new model of how mountains develop promises to be as revolutionary as was plate tectonics some four decades ago. Just as plate tectonics managed to explain the worldwide distribution of earthquakes, volcanoes, fossils and many different rocks and minerals, the new understanding of mountain building shows how tectonic forces, Earth's climate and topography interact to create some of Earth's most spectacular landscapes. Like plate tectonics, the new model also illuminates phenomena that had long puzzled geologists. Computer simulations incorporating many of the model's principal precepts, for example, have proved very successful in mimicking the effects of complex tectonic histories, climatic variability and different geologic settings. Continuing research will provide even more details of how Earth's magnificent mountain ranges grow, evolve and decline, as well as details concerning the importance of mountains in shaping the climate and tectonics of our planet. SA

GALEN ROWELL *Mountain Light*

MORE TO EXPLORE

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