ROOF OF THE WORLD

Colliding continents drove the Himalaya and Tibet into the sky — and may have radically altered Earth's climate.

By Tom Waters

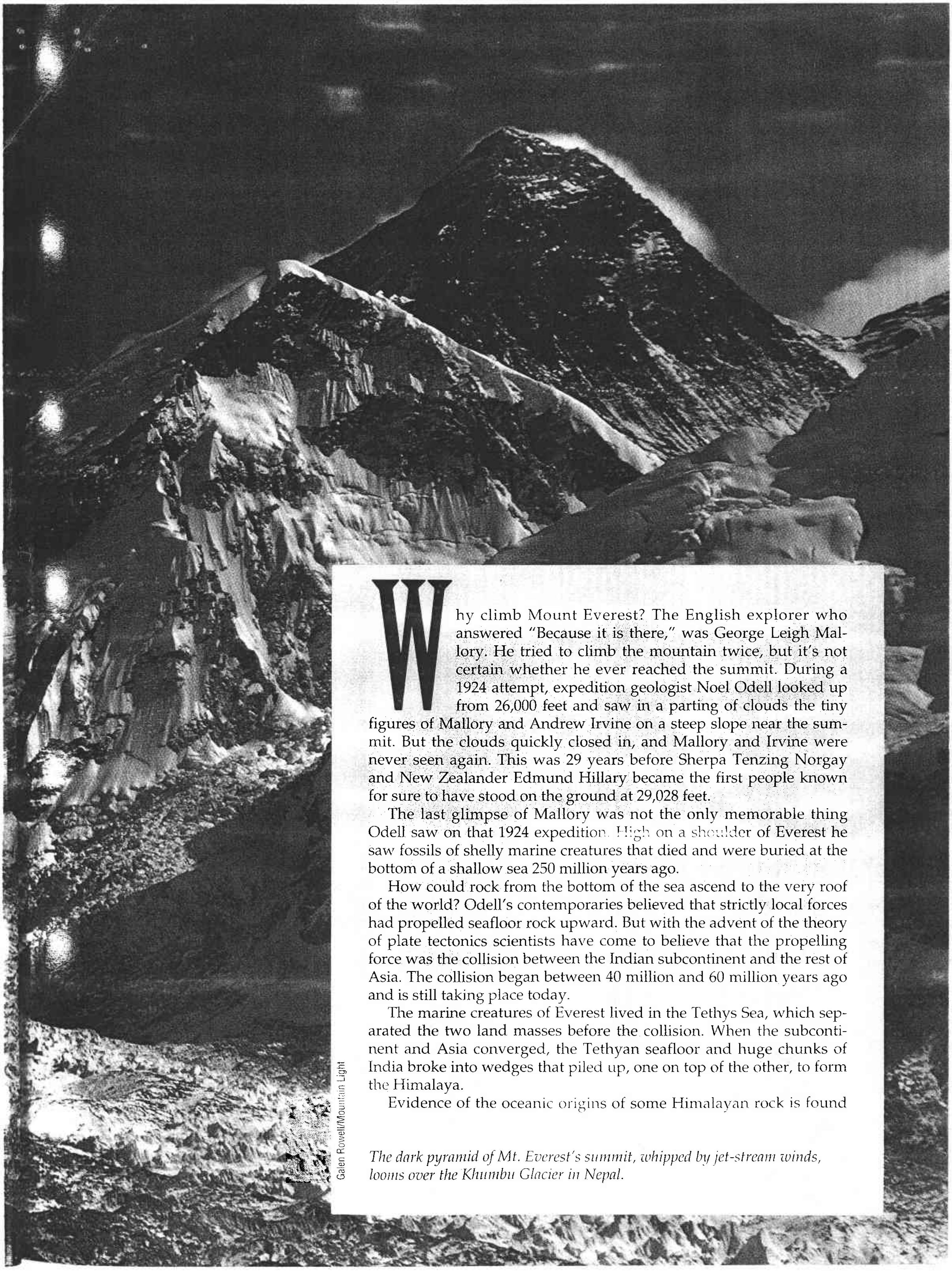
Why climb Mount Everest? The English explorer who answered "Because it is there," was George Leigh Mallory. He tried to climb the mountain twice, but it's not certain whether he ever reached the summit. During a 1924 attempt, expedition geologist Noel Odell looked up from 26,000 feet and saw in a parting of clouds the tiny figures of Mallory and Andrew Irvine on a steep slope near the summit. But the clouds quickly closed in, and Mallory and Irvine were never seen again. This was 29 years before Sherpa Tenzing Norgay and New Zealander Edmund Hillary became the first people known for sure to have stood on the ground at 29,028 feet.

The last glimpse of Mallory was not the only memorable thing Odell saw on that 1924 expedition. High on a shoulder of Everest he saw fossils of shelly marine creatures that died and were buried at the bottom of a shallow sea 250 million years ago.

How could rock from the bottom of the sea ascend to the very roof of the world? Odell's contemporaries believed that strictly local forces had propelled seafloor rock upward. But with the advent of the theory of plate tectonics scientists have come to believe that the propelling force was the collision between the Indian subcontinent and the rest of Asia. The collision began between 40 million and 60 million years ago and is still taking place today.

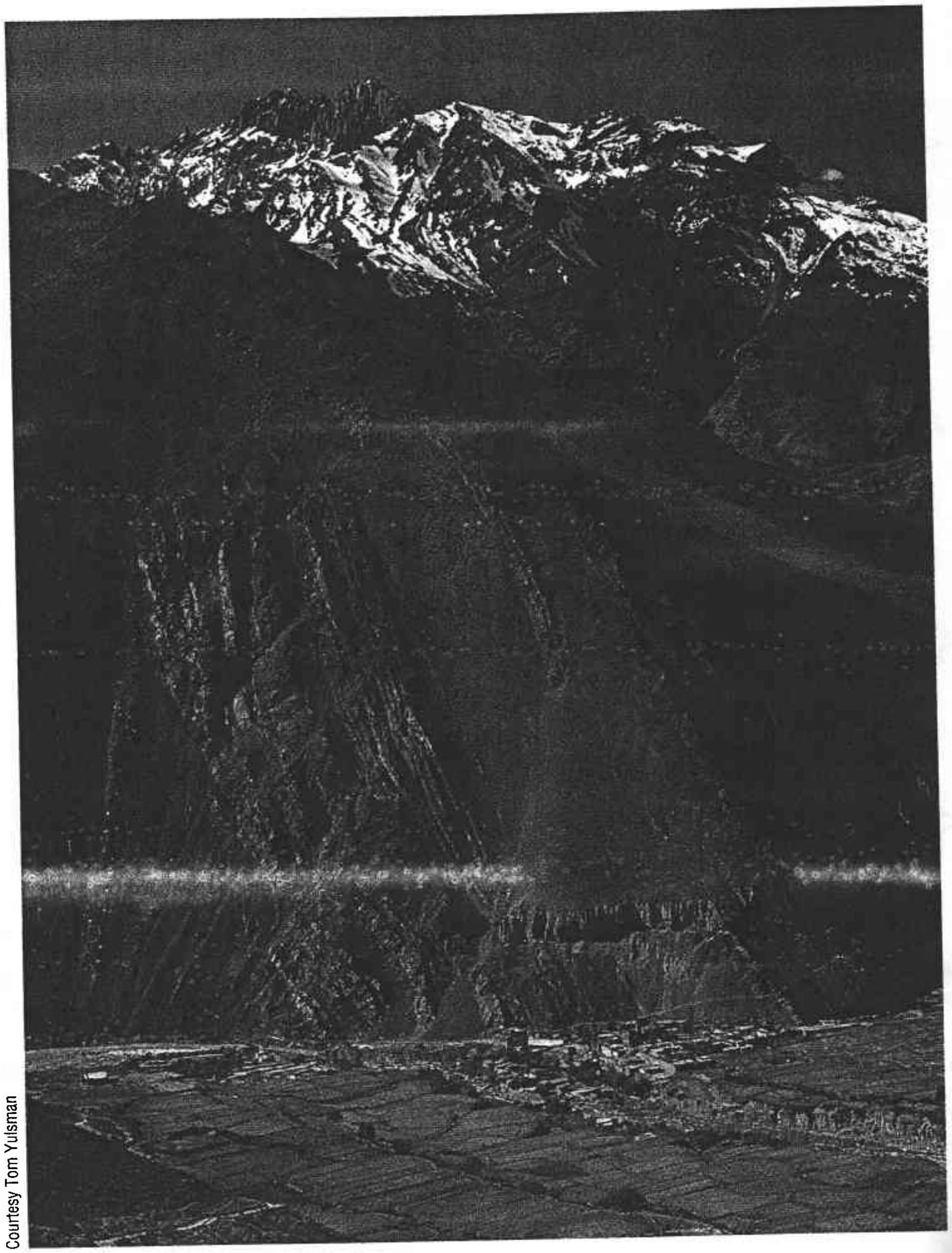
The marine creatures of Everest lived in the Tethys Sea, which separated the two land masses before the collision. When the subcontinent and Asia converged, the Tethyan seafloor and huge chunks of India broke into wedges that piled up, one on top of the other, to form the Himalaya.

Evidence of the oceanic origins of some Himalayan rock is found



The dark pyramid of Mt. Everest's summit, whipped by jet-stream winds, looms over the Khumbu Glacier in Nepal.

Galen Rowell/Mountain Light



Courtesy Tom Yulsman

The Himalaya Mountains were born in a collision between the Indian subcontinent and the rest of Asia. Evidence of this birth appears in vertical rock layers behind the Nepali village of Kagbeni on the Kali Gandaki River. The layers were tilted upright by the collision.

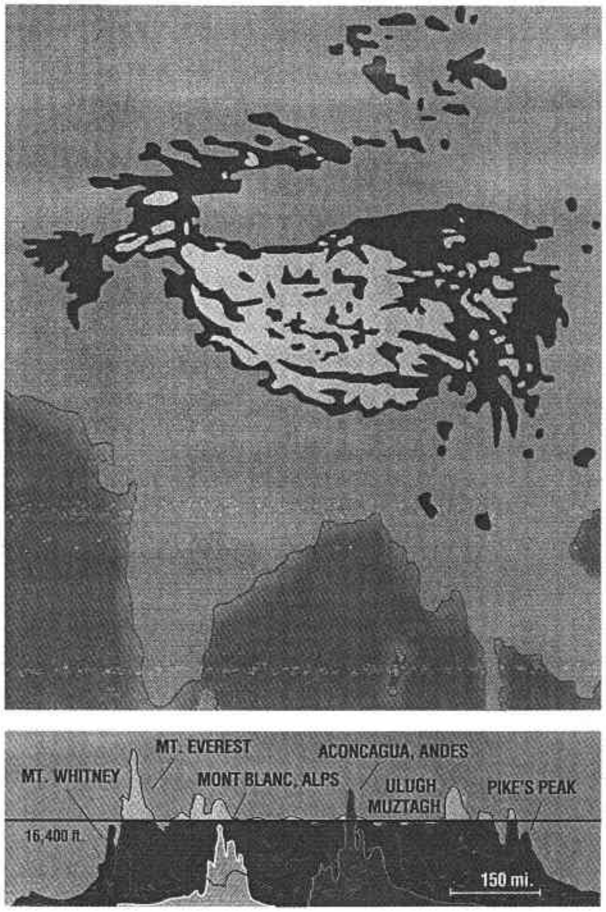
not just on Everest. Scientists have catalogued fossilized sea lilies and corals at many elevations in the region. And in villages in the Kali Gandaki river gorge, where farmers grow fruit and grain in the shadow of 26,810-foot-high Dhaulagiri, Nepali children hawk *salagramas* to travellers. Within these round, dull-black rocks are ammonites, fossilized shells shaped like tightly curved rams' horns.

The monumental collision that thrust seashells into mountain light also forced a region the size of France up to an average elevation three miles above sea level, higher than the highest summits in the Rockies. This region just to the north of the Himalayan peaks is the Tibetan Plateau. Scientists have long known that the low atmospheric pressure that develops in summer over the the vast plateau initiates South Asia's annual monsoonal rains. But the uplift of the plateau and the Himalaya may have done much more than create a regional weather pattern. According to a new theory, it may have reshaped the climate of the entire world, causing a cooling trend 55 million years long and initiating the cycle of ice ages that over the last two million years has, in turn, reshaped the face of the globe.

According to the theory, proposed by oceanographer Maureen Raymo of the Massachusetts Institute of Technology and paleoclimatologist Bill Ruddiman of the University of Virginia, the climatic reshaping has been accomplished through chemical weathering. Chemical reactions between water and rock that occur with this form of erosion remove heat-trapping carbon dioxide from the atmosphere. In the towering Himalaya, monsoon rains combined with incredibly steep slopes produce the highest rates of chemical weathering on Earth, rates so high that the carbon dioxide content of the atmosphere has been lowered substantially. This has led to global cooling — a kind of icehouse effect — the mirror image of the global warming expected to result from human-induced increases in CO_2.

Raymo and Ruddiman are not the only researchers investigating links between climate and mountain-building. Others have suggested that global cooling in the past few million years actually has accelerated the rate of uplift of peaks in the Himalaya and in mountains all around the world. The mechanism is, strangely enough, a kind of erosion again. Cooler climes, according to the theory, led to increased storminess and growth of glaciers, which eroded huge volumes of rock from the mountains. Like a freighter that rides higher in the water after its cargo has been removed, the mountains "floated" higher on the underlying mantle as rock was unloaded.

Thus, uplift of the Himalaya and the Tibetan Plateau could have led to cooling, which accelerated the uplift, which led to further cooling, and so on. In fact, one major problem facing the researchers is how to put the brakes on the mechanism they propose. There has been so much erosion in the region that, according to their theoretical model of the process, the atmosphere's concentration of CO_2 should have gone to zero.



Source: Peter Molnar

The light gray areas on the map of Asia show elevations in excess of 16,400 feet; the brown areas show elevations between 8,200 and 16,400 feet. The Himalaya forms the curving southern edge of this highest region on Earth, with the Tibetan Plateau directly behind it. Only isolated peaks in North and South America, Africa and Antarctica reach 16,400 feet and none do in Europe, as can be seen in the simplified profiles of mountain ranges below the map. (North American ranges are in purple, European in yellow and South American in green.)

The Earth was a very different place a little more than 60 million years ago, when Everest's seashells were still underwater. Paleoclimatologists believe that the climate was 15 to 20 degrees Fahrenheit warmer on average than at present, and sea level was two feet higher. Shallow seas like the Tethys covered large parts of the world's continental shelves. Then the Tethys closed and India slammed into the underbelly of Asia. Starting about 55 million years ago, global average temperature began to decrease, continuing at an uneven pace right to the present.

To estimate past temperatures, researchers enlist the aid of foraminiferans, singled-celled marine creatures that construct elaborate mineral shells around their bodies. Fossilized foraminiferan shells act as recorders of ocean temperature. They contain two isotopes of oxygen in the same proportion that existed in the ocean water at the time they lived. When ocean water cools, the proportion of one of the isotopes, oxygen-18, goes up. By analyzing foraminiferans taken from cores of seafloor sediments, scientists have found that oxygen-18 has been increasing in the world's oceans for the last 55 million years. There have been periods of slightly decreasing oxygen-18. But these fluctuations appear to be short-term phenomena superimposed on an overall long-term increase in oxygen-18, indicating a long-term temperature drop.

Most scientists studying climatic history believe this cooling must have been caused by a decrease in atmospheric CO_2, which affects the global climate because it is transparent to visual light but not to infrared. Much of the solar energy reaching Earth comes in the form of visual light, but much of Earth's reradiated energy leaves in the form of infrared. Since CO_2 allows the incoming energy to pass but blocks the outgoing, it tends to increase Earth's temperature. When CO_2 in the atmosphere decreases, scientists believe, more infrared escapes and the climate enters a cool phase.

To determine the concentration of atmospheric carbon dioxide in the distant past, scientists analyze air bubbles trapped in ice samples cored from Greenland and Antarctica. Unfortunately, this CO_2 record extends back only 175,000 years. There is no direct evidence that CO_2 had anything to do with climate change before that. Still, CO_2 and temperature have fluctuated in parallel since then. Carbon dioxide was high during brief, warm interglacial periods (like the one we're in now) and low when the world returned to cool ice age temperatures. Based on this evidence, Raymo and Ruddiman believe that the generally cooler temperatures of the last 55 million years were caused by lower levels of CO_2 in the atmosphere.

The question, then, is this: Why did the level of carbon dioxide decrease? Raymo teamed up with Ruddiman to find an answer in 1985, when she read about mathematical models of the Earth's climate system that attributed the change to a decrease in volcanism spewing CO_2 into the atmosphere. Although these models were in some ways very powerful, Raymo says, they had CO_2 falling fastest 160 million years ago, more than 100 million years before the climate is known to have begun cooling.

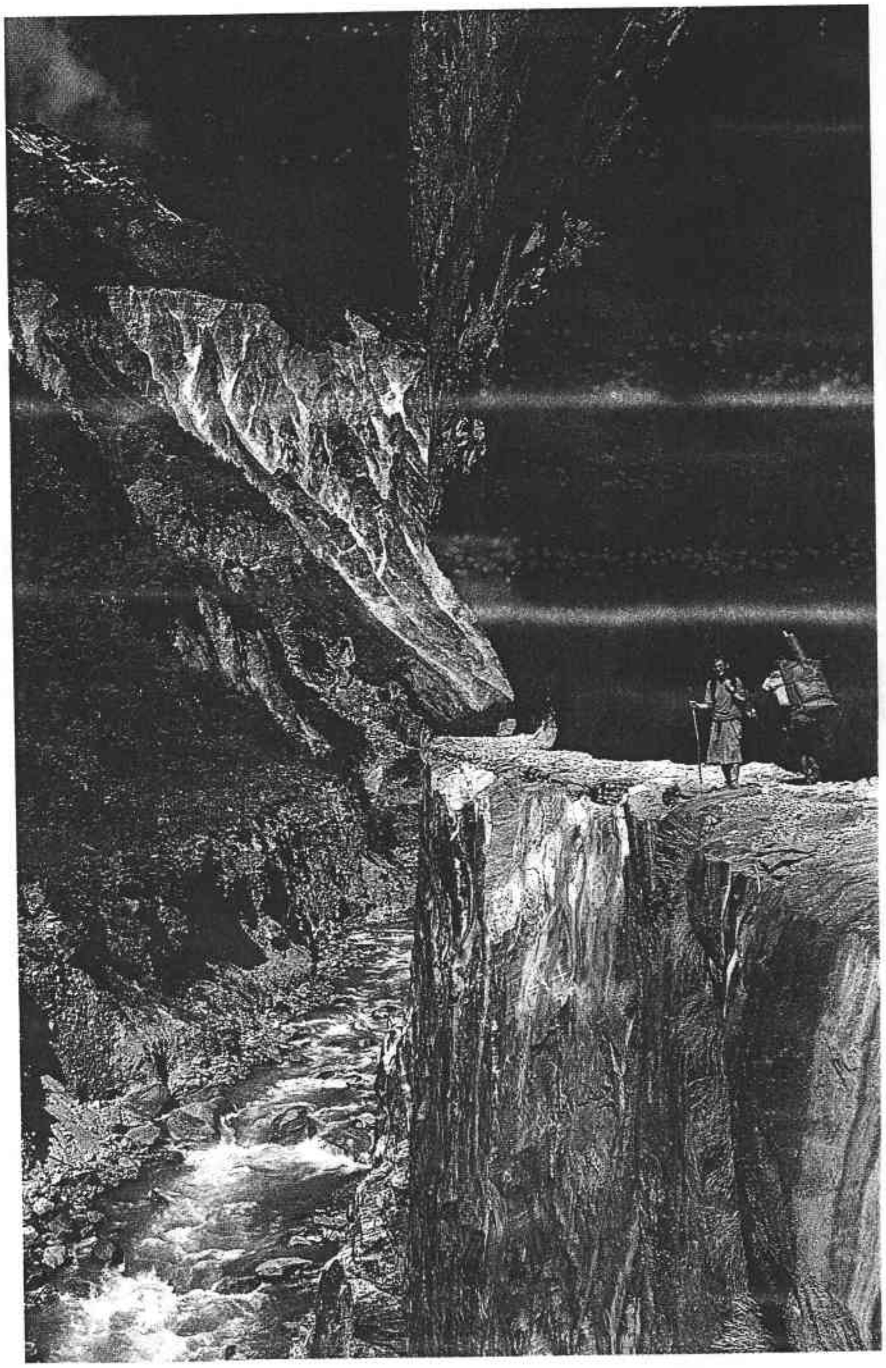
"The timing was way off," she says, "but I knew the uplift of the Tibetan Plateau had happened at about the right time to have something to do with the climate change."

Ruddiman had been considering how uplift could have affected Earth's patterns of air circulation. Raymo joined him in an effort to see how uplift could affect climate through chemical weathering. The theoretical model they have come up with brings together many areas of geochemistry, geophysics and atmospheric science, and it might be represented in its purest form as a flow chart. But it is best understood as a story.

When the Indian subcontinent collided with Asia, the raising of the Tibetan Plateau changed the local weather patterns. When the sun beats down on the thin air above the vast plateau every summer the air warms rapidly and begins to rise. "Air is leaving the region, pressure is going down, so air has to come in and replace it, and that's the air from the Indian Ocean," Ruddiman explains.

This air initially comes laden with moisture, but the water never reaches the plateau itself. It falls instead as rain over the plains of India and in the Himalaya, the annual summer/fall monsoon. "The plateau creates the monsoon," Ruddiman says. "Without it the models suggest that you'd have a dry, almost desert condition in the southern Himalayan region."

The monsoon associated with the Tibetan Plateau is by far the strongest in the world. This is because no other region produces as intense and widespread a low pressure system in such close proximity to tropical waters as the plateau does. Tibet's position near



the Indian Ocean means that air drawn toward it during the monsoon carries an exceptional amount of water.

When the heavy monsoon rains fall in the Himalaya, they wash over a huge area of exposed rock. Because this mountainous region is so high, so steep, and so deeply wrinkled, it presents a much larger surface area to the elements than less-rugged regions of the same area. For this reason, the Himalaya is subject to a rate of weathering that is as extreme as its topography.

Raymo and Ruddiman's model hinges on high rates of chemical weathering, which occurs when molecules in rock react with water, dissolving some of the substance of the rock in the water. It contrasts with mechanical weathering, which occurs when water, wind or ice physically breaks rock into small pieces and carries the pieces away. Mechanical weathering ultimately produces solid material like sand. Chemical weathering produces dissolved carbonate minerals, billions of tons every year, that rivers carry to the oceans.

Prior to the uplift of the Himalaya and the Tibetan Plateau, no region stood nearly as tall, and no mountainous area likely was subjected to monsoonal rains as intense. Thus, the uplift of the region likely resulted in a huge increase in chemical weathering. In fact, the Himalaya and the plateau are estimated to produce 25 percent of all dissolved minerals that reach the ocean, even though they cover only 5 percent of the Earth's land surface.

Chemical weathering affects climate because the reactions between rock and rainwater often involve CO_2 that rain absorbs from the atmosphere. When carbon dioxide dissolved in raindrops comes in contact with silicate rock, it enters into a chemical reaction that produces the dissolved carbonate minerals. After this dissolved carbonate finds its way into the oceans it is eventually deposited on the seafloor as sedimentary rock, usually limestone. This locks the CO_2 away, insuring that it won't re-enter the atmosphere for many millions of years.

In this way, chemical weathering of silicate rock sucks carbon dioxide out of the atmosphere. Notwithstanding the marine rocks exposed on Everest and in other locations, most of the rock exposed in the Himalaya and Tibetan Plateau is silicate.

Even if there were no Himalaya and Tibetan Plateau, chemical weathering and removal of CO_2 from the atmosphere would be occurring on a grand scale. The process is a fundamental part of the Earth's carbon cycle. Emission of new carbon dioxide into the atmosphere by volcanism completes the cycle. Volcanic activity emits 300 million to 1.1 billion tons of the gas every year. That's much less than the 20 billion tons human beings are adding to the atmosphere every year by burning fossil fuels. But on the geologic time scale, volcanoes are the primary source. We will stop burning fossil fuels soon because we simply will run short. But volcanism will continue. What's more, the carbon in fossil fuels is itself nothing more than atmospheric CO_2 converted into organic form by plants millions of years ago. Volcanoes are, in fact, the ultimate source of fossil fuel CO_2.

The balance between the carbon dioxide emitted by volcanoes and the amount of the gas removed by chemical weathering largely determines the concentration of carbon dioxide in the atmosphere. Raymo and Ruddiman believe that during most of the last 55 million years that the climate has been cooling, the rate of volcanic input of carbon dioxide has held steady.

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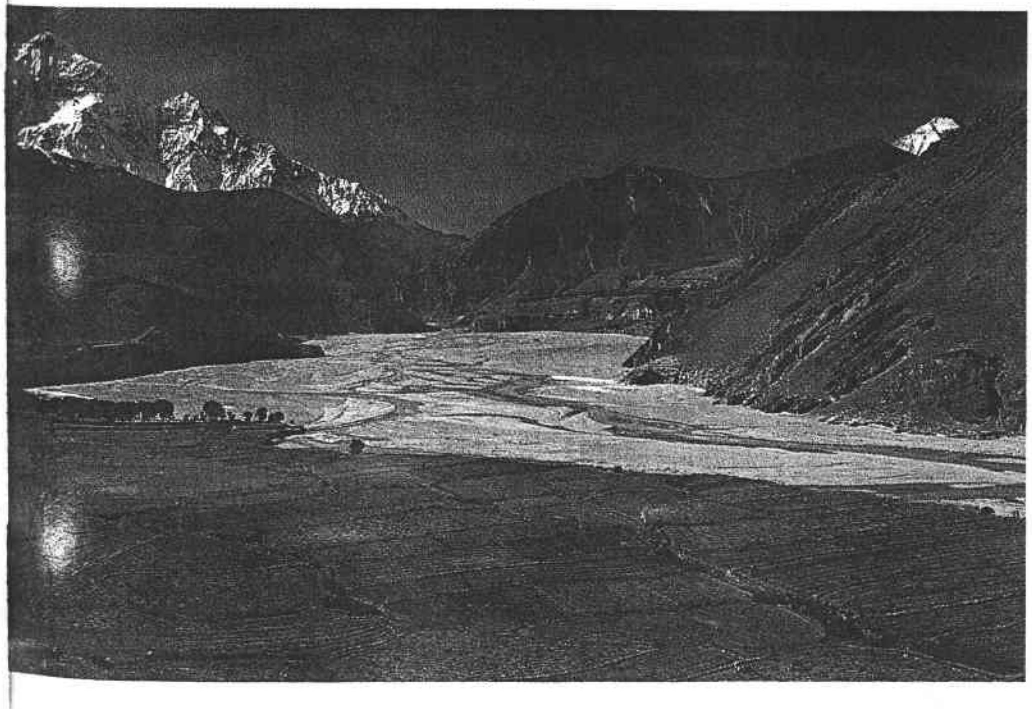
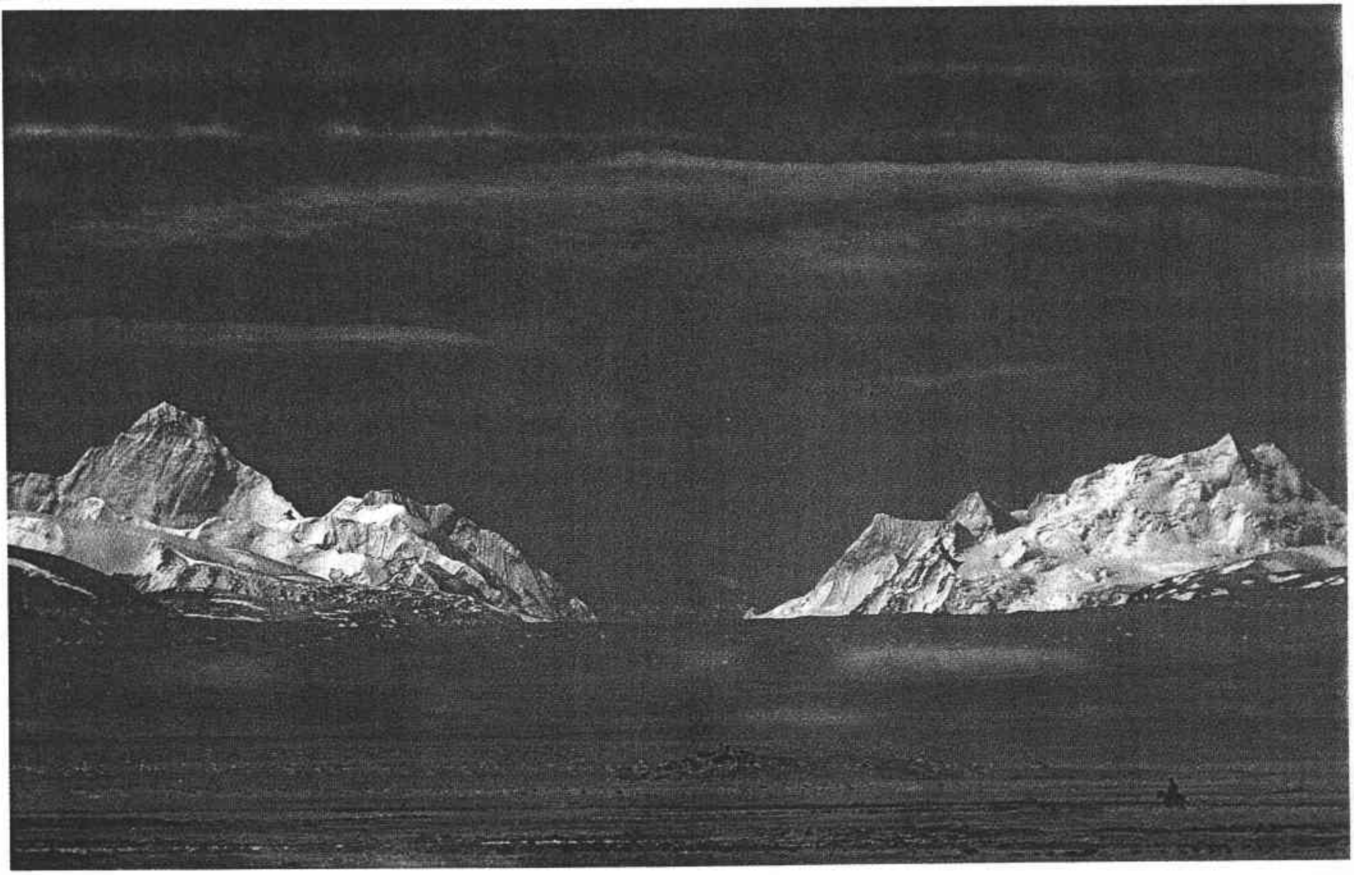
Water cascading over bare rock, as in the waterfalls in the Nepali village of Tal (upper left), causes chemical weathering, which draws carbon dioxide out of the atmosphere. Flowing water also erodes rock mechanically. Severe erosion along Nepal's Marsyandi River (left) has forced relocation of a trail directly into a cliff face. Nepal's Kali Gandaki River (below) has carved a gorge that is among the deepest in the world. Erosion removes so much rock from the range that the crust in the region "floats" higher in the underlying mantle, much as a freighter rides higher in the water after its cargo has been removed.





Nangpa La, the pass seen in this view looking south from the Tibetan Plateau, is a tremendous gap in the Himalaya. At an elevation of 19,000 feet, the pass leads into Nepal between the 26,000-foot Cho Oyu massif to the east (left) and Rolwaling Himal, the massif to the west.

During the same period, the rate of CO_2 removal by chemical weathering has increased by 25 percent, thanks to the uplift of the Himalaya and Tibet. But this presents a problem.

"At some point," Raymo says, "let's say you just keep eroding material so you're drawing down CO_2. And let's say it's coming in at a fixed rate from volcanoes, and you're taking it out faster than you're putting it in. You can relatively quickly strip the atmosphere of CO_2. And by relatively quickly I mean about a million years."

This would lead to what Raymo and Ruddiman call a runaway icehouse effect. The Earth would then become as cold and lifeless as Mars. If chemical weathering has indeed been increasing at the rate they suspect, then something must have been providing extra CO_2 to the atmosphere.

The two researchers are now trying to determine what that something might be. They are not looking for some deus ex machina, a source of new CO_2 that just happened to come along at the very moment when it was needed to save life on Earth. Such a lucky coincidence would make any scientist suspicious of the whole theory. What Raymo and Ruddiman need is a sort of automatic mechanism by which CO_2 depletion and global cooling could limit themselves.

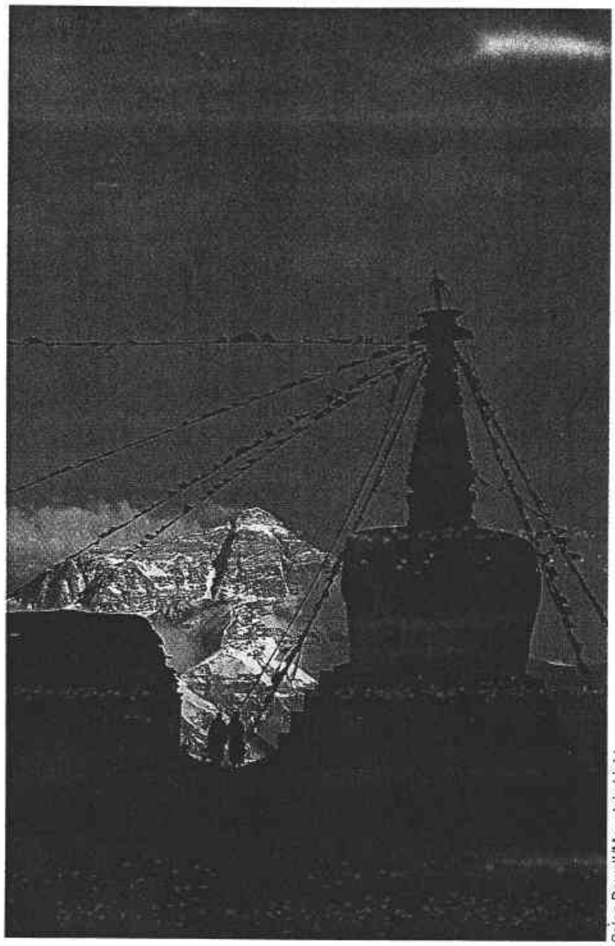
Such limiting mechanisms are known as negative feedbacks. Raymo believes that the feedback preventing a runaway icehouse effect was most likely linked to the movement of carbon from atmospheric CO_2 into the bodies of plants and animals and then back into the atmosphere, sometimes with a side trip into coal, oil or gas. This loop is called the organic carbon subcycle. The growth, death and decomposition of a tree make up a part of this subcycle; so does the burning of fossil fuels.

Since temperature affects many of the processes involved in this subcycle, it is very plausible that it could provide a negative feedback, Raymo says. Lower temperatures at the ocean surface due to global cooling, for example, could lead to higher oxygen concentrations in deep ocean water. This increased oxygen could help sustain an increase in the productivity of microorganisms that convert organic carbon in the ocean back into CO_2. As these organisms produce more and more CO_2 they prevent it from being buried on the ocean floor. This CO_2 would then find its way back into the atmosphere, preventing a runaway icehouse effect. Raymo is looking for evidence of this or some similar process.

There may also be weaker positive feedbacks that are trying to push the decrease in atmospheric CO_2 further. Earth's geochemical cycles are notoriously complex, and attempts to map them completely lead to flow charts far more complicated than any governmental organizational chart — "one big spaghetti diagram," as Raymo puts it.

In this spirit, she and Ruddiman also propose a positive feedback by which the uplift of the Himalaya and the Tibetan Plateau could be accelerated by the resulting climatic effects. With this proposal, they are building on the work of two other researchers, seismologist Peter Molnar of the Massachusetts Insitute of Technology and geologist Philip England of the University of Oxford in England. In a 1990 paper in the journal *Nature*, Molnar and England described a mechanism by which cool climates could cause an increase in erosion, which in turn would cause mountaintops to rise.

Cool climates can increase erosion in two ways. First, they may be accompanied by increased storminess, which means more water flowing over mountain slopes and through river valleys. Second, they bring glaciers into being. Glaciers are powerful agents of erosion, as a look at Yosemite Valley will confirm. Today it is broad, rounded and steep-sided, essentially a U-shape in cross section. But it once was shaped like a narrow V, until a glacier bulldozed its way through, gouging out millions of tons of rock.


Galen Rowell/Mountain Light

Mt. Everest (known locally as Chomolongma) is framed in the silhouetted Rongbuk monastery in Tibet. A pass on the eastern side of the mountain is called Changri La.

But why would increased erosion make mountaintops rise? Rivers and streams do most of the wearing away of rock, cutting valleys deeper and deeper as they go. Enough weight is removed from the crust by this process to cause it to "float" higher in the mantle. Since mountaintops usually erode very little, they rise up and stay up as the crust rises. Meanwhile, the steepened terrain causes the rivers to cut deeper still. The net result is that as valleys are being eroded lower and lower, mountain peaks are getting higher. This actually leaves the average elevation of a region almost unchanged.

What began as a flat landscape at an elevation of X gradually turns into a mountainous region with valleys much lower than X and peaks higher than X, but an average elevation of just a little less than X. When this happens to the Tibetan Plateau, where X equals three miles, the result includes the highest mountains in the world. The result also includes a cooler climate and thus more erosion. This creates a positive feedback that drives the world to cooler and cooler climates.

About two million years ago, the temperature seems to have passed a threshhold. Instead of decreasing steadily, the global average temperature entered into a cycle: the alternation between extra-cold ice ages and warmer interglacial periods. The cycles may be caused by variations in Earth's orbit that affect the amount of sunlight reaching the Northern Hemisphere during the summer. But the cycles did not begin until the planet reached a cool enough temperature for the orbital cycles to have an impact. And since the ice ages began, they have had a significant effect on the rate of erosion in the Himalaya, the Tibetan Plateau and elsewhere.

Geological evidence suggests that the Himalayan peaks began a period of rapid uplift about two million years ago, about the time of the first ice age. Molnar believes this uplift was caused not by any change in the tectonic forces acting on the mountains, but by the erosive power of glaciers that appeared at that time. "I wouldn't be surprised if you didn't have high peaks in the Himalaya three million years ago," he says, "but you did have an elevated terrain with gentler slopes."

The top of Mount Everest is believed to be rising today at about a tenth of an inch per year, while the Himalayan valleys erode at about twice that rate. But the Himalaya is not the only mountain range whose peaks appear to have risen since the advent of ice ages. The Rockies, the Pyrenees, the Alps, the Southern Alps of New Zealand — all appear to have risen in the past three million years. All probably changed to their present rugged form from gentle-sloped ranges similar to today's Appalachians.

Of course, many non-mountainous regions have had their terrain altered by the ice ages. In northern North America, Europe and Asia, there is ample evidence of the passage of the great continental ice sheets: rocks and debris deposited in jumbled moraines where glaciers halted, hills streamlined in the direction glaciers passed, dry beds of ancient ice-dammed lakes. All of this means that you don't have to travel to India, Pakistan, Nepal or Tibet to see the results of the ancient collision of India and Asia. The evidence is to be found all around the world.⊕