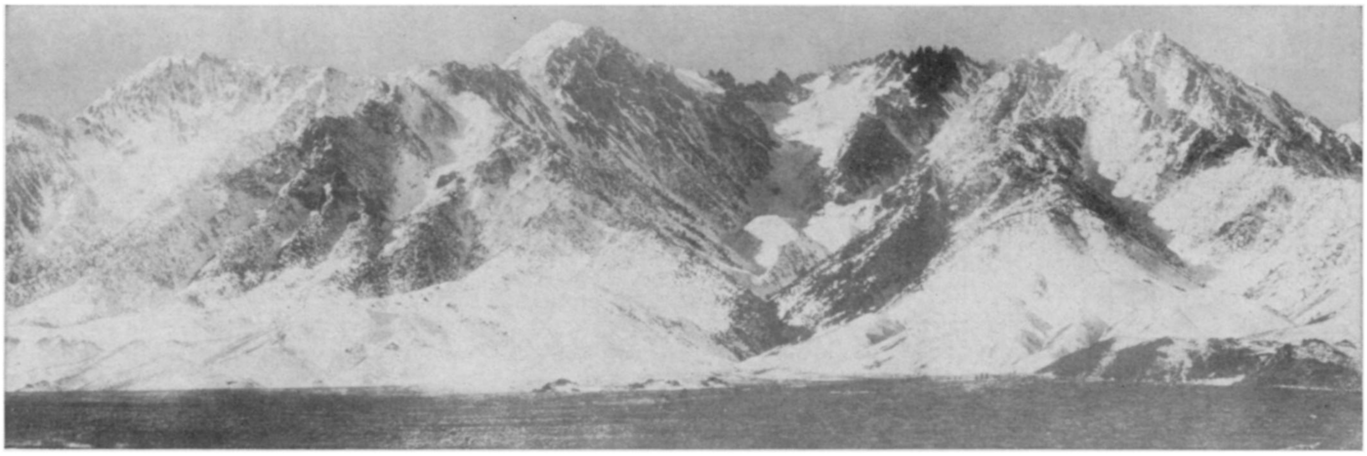


U.S. Geological Survey

The Sierra Nevada mountains, nearly two miles high, are an example of cordilleran-type mountain ranges.

GEOLOGY

Building mountain ranges: a plate tectonics model

Extensive studies of the ocean floor by geophysicists have resulted in a new understanding of the complex forces involved in making mountain belts

by Kendrick Frazier

The processes that raise mountains and crumple the earth's surface have traditionally posed some of the more baffling problems in the earth sciences.

One of the better-developed explanations has been the principle of isostasy —that areas of the crust being loaded with sediments tend to sink and that areas being relieved of some of their burden by erosion tend to rise. Another proposal is that thermal convection in the mantle beneath the continents produces rising subsurface movements that push the mountains upward.

But most major mountain belts seem to have been formed primarily by horizontal compressions. These lateral movements rumple sediments laid down over millions of years, wrinkling them like a pile of blankets pushed from one side. Many early geologists believed that the wrinkling was a result of a slow, steady contraction of the earth as it cooled. The evidence against a shrinking earth, however, is formidable. The distribution of natural radioactivity in the interior, for instance, indicates that the earth is probably not cooling at all.

Then the opposite hypothesis arose, that mountain building is a result of a gradual heating up of the earth's interior, causing the rocks to decrease in volume as they pass from a solid to a molten state, like water in a melting ice cube. Even an expanding-earth hypothesis was proposed, but met little favor.

In the last decade earth scientists interested in mountain building began taking an increased interest in the mounting evidence for continental drift. The original theory became greatly modified by the hypothesis of sea-floor spreading and then, in 1968, was generalized by the sweeping new theory of plate tectonics (SN: 11/8/68, p. 430).

In this view, the earth's lithosphere —the crust and uppermost mantle— is segmented into a number of rigid plates bordered by the world's major seismic zones. Plates grow at the ocean ridges by accretion of magma, are consumed in the ocean trenches, and move horizontally at an average rate of several centimeters per year. Most of the evidence has come from seismic, magnetic and heat-flow studies of the ocean floor.

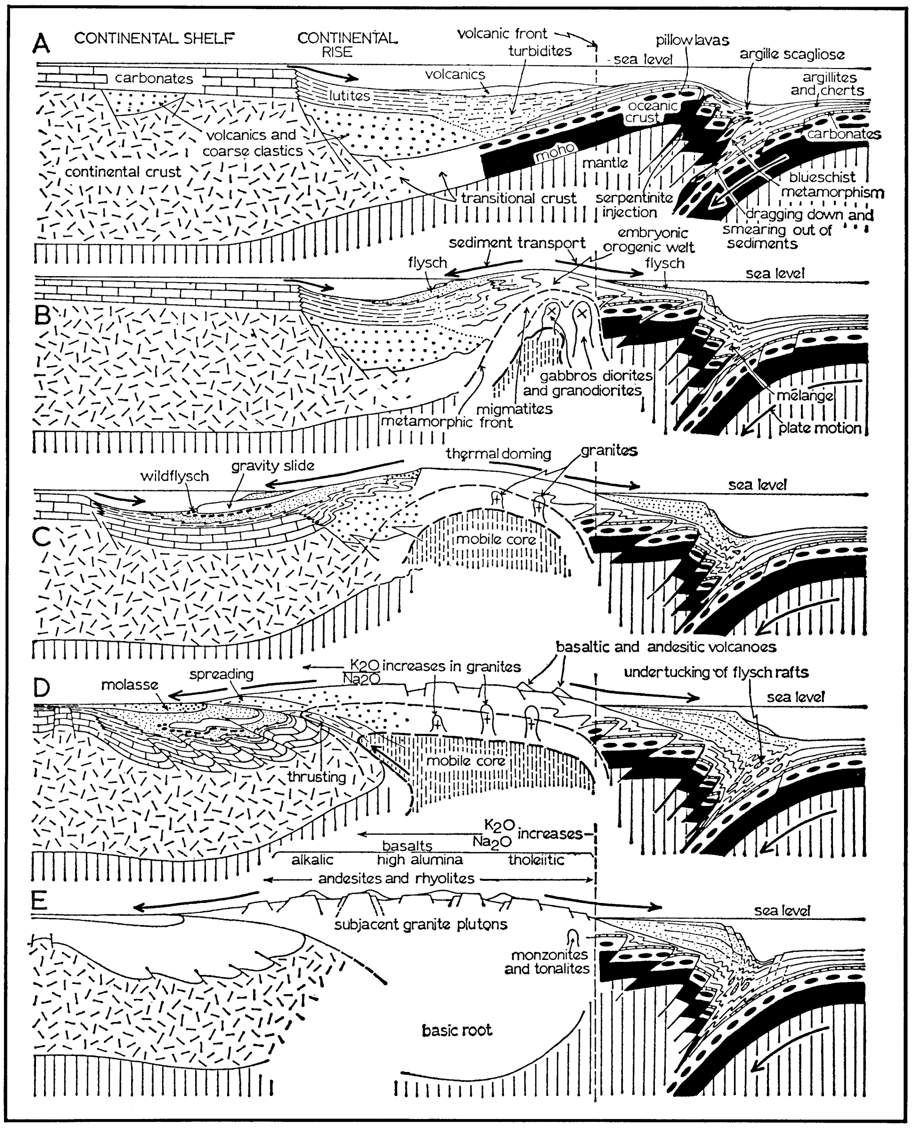
It was then that geologists began to realize what they had been given by their geophysicist colleagues: the first unifying worldwide explanation for continental tectonic processes such as the creation of mountain belts.

In early 1969, Dr. John F. Dewey of Cambridge University in England and Dr. John M. Bird of the State University of New York at Albany, both geologists, were struck by the revolutionary implications of plate theory for continental geology. They quickly began applying the new ideas to the geology of mountain belts; their collaborative studies have helped lead to a new understanding of mountain building.

"It is tremendously exciting," says Dr. Bird. "We can now legitimately say that we know how the world's mountain belts are formed. They are all due to plate motions."

He and Dr. Dewey put it more formally in the May 10 JOURNAL OF GEOPHYSICAL RESEARCH, one of the several papers they have published on the subject in the last few months. "Analysis of the sedimentary, volcanic, structural and metamorphic chronology in mountain belts," they write, "and consideration of the implications of the new global tectonics (plate tectonics) strongly indicate that mountain belts are a consequence of plate evolution."

Dr. Bird finds it ironic, and instructive, that the fundamental answers about the formation of mountain belts on the continents were discovered primarily by studies of the ocean floor. To geologists, who historically have been bound to the continents and to tradition more than other scientists, the lesson is one they probably will not forget. "It was ridiculous for us to



Journal of Geophysical Research

A representation of the evolution of a cordilleran-type mountain belt.

think that we could figure out how to make mountain belts by looking at only 30 percent of the earth," he says. The 70 percent covered by the oceans held the answer.

Drs. Dewey and Bird propose that mountain building occurs in two basic ways. One occurs when a plate of lithosphere that has nothing but an ocean above it descends into a trench. This can be either at the margin of a continent or at the edge of a major arc of islands such as those around the western Pacific Ocean.

The type of mountain belt that results is typified by the Andes of South America and the entire system of western North America that includes the Sierra Nevada, Coast Range, Cascade Range and Rocky Mountains. These they call cordilleran-type mountain belts.

The other occurs when a plate of lithosphere descending into a trench is carrying a continent that collides with an island arc or with another continent. The most striking example of this type is the Himalayas. They have been formed by the collision of the Indian subcontinent with Asia. Another example is the Zagros Mountains of Iran, formed by the collision of Arabia with the Iran plateau.

In the formation of cordilleran-type mountain belts, the dominant mechanism at work is thermal; in collision type mountain belts it is mechanical. Drs. Dewey and Bird, building on the work of many scientists in recent years, postulate a complex series of events producing the mountains by each method.

In the evolution of cordilleran-type mountain belts, wedges of oceanic crust and mantle are first driven oceanward as the plate of lithosphere begins to sink at the continental margin. The rate of descent is probably related to the thickness and density of the plate, both of which increase as the plate grows away from the mid-ocean ridges.

As the oceanic plate descends to depths of 100 kilometers or so, the high load pressures and shear stresses of oceanic crust on the descending plate produce partial melting. The partial melting produces basaltic and calc-alkaline magma. The heat generated by the rise of the magma produces a subsurface dome of rock with magma in the center. As the dome expands and grows toward the continent, the high-temperature deformation and metamorphism begins to affect the sediments of the lower continental rise.

The growing welt soon rises above sea level, forming a trough between it and the continent that eventually fills with sediments. All this material is slowly driven toward and thrust up onto the continent, and development of the mountain belt is completed.

If this process begins adjacent to a continental margin, mountain belts are formed along the edge of the continent, although the deformations can migrate into the continental interior. But if the process begins at a trench a considerable distance from a continent, an island arc grows within the ocean and a small ocean basin forms between it and the continent. This is the situation around the western Pacific.

When the two interacting plates of lithosphere are carrying continents on their backs, the mountain-building process is considerably less subtle. A single trench zone of plate consumption is soon replaced by a cracking and splintering of the lithosphere over a wide area. The collision produces large mountains such as the Himalayas. If one of the plates is carrying a group of islands rather than a continent, the resulting mountains are much smaller, like those of northern New Guinea.

Although the two basic mechanisms described by Drs. Dewey and Bird are, they believe, the fundamental ways in which mountain building occurs, most mountain belts are probably a result of complex combinations of these mechanisms. The Alpine-Himalayan system, for example, has been developing since early Mesozoic times—200 million years ago—by multiple collision resulting from the sweeping of microcontinents and island arcs across the ancient Tethyan-Indian Ocean (SN: 7/4, p. 20). Another complex situation results in the formation of mountain belts, such as the Urals, lying well into the interior of continents. The Urals, they suggest, may be complex combinations of cordilleran belts, microcontinents and volcanic arcs of widely differing ages that became juxtaposed by the driving out of a major ocean basin separating parts of what is now the Soviet Union.

U.S. Geological Survey

The Appalachian Mountains: The relationships of the rocks and sediments are similar to the Atlantic floor.

Frazier

Dewey and Bird: Applying the new ideas to the geology of mountain belts.

The most detailed geological scrutiny conducted by Drs. Bird and Dewey has been on the northern Appalachian Mountains of North America. The Appalachians, geologists now believe, 250 million years ago formed part of a continuous mountain chain extending from Florida across southern Greenland to Spitzberg, north of Norway.

After reviewing and synthesizing geological findings about the Appalachians by many workers during the last decade, Drs. Bird and Dewey propose a model for their evolution based on an opening and closing of a proto-Atlantic Ocean prior to the opening of the present Atlantic.

In late Precambrian times, they propose, a continuous North American-African continent began to distend and break apart. The two land masses continued spreading until they reached their maximum separation in early Ordovician times, about 500 million years ago. Then contraction began. Oceanic lithosphere was consumed in a trench beneath what is now eastern North America, and cordilleran-type mountains were created.

By mid-Devonian times, about 360 million years ago, the sub-sea margins of the two continents collided, causing further mountain building by that process. The continents later split apart again along a somewhat different suture line to create the present configurations of America and Africa.

The strength Drs. Bird and Dewey give to these global mountain-building models based on plate tectonics is their attention to the detailed geology of the mountains involved. Geophysicists have said for several years that plate motions could be responsible for many of the earth's mountain ranges. Now geologists such as Drs. Bird and Dewey are combining the ocean-floor evidence with land-geology data and finding the correlations too close to explain away.

"What we find when we unravel the geometrical and chronological relationships of the rocks and sediments of the Appalachians," says Dr. Bird, "is a pattern that looks just like the floor of the Atlantic Ocean." The same can be said for other world mountain belts.

In the Appalachians are found traces of all the units of the ocean floor: igneous oceanic crust formed at mid-ocean ridges (abundant in northern Newfoundland, for example); continental rise material (abundant in the Taconic Mountains of eastern New York); continental shelf material (the East Coast carbonate strip such as in the cement quarries of Pennsylvania); deep oceanic sediments (found east of the carbonate zone), and melanges of oceanic trench material (also in northern Newfoundland).

Throughout the Appalachians, the displacement of rock zones and the lean of sediment folds toward the northwest indicate strong lateral thrusting in that direction—the same direction in which the oceanic plate of the proto-Atlantic postulated by Drs. Bird and Dewey was moving in Paleozoic times. Newer mountain belts in other parts of the world show clear signs of deformation in the direction in which present adjacent oceanic plates are moving.

"We believe that the whole sedimentary and structural framework of orogenic (deformational mountain) belts is related to the expansion and contraction of ocean basins," conclude the two geologists. "Plate tectonics is too powerful and viable a mechanism in explaining modern mountain belts to be disregarded in favor of ad hoc, nonactualistic models for ancient mountain belts." They believe that plate tectonics probably explains the formation of all the major mountain belts that have come and gone during at least the last billion years of the earth's history. ☐