Plate Tectonics (II): Mountain Building and Continental Geology

The development of plate theory and the growing recognition that the earth's surface has been markedly rearranged throughout its history by plate movements has prompted geologists to reexamine many of their ideas about geological processes. As a result, a new theory of mountain building has been developed, relating mountain building to the destruction of oceanic crust in a trench and the collision of continental masses. Geologists are using the new theory to explain the structures of mountain belts all over the world—from the Alps and the Appalachians to the Urals—and to relate their structures to the movements of the crustal plates. According to some geologists, there is evidence of plate movements and interactions that took place as far back as 2.5 billion years ago. Eventually, geologists hope to understand how platelike blocks of crust first formed on the cooling earth and thus how continents began.

The way in which geologists use plate concepts in their research depends partly on the period of the earth's history under study. For the most recent period, backward from the present to the breakup of Gondwanaland and the opening of the Atlantic about 200 million years ago, data from magnetic studies of the ocean floor can be used to infer past movements of the plates; plate motions can then be used to interpret geological formations on the continents.

Prior to this, however, a different approach is necessary, because the older oceanic crust, having been destroyed in trenches or incorporated into mountain belts, is no longer available for study. In studying the period between 200 million years ago and the time when crustal plates were first formed, perhaps 2.5 billion years ago, geologists are using evidence from continental rocks to locate regions of past tectonic activity corresponding to former plate boundaries. By identifying rock assemblages that are thought to be old oceanic crust, geologists hope to determine plate motions at least qualitatively as far back as the end of the Precambrian era (600 million years ago) and to gain new insight into events throughout much of the Precambrian. In the period before 2.5 billion years ago—extending back to the age of the oldest known rocks (almost 3.5 billion years)—plates similar to those of today may or may not have existed; but some geologists have speculated that tectonic mechanisms such as trenches and spreading centers may have played a role in the history of the thinner, less rigid crustal pieces that are thought to have been present at that time.

Mountain Building

Mountain belts are commonly characterized by their relatively thick layers of sedimentary rocks from successive geological periods which are exposed as parallel "stripes" along the belt. The complexity of the pattern had puzzled geologists for years. Before plate tectonics, it was usually assumed that such mountain belts were formed in place as a result of sinking and sedimentation, followed by compression, folding, and uplift as a result of inexplicable forces.

In contrast, the plate tectonic theory of mountain building, as developed by John Dewey and John Bird of the State University of New York at Albany, and others, assumes that much of the material in mountain belts was formed elsewhere and eventually was incorporated into the belt as a result of plate motion (*1*). According to their theory, mountains are formed at the margins of continents, as a result of the consumption of a plate in a trench or the collision of the continent with other pieces of continental crust. When a trench opens to consume oceanic crust near a continental margin, thermal processes are believed to cause material to rise from the region of the mantle above the descending plate and to form a mountain belt such as the Andes. Continental rocks, however, are apparently too light to descend into a trench, so that, when two continents or a continent and an island arc approach each other, the resulting collision creates mountains by mechanical processes. The Himalayas, for example, are thought to be the result of a collision between the Indian and Asian plates.

Attempts to interpret mountain belts in terms of plate tectonics involve reexamination of the existing literature as well as new field studies of critical areas. Geologists are trying to integrate the geological record of whole regions with plate motions. For example, the Alps, which are one of the most complicated structural belts in the world, are now thought to be a result of repeated collisions between the African and European plates during the opening of the Atlantic Ocean. Therefore geologists are now restudying the Alps; by correlating particular rock assemblages with the margins of the crustal plates as they existed at the time the rocks were formed, geologists are trying to work out a detailed history of how the Alps were formed. A knowledge of the plate motions, inferred from marine magnetic data, and of the geological sequences of rock types in the mountain belt will make it possible for geologists to piece together the system of trenches, spreading centers, and collisions that formed the Alps.

The Caribbean region has also been the site of mountain building for the last 120 million years. The history of the region, like that of the Alps, depends on the interactions of two plates—those of North and South America—whose relative motions are still incompletely known.

Ranges such as the Alps and the Andes are relatively young and are associated with current plate boundaries. But mountain building by plate motions prior to the last 200 million years is suggested by studies of older mountain ranges such as the Appalachians and the Urals. Rock sequences in these mountain belts appear to have a strong resemblance to those in more recent mountain ranges. Analysis of the Appalachian range and of the corresponding Caledonian range in Great Britian—by Dewey, Bird, and William Kidd of Cambridge University—indicates that these mountains were formed in part from oceanic crust and in part from sediments that were originally deposited in a "proto-Atlantic" ocean. This predecessor to the present-day Atlantic Ocean seems to have opened in the late Precambrian, then closed to form the mountains in the late Paleozoic era (about 300 million years ago). According to this interpretation, some of the rocks in the Appalachians represent pieces of old oceanic crust that was entrapped in collisions and trench processes very similar to those occurring now.

Similarly, the Ural Mountains in central Russia are thought to be associated with the convergence and collision of the Russian and Siberian plates some 300 million years ago, and the disappearance of the intervening ocean into a series of trenches. According to Warren Hamilton, of the U.S. Geological Survey in Denver, the convergence process was a gradual one; each subcontinent apparently grew oceanward as island arcs collided with them, and the trenches on the continental margins approached each other. The regions between the trenches and the continents, where volcanic activity often occurs, also migrated oceanward. Eventually, according to Hamilton's analysis, the continental pieces collided, thereby incorporating oceanic crust and the debris from trenches and island arcs into the present mountain chain.

The internal evidence within a mountain belt can show such a sequence of events, according to William Dickinson of Stanford University, when interpreted in terms of the theory of trench processes on continental margins. Although many of the details are not yet understood, magmatic rock is believed to form above and slightly inland from a trench in such a way that its potassium concentration will vary systematically away from the trench. This potassium gradient can be found in the volcanic rocks of most mountain belts. Further inland in a mountain belt, there is typically a lowland belt of sediments that have been deformed from the side nearest the volcanic belt. On the oceanic side of the volcanic belt, a third belt of oceanic material that has been altered by subduction into a trench is often found. These parallel belts are now believed to be good indicators of past plate margins, and, when dated and analyzed for rock types, to allow at least a qualitative reconstruction of the processes by which the mountains were formed.

Formation of Continents

The relative motions of the crustal plates have dramatically altered the map of the world in past eras. Asia, for example, may be an agglomerate of as many as 15 plates that have been joined together within the last 500 million years. The process is continuing today; the Australian plate is thought to be in the process of colliding with that of Southeast Asia.

The geologic history of the western United States is also beginning to be unraveled. Tanya Atwater of the University of California at San Diego has studied the relative motions of the American and Pacific plates and examined their implications for the geology of the regions. Magnetic data obtained from the seafloor off the California coast shows that about 30 million years ago the westward movement of the continental plate overrode a trench, the continuation of which still exists to the south off the South American coast. Atwater examined two models of plate motions since the disappearance of the trench, one of which is based on the assumption that the Pacific and American plates were fixed with respect to one another until they broke along the San Andreas fault system 5 million years ago. A second model, which she thinks is more probably correct, assumes a constant relative motion between the plates and predicts a greater amount of deformation of the region than does the first model. The present relative motion along the fault, according to her analysis, is at the rate of 6 centimeters per year.

The geologic history of the western United States, and in particular of the Rocky Mountains, goes back beyond 200 million years. One of the earliest events appears to have been a rifting process that tore off a triangular piece of the continent from the southwestern corner in the late Precambrian. The missing piece, according to Hamilton, eventually collided with Asia and is now part of northeastern Siberia. After the rifting event, material that became the western mountain belts is thought to have accumulated along the continental margin as island arcs moved in and collided with the west coast.

Even the older Precambrian rocks that constitute the bulk of the central continental masses are all very much deformed, and, according to Dickinson, are probably related to earlier episodes of continental rifting, repositioning, and collision. Of particular interest is the period before about 2.5 billion years ago, when the first large areas of continental crust were apparently forming and when plate concepts may not be valid to interpret the geology. Although ideas about the formation of continents are still very speculative, the success of plate theories in explaining more recent geology has convinced some geologists that continents evolved in a continuous process; previously, many had thought that continents were formed in a single episode very early in the earth's history. A related problem concerns the geochemical differentiation of the earth—how the lighter elements were extracted from the mantle and aggregated in the continental crust. The crust in this early period was apparently much thinner than it is at present, and volcanism was much more common. But there may still have been "soft" crustal slabs (which later hardened into plates) that moved relative to each other and interacted in trench systems, and this process may have been important in the gradual buildup of continental crust and the extraction of elements from the mantle.

Plate theory may also have an impact on some fields of biology. As the history of the earth's surface, especially episodes of rifting and collision of continents, becomes better known, it may help paleoecologists clarify the history of life that is recorded in the worldwide distribution of fossils and allow them new insights into the process of evolution. A single community of organisms that was divided and separated by the splitting of a continent should follow somewhat different evolutionary sequences. Correspondingly, groups of organisms brought together by continental collision would face sudden competition for the available ecological niches. In this way geological history could become a laboratory for the study of evolution, and E. M. Moore and J. W. Valentine have proposed that the fossil record could be used to study such phenomena as species diversification and the general problem of the geophysical influence on evolution (*2*).

To many geologists, the excitement of the last few years lies in being able to explain in detail, with the plate tectonics mechanism, a mountain belt that they had been studying without much progress for years. Specialization in the regional geology of only one part of the world is being replaced by an emphasis on the global applicability of the plate tectonic theory and by the recognition of the similarities between widely separated regions. The problems of applying the plate model to particular circumstances are by no means all solved, but plate tectonics has provided geologists with a unifying concept for interpreting what they see; so far it appears to have been remarkably successful.—ALLEN L. HAMMOND

References

1. J. F. Dewey and J. M. Bird, *J. Geophys. Res.* 75, 2625 (1970).
2. J. W. Valentine and E. M. Moore, *Nature* **228**, 659 (1970).