by Bertram G. Woodland, Curator,
Igneous and Metamorphic Petrology

mountain building

Mallory, the great mountaineer who disappeared more than forty years ago within a few hundred feet of the summit of Everest, is supposed to have said that men climb mountains "because they are there." This famous statement, while it says a great deal about man, says little about mountains. The mountains were not always "there." The very peak on which Mallory lost his life, six miles above sea level, contains rocks which were formed on the ocean floor. This article, and several to follow in coming issues of the BULLETIN, *tells much of what we know about the rise and fall of mountains, about processes which began not long after the birth of our planet and continue today.*

At the present time the earth's land area, comprising about 29% of its surface, has an average height above sea level of 2,700 feet. The agents of erosion, running water, ice and wind, which derive their energy from the sun (an external source) and gravity (an internal source), are forever acting on the land's surface and slowly removing its material to the surrounding oceans. Erosion is, in general, more active the higher the land stands above the sea. Measurements of the rate of denudation (i.e., the load of sediment carried by the rivers) show that the eroding agents would lower the land surface to near sea level in a relatively short time, geologically speaking—say, a few million years, which is very brief in relation to the earth's age, some 4½ billion years. So the question of why there are mountains is a very real one indeed.

The short explanation is that mountains are created by the internal energy of the earth, which acts continuously to renew elevations for further attack by erosion. There is thus a constant struggle between external and internal sources of energy; so far, and apparently for billions of years to come, the internal energy prevails in supplying mountains to be removed by denudation or slumping. Geological studies show that for at least 3½ billion years mountains have been thrust up in one place or another and from time to time. The uplifts are very slow affairs by human standards, although it has been possible to measure the rate of some of the earth's movements. The most obvious manifestations of the earth's internal energy are earthquakes, such as the Alaskan one of March 1964 when an area of some 75,000 square miles was affected by uplift or subsidence (the maximum uplift reported was over 45 feet), and volcanic activity. A further spectacular form of evidence of the effectiveness of uplift in rejuvenating the land is that rocks that must have formed beneath the ocean are now to be found in the highest mountain peaks, e.g., on the peak of Mt. Everest nearly six miles above sea level.

Before attempting to indicate current ideas on the mechanisms and energy sources for mountain building let us first examine some of the characteristics of mountains and the techniques of study applied to the problem of why they are there.

Mountains are not mountains because of high elevation alone but because they stand high above the surrounding land. The higher this differential elevation or relief the more imposing the mountains. Rugged and dramatic mountains may rise 3 to 4,000 feet on the seacoast, while the plains east of the Rockies which are actually higher in elevation are relatively flat and featureless. Thus location of the uplift, as well as amount, influences to some extent the development of relief. More important in this respect is the age of the uplift. Initially, a broad uplifted area may be devoid of relief, but, as rivers form and valleys are cut, relief develops and eventually reaches a maximum. Then it becomes less and less as the residual masses (mountains) far removed from the rivers are gradually worn down. Marked relief can also be formed directly by the uplift process if adjacent blocks are thrust up varying amounts or if uplift of some blocks of the earth's crust is accompanied by subsidence of adjacent ones. In this way *block faulted mountains* are formed, the uplifted masses being separated from the lower blocks by ruptures or faults. Very fine examples of such mountains are the Sierra Nevada range of California and the numerous ranges of Nevada and western Utah where the fault scarps are sometimes exposed by recent movements along the faults. Erosion here does not make the relief but immediately starts to reduce it, following each uplift.

One type of mountain which is not formed by the usual

uplift mechanism is the *volcano*. Here outpourings of molten material from below the crust and carrying with them some of the reserves of the earth's heat accumulate on the surface to great heights and form some of the most majestic mountains in the world, such as Mt. Rainier, Washington, and Fujiyama, Japan. Mauna Loa, Hawaii, is a huge volcanic pile rising over 30,000 feet above the surrounding Pacific floor. Other extinct volcanic mountains in the Pacific have sunk under their own weight beneath the ocean—some to support coral growths as atolls, others to form sea mounts and guyots which have flat tops, formed by wave erosion before they sank.

Dome mountains as the name suggests are more or less circular or oval shaped uplifts, some of which were caused by intrusion of magma (molten rock) into the earth's crust, e.g., the Henry Mountains of Utah, or by intrusion of rock salt squeezed up from depth, of which there are excellent examples in Iran, or by uplift of the whole crust such as in the Black Hills of South Dakota. *Fold mountains* are characteristically formed of parallel ridges and valleys which have resulted from erosion of beds thrown into simple linear wrinkles the arches of which are called *anticlines* and the intervening troughs *synclines*. A classic example is the series of parallel ridges of the Appalachians west of Harrisburg, Pennsylvania. It is to be emphasized that these ridges and valleys are not the simple direct result of the folding but of denudation of such a folded series of rocks.

Other mountain ranges are much more complex than those described above. They are composed not only of intensely folded sedimentary rocks but of large volumes of highly altered rocks, called *metamorphic rocks*, and vast cores of igneous rocks, particularly of a granitic type. Such mountains form the most prominent relief of the continents—the Himalayas, the Alps, the Andes, the White Mountains of New Hampshire, the Blue Ridge of Virginia and North Carolina, the coast ranges of the North American Pacific coast, and many others. Because they form the most prominent relief features of our continents and because the making of these types of mountains has been very important throughout the geological evolution of the earth, at least for the last 3½ billion years, it is with these we will now be particularly concerned.

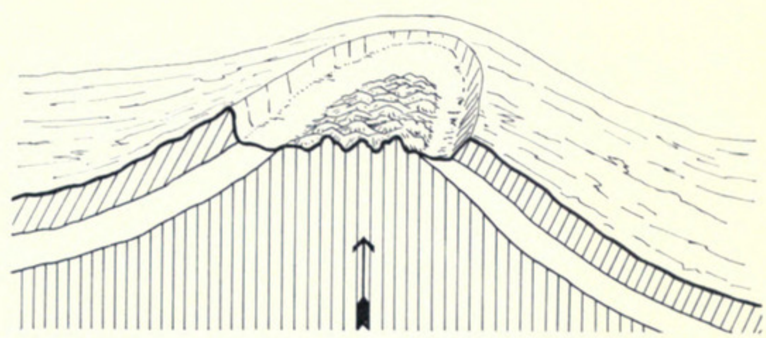
These complex mountains form very long but relatively narrow linear belts which can be traced both by broad physical continuity and approximate contemporaneity of origin for hundreds and even thousands of miles. Within each belt there are, however, a number of zones which differ in details of structure and age of formation. The large thickness of sediments that were originally deposited to form the great masses presently exposed in the ranges demands that the area now uplifted must have experienced a long period of considerable subsidence. This is in contrast to the adjacent continental areas which bear much reduced thicknesses of the sediments of the same age as those in the mountain belt. The latter has thus been a very active region experiencing subsidence of several miles and uplifts of perhaps ten miles or more. The adjacent continental crust areas were relatively stable, moving up or down no more than a few thousand feet. The long subsiding zones which receive great thicknesses of sediment are known as *geosynclines* while the resultant uplifts are called *geanticlines*. Another feature of these belts is the great amount of volcanic and other igneous activity. Much volcanic material is incorporated with the geosynclinal sediments. The nature and composition of the volcanic material alter both in place and time during the development of the mountain belt. Early manifestations of activity in the geosyncline are lavas and igneous rocks of basic and ultrabasic types, some of which when altered now provide us with asbestos deposits in northern Vermont and Quebec. Later the lavas become more acidic and the periodic geanticlines are capped by volcanoes issuing, with explosive violence, a characteristic lava in marked contrast in composition to the quieter effusions of the Hawaiian Islands. Examples of such volcanoes are found today on the Indonesian islands. The mountain-building episode often culminates in the intrusion of truly gigantic amounts of granitic type rocks, such as form the Sierra Nevada mountains. Later in time solutions migrating upward have produced many of the ore deposits from which we obtain our copper, tin, lead, and zinc supplies. But a further important characteristic of these mountain belts is that the

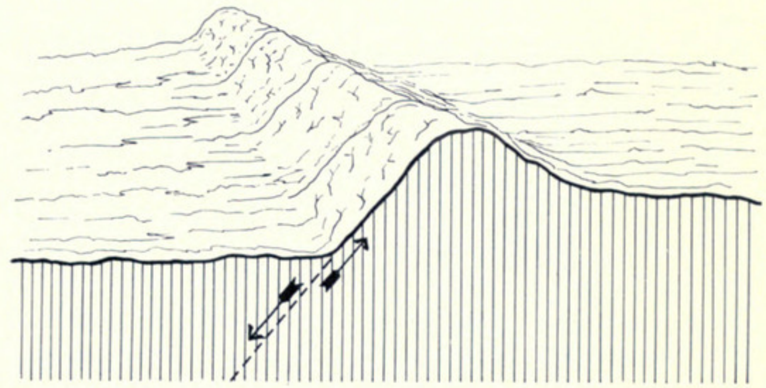
Left: Glacier National Park, Montana, showing ancient flat-lying beds which have been uplifted into a plateau and then deeply eroded to form attractive mountain scenery. Right: Bear Butte, South Dakota, a dome, exposing the core of igneous rock with turned-up sedimentary strata around the base. The previous page shows the Grand Tetons of Wyoming, examples of a block of the crust uplifted between 75 and 50 million years ago; the rocks, however, were reconstructed during an orogeny around 2,600 million years ago.

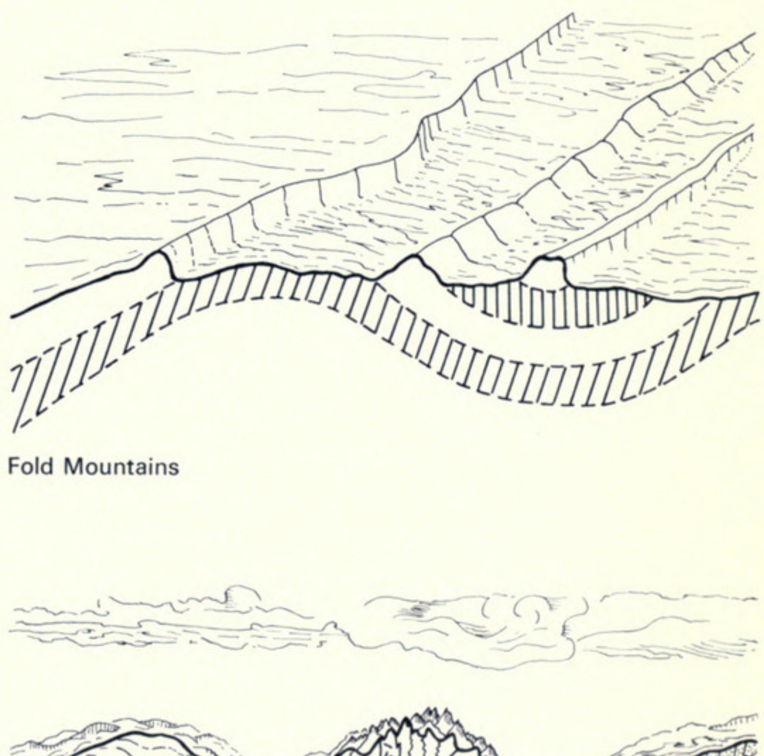
sedimentary rocks have been intensely folded and deformed in a very complex way and large masses of rocks, under the influence of high temperatures and pressure, have been transformed into completely new types. In these metamorphic rocks the deformations have induced new structures, commonly obliterating all of the characteristic features that mark bedded sedimentary rocks. New minerals have grown and chemical compositions may have altered.

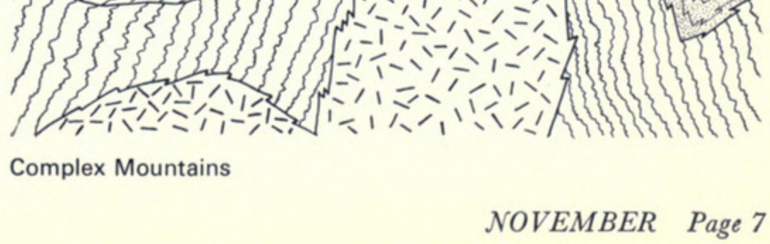
The mountain belts which exhibit the results of the forces supplied by the earth's internal energy on such a great scale are known as *orogenic belts.* At the present time certain orogenic belts are high mountainous regions and are of geologically recent origin, as their birth dates from less than 50 million years although their developmental history goes back much longer. Such are the Alps, Himalayas and the mountains of Burma, Sumatra and Java. Other orogenic belts have reached their acme of activity much earlier, e.g., the Appalachians of Pennsylvania some 250 to 300 million years ago and the New Hampshire White Mountains some 370 million years ago. These mountainous regions owe their present elevation to uplifts long after their orogenesis, with its attendant igneous intrusions and metamorphism, had ceased. Even older mountain systems, e.g., the Adirondack region of about one billion years ago, are high ground today. But many orogenic belts are to be recognized in the low-lying parts of all continents, for example, in Canada around Hudson Bay. Such regions have remained remarkably stable for a very long period of time and we call them stable platforms or *shields.* In them the deep roots of the old orogenic systems are exposed to our view to provide evidence of mountain-building dating back to about 3½ billion years. They are exceedingly complex geologically and we have so far only pieced together the merest fragments of their history. We have no record at all of the first billion years of our planet.

All the tools and methods of all the branches of geology as well as of physics and chemistry are applied in the study of such a complex problem as orogenic belts and their origin. Generations of geologists have studied the sedimentary rocks, determined their order of formation and erected a time scale based on fossil content so that the sedimentary rocks can be traced and followed from one exposure to another and from one mountain side to another, enabling the structure of the once horizontal rocks to be worked out and the form of the complex folds and dislocations to be deciphered. In this way, too, we can determine if whole sequences have been completely overturned so that they are now upside down: they often are. Further careful work also provides evidence of the depositional history in a geosyncline—the varying thicknesses of sediment, the recognition of uplifts that interrupted deposition and caused erosion, whether local or widespread, and events of a more catastrophic nature which caused slumping of already deposited sediment into deeper parts of the geosyncline. Detailed studies of the sedimentary rocks themselves and of any fossils they contain tell us much about the environment in which they formed. By tracing their lateral and vertical extents and changes we build up a picture of the geographic distribution and its alteration with time. These


Dome Mountains


Block Fault Mountains


Fold Mountains


Complex Mountains

data give us a dynamic insight into the history of the trough. The igneous rocks demand study to determine their chemical and mineralogic composition, distribution, age and geographic and chemical relationships. From the mass of data so gleaned generalizing principles are attempted which can be dovetailed into all the other data to present an ever more complete understanding of the nature of events and their timing in the orogenic belt.

The metamorphic rocks need special study and techniques of their own, too. We must try to determine the nature of the original rock types. Assuming that they were sedimentary rocks, for example, we face major problems, as their metamorphism and deformation commonly erases most if not all the evidence that would be available to us if they were in their original state. Not only is the depositional history very difficult to piece together, but frequently even the order in which the rock layers were formed is problematical. This makes it difficult to correlate the rocks from one area to another; and so to build up an idea of the structural disposition and form of the rock masses. However, the rocks in their transformation have within them many data relating to the stages of deformation and recrystallization and the operation of the forces which caused these changes. New textures and structures imparted to the rock bear a systematic relation to the overall structure of an area. By careful recording of data, usually obtained by microscopic examination of numerous rock samples throughout an area, it is possible to appreciate relationships and to understand the geometry of the internal structures. Gross structures can thus be interpreted and directions of movement of the rock masses which produced the structures inferred; it is even possible to recognize two or more stages of deformation overprinted in the same rocks. The perfect cleavage of slate, a low grade metamorphic rock, and the micaceous foliation of schist, a higher grade rock type, are structures which are imparted to the rock during metamorphism and have nothing to do with layering as seen in sedimentary rocks. It is such structures, and others, that are studied to develop relationships and interpret the deformation history. Chemical and mineralogic examination of metamorphic rocks enables us to differentiate rock masses into differing environments of alteration. Deep in an orogenic structure, pressure, temperature, and the availability of solutions that catalyze reactions are variables which produce different products from essentially the same initial rock. The occurrence and distribution of these various zones also tell us much of the dynamics of orogenesis and its mechanisms, although again it is often complicated by the overprinting of more than one type of alteration at different times during the total history of the belt. Also, of course, rocks that have been through one cycle or orogenesis may be incorporated into a new orogenic belt and reworked. In the Alps, the geosyncline which later gave rise to the Alpine orogenic belt formed on a basement of an older European mountain system, called the Hercynian orogenic belt (roughly equivalent in age to the Appalachian orogenic belt south of New York State). The Hercynian rocks were then caught up, deformed, altered, and thrust to great elevations in the Alpine orogenesis. In this way portions of a continent are made over, in some areas probably several times, although the evidence of earlier episodes becomes lost if the later reworkings are too numerous or thorough.

The special study of land forms and their mode of origin also has its part in understanding the orogenic process both in principle and in a particular case. Evidence of erosion surfaces sheds much light on oscillations of the land, particularly in the areas that are regarded as sites of active orogenesis today. Such an area is the Indonesian island arc of the Western Pacific. Here many geologists, particularly the Dutch, have collated a remarkable amount of information, often under the difficult conditions of tropical forest, pertaining to the development of geosynclines, geanticlines, volcanism, deformation and intrusive activity which has been traced over a wide area. It has been shown that the history of an orogenic belt is extremely complex and that the zones of subsidence and uplift migrate in time both along the belt and at right angles to it. It might be mentioned here that the data made available by the study of the Indonesian area, which is still an active orogenic belt as witnessed by the numerous volcanoes and earthquakes and observable recent changes in levels are, of course, supplemented by the study of older orogenic belts which have been worn down by denudation to reveal the deeper structures.

Radioactive dating is proving to be a very useful tool particularly in studying the relationship of the old, now much denuded orogenic belts of a billion years of age and older. Here the evidence is so obscured by the complexities revealed that correlations of rocks can hardly be made in the usual ways. Dating of events such as major intrusions and metamorphisms in the various belts, however, is beginning to enable us to decipher the relationships and ages of the various belts in the shield areas.

This article will be continued in subsequent issues of the BULLETIN.

Special Exhibit

ORCHID SHOW

November 20 and 21

Hundreds of orchids—fresh-cut blooms and flowering plants—will be on display at the Museum November 20 and 21 when the Illinois Orchid Society presents its annual show.

To be held in Hall 9, the display will also include an exhibit showing the native origins of many of the species, a series of paintings of orchids, and an educational exhibit by the Department of Botany. The Society's film The Secrets of Sewing and Germinating Orchid Seeds *will be shown during the two-day show.*