After dealing with the types of mountains, and the tools of the geologist in dealing with theories of mountain building (see November, 1964, Bulletin) in Part I, Dr. Woodland turns, in this article, to aspects of the general structure of the earth as they relate to mountain building. He examines the crust and the mantle of the earth, the topography of the ocean floor and the continental crust.

mountain building II

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

The Crust of the Earth

The field of study called *geophysics* has provided much information particularly about the deeper parts of the crust in orogenic belts and the way it differs from the present day stable platforms and oceanic crust. Thus, the study of earthquakes themselves is beginning to shed light on the nature of the movements in the crust which produce the quakes, while the geographical and depth distribution and periodicity of earthquakes throughout the world provides information on the relationship of unstable zones to crustal structures. The velocity of earthquake waves which varies with depth zones of the earth also enables us to infer conditions within the earth below the crust, data which must be consistent with any ideas of the mechanism and sources of energy for mountain building. Small explosive charges set off in the ocean or on land produce man-made seismic waves, which can be received and analyzed to give data on variations in crustal thickness and rock density. The base of the crust is now defined by a change in velocity of seismic waves; this is called the *Mohorovivic discontinuity* (Moho for short). The accumulation of information on variations of gravity in different parts of the world also adds to our understanding of the nature of the deep parts of the crusts and the region below the base of the crust, called the *mantle.*

Results from such investigations show that the thickness of the continental crust averages nearly 25 miles but increases to 35 miles or more under high mountain ranges. The crust is composed of granitic type rocks in its upper portion and somewhat denser, presumed basaltic types below, immediately above the Moho discontinuity. Oceanic crust, however, averages less than four miles in thickness, not including the water depth, and is essentially composed of material similar to the basaltic layer of the continental crust.

Measurement of variations in the magnetic field has also been rewarding in indicating crustal displacements on a large scale, for example, in the eastern Pacific floor. Another type of work based on the earth's magnetic field is the determination of the direction of magnetism which was sealed into the rocks at the time they were formed. It is believed that this provides information on the ancient magnetic fields (thus the name *Paleomagnetism*) and analyses of these are interpreted by some earth scientists as showing that the continents have not always been in the same position relative to the poles or even to one another. If such movements are accepted, it is necessary to integrate them into any theory of mountain building.

Gravity determinations are, thus, an important source of data about crustal structure. A concept which receives much support from these studies is the generally accepted theory of *isostasy*. Isostasy holds that the earth's crust acts as if it is in a floating equilibrium on a very viscous, but nevertheless yielding, substratum. It is thus analogous to an iceberg floating in the ocean—in general, the higher the land, the thicker the crust, and therefore the deeper the Moho discontinuity. That is, high mountains have deep roots and conversely the depressed crust of ocean basins is just a thin skin.

On the basis of isostasy it would be predicted that an area of the crust should sink if subjected to a substantial additional load, and rise again if relieved of that load. In a number of instances this seems actually to have been the case. Scandinavia and the Hudson's Bay region show evidence of a slow but persistent uplift during the last several thousand years. This is interpreted as recovery from the depressed levels caused when they were loaded with tremendously thick ice sheets during the Ice Age. In the Glacial Epoch also, a much larger lake existed on the site of Great Salt Lake. In the past 16,000 years it has gradually been reduced to its present size. In response to this decrease of load, there has been uplift of the crust to a maximum of over 200 feet, as can be seen in the warped elevated form of the old shoreline around the lake.

Gravity and seismic studies, however, indicate that a straight relationship of height of land to crustal thickness is oversimplified; lateral variations of density occur both within the crust and below the Moho, in the upper part of the mantle. Thus, areas of thin crust can stand relatively high, if their densities are abnormally low. To illustrate: a three-inch column of light balsa wood stands as high in the water as a six-inch column of heavier maple. Anomalous regions of thin crust are present in a large portion of the western United States, particularly west of the Colorado plateau, as well as along the mid-Atlantic undersea mountain range. Seismic wave studies indicate that the crust and the upper mantle have unusually low densities in these areas. These low densities have a direct bearing on the mountain building process.

The Oceanic Crust

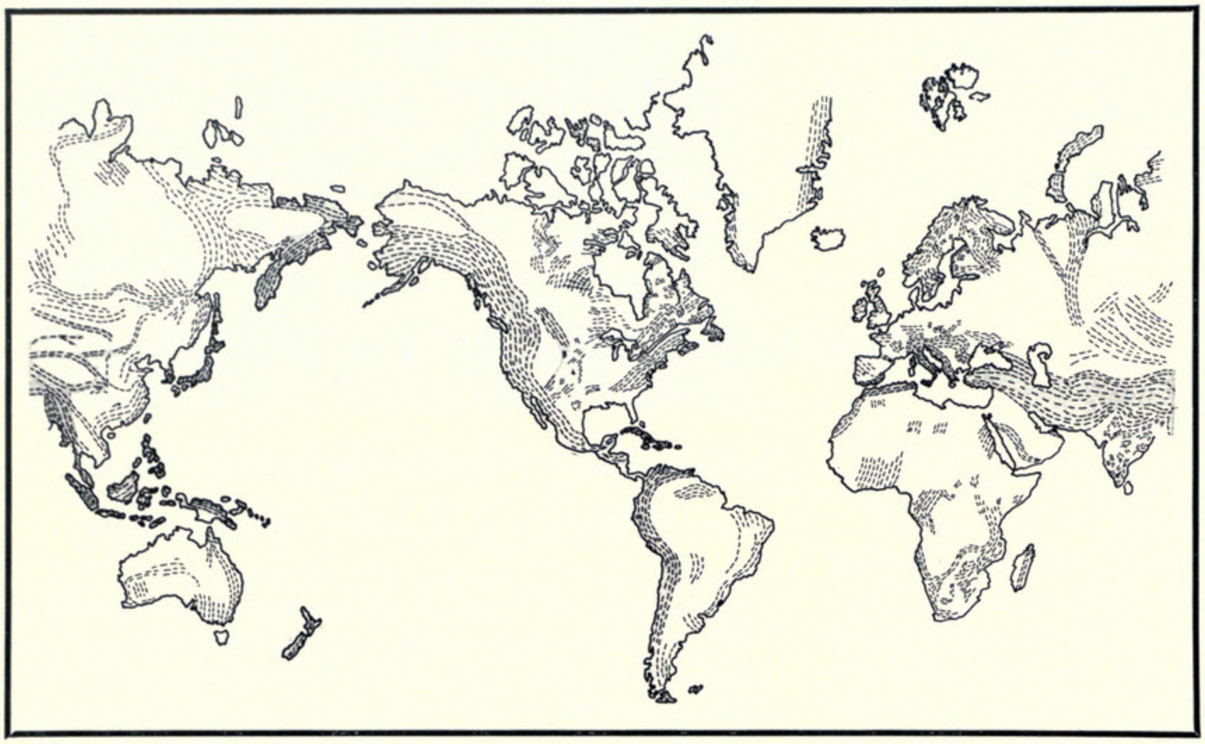
Within the last two decades our knowledge of the ocean basins has greatly expanded. The ocean floor is now known to have a very varied relief. Its major feature is a world-girdling system of mid-oceanic ridges that rise one to two and a half miles above the average ocean depth of three miles. These ridges vary in width from a few hundred to 2500 miles. In many places the summit zone has a median rift valley, sometimes 30 miles wide, along which earthquake shocks originate.

Iceland, which is noted for its active volcanoes, stands on the Mid-Atlantic ridge. A median rift passes through the island in the form of a down-faulted zone marked by active vertical fissures along which the crust is slowly being torn apart. Other volcanic islands, such as Tristan da Cunha, also rise from the ridge system. Along the crests of the ridges the flow of heat from inside the earth is well above the average for the rest of the ocean floors and continents. In many places the ridges are offset along transecting faults.

A rifted ridge in the Indian Ocean connects with the Red Sea rift and thence to the Zambesi River, via the great East African rift valleys. In the current view, these African rift valleys were produced as the result of tension which stretched and fractured the crust along existing faults. The resulting linear troughs formed by the sinking of crustal rocks show lower than average gravity values. (In the same way, the crustal rocks of the Arabian peninsula are believed to have separated from Africa to form the Red Sea; dense rock from the mantle welled up to form the sea floor which has higher than average gravity value.) Recent earthquake tremors originating along the rift valleys, and much active volcanism, indicate that these stresses continue today.

The East Pacific ridge runs into the Gulf of California and up into the line of the great San Andreas fault zone, reappearing off the northernmost coast of California. The 1906 San Francisco earthquake is a result of movement along the San Andreas Fault.

The Pacific Ocean has a number of other interesting features that concern us. It is more or less ringed with geologically young mountain systems, such as those on the west coast of the Americas, and also with an almost complete ring of active volcanoes, the circum-Pacific "ring of fire." Many of these volcanoes form islands arranged in arcs, such as the Aleutians, the Kuriles and the Marianas. Other volcanic arcs occur in Indonesia, which are a continuation of the young mountain ranges of Malaya, Burma and the Himalayas. The lavas and ashes emitted by these circum-Pacific volcanoes are characterized by an interesting type called andesite. The composition of andesite and its violent manner of eruption distinguish it from the basaltic lava emitted by the mid-Pacific volcanoes such as Hawaii. Associated with these island arcs and with the west coast of Central and South America are amazingly deep oceanic trenches, whose depth below sea level commonly exceeds the height of Everest. The deepest sounding ever made, over 36,000 feet, occurred in the Marianas Trench.



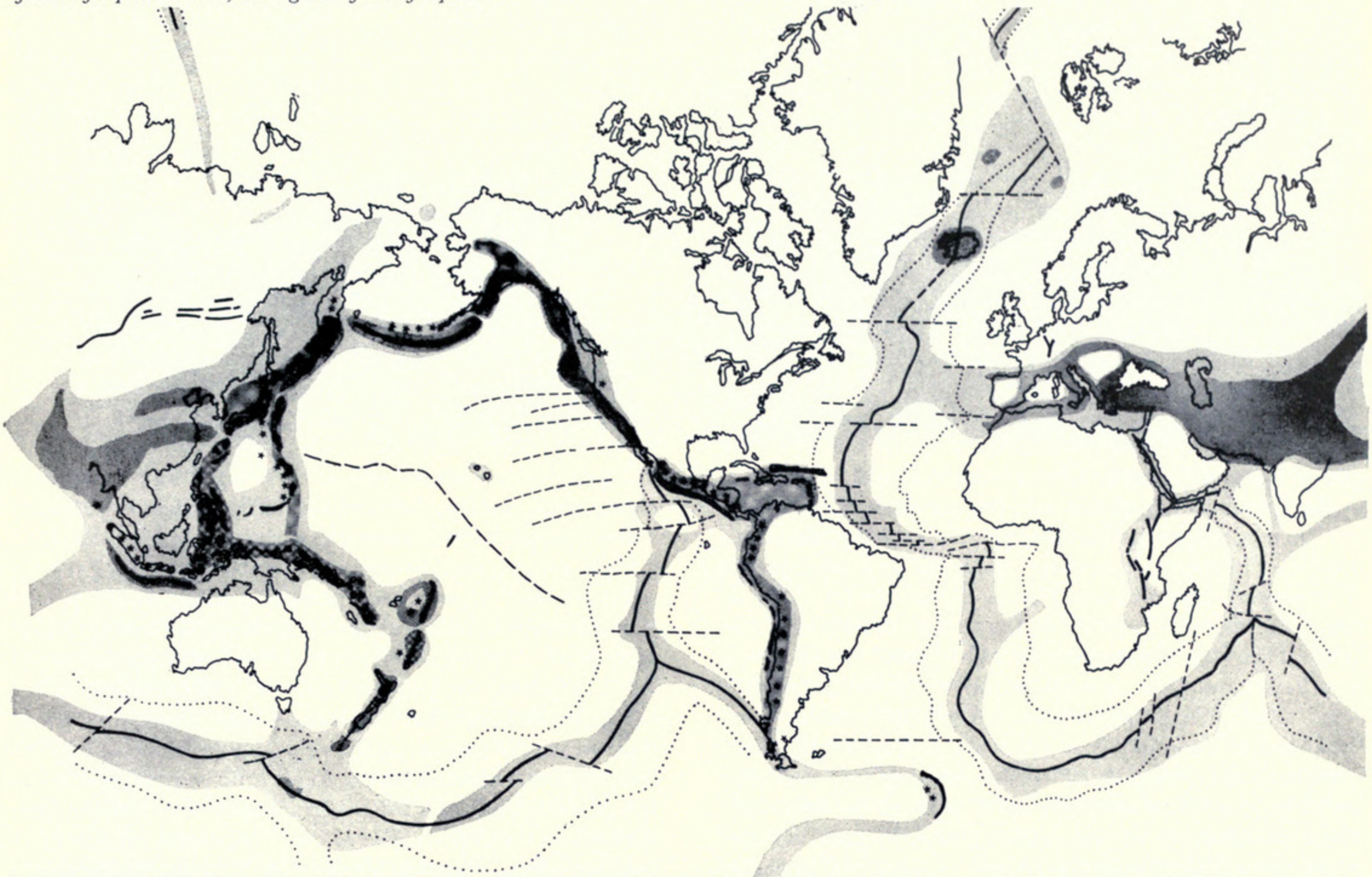
Structural trends of the rocks in orogenic belts. Blank areas include those where there is insufficient data and also where flat lying strata cover the deformed rocks of the crust, such as in Illinois. Greenland is nearly all under ice. The shaded areas are the young mountain ranges formed within the last 100 million years, mainly during the latter half of this period.

This circum-Pacific belt is by far the most seismically active area in the world. It is significant that earthquake shocks originate at different depths in various areas of this belt. Along the line of the trenches, they occur at shallow depths, down to about 40 miles. Beneath the volcanic islands they originate between 40 and 180 miles below the surface. Deeper quakes, some more than 430 miles down, occur on the continental side of the island arcs. Thus, there seems to be an active zone of slippage around the Pacific, which dips away from the ocean and under the continents.

It might be mentioned here that studies of circum-Pacific earthquakes have revealed a puzzling phenomenon. Analysis of waves generated by earthquakes suggests that the crustal movements responsible are preponderantly of the type where one block slides along a vertical fault in an essentially horizontal manner. This movement does not fit the structural and dynamic models favored by many people, which require relative vertical movement thrusting an upper block up and over a lower one along an inclined fault zone.

It is noteworthy that there is no trench off the west coast of the United States, the line of great volcanoes in the Cascade Mountains is inactive, and there is no inclined earthquake zone beneath the coast. The earthquakes of the American west are related to other features such as the San Andreas

● *Mid-ocean ridges (dotted) and median rifts (thick line).* ● *Dashed lines represent faulted offsets of ridges and fault scarps of the eastern Pacific.* ● *The thick, dashed line in the central Pacific is a subsided old ridge.* ● *Rift valleys are shown in east Africa, Siberia and Europe.* ● *Deep sea trenches are shown in solid black.* ● *Lines of stars are Volcanic arcs.* ● *Shaded areas are zones of earthquakes, the darker areas of more frequent shocks, the lighter of less frequent.*



fault, along which the movement of the crust is such as to move the area to the west of the fault in a northwesterly direction relative to the area to the east. All these features of the Pacific are in strong contrast to those of the Atlantic Ocean, whose surrounding coasts are not seismic, and have no festoons of volcanic islands, or rims of young mountains.

Another relatively recent discovery is that the ocean floors, particularly of the Pacific, are dotted with volcanoes which rise many thousands of feet above the ocean floor, only some breaking the surface to appear as volcanic islands or atolls. Many of these submerged volcanoes, or sea mounts, occur in linear trends with nearby volcanic islands and atolls, both active and extinct. When the ages of the individual volcanoes in a given chain are compared, they show a progressive increase in age in one direction; for example, the Hawaiian islands are older toward the northwest. This suggests that the magma source (responsible for the building of volcanoes) has migrated over the years. Because of the distribution of the linear chains relative to the mid-oceanic ridges, it has recently been suggested that it is not the magma source, but the crust itself which has migrated, carrying the volcanoes with it.

Many of the submerged volcanoes have flat tops which were formed by the planing off of the peaks by wave action. With the subsequent subsidence of the volcanoes, these flat-topped occurrences, called *guyots* are now submerged under 3,000 to 6,000 feet of water. Guyots emphasize that the ocean floors are not stable but have been subjected to considerable subsidence and uplift.

Formation of Continental Crust

Closely connected to the problem of mountain building are questions about the origin of continents and the permanence of oceans. Continental crust is characterized by the prevalence of low-density "granitic" type rock or *sial* as it is called. Originally it was thought that this formed when the earth passed through a molten stage much like the slag that floats on molten iron in a furnace. This may have occurred in the initial period of earth evolution or later, when an originally cold earth was warmed up as a result of internal reactions, including that produced by radioactive elements such as uranium.

Nowadays, it is generally held that the earth was never completely molten and that the crust evolved by chemical and gravitational differentiation from the mantle as the earth's internal temperature increased. However, there is disagreement about the time involved in producing the crust, and about whether the crust was formed over only certain parts of the earth's surface (the continents) or over the entire surface and subsequently concentrated into the present continents.

Some data have been interpreted as indicating that the bulk of the sial was differentiated very early in the earth's history, say at least by $3\frac{1}{2}$ billion years ago, and that little has been added since. Other results suggest that the sial has grown throughout geologic time, primarily by welding of new material to the margins of the continents. Granitic type rocks have been produced in recent geologic times which appear to have been derived by differentiation from the mantle (or from basalt which originated in the mantle), thus supporting the idea of continuous growth. However, many other "granitic" type volcanic and intrusive rocks, particularly those associated with the orogenic belts, seem rather to have been derived by melting of pre-existing sial or at least by mixing of such a source with basalt from the mantle.

Assuming that the bulk of the sial was formed early in the earth's evolution, it has been claimed that it did so on the sites of the present continents as a result of inhomogeneities in the mantle; this implies that the oceans and continents have been permanently in their present position, the continents ever changing their shape and relief as a consequence of orogenesis and erosion and changes in sea level. Alternatively, the sial may have formed over the entire earth's surface. Then vast outpourings of basalt along weaker zones may have caused the foundering and oceanization of large areas, the sial being squeezed out laterally in the process and thickening the continents as the oceans grew in size. Concentration and thickening of the sial may also have been produced by the action of slow-moving currents in the mantle which would sweep the sial together into the zone or zones where the currents turn downward. Continued action of such currents is believed to cause continental drift.

Hypotheses that the continents have not always occupied the same positions relative to each other or to the poles have been put forward for many years with supporting evidence based on the distribution of fossils, on past climate indications (particularly glaciation in the Southern Hemisphere continents some 250 to 300 million years ago), and on the fit of the opposite Atlantic coasts. During recent years, studies of paleomagnetism in rocks have given strong support to the idea of drift. Drift, of course, is antagonistic to the idea of permanence of the oceans. It is worth noting that investigations of the ocean bottoms so far have revealed no sediments older than about 100 million years, which is a short part of the total earth's history, while the rocks of the mid-Atlantic ridge are also relatively young (the oldest tested to date is 20 million years old). We shall return later to the questions of continental drift, oceanization of continents and the opposite phenomenon, accretion of oceanic crust to the continents, which are all pertinent to mountain-building theories.

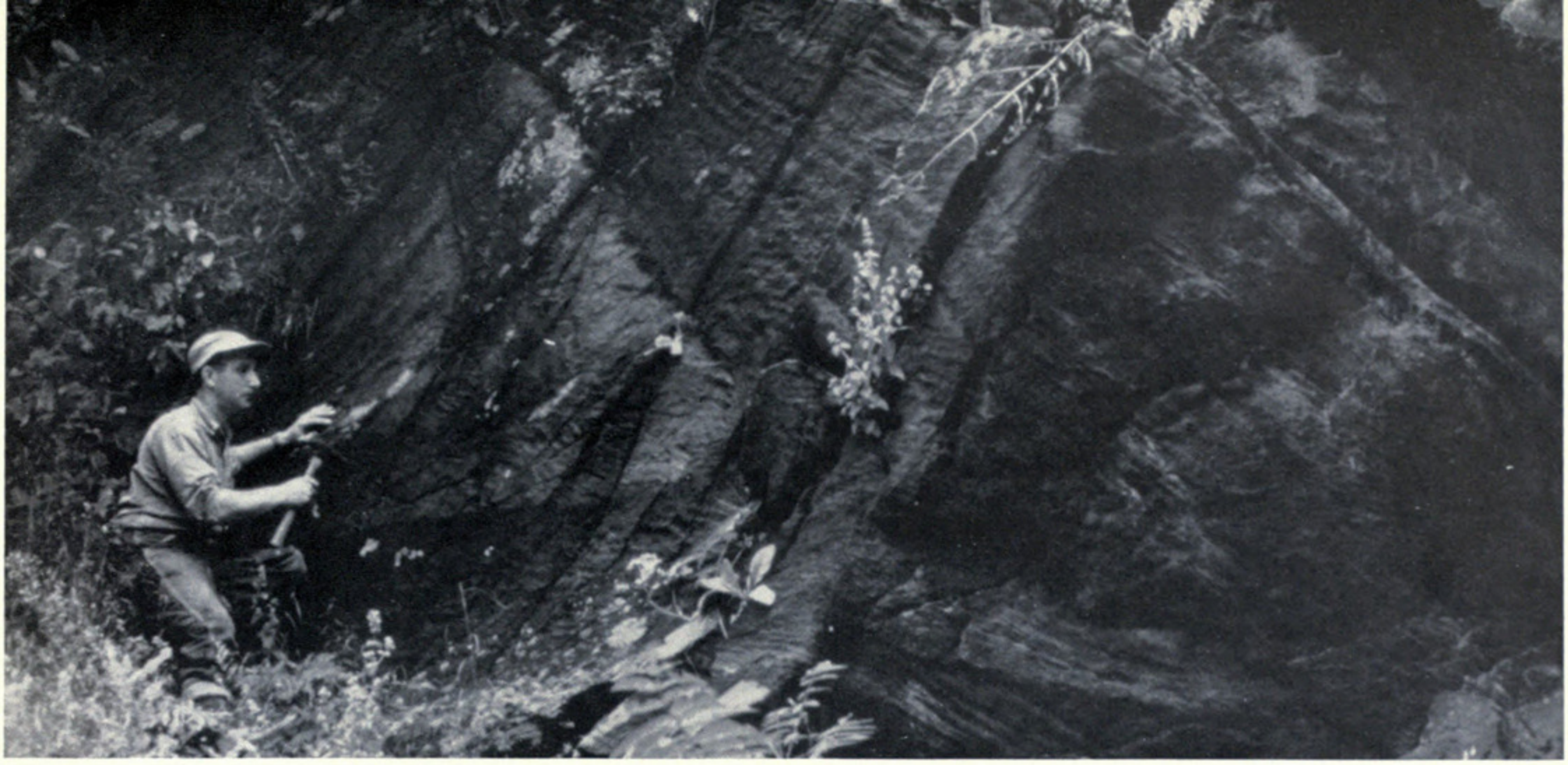
Folded Zones and Crustal Shortening

There are a number of controversies among geologists over the interpretation of geological evidence about the mechanism of the mountain-building process. Foremost among these is the question of *lateral compression*. The severe folding of originally horizontal beds of sediments in orogenic belts, commonly accompanied by recrystallization and development of new structures such as slate and schist, led to the idea that the forces responsible had acted in a more or less horizontal direction, producing a lateral compression. This resulted in the shortening and thickening of the section of the crust affected: the greater the folding and piling of folds or slices of rock on top of each other the greater the shortening. Arising out of such an interpretation, mechanisms to produce lateral compression have been sought. These ideas have dominated thought on orogenic processes for the last century as the complex nature of the linear folded belts became more and more known from geologic studies.

However, during the last 30 years the importance of *vertical movements* has again been stressed (they were prominent in geological writings over 150 years ago). There can be no doubt as to the reality of large vertical movements of parts of the crust. The accumulation of thousands of feet of sediment, the bottommost beds of which were laid down in shallow water as was the sequence to the very top, demands a considerable sinking of the area to accommodate the deposits which isostasy by itself cannot explain. For example, taking a basin with an initial water depth of 500 feet, filling it with sediment, and allowing for isostatic settling would permit only the accumulation of about 1200 feet. Sinking would then cease and the basin would be full of sediment to sea level. Likewise, the presence in surface rocks of metamorphic minerals that must have formed at high temperatures and pressures found only at considerable depths in the crust (e.g., 5 to 20 miles) indicates the extent of vertical uplift and erosion that has occurred. Of course, the proponents of lateral compression as the basic cause of orogenic structures recognize that considerable vertical movement is a necessity to explain the elevation of mountain ranges as well as many other geological phenomena. But the tendency is to regard uplift as a consequence of initial thickening of the crust followed by isostatic rise, which continues as erosion removes the load from the top. Implicit in this is the idea that the uplift mainly follows the folding and thickening of the crust. Geologists who consider that vertical movement is the primary deformation mechanism hold that folding and lateral compression structures are a resultant; in many cases they thus suggest that uplift precedes folding. We shall take up these aspects later and discuss how perhaps the two views can be reconciled.

Geosynclines and Oceanic Trenches

Yet another problem relating to the circum-Pacific region is the question of whether the deep ocean trenches associated with volcanic island arcs are modern examples of geosynclines in their early stages, that is, before being filled with sediment. There used to be strong opinion against their equivalence based particularly on the fact that the rocks of orogenic belts were regarded as having been essentially deposited in relatively shallow seas. The geosynclines would then be similar to areas of sedimentary deposition off the east coast of the United States and the area off the Gulf Coast where over 40,000 feet of mainly shallow water sediments have accumulated. (It is possible that the lower parts of the sedimentary



The author, Dr. Bertram G. Woodland, at work in the field. This photo shows Dr. Woodland collecting rock samples in central Vermont. He has traveled extensively in Great Britain, Norway, France, and the United States observing, and collecting samples for later interpretation. The dark diagonal lines in this photograph are an excellent illustration of folded rock strata.

column were deposited in water of oceanic depths.) However, in these areas there is no evidence of particular crustal unrest and volcanism is, of course, absent. Thus there is no sign that these areas are destined to be future orogenic zones, although they may.

On the other hand, there is some support for the opposite view. Deep sea deposits are known, for example, in the young mountains of Cuba and Timor (Indonesia). Although previously not thought possible, it is now believed that great thicknesses of alternating sandy and shaly rock types, characteristic of many complex mountain belts, may have been deposited in deep water; the sediments that formed them were released from unstable slopes near to land and were transported to greater depths in dense sediment-charged bottom currents called *turbidity currents.* So it is possible that the geosynclines which later gave rise to mountain systems were, at least at some stages in their history, deep-water troughs similar to the modern oceanic trenches. The modern trench, over 25,000 feet deep, just north of Puerto Rico contains an estimated 6,000 to 20,000 feet of sediment probably deposited by turbidity currents. Future uplift of the area could produce island structures much like Barbados, for example.

Considerations of Time

Before turning our attention to the various hypotheses of mountain-building mechanisms we must consider one last aspect—the important one of *time.* It was recognized many years ago that the processes involved in mountain building are very long, taking several hundreds of millions of years from the inception of a geosyncline to its final deformation and consolidation as a relatively quiescent part of a continent. But the paroxysmal orogenic phase was believed to occur over a few tens of millions of years near the end of the whole sequence of events and to occur more or less synchronously in a number of geosynclines in various parts of the earth's crust. Thus arose the idea of relatively short periods of widespread crustal unrest and mountain building; these periodic events were called *revolutions.*

Continued and more detailed study now shows that the history of even one geosyncline is more complex than previously believed and that the time span of deposition, volcanicity and deformation varied from place to place. Uplift and folding migrated in time, both along the geosyncline axis and at right angles to it. Orogenic movement was active over hundreds of millions of years and individual events were not world-wide. Events in one geosynclinal complex may even have overlapped in time those in another complex considered to belong to a different "revolution." In any one particular region, however, it is possible to make out a periodicity: deposition, volcanicity, folding, metamorphism, and uplift are repeated in adjacent zones which migrate in time.

When the crustal history is examined on a broader time scale (over the last 3½ billion years) a crude cyclical arrangement of activity seems to emerge. Ages of crystallization of mineral components of rocks (established by measurement of the time necessary for the breakdown of certain radioactive elements) are assumed to represent periods of metamorphic recrystallization and consolidation of molten material in the crust. These events are broadly interpreted as marking periods of orogenesis. Pertinently dated minerals from all the continents show ages which cluster in periods centered around 2,600, 2,100, 1,750, 1,400, 1,000, 500, 350, and 100 million years ago. These data have tended to revive the idea of a cyclical mechanism controlling the evolution of the crust. It has also been suggested that between the major periods of orogenesis a different type of activity can be discerned—the outpouring of great quantities of basaltic lava on the continents, possibly related to periods of tension in the crust.

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