The Building of Mountains

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WITH JOHN RUSKIN'S dictum in *Modern Painters,* that mountains are the beginning and the end of all natural scenery, the majority of us mountaineers will surely agree; and a visit to the Ruskin Museum at Coniston in the English Lake District will quickly convince us how intensely interested that remarkable artist and critic was, not only in mountain scenery as such, but also in the significance of the geological formations that often build mountains. And long before Ruskin were many natural philosophers who had pondered on the structure of mountains and its possible origin, earlier among them being Leonardo da Vinci, that "brightest ornament of Renaissance learning"; and much later, none more cogently than the eminent savant and mountaineer of Geneva, Horace B. de Saussure, at the end of the 18th century, when he declared: "It is above all through the study of mountains that the progress of a theory of the earth can be accelerated." (*Voyages dans les Alpes,* 1779-96.) But this "Founder of Alpine Geology," as Professor de Saussure has been called, was perplexed by the multitude of facts and phenomena that he had observed over the years in the course of his journeys; and indeed, in finding a synthesis of them all beyond him, he rather pathetically declared: "I recognize that one could almost assert that there is nothing constant in the Alps save their variety!" (*Les Voyages,* Vol. IV, p. 464.) This phase of mountain studies has been called by a later eminent French geologist, Professor E. de Margerie, "The Chaotic Period" in view of the widespread complexity and irregularity of the great rock folds and faults, and the crushing of strata by lateral pressure—"refoulement" of de Saussure. There followed a half-century of more careful and extensive investigation all over Europe, during which the theory of the Geological Succession of rocks was formulated and established by means of fossils in Great Britain and on the Continent; and in Switzerland Professor Bernard Studer, of Berne (brother of Gottlieb Studer, the historian of Swiss mountaineering), began a detailed analysis of the main Alpine region. As a result of this new phase of work, the favored hypothesis was that either direct vertical forces within the earth's crust or igneous irruption and eruption were responsible for the immense upheavals whose records were discernible in the great mountain ranges; hence, "The Vertical or Eruptive Period," so-called by de Margerie. But it is interesting to note that the well-known French geologist, Élie de Beaumont, had amassed evidence at this early stage that all mountain chains have not the same age, and that their respective dates can be fixed by consideration of the principle of unconformities, i.e. the physical breaks or interruptions in the laying down of the strata (*Annales des Sciences naturelles,* XVIII-XIX, 1829-30).

Significance of directed pressure

It was, however, the next important stage of investigation that inaugurated the modern conception of Alpine building, namely "The Tangential Period." In this the earlier ideas gave way to a recognition of dominant lateral stress in the earth's crust, which was responsible for the folds and the faults, but above all for the great thrust-planes and thrust-masses of rock-sheet (*nappe*—French, or *Decke*—German) upon rock-sheet, whether of sedimentary or crystalline material. The pioneer and outstanding master in the new philosophy was Albert Heim, born in 1849 at Zürich, and a professor at the Federal Polytechnic School and at the University of Zürich from 1872 to 1919. Actually, he became the forerunner of a whole succession of brilliant workers from Switzerland, Austria, France and Germany, who tackled the details of the entire Alpine region. One cannot do better than refer the reader to the excellent record in English of their prolonged and intricate researches as recounted in two books: (1) *The Structure of the Alps* by Professor Léon Collet, of Geneva University (an esteemed friend of the writer and a visiting colleague at Harvard from 1927 to 1929); and (2) *The Nappe Theory in the Alps* by Professor Franz Heritsch, of the University of Graz. As Collet himself has said, the outstanding result was "a great geological synthesis, based on evidence that can be examined in the field," and often, indeed, only by the geologist who is also a competent mountaineer.

Summarizing, it was envisaged that the initiation of the mountain-building process took place in a great slowly sinking marine basin, covering rather more than the present area of the Alps, in which an immense thickness of sediments was laid down. For reasons which are obscure this great basin, or *geosyncline* (i.e. syncline on an earth scale), became a region of instability, and its down-sunk, now consolidated, rocks were compressed and buckled by the more resistant crystalline masses lying north and south of it, which moved inwards toward each other like the jaws of a vise. The result of this squeezing of the geosyncline was to cause great upward folds, or *geanticlines,* two in number, to rise out of the geosyncline, and then be overturned with many of their strata inverted. Owing to the active and stronger pressure being directed from the south, these geanticlines were forced outward and northward over the resistant *foreland.* They eventually developed into the two dominant nappes of the Alps, namely the Great St. Bernard Nappe and the Dent Blanche Nappe, from which by subsequent variable erosion such peaks as the Dent Blanche itself, the Matterhorn and others were carved. This was really only part of a complex of effects, which included the intrusion of bodies of granite and other igneous rocks, also a fantastic piling up of far-traveled rock-sheets, and an eventual dissection of the latter by erosion into isolated masses, to give at times the well-known "mountains without roots" (Klippen), e.g. the Matterhorn, Weisshorn, Mythen et al., as well as many other resulting details of structure.

While certain baffling problems do still await solution, the existing general picture confidently presented by this brilliant band of European geologists seems at times almost impossibly unreal and extravagant: but the evidence is there for all to see, if patient search and analysis be diligently undertaken, involving, perhaps, climbing to the various outcrops in sundry cliffs above difficult glaciers! However, there were not a few experienced geologists who were reluctant to accept these revolutionary views as to the building of the Alps. But such was the confidence born of success in the interpretation of the major problems of structure, that many Alpine geologists eventually wished to explain the formation of all overfolded mountain ranges on the analogy of the Alps of Europe. The more conservative element, however, felt that such an extension of the case was quite unproven; and some went so far as to suggest that the Alpine chain with its far-traveled nappes, displaced in some areas to the extent of 80 miles, might be something unique in nature! Moreover, the mode of movement of these immense rock-sheets was much under dispute: was it by direct pushing, or under gravity on uplifted glide-planes lubricated by molten rock material?

The American group of mountain geologists

Now, during the middle of the 19th century, and concurrently with the European work of the "Tangential Period," there arose a school of able American geologists who directed their attention to the Appalachians. The two brothers, W. B. and H. D. Rogers, took, it is claimed, actually the first important step towards understanding the natural history of folded mountains. They discovered that the folded sedimentary rocks: sandstones, shales, limestones, etc., out of which the Appalachians are built, are shallow-water marine types, which locally reach the enormous thickness of 40,000 feet. But in the unfolded regions of the Interior Lowlands to the west the sediments of corresponding age are only a tenth or a twentieth as thick! Another American geologist, James Hall, soon (1859) confirmed this remarkable discovery. Incidentally and by coincidence there was, just a little earlier, a British geologist and disciple of the great James Hutton of Edinburgh, Sir James Hall, who showed experimentally that rock folds were due to horizontal thrusting; and he also considered, as have some after him (e.g. A. Keith, from his Appalachian studies), that the cause of the lateral compression was the forcible intrusion of granite. The only reasonable conclusion regarding the thick column of sediments was that the original floor of the sedimentary basin must have subsided by a like amount to allow of the continuing shallow water conditions. Some people, confusing cause and effect, had even argued that the incoming sediments had weighed down and warped the basin. It was this downwarping of the earth's crust, to form a great elongated trough, that the eminent Professor J. D. Dana in 1873 called a "geosyncline." He regarded the depression as due to lateral compression, for some unknown reason or another, in the outer crust, and the great emerging formational ridges he named "geanticlines": not that anything of the latter on the Alpine scale could, however, be identified in the Appalachians. Dana called mountains made up of geosynclinal sediments "geosynclinal chains." And then the conception was adopted by the Swiss geologists, and through the notable work of E. Haug in particular it became the ruling hypothesis for the origin of folded mountains. But as far as the Appalachians were concerned, it was soon evident that, while considerable thrust from the southeast towards the northwest had taken place, and much folding of the strata in the interior ranges, together with local intrusion of granites and alteration (metamorphism) of formations, the far-traveled masses of the later-formed European Alps were altogether absent. Then, an additional complication in interpretation was the fact, ascertained by careful stratigraphical mapping, that the Appalachians are made up of at least two major intersecting mountain chains of different ages: the *Caledonian* and the *Hercynian,* named after their extensive contemporaries in Europe. But two or more further minor "disturbances" can be detected within the Appalachian belt, thus making up a very complex whole and covering a total span of time for its building that may exceed 400 million years. Many, but not all, types of Alpine structure are to be found in the Appalachians; and it can be added that an immense amount of detailed geological and geophysical work remains to be done to establish an adequate comparison between the ranges. In passing it should be mentioned that in the Appalachian ridges of Pennsylvania is to be seen the classical structure of *inverted relief,* which so often springs a surprise on the layman! This consists of the original arch-bends, or anticlines, occupying the valleys, and the downfolds, or synclines, anomalously forming the hills. It is a phenomenon of long-continued stream-erosion, that a stream will take advantage of the weak, stretched and cracked rocks of the anticline rather than the more compressed structure of the syncline, which latter becomes preserved and tends thereby eventually to form the hills. This is in direct contrast, for instance, with the moderately young Jura Mountains of the Alps, which being at an earlier stage in the cycle of erosion, have their valleys conforming to the original troughs (synclines) and their summits still coinciding with the structural arches (anticlines).

Scottish Highlands and the Norwegian-Swedish Border

During the earlier stages of the aforesaid investigations in the Alps and the Appalachians, fundamental researches were being pursued in the Northwest Highlands of Scotland and in the Jämtland region of Sweden, along the mountainous Norwegian frontier. In the former district the inimitable "Investigator Twins," as they were called, B. N. Peach and J. Horne, had worked out their overthrust theory to explain the anomalous succession of formations and the indications of movement at the great Glencoul Thrust, and elsewhere. Also, concurrently the eminent Swedish geologist, A. E. Törnebohm, "The Giant of the North," working almost single-handed, had shown the same kind of overthrusting, exceeding even 80 miles, of a huge mass of mixed rocks over-riding others often of younger age. It was said of Törnebohm how during his exacting field-work "sometimes his assistants ran away from him, because they could not endure the fatigues or follow him when with his great strides he rambled over the mountains." It has been claimed such an experience is not unique even among modern geological students! But the interesting thing is that Törnebohm pursued his researches and arrived at his overthrust hypothesis independently of Peach and Horne, who were coming to the same conclusion in the Highlands of Scotland, where, for their part, they seem to have been entirely ignorant of his work. Törnebohm's results have in later years been greatly amplified by Norwegian and other investigators in sundry districts of the ancient Caledonian mountain chain, extending even to Spitsbergen and northeast Greenland.

Rockies and Western Cordillera

Turning to the Rockies it is first necessary to emphasize the differences in time and structure between the Canadian and American Rocky Mountains on the one hand, and on the other the vast complex of Cordilleran ranges extending westwards to the Pacific coast. It is an immense and diverse region, and one can only summarize. But it is definitely incorrect, on a geological and orogenic basis, to include within the term "Rockies," as some have done, these other ranges of the interior and the western coastal belt. The latter were elevated mainly earlier than the Rockies; and the same applies to the ranges north of the international boundary in Canada, namely those on the western side of the Rocky Mountain Trench, itself a significant rift-fault feature. The structure (tectonics) of all these interior ranges is composite and often very complex. But there is ample evidence to show that, instead of a single rather violent mountain-building movement (orogeny), there has been a long succession of dynamic events, through the vast span of Mesozoic time, leading up to the final movements of Kainozoic (Tertiary) era. The latter movements, classed as "Alpine" in the European succession of orogenies, are termed "Laramide" in the West, after the Laramie Mountains of eastern Wyoming, where these specific disturbances were first recognized. It is the great crustal compressional movements, with folding and faulting, and locally overthrusting eastward of rock mass on mass, that are the most characteristic structures to be found in the Laramide Rocky Mountain system. These phenomena, too, extend northward into the Canadian Rockies, where mountain-forms consist repeatedly of the tilted block (orthoclinal), or "writing desk," structure. Such forms are to be found at least as far as latitude 59°, but uncertainly beyond, in terms of the Rocky Mountains movement *sensu stricto;* for the ranges to the northwest in Yukon and Alaska are considered to have been predominently due to the rather earlier coastal Cordilleran disturbances. Additional phenomena, confined to the west and south, were those of large intrusions of igneous rocks (batholiths) in places; but their age and relationship are not always clear. An example is that of the huge granite batholith of western Idaho, more than 16,000 square miles in area, which with other small intrusions lies along the western flank of the interior divisions of the Laramide Rockies. But it must be emphasized that normally neither deep-seated intrusions nor volcanic (surface) extrusions are to be found in the Rockies proper. They are confined to the interior and coastal ranges. As opposed to the not-infrequent "lay" view as to mountains in general, the Rockies were *not* elevated by *volcanic* forces. Even the San Juan mountains, of southwestern Colorado, with their widespread Tertiary lavas, are in reality due to a broad dome-like uplift of the region which later became buried by the lavas.

Significance of volcanoes and of mountain granite

It must be fully appreciated that crustal stresses are responsible for almost all the great mountain ranges of the world; and where volcanoes are present, as so notably in parts of the Andes, Central America and the Cascade mountains of the Pacific Northwest, they are only secondary features resulting from tension, or torsion at times, in dislocated belts of mountain terrain. Volcanoes and volcanic action are rare in, or even absent from, regions which are not folded and faulted, for the evident reason that such rupturing of the outer crust is necessary to tap the sources of molten material below. But this deep material (magma) does not always reach the surface to form volcanic vents or even lava flows emitted through fractures (faults). Frequently it tends, in the absence of adequate magma-pressure or of other favorable factors, to become emplaced and solidified within the compressed upheaved tract of the embryo mountain range. Such intrusive bodies are the batholiths, already cited, and we have large-scale examples of these forming the core of the Sierra Nevada of California, and the largest of all in the Coast Range of British Columbia. Moreover, it is only by prolonged erosion and the removal of a vast covering of sedimentary rocks by the action of water and ice that the igneous core has been exposed and the granite or diorite mass laid bare. And so it is in the case of many other existing ranges of the earth, in greater or less degree: e.g. Himalaya, Caucasus, Urals, Altai etc., the core being frequently granitic or dioritic, from which dykes may extend into the relics, if present, of the cover (roof-pendants). But equally frequent in folded ranges is injection by the more basic rock-type, basalt, cutting all formations as dykes or lying conformably within the strata as sills.

Mechanism of mountain building

Space does not permit us to discuss the likely source and the cause of emplacement of these igneous bodies of material, nor yet the problem of the ultimate origin of mountain ranges themselves. An immense amount has been written upon the latter subject, and a large number of hypotheses have been put forward: likely and unlikely, sometimes plausible, often highfalutin. We have not as yet sufficient knowledge of the earth's deep interior, nor of the fundamental geo-physical and geo-chemical factors associated with the materials of the interior, to explain adequately the periodic, if not accumulatively almost continuous, disturbances or *revolutions* that have gone to create great mountain chains. Certainly the old idea of the crustal shrinkage of the earth has been shown to be inadequate; and equally the later theories of continental displacement, or of sliding which, incidentally, introduce more difficulties of all kinds than they explain; as well, moreover, as a widely favored mechanism that would depend on subcrustal convection currents, to quote only three of many "straws" that have been clutched by over-expectant and optimistic geologists and geographers. Even such an apparently well-established principle as *isostasy,* i.e. the relation between elevation and density, or the postulated condition of balance or equilibrium between crustal units, especially within and outside a mountain range, has been called in question: or, at least, controversy is rife over the actual nature of the isostatic adjustment one to the other of these crustal units, and *a fortiori* the late significant adjustment that may give rise to continuing slow elevation of certain ranges, or parts of ranges, as seems to be the case in the Himalaya, for instance.

So attractive, and yet so difficult, are many of these problems that we must agree with the dictum of the great American geologist, James Hall (named earlier), when he declared in his presidential address to the American Association for the Advancement of Science as long ago as 1857: "We are forced to confess that our wonder has been more excited than our reasoning powers."