

THE GEOSYNCLINAL THEORY

(Address as Retiring President of the Geological Society of America)

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INTRODUCTION

The type geosyncline, as is well known, is the Appalachian geosyncline. James Hall, the founder of what is here called the geosynclinal theory, first set forth the fundamental concepts in his presidential address at the meeting of the American Association for the Advancement of Science at Montreal in 1857. The novel and powerful ideas announced at that time were regarded as extravagant by some of his audience, and shortly afterward the Secretary of the Society, the eminent Joseph Henry, wrote Hall a friendly letter cautioning him to go slowly in advocating his new ideas. Probably that is why the presidential address was not published until 1882. In the meantime, however, Hall had given in his volume on Paleontology published by the Geological Survey of New York under date of 1859, a far more effective presentation of his ideas than in the presidential address, and had analyzed the evidence on which they were based. He formulated the principle that "the direction of any mountain chain corresponds with the original line of greatest accumulation, or that line along which the coarser and more abundant sediments were deposited."

In the Appalachian region, as Hall pointed out, nearly 40,000 feet of shallow-water beds were laid down, ten times the thickness of the sedimentary series farther west in the Mississippi Valley. These figures appear still to hold their validity. The heavy localized sedimentary loading caused the crust to subside, and the axis of the trough thus formed determined the trend of the future mountain range. The subsidence of the trough, Hall thought, inevitably caused the strata to be folded, but this folding was not the factor that gave the mountain range its height; rather the thickness of the pile of strata determined the height of the range. Anticipating future ideas, Hall suggested that the downwarping of the sediment-laden trough caused the subcrustal material beneath the trough to flow laterally under the area that supplied the sediments [Appalachia] and also under the foreland, thereby causing these areas to rise. Only in recent years, as the implications of the doctrine of isostasy have become recognized, have these ideas become accepted.

Although Hall claimed to have supporting testimony from the Rocky Mountains for his theory, little or nothing was then positively known of that region. His great generalization was in the fact an "induction" based on a single example, the Appalachians.

In 1866 Dana pointed out that the elevation of the mountains is left unexplained in Hall's theory of the origin of mountains. Later he gave a clear analysis of the main points of Hall's theory, and reiterated his objection of 1866 that Hall had in no way

explained the uplift of the mountain—"the event upon which the existence of any mountain depends," and he therefore pronounced the theory to be seriously deficient (1873a). In the same year Dana published his epochal contributions on the origin of mountains. In the first of these papers (1873b, p. 430) he named the downwarp of the crust in which the sediments accumulated a "geosynclinal," a term since altered in Anglo-Saxon usage to "geosyncline."

In these papers Dana added to Hall's theory the fundamental idea that during the collapse of the geosyncline great folds are pushed up by the action of lateral pressure, forming a lofty fold-chain, or as he called it, a "synclinorium." He pointed out also that the subsidence of a geosyncline to a depth of 35,000 or 40,000 feet meant that a mass of mobile (viscous or plastic) rock, 7 miles in maximum depth and more than 100 miles wide, was pushed aside. "What became of it?" he asked. In the main, it moved eastward, Dana argued, and caused the tract bordering the sea on the eastern side to be arched up as a geanticline parallel with the subsiding trough. The height of this geanticlinal arch would have depended on how far the "mobile rock" could have moved eastward. Thus Dana brilliantly anticipated many later ideas. At this time (1873c) he adopted from T. Sterry Hunt, as he himself records, the important idea that the floor of a geosyncline because of its deep subsidence becomes weakened by the resultant rise of the isogeotherms, and that this weakening causes the eventual folding of the geosynclinal sediments and the birth of the mountain range.

In the final edition of the famous *Manual of Geology*, in 1895, Dana recognized the great importance of the geosynclinal concept by pointing out that Hall's presentation in 1859 "was the first statement of this grand principle in orography." Dana then concisely formulated the theory, and this formulation can be taken as giving the American notion of the theory at the turn of the century. The Hall-Dana theory that mountain chains are born of geosynclines comprised two main tenets: (1) a preparatory stage during which sediments accumulate in a geosyncline, thereby determining the site of the future mountain range and (2) the mountain-making crisis, short in duration, during which the strata are folded and faulted. That the geosyncline was an asymmetric trough bordering an oldland, that it slowly deepened, and that concurrently as it subsided it was kept filled with coarse clastic sediments, these ideas, as we have seen, were part of the original concept. Hall had also some remarkable ideas on metamorphism, such as that "the metamorphism is due to motion, or fermentation and pressure aided by a moderate increase of temperature, producing chemical change," but Dana disregarded them, as well he might.

Dana added, remarkably enough in view of the fact that he was then in his 82nd year and that isostasy as a geologic doctrine had been formulated only a few years before by Dutton in 1889, that an orogenic revolution proceeds conformably with the principles of isostasy—an advanced viewpoint not generally reached until two or three decades later.

From this time onward the Hall-Dana theory passed into world literature. It began to grow magnificently. It became also much metamorphosed, so that versions differing much from the original began to appear. In France the change began with the masterly analysis of the problem by Bertrand (1897), whose ideas were more

fully developed by Haug (1900). These ideas appear still to comprise the fundamental tenets of French geologists, as may be seen on reading the most recent edition of Gignoux's *Géologie Stratigraphique* (1943). According to L. De Launay, in his lucid volume *Géologie de la France* (1921), "a geosyncline is by definition an important long zone in which *bathyal*¹ deposits continuously accumulated to such a thickness that we must conclude that deepening went on simultaneously with accumulation." Leuchs, in 1927, discovered that "we *now*¹ know that geosynclines need not be very deep," exactly 70 years after James Hall had announced that idea.

EXPANSION OF THE GEOSYNCLINAL THEORY

It is not with such mutants that we are here concerned, but rather with the notable additions to the original Hall-Dana theory. These additions involve (1) volcanism and intrusion during the growth of the parent geosyncline; (2) isostatic control during the folding consequent upon appression of the geosynclinal sediments; (3) metamorphism resulting from geosynclinal conditions and the events attending the folding; (4) batholithic intrusion, syntectonic and epitectonic, and the relation between batholithic intrusions and the successive epochs of foldings that comprise a large-scale orogenic revolution; and (5) metalliferous deposition as aftermaths of the successive cycles of igneous activity during the orogenic revolution. This greatly developed and expanded form of the Hall-Dana theory is referred to herein as "the geosynclinal theory." It constitutes a great—probably one of the greatest—unifying principles in geologic science. I propose to examine critically the tenets of the geosynclinal theory, with emphasis on the role of igneous activity. The relation of geosynclinal conditions to metamorphism has remained largely outside the scope of this analysis.

Not often have the tenets of the geosynclinal theory been confronted with the field facts. Born (1930) has analyzed the Cape Mountain fold-chain of South Africa to see how far it conforms to our knowledge of orogeny and to our assumptions. F. E. Suess (1937) and Hess (1940), writing from very different viewpoints, have adversely criticized the geosynclinal theory and deny it *in toto*.

De Launay (1921) in a brilliant chapter on the *Les Chaines de Plissement* in his *Géologie de la France* gives a comparative study of the three Cenozoic fold-chains of France—the Pyrenees, the Alps, and the Jura—and the role the geosynclines have had in determining their histories. A fold-chain is built, then demolished by peneplanation, and a new range is built on the same site. Thus the Alpine chain is superposed in large part on the more ancient Variscan chain. "Nature has acted here just as man does, who ceaselessly rebuilds upon the same ruins."

A French addition to the geosynclinal doctrine, apparently first added by Termier (1903), is that regional metamorphism—"the most energetic and intense of all the metamorphisms," is determined by geosynclinal conditions, and this idea has recently been taken over by Finnish geologists to account for the zonal arrangement of metamorphism. In this concept a gneiss belt represents the keel of a geosyncline exposed by profound erosion; it is flanked on each side by a belt of mica schist which grades

¹ Italics supplied by the present writer.

outward into phyllite. This idea appears to need the support of more field facts before it can be safely integrated with the geosynclinal theory.

OROGENIC PHASES OF THE GEOSYNCLINAL REVOLUTION

The geosynclinal doctrine has been developed more extensively in connection with the Variscan Mountains of Middle Europe than with any other fold-chain. The immense number of detailed studies—English, Belgian, French, German, and Austrian—give us a remarkable store of facts and interpretations on (1) geosynclinal sedimentation, (2) the igneous activity during the evolution and revolution of the geosyncline; (3) folding during the several orogenic crises that comprise the revolution; (4) metamorphism and the development of paligenic granites; and (5) metallogenetic epochs related to the granites intrusive during the successive orogenic crises.

According to some authorities the Variscan geosyncline came into existence early in Cambrian time and lasted until late in the Carboniferous. Although it was affected by the Caledonian folding near the end of the Silurian, it is thought not to have been blotted out at that time but to have received its greatest volume of sediments during the Devonian. In contrast to this view, the Variscan geosyncline is more generally considered to have begun forming early in the Devonian. It extended from Cornwall eastward across northern France, Belgium, and Germany to Poland (Fig. 1). About 40,000 feet of strata were laid down in the deepest part of the trough during the Devonian. Pillow lavas of keratophyre and diabase were copiously erupted during the quiet of geosynclinal sedimentation.

The later history of the geosyncline comprises an extraordinary number of orogenic phases and plutonic intrusions accompanying the successive orogenic phases; and it is this history, deciphered in illuminating detail, that makes the Variscan geosyncline particularly significant to geologic theory.

The name "Variscan" was given by Eduard Suess to the hypothetical mountain arc of late Paleozoic age whose roots are exposed in a belt that extends from the Central Plateau of France northeastward to the Elbe and thence southeastward to the Sudetic Mountains between Silesia and Bohemia (Fig. 2). Subsequently, "Variscan" has come to be used in two other senses: (1) as the direction of fold axes, and (2) as the name for the folding (or orogeny) that extended in time from late Devonian to the end of the Permian. From 1920 onward Stille has given more and more detailed precision to the term "Variscan" as an overall concept for a long-continued crustal revolution of late Paleozoic age. He now recognizes nine separate phases of folding, as shown in Table 1. "Hercynian" is a name frequently used for this revolution, particularly in France. According to Haug (1907), a period of diastrophism began near the end of Early Carboniferous time and continued through the Permian; "these foldings we call Hercynian, *quoique ce terme soit impropre*." The term Variscan is therefore preferred here.

Practical requirements, caused by the absence at many localities of the precise stratigraphic data necessary to date a given pulse, make it convenient to use a hierarchy of terms, in which the successive phases are grouped in triads: Early Variscan comprises the first three phases, Middle Variscan the next three, and Late Variscan the final three. The Early Variscan and Sudetic (4) phases were the most powerful

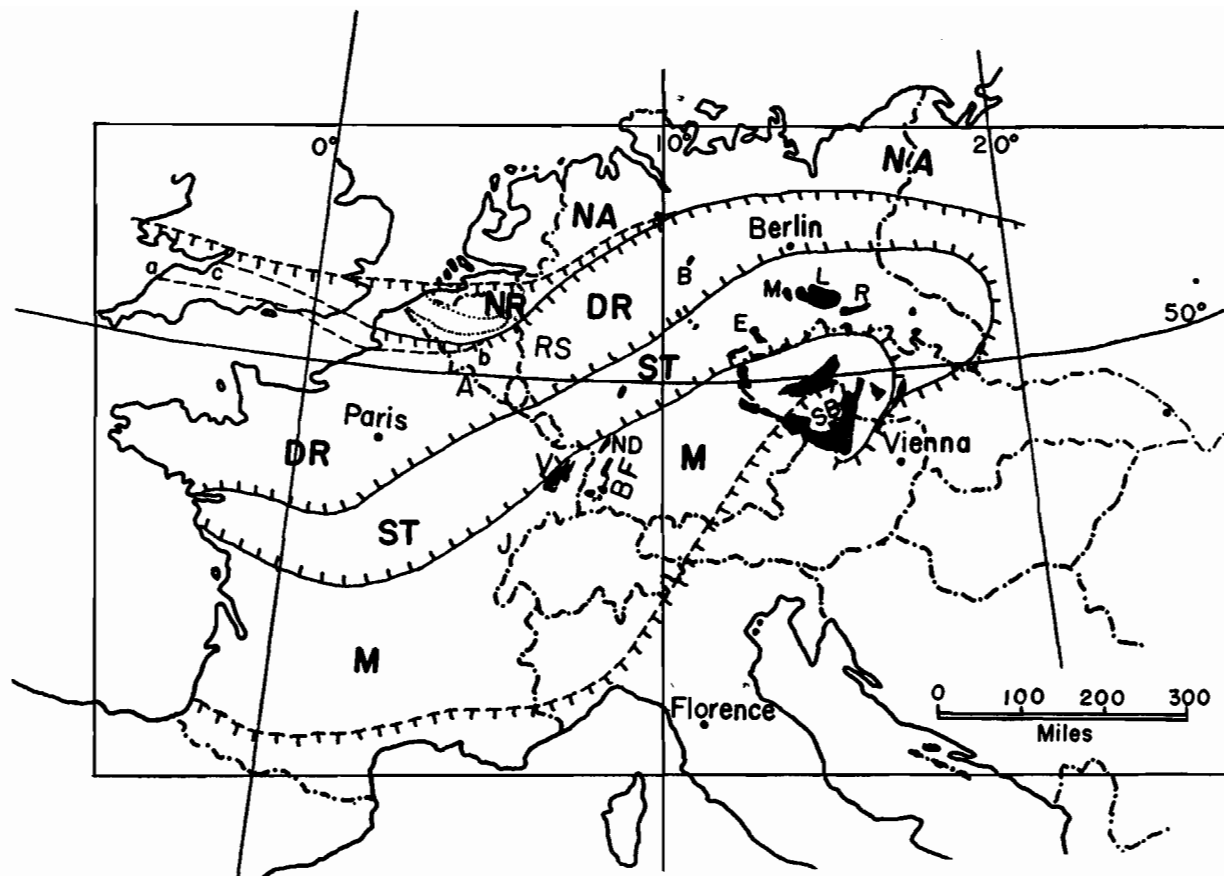


FIGURE 1.—Schematic representation of the development of the Variscan geosyncline

(Compiled from maps by Kossmat, Stille, and Gignoux)

DR = Devono-Rhenan Zone—occupied by Devonian trough (ab = northern border in early Devonian time; cb = northern border in mid-Devonian time); persisted along northern edge as the sub-Variscan foredeep flanking the mountains formed during the Sudetian (4) folding.

ST = Saxothuringian Zone—locus of the Variscan Mountains formed by the Sudetian (4) folding.

M = Moldanubian Zone (underlain by old crystalline rocks)—folded in the Sudetian (4) and Asturian (6) phases.

NR = Northern Rhenan Zone—extension of the geosyncline in late Devonian and Carboniferous time (dotted area is the Brabant anticline).

NA = North Atlantic continent (Old Red Sandstone continent). In early Devonian time extended to northern edge of DR.

M = Meissen; L = Lausitz; R = Riesengebirge; E = Eibenstock; SB = Southern Bohemia; Black Forest (N = Nordrach; D = Durbach); V = Vosges; B = Brocken.

in the axial portions of the folded belt of Central Europe, whereas the later, Asturian (6) folding was the most intense in the northern border zone of the geosyncline, acutely folding the paralic coal belt that extends from Belgium to Westphalia (Fig. 3). In general the orogenic phases of the Variscan revolution increased in intensity during

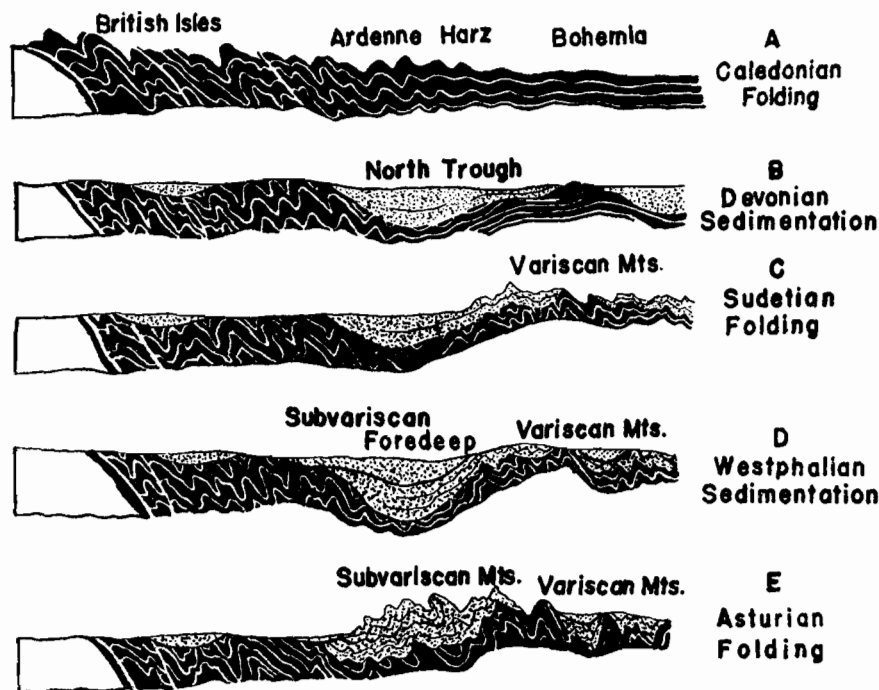


FIGURE 2.—Diagrammatic cross sections showing the development of the Variscan mountains

(Modified from Stille, 1929)

The North Trough comprises the Devono-Rhenan Zone and Saxothuringian Zone of Fig. 1

early Carboniferous time, reached a powerful climax approximately at the end of Mississippian time in the Sudetic phase (4), and became feeble in the Permian.

These terms have received general assent, probably because they are convenient, but they have the added merit that they sharpen our concepts as to what happens during a major orogenic revolution.² American geology would be enormously helped if the Laramide revolution, which is now known to consist of at least eight pulses extending from Cretaceous to Oligocene, were to receive an analogous, widely acceptable mode of naming. As part of his orogenic time law Stille holds that the principal folding phases are essentially synchronous throughout the world, although not necessarily of the same intensity in all parts of the world, and that therefore the terms are applicable the world over. The Appalachian revolution is accordingly considered by Stille (1929) to be Variscan, and its main phase, possibly its only phase,

² A less appreciative view is expressed by Gignoux (1943). "La distinction et la nomenclature des diverses phases successives de plissement ont été poussées à l'extrême par H. Stille (*Grundfragen der vergleichenden Tektonik*, Berlin, 1924); mais le nombre de ces phases s'accroît sans cesse à mesure que progressent les études de détail; (p. 158) visiblement ce ne sont que des étapes dans le continu." But the force of these remarks is weakened when we find that "continuity of folding" is held to mean intervals between pulses as long as all Westphalian time (p. 193).

was the Saalian (7), as Stille suggested in 1924, a suggestion later concurred in by R. C. Moore and R. T. Chamberlin.

During Devonian time the Variscan geosyncline, specifically that portion of it termed by Haug (1910) the Devono-Rhenan geosyncline, received sediments from

TABLE 1.—*Variscan revolution**

TRIASSIC		Pfalzian (9) phase	
PERMIAN			
	Zechstein	Thuringian (8)	"
	Rotliegend	Upper Rotliegend (Saxonian)	Saalian (7)
		Lower Rotliegend (Autunian)	"
LATE CARBONIFEROUS		Stephanian	Asturian (6)
		Westphalian	Erzgebirgian (5)
		Namurian	"
		Sudetian (4)	"
EARLY CARBONIFEROUS		Glyphioceras stage (Culm)	Selkian (3)
		Periclycus stage	Nassauan (2)
		Gattendorfia stage	"
LATE DEVONIAN		Wocklumeria stage (V)	
		Latest part of stage (IV)	
		Marsian (1)	"
		Earliest part of stage (IV)	

* Modified from Stille (1928). The numbers in parentheses after the successive orogenic phases have been put there as aids to remembering the sequence. Roman numerals indicate the fourth and fifth biostratigraphic stages of Late Devonian time. The *Wocklumeria* stage is regarded by Gignoux (1943) as earliest Carboniferous.

the north, where lay the landmass called the Old Red continent or North Atlantic continent. As the Devonian went on, the geosyncline widened, lengthened, and deepened continuously, attaining its maximum extent and depth near the end of the period.

The Marsian (1) phase, named by Schindewolf in 1926, is the oldest definitely dated of the long series of diastrophic pulses of the Variscan orogeny. "Bretonian" had earlier been given by Stille to the opening phase of the Variscan revolution, but according to Schindewolf the Bretonian phase really comprises three separate pulses, for the first of which he proposed the name Marsian. The Upper Devonian of Germany, on the basis of goniatite evolution, is subdivided as of 1938 into five biostratigraphic stages. As the result of progressively sharpening stratigraphic and paleontologic work the Marsian folding has been shown to fall into the middle of Upper Devonian stage IV, comprising the Dasberg beds. The topmost Dasberg beds and the overlying beds of the *Wocklumeria* stage, Upper Devonian (V), 80 meters thick, pass without a break into the Lower Carboniferous. This close determination of the time of folding was first made by Gallwitz in 1928 and later confirmed by others at

several localities, but such precision is seldom possible; it was accomplished by using the principle that the zone in which the folding dies out should show only a short interruption of sedimentation and consequently the age can be most closely determined there. The angular discordance at the type locality, amounting in places to

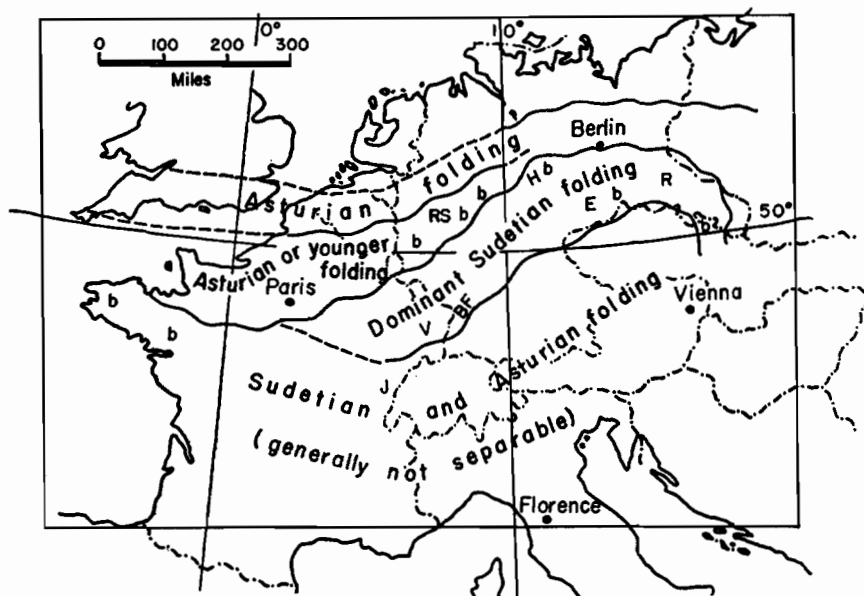


FIGURE 3.—Diagram showing distribution of dominant folding—Sudetic (4) and Asturian (6)—in the Variscan Orogeny

(Some localities where Early Variscan folding (Bretonian) has been recognized are shown by the letter b.)

RS = Rhenish Schiefergebirge; H = Harz; V = Vosges; J = Jura; BF = Black Forest; E = Erzgebirge; R = Riesengebirge.

30°, is a real unconformity, involving folding and erosion of the lower beds. This unconformity is confirmed elsewhere by a basal conglomerate, transgressive on several zones of the Upper Devonian. The discordance at Warstein in Westphalia is as much as 90°, according to PaECKELMANN and Richter (1938).

The brief time allowable for the folding and subsequent erosion fits in well with one of the principal orogenic tenets of Stille, namely that individual orogenic pulses are exceedingly short. Except for the upper portion of the Dasberg beds, nothing of the Upper Devonian is absent. The time indicated is indeed so short that PaECKELMANN favored the idea that the folding and erosion were submarine. However, when we contemplate what the California geologists are finding about the Mid-Pleistocene orogeny—the Coast Range orogeny of Reed or Pasadena of Stille—that a right-angled unconformity was formed, and 5000 to 16,000 feet of strata were removed by denudation, during which the Early Pleistocene beds became beveled by an erosion surface that attained late maturity (Putnam, 1942), all this in a small fraction of Pleistocene time, then perhaps the Marsian phase may be considered to be an orogenic phase of average duration.

The close dating of the successive phases of the Variscan revolution has been sub-

ject to some changes as results of increases in paleontologic information and changes of view as to the time values of certain fossils. In 1930 the Stieger beds in the Harz Mountains, the best known relic of the Variscan Mountains, were thought to be Early Carboniferous, but the finding of *Tentaculites* in them, proved them to be Devonian. The Selkian (3) phase, which had been defined by the stratigraphy and tectonics of the Stieger beds, thereby became indeterminate as to its precise position in the Early Variscan folding, because from the new evidence it might be either Marsian (1) or Nassauan (2). "Cravenian," from the Carboniferous of England, is suggested by H. Schmidt (1939) as more appropriate than Selkian.

The Marsian is considered to belong to the Variscan cycle because the folds it produced strike parallel to those formed during the later Variscan foldings. Although few geologists have shown an inclination to include in the Variscan (or Hercynian) any orogenies earlier than the Marsian, the problem in its broader aspect is still open, namely, when does a revolution begin and when does it end? Witness, for example, the recent account of the Wasatch Range by Eardley (1944), in which a "Sierran-Laramide" revolution is recognized, thus linking together two mighty revolutions. The conjoint revolution is held to be marked by seven stages of compressional deformation, each of which was followed by erosion and the development of unconformities, in the span of time extending from late Jurassic to Oligocene.

IGNEOUS ACTIVITY DURING GEOSYNCLINAL EVOLUTION AND REVOLUTION

The important idea that geosynclinal evolution and the orogenic revolution determined by it are marked by a definite cycle of igneous activity was outlined by Daly (1912). Somewhat later, the hypothesis was developed in more extended form by Kossmat (1921). During Stage I, the stage of geosynclinal sedimentation, according to Kossmat, submarine basalts are extruded in great volume, accompanied by intrusions of gabbro and peridotite. These basic rocks collectively are called "ophiolites." This igneous activity and its products are held to prove that the crust at this stage in the life of a geosyncline is underlain by heavy basic magma (sima). In the next Stage (II), the stage of folding, the kind of magma generated and the resulting igneous activity change markedly: granite magma now becomes the dominant kind, having been formed by the dissolving of the sialic roots of the folds that had subsided deeply into the sima in restoring isostatic equilibrium. At or near the end of the stage of folding, Stage III, marked by isostatic subsidence and granitic intrusion, sets in. The crust, which becomes greatly stiffened and rigidified by the folding and by the enormous masses of granite intruded into it, is no longer foldable, therefore breaks by faulting. These faults facilitate the eruption of lavas, and Stage III is therefore likely to end with the extrusion of lavas on the Earth's surface.

Kossmat further laid down the principle that the fold-chain grows not only in height but also, because of its weight, in depth. The fold-chain projects downward roughly nine or ten times its height. Furthermore, the weight of the fold-chain causes the adjacent foreland to be downwarped. A new trough is thereby formed that flanks the rising fold-chain. Such a bordering trough, a "geosyncline of the second order," becomes filled with sediments produced by erosion of the newly formed fold-chain and eventually becomes affected in part by the final stage of the folding.

These ideas have caused many repercussions. Soon afterwards Scheumann (1924)

named Stage I, characterized by submarine basalts and associated plutonites, as the prototectonic phase; Stage II, the syntectonic phase, marked by intrusion of granite concomitantly with the folding, during which the granite becomes deformed to a gneissic state and therefore appears now as orthogneiss; and Stage III, the apotectonic phase, marked by the intrusion of stocks and batholiths of massive granite, accompanied by pegmatites and lamprophyres.

By 1932 these ideas had become a full-fledged theory to explain the magmatic activity during the Variscan period in Saxony:

Phase I. The magmatic preliminary phase ("proterotectonic," "pre-principal tectonic," "early tectonic" are synonyms) comprising basic ("diabase") eruptions and their silicic end products, the keratophyres. However, as shall presently be shown, this stated sequence is exactly the reverse of what the field facts show.

Phase II. Syntectonic phase of magma movement (principal tectonic, synkinematic, synorogenic are synonyms used by later writers): intrusion of large masses of granodiorite magmas into the central portions of kinetometamorphic anticlines, accompanied by zonal metamorphism. Gneiss domes are formed, surrounded by zones of injection gneiss grading outward into mica schist and phyllite. Pegmatites are pressed out and all the volatile constituents of the consolidating magma escape and become dispersed and permeate the contact aureole. Failure to develop lamprophyres is characteristic.

Phase III. Post, or late-tectonic phase—termed apotectonic, post-kinematic, post-orogenic by other writers, but epitectonic or epikinematic seem preferable, as indicating immediate succession to the preceding phase. Granites intrusive at this stage solidify under static conditions; they are surrounded by normal contact-metamorphic aureoles of hornfelses. They are characterized by the slow escape of their emanations, thereby giving opportunity to form "pneumatolytic concentrates" and, presumably, of ore-forming solutions. Pegmatites occur within the granite masses, and lamprophyres are formed.

Here is an incisive scheme, which though framed for Saxony, may have far broader application. It offers a possibility of throwing needed light on a major problem of geology, of accounting in a measure for the fact that some intrusions have been followed by a cortege of metalliferous deposits and many have not. The hypothesis should consequently be confronted with the facts determined in other regions.

MAGMATIC ACTIVITY DURING THE FILLING OF THE GEOSYNCLINE

Initially it was thought, as implied by the term "early tectonic," that the submarine eruption of basalts and other ophiolites began when the geosyncline was nearly filled. The ophiolites were considered to be the heralds of the impending tectonic revolution. However, stratigraphic evidence shows that volcanism has been active very early in the history of many geosynclines. In the Appalachian geosyncline south of New York, no extrusion of basalts heralded the crustal revolution of late Paleozoic age; but the basalt amygdaloids near the base of the Unicoi formation were erupted almost at the inception of the geosyncline early in Cambrian time. In the Variscan geosyncline, which we take to have begun very early in the Devonian (Gedinnian), the ex-

tended extrusive activity that marked much of Devonian and Carboniferous time began late in the Middle Devonian.

Careful petrographic research seems to have invalidated also the systematic sequence of types announced by some. "Geosynclinal basalts," according to Tyrrell (1937), are extruded in enormous bulk during the growth of a geosyncline. The basalts are mostly true basalts though with a tendency to be accompanied by spilites (albite basalts). They and their associated intrusive masses of gabbro, peridotite, and serpentine are likely to become affected by low-rank metamorphism during the subsequent tectonic revolution and thereby become altered into the well-known green rocks or ophiolites, "which are such prominent constituents of fold-mountain zones of all ages." The total volume of geosynclinal basalt (mainly Ordovician) in the Caledonian geosyncline is estimated by Tyrrell, on very tenuous evidence, to be of the order of 30,000 cubic miles. However, rhyolite was abundantly extruded in this geosyncline in Wales during the Ordovician; and in the Lake District, the Borrowdale Volcanic series was erupted, probably exceeding 10,000 feet in thickness, consisting largely of andesite but topped by rhyolite. The Caledonian revolution began at or near the end of the Silurian and persisted into the Devonian, into post-Lower Old Red Sandstone time. But during Silurian time volcanic activity was feeble; therefore the Silurian is said to have been "the calm before the storm." But when, as in the Sierra Nevada geosyncline, the final stage of sedimentation is marked by the extrusion of enormous amounts of basaltic lava, tuff, and breccia accompanied by keratophyres and other "spilitic" manifestations, we say that this igneous activity is the herald of the coming storm, the prototectonic phase of the predestined crustal revolution.

The Tasman geosyncline (Sussmilch, 1935), which extended from northern Queensland southward more than 1000 miles, is notable for containing several series of highly differentiated lavas. The geosyncline began to form early in Devonian time. Volcanism was active during all of the Carboniferous. Mainly andesites were erupted in earliest Carboniferous time, but somewhat later 3000 feet of andesite, dacite, keratophyre, dellenite, toscanite, and rhyolite were poured out, the more silicic kinds of lava generally predominating. In Late Carboniferous time 10,000 feet of lava, chiefly andesite and basalt, issued at Cracow, Queensland, while at Silverwood 3000 feet of rhyolite, dacite, andesite, and basalt were erupted. Deepening of the sedimentary trough continued until some time in the Permian and 9000 feet more of beds accumulated before the Tasman geosyncline was extinguished.

In the Rhenish Schiefergebirge, where the Devono-Rhenan geosyncline began to deepen extraordinarily fast in Early Devonian time, keratophyric tuffs and flows were erupted during the Coblenzian stage (late Early Devonian). The Lower Devonian, in fact, is the most widespread of the Devonian rocks, and greatly exceeds the rest of the Devonian in thickness. The "labile" nature of the floor of the deepening geosyncline, as indicated by the greatly differing rates of subsidence of adjacent portions, probably made possible the rise of molten magma, says Tilmann (1938), but, as will be shown, the problem is more complex than only an explanation to account for the rise of magma, as it comprises also the highly differentiated nature of the magma or magmas that rose from the depths and were erupted.

Keratophyric eruptions in the Lahn area of the Schiefergebirge opened the extended magmatic cycle that began in Middle Devonian time. Tuff is the most abundant material ejected, lava is subordinate. The rocks, as shown by recent study of fresh, comparatively unaltered material, are of typical alkalic type; aegirine-augite, aegirine, and alkali hornblende, especially riebeckite, are common constituents (Goetz, 1937). They thus conform with the Middle Devonian keratophyres of the Harz, which were the first keratophyres in which aegirine and riebeckite were found, in 1909 by Erdmannsdörffer. The silica content of the Lahn keratophyres ranges between 74 and 56 per cent; alkalis are high, with soda generally predominant, and lime and magnesia are consistently very low. Albite, micropertthite, and anorthoclase comprise the phenocrysts; and homogeneously unmixed crystals of anorthoclase that are sporadically present indicate that the associated albite phenocrysts crystallized from the magma and were not formed by hydrothermal replacement of a prior existent calcic plagioclase. The keratophyres of the Lahn thus prove to be more or less altered (paleotypal) aegirine-riebeckite trachytes. Many of the keratophyric flows are remarkably pillowed, individual flows 200 feet or more thick being pillowed from top to bottom (Kegel, 1932).

The protracted eruptive activity thus began early in the history of the Variscan geosyncline with the submarine extrusion, not of basalt, but of magma of a highly specialized type, presumably therefore the product of extreme differentiation. The keratophyres of the Lahn and Dill areas are Middle Devonian, but in the Upper Devonian only typical subalkalic basic rocks—variolithic basalt, diabase, and picrite were erupted. Thus the petrographic nature of the province changed between Middle and Upper Devonian time from alkalic to subalkalic—an example of a striking change held to be a major problem in petrogeny.

Many of the keratophyres have been called "diabase" and were mapped as such; it was the prevalence of these supposed diabases that helped to strengthen the idea that ophiolites are characteristic of the prototectonic history of geosynclines. Albitic lavas, according to Jung (1928), are enormously abundant and widespread in the Devonian and succeeding Dinantian series of Europe. They have generally been termed keratophyre and albitophyre (the French equivalent of the German keratophyre), but Jung would group them all as albitic trachytes and albitic rhyolites, according to whether they do or do not contain free quartz. Furthermore, according to Jung, the Viséan of the Vosges (approximately Upper Mississippian), contains much mica andesite, rhyolite, albitic trachyte, trachyte, and pyroxene andesite. As Viséan time ended, orogenic movements suddenly began with paroxysmal intensity and the entire geosynclinal zone was folded, and the Variscan chain was elevated. This history, marked by the extrusion of an extraordinarily diversified volcanic series, none of it ophiolitic, immediately preceding the main orogenic crisis, differs widely from that envisaged by the Kossmat hypothesis of magmatic evolution during a folding cycle.

POLYCYCLIC MAGMATIC ACTIVITY DURING FOLDING OF THE GEOSYNCLINE VARISCAN OROGENY

Granite intrusions took place during the Early Variscan orogeny. In the central plateau of France granites cut and have metamorphosed the Tournaisian (Lower

Mississippian); and pebbles of most of these granites are found in conglomerates of late Viséan (Late Mississippian) age. The granites appear to be definitely dated as having intruded during one of the later phases (second or third) of the Early Variscan (= Bretonian) orogeny.

In the southern Black Forest plutonic activity was remarkably diverse. Two groups of granitic intrusives are distinguishable (Hoenes, 1940). Both groups are of early Carboniferous age, and no great interval of time separates them, but tectonic calm had settled over the region before the massive, therefore presumably younger group of granites, was emplaced. The inferior age limit for the time of intrusion is fixed by the fact that granites cut graywacke that carries *Protocanites*, indicative of the first stage of the Lower Carboniferous (Paul, 1940). The older group of intrusions consisting of three or four members began with granodiorite and ended with granite, which produced a notable zone of injection gneisses and was followed by a remarkable cortege of aplite, pegmatite, and lamprophyre dikes. The granodiorite was strongly deformed, so that practically every hand specimen is foliated, the result of coarse cataclasis, development of mortar structure, and mylonitization. Subsequently, as inferred from their massive nature, the second group of granitic intrusions was emplaced. Expectably, the first member of this series should be at least as silicic as the final granite of the preceding group, but actually it is granodioritic; it was followed by alaskite.

The granites of the first group accomplished marked assimilation and produced intense though areally limited migmatitization and granitization. In contrast, the granites of the second group, which appear to have risen to much higher levels in the crust as indicated by their broad border facies of porphyry and by their miarolitic nature, effected no assimilation, contact metamorphism, and migmatitization.

Crucial evidence on time of intrusion comes from the basal conglomerate that overlies the *Protocanites* graywacke. This conglomerate contains pebbles of the schistose granodiorite and of granite of the youngest member of group two, and contact-metamorphosed Devonian-Carboniferous rocks. Above the basal conglomerate are 4000 feet of conglomerates, sandstones, tuffs, and extrusives. Crinoidal limestone 2600 feet above the base of the series contains a rich neritic fauna of middle Viséan age. The two plutonic series are therefore Early Variscan and can be considered to have been emplaced during the Nassauan (2) phase: the deformed granite before the phase reached its climax—the syntectonic granite—and the massive granite after tectonic activity has ceased,—post-tectonic granite, or more accurately, epitectonic.

During a later orogenic phase, these rocks were appressed into a syncline, overturned, and subjected to imbricate faulting. This powerful diastrophism was ascribed by Wilser in 1933 to the Sudetian (4) orogeny, but new evidence, based on further areal, stratigraphic, tectonic, and petrographic work in the middle and northern Black Forest, make it necessary to assign it to the Asturian (6).

In the northern Black Forest region the large Durbach granite mass, according to Wilser, was emplaced during the Early Variscan activity. It has a primary foliation, which was intensified, however, by later cataclastic deformation. The Durbach granite was followed, as is normal petrogenically, by a more silicic granite, the Nordrach granite, which is massive. The Nordrach granite is tourmaliniferous, in con-

formity with its position as a late or final member of a plutonic succession. After the intrusion of the granites, "orogenic sediments" were deposited. They begin with a thick basal conglomerate containing pebbles and even boulders of the Durbach granite. Above the basal conglomerate come sandstone, arkose, coal, and tuff, whose plant remains prove to be of Middle Carboniferous age (Namurian and early Westphalian). This sedimentary series now stands at 60°; it is pinched in between fault slices of an imbricate thrust system, and is overlain unconformably by horizontal beds of late Pennsylvanian (Stephanian) and Permian age. Consequently, the chief folding movement of the Variscan revolution in the Black Forest—what constitutes "chief" is somewhat subjective—took place, according to Wilser (1935), in the Asturian (6) phase. It is perhaps noteworthy that this diastrophic pulse thus regarded as the paroxysmal chief movement was unaccompanied by plutonic intrusion.

Although the evidence for the Variscan revolution in the Black Forest has been but briefly sketched here, it can be seen that an extraordinary series of happenings was crowded into the Early Carboniferous (Mississippian): 1. deposition of biostratigraphic stage 1 (*Protocanites*); 2. deformation accompanied by the intrusion of a group of plutonic intrusions, emplaced in the order of increasing silicity; 3. injection of a satellitic dike retinue of aplite, pegmatite, and lamprophyre; 4. intrusion of a second group of granitic masses; 5. uncovering of the youngest granitic massif by erosion; and 6. piling up of 4000 feet of conglomerates, sandstones, tuffs, and lavas of Middle Viséan age on the eroded surface. Subsequently in Middle Carboniferous time, another series of sediments and volcanics was deposited and was powerfully deformed by the Asturian (6) orogeny.

As shown in Table 2 granitic intrusions accompanied at least five phases of the Variscan revolution. No granite, however, is known to have been emplaced during the first pulse—the Marsian (1), nor during the feeble last two. The intrusives range from quartz diorite and granodiorite to alaskite. Many of the intrusive masses are of batholithic dimensions, some in fact being notably large. The Lauseitz mass occupies 1800 square miles (1400 square miles exposed plus 400 square miles under cover of younger rocks) and the South Bohemian mass is 2000 square miles in extent. These masses occur mainly in the Saxothuringian and Moldanubian zones, as defined by Kossmat (1927) (Fig. 1). Thus these masses bear somewhat the same relation to the Variscan fold-chain as do the batholiths, generally thought to have been emplaced during the Appalachian revolution, which lie east of the geosynclinal axis. Formerly the Variscan masses were considered to be stocks and batholiths, but they have been reinterpreted by the granite-tectonicians as horizontal sheets that were injected into the crust above flat floors. None of the masses show evidence that they originated in place by subcrustal fusion, except possibly some in the southern Black Forest where a particularly deep level of the pre-Variscan foundation of sedimentary and igneous gneisses is believed to be exposed. The pre-Variscan gneisses of the southern Black Forest, the most intensively and repeatedly studied of any gneisses anywhere in the world, are now after detailed re-examination with the most recent ideas in mind, thought to show only a moderate amount of selective fusion (anatexis) and granitization as effects of the Variscan revolution. Although

it is possible that the Variscan granites were formed by anatexis, by subcrustal fusion, or by melting of the sialic downfolded tracts, no compelling evidence for such origin has so far been found.

In assembling this sequence of granitic intrusions during the Variscan revolution, only masses were included whose time of emplacement has been determined from

TABLE 2.—*Granitic intrusions*

Orogenic Phase	Intrusive Masses	Age (millions of years)
Saalian (7)	Schellerhau stock and other stanniferous granites	230
Asturian (6)	Riesengebirge massif	270
Erzgebirgian (5)	Lausitz granodiorite Meissen syenite-granite mass	
Sudetan (4)	Dohna granite; followed by tourmaline granite	
Early Variscan (2,3)	Black Forest Vosges Mountains	

field evidence. Theoretical age determinations based on chemical analyses and differentiation diagrams have been excluded, although such dubious methods have been much in favor. In connection with his study of the Black Forest granites and gneisses Erdmannsdörffer (1939) found that such genetically unrelated rocks as granulite, Rench gneiss, and kinzigite can be plotted to give a normal differentiation diagram; he has thereby dealt what must be considered the *coup de grâce* to the use of differentiation diagrams as substitutes for a real, stratigraphic, and tectonic work.

The evidence as to the Black Forest granites has been given here in some detail, but lack of space precludes giving the same amount of detail for the plutonic sequences in other parts of the Saxothuringian and Moldanubian zones. My main purpose is to put in view the fact that plutonic intrusion accompanied many phases of the Variscan revolution but not necessarily in all zones affected by the different phases. Each epoch of intrusion comprises a series of granitic rocks, some ending with tourmaline granite or followed by metallization. The most notable metallization followed the intrusion of the Saalian (7) granite stocks of the Erzgebirge, but these granites were not immediately preceded by any less silicic granites. Unlike other igneous cycles of the earlier orogenic pulses, the Saalian (7) pulse was accompanied at the Earth's surface by great eruptions of rhyolite, which began early in the Permian and attained their maximum between the end of Early Permian and beginning of the Middle Permian (Weyl, 1938). The Saalian granites brought in tin, tungsten, uranium, and silver, and produced notable pneumatolytic effects. Consequently the tendency formerly was to date any granite characterized by marked pneumatolysis as Saalian (7), and it was indeed a bold step to assign a tourmaliniferous granite to an orogenic pulse as early as Sudetan (4).

Another remarkable feature of the Variscan plutonic activity is that age determinations in years have been made for two successive epochs of granite intrusion—which is an achievement not yet accomplished for any other orogenic revolution. The Riesengebirge granite of the Asturian (6) phase is determined on the basis of a class IV radioactive analysis to be 270 million years in age, and the Saalian (7) granites as represented by the Eibenstock mass is determined to be 230 million years in age, based on a class I radioactive analysis of Joachimstal pitchblende.³ Accordingly, the span of time between the two phases Asturian (6) and Saalian (7), is tentatively 40 million years. The Saalian granites have been regarded as the final differentiates formed by the Variscan plutonic activity; thus their richness in metalliferous emanations was accounted for, but the matter seems hardly so simple. The conclusion now emerging is that a long-continued revolution such as the Variscan is polycyclic and that each orogenic pulse may have its own petrogenic cycle comprising synkinematic, late kinematic, and epikinematic granitic intrusions.

The pre-Permian, Asturian (6) age of the Riesengebirge granite mass involved a nice problem in determination. Pre-Permian age was first inferred from finding in the basal Permian beds pebbles of contact-metamorphic origin derived from the aureole of the Riesengebirge granite; and its Asturian (6) age was determined by the fact that lamprophyre dikes, considered to be genetically related to the granite, cut the very oldest Stephanian beds (late Pennsylvanian) and pebbles of lamprophyre occur in younger Stephanian beds; hence the granite and its retinue of lamprophyres are Asturian (6), "if we take this concept for the folding and igneous activity in not too narrow a sense chronologically" (Petrasczek, 1938, p. 23).

Another important point in this synoptic or comprehensive view of the Variscan plutonic activity as a whole is that the Riesengebirge granite is surrounded by ore deposits, zonally arranged in types that indicate that they were formed at decreasing temperatures outward from the mass (Petrasczek, 1937). But most of the deposits are grouped around the east end of the mass, which is the end that had been indicated by the Cloos granite-tectonic methods to be the position where the magma rose from depth before spreading laterally. Magma and ore-forming solutions thus appear to have risen along the same channel from a deeper hearth.

In the Erzgebirgian (5) phase the syenite and granite of the Meissen massif near Dresden were emplaced. Tectonic pressure was then still active at the time of intrusion, and the syenite facies of the massif is held to be the consolidated crystal mush from which the interstitial liquid had been squeezed out. The Lausitz mass, the largest of the Variscan plutonic intrusives, also is considered to be Erzgebirgian (5). It is a complex body: 30 per cent is muscovite-biotite granite, a hybrid border facies formed by the assimilation of or reaction with the graywacke roof-rock; and 10 per cent are minor varieties, end-stage intrusives of alaskite and aplite. Few or no pegmatites and ore deposits were generated by this intrusion, but many lamprophyre dikes were. The Lausitz mass, according to H. Cloos, rests on a flat floor; if

³ Age determinations of radioactive minerals fall into four classes: I, in which U, Th, Pb, and the isotopic composition of the lead have all been determined; II, in which U, Th, Pb, and the atomic weight of the lead have been determined; III, in which U, Th, and Pb have been determined by standard methods of analysis (as in the two previous classes); and IV, in which U, Th, and Pb, have been determined by microchemical methods. Absolute ages based on class I analyses are definitive, all others are of tentative value.

so, it is an injected mass—an alien mass—whose magma originated elsewhere and hence, if this magma was formed by the melting of the roots of the downwarped geosyncline, as freely asserted in many theories (Kossmat, 1921; Lugeon, 1930; Lawson, 1938), the evidence is elsewhere and inaccessible.

The time of intrusion—Erzgebirgian (5)—is determined largely from tectonic considerations (Gallwitz, 1934); in the succeeding Asturian (6) phase the Lausitz granite was reduced to mylonite along certain zones.

The five successive epochs of plutonic intrusion ranging from Early Variscan to Saalian (7) show the following similar features: the intrusives of all the epochs are granitic rocks, and where intrusives followed one another during a given epoch, the initial member was not more basic than granodiorite or quartz diorite, and the succeeding members arrived in the order of increasing silicity. One important exception occurs—the Brocken mass of the Harz Mountains, the most carefully and thoroughly studied of the Variscan massifs. It is a compound pluton 50 square miles in area, made up of four members. Gabbro was the first to be emplaced and was followed by three injections of granite, the last of which produced powerful pneumatolytic effects. The Brocken mass has been called successively a batholith, a “discordant laccolith” injected above a thrust plane, and lately a ring-dike intrusion (Lotze, 1933). According to the latter two hypotheses, the magma was formed in another place than where its resultant rock occurs; it then became differentiated, and the fractional magmas were moved from their place of origin and injected into their present positions. The magmatic history of the Brocken mass conforms to the scheme of serial differentiation from a parent basic magma, and does not particularly support the oft-expressed idea that the granites of fold-chains are formed by melting of the most deeply subsided portion of the folded geosynclinal prism. “Primary” magma rather than magma formed by subcrustal fusion appears to have been emplaced; and it would seem, therefore, a logical inference that the Brocken mass should be surrounded by a cortege of metalliferous deposits, an inference fully borne out by the facts.

RELATION OF MAGMATIC ACTIVITY TO OROGENY IN SOME NORTH AMERICAN GEOSYNCLINES

We turn now to some examples from North America. The sites and nature of the North American geosynclines have been described by Schuchert (1923), but lack of space precludes their examination from the point of view of this address. Among the more notable geosynclines is the Acadian (Schuchert, 1930). This geosyncline contains much volcanic material in Quebec, New Brunswick, Maine, and New Hampshire. In Gaspé, Quebec, the mid-Silurian section of 13,000 feet comprises 4600 feet of submarine basalt and andesite (Northrop, 1939). The marine Silurian near Eastport, Maine, is 16,000 feet thick, the preponderant part of which is lava and tuff (Bastin and Williams, 1914). Rhyolite of many kinds, andesite, and basalt are represented; in short, the volcanic series is of highly diversified nature. Near St. John, New Brunswick, marine beds of early Devonian (Helderberg) age are intimately interbedded with volcanic rocks, mainly andesite, but including also dacite, latite, rhyolite, and basalt. Thus the Devonian rocks of the geosyncline, like those of the Silurian, comprise a highly diversified series, which is obviously not ophiolitic.

In New Hampshire 5000 feet of pyroclasts accumulated during geosynclinal sedimentation, probably during late Ordovician time, according to Billings (1941). They comprise chiefly rhyolite, quartz latite, and dacite, with subordinate andesite and basalt, a richly diversified series. Later, in Early Devonian time, there was a mild repetition of volcanic activity. The indications are that the Acadian geosyncline is characterized by one of the thickest and most diversified records of volcanism so far known. Such a trough laden with large volumes of volcanic rocks erupted during its subsidence has recently been called by Stille (1939) a pliomagmatic geosyncline. Geosynclines of this kind are thought by Stille to be the only ones that are destined to become the sites of batholithic intrusion. Although this remarkable generalization appears to hold true for many geosynclines, it is far from being well established or understood.

The revolution that extinguished the Acadian geosyncline was a great earthstorm, as Sir William Dawson called it, surpassing every other in the geological history of the eastern border of the American continent. Although the revolution as a rule is tacitly considered to have had but one pulse, evidence is accumulating to indicate that it took place in several pulses: it is probably polycyclic like most other major revolutions. The earliest pulse, Alcock (1935) suggests, took place at the end of Early Devonian time and was followed by another in post-Middle Devonian time. The radioactively dated pegmatites at Ruggles Gap, New Hampshire, and at Portland, Connecticut (260 million years) are conventionally considered, i.e., without precise stratigraphic evidence, to have been injected during one of the later pulses of the Acadian revolution; the absolute age of the Connecticut pegmatite, 260 million years, which rests on a Class I determination, suggests Middle Carboniferous age. From that suggestion the conclusion follows either that the Acadian revolution lasted longer than commonly thought or that the pegmatites are not results of that revolution but are linked with an early forerunner of the Appalachian revolution.

In the Cretaceous Paysatin geosyncline of Washington and British Columbia, the basal member of the geosynclinal prism is andesite agglomerate 1400 feet thick, upon which 20,000 feet of clastic sediments were piled. The downwarping of this "local geosyncline," as Daly (1912) styles it, began as a result of the volcanism. Later, the Paysatin geosyncline was deformed and was invaded by stocks of granodiorite. Here too the geosynclinal magmatic activity was neither notably basic nor prototectonic.

In Montana andesites and latite were poured out in great volume as a late phase of accumulation in the Coloradoan geosyncline, which came into existence according to Schuchert (1939) in late Jurassic time. They were erupted in post-Niobrara time, probably just before the emplacement of the Boulder batholith, which rose to so high a level in the crust that it invaded the pile of lavas which thus constitute its roof rocks.

CONCLUSION

The growth of the geosynclinal theory has been outlined in the preceding pages and the great expansion from the early views of its founders Hall and Dana has been sketched. I have sought to give a comprehensive view of the theory as a whole,

with emphasis, however, on the role of igneous activity during the evolution and revolution of the geosyncline. Some of the supporting evidence from the vast mass of field facts gathered by geologists from all over the globe has been assembled and the interpretations of that evidence have been examined. From that examination it appears that the geosynclinal doctrine is likely to prove to be a great unifying principle, possibly one of the greatest in geologic science. Notable additions to the original Hall-Dana theory involve: 1. the role of volcanism and intrusion during the growth of the preparatory geosyncline; 2. isostatic control during the folding and appression of the geosynclinal prism; 3. batholithic intrusion, comprising synkinematic, late kinematic, and epikinematic phases, and the relation between the igneous intrusions that may accompany the successive phases of folding of a polycyclic orogenic revolution; 4. the regional metamorphism effected during the revolution; and 5. the formation of metalliferous deposits as aftermaths of the several cycles of igneous activity during the orogenic revolution. Few geosynclines show the complete succession of events; depth of erosion, as has long been suspected, probably accounts for the fact that some fold-chains show only part of the phenomena and only the more deeply eroded chains reveal the phenomena of zonal metamorphism and allied features. To determine the validity of these generalizations and to integrate them with the geosynclinal theory as a whole remain as inspiring tasks for the future.

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