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CHRONOLOGY OF TECTONIC MOVEMENTS IN THE APPALACHIAN REGION OF EASTERN NORTH AMERICA

JOHN RODGERS

Department of Geology, Yale University, New Haven, Connecticut

ABSTRACT. The orogenic movements that converted the Appalachian region from a linear belt of deposition into a mountain range were apparently rather spasmodic or episodic; the episodes, which range in age from the late Precambrian to the late Paleozoic, constitute the Appalachian orogenic cycle. Within the cycle, there were three especially strong episodes, or rather groups of strong episodes, commonly distinguished as separate orogenies: the Taconian orogeny during the Middle and Late Ordovician, the Acadian orogeny mainly during the Middle Devonian, and the Alleghanian orogeny during the later Carboniferous (Pennsylvanian) and probably lasting into the Permian. Before the beginning of the cycle, at least the northwestern margin of the present Appalachian region along with a wide strip of ground farther northwest had undergone the Grenville orogenic cycle, which may well have been as long and as complex. The Appalachian cycle terminated with an episode of block-faulting and rift-valley formation, the Palisades "disturbance", during the Late Triassic.

Pre-Appalachian movements.—Tectonic or orogenic movements in eastern North America fall into two major groups: a later group confined to the Appalachian region, which may be called collectively the Appalachian orogenies or orogenic cycle, and an earlier group found within that region but also well beyond it, corresponding to the well known Grenville orogenic cycle (Stockwell, 1961; that is, the major orogenic cycle that affected the Grenville province of the Canadian shield). The latter presumably comprised a sequence of episodes as complex and as long-lived as the Appalachian movements, but in the absence of fossils and of low-grade rocks deposited between episodes, they are still largely unseparated (note however Walton and de Waard, 1963; de Waard and Walton, 1967; Wynne-Edwards, 1965).

Evidence for the Grenville orogenic cycle is clearest of course outside the Appalachians, where flat-lying lower Paleozoic sedimentary rocks rest with profound unconformity on metamorphic and plutonic rocks formed in the granulite facies during that cycle (Ambrose, 1964, and references there cited for localities 54 to 79). These older rocks reappear within the Appalachian belt, first in a series of anticlinoria along the west side, roughly along the line where metamorphism begins in the overlying Paleozoic or post-Grenville Precambrian rocks, and second in certain groups of gneiss domes not much farther southeast. Among the first are the northern Long Range of Newfoundland (Clifford and Baird, 1962), the Green Mountains of Vermont (for example, Brace, 1953), the Berkshire Highlands of Massachusetts (Emerson, 1917), the Hudson Highlands of New York (for example, Balk, 1936) and their extension across New Jersey into the Reading Hills of Pennsylvania, the Mine Ridge-Honeybrook uplift of Pennsylvania (for example, Bascom and Stose, 1938), and the South Mountain-Blue Ridge uplift extending from Maryland across Virginia into North Carolina and Tennessee (for example, King, 1950; King and Ferguson, 1960). Among the second are the gneiss domes around Baltimore, Maryland (Broedel, 1937; Hopson, 1964), and comparable areas in southeastern Pennsylvania (Doe Run-Avondale area—Bascom and Stose, 1932; Mackin, 1962), probably the belts of Fordham gneiss in Westchester County, New York, and vicinity (Hall, 1966), and possibly certain gneiss domes of eastern Vermont and western Connecticut (for example, Chester and Waterbury domes; see the respective state geologic maps). In the anticlinoria, the unconformity between the granulite-facies rocks, though these have retrogressed, and the overlying metasedimentary and metavolcanic rocks, progressively metamorphosed in the greenschist facies, is generally clear, though locally nearly wiped out by the later deformation (for example, Balk, 1936, p. 732-736); in the domes, both sets of rocks have been metamorphosed in the amphibolite facies and generally the unconformity can only be detected by mapping or by radiometric dating of the rocks.

Radiometric ages from the Grenville province where it is unaffected by later deformation range from 800 to 1100 million years (Lowdon, 1960, and subsequent annual reports); such ages are widely distributed over the province. Relic ages in the same range have been determined at a number of places in the anticlinoria (see Faul and others, 1963) and even in the gneiss domes around Baltimore (for summary, see Hopson, 1964); these are mainly zircon and whole rock ages, for most mineral ages record only the later Appalachian deformations.

In summary, a wide belt along the southeast side of North America suffered orogeny between 800 and 1100 million years ago. Only after this cycle of orogeny was over did the Appalachian region develop as such; the older basement certainly underlay the western part of the Appalachian region, but we do not know how far east it extended.

Latest Precambrian, or Avalonian, movements.—The first well known orogenic movements in the Appalachian region are those in the later part of the Ordovician, collectively called the Taconian orogeny. Evidence has been accumulating however of earlier movements, some certainly Precambrian, some only known to antedate the Middle Ordovician.

Evidence of Precambrian movements is clearest in the Avalon Peninsula of southeastern Newfoundland, especially on the north-south Holyrood horst at the head of Conception Bay (Rose, 1952; McCartney, 1954; McCartney and others, 1966). Here the oldest rocks are the badly deformed and mildly metamorphosed Harbour Main volcanics, which are cut by the Holyrood granite. Upon these, probably unconformably, rests the Conception group—dark cherty shale, siltstone, and graywacke sandstone. Unconformably on all these in turn rests fossiliferous Lower Cambrian, the base of a conformable Lower Paleozoic sequence, very little deformed on this block.

Yet on either side of the Conception Bay block, the sequence appears thick and conformable. On the east side, volcanics like the

Harbour Main appear to grade upward into clastics like the Conception, and the Conception grades up into the Cabot group, dark slate below, increasingly arkosic sandstone above. On the west side, the Conception group grades up into the Hodgewater group, again with much arkosic sandstone; this is in turn overlain by the Random quartzite and that by the Lower Cambrian; all these are folded together into moderately tight folds. Disconformities are reported at places in this thick sequence, especially beneath the Cambrian; I saw no evidence for them in the few places I looked, but they may be present elsewhere. Both the Conception group and the Hodgewater and Cabot groups contain however fragments of older volcanic and granitic rocks, and presumably the latter groups represent a clastic wedge derived from some rising source area. In short, there is evidence for two periods of at least local orogenic movement, one accompanying the metamorphism and granitic intrusion, the other during or just preceding the deposition of the arkosic units. Farther west, a tongue of volcanic rocks appears within the arkose (Bull Arm volcanics in Musgravetown group).

In southern Cape Breton Island (Weeks, 1954), Cambrian rocks rest on two different sequences. In one strike belt, Middle Cambrian rocks rest unconformably on metamorphic rocks (George River group). In another, Lower Cambrian rocks rest on quartzite and arkose (Morrison River formation) and these in turn on little or not at all metamorphosed volcanics (Fourchu group); disconformities are reported in this sequence but seem debatable. Juxtaposition of the two belts suggests at least one period of metamorphism before the deposition of the volcanics.

In southern New Brunswick (Alcock, 1938), the sequence is very similar. Low-grade metamorphics (Green Head) are present in one belt; badly deformed volcanics (Coldbrook volcanics) in another are overlain with a basal sandstone by Lower Cambrian strata. Sediments within the volcanics seem more deformed than the overlying Cambrian, and locally they contain pebbles of granitic rock.

In southeastern Massachusetts, Lower Cambrian sediments appear to rest unconformably on older pink granite-gneiss (Dowse, 1950); unfortunately the critical locality is isolated by being surrounded by Carboniferous rocks, but a plausible correlation, for which there is some radiometric evidence (Fairbairn and others, ms)[1], equates this granite with the widespread Dedham granodiorite of eastern Massachusetts and related plutonic rocks (Emerson, 1917, p. 172-181).

Radiometric ages (Fairbairn and others, 1966) confirm the correlation of the pre-Lower Cambrian volcanics in the three Canadian areas mentioned (Bull Arm, *not* Harbour Main, in southeastern Newfoundland, Fourchu in Cape Breton Island, Coldbrook in southern New Brunswick), although the numbers reported (about 500 m.y.) seem too young for Precambrian. They also suggest a rough correlation (with an age of about 580 m.y.) between the Holyrood granite in southeastern Newfoundland (McCartney and others, 1966), certain granitic rocks in southern New Brunswick (Poole, Kelley, and Neale, 1964), and the Dedham granodiorite of eastern Massachusetts (Fairbairn and others, ms).[1]

Elsewhere in the Appalachians vast thicknesses of moderate to coarse clastics suggest orogenic movements in the later Precambrian, for example, the Ocoee group in the Great Smoky Mountains of Tennessee and North Carolina (King and others, 1958) and the Glenarm group in Maryland and Pennsylvania (Hopson, 1964). The latter indeed includes a vast gravity slide breccia (olistostrome), testifying to active orogenic movements in the vicinity.

In summary, there appear to have been late Precambrian orogenic movements and plutonism within and confined to the Appalachian region, but our information about them is still scanty. Along the southeast side, there appears to have been a period of mild metamorphism and granite intrusion; both on the southeast and northwest sides, there was a (perhaps slightly later) period that produced great thicknesses of clastics, perhaps accompanying uplift of older rocks in fault blocks. For the movements recorded in southeastern Newfoundland, the name Avalonian has been proposed in a paper by Lilly (1966).

Pre-Middle Ordovician, or Penobscot, movements.—In several parts of the northern Appalachians, evidence of pre-Ordovician or at least pre-Middle Ordovician deformation has now accumulated. In north-central Maine (Boucot, Griscom, and Allingham, 1964), lower Middle Ordovician sedimentary and volcanic rocks (Llanvirn or higher) rest unconformably on considerably more deformed clastic rocks. These older rocks show an extra cleavage and folding; in one area they have yielded *Oldhamia,* which probably indicates an age not older than late Precambrian (Neuman, 1962). This episode has recently been named the Penobscot disturbance by Neuman (1966, p. 9). In the southern Gaspé Peninsula (Alcock, 1935), upper Middle Ordovician slate and graywacke (Mictaw group; probably upper Caradoc) rest with spectacular unconformity and basal conglomerate on more deformed entirely unfossiliferous clastic rocks (Macquereau group), including volcanics and probably serpentine and small acidic intrusives. W. R. Church (personal communication, unpublished) believes that an unconformity in north-central Newfoundland separates probable Lower or Middle Ordovician rocks from older more deformed rocks, which he suspects are Cambrian. In north-central Vermont and adjacent Quebec, evidence has been accumulating for an unconformity overlain by a basal conglomerate (Albee, 1957; Riordan, 1957; Cady, Albee, and Chidester, 1963, p. 25-27; St.-Julien, 1963); it lies in the upper part of a thick Cambro-Ordovician pelitic sequence, but its stratigraphic position can be fixed no more closely than between lower Upper Cambrian (Dresbachian) and middle Middle Ordovician (Caradoc).

These areas lie in the belt where evidence of later Ordovician orogenic movements (Taconian orogeny) is fairly clear; perhaps the uncon-

[1] M.I.T. 1381—13th Ann. Progress Rept., 1965, p. 2-10. The date of 910 million years reported earlier for the Holyrood granite is now rejected—same report, p. 80.

formities simply record precocious Taconian movements. In Newfoundland, coarse clastic deposits first appear in more western belts in Lower Ordovician (Arenig) rocks, also suggesting precocious movements (see beyond), but on the mainland they appear in the Middle Ordovician (basal Caradoc).

Ordovician, or Taconian, movements.—Evidence for orogenic movements in the Middle and Upper Ordovician is present in many places along the northwestern side of the Appalachian chain, and locally also in the southeastern part. The evidence for the northern Appalachians is summarized by Boucot and others (1964, p. 83-93).

In north-central Newfoundland (Neale and Nash, 1962; Williams, 1964), over a considerable belt Lower and Middle Ordovician volcanic and sedimentary strata (through Llanvirn and possibly higher) are overlain by Silurian volcanic and sedimentary rocks (Lower Silurian-upper Llandovery—where dateable), generally considerably less deformed. Some granitic bodies were emplaced in the interval. Farther southeast, on the other hand, the strata seem conformable or at most disconformable from Ordovician into Silurian, and some beds are of uncertain age.

In western Newfoundland, chaotic structure in the Humber Arm terrane (considered a great klippe or gravity slide by some—Rodgers and Neale, 1963) clearly overlies lower Middle Ordovician (Llanvirn) graptolite slate but is unconformably overlain (Rodgers, 1965) by middle Middle Ordovician limestone with a good shelly fauna (lower but not basal Caradoc).

In northern Gaspé (McGerrigle, 1950; Cumming, 1959), a severely deformed sequence of Lower and Middle Ordovician age (well into the Caradoc) is unconformably overlain by little deformed Silurian (upper Ludlow or Skala, perhaps older) along a long stretch of contact; moreover ultramafic rocks were intruded before the Silurian (Neale and others, 1961). In central Gaspé, on the other hand, small inliers of Cambrian rocks are unconformably overlain by Upper or upper Middle Ordovician (Ashgill or upper Caradoc) limestone with a basal sandy zone (Alcock, 1935); a disconformity is further reported between these beds and the Lower Silurian (not an angular unconformity as stated by Boucot, 1962; and Boucot and others, 1964, p. 92), but the evidence does not seem compelling.

Down the strike to the southwest, the unconformity between the Silurian and Ordovician becomes less obvious (though the hiatus is as great or greater, and both granitic and ultramafic rocks were then intruded—Poole, Béland, and Wanless, 1963), but it can be followed, generally accompanied by a unit of quartzite or quartz-conglomerate, as far as Vermont (Cady, 1960).

In north-central Maine (Boucot, Griscom, and Allingham, 1964), the Middle Ordovician rocks already mentioned (fossils into the Caradoc), locally cut by granitic rocks, are unconformably overlain by Silurian rocks (upper Llandovery to lower Ludlow, depending on locality). Volcanic rocks are common both above and below. To the east, however, both groups grade over into shaly limestone, limy shale, and silty shale in a conformable sequence (Boucot and others, 1964, p. 27; Pavlides and Berry, 1966). Still farther east in northern and west-central New Brunswick, volcanic rocks reappear in the Ordovician, and so apparently does the unconformity (Alcock, 1935; Anderson and Poole, 1959).

In northwestern Maine (Boucot, 1961; Albee, 1961), moderately high-grade metamorphic rocks intruded by granitic rocks (with sillimanite nearby) are overlain with striking unconformity by Upper Silurian (Ludlow) and Devonian rocks. The age of the older metamorphics is debatable, Boucot calling them Precambrian and Albee Cambro-Ordovician; the intrusive rocks give Ordovician radiometric ages (Faul and others, 1963).

In northwestern New Hampshire (Billings, 1956), basal Silurian quartzite (upper Llandovery in at least some places) rests on granitic rock intruding metavolcanics and metasediments. The last are probably Middle or Lower Ordovician, but the correlation is roundabout. Where first worked out, the unconformity is in rather low-grade rocks, but it has since been traced into higher-grade rocks and across New Hampshire and Massachusetts into eastern Connecticut, where a similar unconformity overlying intrusive rocks has been reported (Rosenfeld and Eaton, 1956; Eaton and Rosenfeld, 1960).

In the Hudson Valley in New York State, near the Taconic region, badly deformed Middle Ordovician (up to lower Caradoc) rocks are overlapped with strong angular unconformity by highest Silurian or basal Devonian strata (Ruedemann, 1942; Goldring, 1943; Chadwick, 1944). Southwestward along this unconformity, lower and lower Silurian rocks (Shawangunk conglomerate, then Tuscarora sandstone) come in above and higher and higher Ordovician below (Swartz and Swartz, 1931), up to lower Upper Ordovician (high Caradoc, *not* Ashgill). The unconformity can be traced to the Lehigh River in eastern Pennsylvania and perhaps farther. Finally redbeds (Juniata formation) come in above it (Stose, 1930); these are generally but not universally accepted as equivalent to marine beds farther west now classed as upper Upper Ordovician (Ashgill).

Evidence of Ordovician unconformity is lacking in most places southeast of the general belt described above, but locally it reappears. In southwestern New Brunswick, the lower Silurian (upper Llandovery) Oak Bay conglomerate rests unconformably on folded and cleaved slate of the Charlotte group (Alcock, 1946), from which in 1962 Lower Ordovician (Arenig) graptolites were collected (unpublished information). This unconformity seems to be recognizable from St. John in southern New Brunswick to Penobscot Bay in south-central Maine (Chapman, 1962). Lower Ordovician (Tremadoc) graptolites are known in slate near the top of the Meguma group in southwestern Nova Scotia;

this slate is overlain by quartzite somewhat above which Silurian fossils are found, but the contact is regarded as conformable, or at most disconformable, by most who have studied it (Taylor, 1965, mentions local angular unconformities at this contact in an area in extreme western Nova Scotia and discusses the problem).

In the Arisaig-Browns Mountain area of Nova Scotia west of Antigonish (Williams, 1914), fossiliferous Lower Silurian (lower Llandovery) rocks rest on volcanics in some places and apparently on unfossiliferous conglomerate in others (Malignant Cove formation, called Ordovician but without fossil evidence); nearby and presumably unconformably below are cleaved and crumpled phyllite from which no fossils are reported except a doubtfully Lower Ordovician *Lingulella*.

The Ordovician stratigraphy of the United States and the St. Lawrence Lowland in Canada (Twenhofel and others, 1954; Fisher, 1962) makes abundantly clear that a great wedge of clastic sediment (Queenston delta) pushed westward from the general New England region, beginning in the middle Middle Ordovician (lower Caradoc) in eastern New York State but reaching the Ohio and Mississippi Valleys only in the Upper Ordovician (highest Caradoc or Ashgill). The coarsest sediments west of the mountains are the Oswego sandstone of central New York and the Bald Eagle sandstone of central Pennsylvania, both classed as lower Upper Ordovician (highest Caradoc); above them are upper Upper Ordovician (presumably Ashgill) redbeds, and the Silurian begins with a transgressing marine sandstone (Fisher, 1960). Coarser rocks appear earlier going eastward, however—in the lower Middle Ordovician (low Caradoc) in the Appalachian folded belt in New York and Vermont (Kay, 1942; Berry, 1962), in the lower Ordovician (Arenig) in western Newfoundland (judging by fossils collected and determined by L. M. Cumming in 1964—personal communication). Presumably these sediments record uplifts related to the Taconian orogenic movements.

In the southern Appalachians, a completely comparable but smaller and mostly earlier clastic wedge appears, entirely within the Middle Ordovician of east Tennessee and vicinity (see figs. 1 and 2 in Twenhofel and others, 1954); it began early in the Middle Ordovician (Llanvirn) and was receding when the northern clastic wedge was only just reaching central New York and Pennsylvania. It probably records a pulse of orogeny in the Carolinas, but no direct and compelling geologic evidence has yet been turned up there. At Carysbrook, in the Piedmont of central Virginia, however, the Upper Ordovician (Watson and Powell, 1911) Arvonia slate rests unconformably on granodiorite[1a] that is part of the metamorphic terrain of that part of the Piedmont and that was apparently deeply weathered beforehand; later metamorphism has affected both, producing biotite and garnet in the slate. Furthermore, radiometric evidence, though equivocal, and various other tenuous lines of reasoning lead to the conclusion that the larger part of the metamorphism in the

[1a] This unconformity has been denied by some recent workers (Smith, Milici, and Greenberg, 1964, p. 14), but a field check convinces me of its reality.

Piedmont province, and perhaps some of the older plutonism there, is roughly of Ordovician age (for example, Overstreet and Bell, 1965, p. 114).

Radiometric ages indicating Ordovician emplacement (450 to 500 m.y.) are now known from several granitic bodies in Maine (Faul and others, 1963), Quebec, the Maritime provinces, and Newfoundland (Poole, Kelley, and Neale 1964); several of these bodies are overlapped by Silurian strata. Comparable ages farther southwest are rarer and not easy to interpret, but the best date for the post-Precambrian metamorphism near Baltimore gives an Ordovician age (Hopson, 1964).

To summarize, evidence of deformation and plutonism between the lower Middle Ordovician (locally the Lower Ordovician) and the Silurian is widespread, and where the date can be pinned down it varies from early in the Middle Ordovician to late in the Upper Ordovician. This date agrees with the stratigraphic evidence to the west of the folded belt. The Taconian orogeny was apparently a group of individual pulses localized in different parts of the chain, especially along its western side, and extending over the latter half or two-thirds of the Ordovician period. Granitic intrusion, perhaps representing the core belt of the orogeny, is known in north-central Newfoundland, north-central and northwestern Maine, northwestern New Hampshire, and probably eastern Connecticut, but regional metamorphism in this belt may never have passed the chlorite zone, except in northwestern Maine (Albee 1961).

Silurian movements.—For several areas in northern Maine and adjacent Quebec, Boucot (1962; Naylor and Boucot, 1965) has recently assembled evidence of disconformity or mild angular unconformity at or close to the top of the Silurian (between Lower or Middle Ludlow and Upper Ludlow (or Skala?) or Lower Gedinnian). Stratigraphic evidence for such a disturbance is also found in a wedge of Upper Silurian redbeds and other fine clastics (with widespread evaporites) that pushed westward in the late Silurian (roughly Middle Ludlow; Salina group of New York State), perhaps derived from uplifts in the Appalachians (Fisher, 1960). Boucot has christened it the Salinic disturbance, and further search may uncover additional evidence for it (for example, in the Clam Bank formation of western Newfoundland—Rodgers, 1965), but generally it was overshadowed by the much greater orogenic movements in the Ordovician and Devonian.

Devonian and earliest Carboniferous, or Acadian, movements.—Evidence of Devonian orogeny is almost universal in the Appalachians of Canada and New England, virtually lacking farther southwest. Fossiliferous Lower Devonian strata (ranging at least into the Lower Emsian; see Boucot, 1962) are involved in the major deformation or intruded by granitic rocks in many places, for example, western New Hampshire and eastern Vermont, northern Maine, southern Gaspé and northern New Brunswick, southeastern Maine and southwestern New

Brunswick, several parts of Nova Scotia, and southwestern Newfoundland. Dated rocks later than the main deformation are less widespread, and as they are mostly continental redbeds, the dating is rough. The evidence is summarized by Boucot and others (1964, p. 93-99). In northeastern and north-central Maine, they appear to be lower Middle Devonian; in southern Gaspé (Williams and Dineley, 1967), southeastern Maine and southwestern New Brunswick, and southeastern Newfoundland (Bradley, 1962), they are Upper Devonian; elsewhere they are mainly Carboniferous (in eastern Massachusetts and Rhode Island as high as Middle Pennsylvanian, approximately Westphalian—Quinn and Oliver, 1962). Evidence of multiple movements within the Devonian is poor; the younger Devonian rocks in northern Maine and the Gaspé are gently folded but remarkably little deformed, in places hardly indurated. In southeastern New Brunswick and Nova Scotia (the original Acadia), on the other hand, angular unconformities in the Carboniferous (Bell, 1944; Webb, 1963), show that deformation continued spasmodically well after the Devonian.

In Pennsylvania, evidence has recently been found (Trexler, Wood, and Arndt, 1961) of angular unconformity close to but a little above the top of the Devonian; this is so far the only unequivocal evidence of Acadian orogeny west of the Hudson River. Even farther southwest, however, evidence of considerable deformation older than the main folding of the region has been accumulating (for example, Cloos, 1964), some of which may well be Acadian; thus Pierce and Armstrong (1966) give tentative radiometric and structural arguments for such an age for a fairly large pre-folding bedding-plane fault in southern Pennsylvania.

As in the Ordovician, so in the Devonian a great clastic wedge (Catskill delta) pushed westward (and northward) out of the New England-Maritime region (Cooper and others, 1942; Rickard, 1964). Clastics appear in the Lower Devonian (Siegenian) in Gaspé and in the Green Pond syncline near New York City, in the Middle Devonian elsewhere in New York and Pennsylvania (Eifelian), younger and younger westward and southwestward (Givetian in the central part of the United States). Coarser clastics pushed down the Appalachian trough as far as east Tennessee and continental redbeds reached west-central Virginia, but their distribution suggests that they came entirely from the northeast and that the southernmost sediment-carrying river debouched in Pennsylvania; in contrast with the Ordovician, there was no local source of sediment in the Carolinas. Probably these clastic deposits record uplifts related more or less closely to the Acadian orogenic movements though not necessarily contemporaneous.

Radiometric ages dating the Acadian orogeny in the range 360 to 400 million years are widespread in the northern Appalachians, some being from granitic bodies clearly overlapped by Upper Devonian or Carboniferous strata (Faul and others, 1963; Poole, Kelley, and Neale, 1964); those in Maine and vicinity strongly suggest and those in the

Maritime provinces would be consistent with two pulses of plutonism and metamorphism during the Devonian, perhaps centered in different belts. In the southern Appalachians, although some rocks give comparable numbers, the broad regional spread of "ages" suggests that most of the post-Ordovician numbers record only uplift and cooling, not plutonism or orogeny (Hadley, 1964).

In summary, probably most of the metamorphism and plutonism in the northern Appalachians is the result of the Acadian orogeny; the core belt of their maximum intensity can be followed from central Newfoundland to eastern Connecticut and western Rhode Island, lying a little east of the core belt of the Taconian orogeny. The main orogenic movements are pinned down to Middle Devonian in Maine and the Maritime Provinces, perhaps even to early Middle Devonian or latest Early Devonian in a few places in Maine, but they may have been younger farther southwest, and movements may have continued into the Carboniferous in several places, especially on the southeastern side of the region and toward the southwest in Pennsylvania.

Carboniferous and Permian, or Alleghanian, movements.—The most information on Carboniferous movements comes from the Maritime Provinces, especially from southern New Brunswick and Nova Scotia, where relatively local but spectacular angular unconformities underlie rocks of various ages from basal Carboniferous (date uncertain, presumably lower Tournaisian—locally indeed upper Devonian rocks are present) to mid-Pennsylvanian (Westphalian) (Bell, 1944; Webb, 1963). Several of these unconformities appear to be fairly local in extent; evidently the region was tectonically active much of the time somewhere or other. On Prince Edward Island, indeed, rocks as young as Lower Permian (Autunian?) are mildly folded (Frankel, 1966). In central New Brunswick, the younger Carboniferous rocks (Westphalian or even lower Stephanian) are little disturbed, but farther south even these are considerably deformed; slaty cleavage and some small intrusions cut lower Carboniferous rocks in parts of Nova Scotia. The Carboniferous rocks of western Newfoundland probably record a similar history. At the head of Fortune Bay in southeastern Newfoundland, Upper Devonian redbeds containing pebbles of several older formations (but no plutonic rocks) are themselves cut by a thrust fault bringing those rocks above them, but the date of deformation is quite uncertain (Bradley, 1962).

The Carboniferous (Pennsylvanian) rocks of eastern Massachusetts and Rhode Island (Quinn and Oliver, 1962) show severe deformation and cleavage even at the northern limit of their outcrop, and metamorphism increases southward; in southern Rhode Island, the rocks are garnet schist cut by large granite intrusions. The deformation must post-date the Middle Pennsylvanian (Westphalian), but no upper limit can be assigned.

Except as mentioned in the preceding sections, the sedimentary rocks of the Appalachian Valley and Ridge Province southwest of

New York (Alleghany Mountains) seem to be entirely conformable and to have been deformed together. The youngest rocks involved (Moore and others, 1944; Dunbar and others, 1960) are late Pennsylvanian (Stephanian) in the anthracite fields of eastern Pennsylvania, presumed lower Permian (Autunian?) in the bituminous fields of western Pennsylvania, western Maryland, and northern West Virginia, but from southern West Virginia southwestward, no rocks are preserved younger than mid-Pennsylvanian (Westphalian C). The next youngest rocks anywhere in the Appalachians are the Upper Triassic rocks of the Newark group (lower Keuper, Carnian?—Reeside and others, 1957), preserved in a series of fault troughs within the mainly metamorphic part of the Appalachians from Nova Scotia to the Carolinas; they rest unconformably on rocks of various ages, up to Pennsylvanian in Nova Scotia, to probable Lower Devonian in New England, and to Ordovician in Pennsylvania (pebbles as young as Devonian are known in them in Pennsylvania—see Carlston, 1946, table 1, p. 1004-1005).

The clastic wedge that records the Acadian orogeny extended into the Mississippian, but mainly in a waning phase. The maximum retreat of clastics or advance of carbonates afterwards seems to have been about simultaneous in Pennsylvania (Loyalhanna limestone) and the Maritime Provinces (Windsor formation), namely mid-Mississippian (Meramec, mid-Viséan—Weller and others, 1948). A new clastic wedge then makes its appearance, first in central Alabama, at the southern end of the visible Appalachians, in early Meramec time (earliest Viséan, even earlier than the maximum advance of carbonates farther north). The clastic rocks here (Floyd shale and Parkwood formation) record a southern source, which persisted at least into the Pennsylvanian (Namurian); moreover their similarity to the rocks in the contemporaneous clastic wedge in the Ouachita Mountains of Arkansas and Oklahoma (Goldstein, 1961) suggests that their source was an eastern extension of the highlands produced in the earliest part of the Ouachita orogeny (Ehrlich, 1965; Ferm and Ehrlich, 1965; Thomas, 1965). By late Mississippian time, however (late Chester or earliest Namurian), clastics were appearing all along the chain (for example, Pennington and Mauch Chunk formations), probably from a southeastern or eastern source, and by the beginning of the Pennsylvanian (Pottsville formation, mid-Namurian), clastic deposition was general and moderately coarse over the whole Appalachian region and far west onto the platform of the continent. With some fluctuations it continued so as long as the record indicates, producing the typical Coal Measures of the Appalachian and central interior coal fields.

The orogeny that deformed the Carboniferous and lower Permian along with the underlying strata in the Appalachian Valley and Ridge province, and in the Appalachian Plateau to the west, has classically been considered the Appalachian orogeny or revolution *par excellence;* to it has also been ascribed the metamorphism and plutonism in the vast but ill-known Piedmont province to the southeast. In Alabama, Lower Devonian and doubtful Carboniferous fossils have been found in low-grade metamorphic rocks along the northwest side of the Piedmont province (Butts, 1926, p. 145-147), but elsewhere the youngest known in the province are lower Upper Ordovician (highest Caradoc) (Watson and Powell, 1911). On the other hand, radiometric ages from the Piedmont are spread over the whole range from Ordovician to Carboniferous or Permian, youngest in a central belt and older to either side, suggesting that many of them record not plutonism but only cooling (Hadley, 1964); thus much of the deformation, metamorphism, and plutonism must have been older than Carboniferous. In the northern Appalachians, furthermore, the late- or post-Carboniferous orogeny was relatively minor, being confined to the southeast edge of the region, though vigorous enough there; it is well recorded by radiometric dates in the range 230 to 260 million years in New England, although many of these may also be cooling dates. Accordingly, it seems exaggerated to rate this orogeny as *the* Appalachian orogeny, for all the orogenies here described, after the Grenville cycle, are Appalachian orogenies. The name Alleghanian, proposed by Woodward (1957),[2] is a satisfactory substitute term for the last of these orogenies and enables one to consider them as coordinate, one more important in one region and another in another.

As for the Piedmont, we simply do not have enough geologic evidence to permit us to unscramble the effects of the various orogenies and periods of plutonism as we have been able to do in the northern Appalachians; as noted above, the Taconian orogeny may have been the most significant.

The date of the Alleghanian orogeny is, curiously, the least well established among the Appalachian orogenies. In the southern Maritime Provinces, orogenic movement appears to have been nearly continuous or better spasmodic from the time of the climax of the Acadian orogeny in the Middle Devonian until early in the Permian, and any boundary between the two is somewhat arbitrary; the maximum marine transgression in the Mississippian (Windsor formation, Viséan) may be the most convenient dividing line. In the central Appalachian Valley and Ridge and Plateau provinces, much of the movement must have been post-Carboniferous or post-Lower Permian, but in the southern Appalachians (and in southern New England) the climax need only have been later than mid-Pennsylvanian (Westphalian C), and the stratigraphic history suggests that movement began well before the end of the Mississippian (during the Viséan).

Triassic movements.—Although not strictly orogenic, the movements that accompanied and followed the deposition of the Upper Triassic

[2] Woodward deliberately chose the form Alleghany, with an *a* in the third syllable, from the Alleghany or Allegheny Mountains, whereas the well known Allegheny formation or group, with an *e* in the third syllable, is named for the Allegheny or Allegany (no *h*) River.

(Keuper, that is, Carnian and probably Norian—Colbert and Gregory, *in* Reeside and others, 1957, p. 1459-1461) Newark group seem to have been geographically restricted to the Appalachian region and indeed to its central or axial belt (Nova Scotia to South Carolina, also beneath the Coastal Plain as far as Florida and Alabama). They produced a series of fault troughs, generally asymmetrical, the fault on the side toward which the sediments now dip having been active during much or all of the deposition (Longwell, 1937, p. 436-438). The larger troughs can be grouped into a double line, the present dips being centrifugal and the active faults on the outer side; the arrangements can be likened to a large graben or "rift" system, comparable in style and size to the East African Rift Zone of today, except that the centers of the grabens have been warped up into broad anticlines. Basaltic lava flows and sills (for example, the famous Palisades sill) are intercalated with the sediments, and dikes of similar composition cut them and the surrounding rocks, forming a major dike swarm (King, 1961). Radiometric ages from these igneous rocks run around 195 million years (Erickson and Kulp, 1961). The rocks are further cut by later but probably related faults; folding on the other hand has been mostly broad warping and the rocks are not orogenically deformed. The faults are mostly normal faults, but strike-slip movement has been adduced for some of them (Bain, 1957; Sanders, 1960). The similarities to post-orogenic deposits and structures in many other orogenic belts are striking. The whole episode, commonly called the Palisades disturbance, seems to have lasted through the Upper Triassic, but its end is not known. Undisturbed Cretaceous strata (marine Cenomanian, and locally non-marine Lower Cretaceous, perhaps as old as Neocomian) overlap the Appalachian edifice, including the Triassic fault troughs, all along its southeastern edge.

Post-Triassic history.—The Appalachian Mountains have apparently been subject to continuous erosion since the Triassic, indeed since the late Paleozoic except in the areas of down-dropped Triassic fault blocks. Evidence for their later history is therefore meager and mostly indirect, derived either from the land forms of the Appalachians themselves or from the deposits of the adjacent Coastal Plains and continental shelves. Concerning the land forms, a "classical" picture was established some years ago (Johnson, 1931; Wright, 1931, 1934, 1936) that recognized a modest number of major erosion surfaces or peneplains, one preserved beneath the adjacent coastal-plain sediments and the others represented by accordant mountain summits or hilltops at various levels; these were interpreted as resulting from periods of structural quiescence separated by major episodes of uplift by which the whole chain was warped into a single broad arch. There has never been agreement, however, on the number of erosion surfaces to be recognized; generally opinion has varied between three and five, but some have recognized as many as 12, even in fairly restricted areas, and others have denied the existence of

Tabular summary of orogenic movements in Appalachian region

Orogenic episode and approximate date	Known area of influence	Maximum manifestation
Appalachian cycle		
Palisades		
Late Triassic (Carnian-Norian) 190-200 m.y.	Belt along central axis of already completed mountain chain	Fault troughs, broad warping, basaltic lava, dike swarm
Alleghanian		
Pennsylvanian and/or Permian (Westphalian and later) 230-260 m.y.	West side of central and southern Appalachians, southeast side of northern Appalachians, perhaps also in Carolina Piedmont	Strong folding, also middle-grade metamorphism and granite intrusion at least in southern New England
(early Ouachita)		
(Mid-Mississippian through early Pennsylvanian) (Viséan to early Westphalian)	(Only in southernmost Appalachians in central Alabama)	(Clastic wedge, also possibly broad east-west structures that influenced later deformation)
Acadian		
Devonian, mainly Middle but episodic into Mississippian (Emsian-Eifelian) 360-400 m.y.	Whole of northern Appalachians, except locally along northwest edge; as far southwest as Pennsylvania	Medium- to high-grade metamorphism, granite intrusion
Salinic		
Late Silurian (Ludlow)	Local on northwest side of northern Appalachians	Mild angular unconformity
Taconian		
Middle (and Late) Ordovician (Caradoc, locally probably older) 450-500 m.y.	General on northwest side of northern Appalachians, local elsewhere; an early phase in Carolinas and Virginia	Strong angular unconformity, gravity slides (?), low-grade metamorphism, granodioritic and ultramafic intrusion
Penobscot		
Early Ordovician or older (Arenig or older)	Local on northwest side of northern Appalachians	Strong angular unconformity, slaty cleavage, possibly some intrusion
Avalonian		
Latest Precambrian	Southeastern Newfoundland, Cape Breton Island, southern New Brunswick; probably also central and southern Appalachians	Probably some deformation, uplift of sources of coarse arkosic debris, gravity slides (?)
Late Precambrian about 580 m.y.	Southeastern Newfoundland, Cape Breton Island, southern New Brunswick; perhaps eastern Massachusetts	Mostly low-grade metamorphism, granitic intrusion
Grenville cycle (pre-Appalachian)		
Late Precambrian 800-1100 m.y.	Eastern North America including western part of Appalachian region	High-grade metamorphism, granitic and other intrusion

any, interpreting the land forms as produced in dynamic equilibrium with steadily progressing erosion (Hack, 1960).

The sediments of the Coastal Plain also have a story to tell about what was happening in the Appalachians, but so far it is largely unread. Provenance studies that might provide information on rates of unroofing or on major drainage changes are still to be made, and even thickness and volume estimates are incomplete. Thus we do not know what share of the immense volume of sediments in the Gulf Coastal Plain (Murray and others, 1952) was contributed by the Appalachians; presumably they contributed all the clastic material in the Atlantic Coastal Plain, but the relative volumes of sediments of different ages there are still uncalculated. Judging by thicknesses discovered in deep wells (for example, Spangler, 1950), about three quarters of the sediments in North Carolina are Cretaceous, and the remaining quarter divides very roughly as follows: Eocene (including Paleocene)—10 percent; Oligocene—absent; Miocene—more than 10 percent; Pliocene and later—less than 5 percent.

Unconformities are reported at several levels in the lower half of the Cretaceous and again beneath the Eocene, Miocene, Upper Miocene, and Pliocene; the sediments above each of the Cenozoic unconformities lap over all older strata to rest at least locally on the crystalline rocks of the Appalachian Piedmont. The unconformity beneath the Cretaceous corresponds of course to the oldest erosion surface recognized; in North Carolina its slope is about 0.75 of a meter per kilometer or 40 feet per mile (but it becomes more than twice as steep near the present coastline and offshore). Projected inland, it would stand more than 2300 meters or 7500 feet above sealevel over the crest of the present Blue Ridge in northernmost North Carolina—on the order of twice the present elevation of the land. The unconformity beneath the Eocene has a slope about half as steep; thus if projected it barely clears the Blue Ridge. The unconformity beneath the Miocene has an average slope on the order of 0.2 of a meter per kilometer or 10 feet per mile, roughly the present slope of the upper surface of the Piedmont Plateau. (All these slopes appear to be steeper northeastward along the strike, as in New Jersey.) As all the slopes tend to steepen coastward and flatten inland, these inland projections are if anything too high. Finally, Paleocene or basal Eocene lignite and bauxite deposits occur in old sinkholes (now entirely in residual clay) on one of the lower of the postulated erosion surfaces within the Appalachians (Bridge, 1950; Overstreet, 1964).

From these data, though unsatisfactory, one can conclude that the great bulk of the erosion of the Appalachians took place in the Cretaceous or earlier, and that the present mountains have had a relief not much less than the present since well back in the Tertiary, perhaps since the Eocene. Perhaps one can further conclude that, after the Triassic, the only deformation of the Appalachian region was repeated (or perhaps semi-continuous) uplift, always in the form of a broad probably simple arch whose axis followed the linear axis of the chain as originally marked out by the geosynclinal sedimentation and orogenic episodes of the Paleozoic, and that the "rate" of uplift (whether episodic or continuous) has decreased almost regularly to the present.

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