

American Journal of Science

JUNE 1963

LATE TRIASSIC TECTONIC HISTORY OF NORTHEASTERN UNITED STATES

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ABSTRACT. The Upper Triassic rocks of the New York-New Jersey-Pennsylvania and Connecticut Valley belts, generally considered to be deposits of isolated basins, are inferred to represent remnants of the filling of an elongate rift valley that was 50 to 70 miles wide. In addition, the stratigraphic thickness of the Triassic rocks is held to be approximately 30,000 feet. If these two conclusions are correct, then Late Triassic tectonic history is considerably more complex than previously thought and can be subdivided into four episodes:

Episode 1: Initial graben subsidence without folds; deposition of 30,000 feet of non-marine sediments; extrusive and intrusive igneous activity.

Episode 2: Longitudinal crustal arching in center of initial graben; uplift, inversion of topography, and reversal of drainage; erosion; central parts of pre-Triassic graben floor ultimately elevated more than 30,000 feet; no igneous activity or transverse folds.

Episode 3: Second-generation graben subsidence, development of transverse folds northeast of Hunterdon Plateau, New Jersey, with maximum structural relief exceeding 30,000 feet; no igneous activity.

Episode 4: Offsetting of transverse folds by faults, some with strike-slip displacement of up to 12 miles; development of longitudinal Valley-and-Ridge type folds southwest of Hunterdon Plateau during strike-slip faulting; injection of porphyritic dolerite dikes into faults; formation of mineral deposits along faults.

Extensive erosion took place after episode 4 until the transgressive Coastal Plain marine overlap in the Late Cretaceous, which buried some Triassic rocks. The Triassic structures are inferred to have involved the entire thickness of the crust and to have been controlled by subcrustal processes, the Triassic rocks themselves merely reacting passively.

If the magnitude and complexity of Triassic tectonic history advocated here are correct, then the following regional geologic implications are also suggested:

1. Much of the high structural position and uncovering of Precambrian basement rocks in the medial Appalachians took place in the Late Triassic.
2. Large Triassic faults probably extend well beyond the limits of Triassic outcrop belts, as, for example, along the straight western boundary of the Taconic allochthon in the Hudson Valley.
3. The southward disappearance of the Taconic allochthon in the Hudson Valley may be due to uplift on the Late Triassic transverse Danbury anticline and subsequent erosion.
4. Many rocks now at the surface have been deeply buried.
5. Triassic igneous rocks were emplaced at different ages which bracket the tectonic episodes. If different radiometric ages could be detected between syndepositional and late postdepositional igneous rocks, then some estimate might be made of the time required for deformation.
6. Some Appalachian drainage may have originated on the flanks of the Late Triassic longitudinal crustal arch.

INTRODUCTION

The tectonic history of the Triassic rocks of the New York-New Jersey and Connecticut Valley belts (fig. 1) has recently been shown to be more complex than was formerly supposed (Sanders, 1960). The present paper extends this analysis southwestward to the Schuylkill River (see fig. 2 for locality map) in eastern Pennsylvania and includes a new analysis of the different tectonic episodes; provides quantitative estimates of the magnitude of the

movements involved in them; and mentions some of the regional geologic implications of the Triassic deformation.

An important element in the figures presented here is the so-called broad-terrane hypothesis for interpreting the remnants of Triassic rocks preserved in the individual, isolated lowland areas. The original form of this hypothesis,

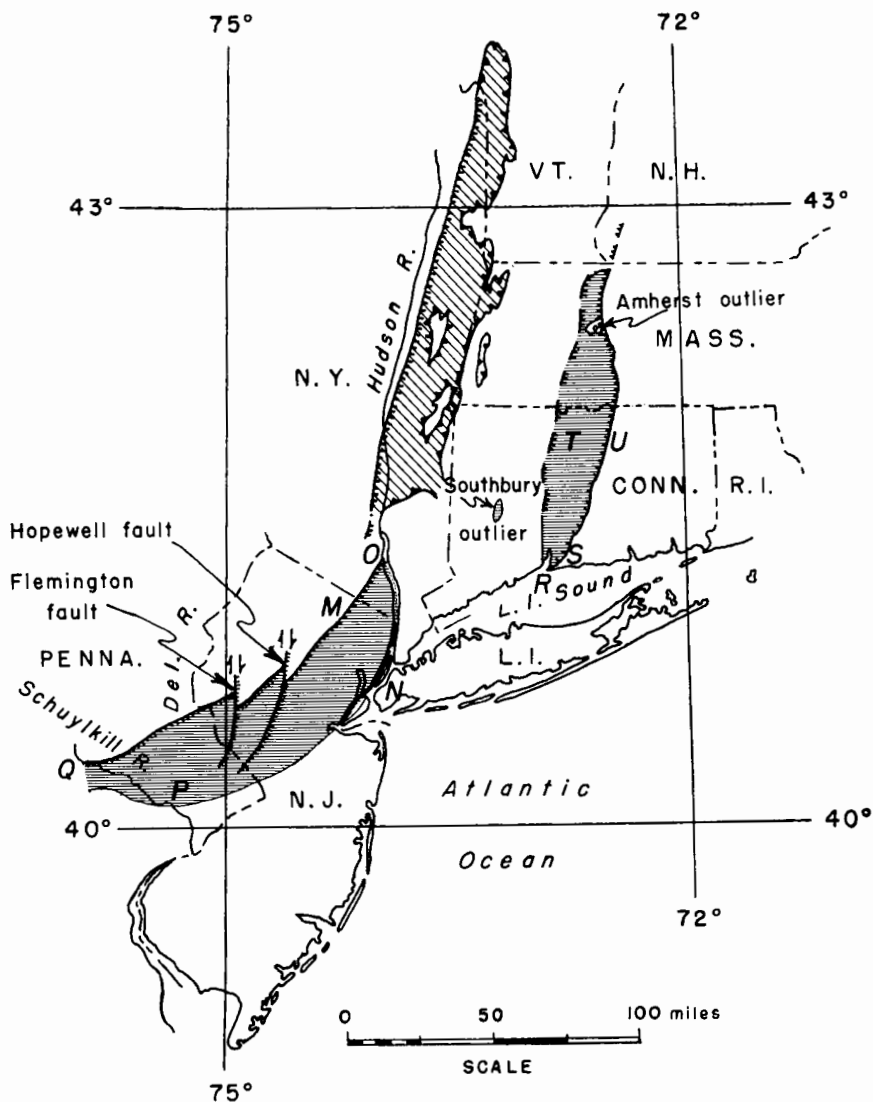


Fig. 1. Index map, showing location of Triassic outcrop belts (horizontal ruled lines) and Taconic allochthon (diagonal ruled lines). Non-Taconic, pre-Triassic rocks shown in white. Base from Tectonic Map of United States, with geologic contacts modified by the writer. New York-New Jersey-Pennsylvania Triassic belt at left, Connecticut Valley belt at right, and Southbury outlier at center (small area in central western Connecticut).

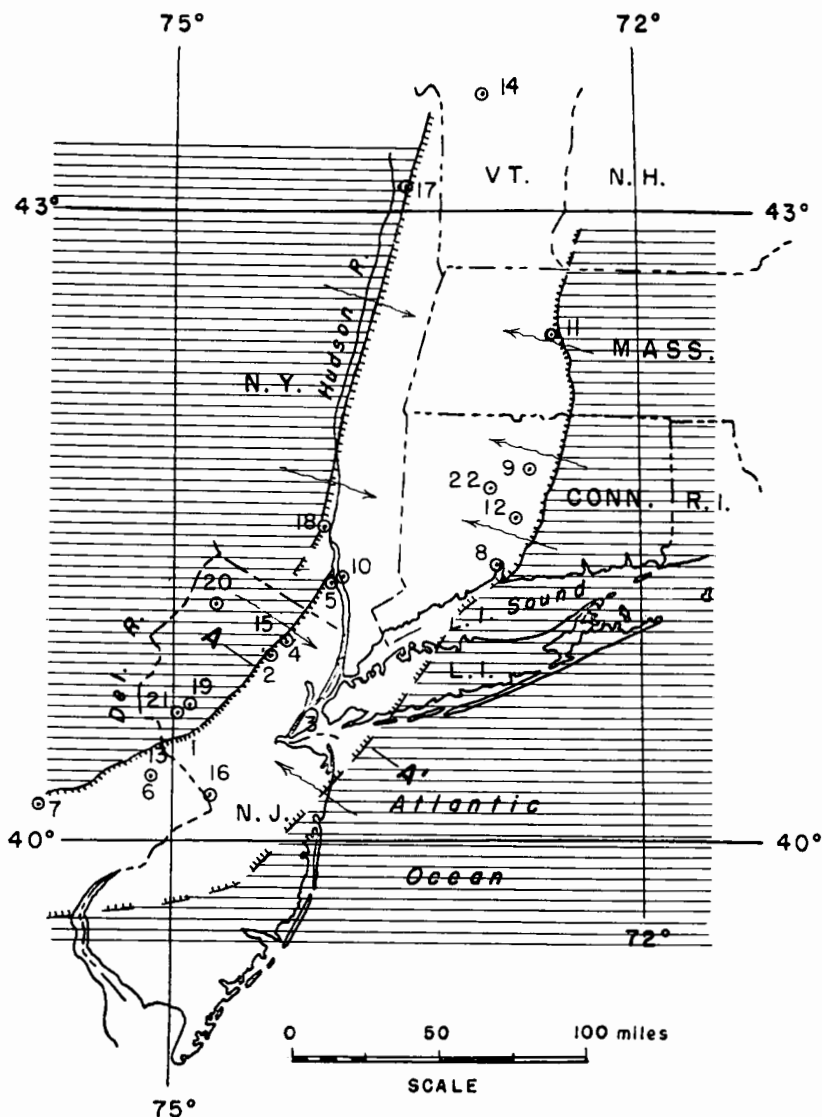


Fig. 2. Locality map and map showing inferred location of Late Triassic graben, northeastern United States. Arrows show generalized direction of drainage into lowland from highlands adjacent to graben. Triassic graben shown in white, pre-Triassic rocks of graben walls (undifferentiated) shown by horizontally ruled lines. Pre-Triassic rocks are feldspathic on southeast side of graben, but non-feldspathic (sandstones, quartzites, and carbonate rocks of Valley and Ridge Province) on northwest side of graben. Line A-A' indicates position of cross section shown in figure 3a. Numbers indicate localities mentioned in text as follows:

- | | | |
|----------------------------|-----------------------|-------------------------|
| 1. Hunterdon Plateau, N.J. | 8. New Haven, Conn. | 15. Copperas Mtn., N.J. |
| 2. Boonton, N.J. | 9. Hartford, Conn. | 16. Trenton, N.J. |
| 3. Staten Island, N.Y. | 10. Peekskill, N.Y. | 17. Bald Mtn., N.Y. |
| 4. Pompton Plains, N.J. | 11. Amherst, Mass. | 18. Newburgh, N.Y. |
| 5. Stony Point, N.Y. | 12. Meriden, Conn. | 19. Clinton, N.J. |
| 6. Doylestown, Pa. | 13. Bucks County, Pa. | 20. Branchville, N.J. |
| 7. Jacksonwald, Pa. | 14. Rutland, Vt. | 21. Jutland, N.J. |
| | | 22. Bristol, Conn. |

which stated that the Triassic strata extended indefinitely in all directions away from the present outcrop areas, has been rejected by most previous students of the Triassic, but generally for reasons that were founded on now discarded concepts of conditions of deposition. A fuller discussion of the stratigraphic data which support the present modified version of the broad-terrane hypothesis is intended elsewhere; for the present purpose, all that is necessary is a clear statement that this hypothesis forms the basis for the measurements given.

According to the present version of the broad-terrane hypothesis, Triassic deposition occurred under nonmarine conditions in a rift valley graben whose width was approximately 50 to 70 miles, measured from the border fault along the northwestern side of the New York-New Jersey-Pennsylvania belt to the analogous border fault along the southeastern and eastern sides of the Connecticut Valley belt (fig. 2). Such a graben is comparable in size to the present East African rift valleys and doubtless extended southwestward, at least, far beyond the small remnant of it examined here. The author surmises that the present analysis will also be applicable to other areas of Triassic rocks that occur along the eastern seaboard from Florida to Nova Scotia, but excludes these other areas from this discussion.

The close parallelism of the Triassic rocks with the central axis of the Appalachians suggests a genetic relationship between the origin of the Triassic structures and uplift of the Appalachians (Keith, 1923; Murray, 1960). It is tempting, also, to entertain the possibility that this Appalachian Triassic rift valley system may have been part of a worldwide fracture zone of Late Triassic age in much the same way that the modern African rift valleys are part of a circumglobal fracture zone (Heezen, 1960), but the close connection with the Appalachians may preclude this interpretation.

The tectonic features described here are all inferred to involve the entire thickness of the crust and to be due to subcrustal conditions. The Triassic strata have behaved passively during their deformation; they merely serve to record the magnitude of movements affecting the rocks on which they lie.

ACKNOWLEDGMENTS

I am indebted to my colleague, John Rodgers, for helpful comments on a draft of the manuscript, and to Professor S. W. Carey, University of Tasmania, Hobart, for stimulating discussions during his tenure as Visiting Professor of Geology at Yale University in 1959-1960 concerning the possibility of finding strike-slip faults in the Triassic outcrop belts of northeastern United States.

LATE TRIASSIC TECTONIC HISTORY

The prevailing concept of Late Triassic tectonic history is that during tensional collapse of the Appalachians, numerous fault troughs formed, and nonmarine sediments and the lava flows accumulated in them. Later faulting and tilting of these deposits have been ascribed to the Palisades disturbance. The existence of some of the transverse and longitudinal folds has been recognized by a few observers, but the implications of their origin with respect to the times of faulting have not been generally examined.

The present paper argues a case for recognition of four discrete episodes of tectonic activity which may have been closely related in time, but whose different mechanics suggest that they did not significantly overlap with each other. The history implied by these episodes is much more complex, and the magnitude of tectonic movements is much greater than has been generally believed heretofore. The episodes and historical summary are first to be considered; afterward, a few general remarks are made in analysis of them.

Episodes of Triassic Tectonic Activity

Previous ideas of Triassic tectonic activity in the Connecticut Valley and New York-New Jersey belts have been summarized recently (Sanders, 1960), so that only the most elaborate of these, the concept of W. M. Davis (1898), need be mentioned here. Davis clearly recognized that the accumulation and deformation of the Triassic rocks (in Connecticut, at least) were part of one general episode of deepseated crustal disturbance. He recognized (p. 141) that deposition had been initiated by subsidence and terminated by uplift. He identified three distinct events of postdepositional deformation: (1) warping without lateral compression perpendicular to the axes of warping; (2) fracturing of the whole into discrete blocks of variable length and width; and (3) rotation and tilting toward the east of the blocks and faulting of their borders with the uplift generally on the east side of the fracture. The only episode of faulting that Davis recognized was the one which occurred prior to the rotation of the individual fault blocks; he supposed that the depositional trough had formed by synclinal downbending.¹ Davis related the transverse folds to unequal yielding of the subjacent crystalline rocks and proposed the remarkable hypothesis (1886, 1888, 1898) that the faulted monoclinical arrangement of the tilted blocks was due to subcrustal shearing in an east-west direction which caused large curved slabs of crystalline basement rock to be straightened out (as curved steel bars can be straightened out in the jaws of a vice) and their upper ends shifted up and down and tilted as the formerly curved pieces became straight and thus were lengthened. Davis did not recognize the existence of a longitudinal arch of regional significance.

Davis (1898, p. 81) assigned the intrusive as well as the extrusive rocks to the period of sediment accumulation: "All the igneous rocks, dikes, sills, and flows were introduced into the body of the sedimentaries during the filling of the subsiding trough, or at least before tilting and faulting had begun".

The present interpretation, on the other hand, though in agreement with Davis that tectonic activity initiated the episode of Late Triassic deposition, terminated it, and continued after cessation of deposition, differs in recognizing four discrete episodes: (1) initial graben subsidence, sedimentation, and basaltic igneous activity (intrusive and extrusive); (2) longitudinal crustal warping; (3) second-generation graben subsidence and transverse crustal warping northeast of the Hunterdon Plateau, New Jersey (no. 1, fig. 2) and (4) displacement of transverse warped structures, concomitant compressional

¹ J. D. Dana also shared this view; hence, he included the Connecticut Triassic as one of the "type" examples of a geosyncline (Dana, 1873). Those who insist on considering the Connecticut Triassic as a geosyncline should remember that Dana was totally unaware of the fault-trough origin of the basin in which the Triassic rocks were deposited. The fault-trough interpretation was originated by Barrell (1915).

folding about east-west axes southwest of the Flemington fault, and emplacement of late basaltic intrusives and mineral deposits. These individual episodes will now be discussed and their magnitudes estimated.

Initial graben subsidence, sedimentation, and basaltic igneous activity (intrusive and extrusive).—The basin in which Late Triassic sediments collected was formed by graben faulting, not by downwarping, as thought by Dana, Davis, and others. The initial faulting along the margins of the graben must have been substantial, at least along the southeastern side, for the basal deposits that were transported northwestward from the uplifted marginal block are coarse-grained in the Southbury outlier of western Connecticut, a distance of 25 miles northwest of the basin margin (fig. 1). Coarse-grained material is generally limited to a belt that is less than a mile wide at higher stratigraphic levels. The fact that boulder conglomerates are banked against the faults at the margins on opposite sides of the graben and occur vertically throughout much of the thickness of the section preserved testifies, however, to recurrent movement along the marginal faults in order to maintain high relief on the uplifted blocks (Barrell, 1915; W. L. Russell, 1922; Longwell, 1922, 1937). These marginal faults must have originally dipped under the graben block at approximately 70° to 75° ; they now dip 55° to 60° in many localities, but have been rotated 15° to 20° during longitudinal crustal arching of episode 2.

The minimum amount of relative subsidence of the graben block is measured by the thickness of Triassic strata preserved; how much more than this occurred is conjectural. Previous field determinations of the thickness of the Triassic strata have ranged from 12,000 to 27,000 feet, but the larger of these figures has been denied by most geologists because of intuitive objections to the great magnitude involved.

Cook (1868) calculated the thickness of the Triassic strata in New Jersey to be 27,000 feet, but he arbitrarily reduced this number to 15,000 feet to compensate for presumed repetition on hidden strike faults. I. C. Russell (1880) calculated at least 25,000 feet and accepted this figure as valid barring hidden faults. Kümmel (1898) calculated 20,300 feet, but reduced this by one-half to one-third to 11,800 to 14,700 because of faults (Kümmel, 1899). Darton and others (1908) considered the New Jersey Triassic to be "at least 15,000 feet thick". Grabau (1921) accepted a figure of 14,000 to 18,000 feet. McLaughlin (1944, 1945) has demonstrated that the sections in the Delaware River valley, which are repeated three times by faults, include only the lower half of the total column. The largest thickness present here is 15,000 feet. The present author's view of the structure of the New Jersey Triassic (Sanders, 1962) is that the two large strike faults, which divide the Triassic rocks into three structural blocks in the Delaware River Valley, curve to the north and displace the Triassic border fault and do not repeat the section in northern New Jersey (fig. 1). Longwell (1928) assigned a thickness of 12,000 feet to the Triassic of southern Connecticut. This figure was based on direct measurement of 6000 feet in tunnels for the upper half of the section (with upper formation only partially represented) and on an additional estimated 6000 feet for the basal formation. W. L. Russell (1922) had earlier presented the view that the thickness of the basal formation had been much underestimated.

The essentially unfaulted northern part of the New York-New Jersey-Pennsylvania belt, however, supplies an unambiguous answer of approximately 30,000 feet that commands acceptance. This same thickness figure may be calculated on the basis of an average dip of 12 to 15 degrees by traverses across the strike of the beds in two mutually perpendicular directions: at right angles to the marginal fault across the homocline from the top of the section to its base, proceeding from south of Boonton, New Jersey (no. 2, fig. 2), southeastward to Staten Island, New York (no. 3, fig. 2), a distance of 24 miles (line MN of fig. 1): and parallel to the marginal fault in a northeastward direction 27 miles from Pompton Plains, New Jersey (no. 4, fig. 2), to Stony Point, New York (no. 5, fig. 2), proceeding from the youngest beds preserved in the axis of the Watchung transverse "half-basin" syncline to the base of the section along the flank of the Danbury transverse anticline (line MO of fig. 1). No reasonably probable fault pattern can be devised that will reduce the thickness figure thus determined by any significant amount. An even larger total might result from measurement along the large longitudinal compressional-type synclinal axis that extends from just south of Doylestown (no. 6, fig. 2) westward to the border fault south of Jacksonwald, Pennsylvania (no. 7, fig. 2), near the Schuylkill River (from base of Lockatong formation to the lava flow (line PQ of fig. 1).

A figure of nearly 30,000 feet can also be compiled for central and southern Connecticut, but not in a single traverse as in the New York-New Jersey belt. In Connecticut, the thickness of the basal formation must be determined from a traverse parallel to the border fault across the strike of very scattered outcrops in the New Haven (no. 8, fig. 2) area (line RS of fig. 1) and the

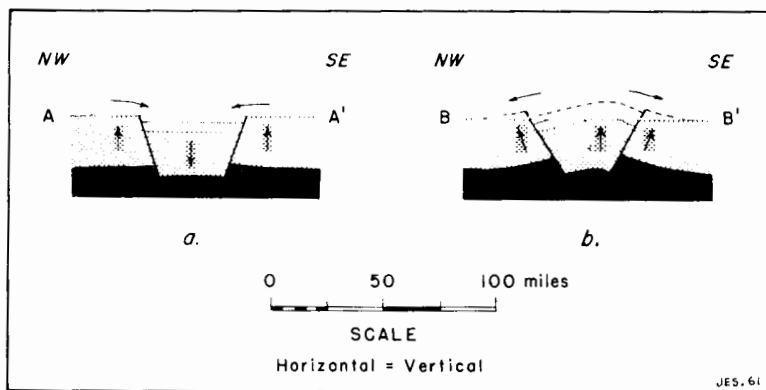


Fig. 3. Cross sections through inferred Late Triassic graben before (left) and after longitudinal crustal warping (right). a.—Section A-A' of figure 2, showing shape of initial Triassic graben after filling with sediment to a thickness of 30,000 feet. Thin black line represents thickest (middle) lava flow (Second Watchung sheet in New Jersey, Holyoke basalt in Connecticut and Massachusetts). Pre-Triassic rocks of crust stippled; Triassic sediments white; and subcrust black. No vertical exaggeration. Arrows at top indicate drainage direction. b.—Section B-B' of figure 4, showing relationships of the present day after all longitudinal crustal arching of episode 2 and subsequent erosion. Arrows at top indicate drainage reversal which is inferred to have accompanied the longitudinal uparching.

upper formation from an extensively covered area north of Hartford (no. 9, fig. 2), 35 miles distant (line TU of fig. 1). In southern Connecticut, only a small fraction of the upper formation is preserved, whereas in central Connecticut, where the upper formation is more fully developed (but possibly repeated by a large strike fault), the basal formation is only partially exposed because of second-generation graben faulting and a northward convergence in thickness. The thickness figures from both the southern half of the Connecticut Valley and northern part of the New York-New Jersey belt agree closely; accordingly, 30,000 feet is taken as a minimum estimate for the amount of initial graben subsidence in these areas (fig. 3a).

Three periods of plateau basalt outpourings were associated with the initial episode of graben subsidence. The figure of three is based on the three lava-flow formations that are interbedded with the sedimentary rocks in the two outcrop belts under consideration. Actually, each of these lava-flow formations is a complex of several flows, some including interbedded sedimentary deposits as much as 250 feet thick. At least eight distinct flows have been found by the writer in southern Connecticut: four in the lower complex and two each in the upper two complexes; as many as eight have been reported from New Jersey (Lewis, 1908; Darton and others, 1908). Dikes and gently concave saucer-shaped intrusive sheets of similar composition to the lava flows were also emplaced during the initial episode of graben subsidence. The latter are locally sill-like (Palisades and West Rock sheets, for example), but when traced in detail can be observed to cross the stratification, in much the same way as the curved dolerite sheets of Tasmania (Spry, 1958; Carey, 1958) and southeastern Pennsylvania (Hotz, 1953). The evidence of differentiation found locally in the Palisades sheet (Walker, 1940) proves that these sheets solidified before tilting of the Triassic strata. These rocks belong in the "pigeonitic rock series" of tholeiitic basalts of Kuno (1950).

The parallelism of the Triassic strata with each other and with the three interbedded lava-flow complexes, as well as the parallelism of the latter to each other and with the base of the Triassic (notably in the New York-New Jersey belt) indicates that the initial episode of graben subsidence took place without important longitudinal or transverse warping.

Longitudinal crustal warping.—The initial episode of graben subsidence is unique in that it contains the only preserved record of sediment accumulation. Considering the amount of erosion that must be invoked as a corollary to the ideas presented here, the point might be raised that any other deposits have been destroyed. The preserved record is ambiguous on this question.

At some time in the tectonic development of the region the strata of the New York-New Jersey-Pennsylvania and Connecticut Valley belts were tilted so that they now dip 15 to 20 degrees away from each other (Russell, 1878; Rice, 1906; Grabau, 1921; Longwell, 1922, 1932; Woodworth, 1932). The writer has elsewhere presented the arguments in favor of the concept that longitudinal crustal warping in the center of the initial graben was not only responsible for this tilting, but also for closing permanently the episode of sediment accumulation by inverting the topography and reversing the drainage which previously flowed into the graben lowland from its uplifted sides (Sanders, 1960).

The locally greater dips of Triassic strata, which range up to 75° , are interpreted to be the results of later tectonic activity that gave rise to the transverse and longitudinal folds.

Uplift along the longitudinal arch caused erosion of extensive proportions; the entire Triassic section eventually was removed along with some unknown amount of the re-exhumed pre-Triassic floor of crystalline rocks (fig. 4). The

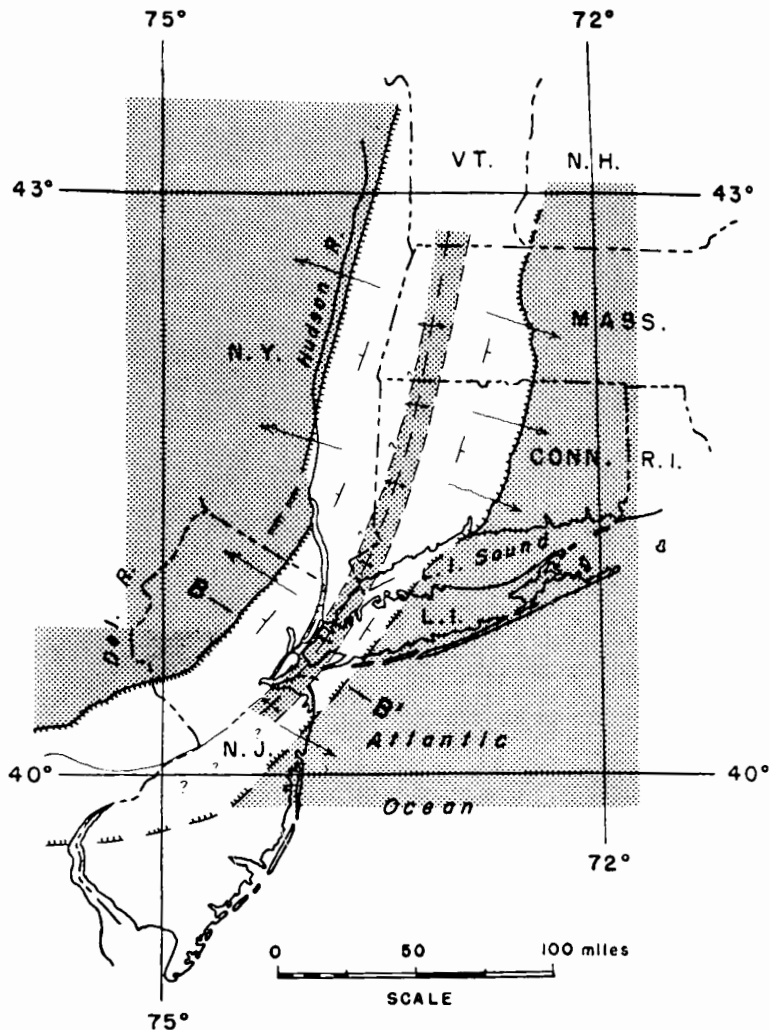


Fig. 4. Map showing location of longitudinal crustal arch in midst of former graben. Rise of the arch reverses drainage out of lowland (shown schematically by arrows) and causes tilting of previously horizontal Triassic strata to southeast on southeast side of arch and to northwest on northwest side of arch (shown by strike and dip symbols). Map was drawn after considerable erosion so that pre-Triassic rocks of graben floor are visible in central part of former graben. Triassic sediments shown in white, pre-Triassic rocks (undifferentiated) are stippled. Line B-B' indicates location of cross section on figure 3b.

magnitude of longitudinal crustal arching cannot be determined with certainty; if the thickness figures calculated here are correct, then it obviously amounted to at least 30,000 feet where the Triassic sediments have been stripped away. A restoration of the arch in cross section is shown in figure 3b; on the basis of this restoration, a maximum of 5000 feet of crystalline rocks removed is assumed, making the total uplift 35,000 feet.

No igneous activity or faults can be assigned to this episode.

Second-generation graben subsidence and transverse crustal warping.—The next tectonic episode is related to the formation of the transverse folds (or warped structures, as they have been called previously) that are so prominent in the topography and geology of the two outcrop belts here discussed in areas northeast of the Hunterdon Plateau, New Jersey (Wheeler, 1939). The exact timing of the events of this episode with respect to the longitudinal arching is not known with certainty; they are inferred to have occurred after longitudinal arching was completed (Sanders, 1960). A new graben block (or possibly blocks) formed, the outline of which was much more irregular than that of the initial graben (fig. 5). This irregularity is held to be closely related to the difference in size of the transverse folds. These transverse folds appear to be limited to the second-generation graben block (fig. 6).

The faults at the margins of the second-generation graben are of two kinds: new, steeply dipping faults, and old, less steeply dipping faults that were active as steeply dipping marginal faults in the initial period of graben subsidence but were rotated in episode 2. The width of the second-generation graben varies; the transverse synclinal structures show a corresponding change of size. Small synclines occur on narrow parts of the graben and large synclines occur on wider parts of it (Sanders, 1960).

The amount of movement along the faults that bound the second-generation graben is not accurately known. Differential structural relief of more than 30,000 feet is indicated in the northern part of the New York-New Jersey belt between the axis of the Danbury transverse anticline north of Peekskill, New York (no. 10, fig. 2), and the axis of the Watchung transverse syncline near Pompton Plains, New Jersey. The total figure for structural relief along the marginal fault closely approaches the value obtained for the amount of crustal uplift in the episode of longitudinal crustal warping. The movement recorded by the other transverse folds generally is much less than this amount. In central Massachusetts, near the north end of the Connecticut Valley belt, however, the whole Triassic section, which is here much thinner, and the underlying crystalline basement are likewise involved in the Amherst transverse anticline (no. 11, fig. 2) which intervenes between the Springfield syncline on the south and Deerfield syncline on the north (fig. 5). In addition to this differential movement associated with the transverse folds, subsidence of 5000 to 6000 feet is estimated to have occurred in central Connecticut to account for the narrow outcrop belt of the lowest sedimentary formation north of Meriden (no. 12, fig. 2).

No igneous activity is known to have been associated with this episode; sediment accumulation related to it is also apparently absent.

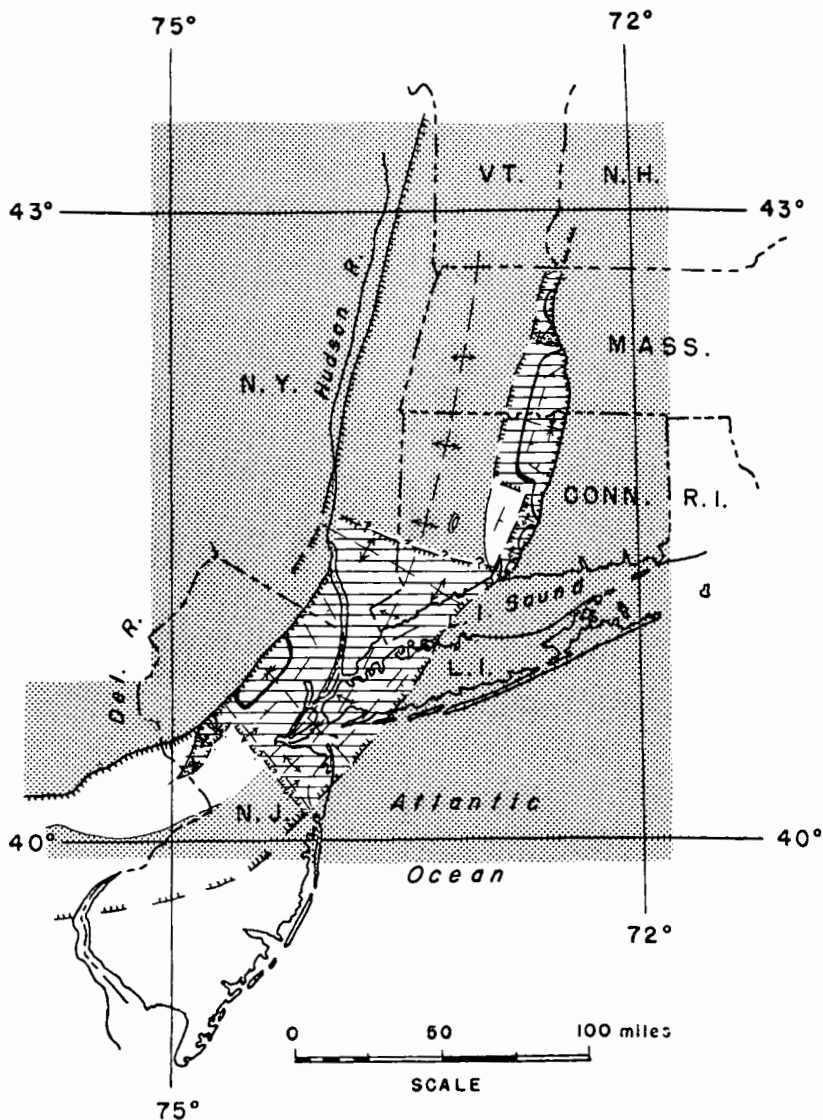


Fig. 5. Map showing location of second-generation graben and transverse folds northeast of ancestral Flemington fault. Area of second-generation graben shown by horizontally ruled lines, pre-Triassic rock (undifferentiated) stippled, and Triassic rocks not involved in second-generation graben shown in white. Triassic outcrops are based on present-day surface except for second-generation graben. Transverse folds are shown by outcrop trace of middle lava flow (black line). Small "crescents" shown southwest of Watchung syncline include New Germantown syncline and Sand Brook syncline, which plunge northwest. These preserve only the lowest lava flow on the modern topography, but are shown schematically here with the second lava flow preserved. The area between these two synclines is inferred to be anticlinal. The basalt at Cushtunk Mountain, N. J., is interpreted as a remnant of the second lava flow in the axis of this anticline.

Fragmentation of transverse warped structures and emplacement of late intrusives (basaltic) and mineral deposits.—The final episode of tectonic activity is represented by the displacement of the transverse folds which had formed on the second-generation graben block. This breakup occurred along faults that in Connecticut are nearly parallel and generally oriented northeast-southwest, diagonal to the axes of the transverse folds. In New Jersey the faults are curved and change trend from northeast-southwest in the Delaware Valley to north-south in areas to the northeast (fig. 7).

The existence of these diagonal faults in Connecticut (and of the eastern border fault, also) was shown by the work of W. M. Davis (1883, 1886, 1888, 1898; Davis and Griswold, 1894), whose accurate analysis and elucidation of them forms a classic milestone of structural geology. A few changes have been made in Davis' final map (1898) and his interpretation of the relationships of the various faulted blocks, but the basic framework that he established has been repeatedly substantiated (Longwell, 1928; Sanders, 1960). Longwell (1922) first demonstrated that these diagonal faults in Connecticut are clearly later than and unrelated to the transverse folds and are not due to torsional stresses that may have occurred during the folding itself. New Jersey faults were discussed by Kümmel (1898, 1899) and Wheeler (1939).

The amount of movement on these late faults varies from a few feet to many thousands of feet. The largest fault yet recognized in this system in Connecticut is the Hartford fault which displaces the Springfield syncline from Hartford to Meriden, Connecticut. This offset is 18,000 feet in a vertical dip-slip direction and 11½ miles in the horizontal left-lateral strike-slip direction (Cedar Mountain to Hanging Hills). The details of the net slip are not known but must fall within these limits. Right-lateral strike-slip displacement of 12

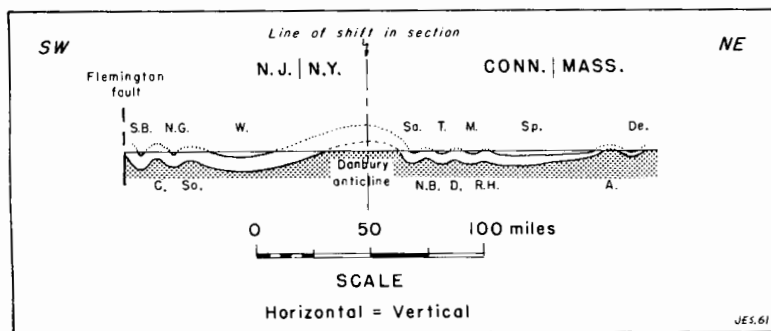


Fig. 6. Longitudinal section, showing transverse folds prior to their offsetting by later faults. Left-hand half of section is along line QMO of figure 1, looking NW with the structure reflected as a mirror image from the Triassic border fault. The section is shifted to the east along the axis of the Danbury transverse anticline, and continues along line RSU of figure 1 and northward. Letters indicate names of folds. Designations for synclines appear above the section (S.B., Sand Brook; N.G., New Germantown; W., Watchung; Sa, Saltonstall; T, Totoket; M, Middletown; Sp., Springfield; and De., Deerfield). Designations for anticlines are shown below the section (C., Cushetunk; So., Somerville; Danbury anticline; N.B., North Branford; D., Durham; R.H., Rocky Hill; and A., Amherst. Transverse anticlines which terminate the section on the southwest and northeast are not named. No vertical exaggeration.

miles and dip-slip offset of 15,000 feet have recently been found by the writer on the Hopewell fault (Kümmel, 1897) in New Jersey (Sanders, 1962).

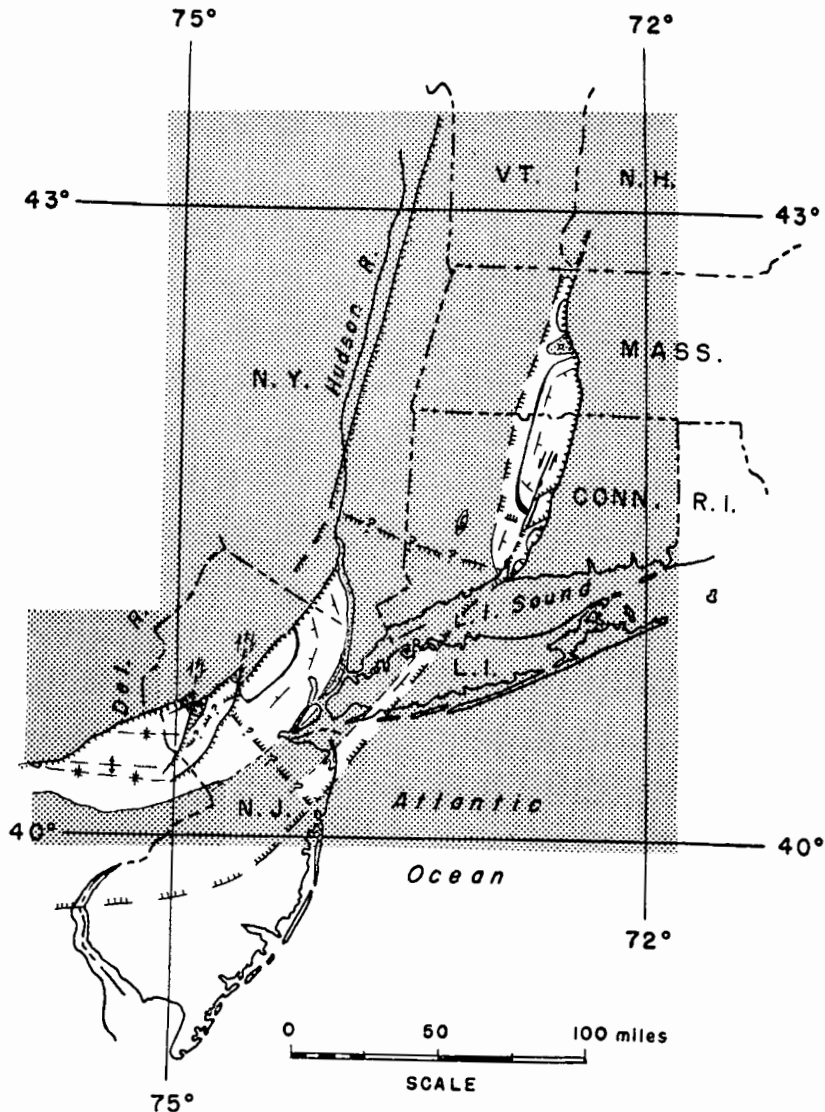


Fig. 7. Map showing geology of Late Triassic outcrops after displacement of transverse folds by late faults, some of which show large strike-slip displacements, and after origin of longitudinal compression-type folds southwest of Flemington faults (shown by dashed lines along axial traces).

Triassic outcrops are those of the present day (except for inferred area shown under western Long Island and eastern New Jersey, which is considered to be present under the Coastal Plain marine deposits) and are shown in white except for middle lava flow (black line). Pre-Triassic rocks (undifferentiated) are stippled.

The Flemington fault (Kümmel, 1897) shows an unknown amount of right-lateral strike-slip displacement as well as more than 10,000 feet of dip-slip displacement (Sanders, 1962). This fault is here inferred to mark an important tectonic boundary in the Triassic outcrop belt. The vertical-type transverse folds with axial planes oriented resolutely northwest-southeast occur only in areas northeast of the Flemington fault. Between the Schuylkill River and Flemington fault in Pennsylvania and southwestern New Jersey, however, large transverse folds are not found and in their stead occur longitudinal folds whose axes are oriented east-west and plunge gently westward. Smaller east-west folds also occur between the Flemington and Hopewell faults (McLaughlin, 1959). These longitudinal folds are inferred to be compressional types and to have occurred during right-lateral strike-slip displacement on the Flemington and Hopewell faults, hence to be entirely younger than the vertical-type transverse folds, which have been offset by strike-slip movements on the late faults. The small transverse folds observed in northern Bucks County, Pennsylvania (no. 13, fig. 2) by McLaughlin (1959), appear to antedate the larger east-west compressional-type folds.

Late dolerite dikes, which were first observed to be porphyritic by Hawes (1875), are associated with the faults that cut the second-generation graben block in Connecticut. These dikes are clearly unrelated to the lava flows that were extruded in the episode of initial graben subsidence as they are located in the faults which offset the warped and tilted lava flows. Although the lava flows were doubtless fed from dikes, the only examples presently known where the association of flows and dikes can be demonstrated within the outcrop area of Triassic rocks are located in central Massachusetts south of the Holyoke Range and involve the uppermost lava-flow (Hampden) formation of Emerson (1898a, 1898b). The other lava flows must have been fed from dikes that are now located outside the Triassic outcrop belt.

Various mineral deposits have also been found along some of the lowland faults and the marginal faults of the second-generation graben (for example, the Bristol, Connecticut, copper mine described by Bateman, 1923). It is not known if the deposits that occur along the marginal faults of the second-generation graben are of the same age as those that are located along the later lowland faults, but the assumption of similar age is made on the basis of the similarity of the mineral assemblages. Chalcocite, bornite, chalcopyrite, sphalerite, galena, pyrite, quartz, calcite, barite, siderite, and locally other minerals are present in these deposits (Bateman, 1923).

Erosional Truncation.—After emplacement of the late porphyritic dikes and mineral deposits, minor faulting may have occurred, but for the most part, the tectonic history by then was complete. The next event recorded by the Triassic rocks is one of erosion and truncation of the tilted, warped, and offset strata. This period of erosion evidently occupied most of Jurassic and Early Cretaceous time. Further subsidence, accompanied this time by marine sedimentation, occurred in the Late Cretaceous in connection with the deposition of the Coastal Plain wedge of sediments. These sedimentary deposits have been only semiconsolidated and dip only very gently seaward; they constitute the upper limit in geologic age determination of the tectonic events here described.

Summary of Tectonic History

The following brief summary is abstracted from the foregoing discussion:

1. Initial graben subsidence, nonmarine sedimentation of a stratigraphic section 30,000 feet thick, volcanic activity, and igneous intrusion.
2. Longitudinal crustal arching in center of initial graben; Triassic strata and an estimated 5000 feet of old crystalline rocks of graben floor ultimately removed by erosion. No faulting or igneous activity.
3. Second-generation graben subsidence, no sedimentation or volcanic activity; transverse folds originate by differential vertical movements, with relative net subsidence of 5000 to 6000 feet or more and structural relief on adjustment faults equal to or exceeding amount of longitudinal crustal arching indicated in 2.
4. Fragmentation of transverse folds of second-generation graben on lowland fault system with both vertical and strike-slip displacement; formation of longitudinal folds southwest of Flemington fault during strike-slip displacement on Hopewell and Flemington faults; injection of late porphyritic dolerite dikes and formation of mineral deposits. No further transverse folds formed.
5. Extensive erosion.
6. Subsidence and Late Cretaceous marine sedimentation of Coastal Plain cover.

Though these episodes seem distinct in the results which they produced, they probably were closely related in time.

Analysis of Tectonic History

The present historical analysis of an ancient graben structure seems especially timely in view of the geophysical interest in crustal structure under large Recent graben areas (Cook, 1961; Talwani and others, 1961). The approach that has been used here deals mainly with quantitative and historical geological aspects of larger problems whose final solutions will doubtless come only after further more detailed geophysical research. Although a gravity and magnetic map of the area has been published by Woollard (1943) and the gravity results also discussed by Longwell (1943), it is hoped that the recognition of the former graben history of the areas of Triassic rocks along the eastern part of the United States will stimulate further geophysical activity of the kind that has been undertaken in the larger modern grabens.

The initial stage of the Triassic graben in eastern United States presumably occurred under conditions similar to those which have been inferred for recent grabens. Seismic, thermal, magnetic, and gravimetric studies in these grabens suggest that unusual crustal layers exist below them. Compressional wave velocities of 7.4 to 7.7 km/sec occur here, the Mohorovičić discontinuity is not an abrupt boundary, magnetic anomalies have been found, and the regions show higher heat flow than is normal elsewhere.

Several possible alternatives may be used to reconstruct the initial stage of the Triassic graben. The simplest interpretation is that the steep marginal faults extend with unchanged dip completely through the Earth's crust (compare Goguel, 1957). Some of the fractures unquestionably did extend through the crust, for they tapped a uniform source of magma that became tholeiitic

basalt upon consolidation, but this fact sheds no light on the attitude at depth of these fractures which at the surface probably dipped 70° to 75° under the graben.

Although he was not so much concerned with the initial stages of the tectonic history, Longwell (1943) invoked warping of a crust of uniform thickness to explain the regional positive gravity anomalies of as much as 40 milligals which had been found by traverses across the longitudinal arch. The mechanism responsible for such warping is still not understood, but nevertheless this explanation seems the only suitable one; it views the regional gravity anomalies as being due to a combination of tectonically caused highs and lows on the Mohorovičić discontinuity at the base of the crust and erosionally caused planation at the top of the crust.

Another approach to the initial graben subsidence and later longitudinal regional arching sequence derives from that applied by Meyer (1944) to the grabens associated with salt domes in the Gulf of Mexico coastal plain region. Meyer interpreted these grabens to be superficial features that are directly related to the rising salt plug below, or to a deepseated horst block in the case of elongate grabens that are not associated with salt domes.

Somewhat analogously, Cook (1961) has suggested that rising convection currents in the mantle may produce linear belts of regional uplift which include elongate axial grabens. The graben on the surface is likewise considered to result from tension and subsidence that occur over a deeper zone of upward convective flow. When the convection becomes less active, the presence of mixed mantle and crustal rock, formed by the previously active currents, may cause regional isostatic arching along an axis that coincides with the center of the former graben.

The later episodes: second-generation graben subsidence, origin of transverse folds, offsetting of these folds by faults with both vertical and strike-slip components of motion, and origin of longitudinal compressional-type folds in conjunction with strike-slip faulting, are less easily related to the conditions that have been invoked to explain the first two episodes. Not only did later subsidence occur, at one time accompanied by transverse warping and faulting, and at the other time, by local collapse and displacement of the transverse folds, but further retapping of the deep magmatic source must also have taken place to explain the existence of the dikes in the faults which offset not only the transverse folds but also the longitudinal folds. The crustal conditions that were responsible for these later episodes lend special interest to the geophysical comparison of older and newer grabens.

The fact that the Triassic graben follows so faithfully the central region of the Appalachian Mountain system (Keith, 1923) suggests, however, that the graben may be closely related to the newly thickened crust that had formed during the culminating Appalachian orogeny which finally obliterated the Appalachian geosyncline. The change from relative subsidence of the graben block with its deep-reaching fractures to regional longitudinal arching apparently without fracturing, however, requires explanation. Both of these episodes could have been caused by general upward movement that was insti-

tuted by the isostatic rise of the newly deformed Appalachians, but the reason for the supposed difference between the two is not known.

The alternations of apparently opposite kinds of crustal behavior that are suggested by the Triassic rocks might be due to some kind of deepseated reversible transformation which includes volume changes, such as the serpentine-peridotite reaction outlined by Hess (1955).

Other concepts, such as crustal thinning or Earth expansion, might also be invoked as explanations of parts of the tectonic history here proposed for the Triassic, but these fail to account for the complete sequence involved.

All these speculations can be tolerated, in part at least, owing to the present dearth of detailed geophysical data. More measurements of crustal properties under the areas concerned should provide a firmer basis for interpretation of the tectonic development and for understanding how the conditions that caused these episodes of deformation of this ancient graben may compare with the crustal conditions under the grabens of the modern world. None of them adequately accounts for the strike-slip faults and associated longitudinal compressional-type folds.

GEOLOGIC IMPLICATIONS OF THE INFERRED TECTONIC SEQUENCE

A list of geologic implications of the views expressed here on the tectonics of the Upper Triassic rocks includes: Late Triassic date of uncovering of Precambrian basement in some medial parts of Appalachians, extension of Late Triassic faults beyond the outcrop limits of Triassic rocks, southward disappearance of the Taconic allochthon in the Hudson Valley, effect on the rocks of such deep burial, possibility of radiometric dating of the igneous rocks associated with the different tectonic episodes, and bearing of the tectonic history on origin of Appalachian rivers.

Uncovering of Precambrian basement in medial Appalachians

The record of clasts in the Triassic fanglomerates along the northwestern border fault in the New York-New Jersey belt (Kümmel, 1898, 1940) clearly indicates that the Precambrian basement rocks were not available in most Triassic drainage networks along the northwestern side of the graben until near the end of episode 1 (sedimentation in the initial graben). The arching and faulting that have caused uplift of many areas of Precambrian rocks in the medial parts of the Appalachians, therefore, may reasonably be supposed also to have resulted from Late Triassic tectonic movements. Localities where the Middle Ordovician rocks rest on Precambrian basement, as near Rutland, Vermont (no. 14, fig. 2) (Thompson in Billings, 1952, p. 14-23), and where Lower Silurian sandstone lies on Precambrian basement, as at Copperas Mountain, New Jersey (no. 15, fig. 2) (Kümmel and Weller, 1902), indicate that the basement was locally exposed in post-Ordovician, pre-Silurian times. Localities where the basal Triassic rests on Precambrian, such as Trenton, New Jersey (no. 16, fig. 2) and Staten Island, New York, indicate that the Precambrian "basement" had been uncovered in the middle of the Triassic graben prior to the Late Triassic. Along the graben walls, however, the Paleozoic rocks formed a continuous blanket above the basement until late in the Triassic, and

present areas of high basement along the sides of the graben exerted no influence on the composition of the Paleozoic rocks. The now-observed isolation of the Paleozoic outcrop belts from each other along the northwest side of the graben in New Jersey and New York is in large part due to uplift of the Precambrian basement on Late Triassic fault blocks. Though the local details are less obvious and less compelling away from the outcrop of Triassic rocks, the present writer is convinced that much of the high position of the "basement" in the Hudson-Housatonic Highlands, Berkshire Hills, and even the Green Mountains anticlinal axis may be due to Late Triassic crustal arching and faulting. This view is offered as an alternative to the idea that these axes were important topographic barriers or source areas during Paleozoic sedimentation on which exposures of the Precambrian basement were abundant, or that uplift along the Green Mountains axis during the Late Middle Ordovician was connected with emplacement of the Taconic allochthon by triggering gravity sliding down its western flank (Rodgers in Billings, 1952, p. 7-14; Thompson in Billings, 1952, p. 14-23). Paleozoic infolding of "basement" and cover can be shown in many localities along the Green Mountains axis, so that the tectonic history is varied and complex. The point argued here is that significant vertical uplift occurred in the Late Triassic as indicated by the complete removal of 30,000 feet of Triassic strata and an unknown additional amount of the pre-Triassic graben floor.

Extension of Late Triassic faults beyond outcrops of Triassic rocks

The two outcrop belts of Triassic rocks that have been considered here are terminated along strike by the combined effects of transverse anticlines and the regional longitudinal arch. In other words, the outcrop belts end along the flank of transverse anticlines where the pre-Triassic basement floor (pre-Triassic depositional surface) strikes directly into the border fault. According to the interpretation presented here, the border faults must extend at least as far beyond the end of the outcrop belt as the width of the anticlinal structure itself. Doubtless these faults extend even further, for they have been shown to include displacements of tens of thousands of feet.² Faults of such size probably do not just suddenly stop. Many of the small aligned outcrops of Precambrian rocks which appear from beneath the Paleozoic rocks of the lower Hudson Valley are inferred to occur on Triassic fault blocks. Platt (ms. 1960b) has shown that the Taconic allochthon in Washington County, New York, is bounded on the west by a normal fault. The present writer considers that this fault is of Triassic age. A striking feature of the Taconic allochthon is the contrast in map pattern of its eastern and western boundaries. The thrust which underlies this allochthon dips at low angles, as can be seen by an exposure of it at Bald Mountain (no. 17, fig. 2) Washington County, New York (Sanders, Platt, and Powers, 1961), by the presence of windows in the allochthon, and by the sinuous and embayed eastern contact. On the contrary, the western

² Stratigraphic displacement along these faults may be much reduced or even apparently disappear where the pre-Triassic graben floor has been faulted against the pre-Triassic rocks of the graben wall as a result of movements associated with the growth of the transverse folds. Nevertheless, the faults may be expected to continue beyond such an area of diminished stratigraphic displacement.

boundary of the allochthon is remarkably straight, and autochthonous carbonate rocks that unconformably underlie the Late Middle Ordovician autochthonous fine-grained terrigenous rocks, which occur just below the Taconic thrust, crop out just west of the allochthon. This straight western boundary is here inferred to be due to the presence there of a Late Triassic normal fault which displaces the Taconic thrust and allochthon. The present writer differs with Platt's interpretation, however, and supposes that the important movement along the major normal fault at the west edge of the Taconic allochthon is up on the west and down on the east. Possibly this fault is a northward extension of the northwestern border fault of the New York-New Jersey Triassic outcrop belt or another fault that is parallel to the border fault but located west of the Green Pond-Schunemunk Mountain synclinal belt of Paleozoic rocks (Terry Offield, personal communication).

Southward disappearance of Taconic allochthon in the Hudson Valley

The Taconic allochthon apparently disappears in the southern parts of the Hudson Valley east of Newburgh, New York (no. 18, fig. 2). The explanation offered here for this disappearance is that the allochthon rises up into the air along the northwestern flank of the Danbury transverse anticline and has been eroded away. That the allochthon descends again to the level of the present topography on the southwestern side of this anticline is suggested by exposures near Peekskill, New York, and by the presence of Taconic-like red slates and bedded cherts which have been mapped as the "Martinsburg" formation near Jutland and along Route 46 west of Clinton, New Jersey (no. 19, fig. 2). Lower Paleozoic carbonate rocks occur both east and west of the red slates and bedded cherts, west of Jutland and in Clinton. The age of these Taconic-like rocks in New Jersey has not everywhere been determined by fossils. Weller (1901) reported Normanskill graptolites (identified by Ruedemann) at Branchville (no. 20, fig. 2) and Jutland (no. 21, fig. 2), New Jersey. In the former locality, the graptolites were found 50 to 75 feet stratigraphically above Trenton-age limestone. Although the aspect of these rocks strikingly resembles that of the Hudson Valley Taconic sequence, they have not been interpreted as belonging to the Taconic sequence owing to their assignment to the Martinsburg formation which is younger than the Cambro-Ordovician carbonate rocks. In view of their great similarity to the Hudson Valley Taconic formations, these New Jersey "Martinsburg" rocks seem especially worthy of detailed re-examination and additional searching for fossils. In addition, Taconic rocks may be deeply buried underneath the Triassic rocks themselves or lie underneath the belt of Silurian and Devonian rocks that is located northwest of and parallel to the Triassic outcrop belt. The eastern margin of the Taconic allochthon is inferred to have been tilted westward by uplift along the longitudinal crustal arch that formed in episode 2.

Effects of deep burial on the rocks

If the figures on vertical crustal movements presented here are correct, or even of the correct order of magnitude, then many rocks near the Triassic outcrop belts that are now exposed at the surface have been deeply buried and

afterward re-exposed. A special study of possible chemical, mineralogic, and textural effects that may have occurred as a result of temperature and pressure changes incident to this deep burial has not been undertaken, but looms as a worthwhile enterprise. Both crystalline rocks and Triassic sedimentary rocks have been involved in this deep subsidence and later uplift. The crystalline rocks around Danbury, Connecticut, probably represent those which have been most deeply buried. These rocks occur at the place where the axis of the longitudinal crustal arch of episode 2 has been intersected by the axis of the Danbury transverse anticline of episode 3. Whether the presumed deep burial was of sufficient duration to cause any noteworthy changes in the rocks is not known.

Triassic sedimentary rocks can be obtained at the present surface which might show the effects of progressively deeper burial. A traverse down the section parallel to the northwestern border fault in the New York-New Jersey belt where the strata strike northwestward into the border fault along the common limb of the Watchung transverse syncline and Danbury anticline should provide a suite of samples that could be examined for possible different facies of diagenesis (Packham and Crook, 1960). The assimilation of individual clasts from Triassic sandstones and conglomerates by late basaltic dikes which intersected the base of the Triassic in Woodbridge, Connecticut, and higher parts of the section in the northeastern part of New Haven, Connecticut, suggests that cementation of some Triassic rocks had not occurred by the end of episode 4, near the end of the interval of greatest depth of burial. The late age of the cement is also indicated by the relationship of cement to mineral deposits, which at Bristol, Connecticut (no. 22, fig. 2) shows that introduction of cement into the Triassic sandstones took place after formation of the late mineral deposits (Heald, 1956, p. 1150). Barite cement also occurs in sandstone near some late dikes (Krynine, 1950).

The radiometric dates suggested in the next section should be useful in estimating the absolute length of time during which the rocks were deeply buried.

Radiometric dating of Triassic Tectonic Episodes

Previous interpretations of Late Triassic geologic history have supported the supposition that any basaltic rock from a Triassic outcrop area comprises a representative sample which can be used to date the entire episode of rock formation and tectonic activity. The interpretation presented here, on the contrary, suggests that these igneous rocks are of different ages with respect to the tectonic events. Careful sampling and dating might yield valuable insights into the length of time involved in the tectonic development of these areas, as well as more definite figures on the length of time that some of the crystalline and sedimentary rocks have been deeply buried. This possibility seems an especially attractive one for attempting to measure the reaction rates in silicate mineral assemblages under natural conditions within the crust.

Origin of Appalachian drainage

The question of origin and history of Appalachian drainage, particularly of those rivers with northwest-southeast orientation, has been much discussed

previously and will not be entered into extensively here. The only suggestions that are appropriate at this point relate to the possible implications of Triassic tectonic history of this drainage development, a subject that has been little discussed (Meyerhoff and Olmstead, 1936; Thompson, 1949). A much more debated question concerns date and mechanism of divide migration.

Little evidence remains of the drainage that developed on the folded Appalachians in the later Permian and Early Triassic. When the graben formed during episode 1 of the Late Triassic, it disrupted the drainage and attracted river flow toward it. Reference to figure 2 indicates that on the northwest side of the graben, a divide between east-flowing and west-flowing streams existed somewhere in the Valley and Ridge Province at this time (Meyerhoff and Olmstead, 1936, p. 37-38). A comparable divide probably existed south-east of the Triassic graben. The latter was referred to by Thompson (1949, p. 33). This drainage pattern can be inferred confidently on the basis of provenance of Triassic conglomerates.

An important inversion of topography and reversal of drainage is considered to have been brought about by episode 2, longitudinal crustal arching in the center of the initial graben. This caused a new divide to originate along the axis of the graben and disrupted the two divides that existed in episode 1. The absence of younger sediments and prevalence of erosion until the Late Cretaceous coastal plain marine transgression occurred may be taken as an indication that drainage out of the area of Triassic outcrops had been permanently established by the changes associated with the episode of crystal arching that terminated initial graben subsidence. The inversion of topography gave rise to an exterior drainage network that must have been northwestward-flowing along the northwestern side of the longitudinal crystal arch and southeastward-flowing along the southeastern side of this arch (fig. 4). Possibly some of the rivers with northwest-southeast orientation in the Appalachians are as ancient as this time of Late Triassic crustal arching. The effect on the drainage created by transverse warping of episode 3 is not known because of the limited area here considered.

CONCLUSION

Late Triassic structural features in the New York-New Jersey and Connecticut Valley belts have been interpreted in terms of a sequence of four episodes of tectonic activity, whose magnitudes have been estimated. These episodes are: (1) initial graben subsidence, sedimentation, and igneous activity; (2) longitudinal crustal arching in center of graben with resultant inversion of topography and reversal of drainage; no faulting or igneous activity; (3) second-generation graben subsidence accompanied by origin of transverse folds, but lacking igneous activity; and (4) formation of a late fault system that includes both dip-slip and strike-slip faults and also longitudinal compressional-type folds southwest of the Flemington fault, injection of dikes of porphyritic dolerite into some faults, emplacement of mineral deposits on some faults. Erosion followed episode 4 and persisted until the Late Cretaceous, when the Coastal Plain marine transgression occurred; Triassic rocks were locally buried by sediments which were deposited during this transgression.

Many explanations of these events are possible and none is given preferred status at this time. A close genetic connection doubtless exists, however, between Triassic structures and tectonic features of the medial parts of the Appalachian orogen.

Extension of the analysis of Late Triassic tectonics leads to the following conclusions:

1. Exposure of Precambrian basement rock in many medial Appalachian areas is a Late Triassic event; much of the uparching of the Green Mountains axis may also have occurred in the Late Triassic.
2. Late Triassic faults extend beyond the outcrop belts of Triassic rocks; one Late Triassic fault is inferred to form the western boundary of the Taconic allochthon in the Hudson Valley.
3. The southward disappearance of the Taconic allochthon in the Hudson Valley is the result of uplift to the south along a Late Triassic transverse anticline.
4. Late Triassic basaltic rocks are of several different ages; radiometric dating of these might yield valuable data on length of time required for tectonic activity and length of time the rocks were deeply buried.
5. Late Triassic longitudinal crustal arching may have been influential in originating some of the Appalachian rivers.

REFERENCES

- Barrell, Joseph, 1915, Central Connecticut in the geologic past: Connecticut Geol. Nat. History Survey Bull. 23, 44 p.
- Bateman, A. M., 1923, Primary chalcocite; Bristol copper mine, Connecticut: *Econ. Geology*, v. 18, p. 122-166.
- Billings, M. P., Rodgers, John, and Thompson, J. B., Jr., 1952, *Geology of the Appalachian Highlands of east-central New York, southern Vermont, and southern New Hampshire Field Trip no. 1*, in Geol. Soc. America, Guidebook for field trips in New England: p. 1-71.
- Carey, S. W., 1958, The isostrat, a new technique for the analysis of the structure of the Tasmanian dolerites, in Carey, S. W., ed., *Dolerite; a symposium*: Hobart, Univ. Tasmania, p. 130-164.
- Cook, G. H., 1868, *Geology of New Jersey*: Newark, N. J., New Jersey Geol. Survey, 900 p.
- Cook, K. L., 1961, The problem of the "Mantle-Crust Mix"—lateral inhomogeneity of the uppermost part of the Earth's mantle [abs]: *Jour. Geophys. Research*, v. 66, p. 2522.
- Dana, J. D., 1873, On some results of the Earth's contraction from cooling including a discussion of the origin of mountains and the nature of the Earth's interior: *Am. Jour. Sci.*, 3rd ser., v. 5, p. 423-443.
- Darton, N. H., Bayley, W. S., Salisbury, R. D., and Kümmel, H. B., 1908, Description of the Passaic quadrangle [N.J.-N.Y.]: U. S. Geol. Survey Geol. Atlas, Folio 157, 27 p.
- Davis, W. M., 1882, Brief notice of observations on the Triassic trap rocks of Massachusetts, Connecticut, and New Jersey: *Am. Jour. Sci.*, 3rd ser., v. 24, p. 345-349.
- 1883, The structural value of the trap ridges of the Connecticut Valley: *Boston Soc. Nat. History Proc.*, v. 22, p. 116-124.
- 1886, The structure of the Triassic formation of the Connecticut Valley: *Am. Jour. Sci.*, 3rd ser., v. 32, p. 342-352.
- 1888, The structure of the Triassic formation of the Connecticut Valley: U. S. Geol. Survey 7th Ann. Rept., p. 455-490.
- 1898, The Triassic formation of Connecticut: U. S. Geol. Survey 18th Ann. Rept., pt. 2, p. 1-192.
- Davis, W. M., and Griswold, L. S., 1894, Eastern boundary of the Connecticut Triassic: *Geol. Soc. America Bull.*, v. 5, p. 515-530.
- Emerson, B. K., 1898a, *Geology of old Hampshire County, Massachusetts*: U. S. Geol. Survey Mon. 29, 790 p.
- 1898b, Outlines of the geology of western Massachusetts; Description of the Holyoke quadrangle: U. S. Geol. Survey Geol. Atlas, Holyoke Folio 50, 8 p.

- Goguel, Jean, 1957, Gravimétrie et fossé rhéna: Koninkl. Nederlandse Geol.-Mijnb. Gen., Verh. Geol. Ser., d, v. 18 (F. A. Vening Meinesz Vol.), p. 125-147.
- Grabau, A. W., 1921, A textbook of geology. Part II, Historical geology: Boston, D. C. Heath and Co., 976 p.
- Gray, Carlyle, and others, 1960, Geologic Map of Pennsylvania: Pennsylvania Topog. and Geol. Survey, 4th Ser.
- Hawes, G. W., 1875, The trap rocks of the Connecticut Valley: Am. Jour. Sci., 3rd ser., v. 9, p. 185-192.
- Heald, M. T., 1956, Cementation of Triassic arkoses in Connecticut and Massachusetts: Geol. Soc. America Bull., v. 67, p. 1133-1154.
- Heezen, B. C., 1960, The rift in the ocean floor: Sci. Am., v. 203, no. 4, p. 98-110.
- Hess, H. H., 1955, Serpentine, orogeny, and epeirogeny, in Poldervaart, Arie, ed., Crust of the Earth—a symposium: Geol. Soc. America Spec. Paper 62, p. 391-408.
- Hotz, P. E., 1953, Form of diabase sheets in southeastern Pennsylvania: Am. Jour. Sci., v. 250, p. 375-388.
- Keith, Arthur, 1923, Outlines of Appalachian structure: Geol. Soc. America Bull., v. 34, p. 309-380.
- Krynine, P. D., 1950, Petrology, stratigraphy, and origin of the Triassic sedimentary rocks of Connecticut: Connecticut Geol. Nat. History Survey Bull. 73, 239 p.
- Kümmel, H. B., 1897, The Newark system; report of progress: New Jersey Geol. Survey Ann. Rept. for 1896, p. 25-88.
- 1898, The Newark System or red sandstone belt: New Jersey Geol. Survey Ann. Rept. for 1897, p. 23-159.
- 1899, The Newark rocks of New Jersey and New York: Jour. Geology, v. 7, p. 23-52.
- 1940, The Geology of New Jersey: New Jersey Dept. Conserv. Geol. ser. Bull. 50, 203 p.
- Kümmel, H. B., and Weller, Stuart, 1902, The rocks of the Green Pond Mountain region: New Jersey Geol. Survey Ann. Rept. for 1901, p. 1-51.
- Kuno, Hishashi, 1950, Petrology of Hakone Volcano and the adjacent areas, Japan: Geol. Soc. America Bull., v. 61, p. 957-1020.
- Lewis, J. V., 1908, Petrography of the Newark igneous rocks of New Jersey: New Jersey Geol. Survey Ann. Rept. State Geologist for 1907, p. 99-167.
- Longwell, C. R., 1922, Notes on the structure of the Triassic rocks in southern Connecticut: Am. Jour. Sci., 5th ser., v. 4, p. 223-236.
- 1928, The Triassic of Connecticut: Am. Jour. Sci., 5th ser., v. 16, p. 259-263.
- 1932, in Longwell, C. R., and Dana, E. S., Walks and rides in Central Connecticut and Massachusetts: New Haven, Tuttle, Morehouse, and Taylor Co., 229 p.
- Longwell, C. R., 1933, The Triassic belt of Massachusetts and Connecticut, in Eastern New York and western New England: Internat. Geol. Cong., 16th, United States, Guidebook 1, Excursion A-1, p. 93-104.
- 1937, Sedimentation in relation to faulting: Geol. Soc. America Bull., v. 48, p. 433-442.
- 1943, Geologic interpretation of gravity anomalies in the southern New England-Hudson Valley region: Geol. Soc. America Bull., v. 54, p. 555-590.
- McLaughlin, D. B., 1944, Triassic stratigraphy in the Point Pleasant district, Pennsylvania: Pennsylvania Acad. Sci. Proc., v. 18, p. 62-69.
- 1945, Type sections of the Stockton and Lockatong formations [Pa., N. J.]: Pennsylvania Acad. Sci. Proc., v. 19, p. 102-113.
- 1959, Structure of the Triassic rocks, in Willard, Bradford, Geology and mineral resources of Bucks County, Pennsylvania: Pennsylvania Topog. and Geol. Survey Bull. C-9, p. 126-141.
- Meyer, W. G., 1944, Grabens in Gulf Coast anticlines and their relation to other fault troughs: Am. Assoc. Petroleum Geologists Bull., v. 28, p. 541-553.
- Meyerohoff, H. A., and Olmstead, E. W., 1936, The origins of Appalachian drainage: Am. Jour. Sci., 5th ser., v. 32, p. 21-42.
- Murray, G. E., 1960, Geologic framework of Gulf Coastal Province of United States, in Shepard, F. P., and others, eds., Recent sediments, Northwest Gulf of Mexico: Tulsa, Okla., Am. Assoc. Petroleum Geologists, p. 5-33.
- Packham, G. H., and Crook, K. A. W., 1960, The principle of diagenetic facies and some of its applications: Jour. Geology, v. 68, p. 392-407.
- Platt, L. B., ms., 1960a, Structure and stratigraphy of the Cossayuna area, New York: Ph.D., dissertation, Yale University, 126 p.
- 1960b, Stratigraphy and structure of the Cossayuna area, New York [abs.]: Geol. Soc. America Bull., v. 71, p. 1944-1945.

- Rice, W. N., 1906, The Triassic, in Rice, W. N., and Gregory, H. E., Manual of the geology of Connecticut: Connecticut Geol. Nat. History Survey Bull. 6, p. 157-222.
- Russell, I. C., 1878, On the physical history of the Triassic formation in New Jersey and the Connecticut Valley: New York Acad. Sci. Annals., v. 1, p. 220-254.
- 1880, On the former extent of the Triassic formation of the Atlantic states: Am. Naturalist, v. 14, p. 703-712.
- Russell, W. L., 1922, The structural and stratigraphic relations of the great Triassic fault of southern Connecticut: Am. Jour. Sci., 5th ser., v. 4, p. 483-497.
- Sanders, J. E., 1960, Structural history of Triassic rocks of the Connecticut Valley belt and its regional implications: New York Acad. Sci. Trans., v. 23, p. 119-132.
- 1961, Tectonophysics of Late Triassic deformation, Northeastern United States [abs.]: Jour. Geophys. Research, v. 66, p. 2557-2558.
- 1962, Strike-slip displacement on faults in Triassic rocks in New Jersey: Science, v. 136, no. 3510, p. 40-42.
- Sanders, J. E., Platt, L. B., and Powers, R. W., 1961, Bald Mountain limestone, New York: New facts and interpretations relative to Taconic geology: Geol. Soc. America Bull., v. 72, p. 485-487.
- Spry, Alan, 1958, Some observations of the Jurassic dolerite of the Eureka cone sheet near Zechan, Tasmania, in Carey, S. W., ed., Dolerite, a symposium: Hobart, Univ. Tasmania, p. 93-129.
- Talwani, Manik, Heezen, B. C., and Worzel, J. L., 1961, Gravity anomalies, physiography, and crustal structure of the Mid-Atlantic ridge [abs.]: Jour. Geophys. Research, v. 66, p. 2565.
- Thompson, H. D., 1949, Drainage evolution in the Appalachians of Pennsylvania: New York Acad. Sci. Annals, v. 52, p. 31-62.
- Walker, Frederick, 1940, Differentiation of the Palisade diabase, New Jersey: Geol. Soc. America Bull., v. 51, p. 1059-1106.
- Weller, Stuart, 1901, A preliminary report on the Paleozoic formations of the Kittatinny Valley in New Jersey: New Jersey Geol. Survey Ann. Rept. for 1900, p. 1-8.
- Wheeler, Girard, 1937, The west wall of the New England Triassic lowland: Connecticut Geol. Nat. History Survey Bull. 58, 73 p.
- 1939, Triassic fault-line deflections and associated warping: Jour. Geology, v. 47, p. 337-370.
- Woodworth, J. B., 1932, Contributions to the study of mountain building: Am. Jour. Sci., 5th ser., v. 23, p. 155-171.
- Woollard, G. P., 1943, Geologic correlation of areal gravitational and magnetic studies in New Jersey and vicinity: Geol. Soc. America Bull., v. 54, p. 791-818.