A Review and Interpretation of the Geologic Setting of the Watchung Basalt Flows, New Jersey

GEOLOGICAL SURVEY PROFESSIONAL PAPER 864-A

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By GEORGE T. FAUST

STUDIES ON THE WATCHUNG BASALT FLOWS OF NEW JERSEY

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A general introduction to the restudy of the volcanism in the Newark basin of New Jersey

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A REVIEW AND INTERPRETATION OF THE GEOLOGIC SETTING OF THE WATCHUNG BASALT FLOWS, NEW JERSEY

By GEORGE T. FAUST

ABSTRACT

The Watchung Basalt flows and the thick sedimentary sequences as now exposed in Bergen, Essex, Union, Passaic, Morris, and Somerset Counties, New Jersey, are part of the remnant of a former graben. This graben has been largely destroyed by erosion. The graben is generally believed on the basis of paleontologic evidence to have been formed in the Late Triassic. About 2½ to 1 million years before the end of Triassic sedimentation in the graben, lava flowed out onto the graben floor to form the large flood basalts of First Watchung Mountain. Approximately 500,000 to 250,000 years after the first volcanic episode a second period of basaltic eruptions produced the lavas of Second Watchung Mountain. Following a lapse of 1½ million years to 600,000 years another flood of basalts formed the lavas of Third Watchung Mountain. As the lavas solidified they accumulated body stresses and most of this stress was relieved by jointing. Subsequently, the region was folded to form an arch. During the buckling of the arch subsidiary border synclines were formed along the contact with the granitic walls of the horsts. This tectonic event produced joints whose abundance and distribution are related to the geometry of the structure. Late in the history of the Newark basin in New Jersey, during the Pleistocene, a continental glacier covered a part of the area. After the disappearance of the glacier, decompression of the crust produced sheeting structures in the basalt. Thus the jointing systems observed today are the results of the combined geologic processes of volcanism, tectonism, and glaciation.

The history of the events involved in the tectonic subsidence and volcanism in the Newark basin bears a parallel relationship to the order of events taking place in the North American plate in its location in the ancient continent of Pangaea. It is suggested here that (1) the rifting to form and develop the Newark graben, (2) the deep rifting associated with the volcanism, and (3) the downfaulting of the graben which produced the central arch and the border synclines are the result of the following events in the continent of Pangaea: (1) the development of a linear zone of tension, (2) deep rifting which separated the North American plate from the adjacent parts of Pangaea.

Basalts form the three ridges known as First, Second, and Third Mountains. The feeder dikes from whence the lava welled forth are hidden by cover. A feeder dike was observed cutting through the lower flow unit of First Mountain, near West Orange, N.J. The areal extent of the Watchungs is now about 500 square miles (1,295 km²); they probably covered an area of 2,000 square miles (5,180 km²). The lavas are tholeiites.

Supplementary topics include a discussion of the characteristics of fissure eruptions and of vesiculation in basaltic magma.

> *"Watchung Mountains—The trap ridges extending from Bedminster and Somerville to Oakland and Darlington are known as the Watchungs or Orange mountains. They are sometimes called First, Second and Third Mountain, beginning with the outermost or eastern one."*[1]

INTRODUCTION

In 1936–37, the author was teaching a course in the theory of annealing, as developed by Williamson and Adams (1919) and Adams and Williamson (1920), to graduate students at Rutgers University. During this course, I became interested in the problems of the cooling of lava flows, such as the nearby Watchung Basalt, and I made some preliminary calculations of the heat-flow relations. Subsequent field observations of the three Watchung Basalt flows disclosed that the problem was more complex than the simple model. Any theory of cooling of the lava flow would have to account for the several types of joints present in these flows and the obviously unequal frequency of the several joint systems. It thus became evident that a preliminary stage in the evaluation of the cooling history of these flows would be a study of the character of the jointing and its uniformity.

This report provides a background for an extensive study of various aspects of the Watchung Basalt flows in New Jersey. Faust and Murata (1953) and Faust, Hathaway, and Millot (1959), in a study of the mineralogy of the Watchungs, reported on

[1] Kümmel (1898, p. 76–77).

stevensite, the magnesium end member of the montmorillonite group. Preliminary results on the jointing systems were reported by Faust (in U.S. Geological Survey, 1961, p. A77). Aeromagnetic maps were prepared and used as a background for this study (Andreasen and others, 1963; Henderson, Andreasen, and Petty, 1966; Henderson, Chandler, and others, 1962, 1963; Henderson, Tyson, and others, 1957a, b; Henderson, Tyson, Gilchrist, and others, 1957, 1958a, b; Henderson, Tyson, Wilson, and others, 1957a, b, c, d; Philbin and Kirby, 1964).

This report is written not only to orient the reader with respect to the location, physiography, and geology of the Watchung Mountains but to indicate something of the order of magnitude, direction, and time sequence of the several physical geologic forces which are responsible for the joint systems in the basalt flows as we see them today. Because geologists differ in their views on the origin and development of the Triassic Newark basin, brief statements of these several theories and a short review of fissure eruptions are included.

There has been a revival of interest in the Triassic basins of eastern North America. One of the unsolved problems which has attracted much attention and is pertinent to this study is the relation of the numerous dikes which occur both without and within (in part) the basins and whose trend is almost always discordant to the structural trends of the basins. King (1961), who has studied this problem in detail, has made some comments on the stress patterns as deduced from these dikes and the structure of the basins.

Some matters of nomenclature require mention at this time. The three ridges that constitute the Watchung Mountains have been known for a long time in popular and scientific usage as First, Second, and Third Watchung Mountains and collectively as "The Watchungs." In addition a shorter usage First, Second, and Third Mountain has been used where no confusion could result. The latter usage has been adopted in this report. The name "Watchungs" is derived from the Indian name "Wach Unks" which means "the high hills" (Torrey and others, 1951, p, 243). This name was given by the Lenni Lenape Indians of the Algonkian group, known to the colonists as the Delawares, who inhabited the region (Federal Writers Project, 1939, p. 30–31).

Another matter of nomenclature concerns the name "trap" and the usage "trap rock" which are very old terms that go back to the early history of mining and quarrying. Trap was apparently first used in Sweden as a rock name by Rinman in 1754, (Tröger, 1935, p. 335). Rinman (1754) was the head foreman of a Swedish iron foundry, and he published a collection of rock terms amongst which was trap. The name since then has been applied to various rocks, but most commonly its usage has been associated with basalt (Johannsen, 1937, p. 245). Schottler (1908, p. 344) applied the term "trap" to basalts occurring in the vicinity of Giessen, and which make up part of the large central-type eruption now constituting the Vogelsberg Mountains in Hesse, Germany. The immense plateau basalts of India are officially known in the stratigraphic nomenclature of India as the Deccan Traps (Washington, 1922; Wadia, 1953). Trap is chiefly a field term, and is applied most frequently as a designation for the source rock of the mineral commodity crushed basalt, which is used in road construction.

The word "trap," as well as "basalt," is used in this report because of its long established use in New Jersey and elsewhere in the Triassic of eastern North America and because no ambiguity arises from its retention. Davis (1882) and Darton (1890), to mention but a few of the early writers, used the term "trap," and Mason (1960) preserves this usage in a bulletin of the New Jersey Geological Survey.

ACKNOWLEDGMENTS

I am indebted to many colleagues with whom I have discussed various problems. In particular, I wish to thank Richard C. Erd, U.S. Geological Survey, who worked with me in the early stages of the project and contributed much to the field studies, the field assistants (Theodore Woodward, Joseph R. Houston, John P. Marble, David Y. Moore, Charles E. Minard, Frank A. Mooreshead, III, Edward D. Frey, L. Robert Gardner, Matthew L. Werner, III, Frederick P. Zoerner, Joseph R. Mraz, and Paul E. Diehl) who worked during the summer months, and Robert L. Smith, U.S. Geological Survey, with whom I discussed some of the facets of the problem.

Various companies that produce crushed stone and operate quarries in this area were very cordial in their cooperation. The engineers, superintendents, managers, and quarrymen in these companies were exceedingly helpful. The engineers and staff of the New Jersey Highway Department, and the engineers and staff of the various construction companies, who were building U.S. Highways 287, 78, and 80, and other highways helped in many ways. The farmers and property owners in the area have been very cordial in extending privileges to me.

I have benefited from the comments and reviews of Thomas L. Wright and Eugene C. Robertson, Edwin Roedder commented on the section "Vesiculation in basaltic magma." The former State Geologist of New Jersey Meredith E. Johnson and the present State Geologist Kemble Widmer have furnished me with well data and aided me in other ways, and I thank them for their help.

LOCATION AND PHYSIOGRAPHY OF THE WATCHUNGS

The Watchung Mountains are in northern New Jersey in Bergen, Essex, Union, Passaic, Morris, and Somerset Counties. They form a crescent-shaped belt about 12 miles wide and approximately 40 miles long trending in a northeasterly direction from Somerville and Bound Brook in Somerset County and reaching almost to the New Jersey–New York border in Bergen County. The Watchung Basalt flows of New Jersey are exposed in three mountain ridges separated from one another by valleys eroded out of the less resistant red shales and brownish sandstones. The basalt flows are part of the physiographic province known as the Triassic Lowland, an area bounded on the west by the Reading prong, on the north by the Manhattan prong, on the east by the Coastal Plain and the Trenton prong, and on the south by the Carlisle prong (Davis, 1912). The four "prongs" are made up of very old (probably Precambrian) metamorphic rocks, while the Coastal Plain is underlain by sediments of Cretaceous, Tertiary, and Quaternary age. The Reading and Manhattan prongs are sometimes referred to collectively as "The Highlands" in Pennsylvania, New Jersey, and New York and that part of the Coastal Plain adjacent to the Triassic Lowlands is sometimes called the Cretaceous Overlap. The physiography of the Watchung Mountains is exceptionally well presented both textually and graphically in publications by Lobeck and Raisz (1930), Lobeck (1952), and Kümmel (1940). Although the lava flows do not crop out everywhere in this belt their areal extent can be estimated to be about 500 square miles (1,295 km^2). The northern and middle part of the Watchung Basalt flows parallel the Palisade Diabase, a stratigraphically correlative intrusive unit, which crops out along the Hudson River. New York City lies abreast the northern part of the Watchung Mountains and is approximately 12 miles (19 km) distant from First Watchung Mountain. The New Germantown trap sheet, a smaller crescent-shaped flow with an inner trap knoll has been correlated by Lewis (1907, p. 115–117) with the Watchung Mountains. It lies in Hunterdon County, near the hamlet of Oldwick, N.J.

A sketch map (fig. 1*A*) shows the outline and relation of the three mountains which constitute the Watchungs and the New Germantown trap sheet. It does not include minor fault dislocated trap masses such as the structure at Sand Brook, near Flemington, N.J. The quadrangle sheets covering this area are shown in figure 1*B*. Place names not shown in figures 1*A* and *B* appear in figure 2.

First Watchung Mountain rises abruptly, as a rocky escarpment above the Raritan Valley and Coastal Plain, which in this area is generally less than 200 feet (61 m) above sea level. From Paterson to below South Orange the escarpment ranges from 690 to 550 feet (210 to 168 m) above sea level and rises to the north to reach a maximum elevation of 885 feet (270 m) above sea level, at High Mountain, a peak just north of Paterson. The height of the ridge drops from 540 to 450 feet (165 to 137 m) as it is followed farther south (Kümmel, 1940). The continuity of the escarpment is broken by occasional notches. The northwest slope of First Mountain is gentle and represents the regional dip of the basalts except where modified by later processes. The valley between First and Second Mountains has an average elevation of 300 to 200 feet (91–61 m). The escarpment of the Second Mountain parallels that of First Mountain, and it is likewise generally continuous except for occasional notches. Its elevation in the northern part ranges from 500 to 665 feet (153 to 203 m) and in the southern part it ranges from 530 to 635 feet (162 to 194 m) above sea level. The valley between Second and Third Mountain is again at an elevation of 300 to 200 feet (91–61 m).

The escarpment of Third Mountain is significantly different from those of First and Second Mountains in that it is discontinuous (fig. 1). It consists of the ridges known as Long Hill; Riker's Hill; the double-curved, hook-shaped Hook Mountain and Packanack Mountain; together with the upturned and folded edge of the sheet to the northwest of Long Hill—called the New Vernon trap sheet. The valley between Third Mountain and the New Jersey Highlands is approximately 300 feet (91 m) above sea level.

The apparently level crestlines of the Watchungs, parts of the Palisade Ridge, and the high hills of Staten Island led Darton and others (1908, p. 1) to the view that these elements define the eastward extension of the Schooley Plain.

GEOLOGIC SETTING

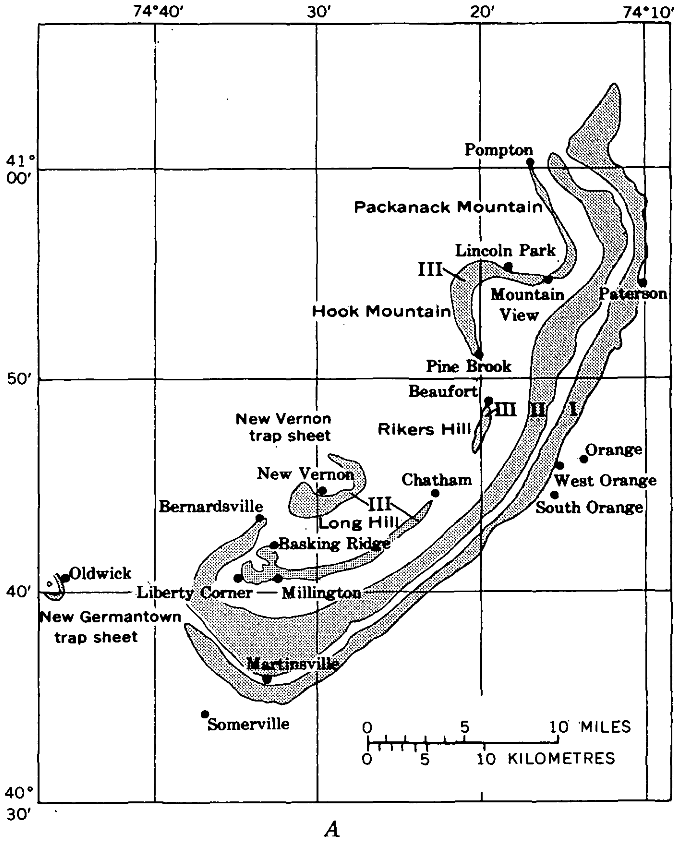
The geologic relations of the Watchung Basalt flows have been described by Lewis (1908), and the geology of the Triassic Lowlands, as a unit, has been summarized by Kümmel (1940) and by Widmer (1964). Wheeler (1939) and Sanders (1963) have introduced new theories to account for the tectonic history of the region. The summary of the geology which follows is based largely on these and other sources.

At the close of the Paleozoic Era the very large compressive forces that produced the folded Appalachian Mountains had been relaxed. At some later time, as a consequence of this change in the mechanical state of the crust, large blocks of the crust dropped down to form troughs or grabens in a region extending from Nova Scotia to North Carolina. This downfaulting was accomplished by displacement of the blocks along major faults or chains of faults which made up the walls of the trough. According to some geologists (Klein, 1969), the grabens were probably not continuous from Nova Scotia to North Carolina but consisted of a series of discontinuous basins. This faulting must have occurred over a period of about 10 million years. The Triassic rocks in New Jersey all belong to the upper third of the Triassic Period, so that we can conclude that this region in New Jersey during the lower and middle thirds of Triassic time was at a sufficient elevation to be yielding sediments rather than receiving them. The basin in New Jersey is referred to as part of the Newark basin.

The geological history of the Newark basin has been interpreted in several ways. The theories of Barrell (1915), Sanders (1963), and Klein (1969) are summarized below for the convenience of future reference.

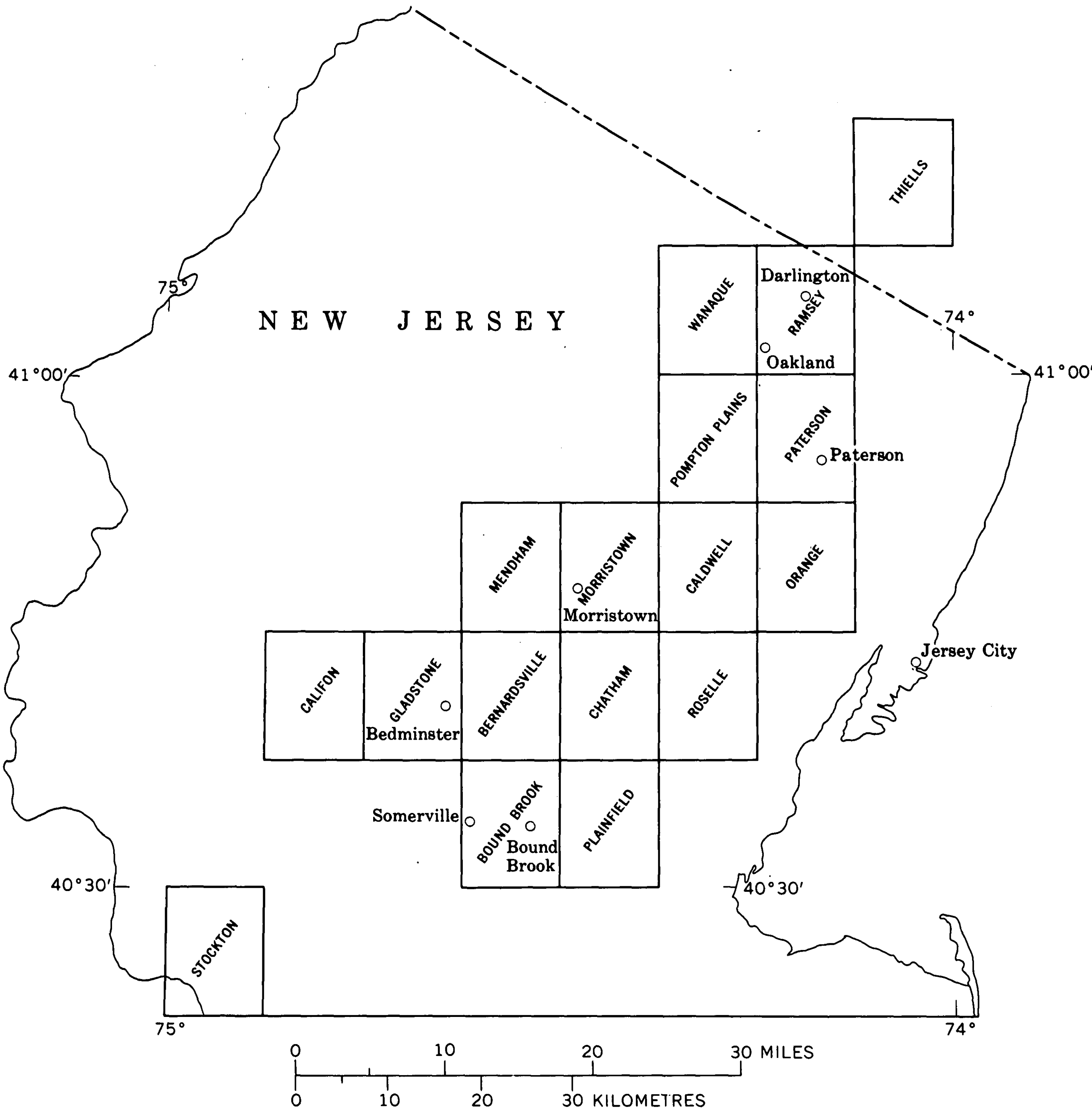
Barrell's (1915) concept of the formation of the Newark basin is summarized as follows:

1. The beginning of the basin was a downsinking of a long trough with a tendency to downwarp on one side and upwarp on the other. This movement was accompanied by the uplift of neighboring areas.
2. The rocks of the uplifted areas were eroded to produce the sediments, the mud and gravel, which make up the rocks formed in the trough. In New Jersey, Kümmel found that "the basal beds disappear toward the north and that sediment came from both east and west." (Barrell, 1915, p. 28–29).
3. The continued accumulation of sediments resulted in a loading over the area of deposition that produced further sinking of the trough. The greatest sinking took place along the margins where the deposition of the sediments was the greatest. The occurrence of conglomerate beds throughout the section indicated regrowth of the mountains supplying the sediments for the basin. This necessitated a boundary consisting of a fault wall along which renewed movement took place. In New Jersey "These areas were therefore basins facing each other and bounded on their outer sides by faults. * * * the western limit of the New Jersey area is still on or near this ancient boundary. * * *" (Barrell, 1915, p. 29). The Triassic section in New Jersey contains at least 15,000 feet of sediments and igneous rocks, so that approximately ". . . three miles of sediment was deposited in the basin in the tract of greatest subsidence. The basin floors in those places subsided at least three miles



A

FIGURE 1.—Outline maps of area. *A*, Sketch map showing the outline of basalt outcrops of the three Watchung Mountains and the New Germantown trap sheet (modified from Lewis, 1908, pl. 10). I, II, III refer to First, Second, and Third Watchung Mountains. *B*, (see facing page) Index to the U.S. Geol. Survey topographic quadrangle maps, scale 1:24,000, covering the exposure area of the Watchung Basalt flows.



B

during the progress of the period, yet the sediment was sufficiently abundant to keep the basins continuously full of sediments. Slow movements intermittent in nature went forward therefore for a vast period of time, during which erosion planed even deeper into the folded and metamorphosed rocks of the rising tracts of the Appalachian system, the rock waste being swept into the intermontane basins." (Barrell, (1915, p. 31).

4. In the Early Jurassic extensive crustal movement took place in the Newark basin. The crust broke into great blocks by faulting and these blocks were rotated so that they now slope 15° to 20° W. In Connecticut the Triassic rocks slope to the east. The opposite slopes of the two basins suggest that a wide mountain arch was raised between them. The raising of the arch was followed by fracture and settling along the sides. "Where the principal movement of the blocks was tilting, rather than elevation or subsidence relative to adjacent blocks, the upturned edge of each block would form a ridge with a steep face along the fault plane and a gentle slope following the dip of the strata. * * * The least uplift was on the western side of the New Jersey Triassic." (Barrell, 1915, p. 27).

Commenting on the sections in Pennsylvania, Johnson and McLaughlin (1957, p. 35) state "The available facts are not consistent with the hypothesis that Newark sedimentation was initiated by downfaulting along the present north border or by the formation of grabens. The first sediments came from the south, where no evidence of downfaulting has been found. The locations of the Newark basins, and especially the New York–Virginia one, suggest instead they were produced by deep erosion of the least resistant Paleozoic rocks, the limestones and shales of Cambrian and Ordovician age, with some downfaulting along the northwest border. The more resistant crystalline rocks of the present Piedmont formed a lofty highland along the southern border of the Newark trough, while an escarpment of resistant quartzite formed much of its northern limit."

Sanders (1960, 1962, 1963) reexamined the Late Triassic tectonic history of the northeastern United States. His field observations covered the Triassic basins from the Connecticut Valley to the Schuylkill River in Pennsylvania, and his study showed that the tectonic history of the basin is more complex than had been realized by earlier workers.

Sanders (1963, p. 501) on the basis of the data available to him concluded that the isolated basins "represent remnants of the filling of an elongate rift valley that was 50 to 70 miles wide," and that "the stratigraphic thickness of the Triassic rocks is held to be approximately 30,000 feet." He recognizes four discrete episodes:

1. Initial graben subsidence, sedimentation, and basaltic igneous activity (intrusive and extrusive).—The basin was formed by downfaulting and not downwarping. Differential relief was maintained by recurrent movement along the marginal faults. "These marginal faults must have originally dipped under the graben block at approximately 70° to 75°; now they dip 55° to 60° in many localities, but they have been rotated 15° to 20° during the longitudinal crustal arching of episode 2." (Sanders, 1963, p. 506). "Three periods of plateau basalt outpourings were associated with the initial episode of graben subsidence. * * * 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 evidence found locally in the Palisades sheet proves that these sheets solidified before tilting of the Triassic strata. * * * 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 indicates (notably in the New Jersey–New York belt) that the initial episode of graben subsidence took place without important longitudinal or transverse warping." (p. 508).
2. Longitudinal crustal warping.—During this episode longitudinal crustal warping in the center of the initial graben was responsible for the tilting of the New York–New Jersey–Pennsylvania and the Connecticut Valley belts so that they now dip 15° to 20° away from each other. The total uplift may have been as much as 35,000 feet.
3. 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 previously called) that are so prominent in the topography and geology of the Hunterdon Plateau, New Jersey. * * * 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 the wider parts of it." (Sanders, 1963, p. 510).
4. Fragmentation of transverse warped structures and emplacement of late intrusives (basaltic) and mineral deposits.—The final episode of tectonic activity displaced the transverse folds which had been formed on the second generation graben block. "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. * * * New Jersey faults were discussed by Kümmel (1898, 1899) and Wheeler (1939)." (Sanders, 1963, p. 512).

Sanders (1963, p. 514) concluded that the Flemington fault "marks an important tectonic boundary in the Triassic outcrop belt. * * * The Flemington fault shows an unknown amount of right-lateral strike slip displacement as well as more than 10,000 feet of dip slip displacement."

Klein (1969) has summarized the available data of stratigraphic and sedimentological studies on the Triassic basins, and he concludes that the several troughs which make up this basin were all separate basins at the time they were infilled.

The original areal extent and the distribution of the present outcrop areas of the Newark Group has given rise to two hypotheses (Russell, 1892, p. 101–107). The local-basin hypothesis suggests that the presently existing detached basins represent essentially the original extent of the areas of deposition during Triassic time. The broad-terrane hypothesis assumes that the presently existing detached basins are only remnants of the former areas of deposition of the Newark Group and that the missing elements have been removed by erosion. It further claims that most, if not all, of the detached areas were united into a broad terrane during Triassic time.

The two principal objections to the broad-terrane hypothesis, with particular reference to the Connecticut and Newark basins, are based on the observations that no trace of the eroded Triassic rocks between the detached basins exist and no area where eroded sediments could have been deposited was recognized. The first objection was negated by the observations of Triassic rocks in the downfaulted area of the Pomperaug valley in Connecticut by Hobbs (1901), and by the recording of Triassic sediments in a well on Long Island by Wheeler (1938). The second, by the requirements of sedimentary material needed to form the coastal plain of New Jersey (Owens, 1970).

The implication of the broad-terrane hypothesis suggests that the areas and volumes of Triassic basaltic volcanism were far larger than those observed today, a point emphasized by Sanders (1963).

There is general agreement amongst most investigators of the structure of the Triassic rocks in New Jersey that the Newark basin was formed as a graben. Johnson and McLaughlin (1957) proposed that the structure was formed by deep erosion out of Paleozoic limestones and shales. Their view has not been accepted by later investigators, Sanders (1960, 1962, 1963), Klein (1969), Van Houten (1969), and more recently, Rodgers (1970). The source of the sediments is attributed principally to the granitic and metamorphic rocks represented in the Trenton, Reading, and Manhattan prongs and also to the sedimentary rock of the older Paleozoic formations. The direction of transport of the sediments is still an unsettled question, and the various proposals on the subject have recently been discussed by Van Houten (1969).

SUMMARY OF PREVIOUS VIEWS ON THE STRUCTURAL CHARACTERISTICS

All of the geologists who have investigated the volcanic rocks of the Newark basin in New Jersey since Darton's study of 1889 and 1890 agree that they are flows from fissure eruptions. Darton (1889) described the flows as follows:

(1) The extrusive sheets are perfectly conformable to the underlying sediments.
(2) Their upper surfaces are slaglike and deeply vesiculated.
(3) The overlying sediments are totally unaffected.
(4) Trap breccias are observed at some of the basal contacts.
(5) The base of the flows are vesiculated.
(6) There is evidence of successive flows.
(7) There is a general absence of tuffs.
(8) No central cone is present.

Darton reasoned that the general absence of fragmental deposits, excepting a few local beds; the absence of craters; the large areal extent of the Watchungs; and their similarity to the great fissure eruptions of the Western United States described by Von Richthofen (1868) and Geikie (1882) was sufficient evidence to attribute these flows to fissure eruptions.

Darton's (1890) view that each of the three Watchung Mountains was actually made up of successive flow units was investigated by Lewis (1907, p. 110–114, and 1908, p. 148–151). Lewis (1908, p. 150, 152) believed that the composite character of the trap sheets "seems to correspond to successive flows of lava or to successive pulsations of an irregular eruption." The presence of a ropy and vesicular layer at a quarry in First Watchung Mountain he suggested indicated two successive flows (here called two flow units). His study of Second Watchung Mountain, particularly in the vicinity of Bound Brook, led him to conclude that it consisted of two sheets (flow units). In addition he supposed, without field evidence, that these flow units were separated by an intertrappean layer of sedimentary rocks, a view denied by Kümmel (1898, p. 125), whose views on faulting were likewise unsubstantiated. Lewis (1908) was less certain of the composite character of Third Watchung Mountain, and his criteria were admittedly inconclusive.

Bucher (in Bucher and Kerr, 1948) recognized the fact that First Watchung Mountain, in the few exposures that he examined, actually consisted of two flow units—a lower flow unit and an upper flow unit separated by "a thin layer of reddish argillaceous siltstone" and he gave a columnar section portraying these relations for the outcrops in the vicinity of Paterson, N.J. Van Houten (1969) followed Bucher's classification.

It is important to note that this preliminary knowledge of the composite structure of the Watchung Mountains is based entirely on the structure as seen at a few widely separated outcrops. Lewis made his observations chiefly near the nose of the syncline in the vicinity of Bound Brook, while Bucher's studies were chiefly in quarries near Paterson.

The pillow lavas in First and Second Watchung Mountains have been described by Lewis (1915), and their outcrop has been delineated in First Mountain by Fenner (1908).

THE CONTINENTAL GLACIERS OVER THE WATCHUNGS

Northern New Jersey was subjected to several glacial invasions. Salisbury (1892) reported scattered deposits of pre-Wisconsin drift in New Jersey as far south as lat 40°35′N. Widmer (1964) has reviewed the recent studies of this glaciation and points out that the glacial deposits representing this stage lie to the west of Somerville and further that the field evidence available is so meager as to permit few additional conclusions other than its limited occurrence. No evidence of the effects of this glaciation on the Triassic sediments or lava flows has been reported. The Wisconsin Glaciation, in contrast, is well documented. The terminal moraine cuts across the Watchungs in a curved line from Summit to Morristown.

The Wisconsin glacier covered the northern part of the Watchungs as is shown in figure 2. Salisbury and others (1902, p. 67) discuss the thickness of the ice sheet and point out that it was thickest over the Triassic Lowlands. These authors estimate that the average thickness of the glacier in the area considered in this study was about one-fifth of a mile

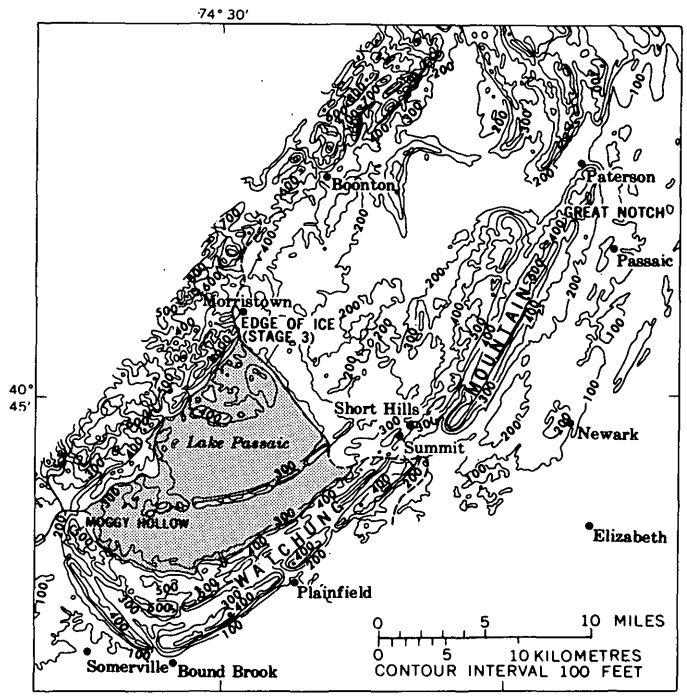


FIGURE 2.—Southern limit of Wisconsin ice sheet over the Watchungs (from Salisbury and others, 1902, pl. 40).

(1,056 ft, 322 m). The map shows clearly that the northern part of Third Watchung Mountain, Hook Mountain and Packanack Mountain, must have borne a considerable weight of superincumbent ice.

When the glacier invaded the area, it caused a depression of the crust below it which was manifested in bending of the rock units and settling. Since the thickness of the glacier increased slowly, there was a gradually increasing pressure applied to the crust. Antevs (1928, p. 107) estimates that the ice sheet maintained itself for about 2,000 years. Recent studies of the retreat of the last ice sheet in New England by Schafer (1968), who used radiocarbon dating, suggest that this period may be twice as long as Antevs estimates. Accordingly, the vertical component of the stress that was impressed by the weight of the ice above the rock was maintained at its maximum value for a significant length of time. The value of this stress varied from an almost negligible value at the end of the sheet to the maximum values farther north. The outcrop edge of Hook Mountain and Packanack Mountain must have been covered by at least an average thickness of the ice sheet. If we use the average thickness of 1,056 feet (322 m) of ice and the weight of a cubic foot of ice as 57.2 pounds, (25.9 kg) we can calculate that the pressure of a column of ice 1,056 feet (322 m) high and 1 square foot would be close to 60,400 pounds per square foot (29.5 kg/cm^2). These values represent the vertical normal component of the stress acting upon, and in the vicinity of the outcropping edge of the lava flow of Third Mountain. When the glacier disappeared, either by retreating or downwasting, a reverse mechanical reaction took place, namely uplift, and the crust strove to recover from its depression. Evidence for this recovery is observed in the postglacial upwarping of the shoreline of glacial Lake Passaic. Reeds (1933) has calculated the changes in elevation for the length of the lake; at Hook Mountain it amounted to about 35 feet (11 m), and at the end of Packanack Mountain to about 67 feet (20 m). The evidence suggests that the largest change in altitude coincides with the greatest thickness of ice. Additional evidence of this upward movement can be seen in the glacial clays in the form of small faults with a throw of a few feet and in the recorded occurrence of occasional very minor earthquakes attributed to the adjustment of the land surface. Sheeting (sheetjointing) occurred in the basalt flows where the ice was thickest (Faust, unpub. data).

STRATIGRAPHY AND GEOLOGIC AGE

LOCAL STRATIGRAPHIC RELATIONS

The stratigraphy of the Newark Group was established by Kümmel (1898). He divided the Newark Group into three formations made up of the Stockton Formation, which lies unconformably upon the older crystalline rocks; the Lockatong Formation, which lies over the Stockton; and the Brunswick Formation, which overlies the Lockatong and is thus the youngest member of the Newark Group. The three Watchung extrusive sheets (First, Second, and Third) were extruded near the end of Brunswick sedimentation. Each of these volcanic episodes forming the three sheets consisted of two events, and each sheet is composed of two separate flows, here designated flow units. The time lag between these multiple events was short. The Palisade Diabase was intruded chiefly into the upper part of the Stockton Formation and the lower part of the Lockatong, but some of the Palisade Diabase intrudes the Brunswick Formation. Lewis (1907, p. 120) pointed out the presence of the recurved Palisade Diabase sheet in the upper part of the Brunswick at Haverstraw, N.Y., where "it reaches *almost* to the top of the series." This observation thus dates the Palisade intrusion as near the end of Triassic sedimentation and is evidence for the conclusion that the Watchung flows and the Palisade intrusion were contemporaneous igneous events. That the Palisade Diabase intrusion is also a multiple intrusive event is shown by the studies of Walker (1969), who demonstrated its composite character on the basis of petrographic and chemical evidence. The first intrusion to form the Palisade sill had cooled sufficiently to crystallize and to undergo some differentiation before the second intrusion was emplaced within it. The multiple events forming the sill thus show a correspondence with the events forming the sheets and their flow units.

The stratigraphic section is given in figure 3 for three representative thicknesses.

Kümmel (1898, p. 34) based his division of the Newark Group into three formations "upon lithologic differences, which imply diverse conditions of sedimentation, and which permit the establishment of recognizable horizons." He observed that there were no sharply marked division planes and that these formations tended to grade into one another through transitional zones, but nevertheless he was able to differentiate between them. The paleontologic evidence is meager but almost all agree that the Newark Group is Upper Triassic (Keuper). (See Johnson and McLaughlin (1957, p. 33), Van Houten (1969).)†

The lithologic assembly of the Stockton Formation according to Kümmel (1898, p. 30) consists of "(a) coarse, more or less disintegrated arkose conglomerates; (b) yellow micaceous, feldspathic sandstones; (c) brown-red sandstones or freestones, and (d) soft red argillaceous shales. These are interbedded and many times repeated * * *." The Lockatong Formation consists of hard dark-colored shales and dark-gray and green flagstones. It also includes carbonaceous shales, black and purplish argillites, dark-red shales, almost flagstones, and thin layers of limy shales. The Brunswick Formation consists of great thicknesses of soft red shales with some sandstone layers. Massive fanglomerate beds occur along the northwest border of the Newark Group. The lithology of these members of the Newark Group have been studied by many workers, and a summary of their work is given by Van Houten (1969). Van Houten (1969) has contributed important studies of the Lockatong Formation and shown that the Lockatong is a large lacustrine lens-shaped body. He has characterized its mineralogy and interpreted its chemistry. Picard and High (1963) found the Brunswick Formation to be made up of alternations of a massive resistant layer rock (chiefly sandstone) and of less resistant beds chiefly mudstones and poorly sorted siltstones in the proportion of 43 percent of the massive resistant layers to 57 percent of

† After this report was completed, studies by Cornet, Traverse, and McDonald (1973) of fossil spores, pollen, and fishes from Connecticut led them to suggest an Early Jurassic age for the younger sediments of the Newark Group. From the youngest sediments of the Brunswick Formation in New Jersey, they have recovered similar "Rhaeto-Liassic palynіflorules."

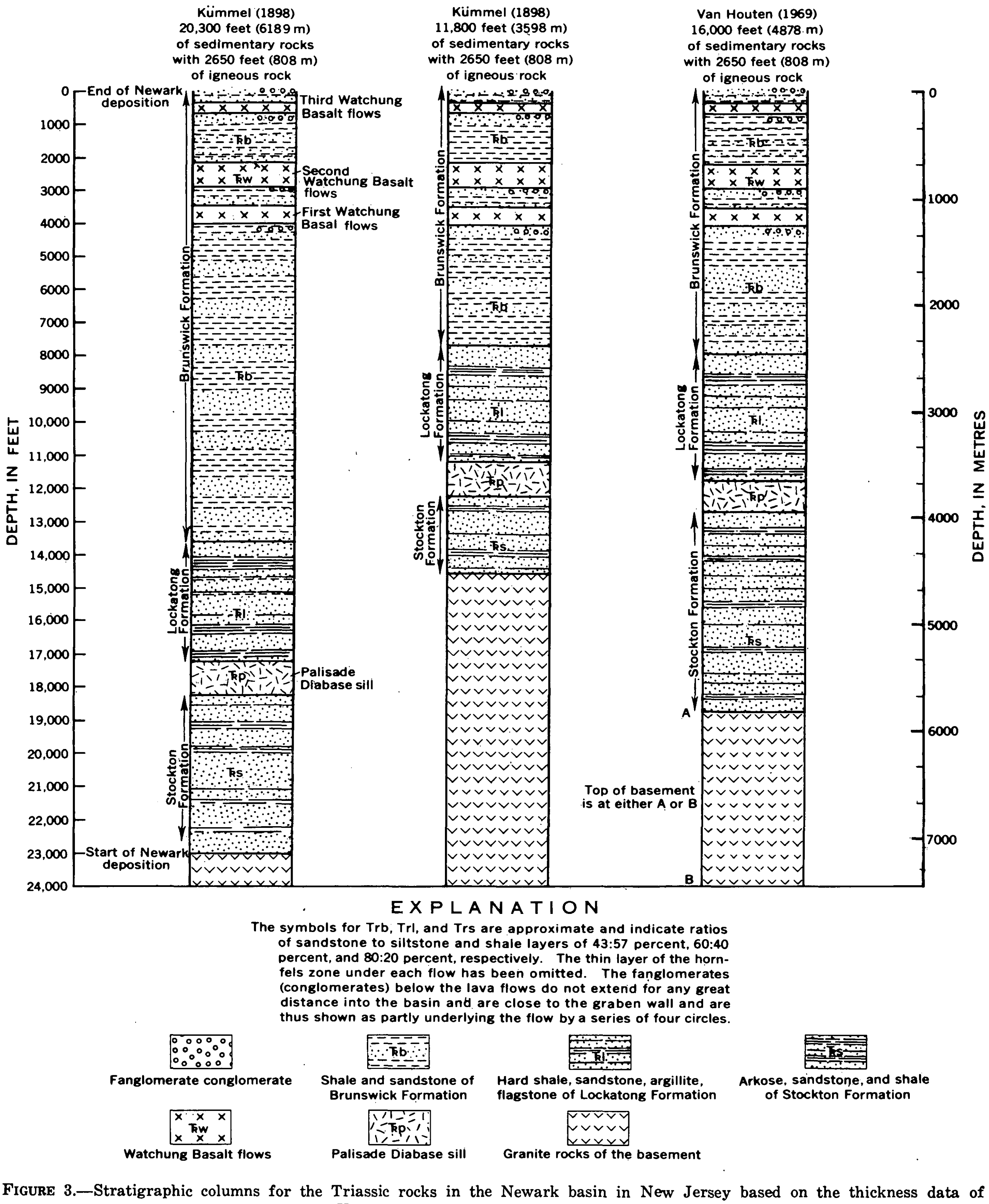


FIGURE 3.—Stratigraphic columns for the Triassic rocks in the Newark basin in New Jersey based on the thickness data of Kümmel (1898) and Van Houten (1969).

the less resistant beds. Van Houten (1969) has evaluated all the lithologic data, correlated it, and drawn a schematic block diagram to portray his views of the stratigraphy of the Newark basin.

The stratigraphic section of the upper part of the Brunswick Formation of the Triassic System which contains the three Watchung Basalt flows is of particular importance to this discussion and is given in table 1; it is also shown in a geologic cross section (fig. 4). On the basis of the mapping that has been completed so far in this study, each of the three Watchung Basalt flows is shown to be made

TABLE 1.—*Stratigraphic sections of the upper part of the Brunswick Formation of the Triassic System in the Newark basin of New Jersey*

	Kümmel (1897, 1898)	Picard and High (1963)	Probable thickness in feet (m)	Noteworthy occurrences of fanglomerates
Brunswick Formation	Alternations of shale, sandstones, and fanglomerates (conglomerate) chiefly along the northwestern wall.	Alternations of "less resistant layer rock" of mudstones and poorly sorted siltstones and of more resistant layer rock of sandstones.	300[1] (91)	Fanglomerates (Kümmel, 1897, 1898; this report, p. A13.)
	Third Watchung Basalt	Upper flow unit Lower flow unit	300 (91)	
Brunswick Formation	Alternations of shale, sandstones, and fanglomerates (conglomerates).	Alternations of "less resistant layer rock" of mudstones and poorly sorted siltstones and of more resistant layer rock of sandstones.	1,500 (457)	Conglomerate at Pompton Lakes (Kümmel, 1898, p. 50; this report, p. A13.)
	Second Watchung Basalt	Upper flow unit 6 ft (2 m) of sedimentary rock in north area[3] Lower flow unit	750 (229)	
Brunswick Formation	Alternation of shale, sandstones, and fanglomerates (conglomerates).	Alternations of "less resistant layer rock" of mudstones and poorly sorted siltstones and of more resistant layer rock of sandstones.	600 (183)	Fanglomerate at Oakland (this report, p. A13.)
	First Watchung Basalt	Upper flow unit A thin layer of reddish argillaceous siltstone[3] Lower flow unit	600 (183)	
Brunswick Formation	Alternations of shale, sandstones, and fanglomerate (conglomerates).	Alternations of "less resistant layer rock" of mudstones and poorly sorted siltstones and of more resistant layer rock of sandstones.		Conglomerate Fanglomerate in a wall near Paterson (Darton, 1890, p. 17.)

[1] A provisional estimate of 300 feet is based on field studies and well-log data (Faust, unpub. data).
[2] This report, p. A13.
[3] Bucher in Bucher and Kerr (1948, see p. 110).

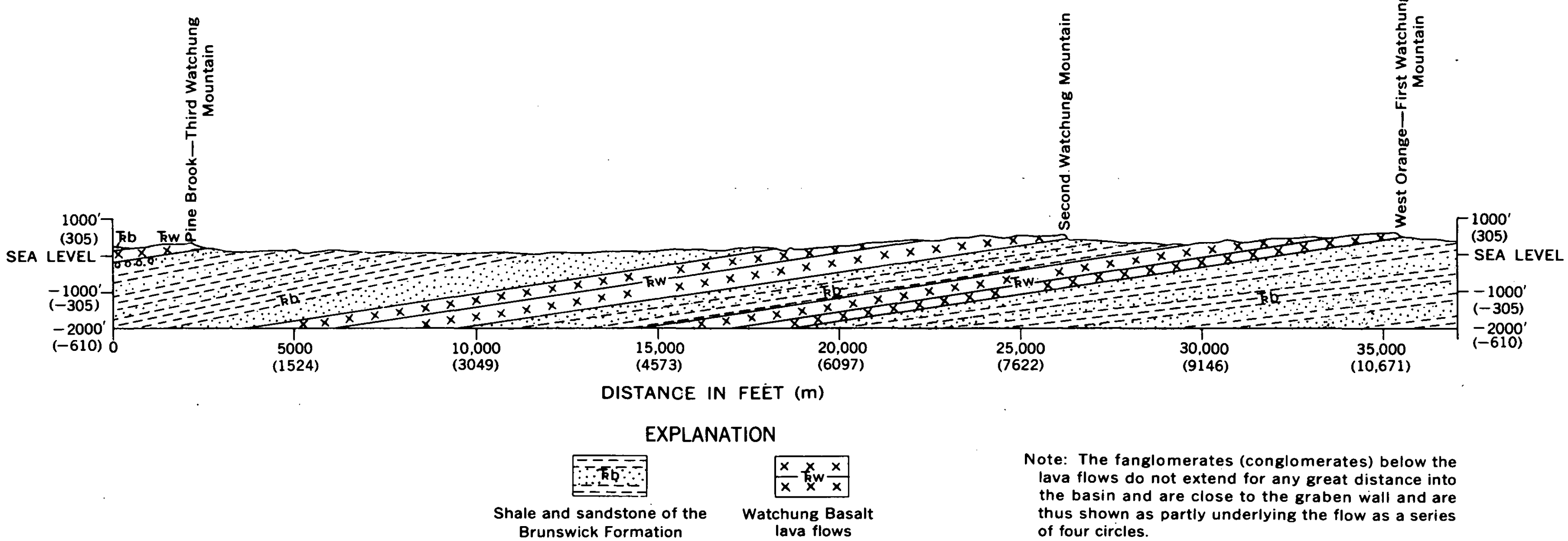


FIGURE 4.—Generalized geologic cross section from west of Pine Brook on Third Watchung Mountain to an exposure just north of West Orange on First Watchung Mountain (compare with fig. 1). The topographic data and the thicknesses of the flows are taken from Darton and others (1908). Most of area is covered with glacial materials, but they generally form so thin a layer that they are not shown.

up of two flow units. This multiple character of the three Watchung Basalt flows proves that the three volcanic episodes producing them were multiple eruptive events. The presence of intertrappean layers of sedimentary materials in the Watchung Mountains had been suggested by Lewis (1907). In this field study no intertrappean layers were found in Third Mountain. Lewis (1907) had suggested that an intertrappean layer may occur in Second Mountain in the vicinity of Bound Brook. I did not find that the flows were separated by an intervening layer, except in the northern part of Second Mountain near the Greenbrook, in North Caldwell, where a section of 6 feet (±) of sediments was measured. In First Mountain, in the Upper New Street quarry, Fenner (1908) noted intertrappean materials between the upper and lower flow units. This was described as a thin siltstone layer by Bucher (in Bucher and Kerr, 1948) and he gave a detailed section.

Although fanglomerate and conglomerate beds were generally not tied down to particular stratigraphic sections by previous workers their position with respect to the three Watchung Basalt flows in a few areas is noteworthy, and these are shown in table 1, at the top of the column; just underneath the Third Watchung Basalt; and just underneath First Watchung Basalt. During the mapping of the northernmost part of Second Mountain, in July 1973, a thick fanglomerate bed was found at Oakland, N.J. The contact between this bed and the overlying hornfels zone was covered, but it is probably within 50 feet or less. Darton's (1890) observations on the fanglomerates below the flows (he called them conglomerates) are the most complete. He noted (p. 17) "that these conglomerate beds were exposed south of Paterson in front of Great Notch, and in considerable force several miles north along Goffle creek, west of van Winkle's station***" and further "The conglomerates are separated from the base of the First Watchung Mountain by an inconsiderable thickness of sandstones and shales, and are succeeded eastward by fine grained materials which dip gently westward towards the coarser beds. At Paterson, a short distance *east*[2] of the conglomeratic outcrop in the gorge of the Passaic, a well was bored 2,100 feet through fine grained sandstones and shales***."

The significance of the fanglomerates as marking "the intermittent re-growth of mountains whose perennial waste kept supplying material for the deposits of the basin" was mentioned by Barrell (1915, p. 29). He further noted that "It is necessary to postulate a boundary consisting of a fault wall in order that renewed movements upon it may maintain such a long continued supply of coarse, yet local waste."

In the present study we are interested in the relations of the fanglomerates to the lava flows. From Darton's (1890) observations that an inconsiderable layer of sandstone and shale separates the conglomerate from the base of the flow, we may conclude that the volcanic episode forming the lavas of First Watchung Mountain took place shortly after the faulting along the boundary wall occurred. Similarly a fanglomerate bed occurs about 50 ft (15 m) (±) below the lower flow unit of Second Watchung Mountain. Fanglomerate beds occur just under the base of the flow forming Third Watchung Mountain. All these stratigraphic observations attest to the relation that faulting along the boundary wall was followed by the formation of a fanglomerate and that shortly thereafter the lava poured out. These relations of the fanglomerates to the flows show clearly that the periods of faulting along the graben walls were unrelated to the volcanism (Faust, unpub. data).

Finally, there exists a dilemma over the thickness of the Newark Group. Cook (1868, p. 174) originally calculated the thickness to be 27,000 feet (8,230 m); but then, because he suspected that hidden faults might be present to increase the true thickness, he arbitrarily cut the thickness down to 15,000 feet (4,570 m). Cook (1882, p. 12) writes: "A very few faults have been found but they are only a few feet in extent.***Taking these data for a basis of calculation it would make a formation not less than 25,000 feet (7,620 m) in thickness." Russell (1878) reexamined the problem and calculated 25,000 feet (7,620 m) with the reservation that significant hidden faults were not present. Kümmel (1898) after intensive field study calculated the thickness of the Stockton Formation (Ꞓs) to be 4,700 feet (1,433 m), of the Lockatong Formation (Ꞓl) to be 3,600 feet (1,097 m), and of the Brunswick Formation (Ꞓb) to be 12,000 feet (3,658 m), giving a total thickness for the Newark Group of 20,300 feet (6,187 m). In 1897, Kümmel examined two faults in the basalt of First Watchung Mountain with throws of 75 (22.9) and 8 feet (2.4 m) respectively, and aware of Cook's (1868) earlier suspicion of hidden faults, *undiscovered in field studies*, he reduced his previous estimate to two revised estimates. The first attributed the Stockton to have a thickness of 2,300 feet (701 m), the Lockatong of 3,500 feet (1,067 m), and the Brunswick of 6,000 feet (1,829

[2] Italics G. T. F.

m), making a total thickness of 11,800 feet (3,597 m). The second estimate made the Stockton 3,100 feet (945 m), the Lockatong 3,600 feet (1,097 m), and the Brunswick 8,000 feet (2,438 m), with a total thickness of 14,700 feet (4,481 m). Johnson and McLaughlin (1957) reported the exposed Triassic section along the Delaware River to have a thickness of 12,000 feet (3,658 m). Sanders (1963) restudied the Triassic of the northeastern United States, and for New Jersey he calculated a thickness of 30,000 feet (9,144 m). Van Houten (1969) arrived at estimates of 16,000 to 20,000 feet (4,877–6,096 m) after a detailed study of the Lockatong Formation and its relation to the Stockton and Brunswick Formations.

The evidence of the recent studies cited above may resolve the dilemma, because it supports the greater thickness calculated by early workers. The oft cited hidden faults have not been found and the lower estimates based on this assumption of their existence are not supported by field evidence in that part of the Newark basin containing the Watchung flows and the Palisade sill. Two thicknesses, of 25,000 and 11,800 feet (7,620 and 3,597 m) respectively, for the Newark Group sediments are used here in the calculations because of the uncertainty as to the true thickness of the group.

TIMING OF FISSURE ERUPTIONS OF THE UPPER TRIASSIC IN NEW JERSEY

The timing of the fissure eruptions in the Newark Group may be estimated on the basis of some recent summaries of the paleontological evidence by Johnson and McLaughlin (1957) and Widmer (1964); their studies indicate that the Newark Group is Late Triassic in age. Widmer (1964, p. 63) argued that because the Triassic Period was 45 million years long and the Newark Group was deposited in less than one-third of that time that the deposition took place in a time span of at least 10 m.y. (See also footnote p. A9.)

Using Widmer's estimate of the time span of deposition, the thickness of the strata above and below the flows as given by Darton and others (1908), a provisional estimate, by Faust, of 300 feet (91 m) of sediments above Third Watchung flow, and assuming a total thickness of the Newark Group of 11,800 feet (3,597 m), then it may be calculated that at least 80 (79.7) percent of the sediments were deposited before the First Watchung flow appeared. If the greater thickness of 25,000 feet (7,620 m) is assigned to the Newark Group, then at least 90 percent of the total thickness of the sediments was deposited before the flows appeared. These calculations suggest that the outpouring of the lava from the fissures started at 2½ or 1 m.y. before the close of the Triassic Period.

It is thus apparent that the deep fissures from which the lavas were erupted were developed very late in the Late Triassic Epoch. Sanders (1963) believes that they were associated with the initial episode of graben subsidence.

Using an average figure of 600 feet of sediments between First Mountain flow and Second Mountain flow and a total thickness of 11,800 and 25,000 feet (3,597 and 7,620 m), a corresponding time interval of about 600,000 or 240,000 years elapsed between these outpourings of the lavas. The thickness of sediments between the Second and Third Watchung flows is approximately 1,500 feet (457 m), and this value yields a corresponding time interval of 1½ million or 600,000 years between the flows. These estimates are summarized in figure 5. The calculated time intervals support the belief that fissuring in the graben was intermittent.

These calculations assume that the overall rate of deposition of the sediments was, on the average, relatively constant. This assumption implies a more or less uniform rate of supply of sediments and some form of tectonism that will periodically downfault the basin with respect to the source area. Krynine (1950, p. 186) pointed out that "The different lithologic types of the Connecticut Triassic are due to variations of one fundamental sedimentary process: rapid erosion and deposition under savanna climate" and that this geologic setting assured an abundant supply of sediments at an almost periodic rate of supply. The almost periodic reappearance of the fanglomerates along the fault walls is suggestive of at least some periodicity to the character of the sedimentation between successive periods of faulting. The principal assumption is open to criticism by some stratigraphers. Rayner (1967, p. 14–15) has discussed the use of rates of sedimentation for the rocks in the British Isles and observes that "Rates of sedimentation are very elusive, however, and they can only be deduced at all reliably either on a very small scale or a very large one."

Sollas (1905), on the other hand, used average rates of deposition as a method to dispute the calculations of Lord Kelvin on the age of the earth, a good example of the use of the assumption on a tremendous time scale. Broadhurst and Loring (1970) studied rates of sedimentation in the Upper Carboniferous rocks of Great Britain, and they emphasize two aspects in the concept of rates of sedimentation, an overall rate and a specific rate. They

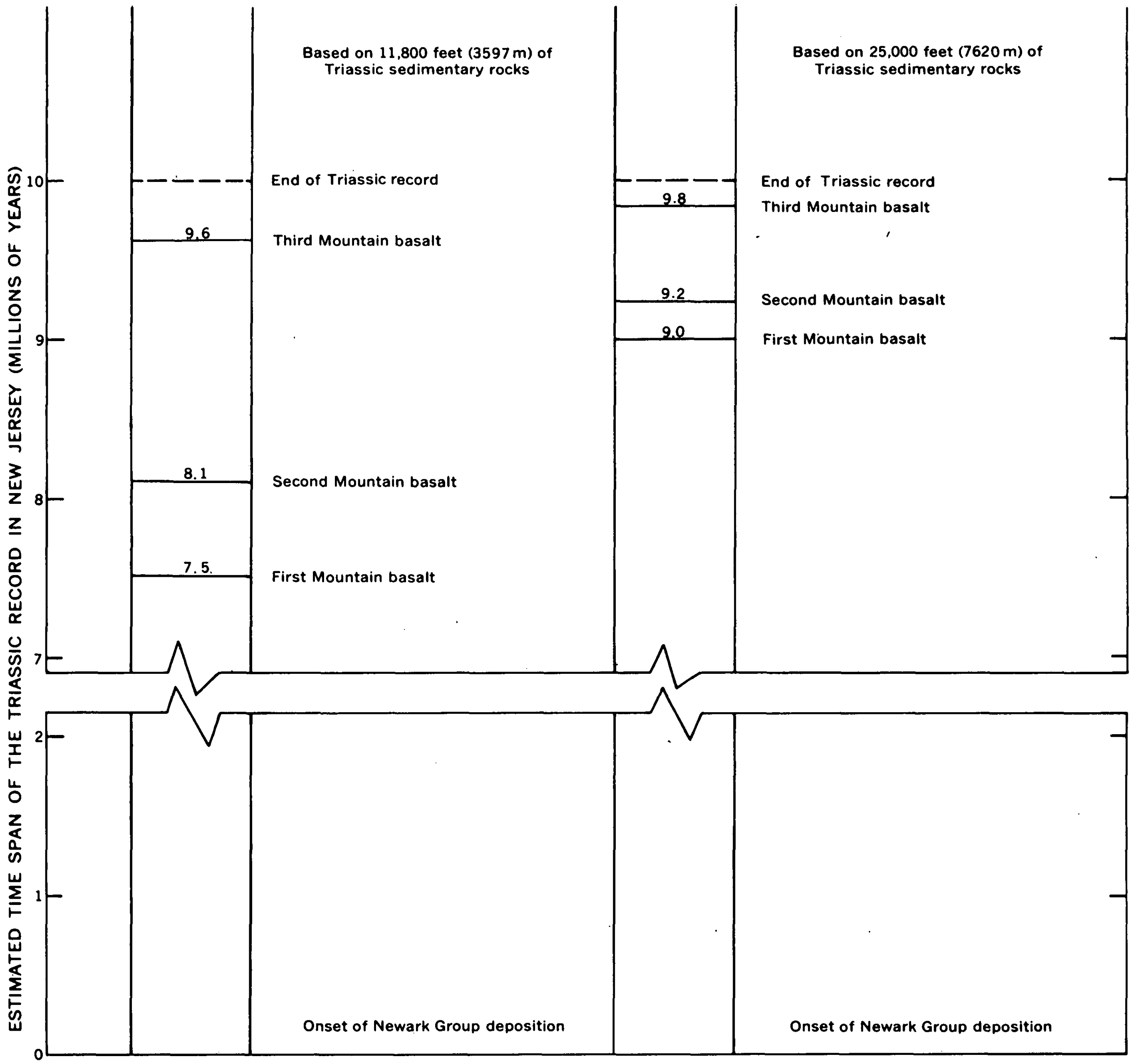


FIGURE 5.—Estimated sequence in time of the extrusion of the Watchung Basalt flows of New Jersey. The calculations are based on the two estimates of the thickness of the Triassic sections of 11,800 and 25,000 feet (3,597 and 7,620 m), respectively.

define (p. 1) these concepts as follows: "The overall rate of sedimentation is the mean rate of sedimentation during a given unit of time in which phases of sedimentation may be interspersed with periods of non-deposition or erosion (sedimentation remaining dominant). The specific rate of sedimentation is the rate of sedimentation at any one moment of time." The specific rate is very difficult or well nigh impossible to determine in most studies. The overall rate of sedimentation is the concept used in these calculations.

Van Hoûten (1969) has recently evaluated, on the basis of stratigraphic and other measurements in sections exposed along the Delaware River in New Jersey and Pennsylvania, the rate of initial deposition of the Stockton, Lockatong, and Brunswick Formations. The thicknesses are 6,000, 3,772, and 6,232 feet (1,830, 1,150, and 1,900 m), respectively, with a total thickness of 16,006 feet (4,879 m). The fastest rate of initial deposition is 600 mm/1,000 years (=1.97 ft/1,000 yr) for the Stockton, the slowest is 215 mm/1,000 years (=0.705 ft/1,000 yr) for the Lockatong, and the rate for the Brunswick Formation is intermediate, 305+mm/1,000 years (1 ft/1,000 yr). He also computed the uniform rate of basin sinking to be about 215 mm/1,000 years (=0.705 ft/1,000 yr) during the entire Newark time, which is the same as the rate of deposition for the Lockatong Formation. From these data he estimates the total Newark episode to have been 22.75 m.y. in duration. Van Houten (1969) also considers several other possible interpretations of the data and arrives at an estimate for the minimum of 14.75 m.y. and maximum of 22.75 m.y. for the duration of the Newark episode and for a minimum of 215 mm/1,000 years and maximum of 325 mm/1,000 years for the average rate of basin sinking and sediment accumulation.

If we use these data of Van Houten (1969) and calculate as before, we arrive at the following values for 16,000 feet (4,877 m) total thickness—85 percent of the sediments were deposited before the First Mountain flow appeared; 3.75 percent of the sediments were deposited after First Mountain flow solidified and before Second Mountain flow appeared, 9.375 percent of sediments were deposited after Second Mountain flow solidified and before Third Mountain flow appeared; 1.875 percent of the sediments were deposited after Third Mountain flow solidified. Using the lower time duration of 14.75 m.y., this yields 12.54 m.y. before the First Watchung flow appeared, 0.55 m.y. between First Watchung flow and Second Watchung flow, 1.38 m.y. between Second Watchung flow and Third Watchung flow, and 0.28 m.y. before the close of Triassic deposition. If the longer time span of 22.75 m.y. is used, the figures become 19.34 m.y., 0.85 m.y., 2.13 m.y. and 0.43 m.y. respectively (fig. 6). The time intervals between the appearance of First and Second Watchung flows and between Second and Third Watchung flows as calculated from Van Houten's (1969) time interval of 14.75 m.y. are closely similar to those just calculated for a section of 11,800 feet (3,597 m) of sediments.

GEOLOGIC AGE OF THE IGNEOUS ACTIVITY

The earliest work on the dating of the igneous activity during the Triassic in eastern North America is that of Urry (1936). Urry used the "helium method" for age determination and dated a specimen of basalt taken from the base of the First Watchung Mountain flow in a quarry on Valley Road, a quarter of a mile north of Notch Road, Great Notch, Clifton, N.J., to be 180±11 million years old. He also dated three diabase specimens taken from the Palisade intrusion at Kings Bluff, Weehawken, N.J., at a distance of 5 to 10 inches (13–25 cm) above the basal contact with the Triassic sediments; 40 inches (1 m) above the basal contact; and 40 feet (12 m) above the basal contact to be 155±8, 165±9, and 165±8, m.y. old. For the diabases of the Connecticut Valley he found that two specimens of the West Rock sill in a quarry at New Haven, Conn., gave ages of 170±12 m.y. and a dike in the same quarry had an age of 175±9 m.y. A drill-core specimen of basalt from 464 feet (141 m) below the surface of the Cape Spencer Flow, Nova Scotia, Canada, yielded an age of 160±8 m.y. The "helium method" is very sensitive to the loss of helium by the host, and as a result it tends to give ages which are younger than they should be.

Erickson and Kulp (1961), using the K-Ar method, dated a specimen of columnar basalt from First Watchung Mountain and found the "apparent age" to be 79 m.y. For the Palisade Diabase sill, they dated biotite separated from the upper fine zone of the sill and found an average age of 190±5 m.y. They attributed the low value for the age of the Watchung Basalt to the poor retentivity of the argon by the basalt. Armstrong and Besancon (1970) have reexamined the problem of dating Triassic mafic igneous rocks, and they analyzed by the K-Ar method the same sample of biotite from the Palisade Diabase studied by Erickson and Kulp (1961). They found an age of 192 m.y. as against the values of 190 and 196 m.y. measured by Erickson and Kulp (1961). The results agree within 1 percent of the Lamont-Doherty date. As a result of their study of the Upper Triassic Newark Group, however, they conclude "The dates for the Palisades diabase, although reproducible and internally consistent, are all suspect."

The most recent evaluation of the age data of the Triassic igneous rocks of New Jersey is that of Lambert (1971). He gives (p. 18) the K-Ar dating of the biotite from the Palisade sill as a "critical point" on the Phanerozoic time-scale with the values of 186±5, and 194±5 m.y. and he observed (p. 29) that "In any case the stratigraphical assignment contains an element of uncertainty, that is, the correlation of the sill with the Watchung basalt."

The paleomagnetic study of de Boer (1968) in which he correlates the three Watchung flows of First, Second, and Third Mountains with the Holy-

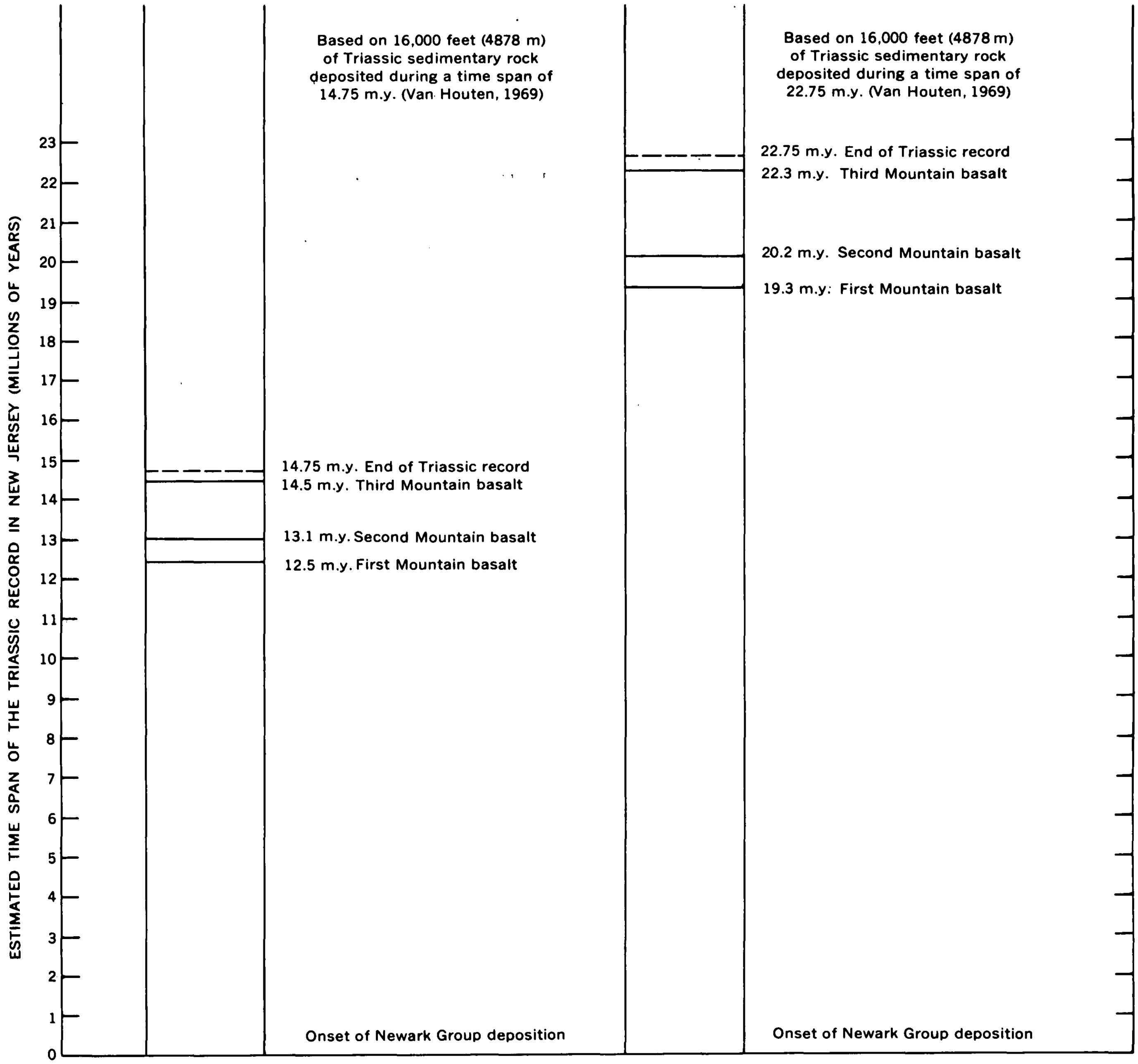


FIGURE 6.—Estimated sequence in time of the extrusion of the Watchung Basalt flows of New Jersey.

oke Basalt flow of Massachusetts is difficult to reconcile with the stratigraphy. This correlation means that the extrusion of the Holyoke Basalt flow, 300 to 600 feet (91–183 m) thick in Connecticut and 575 feet (175 m) thick in Massachusetts could have occupied as much time as the following events in New Jersey:

1. Outpouring of approximately 600 feet (183 m) of lava to form the First Watchung flow.
2. Deposition of approximately 600 feet (183 m) of sediments.
3. Outpouring of approximately 750 feet (229 m) of lava to form the Second Watchung flow.
4. Deposition of approximately 1,500 feet (457 m) of sediments.
5. Outpouring of approximately 300 feet (91 m) of lava to form the Third Watchung flow.

This time interval in New Jersey spanned at least 1 to 3 m.y. Such a correlation would suggest that all during this time the area of the Holyoke sheet was high land and that there were multiple extrusions to form the sheet. Evidence for such a high land in

Connecticut would be extensive erosion within this compound sheet or at its upper surface. Van Houten (1969, p. 317) voices similar objections to de Boer's (1968) interpretation.

REGIONAL STRATIGRAPHIC RELATIONS

A comparison of some time intervals between Triassic events in New Jersey and in Connecticut is given here because of its relevance to the problem of assessing the state of stress in the graben. The rate of relative depression of the graben blocks during Triassic time cannot be accurately calculated. If it is assumed that the relative downward movement was uniformly continuous, the rate of depression for a section of 10,000 feet (3,048 m) of sediments in 10 m.y. would be approximately a foot (0.3 m) of depression in a thousand years. For a section 25,000 feet (7,620 m) thick, it would be a foot (0.3 m) in 400 years. Van Houten (1969) calculated a value of 0.7 foot (0.2 m) per 1,000 years based on the duration of Late Triassic time of 15 m.y. and assuming a uniform rate of basin sinking. The repetition in the geological record of fanglomerates (conglomerates) at the graben walls against the horst, however, suggests that the relative depression was discontinuous—neither uniform nor a succession of a few major movements—but rather spasmodic in response to the unbalance produced by the weathering of the horst and the removal and distribution of the detritus into the basin. Such relations between time and events may be described as "almost periodic."

The best exposed and studied sections of fanglomerates and conglomerates are those in southern Connecticut measured and described by Russell (1922) and Krynine (1950). Russell (1922) found that the fanglomerates had a maximum thickness of 200 to 300 feet (61–91 m) and that they never extended more than about half a mile from the fault plane. He further observed (p. 487) the position of the fanglomerates with respect to the lava flows to be as follows: "The fanglomerate is found *below* the lower basalt flow, immediately *below* the main sheet, *below* the upper basalt flow, and *above* all the flows."[3]

If we interpret the appearance of a fanglomerate along the fault wall to mark the early stage of the weathering cycle in the topographically higher granitic horst blocks, then we can equate the number of fanglomerates observed in sections with the number of episodes of faulting; for the reappearance of fanglomerates means the end of a former period of faulting. From the section given by Russell (1922), we can thus recognize four periods of intermittent faulting bounding the three lava flows. Combining the observations of Russell (1922) with the stratigraphic section of the Newark Group in Connecticut as given by Krynine (1950), in figure 7, we can observe that the lower basalt flow erupted shortly after a fanglomerate appeared; there then followed a deposition of nearly 1,000 feet (305 m) of sediments, and near the end at the top of the section a fanglomerate appeared; this event was followed by the outpouring of the thick main sheet

[3] Italics by G. T. F.

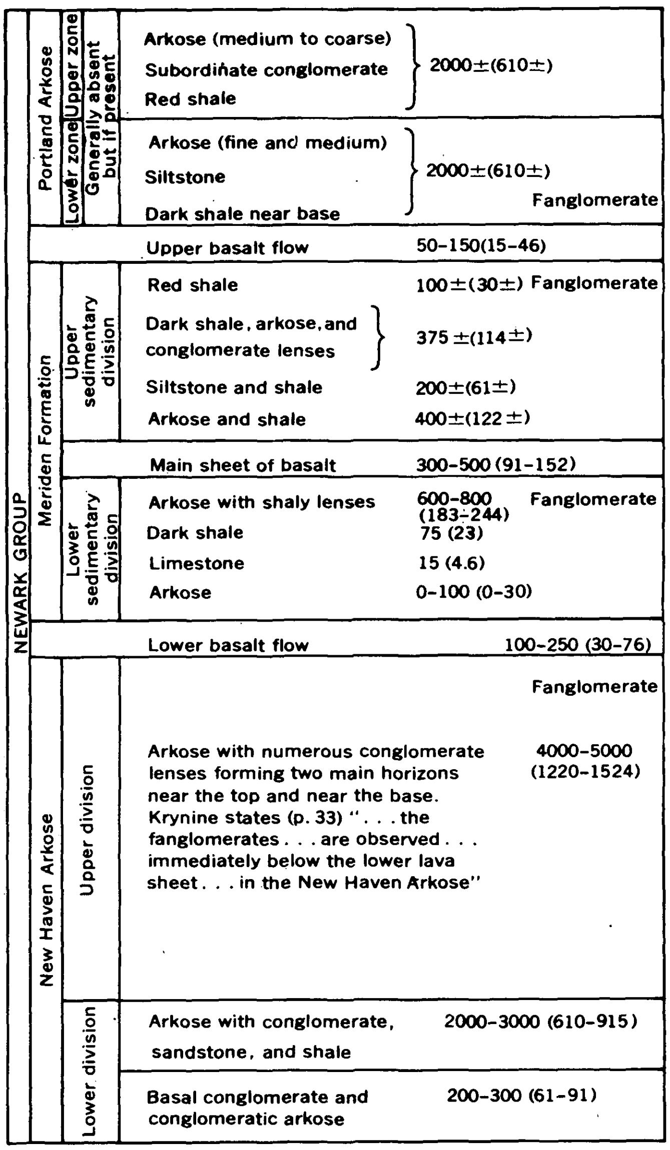


FIGURE 7.—Generalized stratigraphic section of the Triassic of southern Connecticut as given by Krynine (1950) together with the position of the fanglomerates as given by Russell (1922). Probable thicknesses given in feet (metres).

of basalt and on it were deposited nearly 1,100 feet (335 m) of sediments with fanglomerates near the top; thereafter the upper basalt flow appeared, and this was followed by the deposition of about 2,000 feet (610 m) of the lower zone of the Portland Arkose, which contained at least one fanglomerate above the lava flow. It is thus apparent that the lavas did not appear at the time a given period of faulting ended but only after the time interval necessary to allow the disintegration, weathering, and transportation of part of the granite rocks of the horst to form a fanglomerate at the graben wall. If we assume, for purposes of estimation, that the values calculated for the rate of deposition in the Newark basin of 1 foot (0.3 m) of sediment accumulating in a thousand years for the section 10,000 feet (3,048 m) thick and 1 foot (0.3 m) in 400 years for a section 25,000 feet (7,620 m) thick, this would indicate that approximately a million years or alternately 400,000 years elapsed between the eruptions of the lower basalt flow and the main sheet of basalt and similarly about 1.1 m.y. or alternately 440,000 years elapsed between the main sheet of basalt and before the upper basalt flow was erupted. These time-interval values are of the same order of magnitude as those for the stratigraphic section in New Jersey, where the corresponding values are 600,000 or 240,000 between First and Second Watchung, and 1.5 m.y. or 600,000 years between Second and Third Watchung. The good correspondence between the times elapsed between eruptive events in New Jersey and Connecticut casts doubts on the paleomagnetic correlations of de Boer (1968).

The Pomperaug valley near Southbury, Conn., is a small downfaulted part of the former Triassic section. It is isolated from the principal outcrop area of the Triassic in Connecticut and is 15 miles (24 km) west of it. The area has been described by Hobbs (1901) and Wheeler (1937). It contains the lower part of the section and includes two of the lava flows. Hobbs (1901) mapped the South Britain Conglomerate, which underlies one of these lava flows. It is thus evident from field relations in New Jersey, Connecticut, and Massachusetts that the stratigraphic position of the fanglomerates (conglomerates) below the lava flows is significantly consistent. This observation suggests that the extrusions of lava did not coincide with the period of faulting but rather were later than these tectonic events.

An estimate of the time between successive downfaultings along the wall of the fault system is also suggested by these calculations involving the eruptive events. They suggest that the time interval between the fanglomerates, for the upper part of the Triassic section in southern Connecticut, was of the order of half a million years and that an episode of faulting likewise was regenerated on the order of half a million years with the production of an 'uplifted' horst block.

Evidence for this short duration of the periods between faulting is also supplied in a study of the sediments which was made by Krynine (1950, p. 186), who concluded from his research on the Connecticut Triassic that the different lithologic types of rocks "are due to variations of one fundamental sedimentary process: a rapid erosion and deposition under a savanna climate." As an index of the rapidity of erosion, transportation, and deposition, Krynine observed that the feldspars are quite stable. He further observed that the mafic minerals decomposed to form iron oxides and not a montmorillonitic type of clay. Concerning the feldspars he states that they are generally fresh, but that all degrees of weathering and decomposition are present and that most of the alteration is primary—some is postdepositional.

The feldspars make up on the average 30 percent of the Triassic sediments of Connecticut, and the fragments are generally angular or subangular in shape. This persistence of the feldspars is significant as an index of the shortness of the time span that these grains could have been exposed to weathering. Correns and Von Engelhardt (1938) have shown that feldspars are relatively easily attacked under weathering conditions at pH values in the range of 3–11 and that at the higher temperatures corresponding to tropical conditions the feldspars are dissolved in solutions that are even in the neutral range of 6–7 pH units. Although it is not possible at present to quantitatively correlate persistence of the feldspars in sediments with their chemical resistance in a geologic environment, their presence in large amounts in a relatively stable state does support the opinion that the products of weathering did not remain for great lengths of time on their source rocks. The oft-repeated appearance of large quantities of feldspar grains throughout the stratigraphic section attests to their renewed production from freshly weathered granitic rocks. Such fresh rocks would be made available by the postulated intermittent, that is, nonuniform and not quite periodic movements along the fault walls during the process of sedimentation.

THE NATURE AND PRODUCTS OF THE BASALTIC ERUPTIONS

SITES OF THE FISSURES

The sites of the fissures from which the lavas flowed into the Triassic basin have not been located. No evidence for their existence, such as lava filled feeder dikes, has been found in the underlying Triassic sediments well exposed in outcrop to the southeast. The possibility that they exist here and are covered by soil must be considered. The observed greater stability of the basalt over that of the sediments in the Watchungs proper would suggest that the dikes should form topographic "highs." No trace of such dikes has been observed in the sediments of the valleys between the flows. The supposed stability of the trap dikes has been questioned by Russell (1892, p. 106), who noted that under the climatic conditions obtaining in Virginia and North Carolina the dikes were frequently deeply decayed, sometimes to depths of 50 feet (15 m), and that they did not form ridges nor otherwise manifest their presence in the topography.

Intrusive dikes have been found in the vicinity of the Palisade Diabase sill and have been described by Darton (1890), Kümmel (1898), and Lewis (1907, 1908). They all agree that these dikes are extensions from the sill itself.

The difficulty of finding concealed fissures under the flows has been emphasized by Geikie (1882) and Tyrrell (1937). The chief difficulties are first the thickness of the flows themselves, which blanket the surface and conceal all that is below; and secondly, the low probability of finding a feeder dike, of the order of 5-feet (1.5 m) width, exposed by erosion or topographically expressed in a depression, or encountered in excavations or drillings.

In the present investigation, a filled fissure, now a dike, has been found cutting through the basal part of the lowermost flow in First Watchung Mountain near West Orange, N.J., in the cut for U.S. Highway 280. This fissure furnished lava to the still liquid part of the lowermost flow. Evidence for a probable dike was also observed at Moggy Hollow, at the southern part of Second Watchung Mountain.

The diabase dikes which have been found in the crystalline rock along the border fault system have been suggested as possible feeder dikes. Unless, however, field evidence demonstrates an unequivocal relation between the flows and the supposed feeder dikes, the assignment of a Triassic age to these dikes is unwarranted. De Boer (1967) has studied dike swarms in the Appalachians using paleomagnetic methods and shows (p. 2237) "that most of the extensive dike swarms cutting Triassic and older formations probably intruded in a time of regional tectonic and magnetic activity distinct from the late Triassic tectogenesis," and he suggests a Jurassic age for the dikes. King (1961, p. B95) has studied relations of these dikes and shows that (1) "most dikes locally have a common trend," (2) "that these local common trends vary systematically from one part of the Appalachian region to another," and (3) that "The trends of the dikes are everywhere discordant to the trends of the structures of the enclosing rocks, and they are everywhere straighter than these structures." May (1971) has studied the trends of these dikes in eastern North America, West Africa, and northeastern South America and has drawn the trajectories of the principal stress indicated by the patterns of the dikes. He considers their age to be Late Triassic to Early Jurassic. The conclusion to be drawn from these studies of the diabase dikes is that they are unrelated to the principal Triassic volcanism.

PREERUPTIVE CHARACTER OF THE GRABEN FLOOR

The nature of the sedimentary floor onto which the lavas flowed may be deduced from a study of the contact relations. The conformable nature of the bottom of the flows with the underlying sediments as seen in abundant outcrops on the scarp slope of Third and Second Mountains shows that the fissure eruptions took place in open country, a fact deduced independently from stratigraphic studies of the nonmarine sediments that contain the flows. More recently Opdyke (1961) has demonstrated by studies of the natural remanent magnetization in both the sediments and the Watchung flows "that in the Newark Group sediments an inclination error of paleomagnetic significance is not present." In other words the sediments were horizontal, or nearly so, when the flows poured out over them.

In general, along the scarp slope of Third Mountain the lowermost part of the lower flow unit overlying the Newark sedimentary rocks is heavily vesiculated for a distance of about 1 foot (0.3 m) above the contact, and thereafter the vesiculation decreases rapidly as one ascends along the scarp slope. Locally, as at the quarry at Millington the vesiculation in the lower flow unit overlying the sediments is in a zone of about 20 feet (6 m), but the abundance of vesicles varies from the top to the bottom of the zone and is heaviest closer to the contact. The actual contact between the lower flow unit and the hornfelsized sedimentary rock is sharp.

The features recognizable in the contacts exposed on Third Mountain suggest that the flows poured out during a relatively dry season when the sediments were probably just barely moist or, in places, nearly dry. They further suggest that the flow of lava was laminar and that there was a constant and continuous supply of hot fluid lava.

The contact of the upper flow unit with the lower flow unit of the basalt in Third Mountain wherever it has been examined is always sharp and shows no evidence of intertrappean sediments. The base of the upper flow unit is generally vesicular for a short distance of several feet (1 m±) or so above the contact. At the quarry in Millington the pahoehoe surface of the top of the lower flow unit is visible, and the total thickness of the vesicular zone consisting of the vesicular top of the lower flow unit and the vesicular base of the upper flow unit is possibly 15 feet (4.6 m) with varying degrees of vesiculation.

The contact relations between the vesicular base of the lower flow unit of Second Mountain and the sedimentary floor of the graben is variable. Over long stretches it is similar to that of Third Mountain, but at a number of places there is a slight development of pillows as in the cut for U.S. Highway 78 near the village of Pluckemin. Elsewhere, near the temporary ends of a flow, or a former surge of lava, tongues of lava may form which have a resemblance in shape to toes. In some areas both pillows and toes may form suggesting that the lava was flowing over an area with braided drainage. The appearance of the pillows and toes suggests that the flow of lava may have been temporarily halted and later resumed after overcoming a temporary obstacle. The contact between the upper flow unit and the lower flow unit is sharp, generally lightly vesicular, but in a few areas thin zones of pillows or pahoehoe toes are observed. I have observed the presence of an intertrappean layer of Brunswick sediments near the Greenbrook in North Caldwell. These Newark sediments are about 6 feet (1.8 m) thick. The lower contact of the upper flow unit here is vesicular for a distance of about 1 foot (0.3 m) or so.

Only a small number of outcrops in First Mountain have I examined, but at Montclair, South Orange, and at several localities in Paterson and elsewhere the lower flow unit is thinly vesicular and rests on hornfelsized sediments. The contact between the base of the upper flow unit and the vesiculate top of the lower flow unit is separated at several localities in the vicinity of Paterson by a thin intertrappean layer of argillaceous siltstone, as described by Bucher (in Bucher and Kerr, 1948). The base of the lava flow above this siltstone is composed of pillow lavas. Lewis (1915) measured thicknesses of 50 to 75 feet (15–23 m) for the pillow zone at the Upper New Street quarry, and he further examined localities in the vicinity of Paterson. Fenner (1908) using the occurrence of pillows as indication of the former occurrence of a playa lake, mapped the extent of this lake which he called Lake Paterson.

SURFACE CHARACTER OF THE VESICULAR TOPS

When Kümmel (1899) made his field studies on the Newark rocks, he had the opportunity to see many small "farmers quarries," which were opened for road metal, and many shallow roadcuts. The "farmers quarries" were commonly dug out of the upper vesicular zone of the upper flow units because it was the easiest basalt to quarry. The exposures gave Kümmel (1899, p. 36) the chance to observe the pahoehoe tops of the flows and he describes them as follows: "Upper contacts have not been observed in many cases, but the upper surface of these sheets is frequently vesicular, amygdaloidal, and scoriaceous. Locally, a thin layer of waterworn trap particles, intermixed with red mud occurs between the vesicular trap and the unaltered typical red shales, or the vesicles are filled with red mud. The overlying shales conform to the slightly irregular surface of the trap. In frequent exposures the rolling-flow structure named by the Hawaiian Islanders Pa-hoe-hoe, is visible. Nowhere have any tongues of lava been found extending from the main sheet into the neighboring shales."

I have observed a few good contacts of the Newark sediments overlying the vesicular top of the flow, and these showed the pahoehoe surface and the conforming sediments just as Kümmel (1899) described them. Such contacts can best be seen under red shale knolls.

AREAL EXTENT AND VOLUME RELATIONS OF THE WATCHUNG BASALT FLOWS

The areal extent and the volume relations of the Watchung Basalt flows are not generally appreciated. Outcrop areas and drilling operations for water supplies show the area to be at least 500 square miles (1,295 km^2). Using an average thickness of 600 feet (183 m) for First Mountain, this amounts to a volume of 56.8 cubic miles (237 km^3); an average thickness of 750 feet (229 m) for Second Mountain, this amounts to a volume of 71.0 cubic miles (296 km^3); and an average thickness of 300 feet (91 m) for Third Mountain, this amounts to a volume of 28.4 cubic miles (118 km^3). The total volume for the three volcanic episodes is approximately 156 cubic miles (650 km^3) as now delineated. According to Sanders' (1963) views on the former probable width of the graben in New Jersey, this volume may amount to only a vestige of their former volume. Sanders (1963) estimates the width of the graben in New Jersey to be 50 to 70 miles (80.4–112.6 km). Using a width of 50 miles (80.4 km) and assuming for purposes of calculation a length equal to the present eroded remnant of 40 miles (64.4 km), these values for the three Watchung Mountains would become 227 cubic miles, 284 cubic miles, and 114 cubic miles (946, 1,184, and 475 km^3) respectively with a total volume of 625 cubic miles (2.6×10^3 km^3).

The igneous rocks of the eastern Triassic basin extend from Nova Scotia to South Carolina over a distance of about 1,200 miles (1,931 km). The areal extent and volume relations for the lava flows in the Triassic basins including Connecticut, Massachusetts, New Jersey, and Pennsylvania together with the extensive flows in Nova Scotia and the lesser volcanism in Maryland, Virginia, and the Carolinas suggests a rather considerable former areal spread and a volume of possibly as much as 3×10^3 cubic miles (1×10^4 km^3). Their extrusion in the Late Triassic Period constituted a major geologic event in eastern North America. Compared to the lava volumes of the fissure eruptions of the Deccan in India, the Columbia and Snake River areas in Western United States, the Brito-Arctic region (Thulean province), and the Parana basin of Paraguay, Uruguay, and Brazil, the lava flows of the Newark basin were smaller. The volume of the Deccan flows is given by Subramanian and Sahasrabudhe (1964) as 1.24×10^5 to 25×10^5 cubic miles (5.18×10^5 to 10.4×10^6 km^3); for the Columbia River Plateau by Waters (in Shaw and Swanson, 1970) as 0.5×10^5 cubic miles (2×10^5 km^3) and for the Lake Superior region by Walter S. White (oral commun., 1973, conservative estimate) as 60,000 cubic miles (2.5×10^5 km^3).

GEOLOGIC PROCESSES RESPONSIBLE FOR THE JOINTING SYSTEMS

Joint systems were developed in the Watchung Basalt as a result of stress fields set up by three geologic processes which acted upon the rocks of the graben. Cooling of the lava flows gave rise to the "cooling joints." The tectonic forces associated with the post-Triassic folding and the accompanying deformation of the graben produced the "tectonic joints." During the Pleistocene Epoch the northern part of the eroded remnant of the former graben was covered by a continental glacier which compressed the rocks beneath it; and, after the ice melted, the resulting decompression of the basalts is thought to have produced sheeting (Faust, unpub. data).

PETROCHEMISTRY

The Watchung Basalt flows and the Palisade Diabase intrusion were probably derived from the same magma chamber. Accordingly, the chemistry of the Watchung Basalt is of prime interest in discussing the course of differentiation in the Palisade Diabase sill, but surprisingly few analyses of the basalt exist.* Lewis (1908) used eight "superior" chemical analyses to interpret the chemistry of these rocks. Five of the analyses were for First Mountain and three for Third Mountain. He placed these samples in their approximate stratigraphic position—designated as lower, middle, and upper layers—in order to discuss their significance. The analyses of the rocks from First Mountain suggested that Al_2O_3 and (Fe_2O_3+FeO) remained essentially constant throughout the thickness of the sheet and that Na_2O is at a minimum at the middle layer, whereas CaO is at a maximum. Silica increased only slowly towards the top of the sheet, and conversely MgO decreased toward the top. The rocks from Third Mountain showed some differences from those from First Mountain in that there was a noteworthy lower amount of SiO_2; that MgO, Al_2O_3, and CaO were also lower, but less so; and that (Fe_2O_3+FeO) was noticeably higher. The Na_2O and TiO_2 were also higher in the rocks from Third Mountain. Lewis (1908, p. 161) suggested that "The striking differences again appear in the MgO, CaO, Na_2O and K_2O, particularly in the higher CaO and the lower MgO and Na_2O in the 'second layer'."

The specimens from Third Mountain, that were analyzed, came from the quarry at Millington, N.J. When I examined this quarry in 1948 only the upper flow unit, as I characterize it, was exposed, so these analyses are from that flow unit. The specimen from O'Rourke's quarry, West Orange, N.J., comes from the base of the lower flow unit of First Mountain.

Fenner (1931) made four analyses on two pillow lavas from the Upper New Street quarry (Burgers quarry) and the Lower New Street quarry, in Paterson, N.J. He analyzed both the glassy-looking crusts and the finely crystalline basalt inside of the pillows and demonstrated that the glassy-looking crust is not the original glassy selvage and therefore that the analysis of this crust does not define the original

* Abstracts of papers on chemical studies have been published by Black and Piburn (1973) for the Watchungs and by Smith and Rose (1970) for the Pennsylvania occurrences.

lava chemistry. According to my interpretation these specimens came from the base of the upper flow unit of First Mountain.

It was Washington (1922) however, who recognized the relation of the Watchung Basalt to the so-called Plateau Basalts, and he correctly related them petrogenetically to the basalts of the Thulean province, the Deccan, the Columbia River plateau, and elsewhere. He pointed out the chemical similarity of the flood basalts from fissure eruptions and attributed their fluidity to their notable content of ferrous oxide.

I am studying the chemistry of the major and minor elements of these lavas. An average of 36 analyses [4] from the upper flow unit of Third Mountain at Millington, N.J., is given in table 2, column 1, together with the C.I.P.W. norm. Analyses of Washington's average for the Watchungs, Lewis' (1908) average for Third Mountain at Millington, N.J., Nockolds' (1954) average for tholeiitic basalts, Daly's (1933) average for plateau basalts, Water's

[4] Unpub. data of George T. Faust, Laura Reichen, and Angelina C. Vlisidis.

Table 2.—*Average chemical analyses and C.I.P.W. normative data of Watchung Basalt from Third Mountain with other averages of tholeiitic rocks*

	Watchung Basalt, Millington, N.J. Upper flow unit, Avg. 36 analyses, This study (1)	Watchung Basalt, Millington, N.J., Upper flow unit, Avg. 22 selected analyses (2)	Watchung Basalt, Millington, N.J., Avg. 5 analyses, Lewis (1908) (3)	Watchung Basalt, New Jersey, Avg. 8 analyses, Washington (1922) (4)	Whin sill, England, Avg. 5 analyses, Holmes and Harwood, (1928) (5)	Normal tholeiitic basalt (and dolerite), Avg. 137 analyses, Nockolds (1954) (6)	Plateau basalt, Avg. 43 analyses, Daly (1933, p. 17) (7)	Columbia River basalt, Avg. 13 analyses, Waters (1955) (8)	Average Palisade basal-chilled dolerite, Walker (1969) (9)
SiO_2	49.40	49.65	49.52	50.66	50.52	50.83	48.80	52.31	51.98
Al_2O_3	13.58	13.51	13.83	14.28	13.76	14.07	13.98	14.38	14.48
Fe_2O_3	5.08	5.36	5.12	3.41	3.87	2.88	3.59	2.47	1.37
FeO	9.54	9.39	9.88	8.58	8.50	9.00	9.78	9.95	8.92
MgO	5.65	5.59	5.66	6.92	5.42	6.34	6.70	4.46	7.59
CaO	9.15	10.25	7.41	8.60	9.09	10.42	9.38	8.37	10.33
Na_2O	2.96	2.26	3.40	2.92	2.42	2.23	2.59	2.94	2.04
K_2O	.51	.46	.77	.72	.96	.82	.69	1.26	.84
H_2O^+	1.85	1.13	1.76	2.28	1.51	.91	1.80	.74	.88
H_2O^-	.74	.96	.68		.76	----		.39	.16
TiO_2	1.30	1.31	1.47	1.30	2.39	2.03	2.19	2.10	1.21
P_2O_5	.17	.17	.18	.17	.26	.23	.33	.36	.14
MnO	.24	.23	.14	.12	.16	.18	.17	.21	.16
SrO	.08	-----	.01	----	-----	----	-----	----	-----
CO_2	-----	-----	----	----	.58	----	-----	----	-----
Other	-----	-----	----	----	[1] .11	----	-----	----	-----
Σ	100.25	100.27	99.83	99.96	100.31	99.94	100.00	99.94	100.10
C.I.P.W. Norms									
Q	2.26	5.16	0.99	1.34	7.00	3.76	0.92	4.47	2.80
or	3.01	2.72	4.56	4.23	5.68	4.84	4.06	7.46	4.73
ab	25.06	19.13	28.73	24.69	20.45	18.87	21.92	24.85	16.92
an	22.25	25.34	20.18	23.64	23.86	25.95	24.48	22.30	28.23
di	17.69	20.02	12.62	14.60	12.98	19.83	16.50	14.05	18.19
hy	16.98	15.13	19.63	21.18	15.93	17.20	20.20	17.26	23.60
mt	7.28	7.71	7.43	4.92	5.60	4.17	5.21	3.59	2.03
il	2.48	2.49	2.79	2.46	4.54	3.87	4.16	3.99	2.28
ap	.40	.40	.44	.40	.60	.50	.77	.81	.24
cc	-----	-----	----	----	1.32	----	-----	----	-----
Thornton-Tuttle differentiation index	30.33	27.01	34.28	30.26	33.13	27.47	26.90	36.78	24.75
Normative plagioclase	$Ab_{53.0}$ $An_{47.0}$	$Ab_{43.0}$ $An_{57.0}$	$Ab_{58.7}$ $An_{41.3}$	$Ab_{51.1}$ $An_{48.9}$	$Ab_{46.2}$ $An_{53.8}$	$Ab_{42.0}$ $An_{58.0}$	$Ab_{47.2}$ $An_{52.8}$	$Ab_{52.7}$ $An_{47.3}$	$Ab_{37.5}$ $An_{62.5}$

[1] S, 0.06; V_2O_3, 0.05.

(1955) average for the basalt of the Columbia River Group, and Holmes and Harwood's (1928) average analysis for the Whin sill are included in the table for purposes of comparison.

A comparison of the average of 36 analyses of specimens from the Millington quarry analyzed for this study, column 1, table 2, with the average of three specimens from the same quarry reported by Lewis (1908), column 3, table 2, shows reasonable agreement for SiO_2, Al_2O_3, ($FeO+Fe_2O_3$), MgO, TiO_2, and P_2O_5, with small differences for CaO, Na_2O, K_2O, and MnO. Our studies of the section at Millington suggest that these slight differences are unimportant and that they probably arise in part because two of these rocks may actually have been slightly altered. A carefully selected set of 22 analyses of rocks, judged to be the least altered, from within the larger set of 36 analyses was averaged (table 2, column 2). This average is tentatively considered to be representative of the upper flow unit at the Millington quarry.

The average sample for the Watchungs of eight analyses given by Washington (1922) is a very small sample, but since it is derived from the average of five analyses from First Mountain basalts and three from Third Mountain basalts it is more representative than the single set of analyses from the Millington quarry. A comparison of Washington's (1922) average with the averages of the Whin sill (5 analyses), Nockolds' (1954) normal tholeiitic basalt, Daly's (1933) Plateau basalt, and the Columbia River basalt (13 analyses) shows its close affinity to tholeiites. The conclusion that the Watchung Basalt is tholeiitic was reached first by Washington (1922). The C.I.P.W. norms, the Thornton-Tuttle differentiation index, and the calculated normative plagioclase show the variation within those averages. The basalts all carry quartz in the norm.

As early as 1884, Teall had noticed the close chemical resemblance between the rocks of the Whin sill and the basalts, dikes, and diabase of New Jersey and Connecticut.

A comparison of the average of 22 selected analyses of basalts from the upper flow unit of Third Watchung Mountain (table 2, column 2), with the average Palisade basal-chilled dolerite of Walker (1969), column 9, shows some important differences. The Watchung Basalt has lower SiO_2, Al_2O_3, MgO, Na_2O, K_2O, and MnO than the basal-chilled dolerite and about the same amount of CaO, TiO_2, P_2O_5, and MnO. The basalt is significantly higher in total iron oxides ($FeO+Fe_2O_3$). These differences are reflected in the norm by the appearance of more quartz, albite, and magnetite; slightly less diopside, and less orthoclase, anorthite, and much less hypersthene than in the basal-chilled dolerite. The Thornton-Tuttle differentiation index of the basal-chilled dolerite is lower than that of any of the tholeiites listed in table 2, and the plagioclase in the norm is much more anorthitic.

MEGASCOPIC CHARACTERISTICS OF THE BASALT

The basalts of the upper flow unit of Third Mountain are uniformly fine grained, with an average grain size of less than 1 mm. Small lenses, composed almost entirely of crystals 2–3 mm across, appear rarely in an excavation near Myersville and at the cut near Pine Brook. These lenses occur in the section about two-thirds of the distance up from the base of the flow unit. They represent the last liquid to solidify, and because of the increased volatile content of this last liquid, they have completely crystallized. The lower flow unit of Third Mountain is also fine grained, but small phenocrysts about 2 to 3 mm across of feldspar and pyroxenes are sparsely distributed in the rock.

The basalts of Second Mountain show much more variation in grain size. In the lower flow unit they are dense and fine grained near the base, but they coarsen slowly as one ascends in the section until at a zone about two-thirds of the way up from the base the rock becomes coarse grained and resembles a gabbro. The grain size diminishes rapidly above this zone and becomes fine grained to the top. The upper flow unit is more uniform than the lower flow unit, and it has pockets of coarsely crystallized rock above the middle of the unit. These crystals are, however, not as large as those in the lower flow unit. This coarse facies does not form a continuous zone but consists only of a series of discontinuous lenses at about the same horizon. The zones of pillows at the base of the flow units appear to have their individual pillows coated with a glassy-looking rind. These rinds are now however altered, and the rind may crumble when handled.

The basalts of First Mountain, in so far as I have examined them, appear to be fine grained. Lewis (1908, p. 153) made similar observations.

The color of the basalt is normally black, frequently with a greenish tint, but grayish zones are also common. There is considerable variation in color in the altered zones. On weathered surfaces the basalts commonly have a yellow coating of iron oxides. The color varies from grayish-orange (10 *YR* 7/4) to moderate yellowish brown (10 *YR*

5/4).[5] On quarry walls which have been undisturbed for long periods of time, they may have a reddish-brown (pale brown, 5 *YR* 5/2) coating formerly referred to as a patina when quarries were worked for dimension stone. In hydrothermally altered zones they may be greenish, owing to considerable quantities of chlorite.

The tops and bottoms of the flow units are vesiculated. The vesiculation is generally light at the basal contact of the lower flow unit overlying the sedimentary rocks. The size and the frequency of the bubbles increase as the contact is approached. At a distance of 6 inches to 1 foot (0.15–0.30 m) above the contact the vesicles are commonly the size of a pinpoint and then increase to as much as one-fourth of an inch (0.6 cm) in diameter at or near the contact. Less frequently, the individual bubbles are larger in diameter. Locally, the zone of vesiculation may be thicker. The top of the flow unit may be as much as 10 feet (3.0 m) thick, and it is heavily vesicular. In this zone the larger vesicles are at the top. Locally, the concentration of larger bubbles may be so great that clustering produces a scoriaceous variety of basalt characterized by coarse bubbles forming a cellular structure.

Bubbles are scattered sparsely throughout the flow units, and sometimes they collect into single wavy layers, thin zones about one-fourth inch (0.6 cm) thick, and much more rarely into zones 1 foot (30 cm) or so thick. Such zones of vesicles have been observed near the top of the flow unit but well below the vesicular top.

The top of the upper flow unit has a vesiculation pattern similar to that of the top of the lower flow unit, but the basal part of the upper flow unit may be more heavily and more thickly vesicular than the corresponding base of the lower flow unit. The actual tops of the two flow units have the pahoehoe form of a billowy undulatory surface which in cross section resembles a sine wave.

Pipe vesicles, tubelike cavities as much as 4 or 5 inches (10 or 13 cm) long and oriented with their largest axis (the tube axis) normal to the contact, are most commonly observed at the base of the upper flow unit where it lies in contact with the top of the lower flow unit. In the Millington quarry, where the contact could be seen, the base of the upper flow unit conformed to the undulatory top of the lower flow unit, and the orientation of axes of the pipe vesicles also reflected the curvature.

My field observations of the pipe vesicles, also called pipe amygdules, at the base of the lava flow where it rests on an underlying flow or on the Triassic sediments of the Brunswick Formation are in accord with those of du Toit (1907) in South Africa. In his extensive field studies in South Africa and elsewhere, he never observed a pipe vesicle (amygdule) in the upper or middle part of the flows. His view of their origin was that the gases which formed them did not come from the lava itself but rather from air entangled in the lower lava flow or steam formed by the vaporizing of water contained in the moist surfaces over which the lava flowed.

The various vesicles may be empty or filled with minerals. When the vesicles are filled with minerals, the basalt is said to be amygdaloidal.

The Watchung Basalt flows are famous for the beautiful zeolite minerals, prehnite, quartz, gypsum, thaumasite, datolite, apophyllite, pectolite, stevensite, and other associated minerals which have developed in the pillow basalts at the base of the upper flow unit of First Mountain in the vicinity of Paterson, in the area delineated by Fenner (1908) as the former Lake Paterson. These deposits and their minerals have been described by many investigators but in particular by Fenner (1910b) and Schaller (1932), and more recently their mineralogy has been verified by Mason (1960). This type of mineralization, but not in a pillow basalt environment, has been developed on a much smaller scale elsewhere in First Mountain as at the Chimney Rock quarry near Bound Brook, N.J., and to a much lesser extent in Second and Third Watchung Mountains.

MICROSCOPIC CHARACTER OF THE BASALTS

The microscopic character of the Watchung Basalt was determined for Darton (1890) by J. S. Diller and Whitman Cross. Iddings (in Diller, 1898, p. 254–255) described the petrography of the famous columnar basalt from the base of the lower flow unit at O'Rourke's quarry on First Mountain in Orange, N.J. The first detailed study was made by Lewis (1908), and he examined rocks from all three Watchung Mountains. Fenner (1910a, b, 1931) studied in particular the basalts of First Mountain with special emphasis on the pillow lavas. Clark (1916) described a basalt with an ophitic texture from the Chimney Rock quarry in First Mountain. The only measured mode appears to be that of Merwin (in Adams and Williamson, 1923, p. 485), who examined a dense, black, nonporphyritic basalt from the Hatfield and Weldon quarry, in Scotch Plains in First Mountain and found it to consist of

[5] Color designations are based on the "Rock-color chart" of the National Research Council (Goddard and others, 1948).

30 percent plagioclase, $Ab_{45}An_{55}$; 50 percent augite; and 20 percent glass.

According to all observers, the normal crystallized basalt consists of plagioclase of labradorite composition ($Ab_{40}An_{60}$ to $Ab_{45}An_{55}$) occurring as either stout, short, rectangular crystals or as slender lath-shaped crystals; of augite usually of irregular form and commonly colorless or with a brown or greenish tint; of magnetite present as trellis-shaped or fir-tree shaped groups or as dust; and glassy base or mesostasis usually green or dark brown. The mesostasis has probably recrystallized. Chlorite and calcite may also be seen as alteration products. In some varieties of basalt, olivine occurs rarely, and it is usually replaced presumably by serpentine. If the space between the laths of feldspar is filled with granular augite, the texture is diabasic; if large augite crystals or grains enclose many laths of feldspars, the texture becomes ophitic.

THE PROBABLE CHARACTER OF THE PRISTINE GASES IN THE WATCHUNG BASALT

The composition of the pristine gases which were probably exsolved as bubbles into the liquid lava which later solidified as the Watchung Basalt may be approximated from the studies of Shepherd (1938). Shepherd examined the intrusive equivalents of the Watchung Basalt. He pumped the residual gases out of two Triassic diabases, one from New Market, Md., the other from Granton, Bergen Township, N.J. He found that the unaltered diabase yielded a gaseous phase composed of 90 percent water vapor, slightly less than 5 percent H_2, 2 percent of S_2, 2 percent of N_2, about 0.9 percent CO_2, about 0.3 percent F_2, about 0.2 percent Cl_2, about 0.02 percent CO, and a trace of argon. The total volatile content amounted to about 30 cc per gram, which is the normal value Shepherd (1938) found for plutonic rocks. This analysis of the gases is probably representative of the composition exsolved into the Watchung Basalt. Freshly collected basalts from the Hawaiian Islands contained about 5 to 6 cc per gram, and this again is the normal value Shepherd (1938) found for lavas. This value would be the probable gas content of the solidified Watchung Basalt. Shepherd's (1938) data suggest that basalts retain about one-fifth of the gaseous constituents retained by the contemporaneously intruded diabases. This decrease in gas content is chiefly accomplished by the degassing on extrusion of the basalts.

The presence of 2 percent of sulfur in Shepherd's (1938) analysis may be somewhat surprising, but the recent studies of Moore and Calk (1971) have definitely confirmed this. They observe on page 485: "Hence the main vesicle-forming phases in deeper pillows are probably dominated by the compounds of S and C."

HISTORY OF TECTONIC SUBSIDENCE AND VOLCANISM IN THE NEWARK BASIN AS IT RELATES TO THE WATCHUNG MOUNTAINS

STRUCTURE OF THE NEWARK BASIN AT THE CLOSE OF THE TRIASSIC PERIOD

The inherited geometry of the Triassic basins, in their several disconnected parts, is a significant structural problem that has been studied by various geologists. The geometric outline of the Triassic basin in Connecticut was thought by Emerson (1917, p. 48 and 127) on the basis of field studies, particularly of the Bernardston Formation of Silurian and Devonian(?) age, to have been determined in the Devonian Period, and he was followed in this view by many investigators. Bucher (1933, p. 351) recognized the close geometric relation existing between the Triassic basins, extending from Nova Scotia to South Carolina, and the earlier Paleozoic folds, but he concluded from further study of the geological and structural maps of the eastern part of North America that "the line of Triassic troughs cuts across the main axes of the preexisting Paleozoic structure" and that these troughs "represent a new start dynamically which disrupted the old structural lines ***." Movement along the border fault has been estimated by Van Houten (1969, p. 328) to be 18,000 feet (5.5 km) and by Sanders (1963, p. 510) to be as much as 30,000 feet (9.1 km). Ratcliffe (1971, p. 125) made a detailed study of the Ramapo fault system in New York and New Jersey, and he suggests that the fault "has a complex tectonic ancestry perhaps dating from Late Precambrian time" and (p. 136) "The relationship of the large intrusive Palisades phase to the east and the Watchung flows to the west of the basin suggests that the border fault at depth served as an avenue of magma ascent, although magma apparently never reached the surface along the fault," and (p. 131) contrary to Sanders (1963), he considers it "unlikely that the Triassic sediments extended much further northeast than the present exposure of the Triassic unconformity ***."

For the Triassic basin of New Jersey, the inherited geometry has been described by Lewis (1907), Kümmel (1940), and Wheeler (1939). As interpreted in this study, before deformation took place the gross system in the graben consisted essentially of a stratiform mass made up of sediments, the three Watchung Basalt flow sequences, and included near its base the discordant Palisade intrusive. The layers of the stratiform mass were essentially flat lying. This mass was contained between the walls of the horsts. The dimensions of the graben based on Sanders (1963, p. 504, 507) estimates were about 30,000 feet (9.1 km) deep (approx 6 miles) and 50 to 30 miles (80.5–48 km) wide. Geometrically the mass was bordered by marginal faults which dipped under the graben at 70°–75° and thus formed a trapezoidal block which narrowed with depth.

The geometry of the outcrop areas in Connecticut has been discussed by Longwell (1933) and Sanders (1963), who recognized the importance of the preservation of the Triassic rocks in the Pomperaug valley, an isolated outcrop area surrounded by granitic rocks and approximately 15 miles (24 km) west of the principal outcrop area of the Triassic of Connecticut. Longwell (1933, p. 101) comments as follows: The general tilt in the Triassic belt appears to be the result of broad regional uplift in post-Triassic time, with maximum elevation along a north-south axis in western Connecticut. In northern New Jersey and southeastern New York the Triassic strata dip to the west, on the opposite flank of the regional arch. The Pomperaug area of western Connecticut, preserved from erosion by downfaulting, indicates that typical Triassic sediments, with included basalt flows, existed on the crest of this arch, although they may not have been continuous between Connecticut and New Jersey.

The presence of the Triassic rocks of the Pomperaug valley near the crest of the postulated arch is a key point in the argument for the former extent of the Triassic sedimentation and thus of the geometry of the Newark basin.

On the basis of the presently existing geometrical relations of the Triassic outcrops of New Jersey, Connecticut, and Massachusetts, it has been generally assumed that a suitable structural process which could bring about the present configuration in the Newark basin from Connecticut to Pennsylvania would require:

1. that during the close of the Triassic Period or during the Jurassic Period the Newark basin was subjected to a large deformation.
2. that the period of deformation was of long duration—perhaps slow movement over a long period of geologic time.
3. that the obvious longitudinal symmetry of the Newark basin in Connecticut and the Newark basin in New Jersey with strata and lava flow sequence dipping symmetrically in opposite directions indicated uplift over a longitudinal arch.
4. that the "border fault" accompanying the deformation is a normal fault and is indicative of tension in the crust.
5. that compressional forces were ultimately involved in forming the asymmetric syncline abutting against the fault scarp of the Precambrian granitic rocks.

The formation of a wide mountain arch under the Triassic graben was postulated by I. C. Russel (1878). Barrell (1915) concurred in this view and the relationships were further extended and portrayed by Woodworth (1932). His diagram is reproduced in figure 8. Woodworth (1932, p. 158) observed that the Triassic block faulting, over the arch, illustrated "the association of normal faulting with an extended tectonic area***." Barrell (1915) further pointed out that the production of the arch brought about fracturing and settling along the walls and that these processes took place either during the arching or shortly thereafter. The later point is of considerable importance to the study of jointing in the Newark basin.

STRUCTURE OF THE NEWARK BASIN AFTER THE POST-TRIASSIC DEFORMATION

The geometry of the deformed graben in New Jersey cannot be described in detail for much of its contents have been removed. The angular relationships of the structure are the best preserved. The eroded remnant of this Triassic stratiform mass, as observed today, in New Jersey, is tilted about 15°NW. and strikes northeast. According to Sanders (1963) the marginal fault surfaces which originally dipped at 70°–75° under the graben were rotated 15°–20° and now dip 55°–60° in many localities. The northwest horst block of Precambrian granitic rocks, the Reading prong, is topographically higher

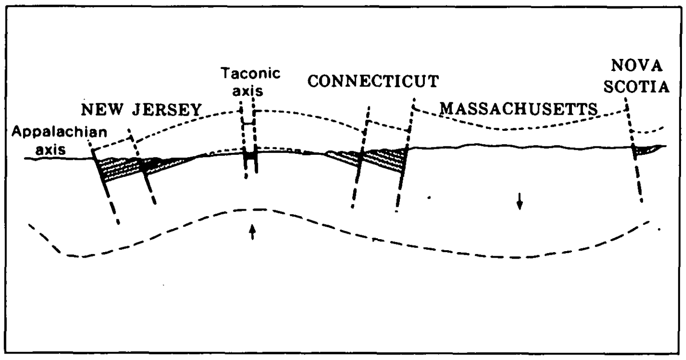


FIGURE 8.—Generalized cross section of the Triassic (patterned) of northeastern North America showing the postulated arching of the crust according to Woodworth (1932, fig. 1).

than the Triassic rocks, and the boundary between them is a large normal fault.[6] The Triassic rocks form the downthrown block. The dip of the fault is to the southeast.

The linear dimensions and the volume of the structure, in contrast, are difficult to estimate. In the post-Newark faulting the cumulative movement along faults amounted to many thousands of feet. In the Delaware River Valley, McLaughlin (1945) measured the section of Triassic rocks from the base of the Stockton Formation to the great diabase sill at Haycock Mountain and found it to be about 12,000 feet (3,658 m) thick. All of this section is below the Watchung lava flows, and thus it must represent the lower part of the Upper Triassic. Widmer (1964, p. 63) points out that "the border fault from Boonton to Stony Point truncates more than 10,000 feet (3,048 m) of Triassic rocks." Sanders (1963, p. 507) gives a thickness of 30,000 feet (9,144 m) for the section in New York and New Jersey.

The suggested shape of the former structure at the close of the period of deformation is that of an arch. Approximately 22 miles (35.4 km) east of the west wall of the graben, on the east side of Trenton, N.J., the Triassic sediments have been exposed lying on the granitic rocks, there the Baltimore Gneiss. The contact dips 15°NW., parallel to the dip of the overlying Stockton sedimentary rocks. As the section is traversed eastward in wells, the granitic rocks are continuously found to lie under the Coastal Plain sediments and their appearance in the well logs deepens to the east, but little is known of the contact of the Newark rocks and the granite. The southeastern horst block of the graben, the Trenton prong, has been largely eroded away. It is not exposed in New Jersey, and its remnant, as revealed in well drilling, lies under the Coastal Plain deposits of Cretaceous age.

The geometry of the remnants of the arch in New Jersey, Connecticut, and Massachusetts suggest that its former geometric shape approximated that of a section of a right cylinder. This broad semicylindrical fold was bounded on both sides by the walls of the horsts, and the hinge line of the fold was parallel to the walls. Evans (1925) estimated the amount of stretching of the surface layers of such a buckled structure by calculating the length of an equivalent arc. He assumed that the neutral surface was halfway between the bottom and top of the stratiform mass, that this section was unaltered in length, and that the angle of dip, $D°$, was the same on both sides. He set t, equal to the thickness of the mass and calculated the stretch s from the relation $\pi t D°/180°$. For a dip of 10°, and a depth of 2 miles (10,560 ft) (3.2 km) the stretch s would be about 0.35 mile (0.56 km); for a depth of 5 miles (26,400 ft) (8.0 km) the stretch s would be about 0.87 mile (1.4 km). For a graben with an original width of 30 miles (48.3 km), this would amount to an increase of about 1.2 percent for the thickness of 2 miles (3.2 km) and an increase of about 2.9 percent for the thicker section of 5 miles (8.0 km). Evans (1925) also gives the following approximate formula to calculate the theoretical height of such an arch:

$$\text{height} = h = \frac{w(1-\cos D°)}{2 \sin D°} = \frac{1}{2} w \tan \frac{1}{2} D°$$

where w is the width at right angles to the strike and $D°$ is the angle of dip. For a graben of 30 miles (48.3 km) width and with a dip of 10°, this suggests a probable height of 1.3 miles (2.1 km) at the crest.

Admittedly, this calculated increase in length due to buckling is a simplified treatment, but it gives us an approximate value for the amount of stretching of the rocks. This extension may be compared with that permitted by the tensile strength of the rocks.

From Hooke's law we have the relation that the strain produced in a body is proportional to the stress applied to it and that it is represented by the equation $E=$ stress/strain where E is Young's modulus. In a tensile strength test on a brittle substance the material is subjected to increasingly higher stresses producing increasingly greater strains until eventually the material fractures. Thus the stress required to rupture the material, the tensile stress, gives us a measure of the strain and therefore of the elongation at fracture. This may be calculated as follows:

$$E = \frac{\text{stress just prior to failure in a tensile test}}{\text{elongation just prior to failure}}$$

and

$$\text{Elongation just prior to failure} = \frac{\text{tensile stress}}{E}$$

The tensile strength of the stratiform mass in the graben may be estimated in the following manner. It will be assumed (1) that the composite stratiform mass behaves as a unit, and (2) that for the sedimentary rocks the proportion of 43 percent sandstone and 57 percent shale is a reasonable distribution. Using the elastic and strength data in table 3, other elastic data, and the thickness data for the sedimentary rocks, lava, and diabase in the stratigraphic columns in figure 3, the average tensile strength is estimated to be 340 lb/in^2 (24 kg/cm^2) and the average value of Young's modulus to be

[6] The so-called Great Fault is formed by the coalescence of numerous faults.

TABLE 3.—*Mechanical strength of selected rocks*

Rock type	Locality	Tensile strength		Shearing strength		Transverse strength (modulus of rupture)		Source of data
		lbf/in²	kgf/cm²	lbf/in²	kgf/cm²	lbf/in²	kgf/cm²	
Granite	----	420–710	30–50	2,130–4,267	150–300	1,422–2,844	100–200	Kessler (1927).
Granite	----	1,308–1,800	92–126	--	--	--	--	D'Andrea, Fischer, and Fogelson (1965).
Granite gneiss	----	854–2,054	60–144	--	--	--	--	Do.
Schist	----	1,273–1,330	89–93	--	--	--	--	Do.
Basalt	Dresser, Polk County, Wis.	2,290	161	--	--	--	--	Do.
Basalt	Near Minneapolis, Hennepin County, Minn.	1,552	109	--	--	--	--	Do.
Basalt	Champion Copper mine, Michigan.	--	--	--	--	3,800	267	Windes (1950).
Basalt	Ahmeek Copper mine, Michigan.	--	--	--	--	2,500	176	Do.
Diabase, coarse grained.	Michigan	--	--	--	--	4,500–5,800	317–408	Do.
Diabase, fine grained.	----do	--	--	--	--	5,200–5,400	366–380	Do.
Gabbro from Duluth Gabbro Complex.	Near Duluth, St. Louis County, Minn.	1,305	92	--	--	--	--	D'Andrea, Fischer, and Fogelson (1965).
Triassic sandstone.	Hummelstown, Pa	--	--	--	--	1,138	80	Kessler (1927).
Triassic sandstone.	East Longmeadow, Mass.	284	20	2,702	190	--	--	Do.
Triassic shale (weathered).	New Brunswick, N.J.	--	--	996	70	--	--	Jumikis (1966).
Sandstone	Amherst, Ohio	135	9.5	--	--	--	--	Obert, Windes, and Duvall (1946).
Sandstone	Waterford, Ohio	206	14.5	--	--	--	--	Do.
Sandstone	----	40–165	3–12	--	--	--	--	D'Andrea, Fischer, and Fogelson, (1965).

2.7×10^6 lb/in² (1.89×10^5 kg/cm²). The unit elongation of such a flat-lying block just prior to fracture is:

$$\frac{3.4\times10^2}{2.7\times10^6}=1.3\times10^{-4} \text{ unit elongation.}$$

This amounts to an extension of 243 inches (21 ft) for a 30 mile width.

A comparison of the estimated increase in length, by stretching, of the Newark rocks in the formation of the arch of 0.35 mile for a graben thickness of 10,560 feet with the estimated elastic extension of 21 feet in 30 miles, for a flat-lying stratiform block, shows clearly that, if the composite assemblage behaved as a single unit, rupture would take place with the formation of tensional cracks. Tensional joints would be developed. Actually, in arching, the graben assemblage did not behave completely as a unit, but slipping along the bedding planes, postulated by Von Bubnoff (1963), must have occurred and tensional cracks and joints must have been formed (fig. 9). As the upper surface of the arch developed tensional cracks, the neutral stress surface would shift downwards toward the compression side. Because the flank of the central anticline is no longer available for observation in New Jersey, this mechanical behavior cannot be proven. For the complementary case of the border syncline, where folding was produced by compression, field observation close to the fault wall has revealed small dragfolds in the shale member of the Brunswick Formation. These appear in the shale beds that are confined by the more competent sandstone layers. These sandstone layers have developed a type of jointing similar to the ball and socket jointing that is sometimes observed in columnar basalt.

THE FORMATION OF A REGIONAL ARCH

The formation of the regional arch by uplift from below may be treated as a problem in the mechanics of buckling. When a system is buckled, it changes its geometry; for masses involving large geologic structures, this change may be very significant. Von Bubnoff (1963) has illustrated rather clearly the geometry of the change which can take place (fig. 9), and has emphasized that a slip surface must develop and that most commonly it is the bedding plane. His sketch suggests the type of space problems ideally developed at the ends of such a fold. The geometric change in a folded slab will depend on the ratio of the length to the thickness of the slab and the curvature of the arch.

The estimated geometric change in, the Newark graben will depend on the thickness assumed for the Triassic section, either 10,000 or 25,000 feet (3,048 or 7,620 m) and on the width of the basin. Sanders (1963) estimates the width of the basin in New Jersey to be 50 to 70 miles (80.5–113 km) across. Field observations show that the preexisting fault plane dipped 70° to 75° under the graben and thus gave rise to a trapezoidal volume (a truncated

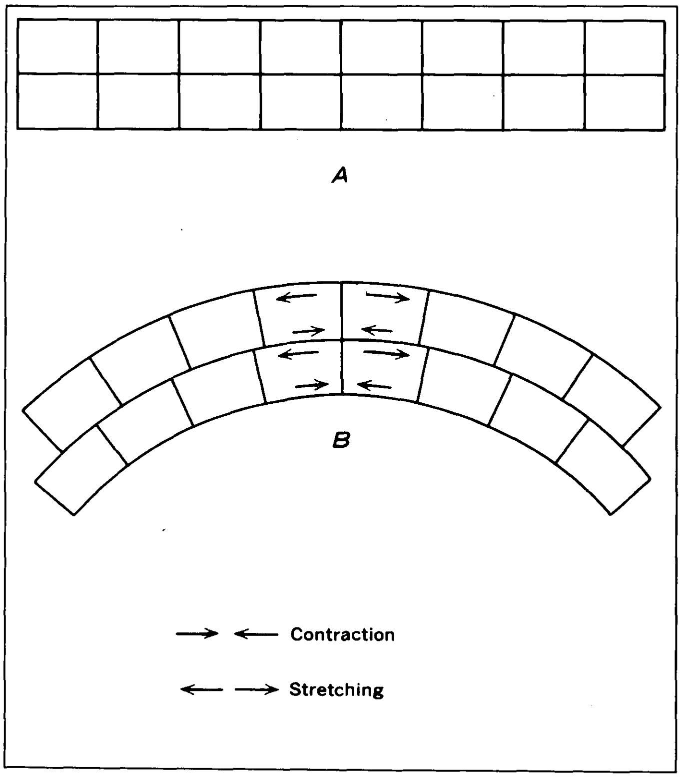


FIGURE 9.—Geometric changes produced by folding horizontal beds to form an arch. The bedding plane becomes a slip surface. (From Von Bubnoff (1963); published by permission of Oliver & Boyd Ltd.)

pyramid with its base at the Earth's surface). Field observations further show that during the arching of the basin a major tension fault developed between the horst and the basin and that the displacement of these elements was of a considerable order of magnitude.

An arch may be produced in this manner by a number of mechanical systems. One explanation assumes that compressive forces were exerted by the granitic walls of the horst upon the layered sequences of the graben in the manner of a vise with slipping jaws. Another explanation assumes a large heat source to underlie the structure. The rocks above the heat source expand and form an arch. Murawski (1968) has shown another mechanism by which arching may take place. If a region is under tension, the weakest structural element may be subject to dislocation. If this element is dropped into a zone where the element is forced to adjust to a new geometry, arching may occur. (See fig. 10.)

If that part of the Earth's crust containing the Newark graben and its structural host, the granitic horsts, were simultaneously subjected to a strong tensional force acting normal to the long axis of the graben, then major rupture with dislocation would occur in the weakest part or parts. If such rupture did take place, then the field evidence should show where it occurred. The graben was not serially shear faulted. The only evidence of a major faulting is that along the graben-horst wall. This observation suggests that the weakest zones in the system were the preexisting fault planes between the graben and the horst walls, and rupture and dislocation took place in these zones with the contents of the graben dropping deeper into the opening created by the pulling apart of the walls of the horsts in response to the tensional force (fig. 10*A*).

This dislocation of the graben probably took place over some period of time, and it was a discontinuous process. As a consequence of the adjustment of the downfaulted block to the limitations of space in its new position, it folded into a central major anticline and two border minor synclines (fig. 10*B*). If, after the forming of this complex structure, erosion takes place to remove much of the central anticline, the border synclines will become topographically prom-

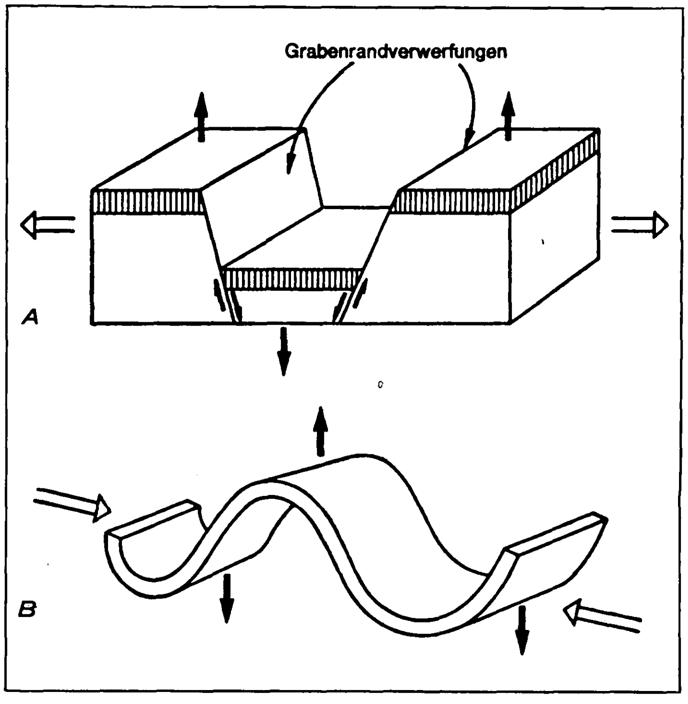


FIGURE 10.—Schematic representation of a tectonic graben (*A*) and folds (*B*). *A*, Wide open arrows = horizontal tension (stretching); narrow solid arrows = vertical relative movement; curved arrows = relative movement on the graben fault border. *B*, Two synclines and one anticline; side open arrows = horizontal compression; narrow solid arrows = vertical relative movement. From Murawski (1968).

inent features, especially if there are resistant layers such as basalt in the layered sequence which compose them. The present topographic expression of the basalt flows of Third Mountain in New Jersey and its counterparts in Connecticut and Massachusetts fit this model. In figure 1, Long Hill, Riker's Hill, Hook Mountain, and Packanack Mountain are continuous parts of the southeast wall of the syncline. The New Vernon trap sheet and two small outcrops against the granitic wall in the vicinity of Towaco, on Hook Mountain, are parts of the upturned edge of the northwest wall of the syncline which are pressed against the granitic wall of the horst. It is my opinion that the structure of the three Watchung Mountains conforms to the structural model proposed by Murawski (1968).

TRIASSIC TENSIONAL HISTORY, ITS EFFECT ON THE DEVELOPMENT OF THE NEWARK BASIN AND ITS GLOBAL CAUSE—A SUMMARY

The history of the Newark basin strongly manifests a state of tension in the earth's crust in the vicinity of eastern North America during Late Triassic and probably extending into Early Jurassic time. Three events in particular signalize tension as the major factor in the geologic forces which prevailed in determining Triassic events. These were rifting with the development of the rift zones and the formation of the graben, deep rifting in the graben which permitted volcanism with the outpourings of the flows and the intrusion of the diabase sills, and finally downfaulting of the contents of the graben with the deformation of the block into an arch with border synclines.

The oft-repeated cycle of downfaulting followed by basin filling suggests a region in a state of isostatic unbalance constantly striving to achieve balance. As a result of the gravitative adjustments in the graben, the sialic roots of the crust in this region were being forced deeper and deeper into the underlying sima, and it in turn was being laterally displaced. Near the end of Triassic time major deep rifting took place throughout the Newark basin. These rifts were multiple and long and the rift zones extended from Nova Scotia to at least as far south as North Carolina. They were also deep-seated rifts, for they tapped locally molten basaltic layers that were probably located in the vicinity of the Mohorovicic discontinuity at a depth of about 20.5 miles (33 km). The multiple character of the volcanicity proves that the rifting was not a single event. It probably consisted of three major periods of rifting, each period in itself being a multiple event. The time relations for these events in the Watchung have already been given.

In seeking a cause for the tensional processes operative in the Newark basin during the Triassic, and probably into the Jurassic, a parallelism between the results of these processes and the major disruptive events involving the breakup of the continent Pangaea is clearly apparent. It is suggested here (1) that the period of graben formation in the Newark basin is a reflection of the state of tensional stress in the continent Pangaea at that time, and (2) that the development of the rift zones which permitted the outpouring of basaltic magma and the major event to affect the Newark basin (downfaulting) occurred during the events leading up to and including the breaking apart of the landmass formerly composed of the then new continents of North America, Europe, and Africa.

It should be noted that Du Toit (1937) was probably the first to point out the connection between the voluminous outpourings of basalt in many regions of the Earth and the timing of continental drift. His views on this subject of volcanism are now generally accepted.

The suggestions, proposed in this publication, concerning the events in the Triassic of eastern North America agree with the interpretations of geophysicists on the subject of the breakup of Pangaea and the formation of the North Atlantic.

Roy (1972, p. 103) on the basis of paleolatitude studies concluded that "the rupture of the block and the opening of the North Atlantic did not follow each other closely in time" and on p. 104 "In fact the block could have ruptured without creating an appreciable longitudinal opening, as the paleomagnetic data presented here seem to indicate" and again on page 113 "The best estimate is that the time of rupture is pre-Upper Triassic * * * [and] that the time of the opening of the North Atlantic was probably Jurassic." Wilson (1963, p. 99) has proposed that the rift that formed the Atlantic developed before the start of the Cretaceous about 120 million years ago.

These data from paleolatitude studies—rupture, and some separation—would correspond to the periods of strong tensional stress in the history of the Newark basin.

SUPPLEMENTARY TOPICS

SOME CHARACTERISTICS OF FISSURE ERUPTIONS

Fissure eruptions are one of the important types of volcanic phenomena and are so-named because they originate from fissures—long cracks rending the surface of the earth. The lava ascends to the surface along the crack or system of innumerable cracks and wells forth for the most part as a quiet steady stream or sheet. As Sapper (1931, p. 8) has put it "Still more tremendous than fissure eruptions on steep slopes are such eruptions in the open country where the whole fissure becomes a volcano." The term "fissure eruption" as used in this study thus refers to those eruptions which take place from fissures of great length, commonly many miles long, and is not concerned with flank eruptions, or fissure eruptions on shield volcanoes.

The considerable fluidity of the lava that issues from fissure eruptions has attracted much notice and has been attributed to their chemistry and volatile content. Washington (1922) has reiterated the observation that these lavas are exceptionally fluid at the time of extrusion, and he attributes the low viscosity to their chemical composition—they contain a notably high percentage of iron oxides, especially ferrous oxide. He based his opinion on the well-known fluxing action of ferrous oxide and manganous oxide in metallurgical slags (Fulton, 1910). Washington emphasizes the field observation that fissure eruptions, in general, show slight explosive activity and concludes that the magmas were not rich in a gaseous phase. It has also been suggested that the fluidity of the magmas giving rise to fissure eruptions has been maintained because of the rapid rate at which the magma moves from its chamber to the Earth's surface. If this is true, then the ascent of lava on a system of innumerable fissures would greatly influence the maintenance of the fluidity and by providing many paths of travel to the surface would allow a large volume of molten rock to be moved quickly.

The eruption and flow rate of basalt from fissure eruptions have been studied by Shaw and Swanson (1970, p. 292) with particular reference to the basalts of the Columbia River Group. They have calculated the probable total time of emplacement of such flows and find that "For example, the 3 m conduit with 3 km strike length gives a total flow rate of about 0.6 km^3/hour for a hydraulic slope of 0.1. A reference volume of 100 km^3 for a 'typical' Yakima flow would then imply a total emplacement time of about a week (2 days for the 5 m conduit, etc.)."

The possibility of even slight explosive activity initiating a fissure eruption has been questioned by Thorarinsson (1966) on the basis of recent field studies. He thinks that the tephra produced at the Eldja fissure eruption in Iceland "resulted mainly from a very vigorous lava fountain activity and not from explosive activity." The geometry of the surface formed by the intersection of a fissure and the surface of the Earth would be similar to that of a long ribbon, and this surface would have a tremendous area. Lava welling forth from this vent and presented, at every instant, with such a large surface would be capable of discharging any significant excess of gaseous phase, and thus there would be no tendency to buildup explosive energy; Iddings (1914, p. 263) has expressed a similar view.

Geological descriptions of the fissure eruptions in the Columbia River plateau (Von Richthofen, 1868, 1901, p. 542; Geike, 1882; Fuller, 1927), the Watchungs (Darton, 1889, 1890 ; Faust, unpub. data), in Britain (Geike, 1882), the Deccan of India (Wadia, 1953, chapter 10), in Iceland (Thorarinsson, 1966), and elsewhere indicate that a fissure eruption proceeds as follows: The fissure or fissures form, followed later by very minor explosive activity, and then the molten lava pours out of the fissure system as a great flood. The lava fills all the depressions in the land surface and levels the topography which it covers in a manner analogous to water flooding. It is possible in examining a lava field of some recent fissure eruptions to actually map the flowlines on the surface of the lava sheet as was done at Mount Eccles (Boutakoff, 1963). If the eruption takes place over a flat land-surface, the flood pours out over vast areas, and the flows may attain great thicknesses. There may be a succession of flows so that one sheet lies directly above another, or the flows may alternate with sediments deposited during an interruption in the volcanism. During an eruption, the fissures may lengthen. If a fissure is closed with solidified lava, it may reopen to permit the flow of lava again. This passage of several flows of lava through the same fissure gives rise to multiple dikes. Old fissures may be paralleled by new fissures from which the lava flows. Some lava-filled fissures never opened at the surface.

Regarding the fissures he observed, Geikie (1882, p. 282) writes: "These fissures, whether due to sudden shocks or slow disruption, were produced with such irresistible force as to preserve their linear character and parallelism through rocks of the most diverse nature, and even across old dislocations having a throw of many thousand feet. Yet so steadily and equably did the fissuring proceed over this enormous area, that comparatively seldom was there any vertical displacement to the sides. We rarely met with a fissure which had been made a true fault with an upthrow and downthrow side."

The closing stage of a fissure eruption was interpreted by Tyrrell (1937, p. 103) to be indicated by the presence of cones along the fissures, which "merely mark the sites of the feeble final spasms of activity." It is obvious, as Tyrrell points out, that the preservation of these fragile cones, almost intact, after tremendous volumes of lava have poured out, 3 cubic miles (12.5 km^3) at Laki in 1783 (Helland, 1886) is testimony to their very late development in the dying stages of the eruption. The closing phase of the fissure eruption at Mount Eccles in Victoria, Australia, is illustrated in figure 11, where a line of small cones traces the position of the fissure from which welled the large volume of lava. It is also apparent from these illustrations that, owing to the vast areal extent of fissure eruptions, the detection of the fissures may be very difficult. This is particularly true in an area whose topography was relatively flat previous to volcanism and where erosion has removed the surficial evidence of the fissure. Fuller (1927) has described the field appearance of such a filled fissure, which is now exposed as a dike in a tributary to the Salmon River in western Idaho, and he points out that the formation of this dike marked the closing phase of a fissure eruption.

The shape of a fissure eruption in open country, where it is unlimited by topographic barriers, tends to be pseudorectangular with its longest dimension parallel to the fissure system. This is illustrated in the schematic diagram of Von Knebel and Reck (1912) given in figure 12. It is for this geometric reason that fissure eruptions are called linear eruptions by some petrologists and volcanologists (Von Wolff, 1914, see p. 304, 306, 409).

The concept of lava flowing out in the manner of a flood had been envisioned by a number of geologists in addition to Von Richthofen, (1868). Powell (1875, p. 196), in his explorations of the Colorado River observed "The fissure of this fault has been the channel through which floods of lava have been forced from depths below into the upper world." Dutton (1880, p. 176) observed in his discussion of the history of the Tushar "while the grander floods poured out over everything and spread out over great expanses of the mountainside." Geike (1882), aware of the work of these authors, used the term "flood basalt" to designate the rocks formed by a fissure eruption in allusion to the manner of em-

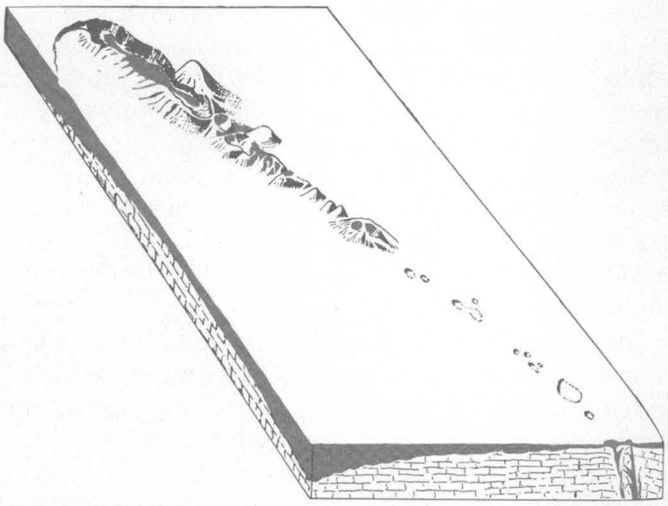


FIGURE 11.—Block diagram of the Mount Eccles fissure eruption in Victoria, Australia, showing the late-stage vents which trace the course of the fissure. From Boutakoff (1963), with permission of the Director of the Geological Survey of Victoria.

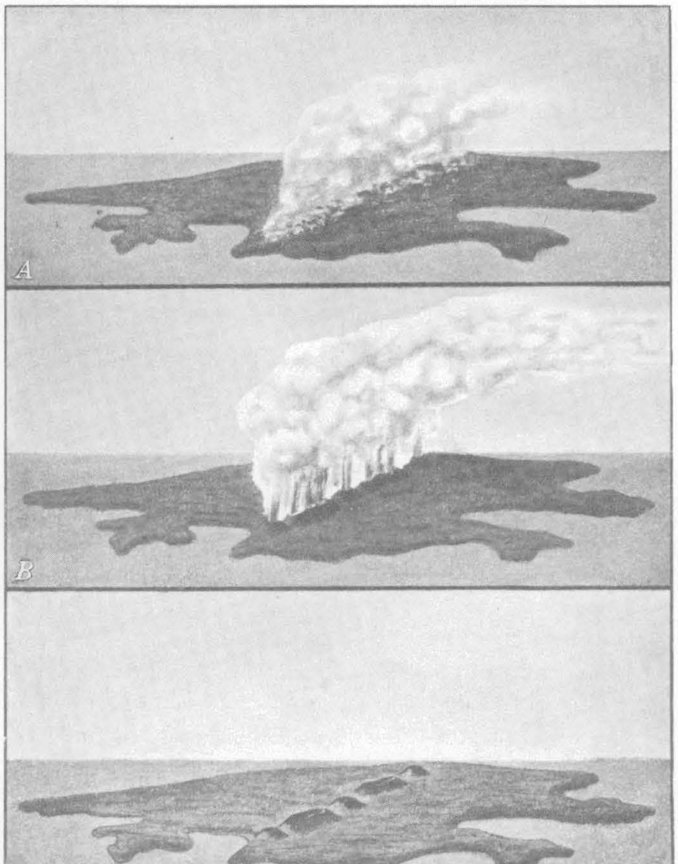


FIGURE 12.—Schematic representation of a fissure eruption showing the linear formation of the late stage vents in the closing phase (*A* and *B*) and after the eruption has ceased (*C*). Taken from Von Knebel and Reck (1912).

placement of the lavas. Although such rocks have also been called plateau basalts, because some plateaus are formed of these rocks, Tyrrell (1937) remarked that the occurrence of these lavas as plateaus is due solely to geologic changes unrelated to volcanism. Schneider (1911, p. 48, 50, 66) called fissure eruptions "pedionites" based on the Greek word pedion meaning flat. He regarded such eruptions as producing the least limited type of volcano.

The actual time span of fissure eruptions and their geometric extent are known for only a few of these events. Data given by Barth (1950) and Rittmann (1962) for eruptions in Iceland are summarized as follows:

Laki eruption:
- Length of fissures = 25 km (about 15.5 miles)
- Volume of lava = 12 km^3 (about 2.88 cubic miles)
- Volume of fragmentary material = 2 km^3 (about 0.48 cubic miles)
- Flooded area = 565 km^2 (about 218.1 square miles)
- Climax of the eruption = 4½ months after it started.
- Date of eruption = 1783–85 A.D.

Eldja eruption:
- Length of fissure = 30 km (about 18.6 miles)
- Volume of lava = 9 km^3 (about 2.16 cubic miles)
- Volume of ash not known.
- Flooded area = 700 km^2 (about 270.3 square miles)
- Date of eruption = Around 950 A.D. when Iceland was first settled.

Fissure eruptions were first called massive eruptions, and it is of interest that the first recognition of the importance of fissure eruptions was made on the Pacific coast in 1868 by Ferdinand Baron Von Richthofen. Von Richthofen's (1868) work was ridiculed in England by Scrope (1869) and did not find favor in Europe until 1881–82 when Sir Archibald Geikie after his return from field study in the western United States affirmed the field observations on massive eruptions made by Von Richthofen and exposed the error of Scrope. Scrope had made extensive geomorphological studies of the volcanoes in the Auvergné region of France, and he had observed the results of the erosion of the cones and craters of central-type volcanoes; on this basis he concluded that Von Richthofen had erred and that he had examined the erosional remnants of the former loci of volcanism (Geikie, 1882, p. 276). Geike was an admirer of Scrope's work, but he was troubled by his own observations of the lava flows in the British Isles, specifically in the basaltic plateaus of Ireland and Scotland, where he found the abundant related dike swarms and no connection whatsoever with any central type vents. Geikie in order to satisfy his own doubts of Scrope's (1869) aggressive condemnation of the work of Von Richthofen (1868), traveled to the Columbia River plateau and made extensive studies in the area, and he described his conclusion as follows (Geikie, 1882, p. 277–278): "A recent journey in Western America has at last lifted the mist from geological vision. Having travelled for many leagues over some of the lava-fields of the Pacific slope, I have been enabled to realize the conditions of volcanism described by Von Richthofen, and without acquiescing in all his theoretical conclusions, to judge the reality of the distinction which he rightly drew between 'Massive Eruptions' and ordinary volcanoes with cones and craters."

Although Geikie (1882) accepted unequivocally Von Richthofen's (1868) concept of massive eruptions, some of his English colleagues, still influenced by Scrope, were more reserved; 17 years later, for example, Bonney (1899, p. 133) wrote "Before preceeding further in the study of natural dissections of a volcanic mountain we may pause to examine *one rather abnormal form of eruption, traces of which may be occasionally recognized.*[7] Fissure eruptions, as discharges of this kind are called, are characterized by the general absence of cones, at least of any importance, and by the large area which is covered by the lava-flows." Bonney then gave an account of fissure eruptions including Geikie's (1882) descriptions. Harker (1909) on the contrary recognized the importance of Von Richthofen's discovery and noted its wide application in volcanology.

American geologists were, in general, quick to recognize the concept of massive eruptions, as, for example, Darton (1890, p. 16) and Russell (1897, p. 252), who specifically credit Von Richthofen with the discovery.

As Tyrrell (1937, p. 100, 102) has put it "The fissure eruption theory, promulgated by Von Richthofen and popularized by Sir Archibald Geikie, has been almost universally accepted * * *."

Several volcanologists urged that a distinction should be made between fissure eruptions and flank eruptions on central-type volcanoes. Sapper (1931) and Rittmann (1962, p. 46) have both made such

[7] Italics by G. T. F.

statements. They emphasized the two major points of difference—firstly, flank eruptions are fissures on central-type volcanoes, whereas fissure eruptions have no relation to central-type eruptions, and secondly, the length of the fissures in fissure eruptions is of a much higher order of magnitude than the short fissures forming the vent of flank eruptions.

The possible relationship between fissure eruptions of the massive type and the domes of the Hawaiian type have been considered by Stearns and Clark (1930, p. 139) and Cotton (1952).

VESICULATION IN BASALTIC MAGMA

THE PROCESS OF BUBBLE FORMATION AND MOVEMENT

Vesiculation is the process by which a very viscous liquid, such as a basaltic magma, exsolves a gaseous phase to form bubbles. The interfaces of these bubbles with the liquid are commonly spheroidal. Their former presence in the magma is attested to by the presence of cavities in the basalts called vesicles. The formation of bubbles in silicate melts has been studied extensively by glass technologists, and especially reported by the Deutschen Glastechnischen Gesellschaft (1955). To a lesser extent it has been investigated by silicate chemists concerned with metallurgical slags. Their experimental studies and particularly their large-scale industrial plant practices show that:

1. If a molten silicate melt flows over a rough surface, bubbles will form. When the melt wets the surface, bubbles are nucleated by the air entrapped between the melt and the rough surfaces.
2. Large bubbles will move more rapidly than small bubbles—this follows from a consideration of the term r^2 in Stoke's law
$$v=\frac{2r^2\cdot g\ (\rho_{\text{melt}}-\rho_{\text{gas}})}{9\eta}$$
where v = the rising velocity of the gas, r = radius of the bubble, $(\rho_{\text{melt}}-\rho_{\text{gas}})$ = difference in densities, g = acceleration of gravity, and η, the viscosity.
3. A decrease in viscosity of the melt will increase the rising velocity—also apparent in the above equation—as η gets smaller, v increases.
4. As a bubble rises through zones of supersaturation, it grows by diffusion of gases through the melt, and, as its radius increases its rising velocity increases. The converse situation obtains if the bubble enters zones of undersaturation.
5. Bubbles that reach the surface of the melt may burst—this will depend on the thickness of the film of glass containing the bubble, the internal pressure of the bubble, and the surface tension of the melt.

It had formerly been assumed that the large bubbles grew chiefly through the coalesence of small bubbles as they collided on their ascent in the melt and that the larger bubbles served as collectors of small bubbles which they then dragged along with them. Modern studies show that this mechanism plays only a minor part in the growth of bubbles. Bubbles grow by diffusion of gases from the melt at the level where the bubble temporarily rests. As the bubble moves to higher levels in the melt, more gases diffuse to it and its size increases; this growth goes on until the bubble reaches the surface of the melt or another interface.

Experimental studies on glasses indicate that thermal shock may aid in the nucleation of bubbles. A system is said to be in thermal shock when it, or any part of it, is suddenly subjected to a drastic change in temperature.

BUBBLE FORMATION IN A NATURAL LAVA FLOW

The basalt magma when it is in the earth, before extrusion, will have its internal pressure (=the vapor pressure) at a much lower value than that of the external pressure. If, as the magma ascends to the surface, its vapor pressure exceeds the external pressure upon it (sum of hydraulic pressure of overlying lava and the atmosphere), then gases will be exsolved to form bubbles.

As the lava continues to flow over the rough and porous sandy floors, this movement could supply considerable trapped air and steam which could be incorporated as bubbles in the flow.

The process of bubble formation and movement is thus regulated by two phenomena—the equilibrium process and the rate processes. The equilibrium process is controlled by the vapor pressure of the melt. If, as during a volcanic eruption, the external pressure is reduced, then vesiculation of the lava can take place. The vapor pressure of a melt is generally not constant, and it can be increased by crystallization of volatile free silicates. The rate processes operating in a melt are nucleation of bubbles, gas diffusion to the bubbles, and the rise of the bubbles in the melt.

The addition of bubbles at the base of the flow when it pours out over rough surfaces is an aid to the rate processes in that it probably provides nuclei.

As the bubbles ascend in the liquid part of the flow their shape may vary, and this characteristic will be dependent upon a number of factors but the most important will be the velocity with which they ascend.

After the flow has come to rest, it continues to evolve bubbles and begins to cool. The natural system is complicated by the fact that the system is losing a gaseous phase to the atmosphere in significant amounts only so long as the surface is still liquid. After the surface of the flow hardens, the loss by escape into the atmosphere is greatly decreased and is probably chiefly limited to escape along the joint systems in the vesicular tops of the flow. After the vesicular top has formed to a depth of a few feet, the bubbles that rise to the liquid-solid interface at the base of the hardened top will accumulate there.

The evolution of bubbles in the lava flow as a result of the exsolution, after it has been emplaced, is a continuous process, but the rate of bubble formation may be changed significantly by a number of other physical factors. These factors may operate so as to produce unusual concentrations of bubbles in the later stages of solidification of the lava flow. As the lava flow continues to solidify the residual liquor will be richer in volatiles, and these will decrease the viscosity thereby aiding the formation and growth of bubbles. Concomitant with these conditions there will be developed a greater tendency for the system to form larger crystals.

Some of the bubbles which migrate to the upper surface of the liquid flow will burst and release the gaseous phase to the atmosphere. The pressure in a bubble is the sum of three pressures, the atmospheric pressure, hydrostatic pressure, and the pressure caused by surface tension. The internal pressure within the bubbles of various sizes caused by the surface tension can be calculated from the formula given by Widtman (1956, p. 498) which states that

$$p = \frac{2\sigma}{r \times 10^{-6}},$$

where σ is expressed in dynes per centimeter, the radius (r) is in centimeters, and the pressure (p) is in atmospheres. The surface tension of the Watchung Basalt has been calculated using the average composition of the 22 specimens (table 1, column 2) the surface tension factors for the oxides given by Morey (1954, p. 198, 206, 207), and taking the factor for FeO as the same as MgO. This gives a value of 405 dyn/cm for the surface tension at 1,200°C. Using the formula for the internal pressure at 1,200°C for bubbles of 1/1,000-mm, 1-mm, and 6-mm radius, the respective pressures are 8.1, 0.0081 and 0.00135 atmospheres. These values show that the pressure caused by surface tension in the liquid lava of the Watchung flows becomes negligible for bubbles 1 mm in radius and larger compared to the atmospheric pressure and the hydrostatic pressure. From Widtmann's (1956) equation it is apparent that the pressure to form a new bubble is tremendously large, and he has pointed out (p. 498): "One can, therefore, assume that one is dealing here primarily with a spontaneous growth of seed nuclei due to 'thermal fluctuations' and that these nuclei can continue to grow later on." Those bubbles that do not burst will retain their gas, and this gaseous phase will probably react with the walls of the vesicles as the temperature drops in the system. Some of the gas may redissolve in the melt. Any gas not used up in such reactions will later escape in the process of weathering.

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