

THE HOLYOKE RANGE AND CONNECTICUT VALLEY STRUCTURE.

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ABSTRACT. The Holyoke Range owes its relief to a thick basalt flow which is one of a series of formations filling a deep basin. The clastics were washed from an eastern highland but the volcanics came from centers near the middle of the valley. The principal notches are located on fault traces. The east side of the faults moved southward essentially horizontally relative to the west wall. Movement was contemporaneous with basin fill. The southward movement caused greater flexure than fracture. Compression of the eastern basin fill between the eastern highland and the western basin is conspicuous.

LOCATION AND SIGNIFICANCE.

THE Holyoke Range is at the north end of the wide part of the Connecticut Valley. Triassic sedimentary and volcanic rocks underlie the lowland and strike parallel to the length of the basin except at three places. The Holyoke Range is the most conspicuous of these localities. One hundred feet of relief is unusual in the lowland but the range rises more than 800 feet above its surroundings. (Plate I.) A thick basalt flow usually covers its top and south slope.

The main ridge extends almost due westward for nine miles from the crystallines of an eastern highland to the Connecticut River. The Mount Tom Range is west of the river and has the same formations but turned so that they strike parallel to the length of the valley. The position of the Holyoke Range affords a particularly good cross section of the valley and an opportunity to examine its structure not available elsewhere.

The region is particularly significant for a number of reasons and the most important ones are listed below.

1. It is one of two localities where a recognized horizon can be followed directly outward from the eastern highland to the center of the basin and the textural variation in the sediment observed at short space intervals.
2. It is one of two localities where the thickness of the main lava flow can be measured across more than half the width of the basin.
3. It is the only place where flow directions in the main lava sheet have been identified as outward from contemporary volcanoes.
4. Two key horizons separated by a thick conglomerate facilitate mapping fault traces and dating movements relative to stage of basin filling.

These and many minor reasons make this range a key region in study of Connecticut Valley structure.

SCOPE OF THE STUDY.

This study proposes to analyse the formation displacements at the north end of the Connecticut Valley occurring since extrusion of the Holyoke flow. A detailed map shows the fault and flexural displacements in the Holyoke Range. (Fig. 1.) A more general plan for a larger area shows the diminishing magnitude of distortions to southward and westward. (Fig. 2.) The principal structural and stratigraphic units have been computed to a datum plane 100 feet above sea level to eliminate features which are more impressive than important. (Fig. 3.)

Present expositions of Connecticut Valley structure are incompatible with so many observations that a new explanation seems necessary to account for the movements causing the displacements. The outline for a tentative picture of structural development in this region is offered; it should be regarded as strictly tentative but not incompatible with any known observations.

The region has been used as a practise ground for college survey classes for more than 12 years. Most of the territory has been surveyed twice and the author has been with parties for at least half their field periods. During this time he has examined the area in minute detail. The map is a simplification of one on 500 feet to the inch compiled from party stadia survey plans. Each field plan was approximately one half mile east and west along the crest of the range and extended down the north or south slope to the nearest road.

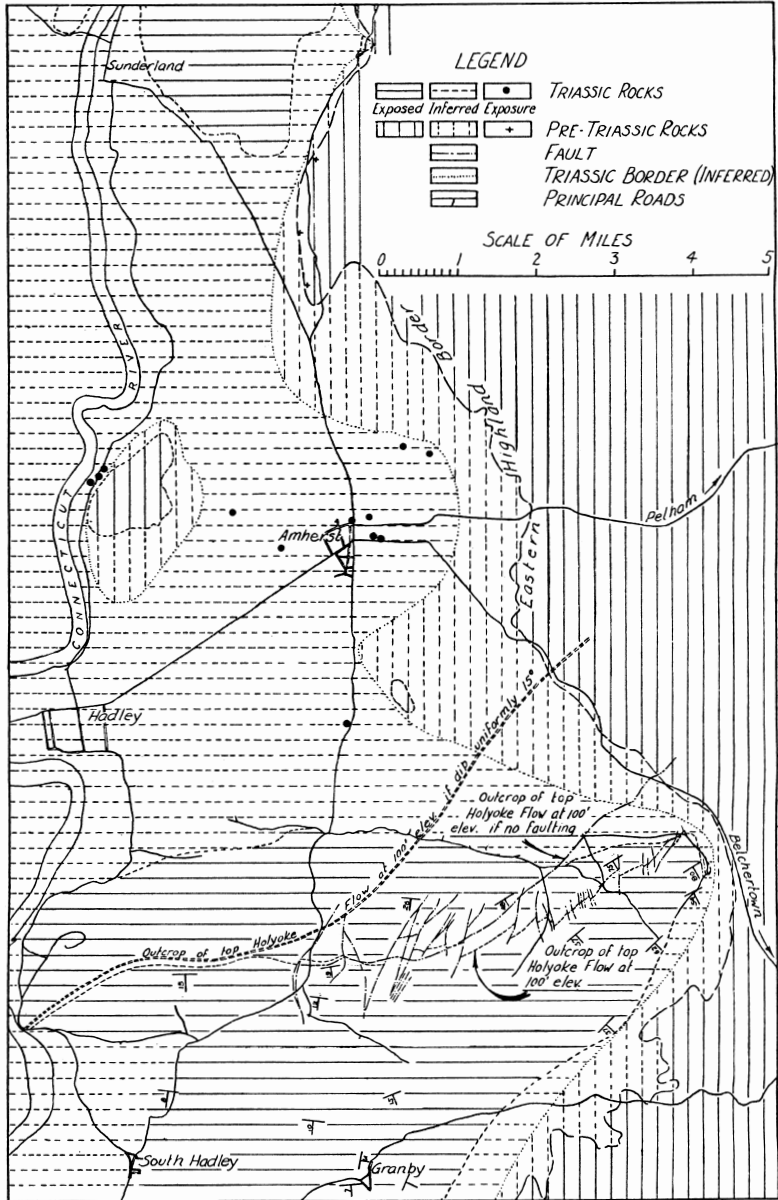


Fig. 2. Map showing location of the principal roads, rocks and structures near the Holyoke Range.

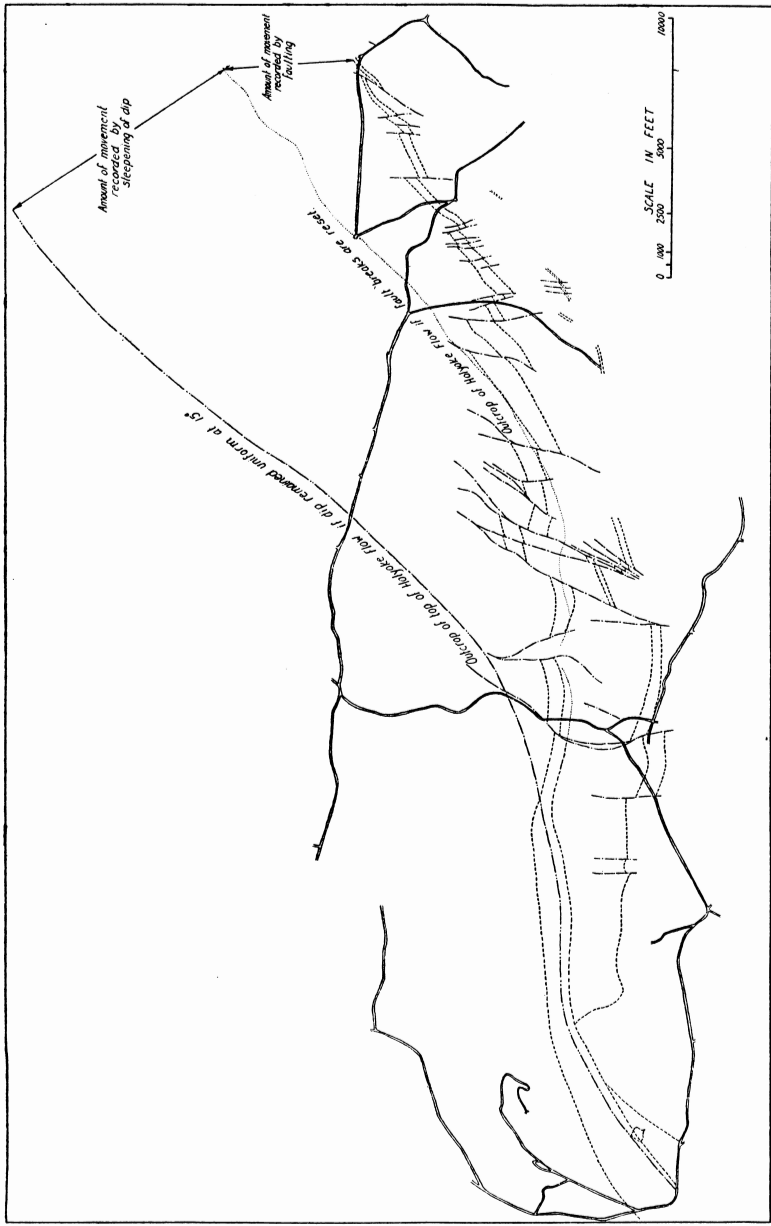


Fig. 3. Map showing position of formations and structures computed to datum at 100 feet above sea level. The roads have the same position that they occupy in Figure 2 in order to show shift of structures at a different level. Note the outcrop position of the top of the Holyoke flow (1) if faults are reset and (2) if the flexures are straightened to the average outside the highly deformed zone.



Fig. 1. Topographic and geologic map of the Holyoke Range. The different volcanic horizons are indicated by different symbols. The sedimentary formations can be distinguished by their position relative to these key horizons.

SUMMARY.

A few features of the structure are preeminent and are listed below to clarify the presentation which follows.

Faulting.

1. The faulted zone is located in the eastern half of the range.
2. The fault planes are vertical and their trace is usually curved with the center of the radius of curvature east of the fault except in the case of the far eastern ones.
3. Fluting on the fault plane, too deep to be the result of an occasional or incidental movement, is almost horizontal.
4. The eastern block has moved southward and upward relative to the western block along all eastern faults. Near the west end of the faulted section many long blocks are gently arched and the bordering fault splinters are depressed relative to them.
5. The east end of the Holyoke flow has moved south 5000 feet as a result of all fault displacements.
6. At least one fault made a scarp in the oldest part of the Granby tuff bed and does not displace a lava flow in the middle of it. Along western faults, displacement of the Granby tuff bed is usually less than that for the top of the Holyoke flow. These facts suggest that movement was contemporaneous with basin fill.

Flexure.

1. Dip in the western part of the Holyoke Range is $15^{\circ} \pm 3^{\circ}$. Dip increases progressively from the Notch eastward and attains a maximum of 80° at the east end. Overturned beds are unknown.
2. Dip, in the steeply inclined zone, is southeastward towards the highland border and for any meridian becomes more gentle to southward.
3. Steepening of dip requires that the east end of the Holyoke flow shall have moved southeastward 9800 feet. (This is a southeast rotary movement in contrast to the simple southward movement along the faults.)

Other features.

1. Both the Holyoke flow and the overlying conglomerate formation are thickest at the Flat Mountain section.

2. One very persistent volcanic center is situated on Dry Brook southeast from Mount Holyoke and another is located near Mount Hitchcock. The Holyoke flow poured northwestward and eastward from the Mount Hitchcock center.
3. The arkose beneath the Holyoke flow is very thick west of these volcanoes.
4. About one half mile of sedimentary and volcanic rocks overlie the Holyoke flow along the line of the South Hadley to Granby road. The upper beds are almost undisturbed.

Outline of tentative structural history.

While the basin was being filled with sediment and volcanic products, the deposits were affected by a southward or south by southwestward movement of the eastern highland. Rotation of the northeast end of the thick, competent Holyoke lava caused it to be compressed between the inactive fill to westward and the highland buttress to eastward. It broke on many fault planes. The eastern fault blocks were thrust and tipped upward to the west as they were compressed during the main southward or south by southwestward movement. Concentrated displacement occurs only in competent formations like the lava and movement is disperse in arkose and shale distant from the volcanics. Most movement in this region antedated deposition of the Chicopee shale which is only slightly disturbed.

STRATIGRAPHIC SEQUENCE.

The main problem under consideration deals with the structures in the Holyoke Range; therefore formation sequence and characteristics need be described only in sufficient detail to clarify later reference to them. Variation in character of the rocks yields some information on the early topography.

The formations represented in the area are given in the following table.

TABLE OF FORMATIONS.

	Chicopee shale	}	1200 to 1650 feet.
	Longmeadow sandstone	}	
Triassic	Granby tuff, agglomerate and lava		5 to 1000 "
	"Second" arkose and conglomerate		10 to 1450 "
	Holyoke lava flow		100 to 550 "
	Sugarloaf arkose		4000 (?) "

Pre-Triassic Complex of schist, gneiss and granite

The Sugarloaf arkose underlies most of the lowland north of the range. Distribution around Amherst and South Amherst is based upon well samples. Here it lies upon gneiss or granite with the contact at about 100 feet above sea level. The rock has numerous cobbles, especially in the lower beds near the east end of the range. Pebbles are usually less than two inches in diameter west of Bare Mountain but become progressively larger and more numerous eastward; two-foot boulders are not unusual at Flat Mountain. The bed immediately below the Holyoke lava changes from a ferruginous, sandy shale at Mount Holyoke to a fine arkose with one-eighth of an inch grains at Bare Mountain; it has one-inch pebbles at Mount Norwottock and three-inch cobbles are present at the east end of the range. Size indicates an eastern source for the material and cross bedding shows southwestward flowing streams. Stream grades were steep when the two-foot boulders were rolling into the basin but the topography was more subdued when the gravel bed below the Holyoke flow was deposited. This basin must have been flat at that time because it was covered by a lava flow whose gas tubules indicate that it moved eastward up against the gentle alluvial slope as far as the highland border.

A series of volcanic cones, piled on top of one another, lie in the Sugarloaf arkose north of Mount Hitchcock. The entire series is 1000 feet thick; 2500 feet of the base of the lowest cone is exposed and the diameter must be greater since the mountainside cuts the cone near its northern edge. Fingering masses of diabase penetrate the arkose just north of (below) the base of the volcanic cones. Arkose appears in all states of dispersion through the diabase, from individual grains to disjointed, irregular masses. No angular rock outlines were observed. This behavior is interpreted to indicate that the arkose was incoherent when the diabase intruded it.

The Holyoke lava rests upon these volcanics and the Sugarloaf arkose surrounding them. At least two flows are present from the Connecticut River to near the eastern end of the range; more may occur but they have not been identified. The lower flow is about forty feet thick, has a vesicular top at many places and its upper limit can be recognized elsewhere by discontinuity in change of rock texture. The lava is about 100 feet thick at the east end of the range, attains 225 feet thickness at the first road to westward and reaches its maximum thickness of 560 feet at the east end of Flat Mountain. The

lava is thinner westward and is 450 feet at Hilliard Knob, 350 feet at Norwottock, 240 feet at Bare Mountain and only 230 feet where it rests upon the volcanics west of Mount Hitchcock. The basalt is 400 feet through at Mount Holyoke and at most points west of the line of old volcanoes. Gas tubules in the flow just west of the Mount Hitchcock volcanic group are bent over to the northwest whereas at Mount Norwottock they are bent eastward. Flow is thereby identified as away from the thin area near Bare Mountain to basins under Mount Holyoke to westward and below Flat Mountain to eastward. These basins must have formed almost contemporaneously with extrusion since the regular progressive eastward coarsening of the sediment immediately below the flow indicates an unbroken aggradation slope during immediately preceding time. The writer believes that the Flat Mountain basin is above the zone of major movement in the crystalline floor. The top of the flow has many hummocks of scoria, particularly from Bare Mountain to within one and one-half miles from the east end of the range. These hummocks are in groups and the groups appear at wide intervals.

Conglomerate and arkose overlie unweathered scoria of the Holyoke flow to at least one mile west of Bare Mountain; some scoria seems to have been eroded along Dry Brook. This indicates that aggradation from the east was renewed after extrusion at a rate even greater than before. Also the sediment is bouldery even west of Bare Mountain and the coarse content is greater than below the flow. This arkose and conglomerate is 1250 feet thick east of Flat Mountain where it increases to a maximum of 1450 feet; the beds thin to 1420 feet at Hilliard Knob, 970 feet at Mount Norwottock and 550 feet at Bare Mountain. Volcanic activity in the region from Mount Hitchcock to Mount Holyoke prevented continuous sedimentation in more westerly regions and the thickness has little significance. The greatest thickness in the vicinity of Flat Mountain, where the fan slopes begin to rise and the lava surface to drop eastward, indicates that the major basin-making movement continued in that vicinity.

The overlying Granby tuff is partly agglomerate and has lava flows in it. The most continuous of these flows becomes the posterior sheet of the southern Connecticut Valley; it lies at the bottom of the series where the volcanics have moderate thickness but is absent in the eastern region where they are

thin and is near the middle in the vicinity of the three volcanic centers south of Bare Mountain, Mount Hitchcock, and Mount Holyoke. The Bare Mountain volcanic center is located on a power line. Two hundred feet of volcanics west of the power line end abruptly against sandstones east of it. This is interpreted as a fault contact. The volcanics to west and sandstones to east are capped by a continuous flow so that the fault is considered to be contemporaneous with the volcanic outbursts. Agglomerate occurs principally from the power line to Holyoke and this is near the main volcanic centers. Fine ash beds appear farther east; lapilli over one half inch occur but are not abundant.

Arkose and conglomerate cover the ash but agglomerate particles were not recognized in the conglomerate. Pebbles up to three inches are abundant as far west as the volcanic center south of Bare Mountain. Fine sandstones and shale prevail farther west. All beds between Granby and Holyoke are fine textured.

STRUCTURAL FEATURES.

Two types of structures record rock movement in the range. A flexural type formed without causing discontinuity in the beds and appears as progressive eastward steepening of dip. A fracture type appears as numerous fault planes of considerable displacement. The flexural structures suggest a south-eastward and upward movement of the east end of the range. The faults show a major southward component slightly below the horizontal and a minor westward component of movement for the east side of the fractures.

Faulting and associated drag.

The faults have remarkably similar features. All dip nearly vertical. The trace of the large, more continuous faults strikes southwest north of the lava and curves to a southerly direction in the younger beds. Deep groovings on the fault walls incline southward at 5° to 10° or much more gently than the dip of the beds. The east side has moved southward relative to the west side on twenty of twenty-five faults in the Holyoke flow. This is not only the most numerous type but represents the aggregate movement also.

The features of the predominant fault type are exhibited best by the break west of Flat Mountain where Sugarloaf

arkose east of the fault rests against Holyoke lava. Arkose beds in the coll between Flat Mountain and the small knob to westward strike northeast and dip 32° southeastward to within twenty feet from the fault. The strike in a narrow zone adjacent to the fault is north to northwest and the dip is 5° westward. The structure resembles a southward plunging anticline; however, the gentle limb should be regarded as due to drag by either upward or southward movement of the eastern block. That the movement is southward is established by the gentle southward pitch of flutings on a fault plane cliff and by almost perpendicular intersection of fracture cleavage with the fault surface.

Rocks east of the unusual type of fault are depressed relative to those westward. Outstanding examples of this type are the Notch fault and the east Norwottock fault. No unusual feature was observed in the east wall of either of these faults but it was noted that the west block was uparched to suggest compression. Uparching is sufficient to produce several degrees variation in strike at both Mount Norwottock and Bare Mountain. No conclusive evidence of direction of movement along this sort of fault was obtained. A poor flow cleavage in the chlorite walls of a subsidiary break in the west wall of the Notch quarry suggests vertical movement. The only explanation which seems to account for these faults of unusual type and arching to westward is that they form one side of a wedge pinched between a pressure block on the east and a slightly yielding one on the west. The western block is forced up a small amount and the pinched block is depressed an equal distance.

The fault along the power line through the east Notch does not displace the lava flow in the Granby tuff and must be earlier. Some part of the movement is later than the faulted agglomerate below the same flow. Displacement of the Granby tuff bed along faults west of Hilliard Knob is usually slightly less than displacement of the top of the Holyoke flow. No difference in displacement of the two horizons was recognized farther east because of poor exposure of the tuff. Certain abrupt changes in thickness of the Holyoke flow near faults, as just east of Flat Mountain, may be due to contemporary fault basins. Available evidence indicates that movement was in progress before the explosive volcanic stage and may antedate even the Holyoke flow.

Small faults occur in the vicinity of the volcanic center south from Mount Hitchcock. They displace the Granby tuff and its lower lava flow but do not seem to affect the Holyoke flow. They are regarded as local features associated with the nearby volcano.

Flexural displacements.

Progressive steepening of dip from Bare Mountain to the east end of the range is the outstanding feature of the flexures. The increase in dip is almost a mathematical progression; the product of the reciprocal of the distance from the westernmost disturbed zone near Bare Mountain relative to the total length of the disturbed zone and the sine of the angle of dip is approximately a constant. Since sine of the angle of dip measures the relative movement of points in a flexed surface, each unit in the region from Bare Mountain eastward may be considered to be uniformly flexed with deflection at the east end being the cumulative sum of all units.

Dip of the Holyoke flow from Bare Mountain westward is $15^{\circ} \pm 3^{\circ}$. This inclination has increased to 19° in Notch Mountain, to 26° in Mount Norwottock, to 35° in Hilliard Knob, to 48° in Flat Mountain, to 57° at the Granby road, to 75° beyond the next road to eastward, and is 80° at the east end of the range. Dip steepens north of the range in the depressed fault blocks and is 68° at one place near Hilliard Knob; the dip flattens south of the range in some of these depressed masses and beds are almost horizontal where the Notch fault crosses the Amherst-South Hadley road near Aldrich Lake. These "drag" features along the faults of "unusual" type are not disregarded but they appear in areas so local that they have negligible weight in computing averages over one mile length of the range.

Strike changes also; it is almost E.-W. from near Mount Holyoke to Bare Mountain. Within the highly disturbed zone, outcrops of beds begin to parallel the highland border southeast of the range and are strictly parallel to it for two and a half miles at the east side of the Triassic area.

Disturbance of strike and dip decreases in areas of younger beds to southward as well as westward away from the crystalline rocks. Dip diminishes from 19° at the Notch Mountain to 12° at Aldrich Lake and is only 10° near Granby. Similar changes recur at many places in the more disturbed zone far-

ther east but nowhere does dip diminish northward away from the crystalline area or from the younger sediments south of the Granby-South Hadley road. The less disturbed condition of the younger beds could be explained simply if most of the movement antedated their deposition. However, beds comparable in age with some which have 10° dip northwest of Granby have 37° dip at three miles northeastward. Southward fading of the movement, or at least of its record, is more complex and the author believes it continued in some degree until near the end of the sedimentary period.

Formations between the top of the Holyoke flow and the sandstone along the Granby-South Hadley road are approximately one-half mile thick. Using this thickness, the outcrop position for the top of the Holyoke flow at a dip of $15^\circ \pm 3^\circ$, as in the almost undisturbed zone, has been determined. Its eastern extremity is 9700 feet northwest from the position established by resetting the fault blocks and 14,300 feet N.N.W. from its present position. This indicates a southeastward movement by flexure of 9700 feet or almost twice that attained by faulting.

INTERPRETATION AND STRUCTURAL HISTORY.

Presentation of a history for the structural development of the region requires due regard for all the facts and particularly the following.

1. Movement by flexure exceeds in amount movement by fracture.
2. Two-thirds of the sediments and volcanic materials accumulated in the brief period represented by the active period of two volcanoes. They were not lithified appreciably, except near these volcanoes, until after deformation.
3. The faults are almost north-south in the younger beds but curve to a more northeasterly direction in the older rocks.
4. Movement along most faults is almost horizontal.

Before the Holyoke flow was extruded, this region had an eastern highland of crystalline rocks fronted by alluvial fans extending to an alluvial plain. The plain and part of the fans subsided to make shallow basins under what was to be Flat Mountain and the Mount Tom Range. An active volcano near Mount Hitchcock was one source for lava of the Holyoke flow. Outwash from the northeast covered the flow with arkose and

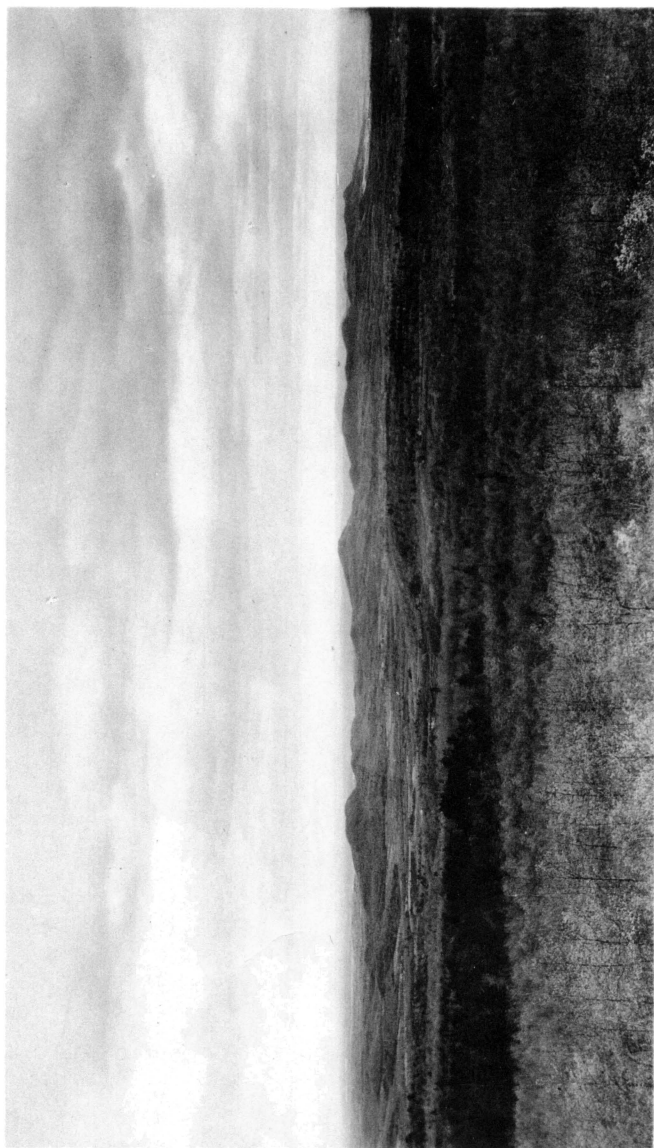


FIG. 1. View of the Holyoke Range from the northeast. The high point at the left is Flat Mtn. Mt. Norwottock appears in the center. The continuous ridge at the right has Bare Mtn. at its left end, Mt. Hitchcock in the middle and Mt. Holyoke at the far right. The Mt. Tom Range appears directly over Bare Mtn. The hills in the foreground are part of the eastern highland.

conglomerate except along the east edge of the western basin where a volcano had become active on Dry Brook. Southward movement of the east part of the basin broke the Holyoke flow at the east Notch on the power-line fault and elsewhere at places as far as Flat Mountain. The Dry Brook and power-line volcanoes became very active and ejected the Granby tuff and associated lava flows. Steep dips and faults through the tuff bed indicate continued movement of the eastern part of the basin.

The Holyoke flow was the only competent member in the basin fill and it must either turn southward with the movement or break. The faults and joints indicate that the flow broke and the blocks turned at the break surfaces. New fault traces are north-south, but those in older formations are more north-easterly and are a clear record that the structural planes were rotated with the formations. Simple rotation under impulse of the southward-moving force would carry the end of the Holyoke flow far east of its starting meridian and this must produce at least one of a number of possible secondary movements.

1. The Holyoke flow and incompetent sediments could thrust against the eastern highland and force it eastward, which is improbable if not impossible.
2. The eastern highland and basin floor could act as a buttress and foundation and confine the basin movement between the same meridians. This would resolve the force arising from southeastward rotation into an upward westward force normal to the early faults and a southward force parallel to them.

This second interpretation is compatible with all known facts for this region. Caution should be exercised in applying this interpretation to other Triassic basins or to other extremities of the Connecticut Valley. This is particularly essential because a number of faults striking approximately S.S.W. have been identified in the crystalline floor of the shallower basin just to northward; they suggest that individual basement movements may be independent and more southwesterly than the axis of the valley. The eastern highland was the moving block in the Holyoke Range region but the valley or even the western highland might, for a period, become the mobile block elsewhere.

According to the second interpretation the basin fault blocks

are caught between the stable western basin and the eastern highland. They are compressed in an east-west direction and are between the incompetent arkose below and the sands and shales above so that they shear upward over the next block to the west as they move south. An occasional block like the Hilliard Knob and Notch blocks are forced down instead of up and the neighboring long blocks of Mount Norwottock and Bare Mountain are uparched proportionately.

The blocks, once they are started to shear upwards to the west, will continue to do so as far as the eastern buttress or to very close to it. Some upward shear to the east is recorded in a westward dipping shear zone beside Belchertown Pond at the extreme east end of the range. The exposures are poor and the magnitude of the movement could not be determined.

Low degree of disturbance in the younger beds may be due partly to incompetence during the active period and partly to most of the movement antedating their deposition. Slightly steepened eastward dip indicates compression along the eastern highland as far south as Granby. Whether the movement is great and is distributed between the individual clastic particles in the incompetent young sediments is uncertain. This writer believes that over half the movement antedated deposition of the upper part of the Longmeadow sandstone, that much of the movement is distributed through the sediment and that very minor amount of movement is indicated by slightly steepened dips close to the eastern crystallines.

SIGNIFICANT BASEMENT FEATURES.

A few features of the pre-Triassic floor throw some light on the major regional pattern. They cannot affect the facts of Holyoke Range structure but may modify the conclusions of the individual reader. Wells drilled for water in the vicinity of Amherst obtain their flow from the porous sedimentary breccia lying on the crystallines. Almost all the wells enter schist at 100 feet or more above sea level. The South Amherst well is one and, even if the 16° dip towards the Holyoke Range began there, the thickness of Sugarloaf arkose under Bare Mountain would be less than 4000 feet. At Northampton, six miles southwestward, a well was in arkose at 3700 feet depth. If no fault occurs between the well and Mount Holyoke, and no evidence for one has been detected, the well collar is 3150 feet stratigraphically below the Holyoke flow. The arkose must be

more than 6850 feet thick at Northampton in contrast to under 4000 feet at Bare Mountain. If the basin containing the arkose is due to a fault, the fault border of the Northampton basin is west of Bare Mountain. The writer believes that it is, that it lies along a line near the east side of the Amherst Triassic area and that it passes near the line of volcanoes at Dry Brook and Mount Hitchcock. Slight movement along it may have been responsible for the basin marked by the thick lava of Mount Holyoke. Faults in the Holyoke Range are above a more easterly basin.

The Northfield basin-making fault is exposed just north of the French King bridge and it passes diagonally southwest along the face of the partly buried pediment one mile west of Montague. Another Triassic basin abuts on the northwest side of Mount Warner.

All basins and basin borders which have been identified are oblique to the length of the main Triassic area. Multiple basins, crystalline blocks and faults along a general zone make unity of time, place or direction of movement the unusual rather than the expectable. The divergent features of the record at Mount Toby, in the Holyoke Range and at Meriden in Connecticut may thereby become easier to reconcile with one another.

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