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NORMAL FAULTS OF THE LAKE CHAMPLAIN REGION[1]

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ABSTRACT

Between the compressional structures of the Green Mountains of Vermont and the dome-like Adirondack mass lie the Lake Champlain lowlands characterized by normal faults, moderate dips, and a scarcity of folds. The normal faults belong mainly to two systems, one having a northeast-southwest strike and one a north-south strike. It appears that both systems were formed simultaneously, and structural evidence seems to show that the normal faulting occurred in Ordovician time, before the Green Mountain overthrusting. These faults cause the pre-Cambrian surface at the base of the Paleozoic series to descend to the east by steps. A study of the stretching involved in the faulting shows that there were tensional forces acting downward toward the east. The distribution and pattern of the faults indicate a primary relation to the Green Mountains and a secondary relation to the Adirondacks, as though due to shear strains between the sinking geosyncline and the up-standing Adirondacks. The normal faults appear to have been formed during the geosynclinal stage, and although conceivably due to unknown magmatic movements, appear to have been formed by the sagging of the geosyncline under the weight of accumulating sediments or to tensional forces which cause the geosynclines.

LOCATION AND STRUCTURAL SETTING

In the northern part of the states of Vermont and New York there are three large elements of structure which, though different in character, appear to be related in origin. The Green Mountains in the

[1] Part of a Ph.D. thesis presented at Harvard University, June, 1931. The writer wishes to thank Dr. H. F. Cleland, who first suggested that this area presented opportunities for investigation; Mr. G. H. Hudson of Plattsburg, New York, for valuable guidance in the field which he has known for many years; Dr. Rudolf Ruedemann for useful advice during the field work; and Dr. K. F. Mather and Dr. Kirk Bryan who gave much valuable advice and aid in the correlation of field data.

east consist largely of Lower Paleozoic sedimentary rocks greatly compressed into north-south-trending folds and overthrust faults.

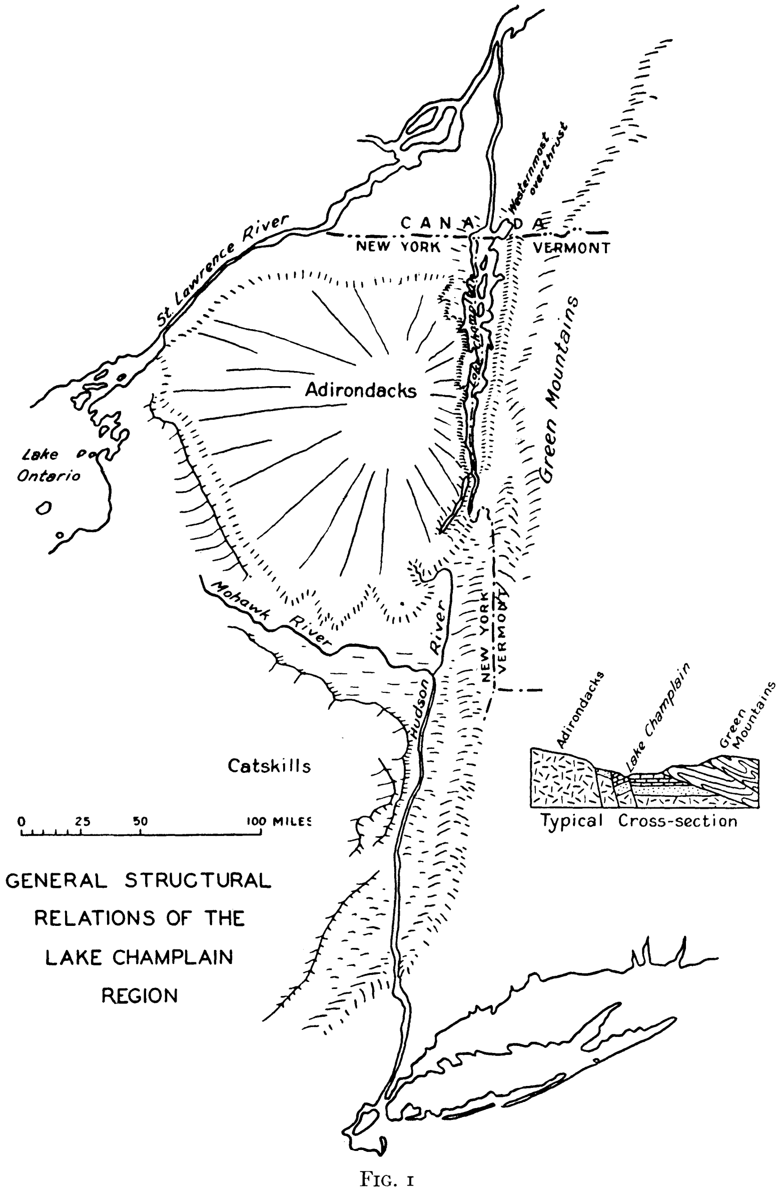


FIG. 1

This area of mountain structure is bordered on the west by the Lake Champlain lowlands which are also composed of Lower Paleozoic sedimentary rocks. The beds in the lowlands have not been compressed, but are characterized by moderate dips and normal faults. West of the lowland area are the Adirondack Mountains. This mass has a dome-like structure with the Lower Paleozoic beds outcropping around the margins and with the Basement Complex of pre-Cambrian igneous and metamorphic rocks exposed in the interior.

The structure of the Lake Champlain lowlands is the subject of this article. The area covered by field work extends northward from the south boundary of the Ticonderoga quadrangle, near Putnam, New York, to the Canadian line. It is bounded on the east by the westernmost overthrust fault of the Green Mountains and on the west by the pre-Cambrian rocks of the Adirondacks. It comprises the following quadrangles: Mooers, Rouses Point, St. Albans, Dannemora, Plattsburg, Milton, Ausable, Willsboro, Burlington, Port Henry, Middlebury, and Ticonderoga.

STRATIGRAPHY

The rocks of the region are: the pre-Cambrian terranes in the Adirondacks, the Cambrian Potsdam sandstone, the Beekmantown dolomite, the Chazy limestone, a thin series of beds probably equivalent to the Black River and Lowville formations, the Glens Falls limestone of the Trenton group, and Trenton shale of probable Canajoharie age, these last all of Ordovician age.[2] There are also dikes of post-Trenton age[3] and Pleistocene deposits. Space, however, is not available here for a discussion of the stratigraphy; suffice it to say that there are divisions within these formations and that they were

[2] Ezra Brainerd and H. M. Seely, "The Original Chazy Rocks," *Amer. Geologist*, Vol. II (1888), pp. 323–30; "The Calciferous Formation in the Champlain Valley," *Amer. Mus. Natural Hist., Bull. III* (1890), pp. 1–23; "The Chazy of Lake Champlain," *ibid., Bull. VIII* (1896), pp. 305–15. H. P. Cushing, "Geology of the Northern Adirondack Region," *N.Y. State Mus., Bull. 95* (1905). J. F. Kemp and Rudolf Ruedemann, "Geology of the Elizabethtown and Port Henry Quadrangles," *N.Y. State Mus., Bull. 138* (1910). G. H. Perkins, "Geology of Grand Isle," *Vt. State Geologist's Report for 1901–2*, pp. 102–74. P. E. Raymond, "The Chazy Formation and Its Fauna," *Annals of the Carnegie Mus.*, Vol. III (1906), pp. 498–598. Rudolf Ruedemann, "Report on Trenton Fossils of Grand Isle," *Vt. State Geologists' Rept. for 1919–20*, pp. 90–101. Gilbert Van Ingen, "The Potsdam Sandstone of the Lake Champlain Basin," *N.Y. State Mus., Bull. 52* (1902), pp. 528–45.

[3] J. F. Kemp and V. F. Marsters, "Trap Dikes of the Champlain Region," *U.S. Geol. Surv., Bull. 107* (1893). H. W. Schimer, "Petrographic Description of the Dikes of Grand Isle," *Vt. State Geologist's Rept. for 1901–2*, pp. 174–83.

of considerable use in locating faults and determining the amount of movement involved. The thicknesses of the formations are indicated by Figure 2.

But it is desirable to discuss the surface of the pre-Cambrian rocks upon which rest the Lower Paleozoic strata, because on the nature of that surface depend certain interpretations of structure. Thus, in the northern part of the Adirondacks, where outcrops are not plentiful, there are apparently many irregularities in the boundary between

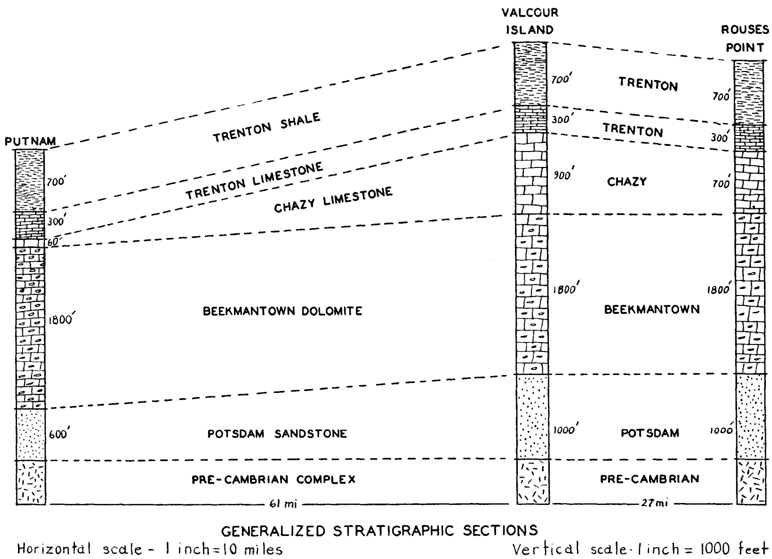


FIG. 2

pre-Cambrian and Paleozoic rocks which admit of two alternative interpretations. The irregularities may be due to inequalities of level of the floor on which the Paleozoic sediments were deposited, or faulting may have lowered or raised blocks so as to make re-entrants or promontories in the line of contact.

To the south of Port Kent, practically all of the pre-Cambrian–Paleozoic boundary line is fault contact, and the re-entrants are obviously due to faulting; but to the north the great development of Pleistocene deposits so masks the structures that such relations cannot be proved or disproved. Consequently, it is necessary to make interpretations on the basis of regional conditions.

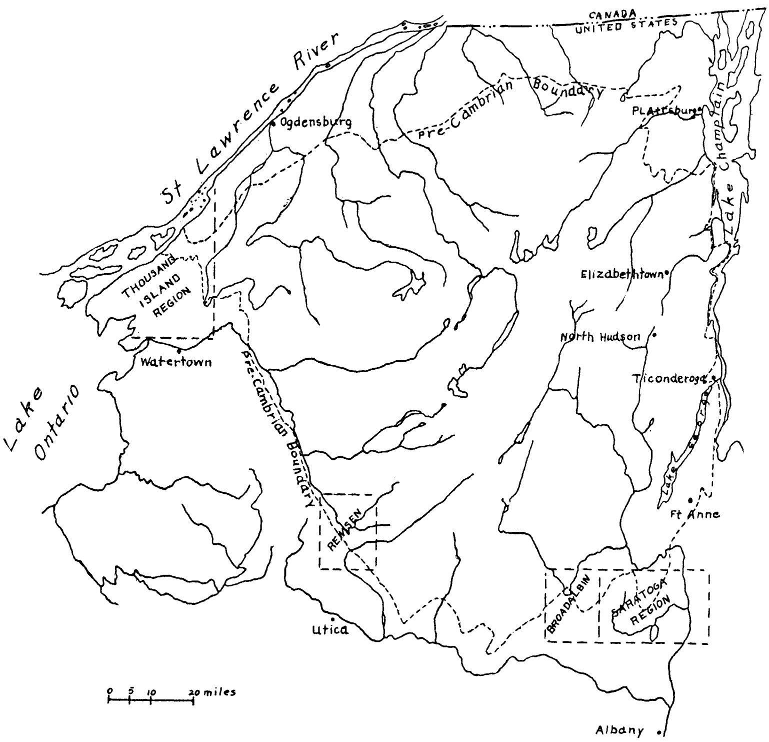
Of the conditions in the northern part of the area it is possible to say only that there seem to be no outliers or inliers of large size and that, therefore, the surface was not very rough. In the eastern and southern parts of the Adirondacks, however, there are many outliers of Paleozoic rocks within the area of pre-Cambrian rocks.

FIG. 3.—Unconformable surface between pre-Cambrian rocks and Potsdam sandstone, Crown Point Center, New York (Ticonderoga sheet).

Kemp[4] has interpreted these as original depressions on the pre-Cambrian floor under the Paleozoic sediments, but, because most of them are located where topographic evidence of faulting is strong and because the rocks in the outliers are lithologically similar to the beds in the Champlain valley where they are normally developed, it is believed that the outliers are due to faulting.

[4] J. F. Kemp, "Pre-Cambrian Topography of the Eastern Adirondacks (abstract)," *Jour. Geol.*, Vol. V (1897), p. 101; "Physiography of the Eastern Adirondacks in the Cambrian and Ordovician Periods," *Bull. Geol. Soc. Amer.*, Vol. VIII (1897), pp. 408–13; "The Cambro-Ordovician Outlier at Wellstown, Hamilton County, New York (abstract)," *Sci.*, Vol. XIII (1901), p. 710, and *N.Y. Acad. of Sci. Annals*, Vol. XIV (1902), pp. 113–15. Rudolf Ruedemann, "Additional Note on Oceanic Currents in the Utica Epoch," *Amer. Geologist*, Vol. XXI (1898), pp. 75–81; "Types of Inliers Observed in New York," *N.Y. State Mus., Bull. 133* (1909), pp. 166–93.

More helpful information upon the nature of the surface of the Basement Complex is contained in the reports of the New York State Museum on the areas at different places along the south and west margins of the Adirondacks. Miller reports that in the Rem-



MAP OF ADIRONDACK REGION SHOWING LOCATION OF PLACES WHERE THE SURFACE BENEATH THE PALEOZOIC ROCKS HAS BEEN STUDIED

FIG. 4

sen[5] and Broadalbin[6] quadrangles the old surface was rather flat, with a relief of 100 feet or less. Cushing and Ruedemann, in their work in the Saratoga and Schuylerville quadrangles,[7] found a relief

[5] W. J. Miller, "Geology of the Remsen Quadrangle, Including Trenton Falls and Vicinity in Oneida and Herkimer Counties," *N.Y. State Mus., Bull. 126* (1909), pp. 35–36.

[6] "Geology of the Broadalbin Quadrangle," *ibid., Bull. 153* (1911), pp. 50–52.

[7] H. P. Cushing and Rudolf Ruedemann, "Geology of Saratoga Springs and Vicinity," *N.Y. State Mus., Bull. 169* (1914), pp. 31–32.

of 75 feet or more, with elevations and depressions not sharp but gentle, as on a surface in old age. The Thousand Islands region[8] is perhaps the most favorable place for studying the nature of this surface, because there the present surfaces on the pre-Cambrian rocks are believed to represent practically the old depositional floor, from which the Potsdam sandstone has lately been removed by erosion. In this locality an abundance of facts shows that the old land had a knob and basin topography with low ridges and valleys trending northeast-southwest. There were few flats and the maximum relief was about 100 feet.

The evidence just considered indicates that south of a line running from about the region of Ticonderoga to the Thousand Islands region the old surface was fairly smooth. The absence of prominent outliers and inliers north of that line shows that no great irregularities existed there. Cushing says of the surface in the northern Adirondack area, "Maximum differences of level of but a few hundred feet are all that are involved, and these comparatively seldom."[9] The conclusion is reached, therefore, that the old land surface had no greater relief than 200 or 300 feet, and that greater differences in elevation now found within small areas on that surface must be due to post-Cambrian faulting.

GENERAL CHARACTERISTICS OF THE FAULTS

The faults of the Lake Champlain lowlands are all, as far as can be determined, of the normal, or gravity, type. The downthrows of those faults trending in a north-south direction are almost all to the east and in consequence the pre-Cambrian surface under the Paleozoic rocks descends by steps to the east. A possible exception is the fault at the shore near Arnold Bay, a little south of west from Vergennes, Vermont, but the strike of this fault changes to northeast-southwest a short distance north of Arnold Bay. The downthrows of the northeast-southwest and other faults may be on either side. There are not many horsts or graben bounded by parallel faults, but, at the intersection of faults, angular blocks may be lower or

[8] H. P. Cushing, H. L. Fairchild, Rudolf Ruedemann, and C. H. Smyth, Jr., "Geology of the Thousand Islands Region," *N.Y. State Mus., Bull. 145* (1910), pp. 54–60.

[9] "Geology of the Northern Adirondack Region," *op. cit.*, p. 419.

higher than the surroundings. It is common for the beds of the downthrown blocks to dip west, toward the upthrown block, the "backward tilting" of Swinnerton.[10] The stratigraphic throws vary greatly in amount, the largest being 4,000 feet, just north of Split Rock Point. Many of those along the pre-Cambrian boundary are about 1,000 feet, as minima. There are many, also, too small to map. G. H. Hudson has discovered and mapped a surprising number of small faults on Valcour Island.[11] In general, the faults are straight, although curving is not uncommon, and a few of them branch.

SYSTEMS OF FAULTS

On Figure 5, which is a map of the region simplified to show the relations of the faults to each other, it is apparent that the faults trend in two main directions, northeast-southwest and north-south. There are some, also, which strike northwest-southeast, and a few which strike east-west. In addition, there are a few small faults with no systematic orientation, which are entirely confined to blocks outlined by the larger faults and which are probably minor fractures formed during the movements of the larger blocks.

The question arises as to whether these sets of faults represent different episodes of faulting. If they do, there is some reason for thinking that the north-south set was formed first. A glance at Figure 5 will show that several of the north-south faults appear to be cut off by those of the northeast-southwest system. This can be seen especially well along the boundary of the Adirondack pre-Cambrian rocks southwest of Willsboro. At no place, however, is a fault of one system seen to be actually offset by one of another system, and the relations are not considered to be definite enough to prove that one system of faults is older than another. On the contrary, there is a situation which suggests that the different systems were developed at the same time. In this case a fault of one system intersects one of another without there being a continuation of either beyond the point of intersection (see the pre-Cambrian boundary north of Ticonderoga and Figure 6). The relations at the points indi-

[10] A. C. Swinnerton, "Block Fault Structure Near Ticonderoga, New York (abstract)," *Bull. Geol. Soc. Amer.*, Vol. XLII (1931), p. 202; "Structural Geology in the Vicinity of Ticonderoga, New York," *Jour. Geol.*, Vol. XL (1932), pp. 402–16.

[11] Unpublished manuscript; "The Fault Systems of the Northern Champlain Valley, New York," *N.Y. State Mus., Bull. 286* (1931), pp. 5–81.

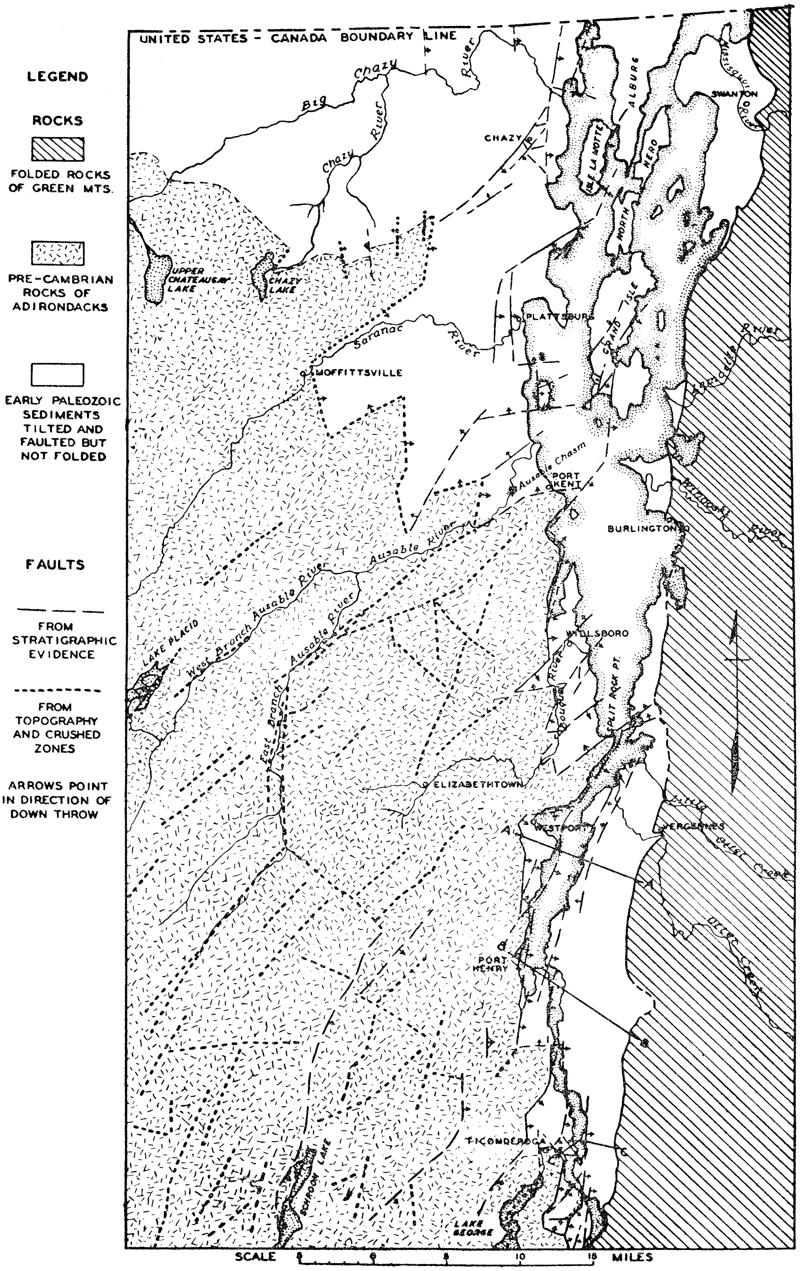

LEGEND
ROCKS
FOLDED ROCKS OF GREEN MTS.
PRE-CAMBRIAN ROCKS OF ADIRONDACKS
EARLY PALEOZOIC SEDIMENTS TILTED AND FAULTED BUT NOT FOLDED
FAULTS
FROM STRATIGRAPHIC EVIDENCE
FROM TOPOGRAPHY AND CRUSHED ZONES
ARROWS POINT IN DIRECTION OF DOWN THROW
UNITED STATES - CANADA BOUNDARY LINE
Big Chazy River
Chazy River
CHAZY
ALBURG
SWANTON
ISLE LA MOTTE
NORTH HERO
UPPER CHATEAUGAY LAKE
CHAZY LAKE
PLATTSBURG
GRAND ISLE
Saranac River
MOFFITTSVILLE
Ausable Chasm
PORT KENT
BURLINGTON
Winooski River
Ausable River
West Branch Ausable River
LAKE PLACID
East Branch Ausable River
WILLSBORO
SPLIT ROCK PT.
ELIZABETHTOWN
WESTPORT
VERGENNES
Little Otter Creek
Otter Creek
PORT HENRY
TICONDEROGA
SCHROON LAKE
LAKE GEORGE
SCALE
MILES

FIG. 5

cated show that the mass outlined by the faults moved as a unit. In Figure 6 it is plain that faults with north-south, northeast-southwest, east-west, and northwest-southeast strikes moved simultaneously. The same interpretation is attached to the curving of the faults in the Mohawk Valley from north-south to northeast-southwest and back to north-south again. Cushing and Ruedemann, in their report on the Saratoga region, suggest that the movements along these curving faults relieved tension acting in a direction intermediate to the directions which would produce either north-south or northeast-southwest faults alone.[12] In other words, the tension, instead of producing one set of fractures normal to the direction of tension, produced faults in two directions, the two directions being old lines of weakness in the basement rocks. Similarly for the Lake Champlain region, it is believed that rather simple tensile forces caused complex movements along lines of weakness in the Basement Complex.

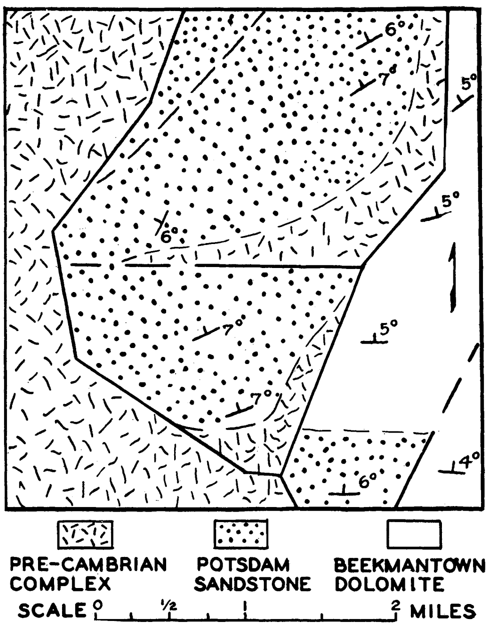


FIG. 6.—Fault blocks south of Ticonderoga

The significance of the foregoing facts is believed to be not that the different systems of faults represent different episodes of faulting, but that there was one period of faulting during which movement was taking place simultaneously in several directions.

DIPS OF THE FAULT PLANES

Previous writings on the faulting in this region contain statements or assumptions that the fault planes are vertical or nearly so, but the facts learned in the present investigation tend to oppose that view.

[12] "Geology of Saratoga Springs and Vicinity," *op. cit.*, p. 64.

Not many of the fault planes can actually be seen, but a few are well exposed. At Treadwells Mill (Plattsburg sheet) on the Saranac River about 3 miles southwest of Plattsburg, New York, there are some very small faults in the Beekmantown formation which strike N. 54° E. and dip 65° SE. Ausable Chasm (Plattsburg sheet) contains a number of faults of unknown, but probably small, displacements in the Potsdam sandstone. A few of them are almost vertical, although most of them have dips of 60°–70°. One of the best exposures of a fault in the whole region is on the shore at the south edge of the village of Essex, New York (Willsboro sheet). There the Trenton shale is thrown against the Chazy limestone by a fault which strikes N. 47° E. and dips 60° SE. On the Bouquet River about 2½ miles west of Essex a fault between the Potsdam sandstone and the pre-Cambrian rocks is seen to have a strike N. 45° E. and a dip 65° SE. At Whallon Bay (Willsboro sheet) just west of Split Rock Point there is a remarkably good exposure of a fault between Trenton limestone and pre-Cambrian rocks. This fault, which is the greatest known in the region, strikes N. 60° E. and dips 55° NW. At Arnold Bay about 6 miles west of Vergennes, Vermont (Port Henry sheet), is a north-south fault with a downthrow to the west. It lies between Trenton shale and Beekmantown limestone, strikes N. 9° E. and dips 48° W. A photograph of a fault at Bluff Point (Plattsburg sheet) was made in 1897 by G. H. Hudson.[13] At the time the writer visited the locality the fault plane was covered with slump material and refuse from nearby camps, so that no measurements could be obtained, but it appears from the photograph that this fault plane must dip only about 65°.

Thus, it is seen that nearly all the fault planes exposed depart considerably from the vertical. The average dip is probably between 60° and 70°. Sixty-five degrees is the figure used in calculating the amount of stretching, except where the dips of the fault planes are known to be different.

FAULTS IN THE ADIRONDACKS

In this investigation faults were mapped only in the areas of Paleozoic rocks, but it is known that the same systems of faults ex-

[13] G. H. Hudson, "Interesting Geologic Features at Champlain Assembly, Cliff Haven," *N.Y. State Mus., Bull. 196* (1917), pp. 149–60, Fig. 5.

tend into the area of the crystalline rocks in the Adirondacks, for, although their detection in the crystalline rocks is not so easy as it is in the sedimentary rocks, the existence of many of them is demonstrated by a variety of evidence. Aside from observed continuations of the faults in the Paleozoic rocks, the evidence consists of four types of facts: namely, long straight boundary lines between formations, crushed zones, topographic expressions of faulting, and outliers of Paleozoic rocks within the area of pre-Cambrian rocks. Those faults within the crystalline area which are shown on Figure 5

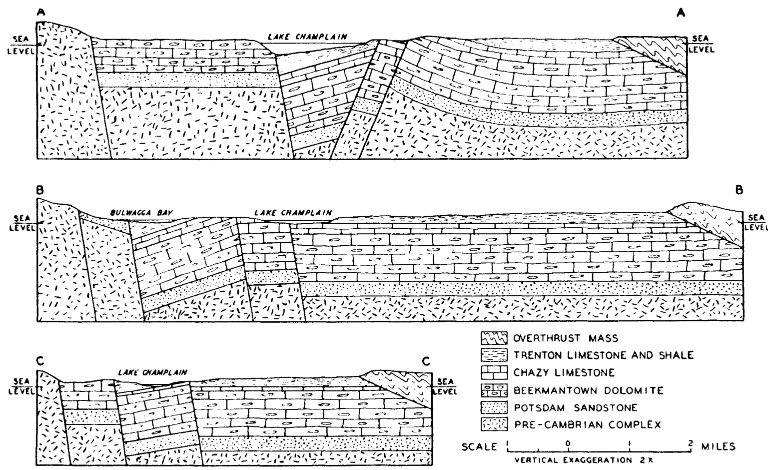


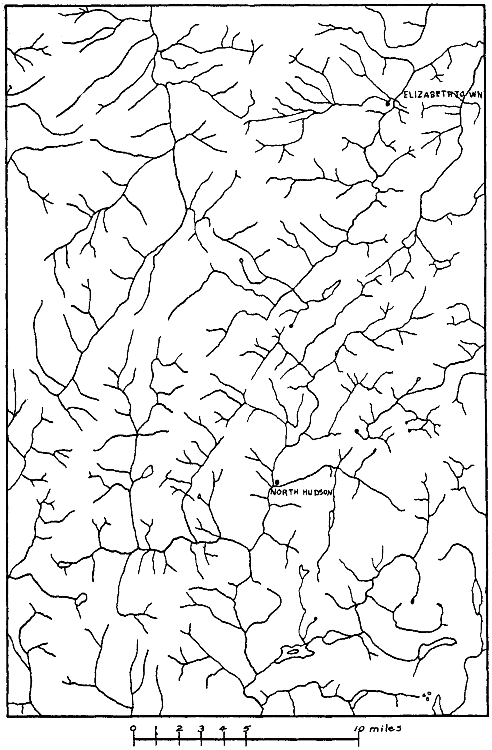
FIG. 7.—Cross sections. For locations see Fig. 5

have been taken mainly from the reports of the New York State Museum.[14] The reader is referred to those reports for the proof of the faults, although Figure 8 is given here to show some of the topographic evidence for faulting in the Adirondacks. Balk says, however, that many of the northeast-southwest lines in the topography are due to closely spaced regional tension joints in the anorthosite.[15]

[14] Kemp and Ruedemann, "Geology of the Elizabethtown and Port Henry Quadrangles," *op. cit.;* J. F. Kemp, "Geology of the Mount Marcy Quadrangles," *N.Y. State Mus., Bulls. 229 and 230* (1921); J. F. Kemp and H. L. Alling, "Geology of the Ausable Quadrangle," *N.Y. State Mus., Bull. 261* (1925); W. J. Miller, "Geology of the Schroon Lake Quadrangle," *N.Y. State Mus., Bulls. 213 and 214* (1919); I. H. Ogilvie, "Geology of the Paradox Lake Quadrangle," *N.Y. State Mus., Bull. 96* (1905).

[15] Robert Balk, "Structural Geology of the Adirondack Anorthosite," *Mineralogische und Petrographische Mitteilungen,* Band 41 (1931), p. 419.

It is of considerable importance that these faults in the Adirondacks belong to the same systems as do those in the lowlands. There can hardly be any doubt that they are part of the same deformation.



ADIRONDACK DRAINAGE
(From New York State Geological Map)

FIG. 8

MOHAWK VALLEY AND ASSOCIATED FAULTS

That the fault structure of the Lake Champlain region extends south of the limits of mapping done by the author is well shown by the early work of Vanuxem, Hall, and Darton and the more recent work of Cushing and Ruedemann, Miller, and others.[16] The full ex-

[16] Lardner Vanuxem, *Natural History of New York*, Part III, Third Geological District (1842), pp. 203–11. C. E. Hall, "Field Notes on the Geology of the Mohawk Valley," *N.Y. State Geologist, Ann. Rept. 5* (1886), pp. 8–10, and *Ann. Rept. 14* (1895), pp. 54–56. N. H. Darton, "Geology of the Mohawk Valley," *Forty-seventh Ann. Rept., N.Y. State Mus.* (1894), pp. 601–25; "Preliminary Description of the Faulted Region

tent and characteristics of the faulting however, have not been ascertained.

The Mohawk Valley faults are mainly between Schenectady and Little Falls. Most of them have rather small displacements where they cross the Mohawk River, the stratigraphic throws given being 200–310 feet. To the north, as the faults run into the Adirondacks, the displacements become greater. They strike mainly northeast-southwest and most of them have downthrows to the east. They curve considerably, varying between northeast-southwest and north-south, and branch at several places. The fault planes exposed are almost vertical.

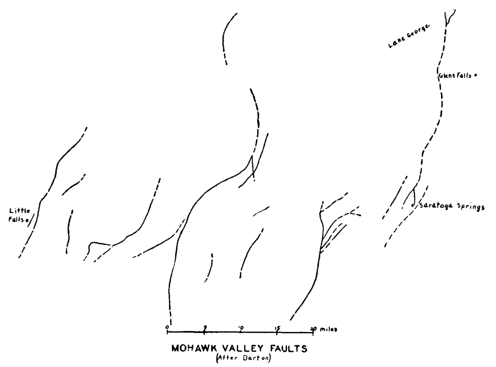


FIG. 9

These faults do not extend far south of the Mohawk Valley. The northern limit of the faulting has not been determined. Most of the faults were traced by Darton north to the crystalline rocks of the Adirondacks and one was traced by him into the crystalline rocks as far as the outlier at Wells.[17] At the east end of his map there is a long fault which runs northeast-southwest through the Saratoga region as far as the south end of Lake George. In fact, Darton believed the lake basin to have been excavated out of Paleozoic rocks on a fault block.[18] The writer has mapped faults into the north end of Lake George; so it seems that there must be a connection between the Mohawk Valley faults and the Lake Champlain faults.

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of Herkimer, Fulton, Montgomery, and Saratoga Counties," *Forty-eighth Ann. Rept., N.Y. State Mus.* (1894), pp. 30–56. Cushing and Ruedemann, "Geology of Saratoga Springs and Vicinity," *op. cit.* Miller, "Geology of the Remsen Quadrangle, etc.," *op. cit.;* "Trough Faulting in the Southern Adirondacks," *Sci.*, Vol. XXXII (1910), pp. 95–96; "Geology of the Broadalbin Quadrangle," *op. cit.*

[17] Darton, "Preliminary Description of the Faulted Region of Herkimer, etc.," *op. cit.*, p. 47.

[18] *Ibid.*, p. 52.

Typical Lake Champlain structure is present in the Saratoga region. Cushing and Ruedemann[19] describe the structure west of the overthrusts as characterized by normal faults with few folds. A general northeast-southwest strike is present, but there is a noticeable tendency of the faults to curve from northeast-southwest to north-south and back to northeast-southwest. Cushing and Ruedemann suggest that this may be due to the fact that tension toward the southeast was relieved along two previously existing directions of weakness. The downthrows are mainly to the east, although a few are to the west. The blocks are tilted slightly to the west and only a few horsts and graben are present. The fault planes are reported to be vertical. The stratigraphic throws are rather great, as may be seen from the following estimates: Hoffman's Ferry fault, 1,300–1,600 feet; West Galway fault, 250–300 feet; McGregor fault, over 1,400 feet; Woodlawn Park fault, 300 feet. It is interesting to note here that none of these normal faults has been found to cut the overthrust faults east of the normal-fault area and none has been found in the overthrust masses. The writers of the report believe this to mean that the normal faulting was earlier than the overthrust faulting.[20]

Lake George, as stated before in this paper, forms a connecting link between the faulted area studied by the writer and the faulted area of the Mohawk Valley. Faults have been traced to both ends of Lake George. Certain of them obviously run some distance in the lake. Kemp,[21] in discussing the physiography of the lake, concluded that faulting has been very important in the formation of the basin. The connection between the two areas would, without doubt, be more apparent if all the intervening region were mapped in detail, but even with the evidence at hand it appears certain that the faulting of the Mohawk Valley is the same as that in the Lake Champlain region.

[19] Cushing and Ruedemann, "Geology of Saratoga Springs and Vicinity," *op. cit.* pp. 53–65.

[20] *Ibid.*, p. 145.

[21] "Notes on the Physiography of Lake George (abstract)," *Amer. Geologist*, Vol. XXVIII (1901), pp. 331–32; *Sci.*, Vol. XIV (1901), p. 774; and *N.Y. Acad. Sci. Annals*, Vol. XIV (1902), pp. 141–42.

WESTERNMOST OVERTHRUST

The westernmost overthrust of the Green Mountains was chosen as the eastern limit to the area of this study, because it marks the boundary between the lowland area of tensional structures and the

FIG. 10.—Overthrust of Chazy limestone on crumpled Trenton shale, Lime Rock Point (St. Albans sheet).

mountain region of compressional structures. The boundary drawn on the maps does not represent a single overthrust fault, for in certain places, where small slices were found underneath the larger overthrusts, the line was drawn along the underlying minor fault. At other points the boundary is along the main overthrusts. No attempt has been made to show the complexity of the overthrusts nor to indicate on the maps what rocks compose the overthrust block, because the overthrusts were studied only to locate the boundary of the lowland area and to determine whether or not they were cut by the normal faults.

A satisfactory answer to the question of whether the normal faults cut the overthrusts was not obtained. There are localities, such as that east of Split Rock Point, where normal faults of considerable size trend directly toward the overthrusts and where it would seem that the true relations could be determined, but at these places the cover of Pleistocene material happens to be so complete that the relations cannot be determined definitely.

The evidence, as far as the writer knows, seems to indicate that the normal faults are older than the overthrusts and do not cut them. This belief is supported by the fact that the overthrusts are definitely not cut by normal faults over certain rather great distances, as in the northern half of the Milton quadrangle and south of Vergennes, Vermont (Port Henry sheet), where the overthrust is marked by a continuous limestone ridge 8 or 9 miles long. These distances seem too great to have escaped faulting by mere chance. The general straightness of the overthrust line as compared, for example, with the pre-Cambrian boundary line of the Adirondacks, where faults are known to be present, also favors this idea. Offsets of the overthrust faults by normal faults might exist without detection in a few places, however, such as east of Split Rock Point, at Vergennes, and southwest of Snake Mountain (Port Henry sheet), but there is no strong evidence for offsets in those localities.

CRUSTAL STRETCHING

Figure 11 is an attempt to portray the crustal stretching involved in the Lake Champlain faulting. The vectors show the amount and direction of stretching and, consequently, indicate something of the nature of the forces which caused it. The basis for calculation is that the heave of the faults is the amount of stretching. The fault planes have been assumed to dip 65°, except where actually known to be different. This assumption appears to be justified by measurements of fault planes exposed at various places in the region. It has been assumed, also, that all the movements have been dip-slip movements, because the few striations which have been observed were nearly in the directions of the dips of the fault planes. Each vector was con-

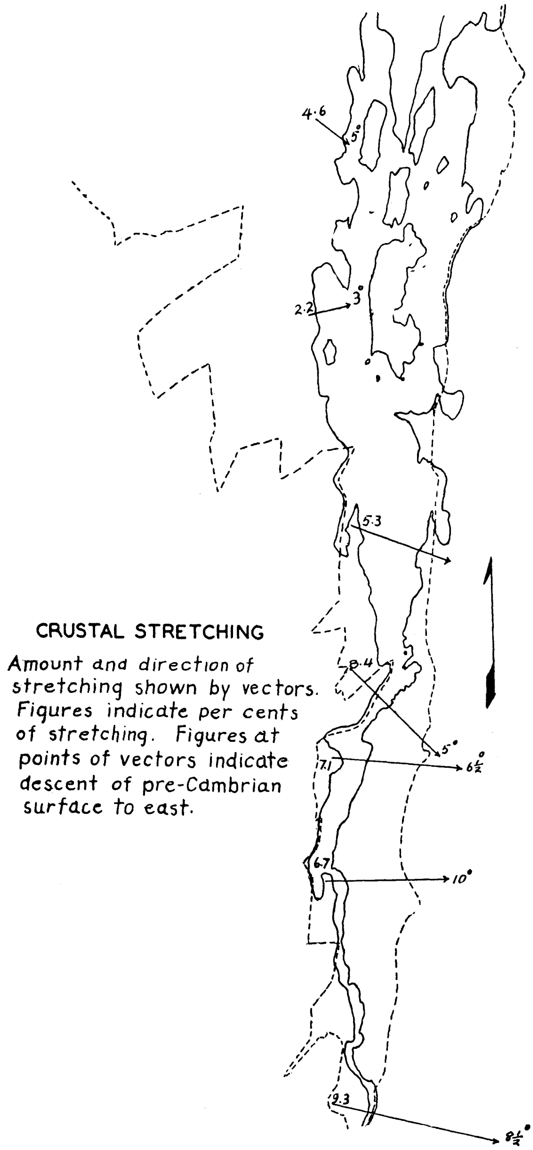


FIG. 11

structed for the faults in a narrow zone across the lowland area at localities where the faults are fairly well known. Except for the two northernmost vectors the zones extend from the pre-Cambrian rocks of the Adirondacks to the easternmost point at which the structure appears to be rather definitely known, and do not include the shale areas just west of the overthrusts where faults cannot be detected. The amount of stretching, in percentages, is indicated by the figure at the base of each vector.

The surface at the base of the Paleozoic series is known to descend to the east by steps. The amount of that descent is indicated by the figures at the points of the vectors. The figures represent the dip of a line from the pre-Cambrian rocks along the Adirondack boundary to the base of the Potsdam sandstone at the easternmost point where the elevation of that horizon can be determined.

These reckonings involve several uncertainties and, consequently, are only approximate. Some of the matters of uncertainty are: the dip of the fault planes, the direction of movement on the fault planes, the possibility that the thickness of the lower rocks may change to the east, the possibility of undetected faults, and the possibility of error in the calculation of the stratigraphic throws.

Because of the uncertainties involved, these calculations cannot be considered accurate. They mean little more than that there were tensional forces from the east and southeast, that the forces were greater or their results more pronounced in the southern part of the area, that the pull was downward to the east, and that the downward component of the forces was greater or its effect more evident in the southern part of the area.

ASSOCIATION WITH GREEN MOUNTAINS AND ADIRONDACK MOUNTAINS

Geographically the Lake Champlain normal faults are associated with the Green Mountains and the Adirondack Mountains. These faults are found only in a broad zone west of the Green Mountains, and the intensity of the faulting appears to be greatest near the Green Mountains. On the other hand, the normal fault structure is not present in those mountains nor has it been found throughout their western border zone. Apparently, it does not extend far south of the Mohawk Valley, and, although it reaches Canada on the north, it seems to be diminishing in that direction (see Fig. 11). In fact, the greatest development of the normal fault structure seems to be in the vicinity of the Adirondack Mountains. In the opinion of the writer, the association with the Adirondacks is secondary to the main association with the Green Mountains. This seems true, because the pattern is not the kind to have been produced by the Adirondack doming movement, for it is neither radial nor concentric as might be expected if caused by doming. Neither is the distribution of the faults that which would be expected if they were primarily related to the almost circular Adirondack mass, for they are almost all in the eastern half of the dome[22] and seem to follow the Green Mountain front. Furthermore, the direction of the faults and of the stretching (see Figs. 5 and 11) does not vary from place to place about the margin of the Adirondacks as it should if it were caused by the same forces that raised the Adirondacks.

It is suggested that these relations are the result of forces which were present all along the border of the Green Mountains and associated ranges, but which were noticeably active only in the vicinity of the upstanding Adirondack area.

DATE OF THE NORMAL FAULTING

The foregoing discussion of the systems of faults has shown that the normal faults of this region were produced simultaneously. The faulting is, therefore, considered as one deformational event, whether it occurred in a short space of time or whether it extended over a great length of time. There is not a question of dating the different systems.

STRATIGRAPHIC EVIDENCE

The youngest rock affected by this normal faulting is the Trenton shale. The oldest rocks known to be unaffected are Pleistocene sediments. The relation of the dikes to the faults is unknown, and the age of the dikes is not known any more closely than that of the faults. The stratigraphic relations obviously do not furnish much information about the time of faulting, for they show only that it was post-Trenton and pre-Pleistocene.

STRUCTURAL EVIDENCE

The structural relations give closer limits to the date of faulting. As far as has been determined in this region the normal faults do not

[22] Cushing, "Geology of the Northern Adirondack Region," *op. cit.*, p. 406.

cut the overthrust faults. There seems to be no reason why the normal faulting should not extend into the area of the overthrusts, for the normal faults are found immediately west of it. They are not so abundantly evident near the overthrusts, however, but the difficulty of detecting them in the shale areas along the overthrusts probably accounts for the scarcity of known faults there. This does not explain the absence of the normal faults in the overthrust blocks nor the lack of offsets of the overthrust planes, because in certain areas, at least, the overthrust masses present good mapping conditions. It is believed that the absence of the normal faults in the overthrust area is due to their having been covered by the overthrust masses. If so, the normal faults are older and the time of overthrusting is the later limit to the time of normal faulting. Cushing and Ruedemann incline toward this view for the Saratoga region.[23]

TIME OF THE OVERTHRUSTING

With the time of normal faulting placed between the Trenton epoch and the time of overthrusting, the date of the overthrusting is next to be considered. This compression has been assigned to three different deformations, the Taconic Disturbance, the Acadian Disturbance, and the Appalachian Revolution.

In the Lake Champlain region the stratigraphic relations prove only that the deformation was post-Trenton and pre-Pleistocene in age. In recent years considerable doubt has been cast on the reality of the Ordovician disturbance, particularly its effect in Vermont.[24] Because the folds and overthrusts of the Green Mountains connect with and have the same characteristics as those in the Appalachians, some have assigned the Green Mountain deformation to the Appalachian Revolution.[25] Most recently, however, Schuchert has reviewed the field evidence and concluded that the "Taconian" disturbance at the end of the Ordovician period was the main deformation affecting the Green Mountains.[26] The Acadian and Appalachian

[23] "Geology of Saratoga Springs and Vicinity," *op. cit.*, p. 145.

[24] T. H. Clark, "Review of the Evidence for a Taconic Revolution," *Proceedings Boston Soc. Natural Hist.*, Vol. XXXVI (1921), pp. 135–63.

[25] Arthur Keith, "Cambrian Succesion of Northwestern Vermont," *Amer. Jour. Sci.*, Vol. V (1923), pp. 97–139, and *Vt. State Geologist's Rept. for 1923–24*, pp. 105–36.

[26] Charles Schuchert, "Orogenic Times of the Northern Appalachians," *Bull. Geol. Soc. Amer.*, Vol. XLI (1930), pp. 701–24.

deformations were important, but they affected areas farther to the east.

Conclusion.—It is concluded that the Lake Champlain normal faults were developed after the Trenton epoch and before the Taconic Disturbance, or in late Ordovician time.

ASSOCIATION OF NORMAL FAULTS WITH OVERTHRUSTS

If the association of the normal faults of the Lake Champlain region with the Green Mountain structure is due to causal relation of the two structures, there should be similar associations of normal faults with overthrust faults elsewhere. A few random examples of such relations will be cited in the following pages.

GREEN MOUNTAINS AND ASSOCIATED RANGES

It might seem that normal faults should be found all along the west side of the Green Mountains and associated ranges. As a matter of fact, no great development of them is seen south of the Mohawk Valley, though scattered faults exist in the Catskills and southward. How far into Canada the structure extends is not known, but the intensity of the faulting appears to diminish north of the Adirondacks. Thus, it seems, although the pattern does not appear to have been produced by the Adirondack doming, that this faulting is confined to the vicinity of the Adirondacks. In a foregoing section it was suggested that the tension postulated along most of the length of the present mountain border was relieved by barely noticeable adjustments over wide areas, whereas adjacent to the more rigid and upstanding Adirondack mass it was concentrated to produce faults.

JURA TABLELAND

An interesting example of normal faulting associated with compressional structures exists in the Jura Tableland north of the Jura Mountains.[27] About eighty important normal faults are known in this region, ranging up to 1,500 meters in stratigraphic throw. Most of them have a north-south strike, but a few are east-west. The fault planes dip from 80° to 85°. Horst and graben structure is characteristic. These faults were formed before the time of the last thrust movements in the Juras.

[27] L. W. Collet, *Structure of the Alps* (London: Edward Arnold & Co., 1927), pp. 134–38; A. Heim, *Geologie der Schweiz*, Band I (1919), pp. 553–65.

WESTERN UNITED STATES

In the western regions of the United States are several examples of normal faults associated with overthrusts. Certain of the normal faults in the foothills in Wyoming and Montana appear to have been formed during the compression of the Rocky Mountain beds.[28] They are, for the most part, fractures in dome structures. They differ, also, from the Lake Champlain faults, as they were formed during the compression rather than before it.

In the Lewis and Livingston ranges of Montana there are said to be normal faults west (back) of the overthrusts.[29] These, however, are younger than the overthrusts and cut them.

The normal faults which are known to be present near the Absaroka-Owl Creek Mountain front and in the margin of the Bighorn basin were formed soon after the development of the Heart Mountain overthrust.[30] They have not been studied in detail.

In southwestern Wyoming there is a belt of normal faults just east of the Absaroka overthrust in the overridden mass.[31] The normal faults have not been mapped and the relations to the overthrusts are not well known, but they have been ascribed to settling after the overthrusting.

Normal faults are associated with the Bannock overthrust fault in Idaho and in northern Utah. Both types of faults have been studied by Mansfield[32] who states that the normal faults are relaxa-

[28] T. A. Link, "The Origin and Significance of 'Epi-Anticlinal' Faults as Revealed by Experiments," *Bull. Amer. Assoc. Pet. Geologists*, Vol. XI (1927), pp. 853–67.

[29] R. G. McConnel, "Report on the Geological Structure of a Portion of the Rocky Mountains, Accompanied by a Section Measured near the Fifty-first Parallel," *Can. Geol. Surv.* (1887); Bailey Willis, "Stratigraphy and Structure of the Lewis and Livingston Ranges, Montana," *Bull. Geol. Soc. Amer.*, Vol. XIII (1902), pp. 305–52.

[30] D. F. Hewett, "The Heart Mountain Overthrust, Wyoming," *Jour. Geol.*, Vol. XXVIII (1920), pp. 537–57.

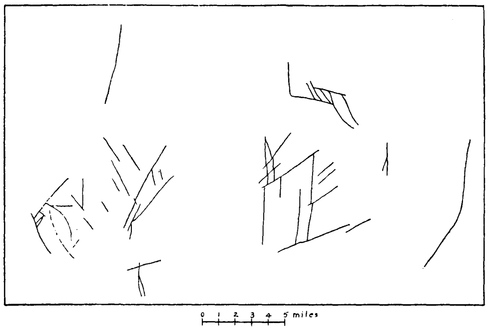
[31] A. C. Veatch, "Geography and Geology of a Portion of Southwestern Wyoming, with Special Reference to Coal and Oil," *U.S. Geol. Surv., Prof. Paper 56* (1907).

[32] G. R. Mansfield, "Types of Rocky Mountain Structure in Southeastern Idaho," *Jour. Geol.*, Vol. XXIX (1921), pp. 444–68; "Structure of the Rocky Mountains in Idaho and Montana," *Bull. Geol. Soc. Amer.*, Vol. XXXIV (1923), pp. 263–84; "Geography, Geology, and Mineral Resources of Part of Southeastern Idaho," *U.S. Geol. Surv., Prof. Paper 152* (1927). R. W. Richards and G. R. Mansfield, "The Bannock Overthrust, a Major Fault in Southeastern Idaho and Northeastern Utah," *Jour. Geol.*, Vol. XX (1912), pp. 681–709.

tional features which resulted from the overthrusting. Some of them appear to be satisfactorily explained that way, but others, according to his diagrams and cross sections, appear to be older than the overthrusts.

The Wasatch Mountains in Utah contain overthrusts with younger normal faults associated.[33] These faults are also thought to be due to relaxation after overthrusting.

The Spring Mountain Range in southern Nevada furnishes another example of overthrusting followed by normal faulting.[34]



MUDDY MOUNTAINS FAULT PATTERN
(After Longwell)

FIG. 12

The Muddy Mountains region of Nevada, recently described by Longwell, has a marked development of overthrusting and normal faulting.[35] Many of the normal faults are younger than the overthrusts, but some are older. Longwell thinks that the older ones may have been produced by relaxation after an earlier overthrusting. It is interesting and perhaps significant that the pattern of the Muddy Mountains faults is very similar to that of the Lake Champlain region.

This review of mountain border normal faults, brief and incom-

[33] G. F. Loughlin, "Reconnaissance in the Southern Wasatch Mountains, Utah," *Jour. Geol.*, Vol. XXI (1913), pp. 436–52; Eliot Blackwelder, "New Light on the Geology of the Wasatch Mountains, Utah," *Bull. Geol. Soc. Amer.*, Vol. XXI (1910), pp. 517–42; Hyrum Schneider, "A Discussion of Certain Geologic Features of the Wasatch Mountains," *Jour. Geol.*, Vol. XXXIII (1925), pp. 28–48; F. B. Stillman, "A Reconnaissance of the Wasatch Front between Alpine and American Fork Canyons, Utah," *Jour. Geol.*, Vol. XXXVI (1928), pp. 44–55.

[34] D. F. Hewett, "Structure of the Spring Mountain Range, Southern Nevada (abstract)," *Bull. Geol. Soc. Amer.*, Vol. XXXIV (1923), p. 89.

[35] C. R. Longwell, "The Muddy Mountain Overthrust in Southeastern Nevada," *Jour. Geol.*, Vol. XXX (1922), pp. 63–73; "Structural Studies in Southern Nevada and Western Arizona," *Bull. Geol. Soc. Amer.*, Vol. XXXVII (1926), pp. 551–84; "Geology of the Muddy Mountains, Nevada," *U.S. Geol. Surv., Bull. 798* (1928).

plete as it may be, suffices to show that an association of normal faults with overthrusts is common.

SUMMARY OF FACTS

Thus far it has been the aim of the writer to give the characteristics, relations, and associations of the Lake Champlain faults, and of other associated faults, for the purpose of determining the origin of the structure. There now follows a summary of the most significant facts which must be explained and from which a theory of origin may be derived.

1. The structure was produced by tensional forces acting with a downward pull toward the east or southeast.
2. The faulting of the different systems occurred simultaneously and, as far as has been determined, it all took place before the overthrusting of the Green Mountains.
3. There is a definite relation of the normal-fault structure to the Green Mountain structure and a somewhat secondary relation to the Adirondack structure.
4. Normal faults commonly occur in association with mountain structures.

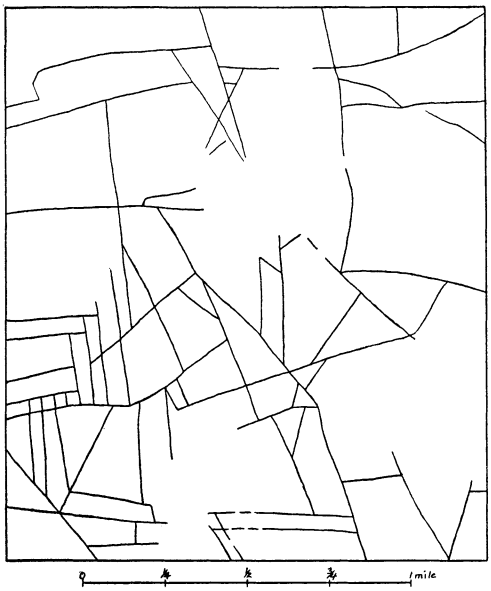
POSSIBLE EXPLANATIONS

FRACTURE DURING THE DOMING OF THE ADIRONDACKS

The association of the Lake Champlain faults with the Adirondacks might suggest that the same forces produced both. This has been shown in a foregoing section to be unlikely, however.

COLLAPSE STRUCTURE

Certain areas of complex normal faulting are believed to have resulted from the collapse of the crust during the withdrawal of large quantities of magma from beneath. Areas of this kind are typified by some of the mining districts of the Southwest. That normal faulting would result from such a cause is reasonable, and the association of the faults with the lavas is very definite in certain of these places. Probably the first faults to develop in such a process would follow previously formed joint planes. Later ones would develop partly along joints, but also in other directions according to the stresses placed on the different blocks during the settling. Faults of this type are known at Tonopah, Nevada;[36] Ray, Arizona;[37] and Bullfrog, Nevada.[38] It is evident in comparing the patterns of these faulted areas that considerable differences exist between the examples of this type of structure. The Tonopah faults are noticeable for the right-angle pattern, the distinct blocks, the straight faults,



TONOPAH FAULT PATTERN
(After Spurr)

FIG. 13

and the existence of long faults cutting many short ones. The Ray district is characterized by the irregularity of the blocks, the presence of several long branching faults, and the curvature of many of the faults. The Bullfrog pattern is marked by a great development of branching and by curvature of the faults in a way to make a sort of net structure. These differences are probably due to differences of the arrangements of the joints in the rocks before faulting, the man-

[36] J. E. Spurr, "Geology of the Tonopah Mining District, Nevada," *U.S. Geol. Surv., Prof. Paper 42* (1905).

[37] F. L. Ransome, "Ray Folio," *U.S. Geol. Surv. Folio 217* (1923).

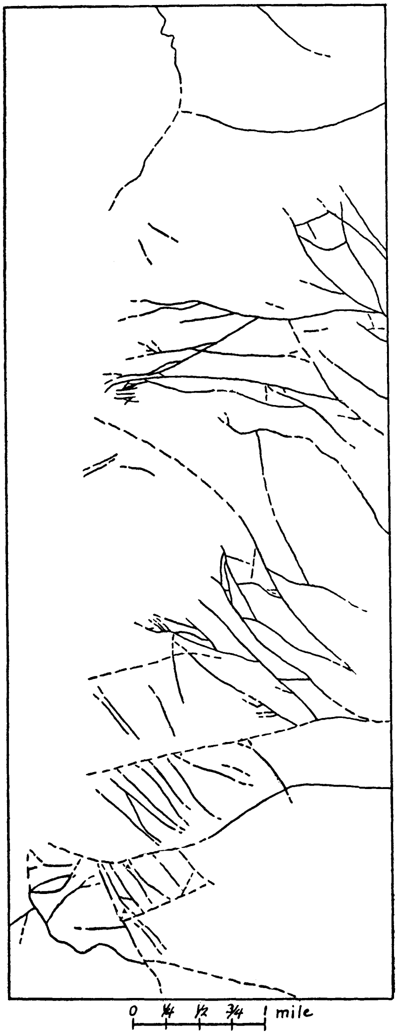
[38] F. L. Ransome, W. H. Emmons, and G. H. Garrey, "Geology and Ore Deposits of the Bullfrog District, Nevada," *U.S. Geol. Surv., Bull. 407* (1910).

ner of fracture of the rocks, the shape of the magma chamber, the course of events during the extrusion, the distribution of the extrusive rocks, and perhaps to other factors. In spite of all these differences in the patterns, there are certain common characters which distinguish them as a type. The great irregularity and complexity of

RAY FAULT PATTERN
(After Ransome)

FIG. 14

the faulting are especially apparent. Separate blocks are common, perhaps more common than they appear to be on these maps which are necessarily not complete. Small faults within the blocks are characteristic. Systems of faults are poorly developed. In general, the structure is that of a jumble of broken blocks. It differs from the Lake Champlain structure by a greater complexity, a greater irregularity, and a greater development of separate blocks. The absence of any large amount of extrusive material from the Lake Champlain region and the distance from large-scale igneous activity of any kind also seem to indicate that the Lake Champlain normal faults did not result from the movement of magmas beneath. It must be admitted, however, that there is not sufficient evidence to show with certainty that magmatic movements had no part in the formation of these faults, for there may have been movements of which we have little or no direct evidence.



BULLFROG FAULT PATTERN
(After Ransome)

FIG. 15

EPI-ANTICLINAL FAULTS

The explanation proposed by Link for certain normal faults in dome structures east of the Rocky Mountain front and for the flaws in the Jura Mountains might be applied here.[39] The idea is, briefly, that tension develops on the outside of an advancing lobe or salient. The tension is in the direction of curvature of the salient, and normal faults develop at right angles to the axes of the folds in the advancing salient. The faults he discusses are mainly within the area of folds, but it seems possible that the stretching would extend out into the unfolded area. The normal faults in the unfolded rocks of the Jura Tableland north of the folded Juras may have been produced in that way. The Lake Champlain faults have about the same position relative to the salient of the Green Mountain folds as the Jura Tableland faults have to the Jura Mountain system. There are, however, certain objections to such an

[39] Link, *op. cit.;* "En Échelon Folds and Arcuate Mountains," *Jour. Geol.*, Vol. XXXVI (1928), pp. 526–38.

explanation for the Lake Champlain faults. The Lake Champlain faults are not normal to the axes of the Green Mountain folds. More important is the fact that the stretching indicated by the Lake Champlain faults is directly opposite to the direction of the thrust forces, and not concentric with the margin of the advancing lobe.

RELAXATION AFTER OVERTHRUSTING

It has been stated in the foregoing pages that many of the normal fault structures associated with overthrust faults and folds are later than the overthrusting and folding. For such normal faults, the common explanation—relaxation after overthrusting—seems reasonable. According to that explanation the loading of certain areas with the overthrust masses and the concentration through folding and overthrusting of the geosynclinal material into a narrower zone cause the newly deformed belts and their borderlands to settle under the increased weight.[40]

For the Lake Champlain faults and others which were formed before the overthrusting, the theory of relaxation after overthrusting is not applicable, unless an earlier time of overthrusting of which there is no evidence is postulated.

TENSION IN THE GEOSYNCLINE

The Lake Champlain faults appear to be as definitely related to mountain structure as are those formed later than the overthrusting, and it is believed that they, too, result from some part of the process of mountain making. That part of the process which precedes the compression is the geosynclinal stage. It is the opinion of the author that these faults were caused by tensional forces which existed between the upstanding Adirondacks and the sinking geosyncline during the geosynclinal stage.

One of the features of the geosynclinal stage is the loading of a narrow zone of the earth's crust with a great mass of sediments. As has been pointed out before, however, the depression of a geosyncline cannot be a simple process of isostatic sinking under the ac-

[40] G. H. Chadwick, "Hypothesis for the Relation of Normal and Thrust-Faults in Eastern New York (abstract)," *Bull. Geol. Soc. Amer.*, Vol. XXVIII (1917), pp. 160–61; J. B. Woodworth, "Relations of Fault-block Mountains to Folded Chains (abstract)," *Bull. Geol. Soc. Amer.*, Vol. XXXI (1920), pp. 115–16; and "Contributions to the Study of Mountain-building" (ed. A. C. Swinnerton), *Amer. Jour. Sci.*, Vol. XXIII (1932), pp. 155–71.

cumulating sedimentary load, for the volume of displaced material at the base of the isostatic column is necessarily less than the volume of the sediments and the sediments will pile up more than they will depress.[41] That still leaves the possibility that, although other forces operate to produce the geosynclinal depression, the weight of the sediments is an added factor of some importance. Lawson says: "The sediment is a load imposed upon the earth's crust and, when the deposit becomes thick enough and the area of the geosyncline is large enough, this load depresses the crust as compensation proceeds, thereby contributing to the development of the geosyncline. The initiation of a geosyncline, however, must be due to some other cause than loading alone."[42] Lawson discusses several typical situations and shows that where areas subject to loading are adjacent to rising areas there must develop shear strains between the rising and the sinking areas which result in flexure or normal faults. The relations in the Lake Champlain region approximate, although they are not exactly the same as, those postulated by Lawson. The normal faults appear to have been formed between the rising Adirondack area and the sinking geosyncline. The distribution and direction of the tensions, as indicated by the faults, are according to expectations; the time of faulting is in agreement with the theory; and the relation of the faults to the Adirondacks and the Green Mountains is explained. The directions of the faults were probably controlled in part by pre-existing lines of weakness. It is not certain, however, that the sedimentary loading would develop enough tension to cause the faults, or that the geosynclines are not downwarps caused by compressive forces that would prevent the development of any tension. Indeed, it would appear that the sedimentary load could cause tension only if the geosyncline were in a state of little or no compression, and that raises the question of how geosynclines are produced.

W. H. Bucher has advanced the idea that geosynclines are produced by tension and that the geosynclinal stage is characterized by a state of tension. That might explain these faults, with or with-

[41] A. C. Lawson, "The Geological Implications of the Doctrine of Isostasy;" *Bull. National Research Council*, Vol. VIII (1924), pp. 3–22; R. T. Chamberlin, "Isostasy from the Geological Point of View," *Jour. Geol.*, Vol. XXXIX (1931), p. 11.

[42] Lawson, *op. cit.*, p. 17.

out the added effect of the sedimentary load. A full statement of this theory has not been made, but the idea of particular significance here is that ". . . . 'mobile belts,' such as the Appalachian and Alpine systems . . . . owe their origin to tensional crustal stresses which create the geosynclines while later compressive stresses throw them into folds."[43] Thus, he postulates tension during the geosynclinal stage, but does not attribute it to the weight of sediments. If geosynclines originate from such tensional stresses and develop in a state of tension, then normal faults might well be produced along the margins of the geosynclines, especially near areas which tend to rise rather than to sink with the geosynclinal areas. Full consideration of this theory cannot be made until a complete statement of it has appeared.

[43] W. H. Bucher, "The Mobile Belts of the Earth (abstract)," *Jour. Wash. Acad. Sci.*, Vol. XXI (1931), pp. 489–91; "The Pattern of the Earth's Mobile Belts," *Jour. Geol.*, Vol. XXXII (1924), pp. 265–90.