

THE  
AMERICAN JOURNAL OF SCIENCE  
[FIFTH SERIES.]

---

ART. VII.—*Cambrian Succession of Northwestern Vermont*; by ARTHUR KEITH.\*

*Introduction.*

Along the western border of Vermont the closely folded portion of the Appalachians runs in a general north-south direction from southern New England and New York into Canada. This belt of rocks has been the subject of diverse opinions among geologists for about three generations. Some geologists placed the rocks of this belt at the base of the Paleozoic section, while others assigned them to the middle of that section. For instance, a single formation known as the "Red Sand-rock" has been assigned to various positions from basal Lower Cambrian to the Silurian (Oneida). The Taconic system of Emmons is founded upon these rocks, and the controversies as to facts and as to taxonomy which raged about that system are not even yet settled. In this paper, which is a preliminary statement of new results in stratigraphy and structure, no attempt will be made to enter into details as to these controversies. A few of the salient advances toward their settlement will be cited, however, so as to show the bearing of the present discoveries.

This belt of intensely deformed rocks runs the whole length of Vermont—160 miles. A preliminary analysis of the southern half of this belt including the northern half of the Taconic Range has already been written by the author but is unpublished. The structure of this southern portion, as well as its stratigraphy, and the larger questions involved differ so radically from the northern portion that it seems best to describe the latter in a separate paper. The main facts and conclusions

\* Published with the permission of the U. S. Geological Survey.

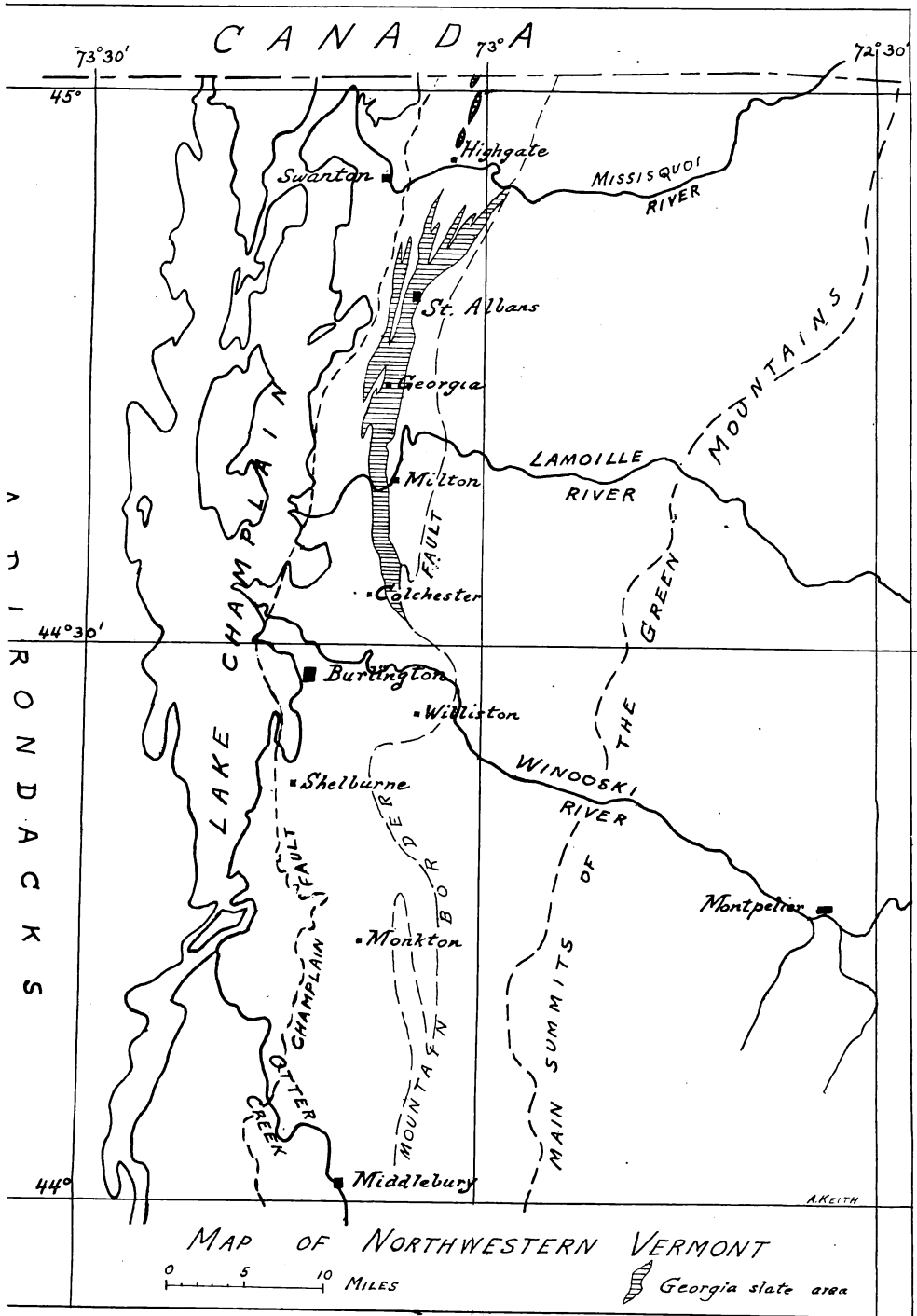
concerning this northern portion are accordingly presented herewith.

### *Geography.*

The region under discussion is that part of the great Appalachian Valley locally known as the Champlain Valley. A considerable percentage of it is occupied by Lake Champlain, and it lies between the Adirondack Mountains of New York on the west and the Green Mountains of Vermont and their foothills. The eastern or Green Mountain side of the Valley has a nearly north and south trend, while the Adirondack margin turns westward around the mountains near the Canada border. Thus, the Valley widens at the north and merges with the larger St. Lawrence Valley. The Vermont portion of the Valley, which alone will be considered in detail, is drained by Otter Creek, Winooski, La Moille, and Missisquoi rivers, all flowing into Lake Champlain. The lake is 101 feet above sea level, and the Valley consists of low, rolling hills less than 500 feet above sea, separated by smooth, shallow valleys. Above this general low level, underlain for the most part by limestone, dolomite, or marble, rise a few hills formed of quartzite. These are most numerous in and around the town of Monkton and there form a considerable interruption to the open floor of the Valley. They rise to a maximum height of 1,271 feet above sea, and form a broken line of hills or low mountains for 35 miles north of Winooki River. The Champlain Valley east of the Lake is from five to 15 miles wide, and only the northern 70 miles of it are discussed here in any detail.

### *General Geology.*

*Historical.*—All of the rocks here described were placed by Emmons from 1840 to 1860 below the Potsdam in his Taconic system, for stratigraphic reasons. This view was opposed strongly by Hall and Logan, who in 1842 and later placed parts of this system (the "Red Sandrock" and the black slate along Lake Champlain) in the Silurian of that time. Fossils were discovered in the "Red Sandrock" by Perry and G. M. Hall in 1847. Their true meaning was not understood until they were



correlated by Billings in 1861 with similar fossils from Canada and assigned to the "Potsdam group." Fossils had already been found in the black slates along Lake Champlain which determined them to be "Lower Silurian" (Ordovician). These two formations were found in contact near Burlington and at Snake Mountain, west of Middlebury and in the southwest part of this area, where the Cambrian sandstone rested upon the slate, thus determining the presence of thrust faults in this region. Hitchcock had pointed out in 1861 that a fault was necessary if the view of Billings as to the Potsdam age of the "Red Sandrock" was correct. Shortly after this, in 1871, fossils of early Ordovician ("Lower Silurian" of that time) and probable Chazy age were found by Wing in the marble at West Rutland, assigned by Emmons to his Taconic system. This marble formed the upper part of the Eolian limestone of Hitchcock. Thus, it was necessary to cut important formations from the middle and upper parts of Emmons' Taconic system. In 1881 Dana assigned the "Georgia shales" to the Potsdam epoch, and in 1885 Whitfield stated that "the typical Potsdam of New York\*\*\*\* and the Acadian beds [Georgia slate] of Canada and Vermont\*\*\*\* are not appreciably different in age."

In 1883 Walcott began the examination of the folded belt at many points in Vermont and New York and found fossils at many localities. He made extensive collections and found fossils of two general ages—Lower Cambrian (Middle Cambrian of that time) and Lower Ordovician. The Lower Cambrian fossils were found at many places through the entire length of the belt, while the Ordovician fossils were limited to its southern half in Vermont. On the basis of these discoveries Walcott concluded that the "Taconic system" was not a serviceable or proper unit, since it included beds of two diverse ages. Walcott's discoveries established the Lower Cambrian age of the quartzites flanking the Green Mountains on the west and also the Lower Cambrian age of certain slates and dolomites in northwestern Vermont. Other slates of similar aspect in the Taconic Range of southwestern Vermont were also determined to be Lower Cambrian. His collections from the Parker quarry, in the town of Georgia, in northwestern Vermont, were extensive and of great importance from a paleontological standpoint.

This locality was already well known, and the fossils therefrom had been assigned to the Potsdam by Billings. Other Lower Cambrian fossils were collected by Walcott in the same general section in Georgia. Certain collections from Georgia were stated by him in 1886 to have an Upper Cambrian aspect. In 1912 fossils of a few collections made from limestones near Highgate Falls were assigned by him to the Upper Cambrian in his *Monograph of Cambrian Brachiopoda*, but their stratigraphic position and exact locality were not known.

On the basis of his collections Walcott established the section in Georgia as the type of the Lower Cambrian and in 1891 gave it the name "Georgia series." This name was for years the standard name for the Lower Cambrian series, until in 1912 Walcott proposed the name Waucoban for that series on account of the varied usage which had been given to the term "Georgia." Collections of fossils have been made in northwestern Vermont since those of Walcott, but none changed the general understanding of the Cambrian stratigraphy.

The work of the present author in that region consisted of three weeks of reconnaissance in 1909, of three weeks of more detailed work in 1921, and two weeks of detailed work in 1922. Before 1917 much very detailed work had been done by the author in the Taconic Range and adjoining portions of the Valley between the Taconic Range and the Green Mountains. In the course of that work doubts arose as to the accepted classification of the rocks that were of such magnitude as to compel examination of all areas which might throw new light on the problems. In September and October, 1921, numerous discoveries of fossils were made by the author in northwestern Vermont, and a large number of new formations were distinguished. By means of the detailed stratigraphy and the fossils the characteristic and exceptional structure of the region was determined. The fossils are now (1922) classified by Walcott as of three ages—Lower Cambrian, Upper Cambrian, and "Saratogan." The Lower Cambrian and "Saratogan" fossils were given preliminary identifications by Schuchert, who had discovered the Lower Cambrian fossils jointly with the present author, and later were examined in detail by Walcott and referred to the horizons above mentioned. Lower and a few Upper Cambrian fossils had already

been described by Walcott from Vermont, his Upper Cambrian then including Saratogan. As now understood by him and by Ulrich, Schuchert, and other paleontologists, the "Saratogan" fossils are younger than the true Upper Cambrian, or St. Croixan. The Saratogan fossils discovered in the bowlders of the Swanton conglomerate are thus the first of that age to have been obtained in Vermont. The position of each of the collections in the Cambrian sequence was determined by the work of the present author. Further discoveries by the author were made in July, 1922, in company with Dr. Schuchert; numerous cephalopods were found at the border of the village of Brandon in limestones (equivalent to the Williston limestone) and pronounced by Schuchert to be "Saratogan" and the same as those in the Swanton conglomerate bowlders. A new locality for Upper Cambrian fossils was found in 1922 by Messrs. Schuchert, Sayles, Swinnerton and the author, at the lower end of the gorge at Highgate Falls; Upper Cambrian fossils were very abundant and large collections were made.

In September, 1922, fossils of Black River (Mohawkian) age were found by Schuchert and the author in the Georgia slate in Highgate.

The term "Saratogan" is used here to denote the time of the Saratoga fauna of New York. This term was introduced by Dr. Walcott and used by the New York Survey as synonymous with Upper Cambrian. In 1910 it was used by Ulrich and Cushing as synonymous with "Ozarkian" in New York. In 1912 these beds were doubtfully retained in the Cambrian by Walcott, and the term was abandoned by him, in favor of St. Croixan, as a name for the upper series of the Cambrian. By other geologists these beds have been referred to the Cambrian and to various portions of the proposed "Ozarkian system." Thus there is an increasing tendency to exclude the "Saratogan" beds (Potsdam-Hoyt) from the Cambrian, on the ground stated by Walcott in 1912 that they "are not typically of Upper Cambrian age." Since the proper systemic position of these beds is in doubt, it seems preferable in this paper to quote the old term, without decision as to its inclusion in the Cambrian or a later system.

*Stratigraphy.*—The sedimentary rocks of this district fall into three groups or sequences, each prevailing in a

distinct belt and each exhibiting important differences from the other belts. These three sequences, originally far apart east and west, are now jammed together along great thrust faults. The western sequence is found almost wholly west of the Champlain fault, which lies along or near the eastern shore of Lake Champlain, and extends far southward through Vermont and New York. Most of the area east of that fault is underlain by rocks of the middle sequence. These rocks narrow southward and end west of Middlebury between the Champlain fault at Snake Mountain and another nearly parallel fault called the Weybridge fault. The latter fault gradually traverses the valley with a trend north and northeast until it joins the main fault at the border of the Valley and the Green Mountains, about ten miles southeast of Burlington. Between the Weybridge fault and the Green Mountain border fault lies the eastern sequence of formations, from Middlebury northward to Essex, on Winooski River. Thence northward to Canada the eastern sequence forms a narrow belt along the mountain border fault. The eastern sequence cuts across the central sequence for 30 miles and south of the latitude of Middlebury is in contact with the western sequence, the middle sequence having been entirely overridden.

The eastern sequence begins with a heavy quartzite and forms a cycle through dolomite, marble, and limestone into slate. Most of these formations, and perhaps all but the upper two, are of Lower Cambrian age. The western sequence likewise begins with a quartzite (Potsdam), which is, however, of "Saratogan" age, and passes upward through a lithologically similar cycle of Ordovician dolomite, marble, limestone, and slate. The mass similarity of these two sequences is very strong, although the eastern sequence is considerably thicker, and it has required the positive evidence of fossils to demonstrate their distinctness. The central sequence also begins with a quartzite, passes upward in a general cycle through dolomite, limestone, and marble into slate. The basal quartzite is of Lower Cambrian age, the same as the basal quartzite of the eastern sequence; four of the formations are Lower Cambrian and are overlain by the Upper Cambrian Milton dolomite and Highgate slate, followed by the Middle Ordovician Swanton conglomerate and Georgia slate. The two lower formations of

the central sequence differ materially from those of the eastern sequence of the age, while most of the overlying dolomites in each sequence are similar or the same.

*Structure.*—Most of the Champlain Valley occupies a synclinal basin between the Green Mountain anticline on the east and the great dome of the Adirondacks on the west. This synclinorium shows older and lower rocks on the east on account of the general westward overlap and nondeposition of the older beds. This general overlap relation accounts for the great differences between the eastern and western sequences. The orderly succession of beds in the syncline is further greatly disturbed by north and south thrust faults with great westward movement. The two principal faults are the Champlain fault, near the east shore of Lake Champlain, and the Green Mountain border fault, along the west foot or border of the Green Mountains. In the Champlain Valley north of the Taconic Range deformation and shortening have been accomplished on these thrust faults with almost no visible folding. The contrast in this particular between the sliced structure of the Champlain Valley and the hundreds of doubled up and overturned folds of the Taconic Range is one of the most abrupt in the Appalachians.

Including the Champlain fault and the Green Mountain border fault, there are from three to seven faults in any single cross section, and the width of the belt between the faults is only from three to ten miles. In the entire belt there are only half a dozen places where distinct anticlines or synclines are present. The reason for this is probably to be found in the fact that all of the sequences are composed of heavily bedded and competent rocks, especially in their lower two-thirds. In these the tendency under pressure is to shear instead of to fold or crumple, and they are further qualified by being directly upon the pre-Cambrian rocks to transmit thrusts derived from them. Thin limestones and shales which lend themselves readily to close folding and crumpling are found only in the upper parts of each sequence. Such beds simply rode along on top of the massive rocks below them which transmitted the thrust. The truncation of successive formations along the Champlain fault is impressively shown northeast of Highgate Springs.

All of the faults dip to the east, some at high angles,

while others are nearly flat. The Champlain fault at several places is within a few degrees of horizontal, but most of the faults appear from the meager exposures of them to dip at angles of 40 degrees or more. As a result the Valley is cut into series of long, narrow slices, each rising westward upon the next slice. The total amount of shortening has not yet been worked out, but it is undoubtedly much greater than one-half of the original width. This district lay between the upthrust, advancing arch of the Green Mountains and the passive buttress of the Adirondacks against which the different formations abutted, which position was a sufficient reason for the extreme faulting and narrowing of the deformed belt. The fact of the great narrowing is further evidenced by the great westward swerving of the Green Mountain anticline and of the various folds lying to the east of it. This swerving or protrusion diverts the folds more than 10 miles west of their normal trend and position in Vermont, so that the axes of the folds run well to the west of north instead of east of north as is customary. A direct result of this excess compression is seen in the exceptional uplift of the lowest Cambrian rocks between Middlebury and Burlington, and in the eastward projection and uplift of the Cambrian and pre-Cambrian of the Adirondacks immediately to the west. Put in other words, one of the principal cross-anticlines of the Appalachians is shown here in close association with its cause—an unusually great westward thrust of the eastern masses.

The faults of this district are of three different ages: first came the flat overthrust of the Champlain fault; later on, probably in the same general epoch of folding, this was compressed, folded up, and dissected by later faults. This process has left numerous rather flat-lying and disconnected scales of the old overthrust mass, with parts of the underlying mass exposed between them by erosion. These features are well shown near Mt. Philo in Ferrisburgh, 12 miles south of Burlington. At a still later date normal faults were produced. These appear principally to the west of the Champlain fault and are numerous along the Adirondack margin. They trend well to the east of north, a direction considerably in contrast with the nearby thrust faults. In a few cases the normal faults appear to dissect and offset the thrust faults, but

conclusive evidence of it has not yet been found. The Weybridge fault, three miles west of Middlebury, may be of this origin. The formations east of that fault are younger than those west of it, so that it is either a normal fault with the downthrow on the east or it is a thrust fault dissecting the old Champlain fault and thrusting up younger rocks which previously had been covered by the overthrust. There are no data at present at hand to determine the age of the normal faults. The various thrust faults, however, are of the regular Appalachian type and, therefore, were probably produced at the end of the Paleozoic era. The general position of the Mountain Border and the Champlain faults is shown on the map.

#### *Detailed Stratigraphy.*

This paper concerns itself mainly with the rocks of the central sequence, which extends from the Canada border 70 miles southward to Snake Mountain, five miles west of Middlebury. The detailed succession of these rocks has been unknown until unraveled by the author in 1921 by detailed mapping and discovery of fossils. The older method of correlation between widely separated cross-sections failed to solve the problems, because no two sections ten miles apart gave the same succession, on account of the complex fault systems and overlaps. The western and eastern sequences will only be briefly treated in this paper in order to show the larger stratigraphic variations. The rocks of the eastern sequence have already been divided into formations and mapped over large areas by the author, and they will be made the subject of a separate paper. The rocks of the western sequence have not been thoroughly examined as a whole, although close work has been done in limited areas by various geologists.

#### *Central Sequence.*

*Monkton quartzite.*—This is the oldest formation of the central sequence. Its base is not known, because the lowest beds rest on the Ordovician rocks along a thrust-fault plane. The name is taken from the town of Monkton, 20 miles nearly south of Burlington, where the relations of the quartzite to the overlying beds are

well and repeatedly shown. The quartzite was included in previous reports with the overlying Winooski marble and the Mallett and Milton dolomites and the whole termed the "Red Sandrock."

Except for a small mass east of Highgate Springs, the Monkton quartzite is not found north of La Moille River, eight miles north of Burlington, being there cut out along several thrust faults. For the same reason it disappears at the south end of Snake Mountain. In Monkton it forms several anticlines on the major cross anticline already described. The general uplift there is higher and broader than elsewhere and brings this quartzite into direct contact along a fault with the Cheshire quartzite of the eastern sequence, which is of the same age. Owing to the superior hardness of the Monkton quartzite it resists erosion, and nearly everywhere its outcrop is marked by hills or low mountains. The lines formed by these are interrupted because the quartzite is cut out for short distances by faults.

The Monkton quartzite has a decided reddish color varying from reddish-brown through brick-red and purple to light shades of red, pink, buff, and white. The white beds are more numerous at the top, especially north of Burlington, where they are as important as the vari-colored beds. Striking contrasts are formed by the white and vari-colored layers, particularly in the cliffs along Lake Champlain. The formation consists almost entirely of quartzite in layers from a few inches up to three feet in thickness. A few seams and beds of reddish or purplish shale are interbedded with the quartzite in the lower part of the formation, most of them being only a few inches thick. In the upper part of the formation a few thin layers of gray or pink dolomite form a transition into the overlying Winooski marble. Quartz conglomerate in thin layers has been reported from a few places by several geologists but has not been observed by the writer.

The formation outcrops freely and forms extensive cliffs and ledges. Where it borders Lake Champlain the cliffs are nearly continuous, being mainly in the lower part of the formation. The upper part of the quartzite also makes very extensive exposures and forms large dip slopes which may show the surface of a single bed for 50 or 60 feet down the dip. On these broad exposures

the minor characteristics of the formation are well exposed; ripple marks and mud-cracks are very common, and there are numerous rain-drop impressions and trails of animals. Cross-bedding in the quartzites is very common and there are numerous seams of coarse material which are too fine to be called conglomerate.

Fossils have been found in this formation, mainly trilobites, and have been determined by numerous paleontologists to be of Lower Cambrian age. Practically no fossils are found in the fresh rock, but they appear in feebly calcareous quartzites near the top of the formation where the thin beds are considerably weathered. Thin slabs of this kind are occasionally found practically covered with trilobite fragments. The full thickness of the formation is not known, as it rests upon a fault plane, but 300 feet of the quartzite are to be seen in the sections in the township of Colchester.

*Winooski marble.*—This formation outcrops in nearly continuous belts from Snake Mountain to Canada. Here and there it is cut out for short distances along fault planes and is repeated by them in parallel bands. The formation name is a very old one given for the fine exposures along Winooski River in Burlington. At that point marble was first quarried from the formation, and it is still obtained from other quarries near Swanton.

The formation consists mainly of dolomite which has a prevailing red or pink mottled color. Interbedded with these colored beds are considerable layers of light gray dolomite. A few of these gray beds are rather coarsely crystalline, but most of the dolomites, both gray and colored, are very dense and have a marked conchoidal fracture. The dolomites, especially the mottled beds, are slightly siliceous and are very hard and tough. Their resistance to erosion is considerable, and the different beds form long ledges over the hollows and slopes which usually accompany the formation. The characteristic feature of the dolomite is a very marked wavy, lumpy surface for the individual layers. This is brought out on the weathered surfaces by thin films and seams of siliceous, shaly matter which stand in relief. This peculiar structure of the dolomites is present in practically all of the finer-grained beds. This feature made possible the use of the stone as ornamental marble, especially layers in the lower part of the formation.

which are strongly mottled buff and red or purple in addition to the wavy bedding. For decorative purposes this stone is sawed parallel to the general bedding plane, thus intersecting the mottling and the wavy surfaces and producing extremely variegated patterns.

At the base of the formation the dolomite is interbedded with quartzite layers for a thickness as great as 50 feet, forming a transition into the underlying Monkton quartzite. Just below the top of the Winooski there is a marked horizon of red, buff, and purple quartzite layers interbedded with pink and buff, mottled, fine-grained dolomite for a thickness of nine feet. In the pink dolomite just above this quartzite there are a few inches of edgewise conglomerate containing thin, flat dolomite pebbles. The quartzite layers at this horizon form broad, flat surfaces like those of the Monkton quartzite which they strongly resemble, and also show ripple-marks, mud-cracks, and annelid trails. These beds and the underlying mottled pink or purple dolomites aggregating 85 feet are well exposed at Winooski Falls in Burlington.

At this same topmost horizon, 11 miles north of Burlington and also 3.5 miles N 20° W of Highgate Center, a coarse conglomerate or breccia is found in several layers aggregating from 5 to 30 feet. The pebbles in the conglomerate are of various kinds of dolomite, gray, mottled pink, buff, or grey calcareous sandstone and quartzite, while the matrix is a sandy buff dolomite with the purple, slaty streaks characteristic of the Winooski. Many of the pebbles are more than a foot (as long as two feet were seen) in diameter with an average of five or six inches, and the majority are rather angular. In this conglomerate are scattered knots of brilliant red jasper of vein origin.

There is an abrupt change above the topmost quartzite of the formation to the massive gray beds of the Mallett dolomite. The formation thins southward from its greatest thickness of 400 feet about 12 miles north of Burlington. Along the east side of Snake Mountain the Winooski is very poorly exposed and is probably less than 100 feet thick.

Fossils have been found in the Winooski marble by many geologists. As early as 1847 a few were found by G. M. Hall and Perry and were assigned to the Silurian by James Hall. In 1861 Billings correlated them with

the Potsdam. Walcott in 1883 found fossils in the pink dolomite and referred them to the Lower Cambrian.

*Mallett dolomite.*—Massive light and dark gray dolomites make up practically all of this formation. There are fine exposures of them on the shores of Mallett Bay (a part of Lake Champlain) five miles north of Burlington, for which the formation is named. Beginning 100 feet from the base there are two or three beds of fine white quartzite, cross-bedded and ripple-marked, and sandy dolomites are numerous, in many places grading into dolomitic sandstone. The sand in these beds consists of glassy, rounded quartz grains which stand out in relief on weathered surfaces. Between St. Albans and the Canada border a few beds of shale make their appearance between the dolomites. The bedding is usually plain and even, and most of the layers are less than a foot thick. Secondary quartz in geodes is common in the dolomites. A few beds of pink dolomite are seen here and there, apparently in the lower part of the formation, but these may be repetitions of the Winooski by faulting.

The beds of this formation are very hard and tough and resist erosion so as to make ridges wherever the formation appears. Large ledges are numerous and are usually weathered to a dark gray, or even a black surface. A few fossils of Lower Cambrian age were found by Walcott in some thin layers in the upper part of the formation in the towns of Georgia and Highgate.

The contact of this dolomite with the overlying Colchester formation is usually sharp, but a few sandy beds in each formation seem to make a rather poor transition between the two. The Mallett dolomite is between 700 and 800 feet thick, where all is present, but it is reduced to a thickness of 50 feet in the eastern part of Swanton township, probably by Lower Cambrian erosion.

*Colchester formation.*—This formation differs from preceding ones in that it contains numerous shaly and slaty beds with which are interbedded sandstones and dolomites. The formation is named for its good exposures from one to two miles north of Colchester Village in the town of Colchester, which borders Burlington on the north. This formation extends from Canada to Monkton, where it is cut off against a thrust fault.

South of that point its position in the eastern sequence is taken by a formation of similar aspect but with less shale and more dolomite.

The greater part of the formation is made up of shale in the northern sections. The amount of this diminishes southward and beds of calcareous sandstone and sandy dolomite becomes more numerous. The shales are usually dark or black, distinctly banded, and much speckled with little scales of mica. Interbedded with these are thin layers of gray sandstone locally argillaceous and in other places calcareous. In Highgate and Swanton the formation contains many non-banded massive layers, which weather light gray or white, and many very strongly bedded layers which are used for flagstones. A few layers of sandy dolomite are also present here and there.

A notable feature of the formation is a peculiar tough, dark gray dolomite which weathers with a brick-red surface. This forms lenses as much as five feet thick and 50 feet long near the base of the formation. Several of these are present in the section at the Parker quarry (now the Howard quarry), two miles and a quarter north sixty degrees west of Georgia. In Swanton they are numerous and prominent and are closely associated with a peculiar conglomerate formed of irregular dolomite boulders in a slate matrix. The dolomite boulders consist for the most part of the reddish-brown dolomite, but there are also some gray or sandy dolomite fragments. The whole group of beds appear to be of intraformational character.

The Colchester also contains another set of lenses consisting of massive blue marbled limestone, sharply separated from the slate. They are best shown two miles southeast of Swanton, where two of them are surrounded by gray slate. The lenses measure 100 by 60 feet and 105 by 75 feet, the longer axes lying northwest-southeast. No thickness and no original relations to the slate can be determined, owing to the cleavage. Peculiar patches of rusty dolomite grade into the limestone, and the whole resembles a reef deposit. This limestone very closely resembles some of the boulders in the later conglomerates, and even a whole lense may have become a boulder. The contact of the formation with the overlying Milton dolomite is sharp and represents a hiatus, since the Milton is of Upper Cambrian age. One mile

northwest of Highgate Center the contact shows a visible unconformity. The formation usually occupies narrow valleys or hollows.

This formation has furnished a large part of the Lower Cambrian fossils from Vermont, and most of them have come from the Parker quarry. The presence and age of the fossils there has long been known, and many fine museum specimens have been obtained there. Much material was excavated by Walcott and a fine collection secured. Another locality which promises to yield many Lower Cambrian fossils was found by the author in September, 1922. This is at a small flagstone quarry nearly three miles southeast of Swanton.

Edson reported the discovery of *Paradoxides* in shales in the town of St. Albans, which indicates strongly that Middle Cambrian is there present. He also reported finding *Agnostus* in the same place, thus indicating Middle Cambrian or later beds. It is thus possible that some of the shale called Colchester is of Middle Cambrian age, but it has not yet been practicable to distinguish such beds as a formation. If Middle Cambrian shales are present, they can only extend a few miles to the north and south before being cut out by the Milton dolomite. This possibility is strengthened through the finding by B. F. Howell at the same locality in 1922 of apparent Middle Cambrian fossils.

The thickness of the formation varies from 200 to 250 feet at the south and from 20 to probably 500 feet at the north. This fact taken in connection with the great reduction of the underlying Mallett dolomite in the township of Swanton gives evidence of important erosion and overlap.

*Milton dolomite.*—The beds of this formation are practically continuous from Canada to Monkton. They are best exposed in a wide belt passing through the town of Milton about three miles west of Milton village. The formation consists almost entirely of massive dolomite both fine and coarse-grained. Most of the beds are thick (from one to four feet), especially in the lower part of the formation, and as a rule the bedding is difficult to determine. The dolomites vary in color from dark bluish-gray or steel-gray through light gray to buff, most of them weathering with a dark surface. Beds of sandy

dolomite are fairly common in this formation, as in the other dolomites in this region, but there is only a little dolomitic sandstone, mainly in the upper third of the formation.

A peculiarity of the Milton is its considerable content of black chert. This forms small, irregular patches and pockets much broken during the rock movements, and is very seldom found in layers. This chert weathers out in black spots which readily catch the eye. Chert is of rare occurrence in the formation of Vermont and its abundance in this dolomite makes it a very distinctive formation. Numerous large rough ledges are made by the formation, much spotted with black chert and white quartz knots, or geodes with quartz crystals. In a few places there are doubtful cryptozoa near the top of the formation.

Another peculiarity of this dolomite is its large content of dolomitic conglomerate. This is present at many horizons throughout the formation and almost invariably appears at the top. The conglomerate is formed mainly of pebbles of dolomite and dolomitic sandstone, of which the source is probably the beds of the same character in the lower parts of the formation. The dolomite pebbles are dark gray or bluish-gray to light gray and the sandstones are light or dark gray. A few pebbles of slate are also found. Most of the pebbles are decidedly angular, resembling a breccia, but some of them are rounded. The matrix of the conglomerate is dolomite and is like the bulk of the formation. The different colors of the pebbles and the matrix usually make plain the nature of the rock.

The beds resting upon the Lower Cambrian Colchester formation one mile northwest of Highgate Center are conglomerate and cut out six feet of the Colchester, bringing out the unconformity strongly. The upper 80 feet of the Milton at Highgate Falls consist of slabby dolomite and limestone interbedded with eight layers of conglomerate. All of the conglomerates resemble tillite in texture, but only one, 15 feet from the top, contains boulders of foreign origin. This bed is a giant conglomerate 26 feet thick, holding bowlders of many kinds of limestone up to eight feet in diameter. The enormous differences in size, kind, and angularity of the bowlders strongly suggest that this bed is a tillite. The evidence of glacial

origin for the other conglomerates is weaker, and it is safer to call them intraformational.

The slabby limestone and dolomites near the top of the formation at Highgate Falls yielded in 1922 numerous fossils, mainly trilobites and brachiopods, which were determined by Schuchert to be Upper Cambrian. No fossils have been found in the middle and lower parts of the formation. Paradoxides heads have been found by Edson in the town of St. Albans and so identified by Walcott, therefore it is possible that the Middle Cambrian is represented either in the lower massive part of the Milton or in the higher part of the Colchester. The formation is about 800 feet thick where it is all present. The massive character of the beds makes precise measures of the dip and the thickness difficult. A few miles southwest and northwest of St. Albans the formation is entirely cut out by erosion preceding the deposition of the Swanton conglomerate.

*Highgate slate.*—This formation extends from Canada into the town of Milton, a distance of 25 miles. Its principal development is in the township of Highgate, where it forms a broad area. A fine section of the formation is shown at Highgate Falls, close to Highgate Center, and in adjoining areas. The formation consists mainly of dark slate, in places black, and usually banded. The banding is in most places regular, sharp, and clear, and strongly resembles the seasonal banding of glacial deposits. The dark and the light layers are evenly spaced and from one-eighth to one-fourth of an inch in thickness. In the lower part of the slate at Highgate Falls the light bands consist of fine sandy shale or sandstone seams. About 40 feet above the base at Highgate Falls there is a zone nearly 6 feet thick of a slate filled with small pebbles of limestone that range up to 4 inches across.

In the lower part of the slate at Highgate Falls are several beds of tough gray dolomite a foot or so thick and weathering to a rusty brown. These beds were folded and torn apart and their segments separated by many feet, and the banded slate flowed between and around them as if plastic. Thus is brought out an extreme deformation and shortening in a section that at first sight seems simple.

Interbedded with the slates are numerous thin seams of blue limestone an inch or two in thickness. These are very evenly spaced between layers of slate of about the same thickness and constitute a very marked horizon. One-third of a mile northwest of Highgate Center these layers thicken and outcrop in the railroad-cut as a strongly banded limestone mass 35 feet thick. These are probably the highest beds in the formation near Highgate. The thin limestone layers yielded fossil trilobites to the author in 1921 at numerous localities, the most important being in and near Highgate Center. A determination of these fossils by Walcott placed them in the Upper Cambrian. Locally these limestones thicken and form good-sized lenses. The most prominent instance is two miles N. 15° E. of Highgate Center, where a lense of blue limestone is 600 feet long and about 50 feet thick. Upper Cambrian trilobite fragments are common, along with some orthoid brachiopods and plates of cystids, but all are so poorly preserved as to be undeterminable. Brachiopods collected by Walcott near Highgate Falls and described by him in 1912 as of Upper Cambrian age turn out to be from the Highgate slate, Trilobites collected in 1922 by Schuchert and the author, two miles north of Highgate Center, are of Upper Cambrian age.

The formation is at least 300 feet thick at Highgate Falls. The amount of distortion and repetition as shown by the dolomite beds is enormous, and the top of the formation is cut off by a thrust fault in this section. No other reliable one was found, however, so that the original thickness of the formation is not known. Doubtless later formations of Upper Cambrian age were deposited on the Highgate, but nothing is known of them in this region. At several localities northwest and southwest of St. Albans the formation was removed together with the Milton dolomite by the pre-Swanton erosion.

*Shelburne marble.*—Outcrops of this formation are mainly in a wide band between the town of Colchester, three miles northeast of Burlington, and the town of Hinesburg, 12 miles nearly south of Burlington. Two much smaller parallel strips of marble are found in the town of Shelburne in addition to the main belt. The name of the formation is taken from its many exposures

in Shelburne. The marble there follows next above the Milton dolomite, a position which is occupied by the Highgate slate farther north.

The formation is composed almost entirely of marble, always light colored, and for the most part white. Other colors are light buff or cream, bluish-white, and various beds are mottled with cream and white or blue and white. A few thin beds of light gray dolomite are found in various parts of the formation. Ledges of the marble are fairly common on the hills and usually are conspicuous on account of their whiteness. As a rule the formation occupies low ground and is accordingly much covered with the sands and clays of the glacial epoch. For this reason there are no precise data as to the northern end and the upper and lower contacts of the formation. The marble shows a thickness of about 200 feet in the section along Winooski River, but no upper limit is there shown, and the whole thickness of the formation is doubtless twice as great.

Four and one-half miles north of St. Albans back of the estate known as Rockledge a mass of bluish or white marble was discovered which is possibly a part of the Shelburne or a marble lens out of the Colchester. This mass has the shape of a large lens about 170 feet long, 110 feet wide, and six or eight feet thick. Just south of this a similar marble mass measures 90 feet by 50 feet. The contacts with the underlying Highgate slate and the overlying Swanton conglomerate are sharp and distinct. The conglomerate passes north from the marble on to the Highgate slate with a sharp and somewhat unconformable contact. No fossils are found in this marble, although extended search was made, but it is probably of Upper Cambrian age, since it overlies the Highgate and is beneath the unconformity at the base of the conglomerate. It is suggested, however, by Sayles that these marble masses are enormous boulders in the base of the Swanton conglomerate. Their huge size is an obstacle to this conception and requires the additional concept of transport by ice as the most capable agent. Boulders of eight and ten feet of the same kind of marble are common in the Swanton conglomerate, however, and one boulder of 60 feet and a possible boulder of 140 feet have been found, so that it is difficult to set a size which is too big for a

bowlder. The existence of limestone lenses in the Colchester of comparable size and material ready to become bowlders lends support to this view.

No contacts are known between the Shelburne marble and the Milton dolomite, which is the next underlying formation. Where the formations cross Winooski River, nearly three miles east of Burlington, the Milton dolomite and Shelburne marble are conformable in dip, but their outcrops are separated by the width of the river. The same conformable relation holds elsewhere. Ten miles north of the end of the marble, however, in the town of Milton, a similar position above the Milton dolomite is occupied by the Highgate slate, which also appears to lie conformably on the Milton dolomite. Whether the Shelburne is older or younger than the Highgate is not yet proven, but probably the Highgate is older, as seemingly is indicated by the marble lenses above described. The disappearance of the Highgate southward may be due either to nondeposition or erosion. Upper Cambrian erosion is the more probable, in which case the Shelburne marble may have followed the Highgate in regular sequence.

*Williston limestone.*—The next succeeding formation is the Williston limestone. It outcrops in a single belt seven miles long beside the Shelburne marble in the towns of Williston, Burlington, and Shelburne. This formation consists of light or dark blue limestone and marbleized limestone. Interbedded with these are some layers of shaly blue limestone and a very little calcareous shale. There are also scattered beds of dolomitic limestone, usually dark blue or gray in color. The beds of this formation are fine-grained, even where the alteration into marble is extensive. Some of the blue limestones are moderately banded with light colored, argillaceous streaks and somewhat mottled with small nests of dolomite. The prevailing blue color and the notably thinner bedding of this formation distinguish it readily from the underlying Shelburne marble.

Fossils are very scarce in this limestone, owing to its greatly deformed condition. In July, 1922, a number of cephalopods and several *Ophileta*-like gastropods were found in the same formation in Brandon by Schuchert and the writer and were assigned by the latter to the "Sarato-

gan.” They are of the same species as those found in the fossiliferous bowlders in the Swanton conglomerates at Corliss Ledge. In September, 1922, Schuchert and Dunbar found trilobites and gastropods in the Williston limestone 4.2 miles southeast of Burlington and assigned them to the “Saratogan.”

Owing to the thin bedding of the formation it is considerably crumpled, and there is no measure of the thickness, which is probably as much as 500 feet. There are no precise contacts between this limestone and the Shelburne, but the differences between the formations are marked, and the change from one to the other is probably abrupt. The Williston limestone is overlain in the towns of Williston and St. George by a fine black phyllite. This appears to lie conformably on the Williston, but its age relation to the latter is unknown.

*Swanton conglomerate.*—The beds of this formation begin about eight miles nearly south of St. Albans and appear at many localities northward to and across the Canada border. The conglomerate is well shown in the eastern part of the township of Swanton, for which it is named. The formation is not continuous but forms disconnected lenses at the base of the Georgia slate. These are common in the towns of St. Albans, Swanton, and Highgate, and unusually good exposures are seen about a mile nearly west of Georgia Center. Doubt would ordinarily arise to the desirability of separating these beds as a distinct formation, or of including them in the Georgia, as has previously been done. Their taxonomic value, however, and the notable aspect of the conglomerate render it of much more than usual importance and justify it as a separate unit.

The formation consists largely of coarse limestone conglomerate, a highly specialized rock from which much is learned as to the history of the region. Associated with the conglomerate are many beds of calcareous grey sandstone, some calcareous quartzite, and subordinate layers of dark grey slate. The conglomerate forms lenses of all sizes up to 30 feet in thickness and three-fourths of a mile in length. The rock consists as a rule of a bluish-gray limestone matrix in which are embedded pebbles and great bowlders of blue limestone. In addition to the limestone pebbles, which make up most of the conglomerate, there are many pebbles and bowlders of

fine white or bluish-white marble, gray calcareous sandstone, sandy limestone, and gray dolomite, and of a peculiar tough, dark-gray dolomite weathering with a reddish-brown surface. A few small bits of black chert and pebbles of dark slate have also been found in the conglomerate.

Most of the pebbles of the formation are considerably rounded and worn. This is especially true of the large boulders, many of which are four to six feet in diameter, a few are ten feet, and one, 3.5 miles north of St. Albans, is even 60 feet long. This boulder is surrounded by conglomerate except where the base is concealed for five feet, and various layers in the conglomerate abut directly against its blunt ends. An obscure and distorted layering in the boulder, which is of massive bluish-white limestone, dips about 70 degrees to the southeast, while the conglomerate dips 10 degrees southeast, and trends northeast instead of almost north like the conglomerate bedding. The boulder is 60 feet long, 15 feet high, and 20 feet wide east and west. Most of the large boulders are of blue limestone, but some are of the bluish-white marble, and in a few localities north of St. Albans, large reddish-brown dolomite boulders form much of the conglomerate. The smaller pebbles are of all sizes and shapes down to fine sand. It is suggested by Sayles that a lenticular mass of blue limestone 140 feet long and 15 feet thick at the Corliss Ledge is a boulder, like many smaller masses of the same kind of limestone. This is discussed under "Shelburne marble."

A peculiar but very common set of pebbles is composed of flat, angular slabs of blue limestone an inch or two thick and in many places more than a foot long. These are sharply angular and evidently have not been carried far from their original formation. About two miles northeast of Highgate Falls the source of these flat limestone slabs is seen to be the limestone layers in the Upper Cambrian Highgate slate. Fossils are numerous in these limestones in Highgate; but none has yet been found there in the pebbles of conglomerate, owing to the difficulty of separating the pebbles from the matrix. At many points, for instance west of Georgia, Lower Cambrian fossils have been found in the smaller pebbles of the conglomerate.

The pebbles of gray sandstone and sandy dolomite are usually rather angular and have exactly the same characteristics as numerous beds in the Milton dolomite and Colchester formation of the Lower Cambrian. The peculiar dolomite pebbles with reddish-brown surfaces are duplicated in beds of the Colchester formation and Mallett dolomite. The source of the boulders and round pebbles of blue limestone and marble cannot be so definitely ascertained. As already suggested, sources that are adequate and contain rocks of the same kind, are found in the Shelburne marble and the Williston limestone, a few miles south of the present end of the Georgia slate. The probability of this source is greatly increased by the discovery in Brandon of "Saratogan" cephalopods and in South Burlington of "Saratogan" trilobites and gastropods like those in the boulders of the Swanton conglomerate.

Closely associated with the limestone conglomerates are beds of gray, sandy limestone and calcareous sandstone. These are from a few inches up to eight or ten feet thick and show occasional passages into quartzite. In them occur fragments of trilobites too small to name, but they show that the conglomerate was marine laid. As a rule the sandstones are above the conglomerates, but in some places they are interbedded or even at the base of the conglomerate. These sandstones are not distinguishable from similar beds in the Milton and Colchester formations and probably were derived from the same source, and even from the erosion of the Milton and Colchester themselves. A few layers of calcareous and argillaceous slate are found interbedded with the sandstones and conglomerates. A notable feature of the sandstones is the rather common inclusion of small pebbles of dark slate. These are angular and of the same character as the Highgate slates.

In a few places massive limestones forms considerable bodies in the conglomerate. Notable among these is one at the Corliss Ledge, described below, where a lenticular mass of light blue limestone has a length of 140 feet and a thickness of 15 feet. It has been suggested that this mass is a boulder in the conglomerate, but its dimensions are such that it could hardly stand transportation; yet another mass 60 feet long described above is almost certainly a boulder.

Nearly five miles northeast of St. Albans, at the Corliss Ledge in the township of Swanton, numerous fossils were found in the conglomerate in September, 1921, by Dr. A. C. Swinnerton and the writer. These are of great importance in that they determine the Swanton conglomerate and the overlying sandstone and the slate beds of the Georgia to be of post-“Saratogan” age instead of Lower Cambrian, as long understood. The preliminary identification of the fossils and the conclusion as to their age were made by Schuchert, who had previously visited that general region in company with the author. Later the fossils were examined by Walcott, who also considers them to be of “Saratogan” age. One collection of the fossils, consisting of cephalopods, a brachiopod, a gastropod, and crinoid columnals, was found in a series of bowlders of blue limestone. These bowlders are squeezed and of lenticular shape, are underlain and overlain by conglomerate, and resemble a layer in that they occupy a horizon from one to two feet above the Highgate slate and a little more than 200 feet long. A second collection, consisting almost entirely of brachiopods, was made from a bluish-gray limestone bowlder about 100 feet south of the other fossiliferous bowlders. The bluish-gray limestone is almost a foot thick, rests directly on the Highgate slate, but is only exposed for a few feet along the strike. Other and similar limestone bowlders contained no fossils. The dip of the conglomerates and sandstones at this locality is about 20 degrees or less to the east, where they rest upon the Highgate slate, and their total thickness is about 30 feet. It was the good fortune of the writer, in company with Dr. Schuchert, to find in Brandon in July, 1922, blue limestones of the same kind as the bowlders at Corliss Ledge and containing the same cephalopods, of “Saratogan” age. In September, 1922, Schuchert and Dunbar found “Saratogan” trilobites and gastropods in the same formation in South Burlington. In October, 1922, the writer found at the Marye Ledge (2 miles S. 30° W. of St. Albans) a bowlder of blue limestone in the conglomerate containing *Lingulella* and trilobites of late Upper Cambrian or “Saratogan” age, according to Schuchert. A nine-foot bowlder of Cryptozoön-bearing blue limestone, probably Beekmantown, was also found. The conglomerate here also contains many bowlders of white

marble up to five feet in length, which are plainly derived from the Shelburne marble.

These fossils demonstrate a great unconformity below the Swanton conglomerate, which directly underlies the Georgia slate. In places, as already mentioned at Highgate, the Swanton conglomerate rests directly upon the Upper Cambrian Highgate slate. In Georgia the conglomerate is close to the Lower Cambrian Colchester formation and contains Lower Cambrian fossiliferous pebbles. In St. Albans the conglomerate rests upon and contains boulders of the Lower Cambrian Mallett dolomite. The whole of the Shelburne marble and Williston limestone were removed before the Swanton was laid down. In other localities the unconformity at the base of the conglomerate is even more strongly brought out. Beginning three miles northwest of St. Albans, and continuing for ten miles southward along the strike, the Georgia slate, underlain by lenses of Swanton conglomerate in places, overlaps and is in contact successively with the Highgate slate, Milton dolomite, Colchester formation, and Mallett dolomite. These missing beds have a total thickness of 1,500 feet, and the Georgia slate cuts across them three times in that distance, so that the erosion preceding the Swanton was long and decided, and the relief of the pre-Swanton surface was considerable. Boulders of amygdaloidal diabase and diorite are described by Logan from limestone conglomerates near Levis, Quebec, Canada, which are older (*i. e.*, Beekmantown) than the Swanton conglomerate. It therefore appears that the erosion surface had reached down even to the base of the Lower Cambrian, where there are bodies of such diabase and diorite.

*Georgia slate.*—The Georgia slate lies in a belt 34 miles long whose southern end is in Colchester and northern end in Highgate. North of the main belt there are several narrow strips of the formation extending to Canada, and several prongs of the slate project from the main formation in the vicinity of St. Albans. In the town of Georgia, for which the formation is named, the belt is at its widest—about three miles—and narrows to the north and south. Georgia Center is 20 miles south of Canada and 17 miles nearly north of Burlington. The map shows the general distribution of the slate, but

it is possible that small areas of other slates are included in the general area.

The formation consists almost entirely of slate, as a rule of a dark-gray or bluish-gray color. Much of it is banded, a character which is easily seen on the weathered outcrops, which are apt to show a whitish surface. At the base of the formation lie several specialized and very important beds, chief of which is the Swanton conglomerate, which has been separated as a distinct formation. It is possible that there are other and higher conglomerates, but all now known are explainable as basal beds. The slates are soft and occupy low ground except in the town of Milton, where they rise sharply in Cobble Hill over 500 feet above the valley. At that locality the slates seem more siliceous than elsewhere, but otherwise differ little from the average.

The lentil described by Walcott as forming the middle of his "Georgia formation" proves to be part of the underlying Milton dolomite thrust up on a fault and locally capped by the Swanton conglomerate. At this point, about a mile nearly west of Georgia Center, there are remarkably fine exposures of the Swanton conglomerate and of its relations to the Milton dolomite. The Georgia-Milton contact is also exposed at that locality, where the interevening Highgate slate appears to be cut out in places by erosion. Only two exposures of the Georgia-Swanton contact are yet known, although in many places the two formations are separated by only a few feet, and are conformable in dip.

The Georgia slate lies in synclines, and its upper part has been removed by faulting or erosion. Its original thickness is therefore unknown, and even that of the portion remaining can only be estimated. There are no continuous sections of any considerable part of the formation, and the cleavage and variable dips of the slate make measures untrustworthy. In Georgia the slate forms a belt three miles wide, and its thickness is likely to be over rather than under 2,000 feet. Hitchcock considered the slate to be 3000 feet thick and Walcott assigned to it a thickness of 3,500 feet or more.

The beds named Georgia slate have been studied for one hundred years and assigned to many different horizons. Their earliest appellation, "Primitive Argilla-

aceous slate," was given them by Chester Dewey in 1824. From 1840 to 1860 Emmons assigned them to his Taconic system, lying beneath the "Silurian." In 1847, and until 1861, James Hall called them "Hudson River group" or "Lorraine shales (Silurian)." Logan considered them in 1859 and later to be of the age of the "Hudson River group" or even younger. Edward and C. H. Hitchcock in 1861 called them "Hudson River group (Silurian)." Thus the issue as to their age—"Silurian" or pre-Silurian—was early joined, and it was vigorously contested. The beds were definitely excluded from the Silurian by Billings in 1861, on the basis of fossils found by G. M. Hall and J. D. Perry, and were assigned to the Potsdam horizon. These fossils were shown later by Walcott to be of Lower Cambrian age, and in the work by the present author they have been found to come, not from the Georgia slate, but from the Colchester formation and underlying beds of the "Red Sandrock."

In 1861 in his original use of the term Georgia slate, Hitchcock included only the slates of Georgia and their supposed equivalents elsewhere. This usage was followed in the main by other geologists. The underlying limestones and sandstones were treated as another formation—the "Red Sandrock." In 1881 Marcou applied the term Georgia only to a narrow belt of slate passing through the Parker quarry in Georgia and called the main body of Georgia slate the "St. Albans group," all being assigned to the upper part of the Taconic system of Emmons. In this "group" were included numerous masses of limestone (called Swanton conglomerate in this paper) and of white quartzite (Cheshire) to which he applied the term "lentils." In 1884 C. H. Hitchcock and Whitfield called the Georgia slate Potsdam and Cambrian. In 1886 Walcott used the name Georgia both for the "Georgia shales" and for a larger "Georgia formation" which included the slate and the underlying beds, the Highgate slate, Colchester formation, Milton dolomite, and Winooski marble of this paper. All these beds he stated to be of Middle Cambrian age, as he had not then determined the true position of the *Olenellus* fauna which they contained. Later, in 1891, Walcott used the term Georgia as a series name for the Lower Cambrian, basing it upon the Georgia section. There has been

considerable use of the term in this sense, but in 1912, on account of the varied usage of the name, it was given up by Walcott in favor of Waucoban, a name derived from California. In the present paper the formation is somewhat restricted from Hitchcock's original limits by cutting off about 300 feet of beds (Highgate slate) from the base of the formation, because they are of Upper Cambrian age, while the bulk of the Georgia slate is post-"Saratogan," and because there are between the two parts two great unconformities, as described under Colchester formation and Swanton conglomerate.

The fossils found in 1921 in the Swanton conglomerate underlying the Georgia slate showed it to be of post-Potsdam age instead of Lower Cambrian, as long supposed. How much younger than Potsdam the slate was could not be determined then, as in the few contacts known the slate appeared to lie conformably on the conglomerate. Its precise age was not determined until September, 1922, when two localities were found in Highgate which settled the matter. At the Oliver Grandge farm, 4.5 miles N. 10 E. of Highgate Center and .5 mile from the Canada border, the slate was found by the author on September 19, lying unconformably on the Highgate slate and separated from it by only a little lense of Swanton conglomerate. The gray, slightly sandy slate of the Georgia cuts out 2 feet of the Highgate slabby limestones, the two formations dipping easterly from 10 to 15 degrees. In the Georgia slate, 30 feet above the Highgate, Upper Cambrian fossils were found in several small masses resembling squeezed boulders of öolitic limestone. The fossils were fragments of trilobites, brachiopods, tiny gastropods and cystid columnals. On the following day fossils were found by Schuchert in gray slate of the Georgian formation that rested immediately on the banded limestone and slate of the Highgate. On September 21, the author found another locality, a mile S. 20 E. of the above, where substantially the same fauna but of other species was more plentiful, especially the trilobites, in arenaceous limestone layers in gray slate. The fossils from these localities, according to the field determination by Schuchert, were at least as young as Black River and possibly as young as Trenton. More thorough examination in the

laboratory will determine the age of the fossils with precision.

These fossils enable us to correlate the Georgia slate with the general period of shale deposition in the Hudson Valley during the middle Ordovician. Since the Georgia slate rests on the Upper and Lower Cambrian and nowhere on Chazy, Beekmantown, or "Saratogan," the great taxonomic importance of the erosion and later eastward overlap thus brought out is very apparent. A similar relation holds in Piedmont Virginia, and it has long been the author's opinion that the eastward tilting at that time was one of the important Appalachian movements.

#### *Eastern Sequence.*

*Cheshire quartzite.*—This is the basal formation of the Lower Cambrian in Vermont and Massachusetts, and rests upon many formations of the pre-Cambrian. In northwestern Vermont the pre-Cambrian beds are usually phyllites with underlying dolomite and greywacke, all of probable Algonkian age. In southern Vermont older gneisses and granitic dioritic rocks of probable Archean age are in contact with the Cheshire quartzite. The formation is nearly continuous along the west foot of the Green Mountains throughout the length of Vermont. In the vicinity of Rutland, half-way north through the State, the quartzite is cut out along thrust faults for twelve miles, and the same is true for a stretch of about 15 miles south of Colchester. The formation was named from its exposures in the town of Cheshire, Massachusetts, not far from the south border of Vermont.

The formation consists mainly of clear white quartzite, with a central portion about 100 feet thick in which beds of dark grey or blackish phyllite are numerous. At the base there is in most localities a thin zone of conglomerate, rarely more than 10 feet thick. The formation varies considerably in thickness, being thickest in the middle portion of its course through Vermont and thinner to the north and south. A good measure of the formation in Wallingford, sixteen miles south of Rutland, gives 800 feet of massive quartzite. In the section at Bristol the quartzite appears to be over 1,000 feet thick, but the lower portion and the base are not well exposed.

Except in the conglomerates at the base the sand grains of the quartzite are very fine and evenly sorted. The most of the quartzite beds are massive, have a marked conchoidal fracture and very little bedding, and are from one to three feet thick. This is especially true of the uppermost beds, where it is often impossible to determine the bedding. Cross-bedding is occasionally seen in the quartzites, usually in the lower part of the formation, but as a rule the formation is devoid of structures other than ordinary bedding. In the central part of the formation beds of phyllite and slaty banded sandstones alternate in layers of an inch to two feet in thickness and form perhaps half of the strata for 100 feet in thickness. These are well seen in Forestdale, three miles northeast of Brandon, and 14 miles southeast of Middlebury.

The basal conglomerate usually consists of white and blue quartz pebbles an inch or less in diameter, closely sprinkled through a siliceous matrix. In places the pebbles are much coarser, and boulders as much as three feet in diameter are known. These large boulders, as well as most of the others, are of white quartz. In the coarse conglomerates there are also scattered pebbles of feldspar and quartzite, and, in a few cases, of fine granite. The best exposure of this type of the conglomerate is in Chittenden, ten miles east of north from Rutland. The source of the conglomerate pebbles seems to be in all cases the various formations of the pre-Cambrian. There is a considerable calcareous element in the conglomerate where it rests upon the Algonkian dolomite, about ten miles southeast of Middlebury and near Lake Dunmore. At this point the conglomeratic base of the formation is shown in the bed of Sucker Brook resting on an eroded surface of Algonkian dolomite.

In most places the quartzite is sharply defined from the overlying Rutland dolomite, and not infrequently the entire change from clean, vitreous quartzite to pure, gray dolomite is accomplished in five or six inches. In a few places, for instance five miles north of Rutland on the south slopes of Blueberry Mountain, there is a transition upward from a vitreous quartzite through calcareous quartzites and sandstones and interbedded dolomite beds for about 50 feet.

A few fossils have been found in this formation, most

of them by Walcott, at several points from Lake Dunmore near Middlebury southward to Massachusetts. Fossils were also found by Wolff near Rutland. All of the fossils in the formation have been determined by Walcott to be of Lower Cambrian age. The formation appears to be equivalent in age with the Monkton quartzite, but deposited under different conditions and in a different bathymetric zone, as will be discussed under "Sedimentation."

*Rutland dolomite.*—This formation lies along the eastern margin of the Champlain Valley and its southern extension between the Taconic Range and the Green Mountains. It is practically coextensive with the preceding Cheshire quartzite and is cut out by faults between Colchester and Hinesburg, like the Cheshire quartzite. It is very well developed in the valley around Rutland and receives its names from that place.

The formation consists mainly of dolomite, generally of a gray color. Beds of a dark bluish-gray dolomite are numerous in the lower and upper parts of the formation, while light- and dark-gray layers are found throughout its thickness. A few light buff, almost white, beds of limestone are found in the upper part of the formation just north of Rutland, and a few layers of blue limestone are scattered at various horizons through the formation. The interbedded sandstones at the base of the formation have already been described; such beds are rare at other horizons. Most beds in this formation are fine-grained, but here and there medium-grained dolomites and a few coarse layers are found. The coarse-grained beds are not otherwise different from those of fine grain, and there seems to be no predominance of coarse grain at any horizon. Here and there the dolomites, especially the coarser-grained ones, contain scattered nodules or geodes of vein quartz of small size. In the town of Monkton the base of the formation consists of a few feet of fine dolomite of a light buff or cream color, more or less mottled with pink. These beds appear to be representative of the pink mottled Winooski marble which farther west in the same town overlies the Monkton quartzite. The two formations are now in contact, having been brought together on the Weybridge fault.

Fossils have been found in numerous parts of the Rut-

land dolomite. Most of them were discovered by Wolff at various horizons in the township of Rutland and were determined by Foerste to be of Lower Cambrian age. The formation is equivalent to the combined Winooski marble and Mallett dolomite of the central sequence, since they rest upon the quartzites of the same age and are followed by the same strata. The Rutland dolomite is probably in the vicinity of 1,000 feet in thickness; there are no continuous sections of the formation, however, and the full content of the formation has to be built up from scattered sections.

*Colchester (?) formation.*—Beds of Colchester age appear in the eastern sequence in the town of Hinesburg and are found southward to Massachusetts, with many interruptions due to folding and faulting. These beds in the towns of Monkton and Starkboro, adjoining Monkton on the east, have the same characteristics as the Colchester formation from Monkton northward. Toward the south, however, in the towns of New Haven and Middlebury, beds of light buff dolomite weathering with a rusty brown or tan colored surface come into the formation. The gray dolomite and dolomitic sandstone or quartzite characteristic of the Colchester continue well marked toward the south. As a whole, the formation thickens considerably to the south.

A conclusion has not been reached as to the advisability of a separate name for the beds of this age in the two sequences. The beds overlying the Colchester formation in its southward extension are of practically the same character as the Milton dolomite and will not be described here in detail. The overlying dolomite contains none of the chert so common in the Milton, but the marbles and limestones closely resemble the Shelburne and Williston formations.

#### *Western Sequence.*

*Potsdam quartzite.*—Strictly speaking, the Potsdam beds of the western sequence do not outcrop in the area here discussed in detail, which extends from Canada southward to Middlebury. Potsdam rocks, however, are found in the town of Shoreham, about 15 miles southwest of Middlebury, and just west of the Champlain

fault in Snake Mountain. The Potsdam here is limited to small areas with a maximum length of four or five miles and less than a mile wide. The Potsdam rocks of this locality differ little from those of the well-known Potsdam areas around the east flank of the Adirondacks. They consist of fine-grained, white quartzite composed almost wholly of rounded quartz grains, and are somewhat calcareous at the top. The quartzite beds closely resemble those of the Cheshire quartzite, except that they lie in thinner layers, so that the bedding is more distinct. The calcareous quartzite at the top of the Potsdam is, however, like many calcareous dolomitic sandstones in the Swanton and Georgia formations and also in many Lower Cambrian horizons. The base of the formation is not exposed, since it appears on anticlines more or less faulted. The full thickness of the formation is not known, but probably 300 feet are exposed. No description will be given here of the overlying Ordovician rocks, the Beekmantown, Chazy and Trenton limestones, and the black slate of Trenton age.

### *Historical Geology.*

#### *Sedimentation.*

*Deposition cycles.*—The Cambrian rocks of this region were deposited in an order or cycle, which is often to be seen in other regions as well, consisting of a basal conglomerate, quartzite, carbonate rocks (mainly dolomite), limestone, and shale. This is a very common response to the environment of a deepening sea and a later uprising land, which in turn are the expression of warping of the crust of the earth. This cycle is manifest in each of the three sequences of this region, the main difference being that the western cycle begins with the Potsdam of younger age, while the cycles of the central and eastern sequences are mainly in the Lower Cambrian. In each sequence the proportion of land waste is at first extremely high, changes abruptly to a minor element at the end of the quartzites, rises to a majority in the middle of the section, descends to little or nothing in the upper dolomites, and sharply increases with the incoming shale.

*Lower Cambrian.*—The expansion of the sea which permitted the Lower Cambrian sediments to be deposited

affected the entire length of the Appalachians—over 1,500 miles on the mainland of North America—but only in a narrow belt. Previous to this movement all the eastern part of the continent was land, and erosion had cut widely and deep into or even through the Algonkian sediments. The basal deposits of the Cambrian extended far to the east of the Lake Champlain region and even of the Green Mountain area, but are not present around the Adirondacks. The westward overlap of the Lower Cambrian is thus very extensive and cuts out a large series, whose thickness of about 2,000 feet gives a minimum measure of the trough. This overlap is one of the most important in the Appalachians and is a fitting beginning for the Paleozoic.

Land lay near at hand in the Adirondack region and its extensions of those days to the north and south. This was the most important land axis of the early Paleozoic and persisted with diminishing strength well through the Paleozoic. East of this lay the Lower Cambrian sea, its western margin directly in this area and its eastern shore at a considerable but unknown distance east of the Green Mountains.

The position of the strand in this region is well shown by the Monkton quartzite, whose red muds and sands give plain evidence of subaerial deposition, and whose occasional marine fossils show incursions of the sea. At the same time the clean, sorted sands of the Cheshire quartzite with a few marine fossils were originally deposited many miles farther east under the clean sea water. The same story is told by the great thickness of these sands along the Green Mountain front and their thinning to the east, where they can be traced across the Green Mountains east of Rutland and around them at the border of Massachusetts.

A similar plan of land and sea is recorded in the Winoski marble, especially in its topmost quartzite layers which duplicate the Monkton. By later formations, the Mallett and Colchester, deeper waters are shown, but terrigenous beds are numerous, and intraformational conglomerates show that the sea waters were very shallow from time to time and that there was even strong erosion and local removal of the Mallett dolomite. At the end of the Colchester formation the land was uplifted

and subaerial erosion of this region began. Much of the Lower Cambrian sediment was swept away, and a surface of considerable relief was produced, the erosion being deepest at the north and west. Whether this took place in Middle or Upper Cambrian time can not at present be shown. No beds of Middle Cambrian age in place are as yet certainly known, and it is most reasonable therefore to assign the erosion to that epoch.

Between the movements which began and ended the Lower Cambrian cycle there were several minor oscillations recorded in the intraformational conglomerates due to more active erosion. The principal ones of these are at the top of the Winooski marble and at the base of the Colchester shale, which are of only local value. The sandstones of which so many are found in the Mallett dolomite also give evidence of changes of the land, probably due in some degree to tilting.

*Middle Cambrian.*—Deposits of Middle Cambrian time are not known in this region, unless perhaps the Milton dolomite is in its lower part of that age, or unless the upper part of the Colchester formation is Middle Cambrian. With these possible exceptions the land was raised during that epoch and subjected to continuous erosion. The nearest Middle Cambrian sediments are in eastern Massachusetts.

*Upper Cambrian.* The conglomerates which began and characterized Milton sedimentation extended 50 miles in Vermont and with their considerable thickness give evidence of important movement, though possibly limited to northern Vermont and adjoining Canada. Erosion was active, whether by streams or by glaciers. The resemblance of the conglomerates and breccias to tillite is stronger in the upper beds and is pronounced in the topmost or giant conglomerate at Highgate Falls. Depression of the land again changed the scene, and an influx of muddy water produced the Highgate slate. The fine banding of this formation is strongly suggestive of glacial seasonal banding. This suggestion that glaciers were present near this region is apparently lent support by the adjoining conglomerates and breccias of the Milton, which are decidedly angular and unsorted and resemble tillite. While neither of these formations alone furnishes complete proof of a glacial origin, in combina-

tion they render the hypothesis attractive. In short, the rocks of that time indicate a situation closely parallel to the Pleistocene glacial epoch, with its till, sand, and banded clay in the same region. If the Highgate and the conglomerate zone of the Milton represent a glacial epoch, the land high enough to support glaciers doubtless lay at the north and west, as it had in previous Cambrian time.

In northern-central Vermont and adjoining Canada Cambrian deposits have been reported. No fossils have been found in them, however, and their assignment to the Cambrian rests on their relation to limestones and slates which carry fossils of reputed Ordovician age. The supposed Cambrian beds are reported by Richardson to underlie the Ordovician strata. If that is the case, they are more likely to be Lower than Upper Cambrian, since the extension of the Lower Cambrian was eastward across Vermont, while the Upper Cambrian and "Saratogan" waters extended mainly westward. There are no known Cambrian rocks east of Vermont nearer than Braintree and Attleboro in eastern Massachusetts. The beds in Braintree are Middle Cambrian and those of Attleboro Lower Cambrian. Thus, the eastern extent of the Cambrian of Vermont is conjectural. The only known Ordovician beds east of the Green Mountains are the graptolite-bearing limestones of northern-central Vermont, described by Richardson. Silurian and Devonian beds are known near Connecticut River at several localities, and underlying them are strata assigned to the Ordovician on the basis of this position. These facts seem to indicate that there is only a small extension of the Ordovician and also of the Upper Cambrian eastward from the Green Mountains.

"*Saratogan.*"—"Saratogan" deposition produced in this region the Williston limestone and perhaps the Shelburne marble. Other deposits of this time are not known in this district but are found about 15 miles southwest of Middlebury in the town of Shoreham. In that area the Potsdam quartzite forms many outcrops, while many more areas of the formation are found not far to the west along the flanks of the Adirondacks. Still farther to the west and south "Saratogan" deposits are spread over many States. The cycle of deposition which began with

the Potsdam for areas west of the Snake Mountain fault is not manifested elsewhere in northwestern Vermont. The physical relation between the Potsdam and the Williston is not known, and they are probably not exactly equivalent. In view, however, of the great westward tilting of the crust at this time, it is probable that the Williston was a slightly earlier deposit than the Potsdam as the sea spread westward. The waters of the Potsdam time and even of the Ordovician epochs were not deep enough, however, to cover certain high parts of the Adirondack land.

*Middle Ordovician.*—Uplift ended the "Saratogan" deposition, and the erosion cut long and deeply into its strata. When the sea advanced again it found an irregular topography, and the first beds of the Ordovician (Swanton conglomerate) were irregularly distributed. The peculiar nature of the Swanton conglomerate has long since raised the question of its origin. Walcott, reasoning from the fact that most of the pebbles could be duplicated in the Lower Cambrian formations of the region, established it as the type of intraformational conglomerate, and considered that most of the pebbles were broken up from the parent rock soon after its formation and were deposited with little transportation. Since, however, the conglomerate contains Lower and Upper Cambrian and "Saratogan" fossils in the pebbles, it can not be intraformational. Its position resting on the Lower and Upper Cambrian establishes it is a basal conglomerate following an unconformity.

The discovery of its true position does not, however, explain such features as the total lack of sorting of the fragments, which include boulders 10 and perhaps 170 feet in length, mere sand grains, and fine calcareous mud side by side. Furthermore, equally in contrast are the rounding of the large boulders and the sharp angles of flat limestone slabs. The pebbles also contain samples of beds that do not outcrop within miles, these being the most worn, while others of local origin are sharp angled. The amount of transportation shown by these extremes differs enormously and shows some agent differing from ordinary streams. The obvious suggestion is that glacial action was involved in the transfer and accumulation of the deposit. This idea is given support

by the considerable assortment of kinds of pebbles, the distant origin of some, and the local sources of others. The position of the fragments is rather random, as in a tillite, although such a relation has been obscured by the squeezing and folding of the rocks.

Still further support is given to the hypothesis by the banded character of the Georgia slate which followed the conglomerate. Much of this formation is uniform and uniformly banded, like the marine glacial clays of the Pleistocene in the same region. In short, the Swanton-Georgia sequence is a close duplicate of the Pleistocene till-clay sequence. The principal difference is that the Pleistocene beds contain more of the far travelled boulders than the Swanton, a difference attributable, perhaps, to a more local origin of the Ordovician glaciers. Although the glacial origin of the conglomerate and slate is only a hypothesis, it is reasonable and well worthy of consideration. If the conglomerate is a tillite, it is in part submarine because the accompanying sandstones contain trilobite fragments.

#### *Deformation.*

*Pre-Cambrian disturbances.*—The earth's crust in this region has often been deformed, sometimes by mere oscillations up and down and sometimes by revolutions which crushed and upset all previous structures. Earliest of all of which there is record was the intrusion of granite and similar rocks into pre-Cambrian basement rocks. In pre-Cambrian time there was also enormous compression, folding, and mashing of the rocks, by which processes were formed the gneisses and schists. Whether or not granite intrusions accompanied this deformation there is no proof at present, but some intrusions were Archean and older, while others were later and cut the Algonkian rocks. The forces that drove these great masses of molten matter into the Algonkian sediments were enormous and inevitably distorted the crust from its previous attitude. A general uplift of land resulted from these movements, and sediments laid down under water were exposed and deeply worn.

*Lower Cambrian warping.*—A reverse movement of depression began the sedimentation of Lower Cambrian

time. This was of a broad regional nature with a moderate amount of tilting, but no compression sufficient to shorten the earth's crust in this region. The depression went on until about 2,000 feet of sediment were deposited, which gives a minimum measure of the warping. A local reversal and uplift near the end of the Lower Cambrian caused the erosion of over 600 feet of the Mallett dolomite.

*Middle Cambrian warping.*—Oscillations of this kind—broad up or down movements with some tilting—recurred at several times during the Cambrian. The most important took place during or just after the Middle Cambrian, as already described.

*“Saratogan” movements.*—The tilting and submergence that initiated “Saratogan” sedimentation were of similarly great importance, and vast areas of eastern America received deposits of the Paleozoic sea for the first time. The submergence of broad areas west of the Lower Cambrian trough and erosion at the east indicates that the uplift was at the east and the depression to the west. Thus was reversed the arrangement that prevailed during Lower Cambrian time, and a new distribution of the lands was begun which prevailed in a large way through the rest of the Paleozoic era, except for the submergence in the Middle Ordovician.

*Middle Ordovician.*—The Georgia slate, and the Swanton conglomerate where present, rest on two formations of the Lower Cambrian, and two of Upper Cambrian age, and contain boulders of at least one “Saratogan” formation. The erosion into and through these formations is so considerable that we must conclude that there was important tilting and perhaps even some folding, in order that beds so widely separated should be brought to the same surface of erosion. The indication is clear that the changes that followed the “Saratogan” in this region were of the order in diastrophism that usually is associated with the breaks between systems. This has a decided bearing on the Ozarkian system proposed by Ulrich, by showing a great physical break between it and the Ordovician. In this region the uplift and erosion following the “Saratogan” continued until the middle Ordovician. Beekmantown and Chazy beds are common west of the Champlain fault and are overridden by the

Cambrian on the fault. They do not, however, appear east of the fault and north of Middlebury, although the younger Georgia slate is present. These facts suggest that the first uplift from which the fault later developed began between the "Saratogan" and the Beekmantown. Thus the gap after the "Saratogan" is measured by non-deposition of two large formations and erosion into and through six other formations.

*Appalachian Revolution.*—Many subsequent oscillations no doubt took place here, as in adjoining regions. The late Devonian folding that affected New Brunswick and Maine so strongly appeared only as uplift in western New England. No trace of it is seen between Connecticut River and the Catskills except in greatly increased sedimentation, nor does any record remain of any movements after the middle Ordovician until the great deformation which closed the Paleozoic. This is shown here on a grand scale, with all the features which characterize the Appalachian revolution. Long, closed, and overturned folds and thrust faults both folded, faulted and simple, are numerous, and the shortening of the crust in the narrow Champlain Valley is enormous. Over large areas the forces and the reactions were so tremendous that the strength of the rocks was entirely overcome. The minerals were recrystallized, beds flowed or were torn apart, and the aspect of the rocks was very greatly changed. The faults record two periods of thrusting, separated by an unknown interval of time. East of the Green Mountains great masses of granite were forced into the sedimentary rocks. The crust of the earth was jammed and piled up, and its surface rose above the sea. As it rose it began to wear away, but the uplift exceeded the waste, and no doubt great mountains were formed.

*Triassic faulting.*—The next structural event of record is the normal faulting exhibited near the shores of Lake Champlain. The youngest beds cut by these faults are of Middle Ordovician age, so that by that criterion they cannot be separated from the thrust faults, which cut the same rocks. However, the physical incompatibility of these faults—the results of extension of the beds—with the extreme compression of the Appalachian Revolution compels an assignment of them to a date after the com-

pressive strains were satisfied or transferred to other parts of the earth. Furthermore, there is a decided difference in trend between the two fault groups. So far, no normal fault has been found cutting the thrust faults, but the two sets adjoin so closely that probably such a relation will be found. The period which seems most likely for the formation of the normal faults is the Triassic. Everywhere in eastern America the Triassic period was closed by uplift with normal faulting, and no other period of normal faulting is known in the Appalachians. Some of the Triassic faults can be traced from the Triassic belt of New York into districts near to this. Accordingly, the reference of the normal faults of this region to the Triassic is reasonable.

*Cretaceous (?) fissuring.*—Scattered over western Vermont and adjoining areas are numerous dikes of camp-tonite and similar rocks. These have a marked trend a little north of west and nearly vertical attitudes, and they are seldom over eight or ten feet wide or an eighth of a mile long. Evidently these dike rocks were forced when molten into a set of fissures which were formed by a regional strain. The regularity of the fissure trends indicates a corresponding simple tension in a nearly north-south direction. The lack of displacement on these fissures also indicates the simplicity of the strain. Whether the body of molten rock pressing upward furnished the tension at the surface or simply availed itself of channels already formed by other forces cannot yet be determined. If the pressure of the magma were the cause, the uniform plan of the fissures in only one direction seems much less likely than a more random or varied plan. There is neither direct evidence of the age of these dikes, nor are similar sets known in adjacent regions. They are entirely different from the Triassic types, and they are unmetamorphosed, so that they are post-Carboniferous. On general grounds, it seems most likely that they are of Cretaceous age.

*Post-Triassic oscillations.*—The movements of the earth thus far discussed are shown by the overlap, folding, or displacement of the rocks. Subsequent movements there were at many epochs, but their effects cannot be disentangled from far greater changes already wrought upon the rocks. The forms of the land tell

their story, however, and later uplifts and pauses are recorded at many epochs from the Cretaceous down to the present. The pauses are deduced from the plains formed nearly at sea-level during a long stand of the land in one attitude, and the uplifts are evidenced in the present heights of these old plains and their deep dissection by the streams into valleys and lower plains. At least seven of these pauses are known, with a corresponding number of uplifts. There doubtless were many depressions as well as uplifts, but there is no present means of determining any except the latest.

*Glacial tilting.*—One of the depressions accompanied the great invasion of glacial ice from the north, and the view is widely accepted that the weight of ice caused the crust to bend and settle. The reverse movement of uplift accompanied the disappearance of the ice, and the land nearly recovered from its great depression at the north. The tilt that it received in glacial time is now recorded in the inclined plains of glacial clay and sand and in the terraces and deltas which rimmed the margins of glacial water bodies.