GM 16686

THE LOWEST CAMBRIAN AND SUTTON SCHISTS OF SOUTHERN QUEBEC

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THE LOWEST CAMBRIAN AND SUTTON SCHISTS OF SOUTHERN QUEBEC

T. H. CLARK

THE LOWEST CAMBRIAN AND SUTTON SCHISTS

OF SOUTHERN QUEBEC

DEPARTMENT OF MINES

CANADA

GEOLOGICAL SURVEY

Redpath Museum
McGill University
March 22, 1933

Dr. G. A. Young
Geological Survey of Canada
Ottawa.

Dear Dr. Young:

Your letter of March 21 is at hand. In reply I may say that I have no copy with me of the manuscript. The carbon copy sheets included in the present manuscript come from Fairbairn's report to me, the original of which is in the Harvard archives. I agree with you regarding the inadvisability of typing the report as it is, but would have no objection to that procedure if you deem it best. It would, of course, provide you with a copy in case of accident at this end. However, I shall probably add material throughout the report, so that eventually it would need to be typed again throughout. Moreover, in the present condition of the manuscript, the typist would not be able to evaluate the headings correctly.

Suppose that you decide to type the report as it stands. It would then seem best to me to have you return it so that I could make a table of contents and arrange some system so that the typist can easily recognize the division into chapters, paragraphs, etc. This should not take more than a couple of days. This I did not do, for the Director had suggested March 20 as a date upon which it would be agreeable for the Survey to receive the manuscript, and I supposed that the manuscript might be returned to me as was the Lacolle manuscript previously.

DEPARTMENT OF MINES

CANADA

GEOLOGICAL SURVEY

Six weeks will elapse before I can touch the manuscript again. In case you decide not to type it as it stands it would seem best for you to hold it until such time as I shall be ready to work on it again. Under those conditions I will inform you of the date on which I would like to have it back.

As a matter of detail, does it make any difference whatever to you how photographs are mounted?

Yours very truly,

T. H. Clark

Ottawa, Ontario,
March 21, 1933.

Dr. T.H. Clark,
Redpath Museum,
McGill University,
Montreal, P.Q.

Dear Dr. Clark:

The Director has just sent to me the manuscript of your report on the "Lowest Cambrian and Sutton schists of southern Quebec." The Director in a covering note states that you ask to have the manuscript returned in order to complete it and that you hope to be able to complete it by midsummer. The Director has asked me to find out if it would be practicable to assemble "two copies of this report so that we may have one while the other is being revised by Dr. Clarke." He suggests you may have carbon copies of the part already typewritten and that we might prepare typewritten copies of the parts still in longhand.

Looking through the manuscript, I find that the typewritten part is the carbon copy so I presume you have the original. I find also that less than half has been typed and I judge that much of what you have written is subject to revision.

I am inclined to think that if a duplicate is to be retained here, it would be best in the long run, to type the whole of the manuscript as it now stands. This is considerable work and considering that the greater part of the typing done for the staff has to be done by one typist, and that there is much pressing work on hand, and that since your report is still only in a growing stage, much of it would have to be typed later on, I hesitate about proposing to type your report as it now stands.

Please let me know if you have the original typewritten sheets of which you sent us carbon copies, and also please say how soon you would require a copy of the report in order that you might be sure to complete the manuscript by mid-summer.

Ottawa, March 23rd, 1933.

Dr. T. H. Clark,
Redpath Museum,
McGill University,
Montreal, P.Q.

Dear Dr. Clark:-

As suggested by you, I will hold the manuscript until you ask for it. We will postpone typing until you complete the report. As regards photographic prints, if they are not already mounted, please send them unmounted with numbers and titles written on backs.

Yours very truly,

G. A. Young.

GAY:MS

Sent on his request
Aug 15/1934

I would be much obliged for any suggestions as to how we might best accomplish what the Director has in mind.

Yours very truly,

GAY:LMK

122. Copper Mountain, memoir by V.Dolmage. Copy for text (final part) received June 18, 1931. Sent text, edited and with comments, by registered mail to Dolmage May 11, 1932. Dolmage has promised to return revised text before end of year.

123. Bulletin: contributions to Canadian Mineralogy.
Article by Gunning, received May 11, 1931.
Article by Poitevin, received June 13, 1931.
Article by Stockwell, received Feb. 22, 1932; typed copy received and given to Stockwell Nov. 5, 1932.

125. Upper Cretaceous Forminifera, memoir by R.T.D.Wickenden. Copy received May 21, 1931.

126. Lake Ainslie, memoir by G.W.H.Norman. Copy received May 26, 1932. In Hands of author for revision.

128. Pictou coal field, memoir by W.A.Bell. Part received June 4, 1931. Gave Dr. Bell on Dec. 17, 1931. Received completed MSS. June 18 1932. On July 11, informed that no immediate prospects of map being prepared, work on text therefore, deferred until receipt of further notice.

130. Oil, etc., in Western Canada, Ec. Geol. Ser., by G.Hume, new edition. MSS. and 46 figures of revised edition received Nov.16, 1932, but copy still lacks one chapter by Wickenden.

140. Anthropometry of the Beaver, etc., Bulletin by J.B.Grant. Copy received prior to March 19, 1931.

142. Flora of Arctic Canada, notes and MSS. by Ostenfeld. Copy received Nov. 5, 1931. Loaned to Dr. Malte Nov. 5, 1931.

143. Ann. Rept. of Museum 1931. Forwarded to Deputy Minister July 27 1932. Page proof seen and approved but for one change which was recommended to Director Oct. 22, 1932.

Dr Young

Herewith the MS of the second of three reports by T H Clark on his work in southern Quebec.

Dr Clark writes that the report is "not quite finished" and "needs much more attention, mostly of the mechanical sort. There are as yet no bibliography, no table of contents, no plates of photographs, and I also want to insert more concerning the microscopic characters of the sediments concerned."

He asks to have the MS returned to him for these additions, stating that he will be very busy thru March and April but "can almost guarantee its return by midsummer."

I suggest that you explore the practicability of assembling two copies of this report so that we may have one here while the other is being revised. Dr Clark may have carbon copies of the typewritten portions which he could furnish, and the balance in long hand could be typewritten.

The eighth MSS of the Bulletin [illegible] have been received and sent to Mr Dickson

[illegible]

[illegible]

I am [illegible] Dr Clark [illegible] with the matter [illegible]

The Director ~~Dr. Young~~

I communicated with Dr. Clark regarding his manuscript report. As you will note by the attached correspondence, Dr. Clark and I are of the opinion that to type the manuscript as it now stands would be inadvisable.

At the present time we have more manuscript material for typing than we can handle.

I recommend that the manuscript by Dr. Clark (it is incomplete, ~~and~~ the part presented is subject to revision, and no second copy of the typed part is available) be not typed but returned to him in order that he may complete it.

G.A. Young
March 23/1933

In such case, the single existing MS may be returned but should go to Dr. Clark by registered mail & be returned in the same way.

March 23/33 [initials]

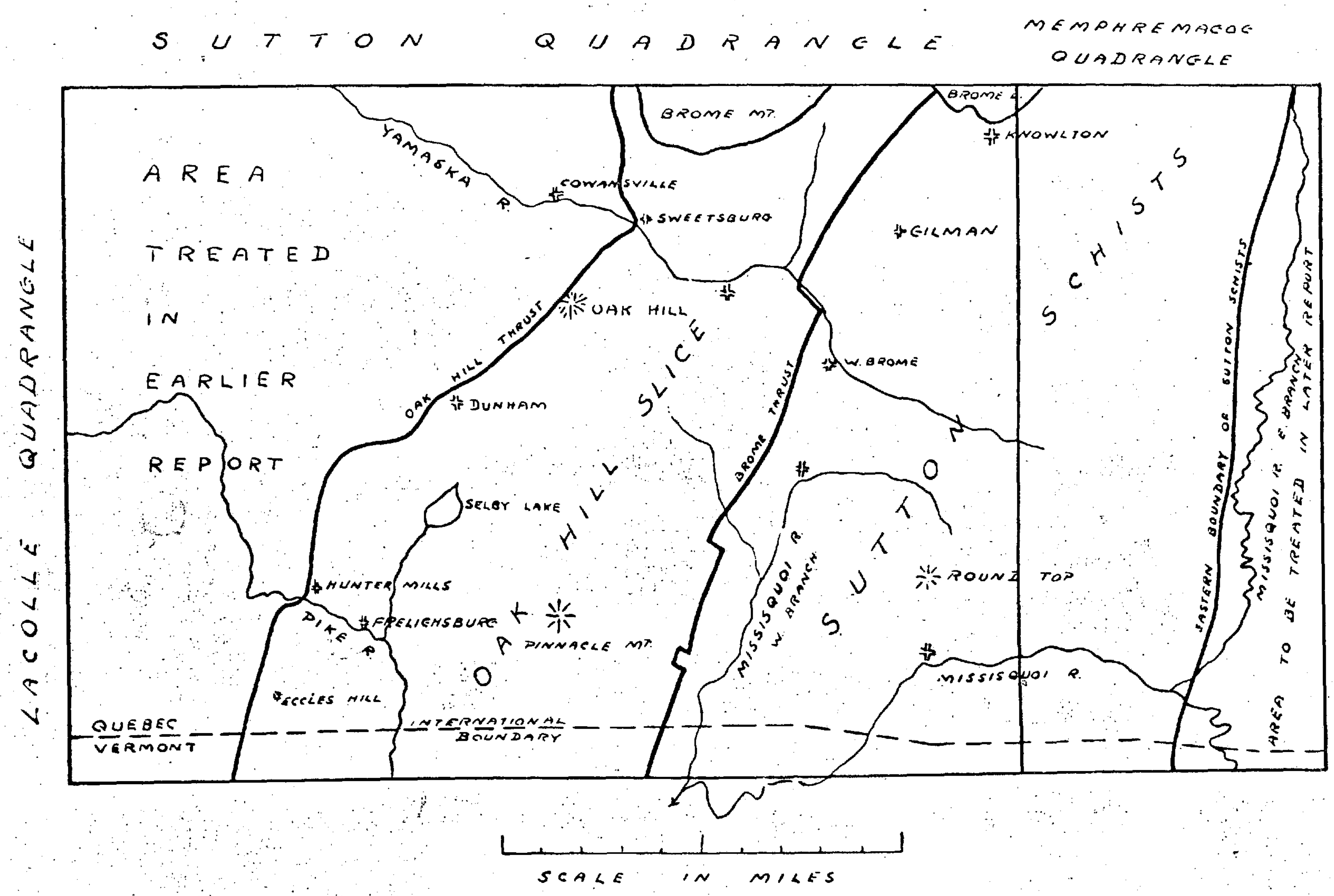
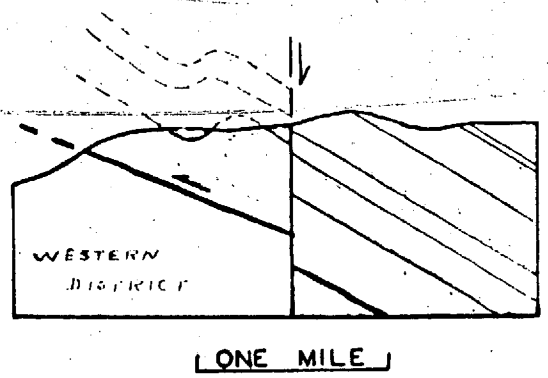
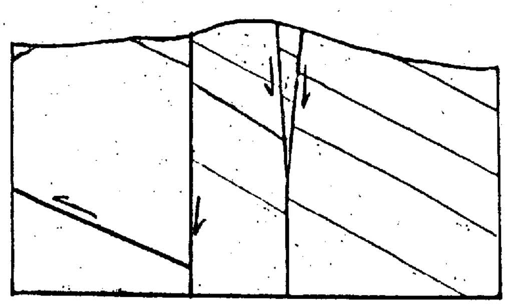


FIG. MAP OF THE SUTTON AND PART OF THE MEMPHREMAGOG QUADRANGLES, SHOWING THE AREA COVERED BY THIS REPORT.

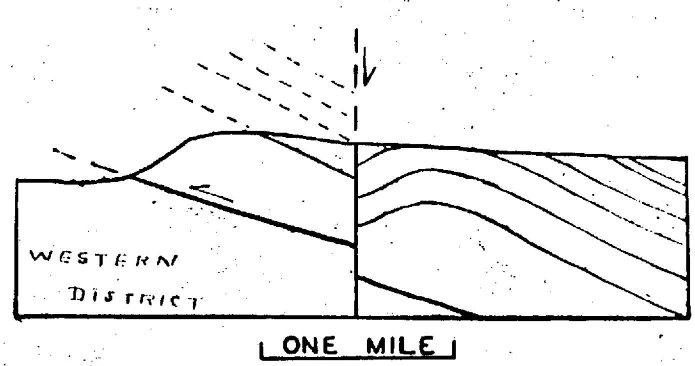


SECTION FROM PHILIPSBURG EASTWARDS



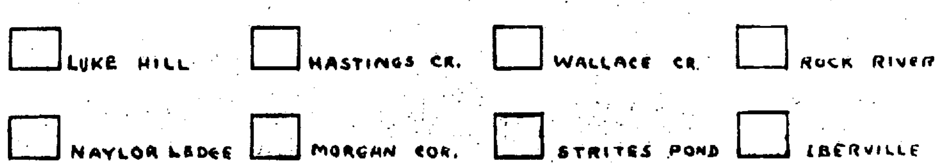
ENLARGEMENT OF ABOVE TO SHOW MANNER

OF FORMATION OF THE "SLIVER" OF WALLACE CREEK



SECTION ALONG INTERNATIONAL BOUNDARY LINE

LEGEND



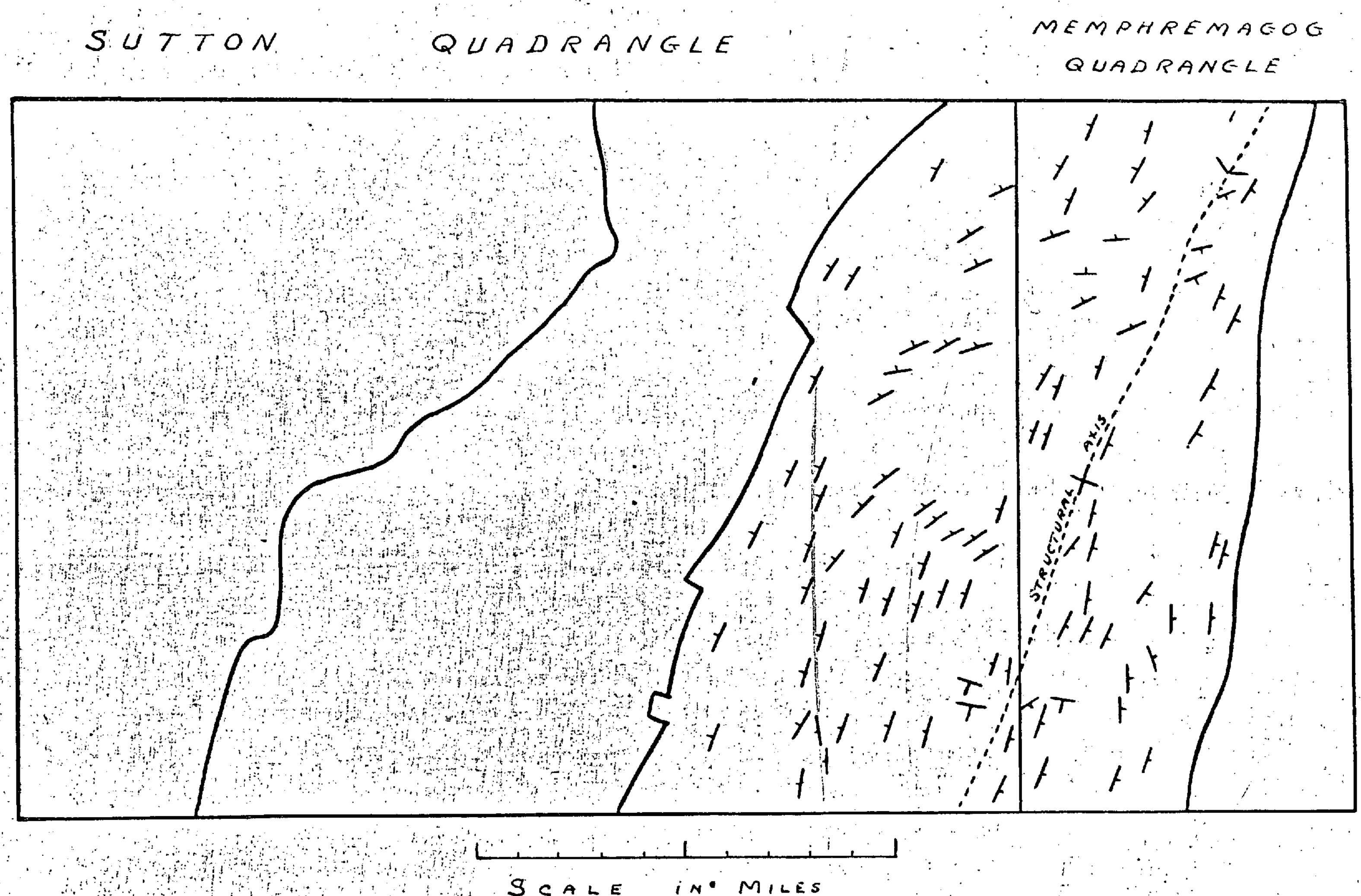


FIG. MAP SHOWING DISTRIBUTION OF DIP AND STRIKE SYMBOLS WITHIN THE SUTTON SCHISTS, AND INDICATING THE STRUCTURE OF THE SCHISTS

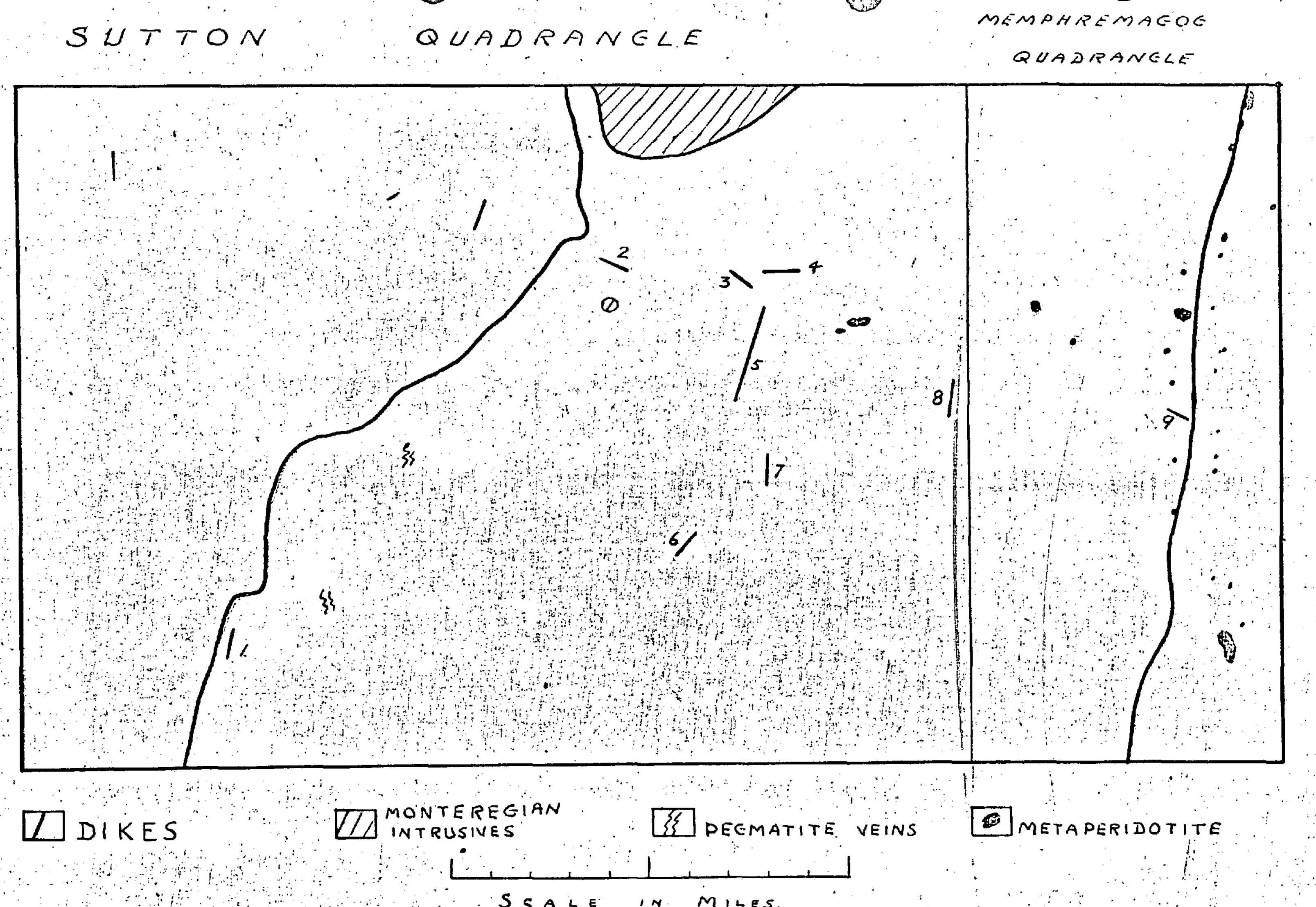
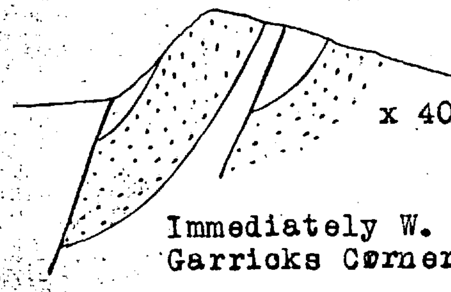


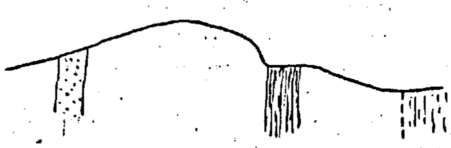
FIG DISTRIBUTION OF IGNEOUS ROCKS. IN AREA COVERED BY THIS REPORT AND IN ADJACENT TERRITORY.

ILLUSTRATIONS OF THE STRUCTURE OF THE UPPER BEDS OF THE OAK HILL SLICE. ALL ENLARGEMENTS ARE IN TERMS OF THE "MILE TO THE INCH" MAP SCALE, UNLESS OTHERWISE STATED.

1 mile S. of Meigs.
Shaly bed in Dunham dol.
Gilman thrust upon Dunham.

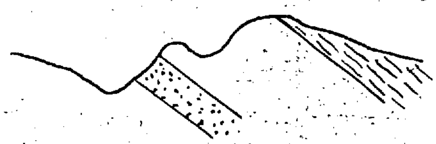


Immediately W. of Garricks Corners

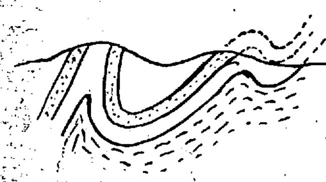


1 mile E. of Meigs.
Shaly bed in Dunham dol.

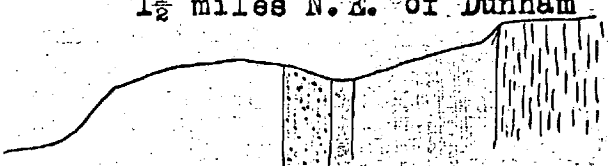
Immediately W. of Garricks Corners



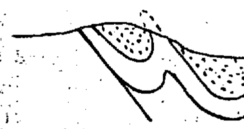
1½ miles N.E. of Dunham



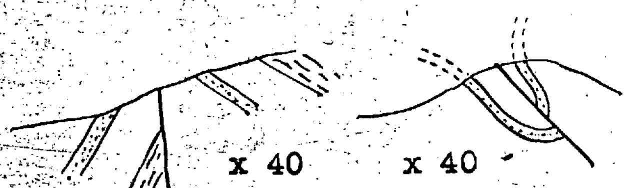
2 miles S. of Meigs



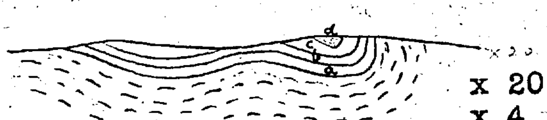
Oak Hill



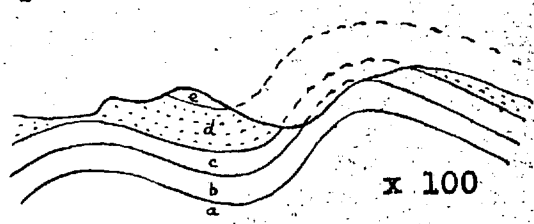
Hunter Mills



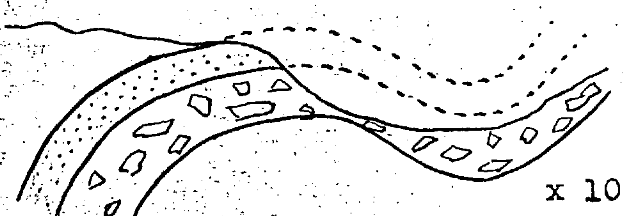
Both from Hunter Mills



1½ miles N.E. of Eccles Hill



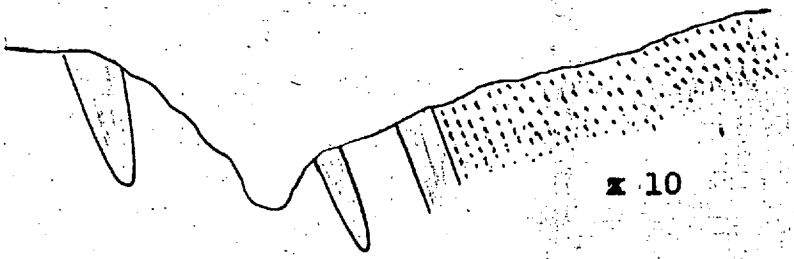
2 miles N.E. of Eccles Hill



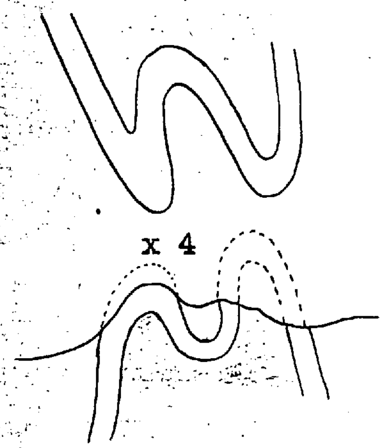
½ mile W. of Sweetsburg

SWEETSBURG SLATE	DUNHAM DOLOMITE
SCOTTSMORE QUARTZITE AND CONGLOMERATE	GILMAN QUARTZITE
OAK HILL SLATE	

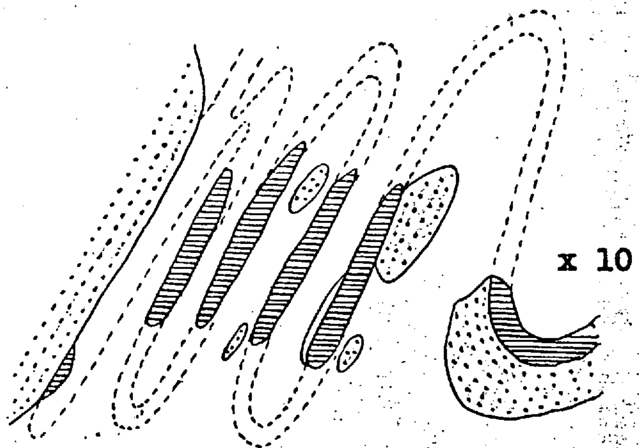
ILLUSTRATIONS OF THE STRUCTURE OF THE LOWER BEDS OF THE OAK HILL BLOCK. ALL ENLARGEMENTS? UNLESS OTHERWISE STATED ARE IN TERMS OF THE "MILE TO THE INCH" MAP SCALE.

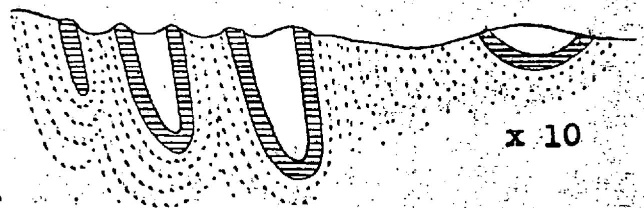


West side of syncline, S.E. corner of Dunham.

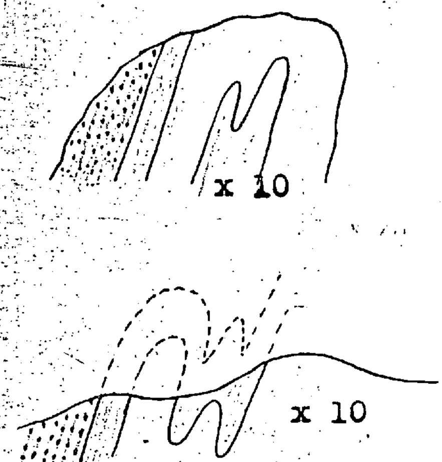


Map and section McCullagh's farm 2 miles S.W of West Sutton

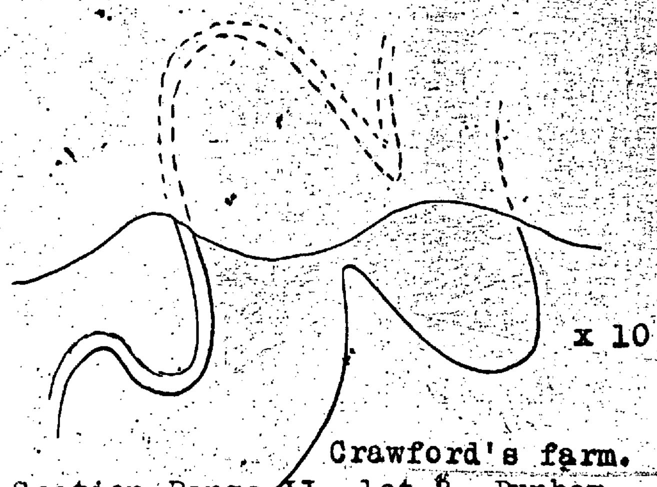




Map and section 1½ miles S.W. of W. Sutton



Map and section near schoolhouse, W. Sutton.



Crawford's farm.

Section Range II, lot 2, Dunham

Sketch of type of cross bedding common in Pinnacle Graywacke. Scale 1" = 1 ft.

Gilman Quartzite	Pinnacle Graywacke
West Sutton Slate	Call Mill Slate
White Brook Dolomite	Tibbit Hill Schist

INTRODUCTION

This is the second of a series of reports contemplated by the Geological Survey of Canada dealing with an East-West strip of country north of and adjacent to the International Boundary in Southern Quebec. The reasons for the field work, of which these reports contain the results, has been given in a previous report. Briefly, it may be summarized as an attempt to provide a satisfactory standard with which geological units of the complicated structure of the Quebec Appalachians may be compared. In particular the Sutton Mountains have never before been studied in any detail, but enough was known to give rise to controversies which have endured over a period of seventy years. The question of age relationships has ever been the ultimate issue while the more fundamental study of structure and metamorphism has been neglected by most investigators. The uncertainty of the whole problem and lack of unanimity of conclusions led the Canadian Geological Survey to undertake a thorough examination of the region.

The present study of the structure and metamorphism was commenced with the immediate object of determining the age relations of the rock. Solution of this problem would allow proper correlation with the territory both to the east and west and thus afford continuous section extending eastwards for 60 miles from Lake Champlain across the folded rocks of the region. This section, it was believed, would provide the key to all further regional or economic work northward in Quebec and southward in Vermont. In addition it was recognized that something might be learned of the early Paleozoic orogenic periods which would prove of value in the unravelling of the geologic history. Also it was believed that some addition might be made to our knowledge of theoretical problems in structural and metamorphic geology. Moreover, this area is, like most mountain-built zones, one of potential mineral resources. Copper, iron, chromium, asbestos, talc, and a few other materials have in the past been extracted, in some cases profitably, from these rocks. To determine how far the geological relations would support the local confidence in their ultimate exploitation was one of our most important tasks.

Locality and Area.

The area treated in this report lies within the Sutton and Memphremagog Quadrangles. Its western border is the Oak Hill Thrust which runs approximately from the vicinity of Eccles Hill, through Dunham to Sweetsburg. On the east it is bounded by a somewhat arbitary line a mile or so west of and parallelling the (East) Missisquoi River, marking physiographically the base of the Sutton Mountains on the east.

This area 350 square miles in extent includes parts of Mississquoi and Brome Counties, and parts or all of the townships of Dunham, St. Armand, Farnham East, Brome, Sutton, Bolton, and Potton.

Physiography.

The region lies completely within the Appalachian Mountain Province. The structural trends, and consequently, the dependent physiographic trends all run at about N.20°E. The region is dominated by the mass of the Sutton Mountain Range, which culminates in Round Top, slighly more than 3,200 feet high. Further details of the topography are given beyond under Physiography.

Outcrops are reasonably common. Some of the mountains are completely exposed. Glaciation has been thorough and the outcrops are, as a rule, quite fresh.

Culture.

The less mountainous part of the area is a thriving agricultural region, depending upon mixed farming with emphasis upon dairy products. No manufacturing is carried on here. Brome Lake is an important summer resort, and parts of the Sutton Mountains deserve as well, although the lack of lakes there operates against their development. The network of roads in the western part is sufficient for all commercial needs. Three roads only cross the Sutton Mountains, at Bolton Glen, Bolton Pass (a provincial highway), and at Sutton Mountain. Gravel is abundant and has been used to advantage, so that it may be said that there are very few bad roads, and these are fast being improved.

Sutton and Knowlton are the largest towns in this area, Frelighsburg, Dunham, and Sweetsburg being important villages, the latter the county seat. A score or more of smaller villages such as Brome, West Brome, Abbott Corners, Abercorn, Glensutton, Highwater and Dunkin are local agricultural communities.

Previous Work.

Sir William Logan, the first director of the Survey, spent the season of 1847, part of 1848, and all of 1849 in southern Quebec. During these years he first outlined his theory of the structure and age relations to which he adhered during the remainder of his life. In the next decade he made occasional short trips but did no protracted work in the area. James Richardson, one of Logan's assistants, was in southern Quebec during 1864-5-6 continuing the earlier work and elaborating upon it. Logan retired from active Survey work in 1869 but continued the work begun many years before up to the time of his death in 1875. His last project, cut short by his death, was to sink a bore hole at Richmond by which he hoped to establish beyond doubt the correctness of his conclusions.

Alfred Selwyn, the second director of the Survey, and James Richardson, spent the summer in 1877 in this area. Selwyn's conclusions were opposed to those of Logan and were generally accepted from that time on. Arthur Webster, an assistant, was here in 1879 and 1880 continuing Selwyn's work. Robert Ells and Henry Ami were on the scene during the early part of 1883, Selwyn during part of 1885, Ells and Ami again during 1886. The discoveries of copper and asbestos made it desirable to re-map the region and Ells continued this work in 1889, 1890, and part of 1891 in and about Brome county.

A lull in geologic activity followed Ells' work until John Dresser in 1902 investigated part of the copper belt. In 1910 he was engaged in mapping the serpentine rocks of southern Quebec. Robert Harvie continued this and other general field work in 1911, 1913, and 1914. G. A. Young spent the summer of 1916 mapping some of the marble formations, and in 1923 F. A. Kerr mapped the eastern half of the Memphremagog quadrangle and worked out the structure and stratigraphy of that region.

Despite the quantity of field work carried out in this region only a small part of it has been published. Richardson, Selwyn, and Ells alone apparently published all of their results. Dresser and Harvie have only summaries of their work in print. A map of the Eastern Townships was, however, prepared by Logan on the scale of 4 miles to an inch. This map he undoubtedly would have published had he remained Director of the Survey a year longer than he actually did. The map was engraved bearing Logan's geological boundary lines, but as far as the writer has been able to ascertain no colored copy exists. Nevertheless the map with Logan's boundary lines was used as a base map for the publication of part of Ells' later report. In places Ells accepted Logan's boundaries without change, in others he drew in new boundaries. As far as the area of this present report is concerned I wish to pay especial tribute to the exactness of Logan's boundaries. Ells' lines are in many cases quite inaccurate, in the light of our present detailed mapping. Some of Logan's lines in the Sutton Mountain area are without apparent significance, but because we lack a legend or other means of identifying their meaning no good purpose can be served by criticizing them. I would particularly refer to a small closed line in the extreme southeastern corner of the township of Dunham. This line quite accurately follows the outcrop of the White Brook dolomite in a small synclinal basin within the underlying chlorite schist. Further the care with which the Dunham dolomite was mapped is remarkable. This is shown by two closely spaced lines resembling a road, but following the intricate folding of that formation from St. Armand Center to Sweetsburg. It is not too much to say that had Logan's map been published the long sixty year drought from 1870 to the present time would have been prevented. True, his ideas of the stratigraphy have not all been substantiated, but the excellence of his mapping was so far beyond that of any of his contemporaries and many of his successors that Selwyn is to be criticized very severely for withholding the map from publication.

Many factors, personal as well as scientific, will explain this wealth of field investigation and paucity of printed results, but are not relevant here. It is sufficient to say that in more recent years the Survey has not been convinced that Logan was so much in error regarding some of his conclusions in Southern Quebec. The field work begun by the senior author in 1927, it was hoped, would help to solve the 80-year old problem one way or the other. Field work was continued until 1931, when contact with Kerr's area was effected, and thus a strip of country 75 miles wide has now been mapped in detail.

Present Field Work.

Southern Quebec has been mapped topographically by the Department of National Defense at Ottawa and two of their sheets, the Sutton and Memphremagog, furnished the base maps for the present investigation. These maps were photographically enlarged from 1 mile to the inch to ½ mile to the inch for field work and all necessary data have been plotted directly on them. Instruments used included tally registers for pacing, automobile and bicycle odometers, Brunton compasses, and a planetable. Roadside outcrops were located by pacing or by odometer. For outcrops between roads pace and compass traverse were made and spaced so as to obtain the maximum amount of geologic information in the least time and with a minimum of effort.* A planetable with telescopic alidade was used to advantage in a few localities where a large scale map was desired.

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* Except in the Sutton Mountains every outcrop has been separately mapped on the data sheets of the Survey. In the mountains, outcrops are largely hidden by the dense growth of hard woods so that meticulous mapping of individual outcrops would have been well nigh impossible in practice and would have entailed at an estimate five or six summers' work. We are convinced that the spaced traverses, with added interpolated traverses across the Sutton Mountains have yielded all the essential information necessary for the purpose of this report.

The senior author commenced work on the western part of this area late in the summer of 1927, being then assisted by H. W. McGerrigle. This work was continued in 1928, C. H. Crickmay and F. M. Hutchins rendering valuable assistance. In 1930 both senior and junior authors collaborated on the Sutton Mountains, having A. F. Banfield and H. W. McGerrigle as assistants. In 1931 the junior author continued his work alone on the Sutton Mountains.

Acknowledgements. The senior author wishes to state that much of the accomplishments recorded in this report are due to help and suggestions received from others, particularly the junior author. The Sutton Mountain area was given the latter as a thesis area by the Survey, and formed the basis of his doctorate at Harvard University. There, he had the valuable assistance of Professors E. S. Larsen and M. P. Billings in preparing the material and report. Both those men also found time to visit the area and discuss problems in the field. Dr. Billings' criticism extended over the entire area, and both authors are indebted to him. The assistants mentioned above have all contributed essential parts to the work. We have received valuable critical observations in the field from Dr. T. L. Tanton who visited the area for the purpose of examining the iron-bearing formations. To many others, for whose suggestions in the field or elsewhere, we hereby

acknowledge indebtedness, particularly Drs. G. A. Young, P. E. Raymond, and A. Keith.

PHYSIOGRAPHIC FEATURES.

Topographic Divisions.

A division into two sub-areas upon a topographical basis is a very simple one; the Sutton Mountains on the east and the Oak Hill Upland on the west. These are separated by the broad Sutton Valley, occupied in part by the Missisquoi River, in part by the head waters of the Yamaska. See figure .

Oak Hill Upland. This area occupies about 170 square miles. No part of it lies less than 400 feet above sea-level, whereas no part of the area to the west lies above 500 feet. The Oak Hill Upland lies in general between 500 and 1,000 feet, steep slopes are rare, but outcrops fairly common. Several subdivisions are apparent. First along the western border is a line of hills forming a very prominent physiographic feature, including the hills at Bull Pond, Oak Hill, Garrick Corners, and Eccles Hill, also Minister Hill in Vermont. This feature can be traced southwards beyond St. Albans, Vermont. Northwards it is not easily recognizable. This line of hills is upheld by the resistant top of the Gilman quartzite formation which outcrops continuously close to the trace of the Oak Hill Thrust, which forms the western limit of this area. East of this line of hills is a broad valley extending from Frelighsburg through Lake Brook to Lake Selby, northwards through Dunboro and Marsh Creek, losing its identity as a valley in the vicinity of Gilman. Still further east is a zone of hills starting to the north with Tibbet Hill and passing southwestwards to Pinnacle Mountain and Spruce Hill. These hills are of somewhat resistant chlorite schist, continuous to the north and south of our area. Pinnacle Mountain owes its dominance not to the inherent properties of the chlorite schist, but to a small capping of much harder graywacke. From this line of chlorite schist hills the topography descends eastwards easily into the Sutton Valley.

The Sutton Mountains. The Sutton Mountains are the continuation in Quebec of the Green Mountains of Vermont and cover an area of about 200 square miles. They have a maximum width at the International Boundary of 12 miles and taper down to a width of 8 miles at the north, about 20 miles along the strike from the boundary. The maximum elevation is attained at Round Top, about 3,200 feet above sea-level, and the highest point in southern Quebec. The average elevation approximates 2,000 feet which represents a relief of about 1,500 feet above Sutton, Glensutton, and Potton valleys. The average slopes vary between 15 and 20 per cent but the rugged character of the country precludes much generalization as to grade. The eastern slope near the topographic axis is as a rule more precipitous than any other part of the mountains.

Viewed from the northwest the southern part of the Sutton Mountains skyline appears as a succession of notches with long low south slopes and steep, short, northward faces. (Plate). The continuity of the southern part of the mountains is in sharp contrast with the more deeply dissected northern part, which latter is transitional to the subdued topography immediately north of Brome county in which only the lithological and structural characters of the mountain area remain.

Sutton Valley. This valley extends southwestward for about 17 miles from Brome Lake. In general the slopes are gentle but those on the east are steeper and less dissected than those on the west. The eastern, Sutton Mountain side, stands also in much greater relief and rises on the average 1,500 feet above the valley floor. The western slope rises between 300 and 500 feet. The longitudinal profile of the valley is discontinuous and the slope reverses at a divide about 1 mile north of Sutton village.

Glensutton Valley. This crosses the south end of the Sutton Mountains in a general east-west direction and joins Sutton Valley at Richford, Vt. and Potton Valley at Highwater, Quebec. It has a length of 15 miles and averages 2 to 3 miles in width. Its slopes are steeper than those of Sutton and Potton Valleys and the average relief is about 1,500 feet. The profile of the valley floor is very flat and slopes gently to the west.

Bolton Pass. This pass extends west 4 miles from South Bolton in Potton Valley and then swings northwest toward Brome Lake for the last 4 miles of its course. (Plate). It cuts through the north end of the Sutton Mountains and is serpentine in plan. Its width is seldom more than 1 mile and the valley walls are steep to precipitous in many places. The valley floor reverses its slope just north of Sally Pond.

Bolton Glen. This glen lies north of Bolton Pass and joins with it 3 miles northwest of Sally Pond. It extends three miles in an east-west direction across the Sutton Mountains and although its relief is similar it is a broader valley than Bolton Pass. Its longitudinal profile slopes gently west toward Brome Lake from an unnamed pond between Bolton Glen and Bolton Center. East of that place it slopes steeply eastwards.

Drainage Divisions.

There are four drainage basins within this area, all of which head in the Sutton Mountains. (Inset). The streams vary in size from mere trickles to small rivers 30 feet across. Their grades show little uniformity, ranging from almost zero to precipitous drops of 30 feet or more. The streams occupying the main valleys take meandering courses across gravel, silt, and sand of the valley floor; this is interrupted in places by a rapid or waterfall where bedrock is exposed. The smaller streams are in general more rapid and show less of these meandering features.

Brome Basin. This basin contains Brome Lake as its focal drainage point. The lake is shallow, with low shores, and is roughly circular in shape. No important streams are tributary to it and it is of local significance only. It drains Bolton Glen, the northwest half of Bolton Pass and the northern end of Sutton Valley.

Yamaska Basin. This lies directly south of Brome Basin and heads on the western slope of the Sutton Mountains. It occupies 6 miles of Sutton Valley north of Sutton village and cuts through the Oak Hill Upland in a number of small depressions. Beyond this area it widens and continues to the St. Lawrence River. The principal river is the Yamaska which finds its source in the numerous small streams of the Sutton Mountains and flows westward across Sutton Valley and the Oak Hill Upland. The drainage across Sutton Valley consists only of small streams but these unite further west to form the river.

Sutton Basin. This basin occupies the southern half of Sutton Valley and drains the adjacent slopes of the Sutton Mountains and the Oak Hill Upland. The principal stream is the western branch of the Missisquoi River which heads just north of the village of Sutton and flows south into Vermont where it joins the main Missisquoi River of Glensutton Valley.

Potton Basin. This includes all of Potton Valley, Glensutton Valley, Dunkin Valley, and the eastern part of Bolton Pass. It drains the eastern and southern part of the Sutton Mountains and includes the southern and eastern branches of the Missisquoi River. The meanders of this stream are particularly notable at Highwater and are well displayed in the flat-bottomed valley where the streams unite. Ruiter Brook, which occupies Dunkin Valley, is the main tributary stream and heads in Fullerton Pond 6 miles north of Glensutton Valley.

Interpretation of Topography.

The present topography of Brome county is of mixed origin. The main features are pre-glacial and indicate a mature stage of development. The minor features are due to the recent glacial activity and the topography has been modified slightly by accumulation of unconsolidated silt, sand, and gravel. The drainage has been entirely re-adjusted and the streams diverted more or less from their former channels.

Relation of Valleys to Structure. The structural units of Brome county trend northeastward and are represented by the Oak Hill upland and the Sutton mountains. The principal valleys already described have all the characteristics of pre-glacial types and both follow and cross the structure. Glensutton is the largest of the transverse valleys and Sutton the largest of the longitudinal ones.

Post-glacial valleys are numerous, especially in the Sutton mountains, but of minor importance to the region as a whole. They are of such recent origin that no structural control is evident. They have steep gradients in longitudinal profile and acute V-shaped transverse sections. Many of them are suspended above the main pre-glacial valleys in true hanging-valley fashion.

Relation of Drainage to Valleys. The streams of the area are all post-glacial in origin and are therefore not in adjustment with the main valleys. The branches of the Missisquoi river found in Glensutton valley have a continuous down grade which indicates that this part of the region responded uniformly to post-glacial uplift. In Sutton valley the pre-glacial drainage has been diverted and a divide passes through about 1 mile north of Sutton village. (Inset). The streams north of this divide head in the Sutton mountains, cross Sutton valley, and cut west through the Oak Hill upland. South of the divide the west branch of the Missisquoi river follows the valley south into Vermont. In this case post-glacial uplift was not uniform and the streams formerly controlled by Sutton valley have been captured by the Yamaska river and its tributaries.

The post-glacial streams are thus seen to be both dependent and independent of the pre-glacial valleys. Waterfalls and rapids are common to both types and indicate a recent origin. The branches of the Missisquoi river obviously are not accomodated to the valleys through which they flow for their meanders do not remotely parallel those of the valley sides. The entire drainage is youthful and was imposed on a topography which in the Sutton mountains was approaching maturity and in the Oak Hill upland was in late maturity at the time of the ice invasion.

Relation of Glaciation to Topography. The region has been thoroughly glaciated and striae on most of the exposures strike about N.160°E. The tops of the mountains show evidence of ice action in surface markings and in erratics foreign to the bedrock. These include boulders of the alkaline rocks of Brome mountain to the northwest and confirm the southeasterly movement of the ice indicated by the striae. Wilson (1906) has described twelve parallel V-shaped notches which cross Round Top (3,200 feet above sea-level) at about 25° east of south. They are from 4 to 10 feet in depth and evidently represent pre-existing fractures which have been gouged out by the ice.

GENERAL GEOLOGY

Although within this area two apparently quite diverse geological terranes can be differentiated, yet it is our thesis that these two differ in metamorphism only, and that fundamentally the whole region consists of but one series of rocks. The boundary between the two districts is an irregular line a mile to two miles west of the depression known as the Sutton valley, passing through Mansville, Brome, and reaching Brome Lake northeast of Tibbet Hill. East of this line the rocks are all metamorphosed to schists of various kinds, westwards is a series of sedimentary rocks resting upon a basement of chlorite schist. These two regions have already been approximately designated, from the physiographic point of view, as the Sutton mountains and the Oak Hill upland respectively. However, because the boundary between these physiographic units is the line of the Sutton valley the physiographic and geologic subdivisions are not quite the same. Hence in the succeeding pages the area of sedimentary rocks will generally be called the Western District, and that of the metamorphic rocks the Eastern District. The correspondence is, however so close that the physiographic terms may often be used without fear of ambiguity.

The Western District.

This is bounded on the west by a continuous thrust fault, called the Oak Hill Thrust, by which its rocks, of Lower Cambrian age, are brought to rest upon the Georgia slates of the ~~Pigeon Hill Block~~ Rosenberg Slice and the Stanbridge slates of the Philipsburg ~~Block~~ Slice, both parts of the region described in the earlier report. The strata of this district rest unconformably upon a mass of chloritic and epidotic schist, demonstrably metamorphosed basic lava flows, and consist of slates, graywackes, dolomites, and quartzites. They are closely folded, overturned to the west, and as stated overthrust on to the younger rocks to the ~~east~~ west?. The uppermost members exposed are slates which are everywhere isoclinally and irregularly folded, due in part to their present position immediately above the Oak Hill Thrust. The slates of this formation have in the past been exploited for iron, as too has the graywacke, without success in either case. At several places along the eastern boundary of the chlorite schist are meagre exposures of ~~a~~ slightly metamorphosed ~~series of~~ rocks identified here with the Oak Hill Series. Their relationships are discussed under the head of the Mansville Phase of the Oak Hill Series. Within the chlorite schist, usually close to its contact with other formations, copper minerals occur and have been mined with indifferent success.

The Eastern District.

The mass of the Sutton Mountains consists of siliceous, felspathic, sericitic, and carbonaceous schists, demonstrably sedimentary, with a few intercalated beds of dolomite indistinguishable from the dolomite of the Western District. This terrane is underthrust below the rocks of the Western District along their mutual boundary. In general the structure is that of an anticlinorium, the structural axis however lying somewhat east of the physiographic axis. Although dikes are rare, much of the schist near the axis has been heavily albitized, which may indicate a magmatic source, not far below, responsible for part, at least, of the metamorphism. A few intrusions of basic rocks have resulted in the subsequent formation of talc, which has been quarried and mined in the past. Chromite is also associated with intrusions. The eastern boundary of this area is an apparently conformable sedimentary contact between these schists and (?)Upper Cambrian slates.

Relation of Present Work to Previous Investigations.

The history of previous investigations in Southern Quebec would make a long story and only the main features are summarized here. Ells' map (1896) is the only one published covering the whole area, and it is convenient to compare it with the one prepared for the present work.

The Oak Hill Series, the Tibbet Hill schist, and the Sutton Series, are all included in the Pre-Cambrian on Ells' map. It is now known that the Oak Hill Series is Lower Cambrian, and that the lower part of the Sutton Series can be correlated with it. The Tibbet Hill schist is in all probability Pre-Cambrian.

Structurally, the angular unconformity between the Sutton and Mansonville Series is now omitted and only a disconformity is necessary according to the present interpretation. The Oak Hill and Brome Thrusts do not appear on Ells' map, but the position of the Sutton axis is approximately correct.

In general the conclusions reached from the field mapping tend to revert to Logan's conception of the stratigraphy of Southern Quebec, in which the rocks, in various stages of metamorphism, are all Paleozoic. Conclusive evidence may never be obtained but the problems are by no means solved by mapping the doubtful formations as Pre-Cambrian. Logan's conception of the structure of the Sutton Mountains as a syncline, which conception was first shown to be erroneous by Selwyn, finds no support in modern investigation.

STRATIGRAPHY.

The Western District.

Pre-Cambrian.

Tibbet Hill schist. The bulk of chloritic and epidotic schists herein comprised extends the entire height of the map sheet, from Brome Lake to the Vermont Boundary. For six miles southwest from Brome Lake it is two miles broad, contracting suddenly to less than a mile for about four miles in the vicinity of West Sutton, thence swelling gradually till its width at the Vermont line is a little over four miles. In general this belt stands higher than the country to the east or west, and culminates in Pinnacle Mountain (2,200 feet), which owes its eminence largely to a superstructure consisting of a syncline of graywacke whose superior resistance has protected the schist below.

Lithology. Macroscopically, the rock presents a great many phases. In color it varies from very dark green through medium green, to dull yellowish green. The less metamorphosed parts are almost invariably blue, greenish blue, or purple in color. It is almost invariably fine textured, with larger crystals of chlorite, magnetite, sericite, or epidote occasionally prominent. Veinlets of quartz, epidote and calcite are common in some phases of the rock, which is on the whole free from veins. Amygdules of the same minerals, also larger irregular nodular masses, are sparingly present. In several places the amygdules, filled with epidote, occur in marked bands an inch to several inches wide, and an inch or more apart. On the whole little diversity of texture is to be seen. In one or two places, particularly opposite the West Sutton schoolhouse, surface features easily explainable as flow lines can be seen, though this is not certainly the true interpretation. The combination of bands of amygdules and this presumed flow structure indicates a lava, and the high chloritic and epidotic content suggests a femic type. It is not impossible that some of the fine-grained, dense, amygdaloid-free chlorite schist is a metamorphosed basic tuff, but of that we have no proof.

Associated with the chlorite schist is a second rock type which raises a problem of origin very hard to settle. At scores of localities, but particularly east and northeast of Pinnacle Mountain, there are numerous narrow bands of a slaty rock, which have the appearance of infolded beds. Were it not for the fact that the lowest superjacent sediment is a slate, superficially indistinguishable from most of these infolded beds, it would be reasonable to consider them as tuffs interstratified with or infolded with the altered lavas. And, where only the lowest member of the overlying series might appear at the bottom of an infolded syncline its distribution and relationship would be essentially similar to those of the rock in question. It was as this Lower Cambrian slate body that I mapped these rocks at first, but gradational types between obvious chlorite schist and the slate in question which began to be discovered rendered such a separation will nigh impossible and tended to discredit the correlation. Finally some bodies of slate were discovered in which were recognizable amygdules sometimes almost round, sometimes much flattened and squeezed. Such structures ended our associating these slaty bodies with the Lower Cambrian slate, and induced us to consider them as, in part at least, lava flows which because of inherent difference in composition, had suffered the formation of slaty cleavage to such a degree that they became true slates. It is not impossible that some of them may be cleaved tuff beds, but of this there is no proof. Only where there is good reason to suppose that they may really be pinched synclines of Call Mill slate are they mapped separately. They may be seen to good advantage in outcrops near the road side about a mile and a half due east from Pinnacle Mountain summit. Here for half a mile north and south several of these bodies may be seen. In the above mentioned localities they are all small, ~~two or three chains~~ 130 to 200 feet wide at the most. However, east of the Brome Thrust similar beds may be seen between Mansville and

west of the Sutton-Abercorn road on either of the two roads, one north of Alva, and one south. Another good locality is the road a mile and a half

Brome, which are quite obviously the metamorphosed Call Mill slate. Hence, in mapping, where such slaty beds are obviously igneous thay have not been separated from the chlorite schist; where, however, they may well be considered to be the Call Mill slate they are accordingly so mapped.

Microscopic Character. Chlorite, epidote, and albite are the essential constituents of the Tibbet Hill schist and compose the groundmass of all the sections examined. Calcite, quartz, magnetite-ilmenite, rutile, titanite, sericite, apatite, and zeolites are prominent accessories.

Chlorite in small flakes and shreds is the most important mineral and its parallel dimensional arrangement indicates the direction of schistosity. It is usually scattered throughout the rock but in places is concentrated in narrow bands which are free of other minerals.

Epidote is prominent as small rounded grains distributed throughout the sections. In places there are concentrations of larger grains which give the rock a characteristic light green color. The large nodular masses of epidote already mentioned are also characteristic.

Albite, or albite-oligoclase, occurs as small irregular grains which are usually clouded with inclusions.

In a few cases remnants of albite twinning are seen whose width indicates an original plagioclase at least as calcic as andesine. Extinction angles measured on the twins and approximate indices, however, show that these grains range from albite to oligoclase in composition.

Calcite is present in large irregular grains lying across the schistosity and contains abundant inclusions of epidote, chlorite, etc. Quartz is found in scattered aggregates of small grains and in places as large isolated crystals. Mica (sericite) occurs in fairly large flakes usually cutting across the schistosity, but is never common. Apatite is consistently present but likewise is not abundant.

Zeolites are common as amygdule fillings. Only the fibrous varieties have been seen in thin section and the species have not been determined. Quartz, calcite, epidote, and chlorite also occur in amygdules as relatively large crystals.

Titanium minerals, although accessory, are important in the Tibbet Hill schist. Magnetite-ilmenite in blue-black irregular grains is common. These probably represent intergrowths, as titanite replaces part of the material in several sections examined. A criss-cross bladed texture of titanite and a black mineral occurs in one section. A reasonable explanation seems to be that the ilmenite of an original magnetite-ilmenite intergrowth is replaced by titanite and that the bladed texture is preserved by the remaining magnetite. Titanite is also found isolated from magnetite-ilmenite in irregular grains, and usually shows some alteration to leucoxene. Rutile occurs in clusters of minute needles, in places twinned, and visible only with a high-power objective. These clusters are elongated in places parallel to the schistosity. The rutile is invariably masked by a brownish-black envelope of alteration products from the edges of which the crystals project in an irregular manner.

Thickness. On Pinnacle Mountain the Tibbet Hill schist outcrops from the 700′ to the 2,200′ contour. The summit contains a shallow syncline of the overlying Oak Hill Series (inset) and if conformable relations are assumed the schist would be at least 1,500 feet thick. No field evidence is available concerning the degree of folding, and if it is unconformable beneath the Oak Hill Series the above relation on Pinnacle Mountain is of no value. An arbitrary figure of 2,000 feet is assumed to be probably of the right order of magnitude.

Age. The exact age of the Tibbet Hill schist is unknown. It underlies the Oak Hill Series and is therefore either Lower Cambrian or Pre-Cambrian. Harvie (1914, p.213) considered these schists to be part of the Cambrian succession, but adduced no evidence or arguments bearing on the problem. Its boundary with the Oak Hill Series shows very few actual contacts. The best of these occurs on the roadside opposite the West Sutton schoolhouse. At the east side of the exposure a few inches of Call Mill Slate (the basal member of the Oak Hill Series) lies in almost horizontal position on the schist. A few yards to the west the slate dips steeply to the west, has a thickness of several feet, and is succeeded by Pinnacle Graywacke. The degree of conformability of the schist-slate contact has not been determined as neither formation contains critical primary structures.

The degree of metamorphism seen in the Tibbet Hill Schist, though low-grade, is considerably greater than that which affects the overlying Oak Hill Series. ~~in which sericite, cleavage, and quartzite are the chief results.~~ This would indicate, but not conclusively, that the metamorphism of the chlorite schist preceded the formation of the Oak Hill Series. However, the abundance of detrital magnetite grains in the Pinnacle Graywacke, and an obviously competent and nearby source for them in the chlorite schist, suggest strongly that the metamorphism and later erosion preceded the Oak Hill Series. If this is so then the Tibbet Hill Schist must be Pre-Cambrian. It is so considered in this report.

Distribution elsewhere. Logan (1866, p. 247) stated that "these chloritic and epidotic rocks constitute a ridge ...... running from the Pinnacle Mountain in St. Armand, to Brooker's Hill in Shipton". This is a distance of about ___ miles. He did not discuss its age or relationships. Ells (1896, p. 66 -67j), concluded that this schist was older than the adjacent Cambrian strata, but mistakenly supposed it to overlie the Sutton Schists. He was of the opinion that the schistosity of the Cambrian sediments, the chlorite schist, and the Sutton Schists was induced at the same time. Dresser in the course of a series of publications on Copper and the Igneous Rocks of the Eastern Townships[1] (1907. Other references can be obtained in Bancroft, 1915. The 1907 paper gives all information necessary) came to the conclusion that this rock was a metamorphosed ~~volcanic,~~ lava with parent rocks varying from quartz porphyry to andesite. He also correctly concluded that these schists are the oldest rocks of the region, and presumed them to be Pre-Cambrian of which he admitted there is as yet no direct proof. His map (1907, and earlier publications), is an improvement on Ells' inasmuch as it differentiates the chlorite schist from the adjacent rocks, naming it Porphyry, etc. For our area, there seems little justification for assigning any less basic type than andesite as a parent rock. Further north along the Sutton anticline and Stoke anticline such justification doubtless exists.

It should be said in justice to Logan that his unpublished geological map of the Eastern Townships delineated with reasonable exactness the extent of this schist body. Although Logan's boundary lines were printed on the base map used by Ells, the latter apparently ignored them in the majority of cases, with the result that his map, published in 1896, is ludicrous in many places. Dresser's map is admittedly adapted from Logan's lines on Ells' map, as are a few other maps published since 1896.

Southwards, chlorite schist is continued into Vermont where C. E. Gordon is at present carrying on geological field work on its distribution and relationships to contiguous formations. Harvie (1915, p. 99) stated that an essentially similar succession of these rocks occurred east of St. Albans, Vermont.

Lower Cambrian Series. Unconformably succeeding the Tibbet Hill Schist comes a series of sedimentary rocks of considerable diversity. The succession is as follows

10. Vail slate
9. Sweetsburg slate
8. Scottsmore quartzite and conglomerate
7. Oak Hill slate
6. Dunham dolomite
5. Gilman quartzite
4. West Sutton slate
3. White Brook dolomite
2. Pinnacle graywacke
1. Call Mill slate

Tibbet Hill schist

Of these the Gilman quartzite and a phase of the Dunham dolomite have yielded fossils, both Lower Cambrian types. In spite of unconformities in the upper part of the section there is no reason to suppose that any of the beds are younger than Lower Cambrian. Beds 1, 2, 3, and 4 are best developed in the central part of the Sutton sheet, being practically eliminated at the Border, and not being exposed north of the latitude of Sweetsburg. The former lack is due doubtless to a combination of faulting and unconformities, whereas the northern lack may well be due to the heavy drift cover, for there are no outcrops of any kind showing along the strike of these beds. The Pinnacle graywacke, scantily exposed at the Border, is abundantly shown in Vermont. Its greatest development is to be seen between North and West Sutton. The Gilman quartzite is the most important member, being never less than four miles wide across the strike and sometimes as much as seven. The Dunham dolomite and Sweetsburg slate are fairly consistently developed from north to south, but certain phases of the dolomite are to be seen only in the southernmost three miles, between Frelighsburg and Eccles Hill. The Scottsmore quartzite is irregularly developed, but mostly in the northern part of the area. The two remaining formations are of very local significance, chiefly from Oak Hill northwards.

All these names are new. Harvie (1915, p. 99) reported that he had traced the Dunham dolomite southwards till it merged with a Lower Cambrian limestone of Walcott's section at Georgia, Vermont. The impossibility of this correlation is discussed on page . Keith in describing very similar geological occurrences in Northwestern Vermont (1923, p. 126) referred to three beds as the Cheshire quartzite, Rutland dolomite, and Colchester shale. In 1932, the first two remained, but the CDlchester, obviously a misnomer, was removed. These appear to correspond in position to our Gilman quartzite, Dunham dolomite, and Sweetsburg slate. It is not possible at present, owing to the lack of published maps of northwestern Vermont, to achieve final correlation between the two sets of names.

Call Mill Slate. From Pinnacle Mountain north to Brome Center wherever a section can be seen showing the Tibbet Hill schist and overlying strata, almost invariably the lowest bed is a dense cleaved shale. Because it is shown to best advantage in the gorge below Call Mill that name has been selected for it. Its southernmost exposure is on Pinnacle Mountain, and thence northeastwards to and beyond West Sutton it is an invariable lower member of the sedimentary series. However, along the contact between the Tibbet Hill and overlying strata that runs from near Boundary Post 608 (southwest of Pinnacle Mountain) northeastwards through North Pinnacle it does not appear until within two miles of West Sutton, its non-appearance being due in all probability to non-deposition, for in several places along that line the Pinnacle graywacke lies directly upon the Tibbet Hill. Further east in a very remarkable series of beds called the ~~Brome Series~~ "Mansville Phase" it is invariably present.

Lithology. Macroscopically this slate shows considerable variations, which are, however, of local significance only. The differences are almost all concerned with color and cleavage, everywhere it is a fine-grained argillaceous rock, except at West Sutton where at the base it contains pebbles of an indeterminable rock up to an inch in diameter. Rarely it is dense, with its cleavage planes widely spaced, scarcely deserving the name slate. Usually it is fissile, slippery to the feel, because of the development of sericite probably, dark purple or nearly black. Other colors are very dark blue, gray, dark green. Occasionally it is mottled green and purple, and when so the green is invariably secondary chlorite segregations, which may elect to lie in certain cleavage planes and so simulate bedding. Stratification never shows as far as we have seen, except in a coarse way in some large outcrops such as the Gorge at Call Mill and at West Sutton, where bands of fine magnetic rock occur near the top. But banding in a hand specimen is unknown. Replacement by hematite, which is one of the distinguishing characteristics of the West Sutton slate is rare in this body, we have seen it in only two or three places, and it is always incomplete.

Microscopically it consists of a fine mat of fibrous minerals, to small to be readily identified, but probably a mixture of chlorite, sericite, and kaolin, together with quartz and a lesser amount of magnetite.

Thickness. The greatest possible thickness, as far as mapping showed, is 165 feet at Call Mill. This is the width of outcrop between the Pinnacle graywacke, which holds up the dam at the mill, and an anticline of Tibbet Hill schist to the southeast. Because occasional tightly folded synclines of graywacke occur in the slate the thickness (all the beds being essentially vertical) is considerably less than the width of the outcrop. It is not likely that the Call Mill slate is more than 100 feet thick at this place, and quite possibly less. Because nowhere else is it as much as 100 feet we may take that as a maximum figure. Elsewhere it varies in thickness from one or two feet to twenty, thirty or rarely as much as fifty feet.

Origin and Development. If we are right in our contention that the Tibbet Hill schist is Pre-Cambrian, then a long time of erosion ensued between its formation and metamorphism, and the beginning of Lower Cambrian sedimentation. In all probability peneplanation had been complete or nearly so. The longitudinal depression which initiated the formation of the Appalachian geosyncline probably first formed along the outcrop belt of this bed. The invading sea, spreading over a nearly flat deeply eroded land found very little sorting to do, the entire regolith was finely decomposed chlorite rock. This soil, if soil it was, merely suffered shifting to some extent, so that an unlayered blanket of mud was spread over the primal sea floor, its depth dependent upon the slight irregularities of the topography amounting to differences in elevation of the order of a hundred feet, as suggested by the variation in the thickness of the bed. Such a picture is at least consistent with all we know about the Call Mill and the basement upon which it rests.

Pinnacle Graywacke. Superjacent to the Call Mill slate is a thick formation consisting of a felspathic sandstone which in many localities carries up to fifty percent detrital grains of magnetite and ilmenite. It is very strongly developed in the central part of this area, and although similarly developed in northern Vermont, its outcrops diminish in size and number from Little Pinnacle and Pinnacle Mountains southwards. South of the road parallel to and north of the border it is very poorly developed and lacks its normal magnetite content, and, too, is unaccompanied by the Call Mill slate. The latter condition points to an unconformity at the base of the Pinnacle, which combined with the fault that is responsible for the localization of the mineralization a mile east of Abbott Corners, is doubtless the cause of the near disappearance of the Pinnacle graywacke near the border. ~~The reason for its near disappearance southward within this area is in all probability the same fault that is responsible for the mineralization a mile east of Abbott Corners.~~ Northwards it occupies Little Pinnacle and a series of prominent hillocks and hills northeastwards towards Brome Center, its outcrops becoming scantier north of ~~the~~ Call Mill and disappearing completely beneath the widespread mantle of sand that covers the country southwest and west of Brome Lake. Its maximum development is in the neighborhood of North Sutton and West Sutton. Its name is derived from Pinnacle Mountain, which, though composed of Tibbet Hill schist, maintains its physiographic form because of a capping of this more resistant graywacke in the form of a synclinal infold. Its occurrence within the Mansville phase of the Oak Hill Series will be mentioned later.

Thickness. Careful measurements have been made of its breadth of outcrop and dips at what is considered its typical locality, that is on the west limb of a syncline well shown north of Mr. W. J. Doyle's house which is on the east-west road in the extreme southeastern corner of Dunham township. A diagram of the section is given on page , showing the relation to the underlying Call Mill and Tibbet Hill formations and also the overlying beds. Its thickness here is 400 feet. Elsewhere in the vicinity of North and West Sutton it maintains this thickness with very little loss, but at West Brome it is reduced, in a complete section to less than 200 feet and to the north the structures are so complicated that little reliable information can be obtained.

Stratification# and Structures. This rock is everywhere well bedded. Except where it is rich in iron minerals it is usually some shade of gray, tinged with green.

Where magnetite-ilmenite makes up a considerable percentage of the rock it may be black, but usually with an iridescent sheen to it. The beds vary from an inch or less to ten feet in thickness, extreme variability being one of its characteristics. Cross-bedding, too, is always prominent as can be seen in plate . This cross-bedding usually shows a very remarkable angle~~s~~ between the beds concerned, so much that it oftens seems impossible to explain the high angles on the basis of deposition alone. T. L. Tanton, in the field, suggested plastic deformation before consolidation as a means of achieving the unconformities of 70° and 80°. However, there is no other evidence to substantiate this, and, though it may have been operative, these high angles can well enough be explained on the basis of the vertical exaggeration upon the squeezing of the folds, thus giving an entirely ~~false~~ misleading picture of the ~~true~~ false bedding. Cross-bedding of the type commonly seen in the Potsdam sandstone not infrequently yields angles of 30° between successive series of layers. This type of structure distorted as above would readily yield the apparently abnormal structures observed.

One type of small scale cross-bedding demands special mention. It consists of a series of cut and fill type of structures superimpos~~ing~~ed upon one another progressively in the same direction with the beds appearing to fan out in the direction of the oldest structures, giving a fimbriate appearance. In one bed examined more than 100 "loose end" beds, made apparent by their magnetite content, converge as shown in the sketch. It would appear that the material was brought from the east and in this instance was deposited progressively from west to east. Local crumpling has doubtless emphasized this type of structure in the way just described, for it is not noticeable on the east limb of the syncline, although north of the next road to the north it occurs in that position.

Petrography. As might be expected from a rock with so variable a composition as a graywacke, no description of a single type will suffice. It is always a sandstone, though in one or two places so fine as to appear shaly; this is exceptional however. Nowhere is it conglomeratic. In composition it varies from an apparently pure quartz-feldspar (chiefly orthoclase) combination through all gradations to a rock in which magnetite-ilmenite grains predominate to the virtual visual exclusion of all else. Detrital micas occur throughout, though are never common. Magnetite-ilmenite (because magnetite is by far the more abundant of these two, ilmenite will not be mentioned hereafter) is the most characteristic mineral. No outcrop is without it. Although the grains are detrital and have lost their corners and edges, there are enough flat octahedral faces left in the vast majority of cases so that the grains reflect light well. A surface of the graywacke with these magnetite grains glistens on this account. ~~In fact, before we had mapped enough of this rock to give it a locational name, we used the term "Glistening" for it.~~ Magnetite grains may be evenly distributed through the rock, which is the most common occurrence, or they may be concentrated in beds varying from paper thinness to a foot or so. It is the relative concentration of the magnetite that is responsible for the clarity of the stratification in this formation, and in detail, most of the cross-bedding is marked in this way, magnetite grains being concentrated usually just above the unconformities. The layers richest in magnetite vary in position, but are most commonly seen near or just above the middle of the section. Strangely enough, these rich beds have yielded to compression quite readily so that they are apt to be contorted into most complicated folds of small dimensions (see fig.). Never, however have we seen them faulted. The quartz-feldspar graywacke never shows th~~eir~~is tendency. The basal beds are usually nearly free from magnetite, and appear as a siliceous sandstone grading upwards to a feldspathic sandstone. At the top of the section the rock is almost invariably more shaly than below with less of the magnetite-ilmenite content, but even so it is still a sandstone. Exceptions to this rule ~~occurring~~ occur a mile west of West Sutton, and a mile northeast of Hillside, where a bed of arkose separates the rest of the Pinnacle formation from the White Brook dolomite. Neither upper nor lower contact is nonconformable except west and south of Pinnacle Mountain, where the graywacke rests directly upon the chlorite schist, and it is succeeded by a dolomite formation which points to a period of quieter deposition.

Microscopical Features. Magnetite makes up one half or less of the slides studied. Quartz is present up to 50 percent and feldspar up to 30 percent. Besides these minerals, which are present in every slide are variable amounts of ilmenite, leucoxene, zircon, (both the latter indicative of the presence of ilmenite), chlorite, kaolinite, sericite, and paragonite. Limonite is rare, and hematite not seen at all. Tourmaline too is rare. Secondary epidote, the crystals lying along a stratification plane, occurs in one place only. Apatite was not seen.

The magnetite grains have rounded edges and corners, but most of them show one or more flat crystal faces. A fringed border of leucoxene, with all stages of alteration plainly shown, surrounds many of the black opaque grains, due to secondary alteration. This alone is good evidence that many of the grains were ilmenite. The grains vary from .1 to .5 mm. in diameter in the slides studied, and in any one slide they are remarkably uniform in size.

Quartz is present as both primary grains and secondary silica deposited in original pore spaces. Feldspars are orthoclase and plagioclase. The latter is mostly untwinned and is generally near the Na, K end of the series, probably almost all of it albite. Both quartz and feldspars are much fragmented and occasionally are difficult to separate. The feldspars are for the most part unaltered, but in some slides the alteration has been practically complete.

Origin and Stratigraphic Significance. Obviously quite a different environment of origin surrounded the formation of the Pinnacle graywacke from that concerned with the formation of the Call Mill slate. The latter called for conditions of quiet spreading of waters over a slowly sinking deeply decomposed land area. At the beginning of Pinnacle time, however, the sediments indicate that relatively rapid elevation of neighboring highlands was taking place, and that the sediments accumulated were the result of disintegration rather than decomposition, and that they were brought to the strand by streams, rather than being found and merely rearranged by waves as in the case of the Call Mill. We see here then the first evidence of any essential differential warping of the Appalachian geosynclinal region. The thick Pinnacle formation is evidence in the first place of a region of no great diversity of rock type elevated to such a height that its slopes prevented the formation of decomposition products to any extent, and also that its rivers were swift enough to bear away the products of disintegration. The composition of the grains is a clue to the kind of rock composing the uplands. Quartz, orthoclase, albite, magnetite-ilmenite are the most important constituents. The quartz-orthoclase-albite combination favors the assumption that granite, granite-gneiss, or similar rock was by far the most abundant type of country rock. Magnetite-ilmenite, however, occurs in grains too large to have had its origin in granite. Rather, the chlorite schist, underlying the Call Mill slate is a perfectly competent parent rock for this mineral. No trace of the granitic parent rock is now exposed. Doubtless further east most of the basement upon which this sedimentary series of Lower Cambrian time was deposited consisted of widespread granites with, probably, little relief afforded by other rock types.

<u>White Brook Dolomite.</u> Succeeding the Pinnacle graywacke is a dolomite bed, within whose boundaries are the headwaters of White Brook, from which it takes its name.

General characteristics. Two unvarying characteristics allow this formation to be recognized from a distance. First its disposition to weather to various shades of buff and brown, and, secondly, the presence within it of considerable secondary quartz in both nodular and vein form.

In color, the fresh rock is extremely variable. Although it may be pure white that color is extremely rare. The commonest color is white mottled with pinkish or purplish patches. Other common colors are dull purple unvaried except by chlorite seams, all shades of gray, culminating in practically a black rock, also various shades of buff and pink in the fresh rock are known, but are uncommon.

The rock is invariably crystalline. The solid colors, purple and gray particularly, are associated with the finest grain, which is everywhere quite easily visible. The mottled or speckled rock is the coarsest, crystals of 2 mm. across being not uncommonly found.

Stratification is extremely rare. Wherever it occurs it is invariably shown by an abundance of sand grains. In fact in such cases the rock is as properly a dolomitic sandstone as a dolomite. Where quartz grains are few stratification is not observed. No other primary structure can be made out.

Its thickness varies from place to place. It is thickest near its southern extremity, where 75 feet is a maximum measurement. Northwards and eastwards it diminishes. It is 36 feet thick at West Sutton, swells to between 50 and 60 feet between North Sutton and Call Mill, north and west of which locality it varies between 20 and 40 feet. In the southeast corner of Dunham it is 32 feet thick, which should be increased by local exclusion of certain phases to 40 feet.

Beside dolomite and calcite, an occasional flake of mica (muscovite) occurs, and here and there wind blown grains of quartz. Rarely do these occur in any abundance.

Secondary minerals present in hand specimens are chlorite, hematite, quartz, and sericite. The chlorite is always present to a greater or lesser degree. In some outcrops it probably makes up more than 10 percent of the rock. It occurs as irregular masses and stringers more related to the schistosity than to any other direction. This chlorite is crystalline, thus eliminating the possibility, if such possibility be granted, of its being detrital. Hematite occurs in precisely the same way. Quartz as a secondary mineral is nearly always present. It occurs as small irregular masses strung out along schistosity planes, and as very noticeable veins of white quartz. These latter may be up to two inches thick, but are usually less than an inch. Several computations in the field of dolomite beds well supplied with quartz veins indicated that between 10 and 20 percent of the rock was quartz. Usually, however, the percentage is much lower, probably more nearly five. The quartz veins, as beautifully shown on the east side of the syncline in the southeast corner of Dunham, show growth at right angles to the walls, in other words the quartz was progressively filling the veins as the veins were widening. Sericite only occurs along schistosity planes and never is important.

The sources of these three common secondary minerals is not hard to find. The chlorite is due doubtless to the alteration of basic impurities in the dolomite or to the impregnation of the dolomite with chlorite. Many exposures give the impression that the dolomite has been soaked with chlorite. The hematite is without a doubt related to the hematite that characterizes and sometimes composes the West Sutton slate, whence migration of a matter of feet only would bring the hematite to rest in the dolomite. The quartz needs no explanation.

Distribution. As with the underlying beds this formation fails to outcrop at the northern boundary of the area, though it ~~doubtless~~ may extend that far under the cover of drift. No outcrops of it have been seen south of Hillside though a depression on Little Pinnacle may indicate its presence. At the southwest corner of that hill, however, the Pinnacle graywacke and the Gilman quartzite are in contact, and remain so, with some structural complications, southwards to the border, thus eliminating the White Brook dolomite and the West Sutton slate. Inasmuch as the complete section is seen again in Vermont, with no essential change, it is probable that the stratigraphic anomaly is due to a fault which traverses Little Pinnacle and thence travels strikewise to the border about a mile and a half south-southeast of Abbott Corners, about midway between boundary posts 608 and 608C.

The West Sutton Slate. Superposed upon the White Brook dolomite wherever it occurs is a slate body of variable thickness, well shown in the vicinity of West Sutton. In general, where it is not strongly hematitized it is indistinguishable from the Call Mill slate. For the most part it is an impalpably fine mud-rock varying in color from shades of medium and dark gray to dark blue-black. Stratification never appears except as noted below. One of the most constant characteristics is the presence of hematite. This may occur disseminated throughout the rock as invisible particles whereby the rock gives a dark brown or dark purplish red streak, or it may occur as discrete masses of hematite, usually concentrated at the base of the bed, near the contact with the dolomite. In some places it is so pure and abundant that it has been worked as an iron ore. Needless to say, its abundance is not sufficiently great to justify its exploitation. (see chapter on Economic Geology).

At West Sutton, half a mile northwest of the four corners, it reaches its greatest thickness, estimated at that place to be 250 feet; elsewhere it is less than 100 feet, usually about 40 feet. Also at that place it contains grit beds which betray its bedding, a structure nowhere else seen.

Origin and Stratigraphic Significance. So similar is the rock to the Call Mill slate that the conclusion that the two beds had somewhat similar origins is not to be denied. During White Brook time tranquillity prevailed. Little, if any, detritus was washed into the sea by the streams, whose gradient was reduced by their own efforts or by diastrophic warping. Weathering once more deeply attacked the country rock, so that upon gentle uplifting a mass of ready-made silt was available. This was spread far and wide, blotting out the dolomite and inaugurating a second cycle of deposition. On account of the great local thickness of this formation at West Sutton it is extremely likely that here was the debouchure of a stream and that the relatively great local thickness is due to deltaic accumulation. The uppermost beds are gritty, noticeably so, as if prophetic of the succeeding formation.

Gilman Quartzite. None of the preceding formations have been mentioned by earlier authors. This formation. the thickest of the Lower Cambrian Series, was noted by Harvie (1913, 1914), and later Keith (1923, p. 126) correlated a quartzite in what appears to be homotaxial position with the Cheshire quartzite of Southern Vermont. So very different from Keith's description of the Cheshire is our quartzite that we have not adopted his name, but given the name Gilman to it, from a locality four miles east of Cowansville, where outcrops are common.

This is by all means the greatest of all of the Lower Cambrian formations. Its width across the strike reaches 7 miles and never falls below 4½ miles.

Characteristics. In color this rock is usually light gray or buff. However it usually weathers to a lighter color, not infrequently almost pure white, and at a distance appears polished. In contrast to the brown weathering White Brook dolomite and the dark gray rough looking weathered surface of the Pinnacle graywacke this rock is distinguishable at sight some distance away. It is almost always discolored along interior joints and cleavage planes with limonite, which however, almost never shows at the surface. The Pinnacle graywacke, in spite of its high iron content, rarely shows any limonitic discoloration. In the basal part of the formation the rock is a coarse grit, light colored as a whole because of the abundance of quartz grains, but with a dark greenish matrix containing much secondary chlorite in masses up to 4 inches across. This phase may be seen at the fork of the roads west of the schoolhouse at North Sutton, and at several isolated outcrops northeast of Frelighsburg and south of Selby Lake, and again a mile and a half south-southeast of Meigs. The basal beds of the Gilman quartzite at the syncline in the southeast corner of Dunham are for the most part shaly, although at the very base a few inches of grit with grains and pebbles of blue quartz occur.

It is usually a quartz sandstone of very fine grain, so fine as to deserve to be called a shale. (In fact, our earliest field name for this rock was "shaly quartzite". Much of the "shaliness" however is due to cleavage and hence might better be called "slatiness"). Only exceptionally can one see a grain of feldspar in the coarser phases, but flakes of muscovite abound in the less cleaved shalier type. Sericite abounds along cleavage planes. With the exception of occasional occurrences where magnetite is visible, only these six minerals (quartz, feldspar, sericite, muscovite, chlorite, limonite) can be seen on megascopic examination.

Near the top, as seen at Oak Hill, beds of conglomerate occur, the pebbles in all cases being quartz and average an inch in longest diameter. In several other localities "conglomerate" was noted, but in nearly every case it turned out to be of the structural type. East of Dunham a few exposures of black siliceous slate occur, but are unknown elsewhere.

Stratification, except in the basal grits and the conglomerates of the uppermost beds is not observable. The rock is essentially even-grained throughout and has been cleaved so extensively that little trace of original characteristics is left. Hence estimates of its thickness rest upon very insecure foundation.

Structure and Thickness. Wherever the structure can be accurately determined the beds stand at a very high angle. At the top of the formation at Oak Hill they are practically vertical, and this condition holds wherever data can be obtained along the western boundary of the formation. Along its eastern boundary, dips are almost impossible to obtain, but the neighboring West Sutton slate and lower beds are invariably steep, seldom less than 70° and generally more nearly 90°. At one place, south of Sweetsburg and west of Scottsmore, the structure shows the rocks to be rather gently folded. This area is a basin, which though exceedingly complicated in the eastern part, is the only place where the Gilman quartzite can be seen to be nearly horizontal. Strikes conform to the general N.20°E. average except in the basin referred to above.

Within the belt of low land that lies between Frelighsburg and Dunboro, occupied by Lake Selby and several streams and swamps, are a number of exposures of the basal beds of the Gilman quartzite. This is a coarse grit with grains of quartz up to a quarter of an inch in diameter, agreeing in all respects with the basal beds as exposed further east save in the greater content of chloritic material. Evidently the West Sutton slate and the White Brook dolomite are not far beneath the present surface. It may well be possible, indeed, that the longitudinal valley has been eroded out of these soft rocks, and that if exposures were complete enough we should see them at the surface. In any event the low belt lies along an anticlinal axis, and therefore the complete section of the Gilman occurs between it and the western boundary of the Gilman.

The thickness of the formation is difficult even to estimate. A maximum value can be found by measuring the distance between the eastern boundary of the overlying dolomite southwest of Pell Pond and the basal beds as they are exposed east and northeast of Frelighsburg. This is, as accurately as can be measured a mile and five-eighths, or approximately 8,500 feet. If the beds are all vertical this would be the thickness of the Gilman quartzite. However, this is far from true. Although steep along the contact with the dolomite, the basal beds are exposed along a strike-wise belt five-eighths of a mile wide (3,300 feet). This indicates either flat dips, contrary to such facts as we have at our command, or a series of folds; either explanation would materially cut down our maximum estimate of 8,500 feet, by an unknown amount, but probably 50 percent or more. Another method, less trustworthy, is to compare the breadths of outcrop of the Gilman quartzite and a formation of known thickness, say the Pinnacle graywacke. The Gilman quartzite outcrops in a belt from 4½ to 7 miles wide, whereas the Pinnacle graywacke varies in general from one-eighth to one-half mile in width. On this basis the Gilman quartzite should be from 36 to 14 times the thickness of the graywacke. Obviously the lower limit for the graywacke is unreliable, for there are places where its outcrop is less than a chain wide. The upper limit is fairly constant and reliable. On this basis the Gilman formation would be 5,600 feet thick, which is not altogether out of harmony with more reliable estimates. Of course, the assumption that the degree of folding is essentially the same in the two formations is not susceptible of proof. The quartzite probably does not dip as uniformly steeply as the graywacke, which would tend to reduce, in applying corrections to our calculations, the width of outcrop of the quartzite, hence reducing the factor 14 and therefore bringing the thickness of the quartzite down to considerably less than 5,600. By using these two methods we can arrive at a figure of, say, 3,000 feet, which is in accord with both methods, and probably is not far from the truth.

Stratigraphic Implications and Origin. A thick formation such as this is of considerable interest in interpreting local environmental conditions. The coarse clastic graywacke pointed to relatively rapid accumulation of the detritus of freshly disintegrated rock. The Gilman clastic rock is fine-grained, siliceous, and even textured throughout most of the formation. Evidently conditions were constant over all but the beginning and end of the time of formation. The grits at the base, which are not everywhere in evidence, may be due to local physiographic conditions of no great importance. The long continued deposition of fine sand and silt argues for a land area in which decomposition and disintegration are both active, and in which epeirogenic uplift was sustained but gentle. Thus weathering would destroy practically all minerals but quartz in an average countryside, and rivers, by no means swift, would be able to deliver their load of fine sand, silt and kaolin mud to the sea. In all probability marine currents were responsible for the sifting of this deposit, carrying the mud away from the zone of agitation, leaving the finer grains of sand which could maintain their position on the sea floor against moderate wave disturbances. Somewhere west of this sandstone there was doubtless deposited a greater amount of mud, either as a thicker bed or a more extensive one. There is today no trace of this. The constant shifting around on the sea-floor would have destroyed any original stratification. Towards the end of Gilman time a temporary rise of the lands appears probable allowing some of the undisintegrated quartz, from veins probably, to be washed to sea as pebbles. This action, too, may have temporarily removed most of the decomposition residue from the land surface so that when it subsided little regolith remained to be moved, and a time of non-clastic deposition succeeded during which the Dunham dolomite accumulated.

Fossils. At a locality about half a mile southwest of the cemetery at Scottsmore this quartzite contains a few poor fossils. The most important type is a brachiopod which though poorly preserved without doubt belongs to the genus Kutorgina. This genus is restricted to the Lower Cambrian. The other fossils are small and delicate branching forms, probably algae and apparently of no stratigraphic significance. Thus, because there is no unconformity of any importance between the Gilman quartzite and the Call Mill slate, the whole series must be placed in the Lower Cambrian. ?

<u>Dunham Dolomite.</u> Conformably overlying the Gilman quartzite is a dolomite in many respects similar to the White Brook dolomite. In fact they are so similar that only detailed field work would show their separateness. On the weathered surface the similarity is striking. Both weather to a brown color which in both is relieved by a network of quartz veins. There are two phases of this dolomite; one running more or

less continuously along the western boundary of the Gilman quartzite, and in basins and infolded zones to the east of this, and a second shown only in a downfolded area within the Gilman east-southeast and south of St. Armand Centre. The former and usual type is almost everywhere a gray rock on the fresh surface, sometimes almost black, rarely a light gray. The weathered zone of brown limonite is seldom more than a surface skin about 1 mm. thick. The second and restricted type is both gray and cream to buff colored, weathering white or pale buff.

The former type extends from the Vermont boundary near Eccles Hill* at post 618 northeastwards along the regional strike through St. Armand Centre, Hunter Mills, Garrick Corners to Dunham, where it makes a mile-wide sweep to the southeast and returns to the regional strike through Oak Hill and Sweetsburg after which its outcrops are somewhat scattered until the mass of Brome Mountain, lying across its strike, cuts it off completely. In addition, basins and

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* A monument here commemorates the repulse of a Fenian invasion by the local militia in 18 .

and downfolded areas within the Gilman quartzite occur throughout its length. The most northerly of these shown on the map lies south of Sweetsburg and west of Scottsmore, where there is a basin more than a mile and a half long and a mile wide. A more northern exposure of this Dunham dolomite within the Gilman quartzite located during reconnaissance surveys at the very beginning of this field work about a mile northeast of Sweetsburg has been searched for subsequently, but in vain. It cannot be of very great size. The structure of the beds on the east side is extremely complicated and is shown in only the most generalized manner on the map. It is interesting to see Logan's boundary lines for the Dunham dolomite, as shown on Ells' map. There Logan realized the impossibility of representing adequately the structure, and indicated by a few well chosen lines the complexities concerned. To the north of the road at the cemetery, half a mile northwest of Scottsmore a small outcrop occurs in which this dolomite and the next two succeeding formations are involved with great complications, folds, thrusts and brecciation contributing to the complexities. A second downfolded area, not so obviously a basin as the former, lies south of Dunham and east of Garrick Corners. This is continued southwestwards along the strike for four miles dying out a mile and a half north of Frelighsburg. Throughout these three main areas the dolomite is reasonably continuous, quite constant in characteristics, but varies considerably in thickness, from nothing up to 65 feet. It contains no fossils, but in nearly every outcrop sand grains are common. Shearing has developed planes of weakness, and the veins filled with quartz make breaking a good specimen out well nigh impossible. It is everywhere crystalline, finely so as a rule, but occasionally the crystals may be 1mm. or more across. Stratification is obscure; it might be said to be lacking except in a few outcrops where a shaly development makes it apparent. This is best seen in the exposures in the vicinity of Garrick Corners and Meigs, where for three miles or so between 20 and 30 feet of dolomitic shale or shaly dolomite occupy the lower middle part of the dolomite body. The shallow folding east of the road a mile and a half south of Meigs is brought out beautifully by this shale. Similar, though not so well developed, shaly facies can be seen a mile south of Sweetsburg, where, as in the locality cited above, it is the only clue to inherent stratification in the Dunham dolomite. It is also well shown for a few chains north of the border.

Rarely is there abundance of quartz grains enough to justify calling the rock a sandstone, but this is the case at Hunter Mills, where three separate sandstone beds occur within the dolomite. It is not without the bounds of possibility that these sandstone beds may belong to the Scottsmore quartzite, for thrusting is demonstrable in this outcrop, but there is no definite proof.

Thickness. Of this calcareous bed Harvie (1915, p. 99) reported 150 feet at Dunham and 50 feet at Sweetsburg. He also reported that the same band is 780 feet thick at Georgia Centre, Vt. Near Eccles Hill our measurements show it to be between 40 and 50 feet thick, swelling rather suddenly in the neighborhood of Hunter Mills to about 100 feet, reaching a 150 feet about two miles southwest of Dunham then thinning to 30 or 40 feet east and west of Dunham, rising again to 120 feet at Oak Hill beyond, which structural complications and skethiness of the outcrops make further estimates impossible. Thus the diminution northward, indicated by Harvie may be true as a generalization, but it is subject to considerable variation.

The second type of dolomite occurs in a downfolded zone within the Gilman quartzite south and east of St. Armand Centre. This contains far more variations than the normal dolomite, and in general can be said to show the following section

6'+	Gray limestone, some layers brecciated
25'	Quartzite, well stratified
10'	Red weathering dolomite, the normal Dunham type
5'	Gray dolomite with trilobite fragments
20'	Beige (yellow and white) dolomite, some beds, especially the lower part, brown weathering.

This order is seen to best advantage three quarters of a mile south of the word Centre of St. Armand Centre and immediately north of the end of the north-south road. There the dips are shallow, in some places nearly horizontal. One half mile west of the road corner indicated above, and south of the road the same succession can be seen, lacking, however, the uppermost limestone. The structure at this locality is that of an overturned syncline, of which only the western limb, with shallow easterly dips, is exposed. Further southwest on the winding road going south to the border much gray limestone occurs, which is probably the uppermost member as shown in the succession above. We have no information as to the continuation of these variations southwards into Vermont, except that in the vicinity of St. Albans a whitish marble, comparable to the nearly colorless variety of the "beige" dolomite occurs associated with the Dunham dolomite. This is doubtless the rock cited by Harvie as containing sponge-like fossils, on which, however he did not report further.

It would appear from these exposures that the Dunham formation was of far more varied composition than the "normal" type of the rest of the area. ~~would indicate~~. Probably the types here described as beige and gray were never deposited further north, for the vagaries of erosion would surely have left some trace of them exposed today.

There is a possibility, of course, that the quartzite of this section is the Scottsmore quartzite and that the succeeding limestone is younger and unrepresented further north. There is, I believe, no way of demonstrating the truth or the fallacy of this suggestion. The quartzite does not resemble the Scottsmore closely, though that is not to be expected in so variable a rock. For the present, considering the entire section as a phase of the Dunham dolomite is the wisest course.

Age. On the basis of fragmentary trilobites belonging to the family Mesonacidae, this formation can be definitely placed in the Lower Cambrian. The underlying formation, the Gilman quartzite, also contains Lower Cambrian fossils. Harvie's (1915, p. 99) correlation of Walcott's Bed No. 1 (1886, p. 15) with the dolomites of the hills east of the Central Vermont railway at Georgia Centre cannot be substantiated, for Bed No. 1 belongs to one stratigraphic succession (Central sequence of Keith; Rosenberg slice of the present author) whereas the dolomites belong to a totally different succession (Eastern sequence of Keith, Oak Hill slice of this work). It would appear that the equivalent rock in the vicinity of St. Albans has been called the Rutland dolomite by Keith (1923, p. 128, 1932, p. 396) but his description is by no means applicable to the Dunham dolomite, hence we are unable to use his name.

Oak Hill Slate. The section at Oak Hill is the most nearly complete one available. It is illustrated in the accompanying sketch (fig.). Visibly in contact with the uppermost Gilman quartzite bed is the Dunham dolomite. The next formation is a tough dark gray slate flecked with limonite. This is the Oak Hill slate. Following that is the Scottsmore quartzitic sandstone, immediately followed by a black shale with fine crumpled white siliceous bands, the Sweetsburg slate. At the base of the hill opposite the Vail cemetery is a third type of slate to which the name Vail has been given. Each of these will be discussed in detail successively.

The Oak Hill slate is a very tough rock, dark brownish gray or black with the stratification shown by limonitic flecks, sometimes continuous as bands, but more usually discontinuous giving the rock a speckled appearance. It rarely breaks along the stratification planes, and seldom with any regularity in other directions. Minor unconformities of considerable angular discordance, can be seen. It weathers but little, showing limonitic stains.

The Oak Hill slate might more properly be called a siltstone than a mudstone. Abundant small scales of mica occur in it, and grains of quartz can be seen in some specimens. Secondary minerals, besides limonite, are uncommon, sericite on fracture planes being the only common one. At one or two places bedding planes are marked with pyrite, which is doubtless the parent of the limonite flecks and bands characteristic of the rock

In distribution this member has not been recognized south of Oak Hill, except at one locality a mile and a half south of Dunham. Its occurrence there does not justify its inclusion on the map, this record being considered sufficient. Its greatest development occurs ~~north~~ south of Sweetsburg, ~~whence it takes its name~~. It is absent from a good deal of the area from Oak Hill northwards, for the succeeding member, the Scottsmore quartzite, is found lying directly upon the dolomite.

Scottsmore Quartzite and Conglomerate. With the exception of the few stretches where the Sweetsburg slate occurs, the Dunham dolomite is followed by a quartzite which, locally, includes a bed of conglomerate. The conglomerate is known only in the northern part of the area save for one outcrop half a mile south of Meigs; the quartzite is best developed in the northern two-thirds, in the southern part it is discontinuous.

The most apparent characteristics of the quartzite are its tendency to weather brown and its banded appearance. Before deciding upon a geographical name we called this the "banded quartzite" to distinguish it from the relatively unbanded Gilman formation. When fresh it is medium gray in color, varying in grain from fine to medium, and with an interstitial filling that is here siliceous, there dolomitic, In fact so strong is the impregnation of this rock with dolomite that many exposures, where the intermediate slate body is lacking, can only with difficulty be assigned either to the Dunham dolomite or this quartzite. Where the secondary filling is siliceous the rock is dense, with, however, the original grains always plainly visible. Moreover, such rock maintains its gray color even on a weathered surface. Also such quartzite is much veined with quartz. Where a considerable amount of dolomite occurs, the rock is usually more of a blue-gray color on a fresh surface, but weathers deeply, for two inches or more inwards, to brown of various shades. This weathering also weakens the rock so that it is very friable, grains of sand rubbing off at the touch. Quartz veins rarely occur in this type of quartzite.

Stratification is usually quite obvious, cross-bedding of no great angular difference is common. On range V, lot 12 Dunham, this crossbedding is well shown, and was the locality where, mapping from east to west, the order of succession of beds was first determined. Elsewhere crossbedding contributed like evidence.

It varies from an inconsiderable thickness to 25 feet. Usually it is from eight to twelve feet thick.

~~Scottsmore Quartzite and Conglomerate.~~ Half a mile due east of Sweetsburg village are several outcrops of the Dunham dolomite, the Oak Hill slate, this quartzite and conglomerate, and the succeeding slate. One of the best outcrops is shown on plate , and in fig. . Just beyond the limits of the photograph the Sweetsburg slate is to be seen resting directly upon the Dunham dolomite. In the photograph the quartzite rests on the dolomite and contains a bed of conglomerate which carries angular fragments, up to 6 inches in diameter, of the Sweetsburg slate. Elsewhere the conglomerate rests directly upon the dolomite. The quartzite and the conglomerate are followed on the west by the overlying slate. In another nearby outcrop the relations between the Gilman, Dunham, Sweetsburg, and Scottsmore quartzite can be clearly seen. In this latter case a thrust has brought the Gilman quartzite to rest against the Sweetsburg, as indicated in ____ .

Two and a half miles south of Sweetsburg in the same stratigraphical position is a bed of limestone and dolomite conglomerate. There seems to be no doubt that the boulders of this outcrop are derived from the Dunham formation. Also a little less than a mile south of Meigs is an outcrop of this conglomerate resting upon well bedded Scottsmore quartzite. In between the boulders is a matrix of sand.

Stratigraphic significance. It will be seen from the table of formations that the development of the beds in this series follows, up to this point, a pretty definite order, as follows:

2	Scottsmore quartzite
1	Oak Hill slate
3	Dunham dolomite
2	Gilman quartzite
1	West Sutton slate
3	White Brook dolomite
2	Pinnacle graywacke
1	Call Mill slate

This order, slate, sandstone, dolomite, is repeated once and partially repeated again. In all cycles the basal slate is thin (up to 60 feet), and in the first two the sandstone is the dominant formation; the two dolomites are thin (up to 75 feet). We have interpreted this as the result of first gentle submergence (with differential elevation) of a decomposed land area yielding the shale, increased elevation favoring disintegration and so forming sandstone, and finally cessation of uplift giving quiet marine conditions allowing calcareous rocks to form. If this cycle of events is to relied upon it appears that the uplift following the second cycle was of short duration, though irregular enough to expose the Dunham dolomite and Oak Hill slate to erosion, and that a long continued period of fairly quiet sedimentation of mud followed (Sweetsburg formation).

Sweetsburg Slate. Most characteristic of the Oak Hill formation is the Sweetsburg slate, which is nearly everywhere the westernmost member of the Lower Cambrian, and rests upon the Oak Hill Thrust. It is a thick formation, being exposed over a maximum width of one mile, half a mile being more usual. Crumpling has destroyed any chance of measuring a section in it and we can only hazard a guess that it must be at least two or three hundreds of feet thick.

Characteristics. This is a dense dark bluish gray to black slate which everywhere contains thin seams, up to 5 mm. thick, of white sandstone. So strongly is the contrast between the appearance of this slate and both the Sweetsburg slate and the Ordovician slates of the ~~Pigeon Hill~~ Rosenberg and Philipsburg ~~blocks~~ slices (see) that in the field we used the descriptive term "banded slate" for it. Only by chance does this rock break along the bedding, shown only by the sandy seams. It is much cleaved, but not regularly so, breaking like the Sweetsburg slate into irregular sharp wedge-shaped masses. It contains a good deal of pyrite or small crystals or veins ~~of pyrite~~ which upon weathering coat the joint and cleavage faces of this rock with thick deposits of dark brown limonite. The sandy seams are colored somewhat by weathering, but not as much as one would expect. On Oak Hill, but not elsewhere, small lenses of quartzite occur infolded with the slate. These may belong to the Sweetsburg slate, or possibly they may be downfolded synclines, much contorted, of the Scottsmore quartzite.

The rock is crumpled in a very complicated way both on small and large scales. In a hand specimen the white sandy layers are rarely straight, usually they are intricately folded. It is not possible therefore, to determine whether the sandy layers are continuous or not.

Stratigraphic significance. As indicated above, under Scottsmore quartzite, this member was deposited at a time of relative stability of the land, which was undergoing decomposition to an extent that considerable mud was transported to the sea. The sandy layers are not, it seems, to be interpreted as due to variations of the intensity of the streams but to the interfingering of the off-shore muds and nearer-shore sandstones. That this could be possible without destroying the clear-cut definition of the sandy layers is a tribute to the quietness of the water.

Vail Slate Member. Two miles due south of Cowansville, on the Dunham - Sweetsburg road, in a quarry opened for road material opposite the Vail Cemetery, is a type of slate different from any of the preceding. It is not found north of here (see next paragraph), but a half mile further south it occurs again to the east of the road, and two and a quarter miles southwest, where an east-west road crosses a stream it can be seen again. Beyond that point it has not been recognized.

Further to the north, west of Bull Pond, and in the vicinity of the intrusive of Brome Mountain, there is an indurated rock which has all the characteristics one would expect to find were the Vail slate slightly metamorphosed. This consists of marked alterations of light and dark bands, with a strong ring to it when struck.

It consists of an alteration of fine and less fine layers of mudstone. On the fresh surface these are with difficulty differentiated. The finer bands are darker, the slightly coarser are not quite so dark, the whole rock being medium to dark gray. On the weathered surface, however, the distinction shows up remarkably well. The finer bands remain dark gray, the others weather to a rusty gray making a marked contrast. The layers vary in thickness, the finer ones on the average are 2 or 3 mm. thick, the coarser ones 4 to 6 mm.

The most remarkable characteristic of this slate is its cleavage, which is so coarse as better to deserve the name jointing. These fractures run in two main directions, thus reducing the formation to blocks of lozenge-shaped cross-section. One of these directions has led to the formation of open joints, now filled with quartz, these traverse the rock in paper-thin seams up to a millimeter thick to the number of a dozen per inch. Along with quartz ~~along~~ in these fractures is considerable pyrite, which easily rusts, but neither quartz nor pyrite occur in the other series of fractures. This alone would be sufficient evidence to allow the conclusion that the quartz filled fractures are the earliest the other set succeeding them in time. Considerable minor movement has taken place along the quartz filled fractures, tiny step faults of one to two millimeters affecting practically every part of the rock.

It is not impossible that this may prove to be merely a variant of the ~~Oak Hill~~ Sweetsburg slate. Its characteristics are so marked that it is here given the rank of a member within the Oak Hill formation. If not it is best considered as the highest member of that formation. The occurrence of the Oak Hill slate on both sides of it is doubtless due to the crumpling it has undergone. ~~If this is the case then the width of the Oak Hill slate is near more than 2,500 feet. But because of the crumpling involved this is meaningless.~~ About 25 feet of the Vail slate can be seen in the quarry and possibly another 25 feet is exposed along the roadside.

The Eastern District.

The Sutton ~~Series.~~ Group

Occurrence, etc. The Sutton ~~Series~~ Group occupies the Sutton Mountains, Sutton Valley, and the eastern half of Brome Lake basin - in all about 200 square miles of the area under investigation. The rocks include mica schist, phyllite, quartzite, and carbonate horizons. They are unfossiliferous as far as known and age relations can only be ~~summarized~~ determined from a study of the lithology and structure. No stratigraphic sequence has been determined as the series is greatly crumpled and deformed. The grade of metamorphism is relatively slight with low-temperature minerals predominating. The schists in the Sutton Mountains area are mostly albitized, with metacrysts up to one-eighth of an inch common, but those of Sutton Valley and Brome Basin as a rule lack this feature. Structurally, the Sutton ~~Series~~ Group forms an anticlinorium whose crest passes through the Sutton Mountains northeast toward the Notre Dame Hills and south into the Green Mountains of Vermont.

The boundaries of the Sutton ~~Series~~ Group are the Brome Thrust on the west, whereby the rocks of the Oak Hill slice are brought into contact with the Mansville Phase and also the Sutton ~~Series~~ Group proper in the southern part of the map. This boundary, like most of the boundaries in this area is a line between N.20.E. and N.30.E. On the east the boundary is less definite, but none the less clear. It is a stratigraphic boundary between the metamorphosed schists of the Sutton ~~Series~~ Group and the unmetamorphosed (uncrystallized) slates of the Mansonville Series. Strangely enough, this latter boundary is not hard to draw. It lacks much of what a good boundary should posses; it does not necessarily separate two rock formations, for the Mansonville Series may well be, and in all probability is, infolded with the Sutton ~~Series~~ Group, but in so becoming it has taken on crystallinity and schistosity and hence becomes part of the Sutton ~~Series~~ Group.

<u>The Mansville Phase of the Oak Hill ~~Series~~ Group.</u> Exposed along the western limits of the Sutton series is a suite of formations of somewhat less metamorphosed types than is usual in the Sutton ~~Series~~ Group. Its best exposures are in the vicinity of Mansville, but it may be found far to the north and south. It consists essentially of low grade schists,

phyllite; and dolomites whose order of succession and relative thickness agree exactly with those characteristics of the Oak Hill Series. So striking are the resemblances of the rocks concerned in all respects save metamorphism and actual thickness, that there can be no escape from the conclusion that this is merely a phase of the Oak Hill Series, attenuated because of limited deposition, exposed in a slightly metamorphosed form. This peculiar phase we have called the Mansville Phase, avoiding the word series because it does not appear to be distinct, except in metamorphism, from the Oak Hill Series, and also because of the possible confusion with the term "Mansonville Series" employed in connection with rocks of the Memphremagog Quadrangle. The correspondence between the Normal Phase and the Mansville Phase is shown in the accompanying table. The "lower sericite schist" is highly magnetiferous, the "middle slate" is rich in hematite, the "upper sericite schist" is almost pure sericite-quartz schist. The two dolomites are indistinguishable, except that the lower has associated with it a dolomitic schist. The apparently great thickness of this "lower dolomite" may be due to the inclusion within it of siliceous beds properly belonging to the "lower sericitic schist". The "lower slate" resembles the Call Mill slate in texture and color. Moreover both these latter formations rest upon chlorite schists, which in the two cases are almost identical.

So confusing were the outcrops of the Mansville Phase when first encountered that it was decided to map two or three of the outcrops accurately by means of a plane-table. Plate shows one of the maps so made and cross-sections of the other two areas. The westerly dip is unusual and is doubtless the result of drag along the Brome underthrust.

Figure shows the plan and section of one of these Mansville outcrops situated 1 mile west of Sutton Junction, west of the first north-going road west of that place. A south pitch is indicated at the north end of this exposure and top and bottom of the section are definitely known. The legend shows the sequence and the table on page indicates the thicknesses.

Figure shows a similar sequence ½ mile south west of the preceding locality which is complicated by a fault. The characters of the rock are identical with those of the first locality.

Figure shows a section of the third locality, 1 mile southwest of Brome Village, west of the road. Its lithology and sequence differ from those of the two previous exposures and it is thought to be the uppermost part of the Mansville. In order to present the evidence logically it is necessary to study again the first two localities.

Plate , mentioned previously, shows a section which can be successfully compared with the highest horizons of the Oak Hill Series. The exposure lies 3 miles northeast of the Mansville outcrops already described but is directly along the line of strike. The field relations do not indicate top and bottom of beds and the section is drawn in its present form only as a result of its lithologic similarity to the upper part of the Oak Hill Series. The evidence is (1) the dolomite marble is highly siliceous and thus resembles the Dunham formation on Oak Hill, (2) the phyllite and slate contain thin quartzitic beds near their contact with the marble which are similar to the Scottsmore quartzite. On the strength of these lithologic resemblances the locality is included in the Mansville formation and in the table (p.) its members are placed opposite the upper horizons of the Oak Hill Series. Thus in figs. and the bottom of the metamorphosed Gilman quartzite is seen, whereas in figure only the top. No information as to the proper thickness of this "upper sericite schist" is available.

Main body of the Sutton schists.

Lithology. The main part of the Sutton Series is divisible into four lithologic types - (1) mica (sericite) schist, (2) phyllite, (3) quartzite, and quartzite schist, and (4) dolomite and dolomitic marble.

The mica schist group is by far the largest in the series. In Sutton Valley and Brome basin these rocks contain little or no albite and are closely cleaved, almost slaty in places, micaceous to talcose luster. Many of the gradational phases may be named chloritic schist or phyllite with equal reason depending upon the whim of the observer. They are fine to medium-textured and in places are high in magnetite. In the Sutton Mountains the mica schist is rich in albite metacrysts and over large areas the rock is gneissoid in character. On the east flank of the mountains albite is less prominent. Much of the schist is carbonaceous and has a steel-gray lustre which is characteristic. Typical fresh exposures may be seen along the main highway in Glen Sutton Valley, especially between Dunkin and Highwater. (Plates to). Along Bolton Pass in the vicinity of Sally Pond the rocks are very coarse-textured and have a gneissoid character. This is also true of Bolton Mountain, a bare ridge northeast of Bolton Glen. In these localities weathered surfaces show coarse quartz ridges up to ½ inch in width standing out in relief.

Microscopic examination confirms the field evidence that the mica schist consists mostly of quartz, sericite mica, and chlorite. The mica and chlorite are intergrown; the flakes are oriented in the direction of schistosity and enclose lens-like aggregates of quartz grains. The "albite" metacrysts previously mentioned are usually not pure $NaAlSi_3O_8$

All these places are in the Mansonville slate - no they aren't but approach oligoclase in composition. They have ragged borders (Plate) and twinning is notably absent. A good basal cleavage aids materially in determining their position in the plagioclase group. They disrupt the schistosity in two ways (1) by mechanically spreading apart the mica-chlorite lamellae, (Plate) and (2) by replacing the schist minerals, mica, chlorite, and quartz. Evidence of the first may be seen in the field where the metacrysts have made pockets for themselves and give the cleavage surface a hummocky appearance. Evidence of the second, or replacement, is shown by the microscope where corroded remnants of the original schist minerals enclosed in the metacrysts preserve the schistosity as a relict structure. (Plate). Had the replacement been complete in all cases this direct evidence would be lacking. Quartz may occur in veinlets up to one-sixteenth of an inch in thickness. These in turn may be mylonitized into augen-like masses in which the grains are broken and strained. Orthoclase occurs in the coarse gneissoid rocks as grains of equal size with albite and quartz; it is rare in the main body of mica schist and never occurs as metacrysts. Magnetite and ilmenite occur commonly as accessory grains, the former usually as octahedrons and the latter with its characteristic leucoxene alteration. Pyrite and pyrrhotite are much less common than magnetite and indicate the oxidizing rather than reducing character of the circulating solutions. Titanite in wedge-shaped and irregular outlines and rutile in minute needles are regularly found. Epidote, apatite, and carbonates are also characteristic accessories. Small brown tourmalines appear in some sections. Green biotite and hornblende are rare. Pink garnets may be seen in some hand specimens but they are usually microscopic and never abundant.

The phyllite group is second in importance to the mica schist and as usual is a gradational type. The term is a convenient one to use for rocks intermediate in texture between schist and slate. On a low ridge west of the highway between Brome and Sutton Junction there is an approach to true slaty cleavage but more typical exposures are minutely crumpled and folded and show cleavage directions rather than cleavage surfaces. The texture is very fine and the rocks are colored gray to black by graphite or carbon dust (Plate). Quartz layers up to one-sixteenth of an inch in thickness may be present and give the phyllite a minutely banded appearance. S-shaped monoclinal crumples are characteristic of the group; they vary from microscopic sizes up to several inches across and in places two intersecting sets may be found. The phyllite is interbedded with the mica schist in zones varying from a few inches to several hundreds of feet. Due to its gradational character sharp contacts are uncommon.

Quartz, sericite mica, chlorite, and carbonaceous matter are the essential constituents of the phyllite. Intergrowths of mica and chlorite are woven between clusters of minute quartz grains and outline also the monclinal flexures previously referred to. Albite-oligoclase metacrysts show the same characteristics as in the mica schist but are in general smaller and less abundant. They are clouded with carbon dust which darkens the lustre on cleavage faces seen in a hand specimen. TIlley, C.E. (Quart. J. G. S. London, vol. 79, p.180, 1923) describes "knots of a black well cleaved mineral, forming porphyroblasts in a quartz-chlorite-muscovite groundmass". Albite twinning is common and the blackness is due to carbonaceous inclusions. (Start area, England). This material clouding the metacrysts shows in places monoclinal folding which is continuous with the original crumpling outside its boundaries. The carbon represents material which the albite could not use during the replacement and is certain evidence of the later age of the metacrysts. Among the accessory minerals apatite is common as euhedral to subhedral crystals and also calcite in twinned, irregular forms. Epidote with blue clinozoisite rims is a regular accessory. Hornblende blades are much less common. Ilmenite, rutile, and titanite among the titanium group, and small tourmalines have also been noted in thin section. Pyrite is characteristic and is found in sharp cubes of all sizes up to ¼ inch. In places it is fractured or contains remnants of mica, chlorite, etc. Pseudomorphs of hydrous iron oxides may also occur where weathering agents have penetrated. Pyrrhotite is less common and lacks the crystal outlines and large dimensions of pyrite.

The quartzite group is important for the evidence it furnishes of the sedimentary origin of the Sutton Series but is of slight areal extent. It occurs in beds several feet thick down to layers measured by a few inches. The rocks are medium to fine-grained and granular to schistose. The color varies from grayish-white to almost black in carbonaceous types. (Plate). The quartzites may be streaked with dark and light layers which represent initial differences in sedimentation. Small pyrite cubes occur in the carbonaceous types and if oxidized form rusty spots.

In thin section quartz is predominant as would be expected and occurs in interlocking, unstrained aggregates which may have a slight elongation parallel to the schistosity. Sericite mica and chlorite are intergrown as in other parts of the Sutton Series but are less abundant and seldom dominate the structure. Albite-metacrysts occur sparingly. Carbonates are characteristic accessories. Magnetite, ilmenite, and titanite are common; rutile needles are relatively rare. Epidote and zircon are likewise uncommon. Apatite is a regular accessory and garnets are found in places.

The dolomite and calcite beds are a calcareous group varying from massive marble to schistose types. The texture is usually fine and sugar-grained but may also be coarse.

(Plate). The color of the fresh rock varies from creamy-white through gray to brown. They occur interbedded with the mica schist and phyllite in small discontinuous exposures a few feet thick. Only about a dozen outcrops have been ~~located.~~ found. The surface weathers brown due to the slight iron content of the carbonate and the rock is much fractured and filled with quartz and chlorite veins of all sizes. In places chalky white feldspar and quartz grains stand out prominently on the weathered surface. Dolomite occurs in untwinned crystals with common grains of quartz. Calcite is characterized by abundant twinning. In places albite and orthoclase are scattered ~~are~~ through the sections, and ~~which~~ are probably of sedimentary origin. Green fuchsite streaks and paler talc have been noted in hand specimens but in thin section may have passed for mica in many cases due to their lack of color. There is sufficient mica in parallel dimensional arrangement in places to give these rocks an irregular schistosity but ordinarily they are massive and abundantly fractured. Accessory minerals include pyrite, chlorite, apatite, and carbonaceous matter.

Evidence of Original Character. There are two lines of attack to this problem - (1) the field evidence, and (2) the mineralogical evidence. These are inseparable for purposes of discussion and converge to the same conclusion that the Sutton Series is sedimentary in origin.

Marble and carbonate schist occur in a number of localities. In all cases they are conformable with the super- and subjacent mica schist and phyllite, show no cross-cutting features, and indicate nothing of an intrusive character. Quartzite is of common occurrence and shows the same characteristics as the carbonate beds. It is more than ninety percent pure quartz.

The mica schist averages about fifty percent of quartz which is an improbable proportion for any rock except a sediment. The fact that these schists now contain abundant albite has no bearing on the problem in hand as this mineral belongs to a later generation. ~~made at a time during which soda was introduced.~~

The phyllite and much of the mica schist contain abundant carbon dust or graphite. The local occurrence of carbon in itself signifies nothing as it is commonly noted in metabasalt and greenstones but in the present case it is widely distributed and in the phyllite forms an appreciable percentage of the mineral content. There is no evidence that it has been introduced and the conclusion therefore seems justified that it is an original constituent of a sedimentary formation.

The total evidence of origin of the Sutton Series converges to one conclusion - that it is of sedimentary character. Metamorphism, both physical and chemical, has masked certain details and it is only by separating these later features that the original character of the rocks can be deciphered.

Thickness. The only continuous section in the Sutton Series in which it is certain that there is no repetition of beds by folding is in the gorge one mile northwest of the end of the road north from Dunkin (Plate). This is a vertical section of about 400 feet in the crest of the anticlinorium. It cannot be regarded seriously as a minimum thickness and is included in the discussion to illustrate the lack of quantitative data concerning the problem.

The axis of the anticlinorium passes much closer to the east boundary of the series than it does to the west. Along the International Boundary where the greatest breadth of exposure occurs west-dipping schist composes 9 miles of the total of 14, and only 5 miles dip east. Further northeast the same outcrop ratio holds but consideration of thickness is less justified here due to the intense flowage which has occurred on the northwest side. The factors to be considered in a discussion of thickness are as follows - (1) the amount of thickening by repetition of major folds on the limbs of the anticlinorium, (2) the magnitude of the displacement along the Brome thrust and the position of the axis of the adjacent synclinorium to the west of the main anticlinorium. Assuming an average west dip of 45° and an east dip of 60°, and neglecting the above factors for the moment, the 14-mile section referred to would represent 32,000 feet measured from the thrust fault on the west and 22,000 feet measured from the contact with the Mansonville Series on the east. The field study shows that the schist west of the axis has been thickened by drag folding more than that on the east and they may for that reason contain more repeated structures. It is unlikely, however, that a restoration of the pre-folded sediments would thin out the western limb to the dimensions then occupied by the east side. In other words the asymmetrical position of the axis can not be explained entirely by the relatively greater thickening of its west limb. There remains then to be considered the thrust along the west boundary. Its throw is unknown but because the basement of Tibbet Hill chlorite schist is exposed east of the Brome Thrust there must be a synclinorium between the Sutton Mountains and the Brome Thrust. Some of the discrepancy in the distribution of the series east and west of the anticlinorial axis may be due to this synclinorium in Sutton Valley. It is also possible that the west side of the basin received a greater thickness of sediments in the first place than did the eastern side. With so many unknowns and variables only an arbitrary figure can be offered for the thickness of the series and a minimum of 10,000 feet is given in the geological column (Insert).

<u>Age.</u> Logan was the first to hazard a guess as to the age of these schists. He did not suspect the presence of thrusts between the Philipsburg area and the Sutton Mountains and therefore his conclusion that "Sutton Mountains would thus appear to be composed of strata which overlie the magnesian portion of the Quebec group" though still partly true cannot be said to rest upon correct reasoning (1863, p. 251). He was thus convinced that they were the metamorphosed equivalent of Cambrian and Ordovician beds, a conclusion that was combatted by Selwyn (1883), and Ells, both of whom subsequently reported on the region. Dresser (1906, p. 509) was the first to complain of the change from Logan's expressed views, but practically no other opinion up to the time of this report has come out.

If the supposition that the Mansonville Series (see p.) is Upper Cambrian, then structurally the Sutton Series must be pre-Upper Cambrian in part. The conclusion reached in the discussion which follows favors a Lower Cambrian age although no direct proof is possible from the present study.

The Mansville Phase of the Oak Hill Series is the key to the problem in that it seems to be, though part of the Sutton Series, a slightly metamorphosed product of the

Lower Cambrian Oak Hill Series. Its relation to the normal phase of the Oak Hill Series has already been given in detail (p.) and it will now be compared with the Sutton schists in order to consider the possibilities of further correlation. Paleontologic data are lacking entirely so that the evidence must rest on lithology, stratigraphy, and structure.

A lithologic comparison with the Mansville Phase is significant. In the Sutton Valley the mica schist is identical with the upper and lower sericite schist of the Mansville Phase but as one proceeds further east the outward similarity decreases due to albitization and coarsening of the texture. The phyllite of the Sutton Series shows the same relationship - in the Sutton Valley it is entirely similar to that of the Mansville Phase but as one works east the original character is masked by albitization. Thin quartzite beds are of common occurrence in the Sutton Series and similar thin beds occur with the phyllite and slate of the Mansville. Dolomite beds occur in a number of localities in the Sutton Series and most of them are brown-weathering types not distinguishable from those described in the Mansville formation.

A complete stratigraphic comparison can not be made as no continuous exposures are known within the Sutton schist which contain more than three of the various units of the Mansville formation. This is partly due to the more intense metamorphism, perhaps also to actual changes in the sequence and thicknesses. A locality 2 miles northeast of Richford, Vermont, and ½ mile south of the boundary furnishes the only stratigraphic evidence in the Sutton Series. Mica schist, dolomite marble, and a thin banded phyllite occur in several adjoining outcrops alongside the road and the drag folds indicate a sequence as named above with phyllite the top member. This is similar to the succession described from the Mansville outcrop in Plate .

Structural relations are developed more fully in the next chapter (p.) but it may be stated here that the Mansville lies at the base of the exposed portion of the Sutton ~~Series~~ Group, because of its unconformable position upon the basement chlorite schist. The lithology of the main part of the Sutton Series is entirely comparable with that of the Mansville and Oak Hill, as already indicated, and it is not unreasonable to suppose that the whole group is Lower Cambrian, though for the most part stratigraphically higher than the Oak Hill Series. There is no trace of an unconformity and the differences in metamorphism bear no relation to the age of the rocks. Further, it would be a remarkable coincidence if the sedimentation in late Pre-Cambrian should so closely resemble the peculiar sequence of slate, marble, and schist found in the Lower Cambrian of the Oak Hill Series.

Some additional information may be gleaned from the estimate of the minimum thickness of 10,000 feet for the Sutton schist. Of this thickness only 300 feet, more or less, at the very base consists of known Lower Cambrian strata. The vast bulk of the schist, therefore, is certainly post Oak Hill. That it might still be Lower Cambrian is entirely possible, though it is far more likely that the middle and upper portions belong to later epochs. Because the Middle Cambrian is but sparingly present in Northern Vermont, and unknown in Quebec, a logical conclusion would be that the Sutton Series is Lower Cambrian in its lower part, the rest being probably Upper Cambrian and even Ordovician.

In the Thetford area, H. C. Cooke first supposed that the Bennett schists which are the northward continuation of the Sutton schists, were Pre-Cambrian but later concluded independently of this present work, that they "appear to be the lower, metamorphosed part of the Caldwell series, which is probably of Cambrian age" (1932, p. 2d) . The Bennett schists of the Thetford area as described by Cooke, and as shown by him to the writer, agree in all essentials with the Sutton schists. It is also interesting to note that Cooke mentions that a "magnetite layer [? Pinnacle Graywacke] is overlain by a very pure crystalline limestone [? White Brook Dolomite] about 10 feet thick". (1932, p. 5d). Cooke concludes (1932, p. 5d) that the "petrographic similarity of the original components of the Bennett schist to the upper part of the Caldwell series, the entire lack of any defined break between them, and the structural relations already described, together seem to indicate beyond a doubt that the schists are merely the lower, metamorphosed part of the Caldwell series". It would appear therefore that the chief difference between the two schist bodies is that the Sutton schists are definitely Lower Cambrian in their lower part, whereas the Bennett schists are almost certainly Upper Cambrian in their upper part.

From his knowledge of the intricate structure in the neighborhood of Richmond, Que., Dresser in 1906 concluded "as it thus seems certain that the Sutton series contains no Pre-Cambrian clastics in the vicinity of Saint Francis River, it is consequently possible, if not probable, that all the clastic rocks of this series, throughout the district, are altered members of the Quebec group, as in this section" (1906, p. 509).

In conclusion it may be said that there is evidence to prove a Lower Cambrian age of part of the Sutton series; there is none for its inclusion in the Pre-Cambrian. Undoubtedly Pre-Cambrian rocks occur elsewhere along the Green Mountains axis, but this does not constitute an a priori reason for assuming, as has been done in the past, that the whole anticlinorium is Pre-Cambrian.

Interval between Ordovician and Pleistocene.

Assuming that Ordovician rocks occur in the Sutton Mountains Massif, there is a great gap between the age of them and of the next succeeding sedimentary rock - post-glacial deposits. Elsewhere, to the northeast and east, Silurian and Devonian sediments were deposited, probably covering much if not all of this area, but such strata have left no trace of their previous existence behind.

Pleistocene and Recent Deposits.

Occurrence. This area is abundantly supplied with sandy till, stratified gravel, and river silt and mud. No special study has been made of this unconsolidated material and only its obvious field characters are recorded here. It is distributed fairly uniformly over the valley bottoms and thins out on the sides of the hills. Its maximum thickness is unknown but is probably less than 100 feet.

Till. The unstratified material is typically a till but in many places contains no clay. Boulders are abundant and are set in a fine sand or gravel matrix. They include gneiss, granite, etc., rocks foreign to Southern Quebec and in all probability derived from the Pre-Cambrian to the northwest. Till is found as far up as 2,000 feet above sea-level in the Sutton Mountains. It is the oldest unconsolidated material in the region and everywhere rests directly on the old Paleozoic rocks.

Stratified Gravel. This material is exposed in hundreds of pits in Southern Quebec as it is excellent road metal and is used extensively (Plate). It is a fine to coarse, well-washed gravel with a few sandy layers. It is invariably cross-bedded and has rather steep fore-set beds. The highest elevations at which it is found in Brome County are at Bolton Centre and Sally Pond, 800 to 900 feet above present sea-level. No marine or freshwater shells have been found anywhere, but as much of it lies above the 600-foot contour which approximately marks the strand-line of the post-glacial Champlain Sea, no marine types at least are to be expected. These gravels overlie the till but if the latter is absent they lie directly on the metamorphosed Paleozoic surface.

Leda Clay. This is known from but one locality, on the south side of Pike River, about midway between Hunter Mills and Frelighsburg, at an elevation of 300 feet. Fossil pelecypods are common in this exposure. Goldthwait (1912, p. 357) has examined the entire mountain front of this area along the Oak Hil Thrust and did not report any Leda Clay. He did mention occurrence of shell localities, but whether they were in clay or (more likely) in sand he did not say.

5. 1912 p. 357

River Silt and Mud. This material occurs in the valley occupied by the Missisquoi River and its West Branch, Pike, and Yamaska Rivers, and is the most recent of the unconsolidated sediments. It is not continuous throughout the river bottoms and is interrupted by rock exposures. The mostbextensive deposits are at the junction of two branches of the Missis$quoi River at Highwater where the streams wind in serpentine fashion through their own mud flats.

IGNEOUS ROCKS.

Bolton Metaperidotite and Derived Rocks.

In the western part of the Memphremagog map area, but outside the limits of the area of this report, there is a great development of effusive and intrusive basic rocks, known collectively as the Bolton Igneous Group. These will be described in the appropriate report as metabasalt, metagabbro, and metaperidotite. Of these, the latter only is found within the area of the Sutton Mountains, and is therefore the only one to be considered here.

The Bolton metaperidotite includes also a number of derivatives, chiefly serpentine, talc, and magnesite. It forms only a minor part of the igneous rocks of this part of Southern Quebec, but to the northeast, especially in the Thetford district it is very extensively developed. Within the present area it outcrops in a zone close to the eastern margin of the Sutton Mountain schist (and also in a parallel zone to the east of the Missisquoi Valley, East Branch), and in scattered localities in the Sutton Mountains, particularly two and a half miles northeast of Sutton Junction, four and five miles north of east of South Bolton and south of the Bolton Pass Road, three exposures near the extreme northeastern part of this report area, one mile northwest of South Bolton and several small areas close to the eastern margin of the Sutton schists. The largest outcrop of this rock is between one quarter and one half of a square mile occupying the hill eroneously named Hawk Mountain on the Memphremagog map. This lies outside the limits of this present report area. Those occurrences within the province of this report are, for the most part, talc and impure soapstone, with more rarely, serpentine. They are usually small, of the order of 100 feet across. Doubtless many more occurrences could be found within the Sutton Mountains, but the soil and dense forest growth effectively conceal them.

The discussion of the metaperidotite is reserved for the report on the adjoining area to the east, where the Bolton Igneous Series is so well developed. In this report reference will be made particularly to the bearing of these talc deposits upon the development of metamorphism within the Sutton Mountains Schists.

Brome Alkaline Intrusives.

Brome Mountain is the most easterly and the largest of the Monteregian Hills. Its southern edge is exposed along the northwest margin of the Sutton sheet. In the course of this work it was not studied in any detail, and is mentioned here only for completeness. The rocks are mostly coarse textured light gray-brown intrusives with dark minerals subordinate. Syenite is the most common species on the south side of the body, but olivine gabbro and anorthosite are found elsewhere, outside the limits of the Sutton sheet. It is doubtless a stock and cuts only the rocks of the Oak Hill Slice.

Numerous small pegmatitic veins between Dunham and Frelighsburg are probably to be related to this intrusion. Veins up to four inches across consisting almost solely of quartz and orthoclase are numerous in one or two localities. About a mile north of triangulation station 33-D-1, and on the west side of the road is a small excavation that exposes what appears to be an igneous rock entirely surrounded by metamorphosed sediments. In all probability this was an abortive outlier of the Monteregian intrusives.

Lamprophyre Dikes.

Trap dikes are relatively uncommon in Southern Quebec but are distinctive in character. They are usually 1 to 2 feet wide, gray-black in color, and of a fine, dense, texture.(Plate). A majority of them are porphyritic and a few amygdaloidal.

The dense groundmass under the microscope is composed of minute brown hornblende needles, albitized plagioclase, and an interstitial paste of chlorite and carbonate alteration products. The general term lamprophyre thus fits all these rocks, and a few correspond to the more specific term camptonite.

Phenocrysts of augite (Plate) and brown hornblende occur up to three-sixteeths of an inch across, and in places there are remnants of olivine. Chlorite and calcite replace these minerals to a considerable degree. Brown biotite is a common accessory and titanite, magnetite-ilmenite, and apatite are also of regular occurrence.

Amygdules up to one eighth of an inch are common. They are usually lined with green chlorite and filled with calcite.

Age. The three igneous types just described intrude the Cambrian and Ordovician rocks with which they are associated. The two latter are fresh and massive and give no indication of having been subjected to the diastrophism which affected Southern Quebec. The Acadian orogeny in Late Devonian time was the last of these disturbances, and the intrusives came in still later. From a knowledge of similar rocks elsewhere in this geologic province it is probable that the granodiorite and alkaline rocks were intruded in Late Devonian time after active orogeny had ceased. Their relation to each other and to the lamprophyre dikes, however, has yet to be demonstrated. The metaperidotite, associated closely with the Bolton metagabbro series, to be described in a later report, immediately succeeds the Ordovician. It escaped the Taconic orogeny, but was affected by the Acadian orogeny.

STRUCTURAL GEOLOGY.

There are two chief structural manifestations in this area, first the anticlinorium of the Oak Hill Slice, and second the massif of the Sutton schists consisting chiefly of the Sutton Mountain anticlinorium and part, at least, of the adjacent synclinorium to the west.

The Oak Hill Anticlinorium.

Between the Oak Hill Thrust and the Brome Thrust lies the Oak Hill Series of Lower Cambrian beds and their Pre-Cambrian basement, the Tibbet Hill schist. The Oak Hill Series is closely folded, the folds for the most part are somewhat overturned towards the west. The youngest beds are seen only along the western margin, and, with a few exceptions due to repetition by folding, older and older beds occur as one goes progressively eastwards until, just east of the strike of Pinnacle Mountain the chlorite schist basement rock is exposed all the way along the strikewise direction. Therefore the Oak Hill Series really outcrops in the western half only of an anticlinorium. The eastern half has been eliminated by erosion and the intervention of the Brome Thrust. This anticlinorium is really a very gentle arch of folded strata. The complete thickness of the Oak Hill Series is only about 4,000 feet, and the difference in elevation between the Oak Hill slate (400 feet) and the Tibbit Hill schist on Pinnacle Mountain (2,100 feet) is 1,700 feet. The total difference in elevation between the base of the Oak Hill Series along the east and west boundaries of the Oak Hill Slice is therefore 5,700 feet. Inasmuch as the width from Pinnacle Mountain westwards across the strike to the Oak Hill Thrust is 37,000 feet, we have means of measuring the amount of elevation concerned in the formation of the anticlinorium, i.e. 5,700 feet vertical elevation in 37,000 horizontal distance, which is a little less than one in seven. The anticlinorium concerned therefore was a very flat one, but effective enough over several miles in bringing to the surface the entire Oak Hill Series.

The anticlinal nature of the Oak Hill Slice is confirmed by the cleavage. This has a relatively low eastward dip on Oak Hill, but the dip becomes progressively steeper and steeper until on Pinnacle Mountain it is almost vertical, but with an eastern inclination. East of Pinnacle it becomes completely vertical, and before the Brome Thrust is reached it turns over to a very steep westerly inclination.

This fan cleavage, as it is called, is approximately parallel to the axial planes of the folds in the Oak Hill Series. In terms of the larger structure comprising all of Oak Hill upland the fan cleavage may be considered as parallel to the axial planes of unknown folds in the Tibbet Hill schist and of that part of the Oak Hill Series which once completely overlay it. The structure thus consists of a low arch with the axial planes of its secondary folds diverging upward.

This defines a normal anticlinorium and the Oak Hill unit is considered to be a remnant of a once larger structure of this type whose axis within the Tibbet Hill schist is marked by vertical cleavage.

The Oak Hill Thrust.

The Oak Hill Thrust forms the western boundary of the anticlinorium and is determined definitely by the fossil content of the adjacent formations. The Stanbridge slate on the west contains a sparse graptolite fauna of Trenton age and the Oak Hill Series which overlies it is known to be Lower Cambrian (p.). The latter series is overturned to the west along the thrust zone, which suggests an east-dipping thrust surface. This conclusion is quite in harmony with the Rosenberg and Philipsburg Thrusts further west, both of which dip east.

It is quite possible of course that drag along the Oak Hill Thrust is partly responsible for the overturning at this place, nevertheless this former conclusion is borne out throughout the Oak Hill Series in every locality giving any structural clue.

In only one place can the actual thrust be seen. In the stream bed below the bridge a mile and a half west of Hunter Mills the two kinds of slate are in contact, and one exposure clearly shows the Sweetsburg resting by faulting upon the Stanbridge. Throughout the zone, mapped as a line, of the Oak Hill Thrust numerous outcrops can be found in which the two types actually are intermingled, one type having been incorporated within the other as the overriding proceeded.

Minor complications of the main folding abound, especially along the strike of the two dolomite beds. Within the Sweetsburg slate, the Gilman quartzite and the Pinnacle graywacke, complications occur, but because of the essential homogeneity of the formations they rarely are seen. The westernmost line of outcrop of the Dunham dolomite in some places offers intricacies of a high order, often quite unresolvable on any mappable scale. Among such are the outcrops between two and three miles northeast of Dunham village, (Ranges lV and V, Lots 14, 15, 16). Here Dunham dolomite and Scottsmore quartzite are intricately folded and probably thrust faulted so that no good purpose can be served by trying to map them in a half-way manner. They are accordingly left as Dunham dolomite. Again half a mile west of the four corners north of Dunham Village is a small outcrop ~~both~~ north and south of the road for a quarter of a mile west of Garrick Corners. North of the road at Hunter Mills thrusts complicate an already over-complicated structure, A mile south of Dunham, on the road to Frelighsburg, there are several outcrops whose relations to each other can not be stated with certainty.

of the road which defies mapping on any ordinary field scale. The same is true of a group of outcrops both north

In nearly all these cases the folding, in which the Dunham dolomite takes part, is overturned to the west.

The White Brook dolomite shows equally intricate folding. In this case a very slight metamorphism in the contiguous rocks introduces an added distraction. Moreover, the folding is not only overturned to the west in most cases, but usually isoclinal. The mapping of the formations at the four corners between Gilman and Call Mill can only be considered approximate, and this is true also of the outcrops for a mile along the road to the northeast. A plane table map of these localities would resolve most of the difficulties, but the outlay of time for such purpose would scarcely justify the added refinement achieved. Further southwest, on Range I, lot 5, Dunham, on the farm of Messrs. McCullagh, the dolomite occurs at the nose of a south plunging anticline, with however, minor unimportant complications which could not be shown on the map. One mile further east it also occurs in half-a-dozen parallel bands separated by either the graywacke or the hematitic slate, but its structure, readily resolves itself into a series of tightly compressed folds. At the north end of the plunging syncline, Dunham, Range I, lot 1, the complications again are considerable but appear to be the result of minor puckerings in the main fold. The only other place where the mapped structural position of the White

Brook dolomite is open to serious questioning is for about half a mile south of Sweet's Mine (Brome Range IX and X, lots 7 and 8). There, in a heavily wooded region, the few outcrops conceivably might admit of different interpretation.

Normal faults and minor thrusts are quite common. One of the most important of the former is that which occurs west of Pinnacle Mountain being traceable from the border northwards a few miles. A thrust near Brome, by which the upper part of the Mansville Phase and the chlorite schist are brought together is easily demonstrable. Normal faults of the tear fault type are common, sometimes mappable, sometimes not. Several are mapped which interfere with the straight course of the Brome Thrust. The one which displaces that thrust where it crosses the Yamaska River is particularly noteworthy for it also displaces a subsidiary thrust lying to the northwest.

The Brome Thrust.

The Brome Thrust, marking the present eastern boundary of the Oak Hill anticlinorium, is not determined from faunal evidence. The dislocation is determined from the stratigraphic and metamorphic relations of the Oak Hill and Sutton Series, and confirmed by the character of mineralization and the local physiographic aspect.

The Mansville Phase of the Oak Hill Series, described on page , occurs only *to* the east of the Brome Thrust. West of that break there is no indication of a diminution in thickness of the exposed beds of the Oak Hill Series. Therefore, along the Brome Thrust, beds stratigraphically equivalent and once stratigraphically continuous are actually decimated in thickness. By no known process of sedimentation can such diminution be explained, and we must therefore have recourse to a fault. Moreover there is a pronounced change in the metamorphism involved. This is very slight west of the fault but everything save the chlorite schist, east of it is transformed into mica schists and marbles. Once again such sudden change can scarcely be explained in terms of anything else but a fault. Hence on two unrelated grounds the Brome fault is made obligatory. There remains the problem of the nature of the fault, which, inasmuch as the actual fracture cannot be seen, must be inferred. The stratigraphy and metamorphism of the normal and Mansville phases of the Oak Hill Series makes a thrust necessary, for a normal fault could not involve horizontal displacement enough to explain those two conditions. The cleavage makes an underthrust necessary, as an overthrust of such dimensions would not only have induced east dipping cleavage in both upper and lower masses, but would also have induced local overturning of the folds. Neither is the case.

This is both complicated & unconvincing. The reader may well ask why, if the Oak Hill overlies the Tibbit Hill on the west side of an anticline, it does not do so on the east side. Why not make the case on the flanks of the anticline beside the Mansville - Sutton anticline?

Because of the implication that the metamorphosed Mansville Phase beds were faulted beneath the normal phase of the Oak Hill beds, it must be understood that the thrust must post date the metamorphism. This is discussed more fully in the chapter on Historical Geology.

In a few localities along the trace of the thrust there is evidence of brecciation. The line, as mapped, probably represents the eastern limit of a thrust zone rather than the sharp boundary of a fault plane.

The evidence of mineralization is corroborative though not coercive evidence of this fault. The eastern limits of the Tibbet Hill schist forms a belt which is the locus of considerable sulphide mineralization throughout its entire length. Dozens of old workings, including the Shepard and Sweet "mines" of Brome County, attest this fact. The mineralization is of a medium to high temperature type and includes bornite, chalcopyrite, pyrite, and pyrrhotite. As the chlorite schist is a metamorphosed lava it is improbable that it is the direct source of these sulphides. It is probable that the mineralization is localized by a fracture zone of considerable extent parallel to the regional strike of the formations, and though it is not supposed that the sulphides and the Brome Thrust are in any sense contemporaneous, it is quite possible that the Brome Thrust fracture systems guided the sulphide-bearing solutions and were in part responsible for their present localization.

The displacements along the Brome and Oak Hill Thrust surfaces are quite unknown but it is probable that they are measureable in thousands rather than hundreds of feet. The stratigraphic break at the Oak Hill Thrust ranges from Lower Cambrian to Middle Ordovician. Upper Cambrian and Lower Ordovician sections in Southern Quebec represent several thousand feet of sediments and if ever deposited on the Oak Hill Series have been entirely eroded. The stratigraphic break along the Brome Thrust is not definitely known but as both the normal and the Mansville Phases of the Oak Hill Series, with respective thicknesses of 4,000 and 300+ feet, approximately, have been brought to lie side by side. The intervening gradation from one thickness to the other has been eliminated. Ten degree original dips are unusual, and would result in a horizontal displacement of approximately 25,000 feet or nearly five miles. On account of the ten degree dip considered, this is certainly a minimum figure.

Sutton Mountains Anticlinorium.

The second tectonic element in this area is the complex of schists in the Sutton Mountains. This unit extends southward through the Green Mountains of Vermont into

On p 89-90 you argue that the Mansville lies at the base of the exposed part of the Sutton group. How can this be if the major structure is anticlinal?

to about the latitude of Quebec City. It is exposed for

Massachusetts, and northwards through the Notre Dame Hills approximately 400 miles, and in Canada averages ten to fifteen miles in width.

So important is the structure of the Sutton Mountains, particularly with regard to the belief that Logan considered that structure synclinal, that a brief statement of the previous views seems in order.

Nowhere throughout any of Logan's writings has the writer come across any statement that would lead one to suspect that Logan was ignorant of the anticlinal structure of the Sutton Mountains. On page 241 of the Geology of Canada, 1863, he wrote "This would shew an anticlinal intermediate between the other two, the axis of which, in its course southward, would apparently run through the highest part of Sutton Mountain". And again on page 251 he wrote "Sutton Mountain, standing between these two anticlinals, ... might be expected to present a synclinal structure. In three transverse sections, however, the strata have been observed to maintain dips, generally at high angles, in opposite directions from the axis of the mountain, with much constancy, for upwards of twenty-five miles". He goes on to justify this anticlinal structure in terms of his erroneous conception of the order of deposition of the beds of the Quebec Group. Somewhat later Richardson (1866, pp. 33, 37, etc) described this structure as a "double synclinal", a term thoroughly in accord with Logan's concept of the structure, a section drawn in accord with which was published later by Selwyn. The latter, following the lead of T. S. Hunt, persisted in an attempt to demolish the results of Logan's researches on the Quebec Group in the Eastern Townships, and in 1883, published what appeared to him at least to be a particularly damning blow. None of the complexities in the section as drawn by Logan is meaningless, whereas the section as drawn by Selwyn, imbecilic in its simplicity, explains nothing more than the anticlinal form of the Sutton Mountains, and is grossly misleading elsewhere. Yet this was the alternative to a view to the destruction of which Selwyn appears to have dedicated himself. The present work has shown more clearly than ever the thoroughness of Logan's work. That he was mistaken in the order of superposition of his Quebec Group is not surprising when we consider that overthrusts were scarcely recognized in his day. (Logan described the one at Quebec as an "overturn anticlinal fold, with a crack and great dislocation running along its summit" (1863, p. 233). Logan's error in his concept of the stratigraphic succession of the Quebec Group was seized upon by Selwyn as a valid excuse for suppressing Logan's geological map of Southern Quebec. Had Selwyn allowed this map to be published, corrections could have been made continuously down to the present. As it was, in a few years time, a map of that region was published by the Survey as compiled by Ells (1896) which in the vicinity of Sutton Mountains could scarcely be more misleading as to structure or stratigraphy. And this was the kind of work that induced Walcott (1890, p.), who in this as in many another controversy was the apostle of steam-roller tactics, to write the following smug and arrogant statement. "It is the region in which Sir William E. Logan worked so long and arduously when building up the "Quebec Group"; also, at a later date, when endeavoring to obtain evidence to sustain his view, that the crystalline rocks were the altered equivalents of the strata referred to the Sillery division of the "Quebec Group". It is the battle ground, where Logan and his adherents have been gradually driven from position to position until, now, there is little left to defend of what seemed in 1863 a well supported position".

It is probably not too much to say that Selwyn's inability to recognize the great merit that was Logan's, and his eagerness to strain at a gnat succeeded only in retarding the understanding of the so-called "Quebec Group".

Within the Sutton and Memphremagog quadrangles these Sutton schists are displayed in two physiographic regions, the Sutton Mountains and the Missis#quoi (West Branch) Valley. Within the mountains the structure is anticlinal, but because the basement of chlorite schist upon which the schists were deposited as sediments is exposed just east of the Brome Thrust, that basement must have a synclinal form under the valley.

Exposures are so poor within the Missisquoi Valley that practically no observations on drag folds can be made in support of the synclinal nature of the structure postulated for that region. Outcrops are common all over the Sutton Mountains and especially along the two transmontane roads. There abundant evidence of the anticlinal nature of the structure can easily be seen both from the dips of the schists and the drag folds developed in them. Strangely enough the physiographic axis of the mountains and the structural axis do not coincide. At the southern end of the range there is nearly three miles difference.

The structural axis pursues a slightly undulating course about N.30°E. through the Sutton Mountains and is well defined south of Bolton Pass. At the south it lies 2 to 3 miles east of the crest of the range - at the north the two coincide. On the open hillside 1 mile northwest of Dunkin a number of outcrops show low dips of 10° to 15° east of north; another mile west the outcrops dip west so that the crest passes through the intervening drift-covered area. The best demonstration of the change of dip is seen in the gorge one mile northwest of the end of the road, 4½ miles north of Dunkin. As one proceeds westward up the gorge the dip is low to the east, then becomes almost horizontal with minor variations east and west, and finally dips permanently west. The change in dip may also be observed in Bolton Pass less than 1 mile east of Sally Pond. North of Bolton Pass to the limits of the present area the structure is greatly confused (p.); still further north, however, the ordinary conditions are resumed and on the Montreal-Sherbrooke highway there is clear evidence of the location of the crest line. On a low road-cut just west of East Ray station on the C. P. R. the change in dip is shown along an exposure a few hundred feet in length which lines up with the position of the axis as determined in the Sutton Mountains.

Along the international Boundary the axis lies 5 miles from the eastern limit of the series and 9 miles from the western limit (see map). The significance of this feature with regard to the thickness of the section has already been discussed (p.).

The Sutton anticlinorium pitches northeast at an average angle of about 10° with the horizontal. There are great variations, however, and in some exposures the crests of the folds in the schists are literally standing on end.

Drag folds are a characteristic feature of the Sutton Series, ranging in size from microscopic to giants more than 1 mile across. They are best developed on the west limb of the anticlinorium but on both sides their development is quite orthodox, the upper (that is, outer, with regard to the axis) beds having moved upwards. Otherwise the Sutton structure would be a simple anticline. There is no regularity in relative movements along the strike and no stratigraphic details are obtainable. In the structure section the Sutton Series is represented diagrammatically with drag folds all controlled by the anticlinorium but it must not be supposed that the structure is as simple as this would indicate.

On the west flank, south and east of Brome Lake, the structure is complex. The normal strike of N.30°E. turns east to 80° in many places forming in plan giant drag folds referred to in the previous paragraph. North of Bolton Glen this aberrant strike continues across the projection of the anticlinorial axis and is seen particularly well on Bolton Mountain, an east-west ridge. Many localities, as in the vicinity of Sally Pond, show and extremely confused and irregular structure in which it is impossible to take strike or dip.

The south end of the mountains and the east flank in general are more uniform in structure. The schistosity strikes in the normal direction about N.30°E. The average dip of the east side is about 60° and that of the west side about 45°.

Schistosity is developed only along stratification planes in the Sutton Mountains. In this respect it contrasts with the axial plane cleavage of the Oak Hill anticlinorium. The evidence of sedimentary character of the Sutton Series has already been given and in support of the stratification cleavage it is only necessary to state that the schistosity follows the dip of the anticlinorium on both east and west sides and is flat-lying along the axis. Thus all dips and strikes refer to both stratification and cleavage.

The limbs of the drag folds, both large and small, are closely compressed as a rule and their axial planes on opposite sides of the anticlinorial axis are not parallel. Instead they converge upward and correspond to Van Hise's definition of an abnormal anticlinorium. In this respect as well as in the type of cleavage developed the Sutton anticlinorium contrasts with the Oak Hill.

The position of the Mansville Phase of the Oak Hill Series within the Sutton anticlinorium is at the base of the sedimentary series along its western flank. Its great reduction in thickness makes it unlikely that it would be found many miles further east. In fact it is restricted to the neighborhood of the Brome Thrust and the Sutton Valley. It escaped the extreme crumpling common in much of the Sutton Series and is thus of value for correlation with the normal phase of the Oak Hill Series.

Normal Faulting.

The Oak Hill anticlinorium shows numerous small displacements which are best described as tear, hinge, or cross faults. The largest one is shown on the map immediately east of West Brome village. Others are scattered irregularly through the anticlinorium and apparently have no regional significance.

The Sutton anticlinorium shows a pattern along its topographic axis which is probably due to normal faulting. Plate shows a panorama of the Sutton Mountains which illustrates this feature. In the southern part a series of notches shows on the skyline with the steeper sides facing north. The contouring in the mountains is too inaccurate to show this feature on the map and due to the dense forest growth no geologic evidence was obtained regarding possible dislocations. The line drawing in Plate shows diagrammatically a set of block faults which may represent the conditions in the Sutton Mountains. Their east-west extent is unknown and the displacement is likewise conjectural. The time of this faulting is almost certainly post-Acadian but beyond that there is no definite evidence. It is probable, however, that the dislocations shown in the present topography are of recent origin, perhaps Tertiary. The faults may have originally formed at an earlier time, but if Cretaceous peneplanation was as effective in Southern Quebec as it is supposed to be elsewhere it is doubtful if the present topography would show any trace of pre-Cretaceous faulting.

METAMORPHIC GEOLOGY.

Introduction

The metamorphism of the rocks in Southern Quebec has two natural divisions - (A) that which is clearly connected with igneous activity, and (B) that which has no connection with igneous activity. The first includes the metamorphism effected by the metabasalt, the metaperidotite, their parent magmas and their derivatives; the second includes the regional metamorphism of the sedimentary series and of the Tibbet Hill schist.

Three metamorphic processes, thermal, dynamic, and hydrous, are responsible for the changes brought about in these rocks. Thermal metamorphism of group A is fairly uniform, but hydrous and dynamic processes, although important, vary considerably. Dynamic metamorphism is less important than hydrous and thermal processes in group B. Thermal and hydrous conditions vary considerably as will be seen.

Metamorphism connected with Igneous Activity.

The metamorphism connected with igneous activity is both endomorphic and exomorphic in its effect. Endomorphism deals with those changes which occur within the limits of the igneous body; exomorphism is concerned with changes occurring in the adjacent country rock whose source can be traced directly to the igneous body. Both types are well developed in Southern Quebec. The grade of metamorphism varies in the endomorphic processes but is uniformly low for the exomorphism.

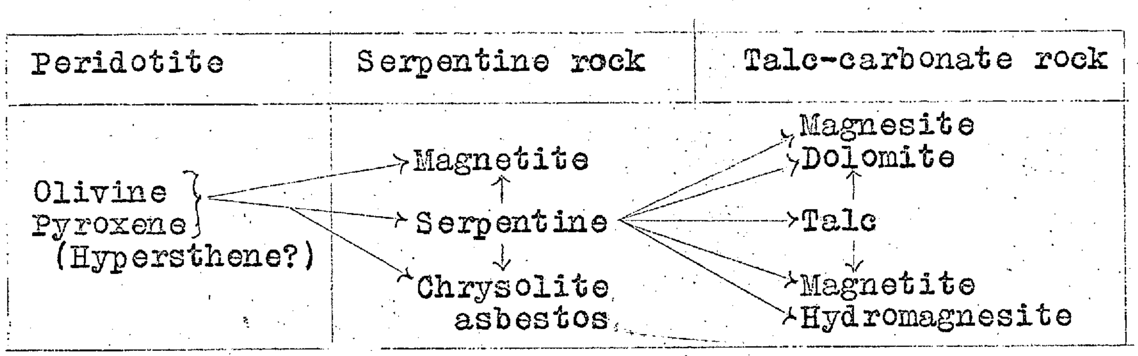
Because of the abundance of talc deposits within the area of the Sutton Mountains a more extended account of the concerned metamorphism will be given here, rather than deferring it to the following report. The talc is the result of the metamorphism of bodies of peridotite (Bolton Igneous Series), which, with their related rock types (metagabbro, metabasalt) are far better displayed in that part of the Memphremagog area beyond the limits of this report.

Bolton Metaperidotite and Derived Rocks. There are four subdivisions to be considered in this group - (1) the metaperidotite itself in which there still remain abundant remnants and pseudomorphs of pyroxene, olivine, etc., (2) serpentine, which forms a rock dominantly of that mineral with, in places, reticulating veinlets of chrysotile asbestos or talc, (3) an impure talc rock, or soapstone, with accessory serpentine and carbonate, and (4) a fairly pure magnesite rock. These types are gradational but distinct enough for classification. Within the Sutton Mountains only (2) and (3) are found.

The metamorphism of these rocks is considered under two heads (1) endomorphic changes, confined to the body of metaperidotite, serpentine, etc. and (2) exomorphic changes, dealing with the effect on the wall and country rock.

Endomorphism. This type of metamorphism is a characteristic feature of the serpentine rocks of Southern Quebec and all the field evidence shows that the secondary magnesium minerals, serpentine, talc, magnesite, and dolomite are confined within the limits of the original peridotite intrusions. Replacement may be complete, as in a few talc bodies, but the lens-like shape and relatively sharp mineralogic change at the contact with the country rock still favors the endomorphic hypothesis.

The mineral sequence determined from field and microscopic data is as follows



The field evidence of the age relations of peridotite, serpentine, and talc is plain. Serpentine veinlets cut the metaperidotite and talc veinlets intersect both. The relations of the carbonates are less clear but they are most probably late in the sequence as indicated. Hydromagnesite veinlets cut the serpentine rocks. Pockets of dolomite and magnesite in talc and serpentine suggest a late age. Microscopic evidence of serpentinization of peridotite minerals is abundant (p. and Plate) and the later change to talc may be seen in certain sections. The succession of olivine, serpentine, and carbonate, may be seen in one section (p.).

The mineral changes caused by endomorphism are relatively simple and include high-MgO types throughout. The chemical changes are more complex and the processes involved afford an interesting field of study.

Serpentinization of peridotite can only occur in the presence of considerable H_2O. (Serpentine has 44 per cent SiO_2, 43 per cent MgO, and 13 per cent H_2O). In the days when weathering processes for serpentine were fashionable the necessary quantity of water was not a problem. Later views of hydrothermal origin also allowed an almost unlimited supply. The most modern view, however, advocates that serpentine may actually be a primary mineral which means that the magma contained a high percentage of H_2O. Gisolf ( ) has interpreted serpentine from New Guinea as of primary origin, preceding the crystallization of olivine. He assumes that the magma was high in H_2O and that as the temperature of crystallization of the system was reached the pressure was still high enough to prevent dissociation of the H_2O as a separate phase. Serpentine might thus crystallize first, and, with relief of pressure, olivine would then form. The reverse process might also hold. If the pressure is low enough at the temperature of crystallization of the system H_2O separates and olivine crystallizes first. If the H_2O is held in the magma reservoir there is an increasing "back pressure" in which olivine eventually becomes unstable and is serpentinized. This is essentially an autometamorphic process.

Wells, F. G. (1929, p. 35) found experimentally that olivine will not change to serpentine at a temperature of 520° C. and a pressure of 267 atmospheres. He considers serpentine to be a late magmatic process.

The equilibrium relations of this system (H_2O-MgO-FeO-SiO_2) are unknown and there is no laboratory support for Gisolf's idea. The process also involves more primary H_2O than most physical chemists care to allow in an ultrafemic magma. On the other hand there are many unexplained field data in connection with serpentine rocks. Pyroxenite and dunite dikes commonly cut through serpentinized rocks to the despair of all laboratory investigators. Primary serpentine would dispose of many such field difficulties and until such time as laboratory evidence is available it is an advantage to consider the possibilities of the hypothesis.

In Southern Quebec the evidence in general indicates that serpentine replaces the pyroxene and olivine of the peridotite and is not primary. On Gisolf's hypothesis it is an autometamorphic effect caused by the "back pressure" of H_2O on the crystallizing peridotite. On the usual hydrothermal theory in which H_2O is derived from outside sources serpentinization occurs with falling temperature, and pressure is not a dominant factor. It is a fact, however, that rising pressure and falling temperature produce the same metamorphism in many instances. This may be true of serpentinization and, if so, provides two possible methods of origin.

Chrysotile asbestos occurs in reticulating veinlets throughout parts of the serpentine. It is never found in fractures in the adjacent country rock and is supposed to form in place from the serpentine by a slight change in equilibrium conditions. The contact of the fibers with the serpentine wall, however, is invariably sharp and the width of the veins is remarkably constant. One would expect replacement to show boundaries of gradational character and variations in the width of the veins in many places. Keith and Bain ( ), in a recent study of chrysotile asbestos in Vermont, conclude that it is introduced along fractures in the serpentine and is not a replacement in situ. From experience in Southern Quebec the writer would concur with this view.

The endomorphic sequence - peridotite to serpentine to talc-carbonate - indicates that serpentinization occurs at a relatively high temperature. The evidence of autometamorphism is not conclusive but the writer prefers this hypothesis to any other.

The talc-carbonate stage of endomorphism is distinctly later and is not necessarily autometamorphic. The change to talc is so closely related to alteration in the wall rock that it is best considered under exomorphism. The change to magnesite is known only in a general way. There is only one large body in Southern Quebec but its field relations are imperfectly known. The chemical changes involve addition of CO_2 and subtraction of SiO_2 and H_2O. There is considerable quartz throughout the magnesite rock and this probably represents the excess SiO_2.

Exomorphism. Exomorphic effects of the metaperidotite and derived rocks are confined chiefly to the talc-carbonate stage in the paragenesis. The common field occurrence of the talc bodies in Southern Quebec is as marginal zones between serpentine and country rock. There are also localities in which only talc, with accessory dolomite, occurs. These represent in all probability original peridotite dikes which were serpentinized and then completely talcized.

Exomorphic effects connected with purely serpentine bodies are not important in Southern Quebec. Actual contacts with the country rock are not commonly exposed but a general field study shows that this stage of metamorphism had no marked effect on the associated rocks.

The talc-carbonate stage produced distinctive and widespread alteration in the country rock contemporaneously with its own formation from serpentine. The endomorphic alteration of talc to serpentine involves considerable transfer and interchange of material. MgO falls from 43 per cent to 32 per cent, H_2O from 13 per cent to 5 per cent, and SiO_2 rises from 44 per cent to 63 per cent. The change from talc to dolomite involves addition of CO_2 and loss of SiO_2 as the main alterations. This phase of paragenesis, however, is of minor importance.

The talc bodies occur mostly in the mica schist of the Sutton Series. The wall rock at all such contacts is highly chloritized and albitized. The schistosity of the rock is less perfect than usual and it is studded with rounded albite metacrysts up to $\frac{1}{4}$ inch in diameter. The qualitative change in chemical composition from normal mica schist to the chloritized variety is addition of MgO, H_2O, Na_2O, and decrease in SiO . Talcization of serpentine involves addition of SiO_2 and loss of MgO and H_2O. Disregarding Na_2O for the moment, the constituents added to the wall rock are seen to be the same as those lost to the talc body, and vice versa. Qualitative field evidence indicates, therefore, that under the right PTC the development of talc in the serpentinized peridotite dikes involved an active interchange of constituents with the wall rock. This interchange results in two distinct zones of replacement approximately bounded by the dike contact. The talc is apparently confined to the limits of the pre-existing serpentine rock and chlorite and albite are developed only in the wall rock. There must have been bodily transfer of solutions over considerable distance to effect this complete separation.

Na_2O, which now forms albite metacrysts, is the only necessary addition during the metamorphism. The metacrysts are confined to the schist and replace the earlier minerals.

Regional Aspects of Exomorphism. The discussion thus far relates only to chloritization and albitization of the schist in the immediate vicinity of talc bodies. This type of metamorphism, however, is not limited to talc localities but is widespread to a less intense degree throughout the Sutton Mountains. There is one prominent hill between Bolton Glen and Bolton Pass on which only greenish chloritized and albitized rocks are exposed. Another such area occurs at Sutton Mountain, east of Abercorn, where the chlorite and albite are so abundant that one or two writers have classified this rock as a chlorite schist, i.e. a metamorphosed effusive.

There is little trace of the regional schistosity in these areas and the rock consists of a felted aggregate mainly of mica, chlorite, and quartz, with albite metacrysts. Numerous other localities of smaller size are known and there are many places in which the bands of chloritized schist are only a few inches in width.

Replacement follows the schistosity in these smaller occurrences and the best evidence of the character of the changes is found in such small bands. The schistosity is much less perfect than in adjacent mica schists and the texture is in places massive and coarse. There is complete textural gradation into normal mica schist. The typical mineral association of abundant chlorite and mica flakes, quartz, and albite metacrysts, also shows complete gradation into normal mica schist. These chloritized zones are characterized in places by magnetite octahedrons as much as three-eighths of an inch across. Epidote, clinozoisite, and calcite, are also common. Ilmenite, titanite, rutile, apatite, tourmaline, and green biotite are accessories.

Albitization is even more widespread as a regional feature than chloritization. Metacrysts are scattered throughout much of the mica schist in which no definite trace of chloritization can be identified. They are characteristic of the rocks of the Sutton Mountains, disappearing gradually in Sutton Valley, and abruptly absent in the Mansonville Series to the east of this report area. An analysis of a composite sample of this material yields 1.62 per cent of NaO_2, which, recast as $NaAlSi_3O_8$ gives 14 per cent of albite in the rock. These mica schists are probably metamorphosed sandstones (p.   ) and though it might appear improbable that they should have contained as much Na_2O as indicated, nevertheless analyses of the non-albite bearing schists show a content of Na_2O as high as the albite bearing rock. The soda therefore has not been introduced, but there is abundant evidence that the crystallization of albite occurred after the schists were formed, as follows: (1) the metacrysts of albite are large and cross-cutting, (2) they contain inclusions of epidote, quartz, carbon, mica, etc. in which the schistosity is preserved as a relict structure, (3) microtectonic study (p.   ) shows that there were no appreciable stresses acting on the rock at the time of formation of the albite, and (4) there is distinct bulging of the schist around many metacrysts.

From the above study of field and petrographic relations of albitization and chloritization it is illogical to dissociate its regional occurrence from its local, more intense, phases in immediate contact with talc bodies. The mineral associations are identical and replacement of the mica schist can be demonstrated in almost every locality. Albitization is most intense near the talc and rocks composed of more than 50 per cent albite may be formed. It occurs in lesser amount throughout the chloritized bands and masses in the Sutton Mountains and in the unchloritized mica schist averages less than 15 per cent. Although it might be assumed that this zoning is due to impregnation of the overlying schists with Na_2O from concealed masses of talcized serpentine and metaperidotite beneath the Sutton Mountains it has already been indicated that the schists themselves are a perfectly competent source of the Na_2O necessary to produce the albite. It is not meant to deny the possibility of greater albitization in the vicinity of such subjacent intrusions on account of the heat and vapors concerned. And it is not out of harmony with the foregoing thesis that since Na_2O is a common emanation from ultrafemic magmas and has great penetrating power, some of the rich albite schists in the vicinity of talc deposits owe part of their albite to such igneous source (for the formation of the mica schists, etc., see p.). The history of the exomorphic effects accompanying the change from serpentine to talc may therefore be as follows - after the Sutton anticlinorium was formed ultrafemic rocks were intruded beneath the arched sediments. In many isolated places and particularly in two zones on the east side of the anticlinorium small dikes broke through to higher elevations. The intrusion probably occurred at considerable depth and the overlying rocks were thoroughly heated as the process progressed. Serpentinization was the first endomorphic change and had little exomorphic effect. The secondary endomorphic change to talc and carbonate occurred after the anticlinorium was formed and stresses had ceased to be active. The newly formed schists were still hot, particularly those nearest the bottom of the anticlinorium, and solutions became very active in transferring material back and forth, resulting, in part, in the formation of the albite metacrysts. At this stage talc formed in contact with the wall rock and chloritization of the schist was contemporaneous. MgO was transported considerable distances to form the green bands now found in the schist and similarly SiO_2 travelled equal distances back to the contact in order to complete the replacement. At a later stage of the chloritization Na_2O may have been introduced to form the abundant albite metacrysts seen in the immediate vicinity of some talc deposits by replacing minerals already formed and present in the schists and chloritized rocks. Since that period erosion has removed thousands of feet of material which then covered this scene of igneous and hydrothermal activity and we can now piece together its metamorphic history.

Since the above conclusions were arrived at a paper by Singewald on albitization of schists in Maryland has been published. Singewald's conclusions, so succinctly put in the following quotation, are so nearly identical to mine that I quote a paragraph, "The albite porphyroblasts of the Wissahickon schist were formed by replacement of the micaceous minerals and to a less extent of the quartz and after the completion of dynamic metamorphism. The textures imparted to the rock by dynamic metamorphism are retained in the albite crystals through the preservation of the accessory minerals. The constituents of the albite are believed to have been present in the sediments from which the schist were derived, and were merely taken into solution and redeposited by the agencies that caused the albitization. (1932, pp. 468-9).

Volume Relations. There is no field evidence of volume change resulting from endomorphism of peridotite and if changes have occurred they are probably small. There is evidence, however, of volume change due to exomorphic action. Albite metacrysts, in addition to replacing the earlier schist minerals, tend to force apart the parallel-arranged mica and chlorite so that the albitized schists have a distinctly lumpy appearance lacking in albite-free types. This effect is entirely different from any crumpling or minute folding of the schist which may have occurred before albitization.

Chloritization, the other major effect of exomorphism, gives no evidence of volume change either in the field or under the microscope.

Metamorphism not Connected with Igneous Activity.

The minerals in the rocks of this group are of uniformly low grade but vary in amount. They originate from both sedimentary and igneous rocks and indicate a convergence to type as described by Leith and Mead ( ). Dynamic and hydrous metamorphism varied considerably but the thermal conditions were rather uniform.

Tibbet Hill Schist. The Tibbet Hill schist is known to be a metamorphosed lava (p.) from the abundance of amygdules and more rarely, flow structures which it contains. Its original chemical and mineral character, however, can only be surmised. The essential minerals now occurring in it are albite, epidote, and chlorite, with calcite, quartz, magnetite-ilmenite, rutile, titanite, sericite mica, apatite, and zeolites as prominent accessories. There are no analyses of this material and therefore no chemical comparisons may be made as in the case of the Bolton metabasalt. The mineralogy of the two rocks is similar except for the absence of actinolite in the Tibbet Hill schist and it is possible that the formation represents an original basalt in which thermal and dynamic metamorphism has proceeded further than in the case of the Bolton metabasalt. Tilley (1923, p. 183) found that chlorite-epidote albite schist had much the same chemical composition as basalt (Start area, England).

This has already been covered in the petrographic descriptions. This adds little

There is little evidence of the mineral sequence. Epidote, albite, and chlorite appear to be contemporaneous; calcite and mica which in most places cut across the schistosity appear to be a later generation. The characteristic titanium minerals, especially rutile and titanite, require more detailed study for determination of their paragenesis (p.). The same general changes in the primary minerals apply to the formation as outlined for the Bolton metabasalt - albitization of calcic plagioclase with development of epidote, chloritization and carbonatization of earlier-formed femic minerals. These changes are accompanied by marked dynamic metamorphism which resulted in the present schistosity of the formation.

Volume relations are unknown but from analogy with the Bolton metabasalt it is probable that a slight increase has occurred.

<u>Sutton Series.</u> The evidence of the sedimentary character of the Sutton Series is definite (p.), and it only remains to examine the present mineral association in order to ascertain the original nature of the sediments.

The Sutton Series is described under four heads (p.) as mica schist, phyllite, marble, and quartzite. Of these, the first two make up most of the series and marble and quartzite form thin beds in certain localities.

I would omit this & incorporate any necessary points in 'The petrographic description' of the Sutton

The principal minerals common to the mica schist and phyllite are quartz, mica, chlorite, albite, and epidote. The phyllites are distinguished mainly by their content of carbonaceous material and finer texture. The gradation to normal mica schist, however, is complete.

It has been shown in the preceding pages that late hydrothermal action has changed the character of the Sutton rocks to a marked degree. The green chloritic bands in the schist, high in albite, chlorite, and epidote are evidence of this replacement, and the much more widespread development of albite metacrysts throughout the schist is a characteristic feature. In outlining the metamorphic history of the Sutton Series from the sedimentary point of view these later features are disregarded and only the essential schist minerals, quartz, mica, and chlorite, are considered.

Mica Schist and Phyllite. The alkalies in a composite sample of albitized mica schist give 1.62 per cent Na_2O and 3.36 per cent K_2O. Recasting the Na_2O as $NaAlSi_3O_8$ for albite and the potash as $HKAlSiO_4$ for mica gives 14 per cent albite and 28 per cent mica. Column 1 of the accompanying table shows the estimated percentages of the remaining minerals.

Mineral	1. Albitized schist	2. Albite-free
Albite	14	--
Quartz	45	52
Mica	28	32
Chlorite	8	10
Others	5	6

A re-calculation for mica schist without albite is given in column 2. The proportions of quartz, mica, chlorite, are shown in whole numbers only.

Petrographic, field, and microtectonic studies (pp.) all indicate that these minerals are recrystallized products resulting from the complex metamorphism of the Sutton Series. The texture is relatively coarse and of dominantly schistose character. The schistosity is determined largely by the segregation, intergrowth, and parallel dimensional arrangement of chlorite and mica flakes.

There is no field evidence of addition or subtraction of material in the formation of the mica schist (later chloritization and albitization disregarded) and it is general experience that no essential change is necessary. H_2O was present as in most processes of metamorphism but may have been more a medium of circulation than of actual combination in the secondary minerals. On this basis the mica schist is probably derived from an argillaceous sand whose principal minerals were quartz and kaolinite. Mica and chlorite were probably accessory minerals. Cementation to sandstone and metamorphism to mica schist followed in order. During metamorphism the quartz recrystallized in larger grains and tended to segregate the remaining material. Kaolinite recrystallized to mica and chlorite may have developed by recrystallization of original chlorite or by development from other accessory femic minerals.

Similarly, the phyllite probably originates from a carbonaceous, sandy mud which graded into coarse argillaceous sand. This textural variation is still preserved in their metamorphic equivalents on a magnified scale. The quantity of carbon has probably remained constant as the thermal metamorphism indicated by the existing minerals has not been sufficiently intense to expel any of it. If gradations to unmetamorphosed phyllite were known the carbon content would then be a valuable index of losses and gains during metamorphism.

Quartzite and Marble Horizons. The thin horizons of quartzite and marble interbedded with the phyllite and mica schist indicate abrupt changes in sedimentation. The quarztite contains mica and is really a low-mica schist originating from thin horizons of quartz sand which were better sorted than the average argillaceous material. The marble bands contain accessory quartz, mica, and feldspar. The carbonate may be dolomite or calcite and the beds represent local calcareous deposits within the clastic sediments.

Variation in Texture. Even a casual field or laboratory study of the rocks grouped in the Sutton Series indicates great textural differences from place to place. The main change observed is in Sutton Valley where the schist is as a rule much finer-grained than in the mountains. Albitization decreases to zero in the valley but this change accompanies, and is not the cause of, the change in texture. The mica, chlorite, and quartz, are each of smaller dimensions although of corresponding proportions and degree of recrystallization.

The cause of the variation is evidently dependent on the length of time during which the necessary dynamic, thermal, and hydrous processes of metamorphism were maintained. The thermal element is the controlling feature in the Sutton Series and the coarser grain developed in the Sutton Mountains area is due to the deep burial of its rocks and maintenance of the required temperature conditions for a longer period of time than obtained in the Sutton Valley area. This conception is in harmony with the exomorphic history outlined in connection with chloritization and albitization (p.). The localization of peridotite beneath the rising anticlinorium in the Sutton Mountains would serve to maintain uniform thermal conditions for longer periods of time than in adjacent areas. In addition, more solutions may have been circulated and the abnormal character of the anticlinorium is itself evidence of the intensity of dynamic metamorphism. The coincidence of the albitization with the area of coarse-grained mica schist has genetic significance whether or not this explanation is the correct one.

Volume Relations. There is no evidence of change of volume during development of the Sutton rocks. There must of course have been decrease in porosity in the early unconsolidated stages but this lies outside the domain of metamorphism. The old conception of molecular volumes is now believed from studies of crystal structure to be invalid and it is no longer good doctrine to state that a mica schist is of smaller volume than the argillaceous sandstone from which it is derived simply because its minerals are of the "minus" type. There must be direct field evidence of volume changes similar to those obtained for albitization.

Oak Hill Series. The structural position and similarity of the Oak Hill and the lower parts of the Sutton Series make possible the conclusion that they are contemporaneous in age (p.). It now remains to discuss the metamorphic aspect of the Oak Hill Series and to indicate its relation to similar features in the Sutton Series.

<u>Contrast with the Sutton Series.</u> The Gilman schistose quartzite comprises most of the Oak Hill Series. It is a fine-grained rock whose essential minerals quartz, mica, and chlorite, occur in approximately the same proportions as in the schists of the Sutton Series. The degree of recrystallization and schistosity, however, is in strong contrast. The mica and chlorite of the Sutton schists is segregated into definite bands with the flakes in parallel dimensional arrangement. In the Oak Hill Series this segregation and dimensional arrangement is less perfect, the flakes are usually minute, and in many thin sections there are clouded spots which are certainly not recrystallized and probably represent argillaceous material which has not yet been sericitized or chloritized. Most of the quartz grains are strained and have been rotated into parallel position with the regional schistosity. Many of them also have faintly rounded outlines. These factors all indicate incomplete recrystallization. The quartz in the Sutton Series schists is highly angular in shape and there is little evidence of strain in the grains.

The two marble formations in the Oak Hill Series are massive, usually fine-textured rocks. The degree of recrystallization and segregation of non-carbonate substances is not as far advanced as in the marbles of the Sutton Series for in many thin sections there is clouded material which is not yet recrystallized. No schistose carbonate rocks are known in the Oak Hill Series. The Sutton marbles are schistose in many places and in general have a coarser grain.

The slates of the Oak Hill Series and the phyllites of the Sutton Series contrast in much the same way as already described for the schists and marbles. Relatively coarse texture, complete recrystallization, and folded cleavage are the main features of the phyllites. None of these characteristics is nearly as well developed, if at all, in the slates of the Oak Hill Series.

Metamorphic Background of the Oak Hill Series. The formation of slates, quartzites, and marbles, such as occur in the Oak Hill Series, is ordinarily explained as due to regional metamorphism. This is admittedly a useful pigeon-hole for thimgs difficult of explanation but at the same time creates a defeatist attitude toward metamorphic problems.

The metamorphism of the Sutton Series is thought to be connected with concealed peridotite and its derivatives and textural differences in metamorphism of the Sutton Mountains and Sutton Valley areas are likewise believed due to distance from this igneous source. In the Oak Hill Series no similar assumption can be made from any field evidence available. The mineral association, however, is quite similar to the Sutton Series and indicates similar thermal and hydrous processes of metamorphism. Dynamically, the metamorphism is less intense. During the main period of metamorphism the two series were further apart than now (the Brome thrust lies between them at present) though it is too hazardous to postulate that the incomplete metamorphism of the Oak Hill Series is merely due to its greater distance from the source of thermal energy beneath the Sutton anticlinorium. It is better to leave the ultimate source unexplained, but it is important to recognize the identity of the metamorphic processes operating here with those in the Sutton Series which are believed to have direct igneous affiliations. With this as a basis a comparison of the metamorphism of the two series is as follows - (1) Thermal conditions approximately the same. (2) Dynamic conditions greater in the Sutton Series. (3) Hydrous circulation probably more active in the Sutton Series. (4) Time of maintenance of these metamorphic processes greater in the Sutton Series. This last feature is the most important and helps to explain the incomplete recrystallization, fine texture, and imperfect schistosity of the Oak Hill rocks as contrasted with the Sutton rocks.

General Discussion of Metamorphism.

The change in mineral composition and texture brought about by metamorphism is dependent on six variables - the temperature T, the pressure P, (including both rock and fluid pressures) the circulating solutions S, the original mineral composition C, the original texture T_x, and the time T_m. If quantitative data concerning each of these variables could be obtained for a system in equilibrium there would be no unsolved problems in rock metamorphism. It is a progressive step, however, to recognize their importance and to realize the limitations of any scheme such as Eskola has proposed in his facies classification. Tilley's metamorphic facies "designates a group of rocks characterized by a definite set of minerals, which under the conditions obtaining during their formation were in perfect equilibrium with each other. The quantitative and qualitative mineral composition in the rocks of a given facies varies gradually in correspondence with variation in the chemical composition of the rock". (Tilley, 1924, p. 167). Group B in this chapter would fall in his "Greenschist facies". The metamorphism connected with the metaperidotite has no place in his classification.

Eskola's system is based on only three of the six variables listed on the preceding page, P, T, and C. In an indirect way it considers S and T_m but it ignores T_x altogether. Sederholm has recently pointed out this deficiency and it appears to be a very real one. Thus the qualitative and quantitative mineral composition of mica schist and phyllite in the Sutton Series are practically identical but they can hardly be said to belong to the same "facies". The degree of granulation in the original rock has an important bearing on the ease with which solutions can circulate and on the manner of transmission of stresses. Therefore texture should always be one of the factors considered.

The accompanying table lists the important characteristics of T, P, S, C, T_x, and T_m. The dependence of T and P is not of great importance in an open system such as that which includes the dynamic metamorphism of the Sutton or Oak Hill Series. Fluid pressure, however, is of importance in relatively closed systems such as those described for the Bolton metaperidotite. S is a "variable among variables", i.e. its absence will not change any of the other factors but if it is present its effectiveness is dependent on each of the other five factors. C, T_x, and T_m are necessary independent variables.

Relation to the metamorphism	Variables	Relation to each other	Associated metamorphic process
Active	T	Dependent	Thermal
	P		Dynamic (rock pressure only)
	S	Dependent or Independent	Hydrous
Passive	C	Independent	
	T_x		
	T_m		

T, P, and S may be further described as "active" variables, i.e. the amount of S may be varied or T and P may be changed while metamorphism is in progress. C, T_x, and T_m can not be accelerated. The active variables, T, P, and S, are included in the three processes of thermal, dynamic, and hydrous metamorphism which have constantly been referred to throughout this chapter.

This conception of a metamorphic facies is broader in its scope than that proposed by Eskola. It may be defined as follows:- "The application of a given temperature T and pressure P, acting in conjunction with dominantly aqueous solutions S, on a rock of given mineral composition C and texture T_x for a given time T_m will produce a metamorphic facies of fixed mineral composition and texture". Expressed mathematically: $M= f(T, P, S, C, T_x, T_m)$.

As equilibrium is rarely attained in rocks and as no quantitative values can be attached to any of the above factors the strict conception of a metamorphic facies is elevated to the realm of philosophy and is only of theoretical interest to geology. The idea is of value, however, in a qualitative way and relative evaluation of the various metamorphic factors is usually possible. This has been done in the preceding discussion of the metamorphism of the rocks in Brome County. Evidence of disequilibrium is abundant, e.g. inclusions of epidote, mica, quartz, etc. in albite metacrysts, but the relative importance of T, P, S, C, T_x, and T_m can be compared from one formation to the next. Thus a purely ideal conception can be made an exceedingly useful tool in the study of metamorphism.

In conclusion let it be emphasized that metamorphism is to be considered not as compounded of unrelated regional, contact, or hydrothermal types, but as a manifestation of common factors acting in different ways to produce different effects. Thus, the successive stages of alternation of an igneous rock after its primary crystallization merely represent different values for the same set of metamorphic factors which could produce a mica schist from an argillaceous sandstone. The difference is one of degree only and acceptance of this broader point of view will go far to raise metamorphism from a descriptive to an interpretative science.

GEOLOGICAL HISTORY.

This chapter outlines the history of sedimentation, structure, metamorphism and geomorphology, as far as each can be deciphered. Most of the material is collected from previous chapters and is placed here in chronologic order as a summary of the main events.

The subject has three natural divisions for purposes of description - (1) pre-Paleozoic history, (2) Paleozoic history, and (3) post-Paleozoic history. There is little evidence of the first period, the second includes most of the active history of the region, and the third is a more passive phase in which the present land surface was developed.

Pre-Paleozoic History.

The oldest rock exposed here is the Tibbet Hill chlorite schist, the reasons for ~~whose~~ Pre-Cambrian age are given on p. . This formation results from the metamorphism of a thick series of basic extrusions, but as to the basement upon which the lavas were poured out no remnant remains. We have a clue, however, in the composition of the thick Pinnacle graywacke, which is composed chiefly of quartz, orthoclase, and magnetite with many other minerals in smaller amounts. The magnetite may be safely assumed to have come from the chlorite schist, but the quartz and orthoclase can only have come from a granitic or gneissic terrane. Such a basement rock we may assume formed the floor upon which basalts, etc., were extruded in Pre-Cambrian time. Metamorphism of the basalts to magnetiferous chlorite schists was also accomplished in the Pre-Cambrian so that at the beginning of the Cambrian the area presented at least two main rock types, granite or gneiss, and superjacent chlorite schist. These were exposed on a land surface which in late Pre-Cambrian time had been reduced to a peneplain.

Paleozoic History.

Lower Cambrian Time. The known Paleozoic history commenced in Lower Cambrian time with the downwarping of the Pre-Cambrian peneplain which initiated the formation of the Appalachian geosyncline. We should, perhaps, be more precise, and call it the Taconic geosyncline, reserving the term Appalachian geosyncline for that one whose sediments were folded in the Appalachian revolution. The initial downwarping was probably of a very gentle nature, allowing the sea to penetrate the geosyncline and inundate the old Pre-Cambrian surface slowly. The evidence for this is the universal presence of a basal (Call Mill) slate, which is an exceedingly fine-grained detrital rock and represents the reworked regolith developed over the old chlorite schist surface. The slight irregularities in this old surface were sufficient to explain the present variations in thickness of the Call Mill slate, from a few inches to about 70 feet.

Meanwhile the New Brunswick geanticline (see Schuchert 193 , p.) was rising and its weathered products were being brought down by streams and deposited within the spreading geosyncline. So rapid was the rise that disintegrated products alone were at first brought down. ~~Those were the result of the breaking up of a granitic rock and hence were at first brought down.~~ These were the result of the breaking up of a granitic rock and hence were rich in quartz and unweathered orthoclase, and also in detrital magentite from the chlorite schists. The result was the accumualtion of the Pinnacle graywacke, which eventually became in this area 400 feet thick. It is quite possible, if not probable, that this formation, which is known to extend southwards into Vermont, and has been seen still further north in Quebec (Dresser, personal communication) is a delta deposit, somewhat modified by shore currents. Along with the sands, rivers would naturally have brought much mud or silt. This material, equivalent to the graywacke in age was doubtless carried further out to the west and deposited directly or nearly so upon the old Pre-Cambrian surface, now buried beneath the several thrust blocks. Following the deposition of the graywacke either erosion of the neighboring highland ceased or the geosyncline became rather suddenly considerably wider so that the locus of clastic sedimentation shifted considerably to the east. In either case, in the area considered clear waters resulted in which fine-grained unfossiliferous (probably) limy precipitates were formed, diagenetically or later, more or less completely dolomitized into the White Brook dolomite formation. Thus was completed the first cycle of deposition, ending with quiet accumulation of non-clastic materials. Meanwhile decomposition was preparing a regolith of finely weathered products on the uplands, which a succeeding slight uplift was to shift seawards where it was spread out as the West Sutton slate, followed, as deeper erosion separated the more resistant (chiefly quartz) remnants of the highlands and rivers bore them to the sea, by a sandstone later to be metamorphosed into the Gilman quartzite. By this time none of the old chlorite schist exposures remained hence no magnetite was available except from exposed portions of the Pinnacle graywacke. Practically, only granitic rocks were available, and under the influence of either longer or more efficient weathering nearly everything but the quartz was weathered to mud and silt. This latter material was doubtless carried still further westwards, and is not at present exposed. The formation of the Gilman quartzite must have occupied a very long time, for its thickness is probably three thousand feet. Once again, as in the case of the Pinnacle graywacke, a cessation of erosion induced the formation of a calcareous rock, called the Dunham dolomite, practically identical with the white Brook dolomite.

Thus the first six formations of the Oak Hill Series can be divided into two cycles of sedimentation as follows:

6. Dunham dolomite	3. White Brook dolomite
5. Gilman quartzite	2. Pinnacle graywacke
4. West Sutton slate	1. Call Mill slate

indicative of rhythmic movements of upland and geosyncline during the early phases of formation.

Of the above formations the uppermost two are fossiliferous, very sparingly so. The Gilman quartzite has yielded a few specimens of Kutorgina, a Lower Cambrian brachiopod (discovered at 4.30 p.m. on the last day of field work in 1930) and the Dunham dolomite has a large number of fragmentary trilobite remains, some of which belong to the characteristically Lower Cambrian family Mesonacidae. These will be described in a forthcoming museum publication on the Paleontology of Southern Quebec.

Succeeding the second cycle of sedimentation a third was initiated beginning with the Oak Hill slate, followed by the Scottsmore quartzite. But there the cycle was interrupted for before the quartzite was developed to any extent further crustal disturbances occurred which locally induced the formation of conglomerates (Scottsmore conglomerate), coarse in some places, in others indistinguishable in the field from the Scottsmore quartzite.

The remaining sediments of the Oak Hill Series are mudstones, called the Sweetsburg slate and the Vail slate. The former has the appearance of cyclical sedimentation that might possibly be seasonal, though its folding makes any attempt to plot successive layers impracticable.

Thus in the original locality of the Oak Hill slice sediments of Lower Cambrian age accumulated to a thickness of at least 3,000 feet and probably 4,000. The western shore of this sea is unknown, but was probably within the present geographical limits of the Sutton sheet. Eastwards the Lower Cambrian sea of Oak Hill time was probably limited quite sharply, and may not have extended far beyond the Sutton-Memphremagog boundary. The reason for this statement is that the Mansville Phase of the Oak Hill Series is but 200 feet thick, a diminution which indicates that the shore line could not have been far distant, a matter of a very few miles, one to five, say, preferably the shorter estimate.

Following or coincident with the formation of the upper beds of the Oak Hill Series came a great widening of the geosyncline. The locus of clastic deposition shifted eastwards and allowed calcareous rocks to accumulate further west. South of Quebec Keith (1932, p. 361) lists a great series of dolomites and limestones overlying what appears to be equivalents of the Oak Hill Series, thus indicating quiet or at least clear water in this part of the trough. At this time, it is believed, the sediments now composing the Sutton schists were deposited. These were laid down in the newly formed eastern and deepening part of the geosyncline, allowing sandstones, shales and locally thin limestones to form. These were later to be metamorphosed into siliceous and carbonaceous schists and marble. How far eastwards the margin of the trough spread in Lower Cambrian time is problematical. Kerr has mapped some formations along the Bunker fault to the east of Lake Memphremagog as Lower Cambrian. If this is so then it gives us a measure of the extent of the Lower Cambrian sea. What thickness of Lower Cambrian beds was deposited in the Sutton Mountain mass is impossible to say. Four hundred feet is the greatest single series measured, although four thousand would seem to be more nearly correct. At what appears to be slightly later in Lower Cambrian time the Milton and Mallett dolomites of the Rosenberg block (in the Lacolle sheet) were made. The site of the deposition of these beds must have been quite close to the western shore of the trough, but because that shore was low, and therefore shedding little sediment eastwards, calcareous sediments could form much closer to that western strand than to the eastern strand, which bordered the rising New Brunswick geanticline.

<u>Middle Cambrian.</u> Within this area we have no record at all of Middle Cambrian events. Beds with the Paradoxides fauna (the St. Albans shale) are known in Vermont a few miles south of the border, so it is reasonable to assume that they once occurred here too. But what the sequence of events was from the close of sedimentation in the Lower Cambrian, through the Middle Cambrian, and on to the beginning of sedimentation in the Upper Cambrian we have no way of telling. Nor is there any fact to indicate the upper stratigraphic limit of the Sutton schist. Conceivably they may all be Lower Cambrian. Possibly they include, if not Middle Cambrian, then Upper Cambrian and possibly Ordovician. too.

There are no higher strata than those of the Sweetsburg and Vail slates on the west or the Sutton schists on the east.

<u>Taconic Orogeny.</u> The folding which has affected both the Oak Hill slice and the Sutton schists is ascribed to the Taconic orogeny. At the close of the Ordovician the entire Lower Cambrian series (and higher beds, if present) was folded into tightly compressed folds. Coincident with the formation of the Philipsburg, Granby, and Rosenberg thrusts further west came the rupture called the Oak Hill thrust, by which the folded Lower Cambrian beds came to lie upon the Stanbridge (Middle Ordovician) slates. The folding

developed not only normal anticlines and synclines, but wider arches and troughs upon which the more apparent folds appear to be superposed - in other words, flat anticlinoria and synclinoria. The Oak Hill slice is the western half of an anticlinorium, the Sutton Mountains are developed from a second, and the Sutton Valley is underlain by a synclinorium. Shortly after the folding erosion began to reduce the Taconic Mountains. In the Memphremagog sheet there is plain evidence that complete peneplanation did not obtain, but while considerable relief was still in existence, intrusions and extrusions of a basic rock began, building up a lava plateau. Within this area we have direct evidence of this only in the scattered metaperidotite masses throughout the Sutton Mountains, with their attendant talcization. Other intrusions, probably of large extent, but not exposed at the present surface, ~~were~~ may have been responsible for the soaking of the folded rocks of the Sutton Mountains with magmatic vapors converting the sedimentary rocks into schists. Penecontemporaneously but later than the development of the schistosity came the introduction of albite throughout the Sutton schist region. ~~and the development of metamorphic products of the serpentine rocks.~~

Acadian Orogeny. Few other events need attention. During the Devonian the Acadian orogeny, of which there is direct evidence in the Memphremagog area, affected this region little except in the formation of the Brome underthrust as a concession to the crustal foreshortening attendant upon that orogeny.

Monteregian Intrusions. The only other event of importance was the intrusion of the igneous rock of Brome Mountain. We have no data to tie down its age exactly. Locally, Brome Mountain truncates the trend lines of the Taconic folding and hence must be post Ordovician. An igneous breccia of consanguinious nature on St. Helen's Island, Montreal, contains xenoliths of Lower Devonian fossiliferous beds. Hence Brome Mountain should be post-Lower ~~Ordovician~~ Devonian. How much later we cannot say, except that sufficient pre-Pleistocene time must have elapsed to allow for the erosion of the original igneous mass, and its sedimentary cover, to approximately its present form.

Post-Paleozoic History.

In this period occurred mainly the development of the present topography by normal stream erosion, and the Pleistocene glacial phase. The early stages are unknown, but in Triassic time some of the basic dikes which do not appear to be related to the Monteregian Hills may have been intruded. By Cretaceous time a peneplain was probably developed similar to that postulated for most of eastern North America. In Tertiary time Southern Quebec was probably affected by the same epeirogenic movements ascribed from other regions to this period and the block faulting in the Sutton Mountains may have occurred at this time. By the close of the Tertiary a fairly mature topography was developed not unlike that existing today.

In the Pleistocene the whole area was buried beneath the continental ice sheet. It advanced across Southern Quebec in a general direction slightly west of north and cut across the longitudinal valleys rather than followed them. When the ice finally disappeared the land stood several hundred feet lower than it does now and a marine arm extended inland known as the Champlain Sea. The succeeding uplift proceeded rapidly and steadily, exposing wave-built beaches containing an Arctic fauna. The upper strandline in Brome County has been destroyed but elsewhere reaches a maximum of about 600 feet above sea-level.

Surface agencies since the Pleistocene have tended to ~~restore the mature topography of the Tertiary by~~ removing glacial debris from the uplands and marine gravel and sand from lower levels. The streams, however, are still of the glacial type and a long period must elapse before they completely accomodate themselves to their pre-glacial environment.

ECONOMIC GEOLOGY.

Exclusive of road materials, those products of the rocks which have secured attention in the past are copper, iron, and talc. On the basis of the present work the first two may be ruled out as economic possibilities, although ~~recently~~ Dresser (1928) has optimistically urged the possibility of copper again becoming an economic factor in this region. Talc and soapstone can scarcely compete with the product of the Madoc rock, but ~~is~~ are by no means out of the running. Practically no satisfactory building stone occurs, ~~here,~~ but many of the formations might be made to yield a good quality of cracked stone for roads, if the need ever arose. Today an abundance of gravel suffices. Locally calcareous rocks are abundant, but usually not sufficiently ~~so, or~~ pure ~~enough, to compete with lime~~ for fertilizer or cement, ~~from commercial uses.~~ manufactured elsewhere.

The various products are discussed in detail below.

Copper.

Much interest in the old copper workings still lingers on in the minds of the people of Brome County, particularly those whose memories carry them back to the days of the American Civil War when copper sold in New York for 55 cents a pound. With the decline in the price of copper, most of the properties which were temporarily productive shut down, although as Bancroft (1915) remarks, it was only the abnormally high price of copper that allowed them to operate at all. However, copper mines, prospects, and indications are widespread over the southern part of the Eastern Townships. Considerable agitation for the establishment of a smelter at some central point, such as Sherbrooke, had been made for some time until, in 1913 J. A. Bancroft was commissioned by the Quebec Bureau of Mines "to make a detailed geological examination of many of the occurrences of copper minerals in the Eastern Townships that figure prominently in the literature, and to ascertain, if possible, how many of them could be depended upon to contribute regularly to a copper smelter..."(1916, p. 14). Bancroft's report is an indispensible guide to a proper understanding of the copper deposits and prospects of the region. In his conclusions, stated at length on pp. 73 - 84, he discounts many factors that have currently been assigned as explanations of the closing down of these properties, such as the drop in the price of copper, the imposition of 3 and 4 cents a pound duty on copper entering the United States, the present cost of labor, and the early lack of transportation facilities. Except for four mines, the Acton mine at Actonvale, Eustis and Capelton mines at Capelton, and the Weedon mine at Weedon, he concludes that "It does not seem at all probable that the ores taken from any of the other properties described in this report have repaid the money that has been spent on them". In no case does Bancroft consider that the showings at any of the "mines" or prospects in the area of this report warrant a continuation of local operation. He does however incline favorably to a systematic program of prospecting. A description of some of the most important prospects, pits and "mines" follows.

Sweets' Mine (Range X, lot 8, Sutton). Bancroft's description of the workings and geological situation can not be improved upon. The following account is condensed from ~~Bancroft~~, together with a few original observations regarding the geological structure. The mine is situated close to (if not actually on) the Brome Thrust. To the east lies the Mansville Phase of the Oak Hill Series. To the west the Tibbet Hill chlorite schist and the normal phase of the lower beds of the Oak Hill Series. Rustiness characterizes some of the rocks in the neighborhood of the mine, due to pyrite with which is occasionally associated chalcopyrite, bornite and chalcocite. These mineralized zones are only a few feet in length, and pinch out, fork or swell when followed along the strike. The maximum width observed (by Bancroft) was five feet. The sulphides are always sparsely distributed, and superficially, at least, give no promise of an abundance of ore below. The main opening is 35 feet long, 8 feet wide and 150 feet deep approximately. It was sunk along the widest of the mineralized zones. Drifts were driven some 30 feet in either direction from the bottom. Half a dozen shallow openings have also been made on the property. Work was abandoned on this property in 1864 when it was found that the copper values declined below the surface, where practically nothing but barren pyrite remained. Bancroft was not surprised to learn that "what ore was shipped away did not pay the freight".

Washer's Mine (Range IV, lot 2, Brome). Rusty bands in the Tibbet Hill chlorite schist betray the presence of pyrite, with which there are disseminated grains of chalcopyrite and bornite. Three openings were made, two of which are said to have a depth of 100 feet and 50 feet respectively. Although a concentrating mill was in operation in connection with this property no information of its successful operation is forthcoming.

Shepherd Mine (Range V, lot 5, E½, Brome). Here, as in the preceding cases, chlorite schists and other rocks, chiefly of the Mansville Phase of the Oak Hill Series, exhibit rusty streaks which led to the exploration for sulphides in the rocks below. Pyrite is disseminated throughout the mineralized belt to a small degree, and with it one may find occasional grains of chalcopyrite or bornite. Three shafts were sunk in 1864 to depths of 67 feet, 75 feet, and 30 to 40 feet. Cross cuts were driven from the first two, and a concentrating mill was erected close at hand. Operations were suspended within a year or so. No ore, it is said, was shipped from this property. Nothing of importance is now to be seen in the cut or on the dumps.

Range X, lot 8, N$\frac{1}{4}$, Sutton. "No trace of copper was observed".

Range X, lot 10, NW$\frac{1}{4}$, Sutton. "No trace of copper was observed".

Range X, lot 11, NW$\frac{1}{4}$, Sutton. "None of the rock exposures examined on this lot would suggest the advisability of further work being done".

Range XI, lot 7, S.E. 1/4, Sutton. "This occurrence is not of economic value."

Range XI, lot 10, S$\frac{1}{2}$, Sutton. "No trace of copper was observed".

Range XI, lot 11, E$\frac{1}{2}$, Sutton. "None of the rock exposures examined upon this lot would suggest the advisability of further work being done".

Range XI, lot 12, W$\frac{1}{2}$, Sutton. "As a mining prospect, the property is of no value".

Range VI, lot 6, Brome. "The property is of no value as a mining prospect".

Range VIII, lot 12, W$\frac{1}{2}$, Brome. "The shaft is now filled up with rock".

Range VIII, lot 13, Brome. "It is very plain that the prospect is of no value".

Pinnacle Mountain mine (1 mile east of Abbott Corners, St. Armand East), was mentioned by Bancroft (p. 61) but not described.

There is, in addition to the properties described and listed above an extensive series of excavations on the southwest side of Pinnacle Mountain. There, close to the boundary of the Tibbet Hill chlorite schist (on the east) with the Oak Hill Series (on the west) is a zone of fractures along which the rocks have been very considerably sheared. Several pits have been dug along the contact between the Gilman quartzite and the Pinnacle graywacke. Nowhere is the dolomite exposed, which is not surprising, for it is missing from Little Pinnacle southwards, but in one or two places traces (unmappable) of the West Sutton slate occur. The entire zone is badly shattered and sheared, making a simple exposition of the structure impossible. p. 161a

Iron.

There are two sources of iron in this area, the Pinnacle graywacke and the West Sutton slate. Occasionally the White Brook dolomite, where it occurs in the Mansville Phase of the Oak Hill Series, contains magnetite, in one place

Several openings and tunnels are visible, and a shaft sunk from the top of the hill is now nearly filled with water. The "mine" was in operation in 1882. As with the other occurrences pyrite and copper sulphides are sparsely scattered through the sheared zone and doubtless the copper values faded out below the zone of secondary enrichment.

Prospects for future development. A note of hope has recently been struck by Dresser (1928), who urges a renewal, not of the old copper workings, but of intelligent prospecting by means of stripping, shallow rock cutting, and diamond drilling. Such prospecting must, however, in the light of past experience, and of the known copper reserves of the world, be considered as a highly speculative undertaking.

in sufficiently large amounts to cause notice. One such is the occurrence noted by Logan (1863, p. 677). Such abundance, however, is never continuous for more than a few hundred feet along the strike. The Pinnacle graywacke consists of sandstone which ~~in part are made up~~ in places up to 50 per cent ~~of grains~~ of magnetite. Where ~~as much~~ magnetite ~~as this~~ is present, ~~or even 30 per cent~~, the rock assumes a dark gray to black color, but invariably yields a white streak when scratched with a hammer, an indication ~~of enough non-ferous silicates to render~~ the rock of no use as an iron ore. Moreover there is invariably a small percentage of TiO_2 in the rock, which probably exists in leucoxene, for there is little ilmenite present. On account of its color, weight and obvious magnetic properties, it is not to be wondered at that it has attracted the attention of prospectors.

A few excavations have been made in this formation, but no subsequent development work has been carried on. There is no indication that any part of the Pinnacle formation would yield iron ore sufficiently rich to justify exploitation. Logan (1863, pp. 679 - 681) lists many localities where the Pinnacle graywacke bears a considerable amount of iron.

The West Sutton slate is almost everywhere sufficiently well supplied with hematite to yield a pinkish or reddish streak. In some places it is practically replaced by hematite. Excavations in this formation have been made at several places within this area, notably on the farm belonging to Mr. Crawford a mile and a half northeast of Hillside and one or two test pits a mile and a half east-south-east of West Brome. The West Sutton slate is rarely more than thirty or forty feet thick, and hematite is almost always present at its base. In some places it is pure specular hematite as at Crawford's, but usually the hematite is disseminated through the slate. In no place is there sufficient hematite to justify further exploration. During or before the American Civil War a few cart loads of ore were hauled to North Troy, Vermont, where it was mixed with local ore and smelted, but obviously the venture was not successful.

Specular hematite in a large mass several feet across occurs in a vein close to the Pinnacle Mountain Copper Mine workings, a mile east of Abbott Corners (Logan 1863, p. 679). Further south in Vermont, in similar geological environment, pure hematite is known to occur in masses several feet across.

Talc.

There seems to be ground for believing that talc occurs in the Sutton schists in sufficient amount and of sufficiently high quality to justify exploiting it some time in the future. At present competition with superior and more abundant material from Madoc prevents development of local product.

~~Talc and soapstone~~ deposits ~~occur~~ in scattered places ~~within the Sutton schists.~~ Doubtless ~~scores~~ more occurrences are waiting to be discovered, but the thick cover of vegetation prevents their recognition. A few of these localities have been worked, but no development is being carried on now. These occurrences have been described by Wilson (1926) with fuller detail than can be given here, and because no work has been done on the various properties it is needless to add to Wilson's excellent report. His description of the general occurrence is worth quoting. "Numerous deposits of talc and soapstone occur in association with the serpentinized intrusions, throughout a belt up to 25 miles wide and 125 miles long extending from the International Boundary to the region southeast of Quebec. The talc and soapstone occur for the most part along the margin of the intrusive, but in a few localities along zones of deformation within the serpentine mass. They are generally grey or green and are more or less schistose. They vary considerably in composition, in some cases consisting of almost pure talc, and in others of a mixture of talc, magnesite, dolomite, and disseminated chromite, or chromite and millerite" ( ). Wilson described all of the deposits he knew about, and excerpts from his descriptions follow:

Sutton (Range V, lot 10) Bed of brook, ¼ mile E of north-south road. Two and a half miles due south of Sutton.

"It consists of two zones of pale greenish grey talc schist 2 feet wide, 15 feet apart, but converging towards the south. Between the schist zones there is a gradual change from the talc schist to massive talc and magnesite and from talc and magnesite to talcose serpentine. The talc and magnesite mixture that forms the greater part of the deposit consists of pale greenish white talc, scattered aggregates of grey magnesite, and disseminated grains of millerite and chromite". The latter minerals "would prevent its use in high grade talcum powder". (p. 97).

Potton (Range V, lot 19). "It is situated near the middle of the lot and about 1,000 feet west of the Missisquoi river road ..... The talc has a grey colour and is, therefore of second-grade quality". (pp. 98-99) Diamond drilling in 1920 evidently did not yield information compelling or even allowing further work.

Potton (Range V, lot 28). Situated on a northeast-facing hill-slope about one and a half miles west of South Bolton Village. The principal opening in the deposit is a pit 9 feet long, 5 to 8 feet wide, and 2 to 3 feet deep, in which there is exposed in succession from east to west 2 feet of grey, talcose, hard schist, 2 feet of soft, pale grey, platy talc schist, 4 feet of broken talcose serpentine, and 1 foot of massive serpentine ...... The material ..... might be used for those purposes in which colour is unimportant, but it is probably too much broken for use as soapstone blocks" (p. 100).

Bolton (Range I, lot 23, property of John Pibus). "This deposit is situated about 5 miles southeast of Knowlton (and three quarters of a mile southwest of John Pibus' house on the Bolton Pass road). The talc deposit lies on the east margin of a belt of serpentine intercalated in the complex of schist and impure crystalline limestone that forms the west limb of the Sutton Mountain anticline. ...... The openings in the deposit (made in 1911 - 1913) include a shaft said to be 28 feet deep, an adit in the hill-side 140 feet long, and several trenches and prospect pits. The adit has now caved in, and the shaft and most of the prospect pits are now filled with debris. ..... The talc seen in the dump from the adit would be satisfactory for most purposes where a white colour is not essential". (pp. 100 - 101).

Bolton (Range II, lot 26, property of George Pibus). "Situated about 1,000 feet southeast of the road from South Bolton to Knowlton (Bolton Pass) and at the southeast corner of the lot. ......

"Only two pits were observed in the property ...."

"In the first pit a zone of platy cream-white talc schist 10 feet wide is exposed. .... In the second pit pale green serpentine cut by seams and veinlets of talc up to half an inch wide is exposed. ....

"Since the zone of talc 10 feet wide in this property is exposed in a single pit the amount of talc known to be present is small, but it is one of the few deposits of high-grade talc in the Eastern Townships and the width of the zone indicates that an extensive deposit may be present". (p. 101).

Bolton, (Range VI, lot 4). Situated about one mile northnorthwest of South Bolton. This deposit though worked at one time is now completely overgrown. Logan's description is quoted by Wilson. "Resting upon a band of the latter (dolomite) is a layer of about three feet of impure steatite, overlaid by 4 feet of dolomite. This is followed by a layer of a few feet of chlorite, to which succeed about 5 feet of steatite; the upper two feet of which are very pure and compact and furnish large blocks free from flaws". (1863, p. 797). Although in 1871, 300 tons of soapstone were shipped hence, Wilson calls this deposit low-grade. "If the deposits do not extend farther along the strike they are not sufficiently large to warrant the erection of a grinding mill except in conjunction with other deposits, of which there are several in the neighbouring district". (p. 104).

One other occurrence mentioned by Wilson is one in Bolton, Range VI, lot 26. It does not appear to be of any importance.

A few additional occurrences have been discovered during the course of the present survey, but they add little to what Wilson has written regarding the origin, general relationships and availability of the deposits.

Brome (Range VIII ($W\frac{1}{2}$), lot 1). Both northeast and northwest of the road corners on this lot are talc deposits. The one to the northeast is the larger and by all means the most interesting. The prevailing country rock is a siliceous sericitic schist, intensely crumpled in places. About three-eighths of a mile along the road north from the corners and 5 or 6 chains east of the road is a mass of partly serpentinized peridotite in which there are masses of chlorite and, in loose pieces, some talc. Some fifteen chains northeast in a clearing is a knob of talc some twenty feet across. It has obviously only recently been discovered, and no exploratory work has been done. It appears to be of good quality. The interesting thing about this occurrence is that the schists in the vicinity of this talc boss are heavily albitized, a condition not observed in any of the occurrences already alluded to.

Brome (Range IX, lot 7). On the east side of the north-south road there is a small amount of talc associated with siliceous schists. No serpentine or igneous rock is exposed here. Very poor exposures of similar associations may be found in Range X, lot 7, (S½) and Range X, lot 8, (S½).

Bolton (Range V, lot 26). Talc occurs here with siliceous schists, but no trace of igneous rocks.

In conclusion, it may be stated that talc deposits are fairly common within the Sutton Mountains. The grades of known deposits vary from high class to low class. Although In no case is the deposit very large, nor is there much hope of finding large deposits under the geological conditions concerned. Nevertheless it is probable that with an improved market opportunity may be available for the exploitation of these talc deposits.

Serpentine.

Throughout the Sutton Mountains exposures of serpentinized peridotites occur. Nowhere, as far as our examination has revealed, is the serpentine of commercial value, nor is asbestos associated with it.

Chromite.

Chromite is a differentiation product of peridotite and is common in the serpentine belt of Quebec. It has been mined for half a century in the vicinity of Thetford. One mile northwest of South Bolton Village is an old excavation in a chromite bearing serpentine. This was quarried for some time, but has not yielded rich enough ore to justify further exploitation. Harvie states that only one shipment of 27 tons has been made. (1912, p. 291).

Limestone.

Although two continuous bands of calcareous rocks traverse this area, namely the Dunham dolomite and the White Brook dolomite, neither is pure enough or thick enough to be used for burning. The White Brook dolomite is in some places colored a beautiful pinkish mauve, and might, if it were not so cut by quartz veins, be used as a decorative stone. Limestone and dolomite bands elsewhere in the Sutton Mountains are too discontinuous to be relied upon.

Slate.

In one or two places the West Sutton slate formation provides a good type of slate at the surface. This is indicative of better quality of stone below. The abundance of hematite usually present in this rock might cause it to weather unpleasantly, although such is not the case in the outcrop, Rarely is there the slightest natural discoloration. This slate displays good cleavage south of the road one mile from West Sutton towards

Farnham Corners. In the gorge below the dam at Call Mill, the Call Mill slate is admirably suited for roofing purposes, and if demand for slate produced in Canada arises this region should be thoroughly prospected.

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