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THE WESTERN HALF OF THE MEMPHREMAGOG SHEET.

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THE WESTERN HALF OF THE MEMPHREMAGOG SHEET

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FOREWORD

This is the third of a series of reports made to the Geological Survey of Canada upon field work carried on in Southern Quebec. The earlier two were concerned approximately with the Lacolle and Sutton sheets respectively. This report deals with the Memphremagog sheet between the Sutton Mountains and Lake Memphremagog. The eastern part of the Memphremagog sheet has already been reported on to the Geological Survey of Canada by Dr. F. A. Kerr (1923).

INTRODUCTION

Locality and Area.

The Memphremagog Quadrangle lies between 72° and 72°30' W. and between 45° and 45°15' N. The international boundary crosses it nearly parallel to its southern boundary and distant therefrom about one half mile. It is divided roughly equally into two parts by Lake Memphremagog which has a course somewhat east of north. This report deals with the geology of that part of the quadrangle in Canada west of Lake Memphremagog and east of the Sutton Mountains, the geology of which is contained in a previous report. This area is therefore about 130 square miles. It is contained within the townships of Potton and Bolton, and save for Mansonville has no town of any size. South Bolton and Bolton Centre are the only other villages. Knowlton Landing and Vale Perkins are two summer resorts on the shore of the Lake.

Physiography.

Like the area previously reported on, this one lies completely within the northern Appalachian Province. As such, the majority of its physiographic features have a north-northeast trend. Nowhere is it so continuously mountainous as are the Sutton Mountains, but the individual hills such as Owl Head, Sugar Loaf, Bear Mountain have elevations of

between 2,200 and 2,500 feet. Most of the area however is a rolling upland varying from 500 to 1,000 feet, up from which stand the hills mentioned and many others. Lake Memphremagog, whose surface has an elevation of 683 feet bounds the area under consideration and empties northward into the Magog river at the town of Magog.

It should be recorded that in the southern part of the area the names Province Hill and Hawk Mountain are incorrectly interchanged on the topographic map (Memphremagog sheet) published by the Department of National Defence.

Culture.

Mixed farming is carried on in the lower part, the hills being unused save for lumbering. Nowhere is the soil very fertile save for some of the flats along the Missisquoi River. The population is scanty. There is no manufacturing, and no mining. Two good highways cross this region from north to south from Mansonville, one runs almost due north through South Bolton to Bolton Centre and thence to Eastman, the other crosses over to Vale Perkins and thence north to Knowlton Landing. The other roads are poor, though they are being constantly improved. From Bryants Landing a good road goes northward to Route No. 1, but its connection southward with Knowlton Landing leaves much to be desired. The population is still largely of English extraction, though

time will doubtless attend to that.

Previous Work.

Nothing was known of this region prior to Logan's work. In the Geology of Canada, 1863, he describes the slates, the felspathic rocks of Owl Head, etc., although the references to the latter type are very scanty, and the synclinal of Silurian and Devonian rocks. The "magnesian rocks" of Logan include dolomites, magnesites, soapstone and serpentine. Selwyn, content with the illusion of his victory in the Sutton Mountains (1883. pp. 1-13), did not pursue the geology beyond where his enemy had left his mark.

Ells (1896, p. 76J) referred to the igneous rocks of the hills as eruptives, quoting Adams (1883). He came to the correct conclusion that the igneous rocks were later than the associated slates, but from erroneous observations, relying upon what he considered to be contact metamorphism.

Dresser's description of the geological relations in the serpentine region farther north is to some extent applicable to our own area. The only detailed description since those of Logan and Ells has been given by Harvie, who in 1912 and 1914 published brief notes on the geology, but a final report of his findings has never appeared. Every essential in the geological relations as we now understand

them was outlined by Harvie, save that he insisted that the "diabase" of Owl Head, etc., was intrusive. Harvie also discovered and reported on fossils of Silurian age from the shores of Memphremagog Lake.

Present Field Work.

The field work upon which this report is based, was carried out in 1930 and 1931. During those years the writer was ably assisted by Mr. H. W. Fairbairn, to whose interest in the igneous rocks of this district and their metamorphism much of the information in this report is due.

PHYSIOGRAPHY.

Topographic Divisions.

In an area so small as the present one there can be no satisfaction in subdividing it into lesser topographic units. However, there are four parts which might be mentioned particularly because they correspond almost exactly with areas of similar geological units. First, the Missisquoi River valley. This, roughly speaking a mile wide southwards from South Bolton, narrows northward to little more than the width of the stream itself. It is occupied for the most part by the aggraded products across which the present stream meanders its way at an elevation between 500 and 600 feet. Between this valley and Lake Memphremagog there are three types of topography, of which the most apparent is that underlain by the extrusives, which being considerably more resistant than the surrounding rocks, stand out in bold relief, making hills such as Bear, Hawk, Owl Head, Pevee, Sugar Loaf, Hogs Back and Place Mountains, which, collectively, may be called the Bolton Mountains. These reach elevations of from 2,000 to 2,500 feet, and which is underlain almost exclusively by slates. And lastly there are the longitudinal lowland belts, in one of which Lake Memphremagog itself lies, and a second runs from "The Brulee" northwards across Sargent Bay and Millington. Less resistant than the adjacent slates, the limestones of

and stand out above an irregular plateau surface which rarely attains a greater elevation than 1,200 feet

these belts have been eroded so as to lie in general below the 1,000 foot contour. Lake Memphremagog itself lies at 683 feet above sea-level and occupies throughout at least four fifths of its length a belt of these soft limestones.

There are but two drainage basins in this area, the Potton basin, occupied by the headwaters of the Missisquoi, and Lake Memphremagog basin. These two basins divide the area more or less equally between them.

GENERAL GEOLOGY.

As with the topographic divisions, so there are four main groups of rocks in this district. They are as follows:

4. Silurian and probably Devonian slates and limestones.
3. The Bolton Series of late Ordovician or early Silurian lavas and associated intrusives.
2. The ~~Hogg~~ Memphremagog complex of slates of Ordovician age.
1. The Mansonville group of quartzites and slates, presumably of Upper Cambrian age.

Neither Logan or Selwyn, nor any field worker in this region prior to Harvie, seems to have grasped even an approximate idea of the stratigraphy and structure involved in this small area. Harvie in 1914 published a very short abstract of his findings in which he discussed all of the above except the Mansonville group. It is with the rocks of the Bolton Igneous Series that there has been the greatest difficulty. Logan supposed that they were in part felspathic sandstones, a determination that was corrected by Adams' microscopical examination. Since then much has been written with regard to their intrusive or extrusive origin, and also their age. Harvie contended that they were all intrusive,

whereas our researches have shown that though the greater part of the rocks are extrusive, intrusive types accompany them. Harvie was correct in dating the igneous rocks as pre-Middle Silurian. Because the Bolton igneous complex is probably continuous with the asbestos-bearing serpentine further north in the Thetford district discussions as to its age and relations may be of wide import and application.

Older Sedimentary Rocks.

Insert pp. 9a & 9b →

Mansonville Series.

Occurrence and Lithology. The Mansonville Series occupies ~~Potton~~ Mansonville Valley over a width of between 1 and 2.5 miles. Its western contact is with the Sutton Series; its eastern is with the Bolton igneous rocks and the Memphremagog slates. The formation is dominantly quartzose and texturally may be divided into quartzite and grit on the one hand, and slate and phyllite on the other.

The quartzite and grit make up most of the outcrops and apparently also of the formation as a whole. The quartzite is grayish white to nearly black and macroscopically free of original minerals other than quartz and mica. Some exposures, however, contain accessory chlorite, sericite mica, calcite, pyrite, etc. The grit tends to be of coarser texture, and rounded grains of quartz up to one eighth of an inch diameter

Look at p. 9

The basal formations in this area we have named the Mansonville and Memphremagog series. Both are predominantly of slate, with minor amounts of quartzite and grit. Limestone is practically absent. Because of the inherent difficulty in mapping and in unravelling the structure of highly folded slate formations whose bedding has been all but obliterated and in which no fossils are to be found, even the broad lines of the classification here presented are open to question. In the Thetford region, the nearest area to the north where detailed stratigraphic study has been made, Cooke has established the order of succession as follows:

	Cooke	Clark, alternative possibilities	
Ordovician	Beauceville series Unconformity and basal congl.	Memphremagog	Memphremagog
Cambrian	Caldwell series and Bennett schists	Mansonville	Memphremagog Mansonville

Two possible correlations of our strata with those of Cooke's region are open to us. In the first place the equivalency of the Bennett and Sutton schist can scarcely be denied. Secondly the Mansonville series with its near basal quartzite is similar to the sedimentary part of Cooke's Caldwell series. The position of our Memphremagog series is more of a puzzle. That the fossiliferous part is equivalent to part of the Beauceville

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cannot be denied, but grave doubt must be entertained as to even the approximate equivalency of the whole of the Memphremagog and the whole of the Beauceville series. As at present mapped and separated, it is not impossible that our Memphremagog includes part of the Caldwell and part, if not all, of the Beauceville. There is no way of settling this question as long as the basal conglomerate discovered by Cooke (possibly Dresser's Magog conglomerate) is unrecognized here, and fossils remain so scarce. Were graptolites more abundant, and confined to the eastern part of the area, one solution would be to group all of the non-fossiliferous rocks together into the Mansonville series and call them the equivalent of the Caldwell. Or better still if the Magog conglomerate, which as Dresser notes outcrops along Castle Brook, southwest of Magog, were more widespread, it might serve as a means of separating the two formations. Because neither of these criteria serves us, I have fallen back upon petrologic differences realizing the unsatisfactory nature of such a criterion, and anticipating a division of these slates based upon more sure determination in the future.

may be seen in a matrix which is usually very fine and also composed mostly of quartz. The large grains are in places corroded and commonly show strain shadows or evidence of granulation. Much of the grit is schistose and intergrowths of chlorite and mica weave in and out around the large competent grains or aggregates of small ones. Fragments of slate occur in a few places. In the fine-grained types the schistosity produces a gray-green rock, which, in the field, is difficult to distinguish from schistose varities of the Bolton metabasalt. Both quartzite and grit are associated with interbeds of slate several feet thick.

Slate and phyllite form the accessory part of the series (Plate). These rocks are less crumpled on the whole than the phyllite of the Sutton Series but do not differ materially from the latter in composition. They vary from black through dull green to silver gray in color, the latter being very fine-grained. Carbon is abundant in the black varieties and occurs as graphite on many cleavage surfaces. Cubes of pyrite up to a quarter of an inch across are common in these carbonaceous slates. Quartz is the dominant mineral in the non-carbonaceous types and together with mica and chlorite forms a fine felted aggregate. Bands of different colored material, usually less than an inch across, are characteristic of the group and serve to distinguish it from the Memphremagog slate. The phyllite sometimes shows two intersecting sets of crumples on the dominant cleavage surfaces similar to those

found in the schists of the Sutton series. One feature that characterizes much of the light colored fine-grained slates is their ability to cleave with plane surfaces. At several localities along the Missisquoi valley this can be seen particularly Bolton Centre and South Bolton, and also about midway between the latter place and Mansonville (see fig.).

A group of outcrops northwest of Mansonville shows the greatest metamorphism of the series (Plate). The quartzite is squeezed into numerous tight folds and shows intense flowage such as that which is characteristic of the Sutton series. The thin slate layers are controlled entirely by the harder quartzite and appear as darker streaks in the grayish outcrops.

Thickness. The Mansonville series is closely folded and much of it appears to be isoclinal. It strikes a few degrees east of north and the cleavage dips are vertical or to the east at a high angle. The quartzite appears as a succession of ridges in two localities - (1) immediately northwest of South Bolton, and (2) on the west side of the highway less than 2 miles south of South Bolton. These probably represent part of the folded series but top and bottom are not known. The exposures indicate, however, that the Mansonville is repeated many times by folding across the

the valley. The structure and stratigraphy are unknown in detail and only a guess can be made as to the thickness. It is given as about 1,000 feet in the geologic column.

Age. There is no definite evidence of the age of the series. It is unfossiliferous* and only long range lithologic correlation is possible at present. The limits between which its age must lie are Pre-Cambrian and Upper Ordovician. It is believed to be probably Upper Cambrian age - the representative in Southern Quebec of the L'Islet formation described by Dresser from various points to the northeast, and equivalent, probably, to the Caldwell Series of Mackay (1921) and Cooke (1931). The basis for this conclusion follows.

The schists of the Sutton axis throughout their entire exposed length of some 150 miles are bounded on the east by slate and quartzite, with or without interbedded lavas. Much of the slate is reddish, and might upon superficial examination be confused with the "Sillery", which is a widespread formation between Vermont and Quebec City. This slate is underlain by quartzite known as the L'Islet, which presumably belongs to the same series. The red slate of the series, does not occur in Potton

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* Harvie (1914, p. 213) reported the finding of cephalopods of the orthoceracone type in the slates of this formation. There is nothing in this report that is out of harmony with our assumption of an Upper Cambrian age for this formation. Unfortunately Harvie did not preserve any specimens, and though our entire party hunted assiduously in the locality as indicated by Harvie, we were not successful in finding any fossils. Harvie assigned the slates of this locality to the Trenton (our Memphremagog series), our assignation is to the Mansonville series.

valley but a few miles north on the Montreal - Sherbrooke highway close to Orford Pond there is a red slate outcrop adjoining the Sutton schists on the east which may well belong to it. As most of the Mansonville is impure quartzite with grit and siliceous slate close lithologic similarity, stratigraphic position, and lithologic near-continuity make it reasonable to correlate it with the L'Islet. There is nothing in the lithology or structure which could preclude this possibility and subsequent work may support this conclusion.

Memphremagog Series.

Occurrence and Lithology. The Memphremagog series lies east of the Mansonville series on the upland east and west of Lake Memphremagog. The exposures are interrupted by much igneous rock (Bolton series) and by synclines of Silurian strata. The series is composed of graphitic slate for the most part and quartzose beds of various kinds are interbedded with it. The slate is usually black and high in carbon and in most places is crumpled (Plate). The interbedded quartzite is of various types; one common type consists of dark gray carbonaceous material studded with pyrite cubes up to one eighth of an inch across. The beds themselves are rarely more than 2 feet across.(Plate). A typical locality is between Bolton Centre and Millington where coarse gritty

material occurs in addition to the fine quartzite. The beds are broken in places, forming a coarse tectonic breccia. Another type of interbedded quartzite more common than the last lacks the carbon and is dull white in color. It occurs in thin layers averaging about 1 inch thick and is usually brecciated. This brecciation is characteristic of the series as a whole and is severe in most localities. In places the brecciated fragments have lost their angularity and may easily be mistaken for boulders or pebbles of a true conglomerate. Usually, however, the original character of the material is revealed by the transition laterally into unbroken beds and by the angularity of the fragments.

Boundary with Mansonville Series. Although a boundary is indicated on the map, it is not intended that such a line should be considered as anything but approximate. Practically all of the slate and quartzite west of the boundary certainly belongs to the Mansonville Series. Eastwards the slate is almost devoid of quartzite, softer, more crumpled, until within a mile or so of Lake Memphremagog, where an abundance of grits makes its appearance. It is not impossible that these grits belong to the Mansonville Series, here brought to the surface by an irregular anticline, but it would be fatuous to attempt more than to delineate with approximate accuracy the main boundary between these two formations. Without doubt, could the real boundary be mapped, its complexities

would be so great as to render it of little value. The Magog conglomerate, which might be expected to serve as a convenient means of separating these two formations has not been observed in this area.

About 1 mile northwest of Channell there is a knob on the west side of the road in which there is at least 18 feet of well-bedded quartzite flanked by slate. The quartzite occurs in beds 6 to 12 inches thick many of which are repeated by folding. Such a thickness of quartzite is unusual in this formation.

Thickness. The Memphremagog slate appears to be isoclinally folded in all localities where stratification and cleavage can be seen together. The heavy quartzite beds everywhere are parallel to the cleavage and dip vertically to steeply east. The strike is uniformly 10° to 20° east of north except where brecciation and crumpling are very intense. The latter condition, together with the disposition of the Bolton igneous rocks in and above the Memphremagog series has prevented the construction of a complete stratigraphic section but it is believed that at least 3,000 feet of the series is present.

Age. No fossil material is known within the limits of the present study. In these same graphitic slates along Castle Brook a few miles north, however, is a locality well

known for its graptolite fauna ( ). Ruedemann gives (1908, p. 30) a list, which follows, of graptolites from the Castle Brook locality.

D. ramosus Hall
Dicranograptus nicholsoni var. arkansasensis Gurley
Climacograptus caudatus Lapworth id. var. laticaulis Gurley
C. kamptotheca Gurley
C. oligotheca Gurley
C. scharenbergi Lapworth
C. wilsoni Lapworth
Diplograptus foliaceus Murchison
D. peosta mut. perexcavatus nov.?
D. truncatus ? Lapworth
Cryptograptus tricornis (Carruthers)
Lasiograptus mucronatus (Hall)
Dendrograptus unilateralis Gurley
D. sp.
Dictyonema sp. incert.
Thamnograptus barrandi Hall
Corynoides calicularis Nicholson

Ruedemann comments on this list as follows: "It will be noticed that these faunules observed in Canada are essentially relict faunules of the climateric fauna of the zone of Nemagraptus gracilis [Normanskill, Lower Trenton]". There is nothing in the faunal assemblage that would induce one to call it Utica. Ruedemann places it in either (or both) Middle and Upper Trenton, but includes the Lower Trenton also. East of Lake Memphremagog the series contains abundant graptolites also of Trenton age. There can be little doubt therefore that the slates described above are of Ordovician age.

The reference of these rocks to the "Farnham series" by Harvie (1912, p. 288) can scarcely be upheld on either a

It is not impossible that the Memphremagog slates span not only both Middle and Upper Trenton,

paleontological, structural or stratigraphic basis. Ells (1896, p. 37J et seq.) was quite justified in assigning these slates to the Quebec City Formation on paleontologic grounds.

Dresser (1925) has called attention to the presence of a widespread conglomerate horizon in the slates in question. He cites localities from Magog on the south to L'Islet Co. on the north. In almost every case the conglomerate consists of boulders of quartzite, grit, etc. in a matrix of slate. It is extremely unlikely, in the opinion of the writer, that many of the twenty one localities mentioned by Dresser belong to the same horizon. Certainly all do not for the conglomerate in Shefford lies within the Oak Hill Slice and cannot be stratigraphically related to horizons further east and beyond the Sutton schists. Especial point is given to doubts as to the validity of the Magog conglomerate by the presence in Bolton of a rock precisely similar to that described by Dresser, but which is known to be post-Ordovician in age and basal to the Silurian series. "A prime difficulty in deciphering the structure of the region has been lack of definite horizon marks" (Dresser 1925, p. 116), but the prime difficulty hitherto has been the lack of a detailed outcrop map upon which stratigraphic units could be plotted with reasonable certainty. Until outcrop maps are made covering the area over which Dresser's Magog conglomerate occurs the formation must always be regarded with suspicion.

Bolton Igneous Rocks.

The upland lying between the Missisquoi river and Lake Memphremagog is occupied largely by slates and quartzites of the Mansonville and Memphremagog series. Scattered over this upland there are a dozen prominent hills, every one of which is composed of igneous rock, to the sum total of which we have given the name Bolton Igneous Series.

Although Logan recognized these rocks, and described them (1863, pp. 248, 250) as serpentine, felspathic rock, and diorite, it is doubtful whether he had any idea of their structural relations to their rock neighbors. Logan had espoused the sedimentary origin of serpentines, the fallacy of which was shown by Adams (1883) in what was one of the first pieces of microscopical petrography carried out on this continent. Ells (1896, pp. 76-85) described the distribution of these igneous rocks very well in a general way, but nowhere in his report can one glean the faintest hint of his ideas regarding the structural relationship of these rocks, save that there seems to be a tacit assumption of their plutonic nature. He might be pardoned for assuming a too close genetic relationship between these igneous masses and dikes which he found nearby.

Harvie, in 1914, influenced too strongly by the crystalline nature of the rock and possibly by Ells' description

of the contacts with the nearby sediments concluded that it was intrusive in spite of his recognition of widespread pillow structure, the value of which as a criterion he minimized.

As we now understand them these igneous rocks are largely volcanic, with a minor amount of plutonic masses. The plutonic bodies we interpret as the feeders of the volcanics, with the possible exception of the serpentines, which seem not to be related to the rest of the series. These rocks are invariably altered and the prefix "meta-" is used to indicate this condition. The group includes metabasalt, metagabbro, and metaperidotite. The metabasalt forms the Bolton mountains and is the most widespread igneous rock in Brome County. The metagabbro and metaperidotite occur in dike-like and other intrusive bodies of small size and local distribution.

Metaperidotite and Derived Rocks.

Introduction. This division includes the metaperidotite, serpentine, talc, and magnesite of the district, which are all derivatives of primary peridotitic rocks. They form a minor part of the igneous rocks in Southern Quebec but to the northeast and especially in the Thetford district they are very extensive. Within the present area they occur in two zones, one on each side of the Missisquoi Valley, and also in scattered localities in the Sutton Mountains. The

two belts in Potton valley tend to converge northward into a wider irregular zone. The eastern one, however, is always larger and follows the strike of the formations, but in detail the exposures are very irregular and occupy a considerable belt. The largest outcrops occur 2 miles southeast of Mansonville where serpentine and serpentinized peridotites form a low, irregular, barren ridge about 1 mile long and less than one quarter of a mile in width. Further north the exposures are numerous but seldom more than a few feet across. Most of this zone lies within the Mansonville slate close to its contact with the Memphremagog slate.

The belt on the west side of the valley appears to be more regular than its neighbor and follows the Sutton Series just west of its contact with the Mansonville. The localities are dominantly talc and soapstone and are seldom as much as 100 feet across.

The remainder of the localities occur in the Sutton Series along Bolton Pass and south along Sutton Valley. They are mostly impure talc and are usually less than 100 feet wide. There may be many more occurrences within the mountains but the soil and vegetation effectively conceal them.

Metaperidotite. As already noted, the metaperidotite occurs mostly in the eastern belt along the Missisquoi valley. Megascopically, these rocks have a groundmass composed mostly

of serpentine in which paler pseudomorphs after pyroxene are embedded. The metaperidotite is of a gray-black color and on a weathered surface these serpentine pseudomorphs become bleached and stand out in relief.

In thin section pyroxenes may be seen in all stages of replacement (Plate). The boundaries are deeply corroded; extinction may be destroyed by the advancing serpentine which forms a compact mat and shows a pseudo-cleavage in place of the original crystal cleavage. At a still later stage when the pseudo-cleavage is gone the locus of the primary mineral may be recognized as a pseudomorph by the finer texture of the serpentine. These irregular areas are sharply demarcated from the coarser serpentine of the groundmass.

Olivine remnants are commonly scattered throughout the serpentine groundmass and stand out in relief as clear, irregularly fractured grains. Serpentine appears to replace them inwards from crystal and fracture boundaries so that remnants remain clear. In the pyroxene the process works along the closely spaced cleavages as well and clouds the entire grain immediately.

Serpentine. Serpentine is closely associated with the metaperidotite. It occurs in vein form and grades insensibly into more massive material derived directly from peridotite. In color it ranges from black to oily green and

its texture is very compact and dense. Both massive and schistose types are common. In places rounded, pebble-like forms of massive serpentine occur in a schistose serpentine matrix. This is well illustrated alongside the Canadian Pacific Railway tracks half-a-mile south of Potton Springs Hotel and seems to be an extreme phase of the irregular jointing which is characteristic of these rocks. It resembles a conglomerate in many respects. Outcropping surfaces may also show a cobweb pattern due to certain veins of serpentine which stand out in relief.

In places criss-crossing veins of silky, green-white asbestos fiber occur in the serpentine. The veins vary in width from several centimeters down to microscopic dimensions. The fiber length, in the cross-fiber type, averages less than one half of the vein width as there are numerous seams of magnetite disseminated through the central zone of the veins. This effectively destroys the continuity of the fiber and reduces its value for many purposes. There are all gradations between this soft fiber and hard, rigid varieties and again between the latter and massive serpentine. Carbonate may occur with the asbestos, apparently replacing it.

Accessory minerals include chromite in disseminated grains or minute veinlets, talc in veinlets or irregular masses, and hydromagnesite in thin white coatings of finely granular texture. Actinolite in radiating, star-shaped aggregates is

found in one locality half-a-mile east of Bolton Centre and has blades more than 1 inch long (plate).

In thin section additional details may be obtained regarding the cross-fiber asbestos. The central zone of these microscopic veinlets is filled, in addition to magnetite grains, with serpentine oriented parallel to the walls. As a rule this slip-fiber has lower interference colors than the cross-fiber. The serpentine groundmass may show unusual patterns, as in S- or V-shaped folds (Plate), but ordinarily it consists of a mat of fibrous to lamellar particles which are entirely without orientation. Chlorite veins may occur but seem to be unusual.

Evidence of three successive generations - peridotite to serpentine to magnesite - may be obtained from one section examined. The groundmass is mainly serpentine and contains pseudomorphs after pyroxene and olivine. A carbonate, probably magnesite, occupies part of the section and retains the nodular texture of the serpentine which is characteristic of its replacement of olivine. Stringers of magnetite which are likewise characteristic of olivine replacement cut across the present serpentine-carbonate boundaries. Neither of these features is characteristic of the direct replacement of olivine by carbonates and the evidence of age relations is thus apparent - peridotite initially, followed by serpentine, then the carbonate.

Talc and Soapstone. These vary in color from white to dark green and gray, depending on the inpurities present. Soapstone may be the finely granular, green, chloritic type or a smooth, gray, massive variety, irregularly and closely jointed. Talc may occur as a schist or as a coarse irregular mat of crystals. It usually contains some carbonate, rusty iron oxide, and magnetite. The weathered surface is slippery, especially if wet, and the talc is conspicuous due both to its light color and its high chemical resistance. Veinlets of talc in places cut serpentine but the opposite relation has not been seen.

Magnesite. Magnesite is found in a well-known locality half-a-mile east of Lake Nick. It occurs as a medium to fine-grained, massive, light gray rock. On a fresh fracture the flashing of carbonate cleavage faces is conspicuous. There is quartz throughout much of the rock and chromite occurs sparingly in disseminated grains. The brilliant green mica, fuchsite, is locally abundant and characteristic. The rock is closely and irregularly jointed and the brownish weathered surface is not distinctive from the lavas of the region.

Thin sections show untwinned magnesite anhedrons as the principal mineral. Some of it is of very fine grain and is associated with irregular veinlets of quartz. Fuchsite is similar to sericite and its green color is visible only in

a thick section. Chlorite and serpentine are accessory minerals and relatively unimportant.

Chromite occurs almost exclusively as rings surrounding carbonate cores and may have separated almost in place during the decomposition of some primary mineral. The carbonate is definitely a late mineral. One section shows four successive rings surrounding the same nucleus (Plate). Such structures indicate the secondary nature of the chromite beyond much doubt although they do not indicate its source.

Metagabbro.

Occurrence. The outcrops of this rock make up only a small part of the exposed igneous area and are invariably of small size. They are dike-like bodies seldom over 30 feet across and are considered to be the feeders of the flow with which they are associated.

Petrography. Megascopically, the metagabbro is medium-grained, and shows all gradations to the fine-grained metabasalt characteristic of the Bolton mountains. Due to intense alteration the texture appears confused in many cases but close inspection usually shows traces of ophitic texture. In fresh material this feature is especially notable and the rock consists largely of interlocking feldspar laths. Less commonly a coarse porphyritic texture occurs with an ophitic groundmass.

The rock weathers to a dull gray-brown surface and in places the feldspar may stand out in relief as whitish specks. Considerable kaolinite and ferric oxide are developed in this weathered zone. On a fresh fracture the metagabbro has a dull greenish-gray cast which is characteristic.

The local structures are variable. Much of the rock is massive and irregularly jointed and the primary textures are fairly well preserved. There are numerous zones, however, in which a chlorite schist is developed. The primary texture in such cases is obliterated and the minerals tend to have a parallel dimensional arrangement.

Many of the minerals may be identified with or even without a hand lens. Under favorable circumstances albite twinning is seen in the interlocking plagioclase laths and the alternation of narrow with wider twins indicates a composition at least as calcic as andesine. Green fibrous amphibole is usually conspicuous and is probably actinolite. Epidote is commonly seen as light green aggregates or tiny veinlets. Chlorite is best developed in the schistose phases of the metagabbro but is present in all specimens to some extent. Calcite cleavage fragments are most prominent in the schistose zones and form a considerable part of the rock. Pyrite and pyrrhotite are conspicuous accessories and occur in irregular grains.

In thin section the ophitic texture of the interlocking plagioclase laths is characteristic. Alteration may be so severe that it is largely destroyed but traces are usually to be found. The grain size is very uniform and porphyritic varieties are rare. The schistose metagabbro is characterized by parallel dimensional arrangement of chlorite and to some extent of plagioclase, calcite, and titanite.

Feldspar makes up the greater part of the sections studied. The least altered material occurs in long laths and is invariably twinned according to the albite law with alternating wide and narrow bands characteristic of calcic plagioclase. A rough determination of indices, however, indicates that it is no more calcic than oligoclase. Maximum extinction angles can not be used for determination since this alteration to more sodic varieties is variable from point to point. A few optically oriented crystals were located and indicated oligoclase-albite in every case. Much of the plagioclase has lost all of its crystal outline and is clouded with small flakes and grains of actinolite, epidote, calcite, and chlorite.

Pyroxene occurs in a very few cases and then only as remnants of the original crystals. It is always uralitized and its relation to this secondary amphibole is especially distinct. It may also be replaced directly by chlorite.

Uralite is abundant in almost all the sections examined. It occurs commonly in large fibrous forms or as minute shreds which cloud much of the feldspar. Pyroxene, the probable source of this material, is rarely found. The uralite is usually colorless but may vary in the same crystal to a light green pleochroic variety in which the optical continuity is preserved in all cases. This secondary amphibole probably belongs to the actinolite-tremolite series.

Epidote and clinozoisite occur in practically all the metagabbro. They are closely associated and are found in small euhedral to subhedral crystals scattered throughout the sections. In places a microscopic veinlet is seen. The crystals may be brilliant and clear or clouded with alteration products through which the high interference colors are seen with difficulty. The blue grains showing cleavage were carefully examined for evidence of inclined extinction, which would indicate zoisite, but none was found.

Chlorite occurs throughout the metagabbro but is particularly abundant in the schistose varieties. Here it has pronounced parallel dimensional arrangement and forms a chlorite schist. Its usual occurrence in the massive metagabbro is in ragged random shreds of varying size which replace uralite. Calcite is its usual associate.

Calcite is found in almost all these rocks. As

noted above it accompanies chlorite and there is a parallelism in the relative abundance of the two minerals. They are least common where augite and much uralite remain; they increase as the latter diminish in abundance. Calcite occurs as small irregular masses or in single elongated forms. In the latter occurrence no uralite remains and the calcite may be occupying the former site of the amphibole. Calcite undoubtedly replaces uralite in other sections examined and this premise is thereby strengthened.

Quartz occurs in many of the sections. It is found in small nested aggregates which suggest a secondary origin. Its abundance varies directly with the quantities of chlorite and calcite present in the rock and indicates the release of silica as replacement went on to later stages.

Leucoxene is an accessory in most of the metagabbro and occurs in two distinct associations. The first is that of titanite-leucoxene in which the high order color of the titanite is almost completely masked by the leucoxene. The second association is with magnetite. Here the leucoxene displays as many as three sets of intersecting lines on its surface which are obviously of a primary nature. Many of these pseudo-cleavages contain magnetite. The inference is that originally an ilmenite-magnetite solid solution was present at an elevated temperature, magnetite exsolved along certain crystallographic planes as cooling continued, and

later hydrothermal action replaced the ilmenite by leucoxene, resulting in the present structure. Eskola (1925, p. 30) describes intergrowths of magnetite-ilmenite with leucoxene along rhombohedral planes.

The remaining accessory minerals have no unusual features. Pyrite and pyrrhotite are fairly common sulphides and magnetite is associated with chlorite in small amounts. Brown biotite and apatite are not common.

Metabasalt.

Occurrence. Metabasalt makes up much the largest part of the Bolton mountains. It is associated with the Mansonville and Memphremagog series and grades into metagabbro. Much of the description given for the metagabbro also applies to the metabasalt. The evidence of its extrusive character is as follows - (1) Pillows are abundant in many exposures. From evidence accumulated in recent years there is no reason to doubt the extrusive origin of rocks containing this structure over a large area. (2) The consistently fine grain over many miles is in general indicative of flows rather than plutonic rocks. (3) In places amygdules are found; these are not diagnostic in themselves but are definite evidence of near-surface conditions. (4) Breccias of and within the metabasalt are known as, for instance, just southeast of the summit of Owl Head. The blocks are of all sizes up to a

foot or so across and are all finer grained than their matrix. The exposure has every appearance of a fractured roof breccia. Ells mentions a breccia at the site of the old Mountain House.

Two types of metabasalt occur - (1) a green uralite rock, and (2) a buff-colored ankerite rock. These are described separately in the following pages.

Uralite rock. The uralite rocks may be either massive or schistose. The massive types are fine-textured, gray-green in color, and grade insensibly into metagabbro. Veinlets of epidote, calcite, and quartz are common. Pyrite and pyrrhotite are regularly distributed through the metabasalt and give rise to rusty pits if oxidized. Amygdules of quartz, calcite, epidote, and chlorite may also occur up to a quarter of an inch in diameter. Breccias are found locally and the angular fragments, usually less than one inch across, are of essentially the same composition as the matrix.

The schistose metabasalt is highly chloritic and dark green in color. The cleavage surfaces are irregular and cross-jointing is well developed as a rule.

Under the microscope details of the alteration may be obtained. Plagioclase is present in all sections and is indeterminable except in a general way. Most of it appears to have indices corresponding to albite or oligoclase. The grains are small, irregular, and covered with secondary

products. In places relicts of the original plagioclase remain and have broad albite twins which indicate calcic plagioclase. These may be seen in a hand specimen as phenocrysts whose boundaries are irregular and gradational into the finer, greenish groundmass. In one section the relicts are outlined by a light-colored rim and the centers are filled with chlorite and other secondary products.

Epidote and clinozoisite are essential minerals in the uralite rock. Blue grains of clinozoisite are particularly abundant. They are usually minute and heavily clouded with impurities and must be examined with a high-power objective. They are usually disseminated evenly through the rock but in places are segregated and thus become more conspicuous.

Chlorite is also essential to this type of alteration and occurs in disseminated flakes, in solid patches and in cross-cutting veinlets. It commonly replaces uralitic amphibole and also forms the filling of amygdules whose borders are studded with quartz, calcite, and epidote.(Plate). In the disseminated form it is particularly abundant in parallel dimensional arrangement in the schistose metabasalt.

Uralite, or actinolite which it approaches in composition, is typical of these rocks and occurs in abundant minute shreds and flakes. In the schistose metabasalt it has a parallel dimensional arrangement but never as perfectly as chlorite. It is identical with the colorless secondary

amphibole of the metagabbro except for its finer size and greater tendency to show a parallel arrangement of the flakes.

Titanite is the fifth essential constituent of the uralite rocks (plate). The grains are always microscopic and many of them require high magnification for their identification. They are irregular in shape and usually heavily clouded with secondary products such as leucoxene. The grains are disseminated rather evenly through the sections and in places have a slight parallel dimensional arrangement.

Calcite is most conspicuous among the accessory minerals and may be identified in a hand specimen by flashing cleavage of metacrysts in the greenish groudmass. Small pits on the weathered surface are directly traceable to solution of this material. In thin section small irregular grains are also common and are scattered unevenly throughout the groundmass (Plate). Quartz may occur with calcite in veinlets but is more common as nested aggregates of minute and polygonal grains. Sericite is characteristically found as very small shreds and needles on plagioclase. In one section uralite is oriented (Plate) whereas sericite has no parallel dimensional arrangement, indicating the later development of the mica. In places, however, sericite is oriented and there is thus no constant relation between its age relations and those of the schistosity.

Olivine and green hornblende are the only primary silicates whose relicts remain in the sections studied. They are rare but are useful as indicators of the source of part of the secondary material in these rocks. Olivine occurs in small, rounded phenocrysts, much fractured and in places enveloped by uralite. Hornblende occurs as unaltered phenocrysts in two occurrences of porphyritic metabasalt - (1) on Johnston mountain one mile southeast of Bolton Centre, and (2) one half mile north of Place pond. The phenocrysts occur in a fine gray-green uralitic groundmass and may be as much as a quarter of an inch in length. In one or two other localities schistose porphyries show green chloritized phenocrysts, presumably of hornblende, oriented in the direction of schistosity. In thin section the primary hornblende is green and pleochroic and in places is enveloped by colorless uralite in optical continuity with it. It may also be chloritized directly with no secondary amphibole forming as an intermediate stage. In one instance strain shadows were noted passing across the broken fragments of the original phenocrysts.

Magnetite and apatite are uncommon in the metabasalt. Pyrite and pyrrhotite are regular accessories, especially the latter sulphide. It is easily visible in most hand specimens as irregular masses and in places under the microscope appears to be corroded.

Ankerite Rock. These rocks form a small but distinctive portion of the Bolton Igneous Group. The exposures are seldom more than a few feet across and are scattered at random throughout the metabasalt. The largest outcrop occurs half-a-mile northwest of Peasley Pond and is about 300 feet wide. It shows traces of pillow structure which relate it definitely to the metabasalt immediately adjoining it. It is also found in one locality associated with metagabbro. A small dike of metagabbro 2 miles north of Channell is bordered with several feet of ankeritized material containing large plagioclase relicts.

The rocks are buff-colored on fresh fracture and usually of fine texture. In the coarsest type carbonate rhombs are easily visible to the naked eye. Dense veinlets and irregular patches of quartz are scattered through the groundmass. Small pyrite cubes are found in many localities. The rocks are usually massive but in places may be schistose. They have characteristic rusty tops which provide the best field method of identification. Several inches of soft iron oxide may have to be removed before the fresh rock is reached. The cause can be traced directly to the ankerite rhombs in the narrow transition zone between oxidized and unoxidized rock which yield rusty pseudomorphs in all stages of formation.

In thin section altered plagioclase forms most of the fine groundmass. Much of it is indeterminable as it is covered with fine mica flakes and other secondary substances. In places, however, indices corresponding to albite and oligoclase can be determined. A few grains show twinning bands indicative of a more calcic type.

Large ankerite rhombs are the characteristic feature of these rocks (Plate). They vary in size, composition and perfection of crystal outline, and in places show strain shadows. Twinning is rare as in most of this carbonate series but is found in a few cases. Microscopic evidence of age relations is seldom available on account of the relatively high crystallizing power of the ankerite, but from a study of the carbonates in the uralitized rocks there is every reason to believe that it is a late mineral.

Sericite is common in the rocks of this group as minute flakes and shreds scattered on the altered plagioclase laths and grains. It is mostly unoriented but in places has a parallel dimensional arrangement. Quartz is found commonly in irregular patches and veinlets. The grains are in places intergrown with the altered plagioclase and are difficult to separate on account of the fine texture. Chlorite is the fifth essential constituent of this group. It occurs in small interstitial patches or in larger masses but is seldom visible in a hand specimen.

Accessory minerals include apatite, rutile, and epidote. The latter mineral, so characteristic of the uralite rocks, is rare, and as no actinolite is seen in the ankerite rocks it is clear that the carbonatization is either a later or independent process.

Thickness. The maximum breadth of any one outcrop of the metabasalt is between 8,000 and 9,000 feet. This is found along the International Boundary across Bear Mountain. From this maximum there are all gradations down to a few feet. The major prominences of the Bolton Mountains, however, all have outcrop widths measured in thousands of feet. There is evidence from the pillows of a steep west dip on the west side of Owl Head and on the east side the layers of breccia dip towards the east. Elsewhere there are indications of a nearly vertical attitude of the flows, but except at Owl Head no concept of the structure is vouchsafed. At that mountain they seem to be disposed in an anticline. It is probable that they are all folded, but not completely so, and that a maximum of 4,000 feet is attained in places.

Age Relations.

Metaperidotite. There is no direct evidence in this area of the relative ages of the metaperidotite and the other rocks of the Bolton series. Contacts are rare and serpentinization of the few observed contacts makes them valueless for a study of age relations.

That the serpentine is older than the Silurian series, to be described hereafter, is proved by the presence in the basal Silurian breccia of pebbles of serpentine. Even without this positive evidence the areal distribution of metaperidotite and derived rocks in Potton and Sutton valleys suggests that they are pre-Silurian and apparently intrude the pre-Silurian sedimentary rocks as small irregular dikes. They are, therefore, with the metabasalt assigned to the late Ordovician, or possibly earliest Silurian.

Metagabbro and Metabasalt. The metagabbro intrudes the Memphremagog series in a number of places as small dikes seldom more than 30 feet across. The contacts are chilled and in places brecciated. One locality on the road between Mansonville and Vale Perkins illustrates very clearly the cross-cutting nature of the contact. The metabasalt is closely allied with these bodies both geographically and petrographically and they are thought to be the feeders to the basaltic flows. This would indicate that the metabasalt overlies both the Memphremagog and Mansonville series unconformably, but, it nowhere occurs within the Silurian series. The metagabbro and metabasalt are therefore post-Trenton and pre-?Middle Silurian, and with the metaperidotite, are placed in the late Ordovician, or earliest Silurian.

Harvie (1912, pp. 289-290) was certainly in error, as was Ells before him, in supposing that the Silurian beds were altered by the intrusion of dikes related to these igneous rocks. Such dikes are independent of the Bolton rocks and are related to either the Stanstead granite or to the alkaline Monteregian intrusions, both of which are known to be post-Silurian.

Silurian Series.

The youngest pre-glacial sedimentary rocks in this area are those which belong to a series of Silurian and also possibly Devonian age. These rocks, lying unconformably upon the Memphremagog slates and the Bolton igneous series, have been folded into closed folds, and nearly everywhere the beds are in a vertical position. However, on the west side of Lake Memphremagog, there has been very little metamorphism; on the east side some of the limestones have been marmorized, the fossils squeezed, and there has been locally an excessive development of sericite. Unless otherwise stated, the remarks below refer to the exposures on the west side of the lake. This series consists of a basal conglomerate, and sandstones, followed by a thick series of calcareous shales. These grade rather rapidly into a dark dove-weathering limestone. Fossils are scarce, but indicate a Silurian age, although Devonian fossils are known from the series on the east side of the lake.

Distribution. These rocks occur, for the most part, in two synclines whose axes follow, in general, the usual N.20°E. trend. The eastern syncline occupies the basin of Lake Memphremagog from the northern border of this area southward to the vicinity of Owl Head. The rocks in this syncline extend inland for one, or at the most, two miles from the shore on both sides of the lake. The western trough is confined to this area. It occupies nearly all of Sargent Bay, whence it proceeds north-northeastwards for six miles, not quite reaching the limits of the map. Throughout this northward extension it is one to two miles wide. Southwards it is much narrower, never as much as a mile wide. It passes between Lake Memphremagog and Sugarloaf Mountain and probably extends as far as, and ends in, the Brulee swamp, eight miles south of Sargent Bay, thus giving this syncline a total length of sixteen miles. At several places isolated outcrops of these rocks occur, particularly west and southwest of Knowlton Landing, where the implication is clear that this western trough is really a double syncline. Also east of the lake one or two isolated outcrops, more or less completely metamorphosed, occur.

Petrography. In general five kinds of rocks are common (a) a basal breccia, (b) a basal conglomerate or sandstone, (c) shales, for the most part calcareous, (d)

a black carbonaceous fossiliferous limestone occurring as lenses within the preceding, and (e) dark colored almost non-fossiliferous dove-weathering limestone. These include the main types west of the lake. On the east side others have been found which will be described in the proper place. The stratigraphic succession is as follows:

(e) dark colored dove weathering limestone

(d, c) Glenbrooke calcareous and non-calcareous shales containing lenses of black fossiliferous limestone

(b) Peasley Pond basal sandstone or conglomerate

(a) George Pond basal breccia, not everywhere present

George Pond Breccia.

Distribution and Characteristics. Intervening between the obvious members of the Silurian series of the western trough and the slates and igneous rocks to the west is a breccia formation named because of its proximity, in its best development, to George Pond. The best location for studying this breccia is north and northwest of the four corners southeast of George Pond. A quarter of a mile north of the schoolhouse at the four corners, and a few hundred feet west there is a series of low hummocky hills which on the west are composed of metabasalt, but for most of their extent are underlain by a breccia which is, superficially, easily mistaken for the metabasalt. It consists of blocks

It was described by Hawie as an agglomerate (1912, p. 214).

of quartzite, slate, and metabasalt of all sizes up to two feet in diameter, set in a fragmental matrix composed of the same materials. Plate shows the general character of the rock. None of the fragments shows any sign of rounding, nor is there any indication of assortment. Metabasalt predominates in this part of the outcrop.

Approaching the road the breccia is seen to have a more and more shaly matrix, with blocks of the harder rock becoming more infrequent, and, remarkably so, more rounded. This characteristic seems to be present in other localities where the matrix is predominantly shaly. Two or three hundred feet north of the schoolhouse a good exposure may be seen in the road and equally good exposures occur along and on both sides of the road northwards for a mile and a half to the next corner. In all this distance the rock is predominantly of a shaly or slaty matrix with only a minor amount of fragments. In this respect it somewhat resembles the tectonic breccia occurring in the Memphremagog slates (p.), but there is no general through-going cleavage in the matrix in question, and the boulders are never linearly continuous, and moreover consist not only of quartzite but also of metabasalt and near the last mentioned road corner of metaperidotite. This slaty breccia, which might with some propriety be called a conglomerate is succeeded by the quartz-pebble and slate-pebble basal conglomerate of the Silurian series.

Thickness. The maximum thickness observed in the George Pond area is slightly in excess of 700 feet. Elsewhere the thickness is far less.

Interpretation. That this breccia is not a marine type is shown by the lack of rounding of the blocks, except as mentioned above in the uppermost part, and the general lack of assortment. The exceptional part just referred to might possibly be marine, which possibility is referred to below. Neither can it be considered a fanglomerate, for such bodies invariably show some signs of stratification. It is not a tillite. There is nothing in its make-up to preclude its being a talus breccia, and such is its origin according to the present writer. The angularity of the blocks of the western part, together with the complete lack of assortment is altogether in harmony with this view. The difference between what has been called the western and the eastern parts of the exposure in the type locality may be explained as due to a change in provenance as the cliff, from which the materials were derived changed its character during self-destruction. We should expect to find that rivers had begun to cut deep valleys into the lava (Bolton) plateau by early, or middle Silurian time, doubtless becoming in many places superposed upon the underlying Memphremagog slates. It is not impossible that post-Bolton peneplanation occurred, so that later rejuvenation of the streams would produce steep

sided valleys of no great depth, which would be more in accord with the present concept. Along such valleys talus material would accumulate, and, wherever the two kinds of rocks were exposed, could only be composed of the available parent rocks. Because the metabasalt would naturally occur in the upper part of a cliff in which both it and the underlying slates were exposed one would expect it to yield the majority of the fragments at first. Also because of the impending invasion by the Silurian sea the rivers would be increasingly incapable of transporting the talus accumulation, which would therefore be susceptible of preservation. The slaty breccia with its rounded pebbles and boulders may be the result of the choking of such a valley with slate fragments and their shifting a little by the streams, which transportation might well serve to partially round the boulders concerned and could only serve to triturate and pack the fragments of slate. Thus a topography initially fairly rough had begun to be smoothed out before the invasion of the Silurian sea. There is no way to evaluate the roughness of that topography, but it was probably not altogether unlike the present in diversity of slopes. There was, in all probability, a considerable lapse of time in between the formation of the breccia and the inclusion of the Silurian sea, giving the breccia time to be consolidated. Otherwise the waves and currents of the Silurian sea, which were capable of carrying pebbles two inches in diameter would have

disturbed the upper shaly parts, and a gradation from breccia to basal conglomerate would be seen. There is no such gradation.

Another feature which favors the interpretation given above is the interrupted distribution of the breccia. In many places the basal conglomerate rests directly upon shale or metabasalt. Such would have been places of little slope where no talus could accumulate. Besides the exposures described above which are continuous for two miles from the four corners northnortheastwards along the western border of the western syncline of Silurian strata, similar breccias are known from very few places. Just east of the road one mile south of Peasley Corners, East Bolton, is a similar rock associated only with metabasalt. However, directly in line of strike with this exposure a mile and a half to the northeast, and a little more than a mile east of Peasley Corners is an outcrop of basal Silurian sandstone resting upon Mansonville slates. Another exposure, unrelated to other Silurian outcrops, is to be seen a mile and a half due west of Vale Perkins. Another locality, of doubtful authenticity, occurs on the east shore of Sargent Bay, about half a mile north of Ritchie Point.

Age. This breccia post-dates the Bolton series and antidates the Silurian series. The latter are Middle Silurian in their lower part. The Bolton series is late Ordovician or more probably early Silurian. Thus the breccia

means that the available detritus of metabasalt, etc., was adequately weathered before the Silurian sea rearranged the existing regolith. The quartz is apparently of vein origin and probably was derived from the quartz veins not uncommon in the Ordovician slates. The slate and quartzites are from the Memphremagog, and possibly the Hansonville series, though no pebble referable to any of the known types of the latter has been recorded. In some layers the quartz pebbles occur almost to the exclusion of other types, only rarely does one find slate pebbles predominating. Quartzite pebbles are always in the minority. The quartz pebbles are fairly well rounded as are also those of quartzite, but the slate fragments are slabby and often angular. The matrix is a brown weathering sandstone, indistinguishable in the absence of pebbles from the overlying sandstone. In some localities there has been a considerable amount of sericitization, but only where slate pebbles are abundant. It appears to be an accompaniment of considerable slipping within the conglomerate. Pyrite is fairly common.

The Sandstone. Succeeding the conglomerate and often interbedded with it, or grading into it, is a series of sandstones. These are of various grains, and are succeeded by a thick series of shales. The sandstones in many places are composed of the same materials that make up the conglomerate, grains of quartz with small fragments of quartzite and slate. Some layers have an abundance of detrital flakes of white mica

though no parent rock save the Sutton schists is known that might have yielded this mineral in abundance. Herein may be additional evidence leading to the fixing of the time of crystallization of the Sutton schists.

In color the sandstones vary from light to dark gray. Invariably they weather to a rust color, possibly from the presence of abundant pyrite cubes.

The measured section at Peasley Pond, where a nearly complete exposure can be seen is as shown below.

75'		Shaly sandstone showing pitted weathering
6'		sandstone and pebble beds
2'		--- no exposures
4'		cross-bedded sandstone
4'		--- no exposures
4'	6"	fine-grained sandstone
1'		cross-bedded sandstone
13'	6"	fine-grained sandstone
1'		quartz grit
1'	6"	sandstone
	9"	quartz conglomerate
7'	9"	sandstone, cross-bedded with pebble beds
2'		gritty conglomerate
7'		cross-bedded sandstone with pebble beds
1'		sandstone
1'	9"	quartz conglomerate
2'	3"	sandstone
2'	6"	quartz conglomerate
	9"	sandstone
	6"	quartz conglomerate
2'	9"	sandstone
1'	6"	quartz conglomerate
	6"	sandstone
4'	6"	quartz conglomerate
2'	6"	brown weathering sandstone
2'		cross-bedded quartz conglomerate
2'		brown weathering sandstone
1'	8"	cross-bedded quartz conglomerate
	6"	brown weathering sandstone
	6"	fine-grained conglomerate
	8"	brown weathering sandstone
2'		fine-grained conglomerate
	10"	brown weathering sandstone
4'	6"	fine-grained conglomerate
17'		--- No exposures
6'		quartz-quartzite-slate conglomerate (The unusual dip, 64°W., is doubtless due to the fact that this outcrop is really a huge boulder, disturbed but slightly by glaciation.)
8'		No exposure. Probably conglomerate but this width is not included in the total given below.
----		Metabasalt
188'	2"	From base of lowest conglomerate exposed

Not only is the section given above an unusually great one for this formation, but it is also remarkable for the constant alternation of conglomerate and shale. In all these conglomerate beds not a single pebble of igneous rock occurs, and this in spite of the fact that the metabasalt occurs actually in contact with the basal conglomerate in this locality.

A section a quarter of a mile north of the four corners near the Glenbrook region and just east of the road shows about 140 feet of sandstones and grit with very little conglomerate. These beds stand nearly vertical (strike 0°, dip 85°W), and adjoin the George Pond breccia on their west. On the east of this section there are no exposures but there is good reason for believing, because of the distribution of outcrops to the south, that these exposures are followed almost immediately by shales. Another excellent series of exposures occurs three quarters of a mile northwest of Vale Perkins both north and south of the east-west road. The outcrops to the north show offsetting by transverse faults. Those to the south can be seen to be basal to the adjoining large exposures of shales. The friable nature of both conglomerate and sandstone allows them to be readily eroded, so that they rarely outcrop. Elsewhere, the fact that the basal beds are easily weathered results in the formation of

strike-wise valleys. Many of these can be seen in the Knowlton Landing region, and also on the west side of Hog's Back.

The Glenbrooke Shale.

Distribution and Section. Following the Peasley Pond sandstone is a section of more than a thousand feet of shales. These are uniformly dark gray on the unweathered surface, micaceous in some places, calcareous in others, and grade rapidly into an overlying fairly pure limestone. An almost complete section of the whole formation can be seen to good advantage along the course of the stream that runs down to Glenbrooke Farm. Further to the south these shales hold, in their lower part, a lens of dark carbonaceous limestone, which in contrast to the shale, is highly fossiliferous. This is called the Knowlton Landing member, and is doubtless the source of the fossils mentioned by various writers from Knowlton Landing. The shales in the lower part weather gray in general, but in the upper calcareous, and possibly dolomitic, part they weather to a dull brown.

The section (measured horizontally) at Glenbrooke is as follows:

	950 on	Mostly pure dark colored limestone, formation
935 - 950	15'	Shales with limestone interbeds. Buthotrepis, Spirophyton, etc. occur at about 940 at brink of falls
935	8"	Light gray, well stratified, crystalline limestone
900 - 935	35'	Siliceous shales, with dark colored limestone beds becoming more common
900	8"	Pure dense, blue limestone
840 - 900	60'	Siliceous shales
820 - 840	20'	Siliceous shales with thin black shale interbeds
707 - 820	113'	Siliceous shales with sandy beds
666 - 707	41'	Shales, less calcareous
630 - 666	(36')	-- not exposed
600 - 630	30'	Calcareous and siliceous shales with limestone lenses
577 - 600	(23')	-- not exposed
495 - 577	82'	Dark carbonaceous or siliceous limestones interbedded with shales. 25' to 30' above the base is the trilobite layer. Trilobite fragments occur for 50' more. Practically pure limestone lenses or continuous beds one inch or more thick are common
340 - 495	155'	Thick-bedded dense siliceous shale. interbedded with carbonaceous thin-bedded shale in minor amounts. Shale flakes or pebbles are common in some layers. It is more calcareous towards the top. A 10' falls occurs five feet below the top. Tendency to weather brown throughout.
155 - 340	185'	Dark micaceous shale, giving way to black and non-micaceous beds at top. Some beds have indeterminable fragments of algae and trilobites. Shale flakes or pebbles common.
130 - 155	(25')	--- not exposed
120 - 130	10'	Dark, brown-weathering shale
110 - 120	10'	Dark, finely micaceous shale
35 - 110	(75')	--- not exposed
30 - 35	5'	Dark shale, weathering brownish
20 - 30	(10')	--- not exposed
0 - 20	20	Peasley Pond sandstones

Assuming the ten foot gap between the Peasley Pond sandstones and the lowest Glenbrooke shale bed belongs to the former formation, there is a total width of 920 feet of Glenbrooke shales in this section. Because the dip is not quite vertical but 88° or 89°, 900 feet would be a better figure to use for the thickness of this formation at its type locality.

The section given above conveys a reasonably good concept of the petrographic character of the formation. It is dominantly siliceous in character, but with considerable amounts especially towards the base of micaceous shales and especially near the top of calcareous beds. Limestone beds are common, thin, one or two inches as a rule, in the upper half; one or two thicker beds are listed.

Age. The age of this formation was stated to be Upper Silurian (Silurian) by Logan (1863, p. 251), although he gave a very brief description of it and its fossils on pp. 435 - 436. Later, Ells made larger collections from both sides of the lake, which were examined and reported on by Ami (Ells, 1896, pp. 154, LXXVII - LXXXI, and 156 - 157, LXXXIII, LXXXIV). In these lists Ami separates what he considered to be Silurian faunas from those belonging to the Devonian. List LXXXIII, containing only Spirophyton cauda-galli is of questionable value. The locality cited is at the very top of the Glenbrooke shales, and specimens may still be found in the uppermost few feet. However, associated with this

fossil of rather doubtful value, at the brink of the falls, there may be found good specimens of Buthotrepis (B. cf. gracilis, Clinton) and some indefinite trails.

List LXXXIV is obviously erroneously quoted, for it is identical with the list given by Logan of the fossils common to the two synclines of Silurian strata. Immediately following Logan's list is the sentence "The schistose plumbaginous limestones, at the Owl's Head, abound in obscure fossils, among which a species of Zaphrentis may be recognized" (p. 436). It is obvious that Ami, seeing the list of fossils immediately followed by a reference to Owl's Head, assumed the latter to have been the locality whence the former was obtained, although Logan's words are perfectly explicit. Ells, (1896, pp. 8J - 15J) gives much information regarding the distribution of these rocks, although he is in error in supposing that the shales of the Glenbrooke section were Devonian. It is true, as he said, that "the fossiliferous Silurian is overlain by a series of brownish-gray, somewhat dolomitic flaggy slates and shales" (1896, p. 8J). Ells did not know that the "fossiliferous Silurian" was merely a limestone member (here called the Knowlton Landing member) within the shale series. Being misled by Ami, his conclusions were quite justified.

Indubitable evidence of the Silurian age of the shales of the Glenbrooke section was first found by Harvie who in 1912 (p. 289) published a report by Raymond, which

is well worth quoting in full.

"The following species were determined:-

Dalmanites lunatus, Lambert; abundant.
Dalmanites, sp. ind.; probably new; common.
Calymene, sp. ind.; rare.
Bronteus pompilius, Billings; rare
Ceratocephala, cf. C. goniata, Warder; rare
Chonetes, sp. ind.; rare
Coelidium, sp. ind.; rare
Operculum of gastropod, like that referred to Oriostoma by Kindle
Orthoceratites, indeterminable; common

"Trilobites form the most important part of this collection. The specimens of cephala and pygidia are numerous, and though distorted, fairly well preserved. The most common one is very similar to Dalmanites pleuroptyx, Green, but differs from that species in having fewer rings on the axial lobe of the pygidium and fewer ribs on the pleural lobes. It is, therefore, referred to Lambert's species, described from the Silurian at Littleton, New Hampshire (Bull. Geol. Soc. America, Vol. XV, p. 480, 1904.) The other species of Dalmanites, represented only by pygidia, is characterized by its rounded outline, the absence of a caudal spine, and the few (about 10 - 13) rings and ribs (8 - 9) on the pygidium. The presence in this fauna of a Calymene and a Ceratocephala of the type C. goniata indicate the middle Silurian age of the strata at this locality.

"The fossils from a second locality, a little higher in the section, are mostly indeterminable. The pygidium of a species of Encrinurus was recognized, and some of the Orthoceratites are identical with those in the lower beds."

Trilobites are quite common within a few feet of strata. They are mostly preserved as limonitic impressions upon the surfaces of highly fissile shales, and great care has to be taken to preserve them from disintegration. Our own collections are essentially similar to Harvie's, and substantiate Raymond's conclusions as to age.

Other exposures. From Sargent Bay northwards the shales of this formation may be followed almost to the northern limit of the map, where the last exposure, within a mile of Malaga Pond, is seen on plate . No conglomerate is exposed hereabouts, though there are exposures two miles to the southwest. In this western trough a wide expanse of shales can be seen west of Vale Perkins, and the synclinal axis of the fold passes near the point of highest elevation. The shore all around Knowlton Landing and Sargent Bay abounds in outcrops of the siliceous flaggy shales. The eastern trough nowhere shows such a complete section as that in the vicinity of Knowlton Landing. ~~[illegible]~~

A little more than half a mile east of the four corners at East Bolton and north of the road is an outcrop of sandstone with a few calcareous shale layers belonging to this series. The importance of this outcrop is that the sandstone is scarcely cleaved at all, whereas the underlying slate, well seen on the east slope of the hill is strongly cleaved. Moreover the stratification and dip of the sandstone bear no relation whatever to those of the slate or to its cleavage, thus indicating more clearly than any other outcrop the complete independence in time of the first folding of the slate and the later folding of the Silurian series. The strikes of the sandstone here do not accord with the regional strike but rather tend towards E-W, as might well be the case close to the base of a syncline.

There is an unusual occurrence of this shale in a roadside cut one mile northeast of Peasley Pond. The rock here is deeply weathered, so much so as to make it probable that the weathering was pre-glacial, or at least pre-Wisconsin. In a vertical section of about two feet it is possible to see the transition from fresh shale below to a reddish structureless clay above. Several feet of till lie in a superior position. Nowhere else has any transition between soil and shale been seen. Glacial action in this locality did not remove all of the residual soil cover and upon the disappearance of the ice

a deposit of till remained unconformably upon the weathered products.

Knowlton Landing Limestone Member. In two localities a black poorly crystalline limestone can be seen within two hundred feet of the base of the Silurian series. One of these is along the shore of the lake a few hundred yards south of Knowlton Landing. There the limestone contains a great abundnace of Favosites and other corals, squeezed brachiopods, Meristina, rhynchonellids, etc., and a few kinds of bryozoa. Enough of this fauna has already been studied to fix its age as Silurian, though the precise horizon must await further paleontological investigation. This is the locality mentioned by Ami (Ells, 1896, p. 154J). About a mile and three-quarters south of Knowlton Landing on the north bank of a creek that crosses the road to Vale Perkins, an abundance of limestone blocks and fragments occur in what must be practically their true position. To the east is metabasalt, followed by 17 feet of conglomerate, 29 feet of grits and sandstone, then 70 feet of shales, then a gap of about a hundred feet, whereupon these limestone fragments occur. They are therefore in almost exactly the same position as the limestone on the shore at Knowlton Landing, and there seems to be no reasonable doubt as to the equivalency of these two limestones. Such limestone has been recognized nowhere else, making the lenticular nature of it certain, and because it occurs within the shale formation, it can be considered as nothing more important than a member. It

is even questionable whether it deserves any more important classification than "lens" or "lentil", or, for that matter, any special designation at all, but it seems best, for the purpose of clarification, to give it a name.

Besides abundant crinoid stems, corals are the most important unit in the fauna. Meristina and one or two other brachiopods are present and also Fenestella with other bryozoa. Ostracods abound. In all the fauna is not unlike that of the Knowlton Landing locality except that Favosites and Wilsonia are rare rather than abundant.

Its thickness can only be estimated at twenty to thirty feet.

Limestone.

Distribution. On the Glenbrooke section the Glenbrooke shale grades upwards within ten or twenty feet to a dark, rather pure, dense limestone, which weathers light bluish gray. This is the highest formation exposed here, and in fact on the entire western side of the lake. Because it occurs along the synclinal axes of the troughs, only a minimum thickness can be given for it. The section at Glenbrooke will suffice, for although it is well shown elsewhere, this is the only place where it outcrops continuously. The figures refer to breadth of outcrop. The section is continuous with that given on page 52.

1760	810	- End of outcrop
1540 - 1760	590 - 810	Shale with limestone lenses giving way to shales, all of the Glenbrooke formation.
1400 - 1540	450 - 590	Predominantly pure limestone
1362 - 1400	412 - 450	- no exposures
1300 - 1362	350 - 412	Alternations of limestone with thin shaly beds
1285 - 1300	335 - 350	Shale
1200 - 1285	250 - 335	Heavy bedded pure limestone
1140 - 1150	(190 - 200)	Beds much disturbed by sharp folds
1087	(137)	Several blocks of light and yellow limestone in intraformational conglomerate.
1000 - 1200	50 - 250	Limestones with occassional bed of brown weathering shale. Limestone is somewhat argillaceous
990 - 1000	40 - 50	Brown weathering shales predominate over limestones
950 - 990	0 - 40	Pure limestones, with occasional beds of shale especially in lower portion.
		Shales of the Glenbrooke formation

The total exposed breadth of outcrop of this limestone is therefore 590 feet. Nothing in the attitude of the beds indicate the center of the syncline. The zone of folding indicated in the section as given above may also be accompanied by faulting, eliminating on the western limb the shaly beds (335 - 350 and shaly interbeds from 350 - 412) seen on the eastern limb. In such a case, which is a purely hypothetical one, the exposed thickness of the limestone would be somewhat more than half the breadth of outcrop. Unless such elimination can be proved, however, 290 feet (allowing for the dip) should be considered the thickness. ~~The section is continuous with that given on p. 59.~~

Thus in this section we have an almost continuous section as follows:-

limestone	290	feet	
Glenbrooke shale	900	"	
Peasley Pond conglomerate	140	"	(187 at Peasley Pond)
George Pond breccia	700	"	
Total Silurian section	2130	"	

Fossils. In one or two localities only have fossils been found in this formation. Crinoid stems occur west of the road from Knowlton Landing to Vale Perkins, and a few obscure brachiopods near Millington. There is no faunal evidence to place this formation into the Silurian. Its gradation into the Glenbrooke shale below is presumptive evidence of its Silurian age.

Extent. The most northerly outcrops along the western trough occur just east of Millington. Thence south-southwestwards they may be seen north and west of Sargent Bay and as far as a mile south of Knowlton Landing. On account of the construction of the syncline from Knowlton Landing southwards it is unlikely that this limestone occurs more than a few hundred feet south of its most southerly outcrop. Northwards from Millington, however, the trough is more than a mile wide, and unless crumpling prohibits it, the limestone should be present beneath the drift to and possibly beyond the swamp east of Peasley Pond.

The eastern trough shows this dove colored limestone at several places along the west shore of Lake Memphremagog from Green Point southwards to about a mile north of Bryant Landing, where the Glenbrooke shale occupies the shore southwards. Inland, however, limestone can be seen on the east-west road north of Green Point, and to the west of the main road half-a-mile south of Bryant Landing. Further south, at Mountain House wharf, black limestones resembling the Knowlton Landing member, with an identical fauna occur. Some parts of these, however, may after later paleontological investigation prove to be distinct and to belong to the limestone.

Insert p. 62a

Stanstead Granite.

East of Lake Memphremagog there occur large areas of a muscovite-biotite intrusive which has been called the Stanstead granite. Though nowhere cutting Silurian or Devonian rocks this granite has always been considered Devonian or later in age, partly because it shows no secondary adjustment to folding, whereas the Silurian (+ Devonian?) limestones and shales on that side of the lake are folded, squeezed, and recrystallized, Two hitherto unnoticed outcrops of this granite occur on the west side of the lake, along the shore opposite Round Island. Their relation to the adjacent metabasalt cannot, unfortunately, be seen. Elsewhere, granite or granite like intrusives occur, but cannot be related to the Stanstead granite to the east.

Insert on p. 62

There is considerable doubt about the age and relations of this limestone at Owl Head. Harvie (1914, p. 214) described the occurrence as follows:- "a triangular area of rocks consisting of limestone apparently lying on black graphitic shales, is found in faulted contact with the igneous rocks of the mountain." He also (1914, p. 215) quotes Kindle's report on the fossils from the locality as follows:- "The collection includes the following species: Crinoid stems, Favosites cf. basaltica, Favosites sp., Zaphrentis sp., Spirifer cf. arrectus, Actinopteria?, Panenka....?, Proetus ... sp.

"The deformation and partial metamorphism of all the material render any determinations beyond generic, highly problematic except in the case of one of the two species of Favosites which is either identical with or closely related to F. basaltica. The very poor state of preservation of the fauna prevents close comparison with other faunas and the most that can be said regarding its correlation is that it is highly probable but not entirely certain that the fauna is of middle or lower Devonian age."

STRUCTURAL GEOLOGY

Although many conditions obtain to complicate it, the general structure of this region can be called a synclinorium. The Mansonville slates lie on the west, succeeded eastwards by the younger Memphremagog slates which extend to and beyond Lake Memphremagog. Further east, Kerr has reported older sediments (his Bunker series) which he tentatively assigns to the Lower Cambrian, without, however, any paleontological evidence. Along the middle line, more or less, of this strip there occur two main synclines of Silurian beds. Both sides of the lake there occur areas of the Bolton Igneous Series, of which there are far more on the west side than on the east.

Folding

The pre-Silurian sedimentary rocks of the Memphremagog synclinorium are in places much distorted. In the Mansonville series a mile and a half northwest of Mansonville village the quartzites are squeezed into tight folds and the interbedded slate shows only as streaks here and there. In most places where the quartzite of the Mansonville series can be seen it is thick enough to have withstood contortion, although it is isoclinally folded so as to show in some places as one band, in others two, three or four. The adjacent slates have suffered

in two ways. In some cases intense crumpling has robbed them of all semblance of their original structure, in others, probably the more abundant in at least their western part the cleavage and stratification coincide yielding cleavage-stratification surfaces several square yards in extent along road cuts.

The Memphremagog slates are everywhere intensely crumpled. Quartzite beds are common but thin, rarely more than a foot thick. These beds have been broken by folding, sometimes squeezed or pulled out, so that their remains give one the impression of quartzite boulders in a slaty matrix. The complications seem to increase as one goes eastward, or towards the axis of the synclinorium. The cleavage of these slates is nowhere as clean as it is in the Mansonville slates further west.

The Bolton igneous rocks show in several places that they have been folded. Wherever pillow structures occur the pillows are more or less steeply inclined, in some cases they are vertical, in no case are they even approximately horizontal. On the east side of Owl Head is a layer of breccia, such as might result from the fragmentation of a lava flow roof and not one that might be confused with the George Pond breccia, which dips 30° or so eastwards. Just west of the Travor Road railroad station there is an outcrop of metabasalt

showing vertical flow structure beautifully. All the evidence therefore conspires to show that these metabasalts, whose original pillows, breccias and flow structures were essentially horizontal, have been folded so that in part at least they have been brought up on edge.

The Silurian series lie unconformably upon the Bolton and Memphremagog series, and occur in two well marked synclines and a few small additional patches. Within the synclines the bedding is uniformly steep, 75° to 90°, except in some outcrops near the axis of the western trough, where dips approaching zero can be found.

The southern part of the western trough is a simple syncline, pitching somewhat to the north, so that the limestone, the youngest member, outcrops along the middle a mile or so south of Knowlton Landing. From the latter place northwards, however, the width of the outcrop of the Silurian rocks is too great to allow one to think of it as a simple syncline. Especially is this true when one considers that at Knowlton Landing the limestone outcrops only at its expected distance from the western margin of the trough, but three quarters of the width of the trough from the east side is occupied by the Glenbrooke shale. The expected structure is a compound syncline such as this.

The median anticline would, on account of the southerly pitch at the northern end of the trough result in the reentrant shown southeast of Malaga Pond. That this structure does not progress smoothly from one end to the other is shown by the widespread occurrence of the limestone west of Peasley Corners, where apparently the structure is as follows:

Whereas at Millington the eastern of the two secondary folds seems to have become the dominant one for there we find the limestone restricted to the eastern position, the western two-thirds being entirely Glenbrooke shale. The swamp east of Peasley Pond may possibly conceal the presence and reveal the existence of the limestone there, but all indications point to the disappearance of this western trough before the northern boundary of this map is reached.

Of the main trough not much can be made out at present, because approximately one-half, and for the most part the central half, of it is under the waters of Lake Memphremagog. Nevertheless it can be said that from the northern boundary of this map area a synclinal axis passes southward from a position under water to the general vicinities of Green Point and Spinney Point. Thence it passes inland and can be picked up about half-a-mile west of Bryants Landing. Whether it ends towards the southsouthwest, as shown, or whether it turns to cut across the shore north of Gibraltar Point cannot be definitely settled. Still farther north, on the east-west road going down to the shore north of Green Point, there is an outcrop of the limestone which indicates another synclinal axis. No evidence of the extension of this axis north or south can be seen. On the east side of the lake these mid-Paleozoic sediments occur over a belt in places a mile wide, but it is not at present

possible to work out synclinal axes. Moreover the strata on that side are far more metamorphosed than those on the west side, in places the limestones are entirely crystallized.

The lack of overturning of the folds affecting these strata is significant. They lie in what has been called a synclinorium. What lies to the east of this structure is at present unknown. Westwards lies the massif of the Sutton Mountains, an anticlinorium, and still west of that thrust faulting and overturning towards the west are the rule. Apparently little mass movement was allowed in the Sutton Mountains or the Memphremagog synclinorium, whereas further west, where the resistance was less, bodily shoving was possible. It would be interesting to know what would be found further east, but so far that region is terra incognita.

Cleavage.

The pre-Silurian sediments contained in the synclinorium are isoclinally folded in all exposures in which there is any evidence of the relation between cleavage and bedding. On this basis the cleavage is probably the axial plane type.

Proceeding east from the Sutton anticlinorium (section EE') the cleavage dips steeply east across the Bolton mountains but becomes approximately vertical in a zone along the west shore of Lake Memphremagog. East of the lake the cleavage dip is uniformly west. The axis of the synclinorium thus lies in

the zone of vertical cleavage (cf. Oak Hill anticlinorium, described in an earlier report.). The axial planes of the isoclinal folds, as represented by the cleavage, diverge upward and the structure corresponds to an abnormal synclinorium as defined by Van Hise.

The Bolton igneous rocks are schistose in many places, especially the metabasalt along the railway between South Bolton and Mansonville, and at the summit of Owl Head. The metaperidotite fractures very irregularly but the dominating breaks conform to the regional structure.

In the Silurian series cleavage is poorly developed, but its dip is the same as that of the pre-Silurian rocks in every locality where comparison can be made. The Silurian, therefore, forms an integral part of the abnormal synclinorial structure. Both cleavage and bedding are uniformly straight and contrast with the contorted structures of the older rocks.

Normal Faulting.

Owing to the crumpled nature of the Mansonville and Memphremagog series, and the sparseness of outcrops, little can be learned regarding faulting within those formations. Numerous faults of the tear type are shown dislocating the western side of the western trough of Silurian rocks. Not one of these faults was seen. All are introduced as explanations of the repeated offsetting to the west of this boundary as one follows it northwards. Some indication of this can be seen on

the eastern boundary, but no such offsets can be recognized in the main (Lake Memphremagog) trough. Minor transverse faults shifting the conglomerate band a few tens of feet can be seen north of the road three-quarters of a mile northwest of Vale Perkins.

Two isolated outcrops of the Silurian series owe their positions in all probability to faulting. One of these is at the abandoned Mountain House wharf, the other about three-quarters of a mile south, along the woods road. With regard to the first of these, the contact between the shales limestones and the metabasalt of Owl Head to the northwest is quite obviously a fault, although there is no reason to suppose that the sedimentaries are far from their normal position. There is no reason to describe the contact on the southeast as a fault or as a normal sedimentary contact. Because, however, there is no room for the basal beds in between the shales and metabasalts to the southeast, a fault is introduced here too.

Further south, along the abandoned road leading to the old wharf are isolated patches of Glenbrooke shale. Lacking all evidence necessary to decide, this has been shown as a sedimentary remnant in place.

No thrusting is known in the area.

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 known connection with igneous activity. The first includes the metamorphism effected by the metabasalt, the metaperidotite, their parent magmas and their derivatives, and also by the Stanstead granite; the second includes the regional metamorphism of the sedimentary series. The late Devonian intrusives are unaltered, so that they are not considered in this discussion.

Three metamorphic processes, thermal, dynamic, and hydrous, are responsible for the changes brought about in these rocks. Thermal metamorphism of group (A) above 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 considers the 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.

Bolton Metabasalt. Metabasalt is the most widespread of the late Ordovician igneous rocks in the area. There is a minor amount of metagabbro associated with it but as the petrography of the two types is similar they are considered together in this discussion.

There are two types of alteration common to the metabasalt represented (1) by a green uralite rock occurring over most of the area, and (2) by a buff-colored ankerite found in scattered patches in the green rock. Field relations show these types to grade into one another.

Chemical Relations. Chemical analyses of composite samples of each type are shown in columns 3 and 5 of the accompanying table. The main difference in the two analyses is in the quantities of CO_2. The question arises - Is the ankerite rock developed by addition of CO_2 to local parts of the uralite rock or has it been a separate type of alteration from the beginning? If the former condition holds ankeritization is a later process than uralitization; if the latter, the two may be contemporaneous.

	Daly's average of 43 plateau basalts	Daly's average of 198 basalts	Uralite rock	#3 re-calculated	Ankerite rock	#5 re-calculated	Average Spilite (Sundius)
	1	2	3	4	5	6	7
SiO_2	48.80	49.06	49.44	51.07	42.64	48.23	51.22
TiO_2	2.19	1.36	1.43	1.48	1.04	1.17	3.32
Al_2O_3	13.98	15.70	15.92	16.44	14.42	16.24	13.66
Fe_2O_3	3.59	5.38	2.33	2.40	2.25	2.53	2.84
FeO	9.78	6.37	8.11	8.38	7.41	8.35	9.20
MnO	.17	.31	.10	.11	.07	.08	.25
MgO	6.70	6.17	6.10	6.30	6.03	6.79	4.55
CaO	9.38	8.95	8.20	8.47	7.20	8.10	6.89
Na_2O	2.59	3.11	3.06	3.16	2.65	2.98	4.93
K_2O	.69	1.52	.50	.52	.41	.46	.75
H_2O	1.80	1.62	3.40	1.62	2.58	2.91	1.88
CO_2			1.31		12.52	1.31	.94
P_2O	.33				Organic matter present		.29
	99.90	99.55	99.90	99.95	99.22	99.15	100.72

Analyses 3 and 5 by F. A Gonyer, Department of Mineralogy, Harvard University.

In column 6 of the table the ankerite rock analyses is re-calculated on the basis of equivalent CO_2 to that found in the uralite rock analysis of column 3. The comparison turns out by inspection to be remarkably good for all constituents and indicates no essential change in composition between 3 and 5

except addition of CO_2. If ankeritization had been a separate process from the beginning it is improbable that this re-calculation would so closely parallel the composition of the uralite rock. The conclusion is that uralitization is an earlier stage of metamorphism and that, locally, excess CO_2 ankeritized parts of the uralite rock.

Column 2 shows Daly's average composition of 198 basalts. A comparison with the uralite rock analysis of column 3 shows a general similarity except for H_2O and CO_2. To make the comparison more direct column 4 shows the uralite rock analysis re-calculated on the basis of zero CO_2 and 1.62 per cent H_2O. The degree of similarity is practically the same. The ratio of Fe'' to Fe''' differs considerably but the amount of total Fe is practically the same in each case.

There is thus chemical evidence for assuming that these rocks were largely basalts which have since been uralitized and locally ankeritized by addition of H_2O and CO_2. Microscopic evidence (p.) shows remnants of ophitic texture in the metagabbro types, and broad albite twinning bands remaining in the albitized plagioclase. Field evidence (p.) includes abundant pillow structure. All these data, while not conclusive in themselves, strengthen the case for basaltic flows with associated gabbroic phases.

Source of H_2O and CO_2. The conception of autometamorphism advanced in recent years to explain the albitization of feldspar in spilite appears to be the most reasonable hypothesis for the uralitization of the Bolton metabasalt. In the type examples there is considerable change in bulk composition as well as in the mineral association but in this case the chemical evidence shows that there has been no essential change in bulk composition. Autometamorphism, literally, means that the magma, in this case basaltic, possessed within itself all the materials necessary to form the secondary minerals now occurring in it. It is a particular case of endomorphism. The Bolton magma would thus contain H_2O and CO_2 equivalent to that in column 3 of the uralite rock. Cooling commences upon extrusion of the lava and typical basaltic minerals, labradorite, pyroxene, olivine, etc., crystallize. The residual magma becomes increasingly charged with H_2O and CO_2 and at some fixed PTC of the cooling system the stability field of each primary mineral is passed and crystallization of secondary minerals, actinolite, epidote, albite, etc. proceeds by decomposition of the earlier ones. The process continues until the H_2O and CO_2 are used up. It may be asked why these volatile constituents do not escape immediately the lava is extruded and so prevent autometamorphism. The Bolton metabasalt is uralitized fairly uniformly and uniform conditions are necessary to explain it. Its thickness is unknown but is probably of the order of several thousand

feet. Moreover the existing portion represents the erosional remnants of its base. If extrusion occurred rapidly in one stage there would be relatively little loss of volatiles in this basal portion. There is some support for this hypothesis in the scarcity of amygdules in the rock indicating that the confining pressure was too great to permit vesicles to form.

Ankeritization is more difficult to explain by autometamorphism. Bruce and Hawley (1928) and Cook (1922) describe carbonatization of greenstones in the Canadian Shield in which the field evidence definitely shows a connection with later intrusives as the source of the CO_2. Cook states in addition that shear zones localize the process by providing channelways. In Southern Quebec the field relations do not show that ankeritization is related either to later intrusives or to shear zones. The known exposures of carbonatized metabasalt are small, few in number, and irregularly distributed. In view of the field and chemical data, therefore, it is a simpler conception to derive the CO_2 from the same ultimate source as the CO_2 connected with the earlier uralitization.

It is difficult to conceive of the large amount of CO_2 necessary for ankeritization being segregated from the cooling lava in so few localities and in such concentration. It seems more reasonable to assume that a fresh supply was obtained through the fissures or vents from which the lava was extruded. Under suitable PTC conditions ankerite would

be stable rather than the uralitic mineral association and limited areas of metabasalt in the neighborhood of such fissures would be ankeritized.

The possibility of such a condition is indicated in one dike-like exposure of metagabbro. As the present erosion surface is practically the same as that upon which the Bolton lavas were extruded it is believed that these bodies were the feeders to the flows. This particular one, about 100 feet across, is elongated strikewise and grades from uralitized to ankeritized metagabbro across the strike. It may represent an uncovered fissure through which came an excess of CO_2 from the magma reservoir below to ankeritize uralitized rocks now eroded away. Whatever the merits of this one, some similar hypothesis must be used to satisfy the field and mineralogic relations of this phase of the metabasalt.

Mineral Association and Paragenesis. The accompanying table (B) gives approximations of the abundance of the minerals found in both uralite and ankerite types of metabasalt. In the uralite rock albitized plagioclase is calculated as pure albite for simplicity and takes up all the Na_2O, calcite uses all the CO_2, K_2O is all given to sericite, and TiO_2 to titanite. In the ankerite rock sericite and albite are calculated similarly. The amount of Fe" in ankerite is approximated from the average value of ω and the percentage of the mineral is then deduced by allotting

p. 103

to it all the CO_2. The remaining mineral percentages in both rocks are estimated from the thin sections.

Table A shows the main trend of the paragenesis from typical basalt minerals through the uralite to the ankerite stage of metamorphism. Olivine is included on the basis of a few remnants which occur in a porphyritic phase of the basalt. (p.). It may not, however, be a characteristic mineral.

H_2O and CO_2 are considered to be the chief additions to the rock. Other constituents may have been added or subtracted but the study of chemical analyses shows that such changes are of little relative importance. No attempt is made to be quantitative by writing chemical equations but certain features of the changes are striking. Microscopic evidence is given on pages and need not be repeated here.

Calcic plagioclase, probably near labradorite, loses much of its anorthite molecule so that a high-Na_2O plagioclase remains, albite to oligoclase in composition. The small amount of K_2O it contains may also be released to form the fine sericite flakes associated with the albitized feldspar. CaO from the anorthite molecule probably combines with H_2O and the other constituents necessary to form epidote and clinozoisite. The latter is especially abundant and indicates a low content of Fe'''. This may be due to abundance of olivine in the basalt or to reduction of Fe''' during the alteration.

Table A - Paragenesis of Bolton metabasalt

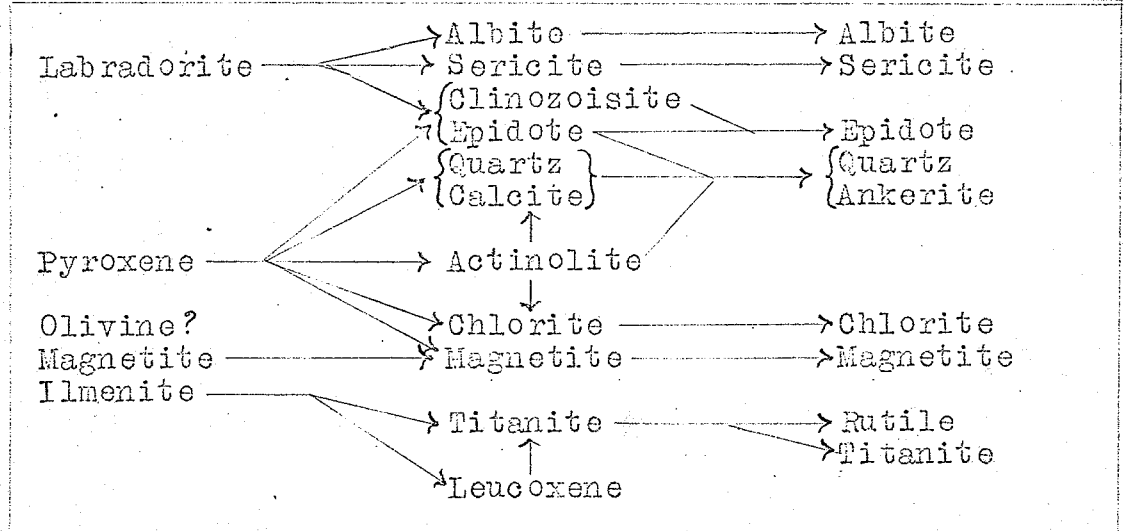


Table B - %age of Minerals

Mineral	Uralite rock	Ankerite rock
Albite	23	20
Chlorite	20	20
Actinolite	20	-
Epidote	} 20 {	.5
Clinozoisite		-
Quartz	5	20
Calcite	4	-
Ankerite	-	34
Sericite	4	3
Titanite	3	1
Rutile	-	1
Apatite	-	.5
Sulphides	1	.5

Table C
Average SiO_2 values

Pyroxene	55
Olivine	25
Anorthite	43
Actinolite	60
Chlorite	30-35
Epidote	40
Albite	65

The relations of SiO_2 throughout the metamorphism are significant. In Table C the average SiO_2 values for the principal silicates are listed. In terms of paragenesis pyroxene to actinolite requires a slight increase in SiO_2 and olivine to actinolite or chlorite requires a considerable increase. On the other hand, pyroxene, olivine, or actinolite going to chlorite release much SiO_2, and the anorthite molecule of labradorite going to epidote releases a little. The amount of free quartz in the uralite rock averages about five per cent, and assuming no introduction of SiO_2 means that the epidote-chlorite types of reaction predominates to a slight extent. There was thus a slight excess of SiO_2 when the metamorphism ceased. The chemical data indicate no substantial change in constituents except for addition of H_2O and CO_2 and thus support this view.

Proceeding further with the paragenesis the ankerite rock contains no actinolite, no calcite, and almost no epidote. Albite and chlorite remain about constant in amount; there is a great increase in quartz, and a new carbonate, ankerite, appears in large amount. The conversion of Ca-Mg-Fe silicates to carbonate releases a great deal of silica, and, as albitization has largely been completed at an earlier stage, the silica remains as quartz.

The amount of Fe" in the ankerite is dependent on the amount of chlorite formed, which is in turn dependent

on the amount of iron in the rock. The comparison of chemical analyses indicates that total Fe is comparable to that of an average basalt but that the early metamorphism to uralite rocks may have involved reduction of much of the ferric portion. The later metamorphism to ankerite indicates no further essential change in the proportions of Fe''' and Fe''. It is interesting to note that clinozoisite, although more abundant in the uralite rock than epidote, is absent from the ankerite rock and only a few grains of epidote occur. The tendency for reduction of Fe''' seems to have been small.

The paragensis of magnetite and the titanium minerals is of major importance and the main trend is shown in Table A. A probable ex-solution relation between magnetite and ilmenite is described on page .

Volume Relations. It is well known that uralite rocks are slightly lighter than fresh basalt. Approximate gravity determination of the Bolton metabasalt show that the ankerite rocks are slightly less dense than the uralite type. This progressive decrease in gravity from basaltic to urlaitic to ankeritic is in harmony with the interpretation of the chemical data which assumes additions of H_2O and CO_2 as the principal change during metamorphism. It is reasonable to assume, therefore, that there has been a progressive increase in volume by addition of these light constituents.

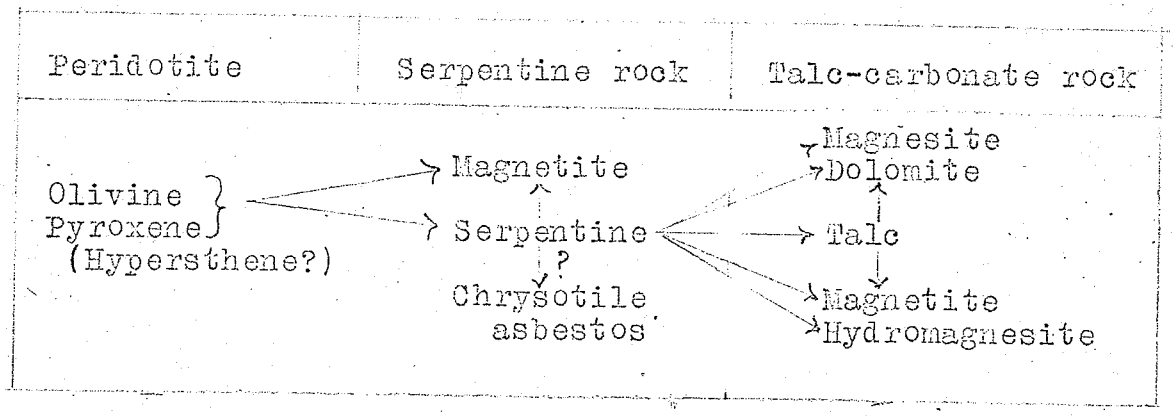
Bolton Metaperidotite and Derived Rocks. There are four subdivisions to be considered in this group - (1) the metaperidotite itself in which there still remains abundant remnants and pseudomorphs of pyroxene, olivine, etc., (2) serpentine, which forms a rock dominantly of that mineral with, in places, 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.

Insert # on p. 82 a

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 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.



The field evidence of 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 (1923) 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 (1932), 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 probablity 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 the 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 a quarter of an 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_2. 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 <u>vice versa</u>. 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 distances 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. For further discussion of the part played by albite in the regional metamorphism of the Sutton schists see the previous report, pp. 125 - 130.

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 (1915). Dynamic and hydrous metamorphism varied considerably but the thermal conditions were rather uniform.

Mansonville and Memphremagog Series. These two series, the Mansonville dominantly quartzite, the Memphremagog dominantly slate, lie east of the Sutton series. No adequate petrographic examination has been made of these rocks but the field evidence indicates that quartz, mica, and chlorite are the essential minerals and that these three minerals occur in approximately the same proportions as in the Oak Hill and Sutton series. The quartzite is not completely recrystallized and the slate is crumpled and fine-textured. In general the metamorphic conditions in these two formations appear similar to those of the Oak Hill series and contrast in the same way with the Sutton series.

Field study shows that the Mansonville series is not albitized and in traversing east across the Sutton-Mansonville contact there is an abrupt change from chloritized and albitized schist to gray quartzite containing accessory mica and chlorite. There is not believed to be any great break between these two formations and thus an explanation of the difference in metamorphism is necessary. From a knowledge of the metamorphism of the Sutton series it may be explained as follows:- The chloritized and albitized schist just west of the contact coincides with a zone of peridotite intrusion which now outcrops at intervals of a few miles as small talc-serpentine bodies. The exomorphism which accompanied the formation of talc resulted in the chloritization and albitization of the schist in this border zone. The solutions penetrating the adjacent quartzite were incapable of any marked replacement on account of the small amount, or entire absence, of Al_2O_3 in this rock. Chloritization precedes albitization and these early solutions, by utilizing all available Al_2O_3, would prevent the later Na_2O-bearing solutions from forming any albite. This is quite analogous to the lack of chloritization and albitization in quartzite beds in the Sutton series and seems to be an adequate explanation of the relations as seen in the field.

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. His 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 described 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 above, 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 as autometamorphic 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 necessarily independent variables.

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

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 on the contrary are "passive", i.e. C and T_x are fixed for any given metamorphic facies, and it is axiomatic that 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 alteration 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.

OROGENIC PERIODS

Introduction

Three main periods of diastrophism are evident in the Paleozoic rocks of Eastern North America - (1) the Taconian of late Ordovician time, (2) the Acadian in late Devonian, and (3) the Appalachian in Permian time. Of these, the Appalachian is best established and most generally recognized and the Acadian is almost as well entrenched in geologic thought. The Taconian has, until recently, been an outcast around which what seemed at one time might become an endless controversy has arisen.

In Southern Quebec the present study shows that the Taconian is the most important period of diastrophism, the Acadian is second, and evidence of the Appalachian revolution is lacking altogether. Nothing is known of pre-Paleozoic orogeny as there are no proven pre-Cambrian rocks in the area, except the Tiblett Hill schist of the Sutton quadrangle.

Taconian Orogeny. The history of the Taconian question is reviewed in my recent paper (1921). The summary shows that most of the so-called "evidence" is inconclusive except in certain localities in New York. The supposedly critical localities usually show slightly metamorphosed Silurian or Devonian overlying highly metamorphosed unfossiliferous slates. It is accepted by most workers that there was a pre-

Silurian or pre-Devonian period of orogeny in the Paleozoic but there has been little evidence of its exact date until recently. That evidence is now accumualting and, among other localities, has been found in Southern Quebec.

The evidence of Taconian orogeny in Southern Quebec is three-fold - structural, paleontologic, and metamorphic. Much of it is given indirectly in previous chapters, and it is summarized here.

Structural evidence. (1) Two elongated basins of conglomerate, shale and limestone known as the Silurian series lie within black graphitic graptolitic slates of the Memphremagog series. One locality, in which the two series outcrop within a few feet of each other, shows an abrupt divergence in strike and dip which is difficult to explain except as an angular unconformity. (2) Pebbles and blocks of the Memphremagog quartzite and slate, together with fragments of the Bolton metabasalt and metaperidotite, occur in the basal layers of the Silurian rocks. (3) The Bolton metagabbro is known to cut the Memphremagog slates. Thus the order of deposition of these three series is apparent, and a summary of structural evidence indicates an angular unconformity between the Memphremagog series and the Silurian sediments.

Paleontologic evidence. The time limits of the

unconformity between the Millington and Memphremagog series are fixed by the evidence from fossils. Graptolites collected at several localities in the Memphremagog series show that it is Trenton, and a varied fauna of corals, brachiopods, etc. in the Silurian place it, in part at least, as early as Niagaran. The break in deposition between the Memphremagog and Silurian series thus represents the time between Trenton and Niagaran but the break between the Bolton metabasalt and the Silurian represents a shorter interval. There is no direct evidence here of anything more than a time gap.

Metamorphic evidence. A direct comparison of the metamorphism of the Memphremagog and Silurian series is possible as they both contain rocks which were originally fine-textured muds. The Ordovician mud is now without exception a well cleaved slate and usually crumpled. Although a weak secondary cleavage can usually be seen, the Silurian mud is on the whole only a shale. No sandstones occur in the Memphremagog series, only quartzites, whereas in the younger rocks friable sandstones are common near the base. Moreover, the Bolton rocks, though somewhat cleaved, are in comparison to the adjacent Memphremagog and Mansonville slates, practically unmetamorphosed from the structural point of view.

The combined evidence indicates beyond doubt that diatrophism occurred between Trenton and Niagaran time.

Acadian Orogeny. A second period of folding occurred in this region late in the Devonian period, and it is accordingly correlated with the Acadian orogeny. There is, it must be said, no direct evidence, in this area, that the folding of the Silurian beds was not delayed until the close of the Paleozoic, but a glance at Schuchert's (1930, p. 709) map of the areas affected by the three Paleozoic orogenies shows the improbability of this region having been affected at all towards the close of the Paleozoic. From the vicinity of Lake Memphremagog northwards along the strike there are outcrops of fossiliferous shales and limestones, all of which are Silurian or Devonian, and there is not one Carboniferous rock known this side of the Bonaventure conglomerate of Gaspé that antedates the regional orogeny. Coercive, if not cogent, evidence, indicates therefore that the folding was Acadian, and not Appalachian.

Conclusion. Recent investigation in Quebec demonstrating the validity of the Taconian indicate that a re-valuation of the extent and intensity of Paleozoic orogenies in Eastern North America is necessary. The predominance of the Appalachian revolution over the whole region is rapidly becoming a fiction which must be removed from geologic thought as soon as possible. The Taconian and

Acadian orogenies are of major importance, at least from Pennsylvania northeast, and the later Appalachian orogeny acted independently even crossing the earlier structural axes in Southern New England (Bailey, 1927). The whole problem must, therefore, be regarded from this new angle.

GEOLOGIC HISTORY

This chapter outlines the history of sedimentation, orogeny, and subsequent structure and metamorphism, and igneous action as far as 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.

Except for the later erosion and glaciation, the entire history of this area belongs to the Paleozoic Era. In terms of rock-making it can be divided very easily into four parts, as follows.

(d) Late Devonian. Intrusion of Stanstead granite

(c) Silurian and Devonian. Silurian and possibly Devonian sedimentation

(b) Late Ordovician. Formation of Bolton metabasalts, etc.

(a) Cambrian and Ordovician. Mansonville and Memphremagog series.

(a) Mansonville and Memphremagog series. According to Schuchert's paleogeography, the material of these sediments was derived from the New Brunswick geanticline to the southeast and was deposited in the southeast side of the St. Lawrence geosyncline. The accumulation of such a considerable thickness of clastic material indicates continuous upwarping of the geanticline and a corresponding downwarping of the sea floor.

Lower Cambrian sedimentation further west (Oak Hill series) was ended by upwarping of this part of the geosyncline

and it was a land mass during all of Middle Cambrian. In the Upper Cambrian there was submergence and deposition of one or two thousand feet of quartz sand with interbedded grit and clay mud, the Mansonville series. This was followed by several thousand feet of red mud and interbedded sand which, although not now exposed in Brome County, probably overlapped to some extent. These sediments can be seen to the north of our area. Their most southerly exposure is along highway No. 1, immediately west of Orford Lake, in line of strike with our Mansonville rocks.

It will be remembered that the limits of the Lower Cambrian sea were placed somewhat to the west of the axis of the Sutton Mountains. The region under consideration therefore was dry land, undergoing erosion while the rocks of the Oak Hill series, and still further west the Milton dolomite, were being deposited in the geosyncline. The renewed downwarping of Upper Cambrian time extended the shoreline eastwards until probably all of this area lay below water, whose eastern shore, indeed, may have migrated tens of miles eastward beyond the position of Lake Memphremagog. The presence near the base of the Mansonville series of heavy quartzite beds composed largely of quartz grains, indicates that the shoreline of the advancing sea could not

have been far away at the beginning of Mansonville time. Higher up in the Mansonville quartzite gives way to grits and those to mud slates, an indication that the shoreline had migrated further eastwards leaving quieter water behind in which the finer muds could be deposited.

Whether the Mansonville beds were ever succeeded by the red shales which outcrop further north or not, it seems likely that a period of erosion separated Mansonville from Memphremagog time. This interval is nowhere within the area marked by an unconformity or a conglomerate (see p. for comments on Dresser's Magog conglomerate). It is also, as has been discussed, uncertain as to what the time limits of the Mansonville series are. We have called it Upper Cambrian. By Ordovician time submergence again became the rule, the Ordovician sea spreading as far as and probably farther than the Mansonville sea. We say probably farther, because the sediments of this sea, herein called the Memphremagog slates, are predominantly slates, and though they occasionally show a thin layer of quartzite, the latter rock forms only a very small proportion of the whole series. Hence the shoreline was in all probability further east from the Memphremagog series than it was from the Mansonville series at an earlier epoch. We do not know whether this spread began in the Lower Ordovician or not, for the only fossils are of Trenton age.

Towards the close of the Ordovician mountain making made itself felt. The two slate formations together with their extensions eastwards and westwards of this area were thrown into folds, elevated, and the resulting (Taconian) mountains subjected to erosion. Before peneplanation was effected intrusion and extrusion of basic rocks occurred, peridotite and gabbro invading the sediments, and basalt pouring out over the surface of erosion then being developed. It is probable that this took place early in Silurian time rather than late in the Ordovician for reasons already explained. The lava flows accumulated in all probability to a thickness of a few to several thousand feet, probably completely blanketing the erosion surface developed upon the earlier Taconian mountains. Some of these flows probably poured into inland lakes, possibly of their own damming, thus developing the pillow structure so well shown in dozens of places. Endomorphic changes doubtless were initiated at once in the peridotite and the gabbro, and at the same time the uralitization and ankeritization proceeded within the gabbro and basalt.

Once more erosion began, this time to carve into the newly formed lava plateau. The next rock to be formed is proof enough that this erosion did not reduce the region to a peneplain, for the George Pond breccia has all the earmarks of a talus accumulation, and so indicates the

existence of considerable slopes, with youthful or mature river systems. There is the possibility that peneplanation had taken place, and that rejuvenation or faulting resulted in cliffs sufficiently high to result in talus accumualtions. The age of the George Pond has been considered to be Middle Silurian. Before this talus material could be swept away by rivers, (The preservation of the above mentioned breccia must be considered to have been fortuitous.) the Middle Silurian sea began its advance over the region, in which a basal conglomerate and sandstone was succeeded by the Glenbrooke shale and ultimately by the limestone, all of Middle Silurian age. Lacking more precise information regarding the limestones on the east side of the lake we cannot yet say how long this sedimentation lasted, but from one or two bits of paleontological evidence, lacking on the west side, there seems to be no doubt about the sea remaining thereabouts at least into Devonian time. Be that as it may, on the west side, the limestone, presumably of Middle Silurian age, is the latest Paleozoic sedimentary rock.

The intrusion of the Stanstead granite is the next event but it one whose exact age is hard to arrive at. Although it cuts fossiliferous Ordovician sediments, nowhere does it cut Silurian (or Devonian) beds. Nevertheless it does not appear to have been affected at all by the folding

that succeeded the deposition of the Silurian beds, and the intense metamorphism of the Silurian limestone on the east side of the lake might well be due to the granite. The metamorphism is most acute nearest the granite and grows less and less conspicuous as one goes away from it.

Diking accompanied the Stanstead granite intrusion, and also the Monteregian intrusions of later date. There is no record of other rock formations prior to the glacial deposits, of which no especial record was made.

ECONOMIC GEOLOGY

In spite of earlier high hopes, nothing has been found in this region to justify any extensive outlay of time or money or equipment save as noted below. Of the metallic materials found chromite, hematite, psilomelane, copper, galena, sphalerite, and of the non-metallics, talc, asbestos, serpentine, gravel, and limestone have been more or less successfully prospected for. No building stone of any value can be found here, except glacial boulders.

Chromite

At about one mile northnorthwest of South Bolton is one of the earliest prospects for chromite in the serpentine belt of Quebec. Chromite occurs in veinlets and disseminated throughout a serpentine, but although a fairly great amount of quarrying has been done, the amount of chromite does not justify further exploration. This occurrence does not appear to have been listed before. Other localities are given by Harvie (1912, p. 291).

Hematite

A short distance southwest of Millington (lot 9, Range IX, Bolton) hematite of the specular variety occurs in large lenses either pure or with considerable quartz. "The largest body is about 40 feet long and 7 feet wide at

the surface, but at the bottom of the pit 70 feet deep it is said to be 18 feet wide." (Harvie, 1912, p. 291).

Psilomelane

Though not in quantity sufficient enough to warrant exploration, psilomelane is known to occur in the meadows north of South Bolton.

Galena and Sphalerite

In the southeast corner of the area there is a mineralized zone extending from the lighthouse south of Round Island south to the international boundary, and inland for half-a-mile or so. Galena and sphalerite with minor amounts of pyrite occur in several spots, frequently in amounts that look attractive, but general surveys tend to discount the worth of the occurrences. Numerous pits have been dug on both sides of the road from Leadville southeastwards, with little success beyond an occasional rich-looking specimen. The most extensive of such workings occurs near the light, and is popularly called the lead mine, a name egregiously misplaced. Fairbairn (1932, pp. 26 - 27) states that "no further developments should be carried on unless there are indications of higher metallic values than are known at present".

Copper

Within this area numerous copper prospects have

been opened. These, with appropriate comments, have been described adequately by J. A. Bancroft (1915, pp. 152 - 186), to whose remarks nothing need be added except in the case of the Memphremagog, or Smith, Mine, situated on the northwest side of Hogsback Mountain. In addition to Bancroft's description which refers to earlier comments by Dresser, Wilson, and others, a recent report by H. W. Fairbairn, (1932, p. 26D) deserves quoting.

"There is insufficient chalcopyrite in this deposit to consider it a copper prospect. The known tonnage of pyrrhotite is likewise too low to warrant installation of a sulphuric acid plant. The only expenditure advisable at present would be for diamond drilling in order to learn something of the deposit at depth. Given a considerable increase in the tonnage of possible ore, the future of the property would then depend on marketing conditions for acid or on new uses for pyrrhotite."

Copper has also been discovered in insignificant amounts in the vicinity of Leadville (Fairbairn, 1932, pp. 26- 27D).

Asbestos

In several of the metaperidotite outcrops asbestos occurs to some extent. In none, however, is there enough to justify further exploitation. The most important of the

prospects is that about a mile and a half southsoutheast of Mansonville where a tunnel has been driven into the side of a hill, but is now abandoned. Considerable short fiber asbestos can be found in the dumps, but not enough nor of sufficient quality to justify mining. Harvie (1912, p. 292) mentions a deposit on lot 9, range VII, Bolton, and another prospect has been dug into near the shore of Grass Pond (lot 16, Range VII, Bolton), with indifferent results.

Serpentine

A recent survey of the metaperidotite outcrops carried out by the Vermont Marble Companies showed that none was capable of producing workable verd antique.

Limestone

The limestone has been burned for lime in several places north and south of Knowlton Landing. In earlier days, before high quality lime and mixed artificial fertilizers were available, local limestones were able to supply the whole amount of lime needed. At present no lime kilns are in operation.

Gravel

Along the Missisquoi Valley there is an abundance of gravel, presumably of late glacial date, of excellent

quality for road making. Of late years several miles of roads have been widened and completely resurfaced with local gravel in the vicinity of the valley. Further east, nearer the lake the glacial deposit appear to be for the most part unassorted, gravel is scarcer, and some of the roads as a consequence are deplorable.

BIBLIOGRAPHY

Many references to the Geology of this area can be found in the early Reports of Progress of the Geological Surgey of Canada. Only those which are of importance are listed here.

ADAMS, F. D.
Notes on the microscopic structure of some rocks of the Quebec Group.
Appendix to Selwyn, 1883 (see below).

BANCROFT, J. A.
Report on the copper deposits of the Eastern Townships of the Province of Quebec.
Province of Quebec, Mines Branch, Department of Colonization, Quebec, 1915.

CLARK, T. H.
Structure and stratigraphy of Southern Quebec.
Bull. Geol. Soc. Amer., 54, pp. 1-20, 1934.

COOKE, H. C.
Thetford map-area, Quebec.
Geol. Surv. Canada, Summ. Rept. 1930, pt. D, pp. 1-14, 1931

Asbestos deposits of Thetford area, Que.
Geol. Surv. Canada, Summ. Rept. 1931, pt. D, pp. 1-24, 1932.

DRESSER, J. A.
Igneous rocks of the Eastern Townships of Quebec.
Bull. Geol. Soc. Amer., 17, pp. 497-522, 1906.

Preliminary report on the serpentine and associated rocks of Southern Quebec.
Geol. Surv. Canada, Mem. 22, 1913.

The Magog Conglomerate; a horizon mark in the "Quebec Group.
Trans. Roy. Soc. Canada, (3), 19, sect. 4, pp. 115-121, 1925.

ELLS, R. W.
Report on a portion of the Province of Quebec comprised in the south-west sheet of the "Eastern Townships" map (Montreal sheet).
Geol. Surv. Canada, Ann. Rept., n.s. 7, pt. J, pp. 1-92, 1896.

FAIRBAIRN, H. W.
Some recent mining developments in Southern Quebec.
Geol. Surv. Canada, Summ. Rept. 1931, pt. D, pp. 25-27, 1932.

HARVIE, Robert
Geology of Orford map-area, Quebec, southern part of "serpentine belt," Bolton Township.
Geol. Surv. Canada, Summ. Rept. 1911, pp. 286-292, 1912.

Geology of Orford map-area, and the southern part of the "serpentine belt," Potton Township, Quebec.
Geol. Surv. Canada, Summ. Rept. 1913, pp. 212-216, 1914.

JOHNSTON, R. A. A.
A list of Canadian mineral occurrences.
Geol. Surv. Canada, Mem. 74, 1915.

LOGAN, W. E.
On the Geology of the country on the south side of the St. Lawrence from Montreal and Lake Champlain to the Chaudière River, Que.
Geol. Surv. Canada, Rept. Progr. 1847-48, pp. 5-92, 1849. Also in the Journal of the Legislative Assembly of the Province of Canada, vol. 8, Appendix G, 1849.

Geology of Canada, 1863.
Geol. Surv. Canada, Report of Progr. to 1863. 1863 et seq.

MACKAY, B. R.
Beauceville map-area, Quebec.
Geol. Surv. Canada, Mem. 127, 1921.

RUEDEMANN, R.
Graptolites of New York.
N. Y. State Mus., Mem. 11, pt. 2, 1908.

MARSTERS, V. F.
Camptonites and other intrusives of Lake Memphremagog.
Amer. Geologist, 16, pp. 25-39, 1895.

SCHUCHERT, Charles
Orogenic times in the northern Appalachians.
Bull. Geol. Soc. Amer., 41, pp. 701-724, 1930.

SELWYN, A. R. C.
Notes on the Geology of the south-eastern portion of the Province of Quebec.
Geol. Surv. Canada, Rept. Progr. 1880-81-82, pp. 1-23J, 1883.

WILSON, A. W. G.
On the Copper mining industry of Quebec.
Summ. Rept. Mines Branch, Dept. of Mines, Canada, 1909, pp. 69-78, 1910.

BRUCE, E. L. & HAWLEY, J. E.
Geology of the Basin of Red Lake, District of Kenora (Patricia portion).
Ont. Dept. Mines, 36th Ann. Rept., vol. 36, pt. 3, pp. 1-72, 1928.

CLARK, T. H.
A review of the evidence for the Taconic Revolution.
Boston Soc. Nat. Hist., Proc. 36, no. 3, pp. 135-163, 1921.

COOKE, H. C.
Kenogami, Round, and Larder Lake areas, Temiskaming district, Ont.
Geol. Surv. Canada, Summ. Rept. 1921, pt.C, 36 pp., 1922.

GISOLF, W. F.
On the rocks of Doormantop in Central New Guinea.
Konin. Acad. van Weten. Amst. (Proc.) vol. 26, p. 191, 1923.

KEITH, S. B. & BAIN, G. W.
Chrysotile Asbestos.
Econ. Geol., 27, no. 2, pp. 169-188, 1932.

TILLEY, C. E.
The facies classification of metamorphic rocks.
Geol. Mag., 61, p. 167, 1924.

LEITH, C. K. & MEAD, W. J.
Metamorphic Geology
Henry Holt & Co., 1915.

BAILEY, E. B.
Across Canada with Princeton
Nature, Nov. 5, 1927.

LIST OF PHOTOGRAPHS

1. Lake Memphremagog, looking south. Owl Head Mountain on right, Bear Mountain in the distance.

2. Peasley Pond with Bolton igneous mountains in background, looking south.

3. Slates of the Mansonville series. Stream gorge 3 miles southsoutheast of Mansonville.

4. Mansonville slates about four miles north of Mansonville, on route 1. Looking northwest.

5. Massive quartzite in Mansonville series, 5 miles north of Mansonville, east of the road, looking north.

6. Quartzite ridge in the Mansonville series, one quarter mile northwest of South Bolton.

7. Flowage folds in quartzite of the Mansonville series. One mile and a half northwest of Mansonville. Looking southwest.

8. Quartzite bed in slate of the Memphremagog series, about one mile west of Millington.

9. Autoclastic breccia. The remains of a once continuous bed of quartzite of the Memphremagog series. About one mile west of Millington.

10. Contorted and brecciated slates and quartzite bands of the Memphremagog series. Four corners east of Malaga Pond.

11. Autoclastic breccia in the Memphremagog series. Four corners east of Malaga Pond.

12. Flow structure in Bolton metabasalt, near Travor Road.

13. Sugarloaf Mountain from base of Owl Head, looking northwest.

14. Distant view of Lake Memphremagog, looking south. Owl Head Mountain in center, Bear Mountain to left and Hawk Mountain to right. Sugarloaf Mountain on extreme right.

15. Radiated actinolite in serpentine near Bolton Centre.

16. Pillow structure in the Bolton metabasalts on the slope of Owl Head near road.

17. Steeply inclined pillow structure. One and one-half miles west of Vale Perkins. Looking east.

18. Detail of pillow structure in the Bolton metabasalts on the west slope of Owl Head Mountain.

19. George Pond breccia. George Pond.

20. George Pond breccia in road, with pebbles of quartzite, grit, and serpentine. One mile and a half west of Peasley Corners.

21. Valley along contact of Bolton metabasalt on left and Peasley Pond conglomerate on right. Looking north. Peasley Pond.

22. Peasley Pond conglomerate, basal beds. Peasley Pond.

23. Peasley Pond conglomerate. Peasley Pond. Looking north.

24. Glenbrooke shale, strongly calcareous. One half mile west of Vale Perkins. Looking south.

25. Most northerly outcrop of the Glenbrooke shale. The hills in the distance, towards which these beds strike, are composed of older rocks. Looking north. Two miles northnortheast of Channell.

26. Glenbrooke shale. Looking south. Note verticality of cleavage. One half mile southwest of Vale Perkins.

27. Pharaoh asbestos prospect in Bolton metaperidotite. One mile southeast of Mansonville. Looking east.

28. Entrance to tunnel. Smith Mine, northwest borber of Owl Head Mountain.