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GEOLOGICAL SURVEY

MEMOIR 211

THETFORD, DISRAELI, AND EASTERN HALF OF WARWICK MAP-AREAS, QUEBEC

BY

H. C. Cooke

Price, 50 cents

No. 2440

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CHAPTER I

INTRODUCTION

GENERAL STATEMENT

The district described in this report is a part of the asbestos-producing area of the Eastern Townships of Quebec. With the exception of the properties of the Canadian Johns-Manville Company at Asbestos, and of the Nicolet Asbestos Mines in Tingwick township, all the mines now producing asbestos in Canada lie within the area here described. The district has also been an important producer of chromite in the past, and although chromite is not now mined, there are still reserves of this mineral that may yet prove of value.

The field work on which this report is based was carried on during the field seasons of 1930 to 1935 inclusive. In 1935, T. H. Clark undertook the study of the fossiliferous Ordovician and Devonian rocks of Disraeli map-area, and has supplied the chapters dealing with these formations.

The work has been facilitated by assistance freely rendered by the managers of the various mines of the district. Access to the mines at all times has been readily permitted, information derived from the hard-won experience of the operators has been available, and other help has been willingly given when required. All of this has materially advanced the investigation.

J. F. Henderson, M. S. Hedley, and A. R. Byers have acted as field assistants in various years, and their efficient services are gratefully acknowledged.

LOCATION AND AREA

The district described in this report is in the province of Quebec, due south of Quebec city. Thetford map-area extends between west longitude 71° and 71° 30′, and from north latitude 46° to 46° 15′. Disraeli map-area adjoins Thetford map-area on the south, between the same parallels of longitude, and extends to latitude 45° 45′. Warwick map-area adjoins Disraeli map-area on the west. Each map-area has an area of about 420 square miles.

PREVIOUS WORK

The first descriptions of the district were by Sir William Logan, in several of the early reports of the Geological Survey, which were later embodied in the Geology of Canada, 1863. Mineralogical and lithological examinations, with chemical analyses, were made at the same time by T. Sterry Hunt, and published in conjunction with Logan's field work. At that time the serpentines were supposed to be altered magnesian limestones. The sedimentary origin of serpentine was not accepted by many European geologists, however, and by the late "seventies" and early "eighties" sufficient field and microscopic evidence had been accumulated to swing general opinion to the modern view that serpentines are usually altered peridotites and pyroxenites, and are, therefore, of intrusive origin. The probability of this origin for Canadian serpentines was upheld by A. R. C. Selwyn, who succeeded Logan in 1869 as Director of the Geological Survey of Canada. At his suggestion, specimens were studied microscopically by F. D. Adams, then petrographer to the Geological Survey; and the results (1)[1] suggested that the Quebec serpentines are also altered peridotites. The new views necessitated a review of the stratigraphy, which was carried out by R. W. Ells. He revised the areal geology of the entire Eastern Townships, and accompanied his reports with maps on a scale of 4 miles to 1 inch, which remain today the only general maps of the region.

The next geological work of importance was that of John A. Dresser, done during the field seasons of 1907 and 1909, and published in 1913. This work was a moderately detailed reconnaissance of the belt of igneous rocks associated with the asbestos and chromite deposits, and extended from near Richmond on the southwest beyond East Broughton on the northeast, a distance of about 70 miles. The greater part of the work was devoted to the study of the asbestos and chromite deposits, and of the external and internal relations of the intrusives with which they are associated. Dresser not only proved the serpentines and associated rocks to be of igneous origin and intrusive, but advanced the hypothesis that the granites, gabbros, and pyroxenites of the district were derived from the same magma as the serpentines by gravitative differentiation after intrusion. His study of the genesis of the asbestos and chromite bodies markedly advanced our knowledge of these obscure deposits.

The next worker was Robert Harvie, who spent the four field seasons of 1915 and 1919 to 1921 in the area comprising, roughly, the southern half of Thetford map-area and the northern half of Disraeli map-area. Harvie wrote little, but prepared a very accurate outcrop map of the district studied, which has proved of great value in the present investigation. Harvie's views were largely expressed in a paper by his field assistant for 1916, J. K. Knox, which describes the southwestern part of the Thetford-Black Lake mining district.

The principal papers dealing with the geology and mineral deposits of the area under consideration are given in the following bibliography, together with others that discuss the genesis of asbestos, chromite, and serpentine in general.

[1] The numbers in brackets refer to the Bibliography, p. 3.

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CHAPTER II

PHYSICAL FEATURES

Southeastern Quebec includes parts of two physiographic provinces, the St. Lawrence lowland and the Appalachian upland. The former, northwest of the area under consideration, is a flat plain elevated, at St. Lawrence river, about 200 feet above sea-level, and rising inland at the rate of 5 or 6 feet to the mile. The northwest corner of Thetford map-area, about 50 miles from the river, is very close to the southeast border of this plain.

From the southeastern edge of the plain, 450 to 500 feet above sea-level, there rises abruptly a high ridge, part of a chain of hills extending from the United States boundary line into Gaspe. In Thetford map-area this ridge is about 12 miles wide, and summits attain a maximum height of about 2,000 feet. The ridge is highest in the northwestern part of Thetford map-area, and gradually falls away to about 1,400 feet as it approaches Chaudière river on the northeast, and Danville to the southwest. Near Danville it is broken into a series of isolated summits that rise above a plain-like area about 750 feet in elevation; southwest of Danville the ridge rises again to heights of about 3,000 feet near the United States border.

This range is known as the Sutton range near the border, and as the Shickshock mountains in Gaspe. In Thetford area it consists of silicified schists termed the Bennett schists, probably of early Cambrian age, and has a general anticlinal structure.

Between the Sutton range and the New Hampshire-Maine border to the southeast lies a maturely dissected plateau about 50 miles wide, with elevations of 1,100 to 1,300 feet above sea-level. Its southeastern boundary is the Lake Megantic range of hills, which lies mainly in the United States, although in part forming the Quebec-Maine boundary. The plateau, carved from moderately soft Cambrian and Ordovician sediments, is broken by a series of hills that rise, in places, as much as 1,000 to 1,200 feet above it. Some of these, such as Big and Little Megantic mountains, and a hilly area at the south end of lake St. Francis, are granites intrusive into the sediments, and are supposed to be of Devonian age. A second set of hills is composed of basic igneous rocks, peridotites, pyroxenites, gabbros, and basalts. They form a rather irregular ridge or string of knobs, 1 to 3 miles wide, running from beyond Danville nearly to the east boundary of Thetford map-area, and throughout that distance paralleling at no great distance the southern boundary of the Sutton range. A third set of hills, the Stoke Mountain ridge, is underlain in part by Devonian conglomerates and sandstones, in part by lavas and other rocks. It forms a ridge, 2 to 4 miles wide, extending from lake St. Francis past Sherbrooke. Within Disraeli map-area this ridge rises only some 300 or 400 feet above the plateau surface, but farther southwest the highest point, mount Chapman, is 2,100 feet above sea-level.

When the Sutton range is viewed from a distance, it appears as a reasonably level-crested ridge falling away gradually to the northeast and southwest. This appearance is checked by an examination of the contour map, which shows the highest peaks approximating fairly closely an elevation of 2,100 feet. Mount Adstock, a mass of gabbro lying 10 miles southeast of the highest part of the Sutton range in Thetford quadrangle, is 2,200 feet above sea-level; and mount St. Sebastian, 25 miles farther to the southeast, is 2,700 feet above sea-level. These facts, and others that might be gathered from an inspection of the region as a whole, suggest that these higher parts may be remnants of an ancient erosion surface or peneplain uplifted, perhaps in middle Tertiary time, and since reduced by erosion to its present mature topography. The hypothesis is strengthened by the fact that in Gaspe the continuation of this range is characterized by wide, flat-topped summits.[1] If the conclusion is correct, the general contour, coupled with the drainage patterns about to be discussed, indicate that the uplifted peneplain sloped toward the St. Lawrence, and was warped so as to be lowest near Danville and Chaudière river, and highest about the middle of Thetford quadrangle and again near the International Boundary.

The drainage of the region has marked peculiarities that strongly support the hypothesis outlined. Although the rocks of the region are mainly easily eroded slates and sandstones or quartzites, with steep dips and northeasterly strikes, neither the principal streams nor many of the smaller ones conform to the underlying rock structure, but on the contrary tend to cut across it at right angles. Thus, St. Francis river, the largest stream of the region, which drains the greater part of the interior plateau from lake St. Francis to the International Boundary, assumes near Sherbrooke a northwesterly course and cuts indifferently across the rocks of Stoke Mountain ridge, the plateau area, the Sutton ridge, in which it has incised a valley 500 feet deep or more, and the St. Lawrence lowland. Nicolet river, the next large stream to the northeast, rises on the northwest flank of Stoke Mountain ridge and likewise follows a northwesterly course to the St. Lawrence. Bécancour river, northeast of Nicolet river, receives various affluents that follow northerly and northwesterly courses. At least four of them cut directly across the highest part of the Sutton range, and rise near the southeastern side or on the plateau beyond. To do this they have cut valleys through the range, the bottoms of which are 900 to 1,400 feet below the summits. Still farther northeast the Beaurivage and Chaudière rivers behave in exactly the same manner.

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[1] Alcock, F. J.: Mount Albert Map-area, Quebec: Geol. Surv., Canada, Mem. 144, pp. 11-15 (1926).

CHAPTER III

GENERAL GEOLOGY

GENERALIZED STATEMENT

The sedimentary rocks of Thetford, Disraeli, and Warwick map-areas range in age from Cambrian (?) to Devonian. It was formerly supposed that Precambrian strata underlie the northern part of Thetford and Warwick map-areas, along the axis of the Sutton anticline; but the writer's detailed investigations have shown that there is no break between the supposed Precambrian and the less metamorphosed Cambrian (?) strata. It is concluded, therefore, that the former are merely the lower, more metamorphosed part, the latter the upper, less metamorphosed part, of the same series. This series, and the next overlying series, have been traced eastward by the writer from Thetford area into Beauceville area, described in 1921 by B. R. MacKay (92); and his formation names are accordingly used for the region under discussion.

The oldest rocks of the area are the Caldwell series, a succession of more or less pure quartzites, slates, and lavas. They lie unconformably beneath strata considered Ordovician; and farther south, in Lake Memphremagog area, Clark has found Cambrian fossils in petrographically similar strata that apparently occupy the same stratigraphic position. They are, therefore, provisionally considered Cambrian, although no fossils have been found in the areas now under consideration. The lower, highly metamorphosed parts of the Caldwell series have been termed by Harvie (86, page 21) the Bennett formation, and the term Bennett schist will be retained in this report for purposes of easy reference. The Caldwell series above the schistose part consists mainly of thick beds of quartzite separated by thin bands of slate, and this part was termed by Dresser (54, page 20) the L'Islet formation, following nomenclature adopted for the area around Levis. Above the quartzite formation, in Thetford area, lies a considerable body of red and grey slates, with a little interbedded quartzite, which was termed by Dresser the Sillery formation. Thick flows of lava, mostly though not entirely basaltic in composition, are found in the Caldwell, generally at or near the top of the quartzite member.

Unconformably above the Caldwell series is found a thick series of black slates and quartzites, which is known as the Beauceville series. It is the Farnham series of Dresser, and the Disraeli series of Burton.

Sediments of Lower Devonian age overlie the Beauceville series in Disraeli map-area. They consist of heavy beds of conglomerate, slate, and limestone. Following Burton (20, page 118) they are termed the Lake Aylmer series.

All these sediments have been closely folded along east-northeast axes, so that they now have steep to vertical, in places overturned, dips, except on the crests of folds. There appears to have been uplift without much folding after the deposition of the Caldwell series, more or less folding after deposition of the Beauceville, and strong deformation during or after the deposition of the Devonian. In Beauceville area, according to MacKay (92, page 33), the post-Ordovician deformation appears to have been as great as, if not greater than, the Devonian deformation. In Disraeli map-area, however, both Ordovician and Devonian rocks seem about equally deformed, suggesting that the main period of folding was Devonian or later.

With the sediments are associated various intrusives. The oldest is a gabbro that forms long sills in the Caldwell series, but has not yet been found to intrude the Beauceville series. Later, great masses of peridotite and pyroxenite were injected. These likewise occur mainly within the Caldwell series, but also intrude the Beauceville series in the district between Thetford and Beauceville map-areas. The gabbros and to a less extent the peridotites and pyroxenites have been folded along with the sediments in which they lie, and have been much fractured and broken by the stresses to which they have been subjected. Small masses of granite, and dykes of feldspar, are associated with the peridotites and pyroxenites, and may possibly be differentiates of the basic magma. They may also be offshoots of underlying masses of later granite, usually considered Devonian, of which large bodies appear in the southeastern part of Disraeli map-area, and in other parts of the interior plateau to the south and southeast.

The valuable asbestos and chromite deposits of the region are associated with the peridotite and pyroxenite masses.

Table of Formations

Pleistocene and Recent		Boulder clay, stream deposits
Palæozoic—		
Devonian or later		Granite
Lower Devonian	Lake Aylmer series	Conglomerate, slate, limestone
Post-Ordovician		Peridotite, pyroxenite, granite
Ordovician	Beauceville series	Conglomerate, black slate, quartzite
Post-Cambrian (?)		Gabbro
Cambrian (?)	Caldwell series	Quartzite, lava, tuffs, red and green slates (Bennett schists)

CALDWELL SERIES

BENNETT SCHISTS

The Bennett schists occupy the northwestern half of Thetford map-area, some 4 or 5 square miles of the northwestern corner of Disraeli map-area, and the northwestern half, or more, of Warwick map-area. They have no definite boundary, but pass by gradual decrease of metamorphism into the quartzite member of the Caldwell series. Toward the centre of the area they occupy, the original bedding is largely destroyed by metamorphism, though it can be detected in places; but toward the edges of the area there are many places where it can be determined for some distance into the schistose mass. For this reason the boundaries of the schist area as mapped by one observer rarely coincide with those indicated by another observer.

The principal rock of the schist area appears to have been greywacke varying through impure quartzite to fairly pure quartzite. The very pure quartzites have not been much affected by metamorphism, as a rule, but the less pure types have been converted into sericite schists carrying high percentages of quartz with some chlorite. In places, as for example in Disraeli map-area northeast of Breeches lake (Garthby tp., range II, lot 21), the schist carries numerous, large crystals of garnet, now largely altered to chlorite; suggesting that the greywacke may have carried more or less lime. In other places secondary hornblende is largely developed, or other minerals like tourmaline or some of the aluminous minerals, forming knotty schists.

In the main, therefore, the Bennett rocks are now silvery sericite schists, distinguished by their extreme schistosity and crumpling. In certain areas, as north of Thetford, the schist is very highly crumpled. A single linear foot along the strike will exhibit from five to thirty small plications; these in turn form parts of larger folds a few yards across, and these again are parts of still larger folds.

In a number of places schists occur that have clearly or probably developed from the metamorphism of shales or slates. Generally, metamorphism has been extreme enough to produce hard micaceous types, true phyllites or dark mica schists. The original rock has commonly been a dark grey slate, but in a few places it has been a red slate. Rocks of these types may be seen southeast of Kinnear Mills, and are widely developed in the northern part of the east half of Warwick map-area.

Lenses of magnetite are found in a few places, interstratified with quartzite and siliceous schist. The most important are those at the so-called Leeds mine, in lots 7a and 7b, range V, Leeds tp. They have been described in some detail in the "Report of Mining Operations in the Province of Quebec for 1912," pages 100-105. The lenses range in size up to 7 feet in width and 200 feet in length. The ore is diluted by considerable silica in small grains, so that it is not of commercial grade. Two analyses cited in the above report show 42·5 and 53·7 per cent of iron respectively.

Limestone forms a very minor constituent of the schist area. Outcrops of crystalline limestone, probably parts of a single band originally, were found in Leeds township in range V, lot 7b, range IV, lot 3b, range III, near the boundary between lots 2 and 3, northeast end, and on range line II-III just at the boundary between Inverness and Leeds townships. In the most eastern outcrop the band is not more than 10 feet thick, and is a very pure calcium carbonate. On the west it is more than 100 feet thick, and weathers to the deep brown colour characteristic of many magnesian limestones, probably owing to the presence of some iron carbonate.

In Warwick map-area limestones were found in several places. A brown-weathering dolomite is found at the north boundary of the area on the road toward Beaudoin, where it is associated with chlorite schist. To the southwest, along and south of the road, there are good outcrops of fairly pure crystalline limestone. One of these outcrops, in Wolfestown tp., range VIII, lot 1, about a quarter mile south of the road, is crowded with crystals of magnetite and some other minerals. Some small pits have been sunk on this outcrop, apparently to investigate the iron content.

Two miles south of St. Fortunat a band of rusty-weathering dolomite was traced about a mile across lots 10, 11, and 12, range VII, Wolfestown tp. The dolomite contains considerable quartz, which forms a siliceous residue on the weathered surface. About a mile northeast of the last exposure further outcrops appear, doubtless a continuation of the same band.

The widest carbonate band in Warwick area lies immediately north of a band of chlorite schist which appears to be a metamorphosed lava. It can best be seen about 2 miles north of Boudreau hill, in Wolfestown tp., ranges X, XI, lots 5, 6, and 7, where it ranges up to 30 feet in thickness, and from well bedded to massive. It appears to be a very pure, white or creamy calcite.

Chlorite rocks, commonly but not invariably schistose, constitute a part of the Bennett schist secondary only to the sericite schists. However, the actual proportion of chloritic types is relatively small, perhaps 1 per cent or 2 per cent of the whole. In mapping Thetford area no attempt was made to separate the chloritic types from the others, as time did not permit; but this was done in Disraeli and Warwick areas. The chlorite rocks appear to have been basic lavas or tuffs, metamorphosed and rendered more or less schistose. Proof of this was obtained in all three map-areas. In Thetford area two localities were found where the original nature of the rock is clear. The first is in Inverness tp., range V, northwest end of lot 2, where the ordinary chlorite schist grades, with decreasing metamorphism, into a partly chloritized flow breccia made up of amygdaloidal nodules of lava in a matrix of flow-textured, slightly sheared basalt. The second is in Ireland tp., range IV, lot 19, where a recognizable lava flow is interbanded with the schists. It is about 100 feet thick, strikes north 75 degrees east, dips 80 degrees south, and can be traced for some hundreds of feet. The lower contact, visible at the west end of the outcrop, is fine-grained and distinctly flow textured. About 30 feet of massive, slightly flow-textured lava lies above the contact, and the remaining upper part, some 70 feet, is pillowed.

In Warwick map-area some fairly wide bands of chlorite schist have been differentiated and traced. The rock is massive and dark green, weathering to dark green, yellowish green, or dull brown. For the most part there is no recognizable structure of any kind, except that in a few places the rock is filled with small, whitish nodules resembling amygdules. The origin of this rock was obscure for some time, until an outcrop was found, about a mile east-southeast of North Ham village, where the original structures have not been destroyed. At this place a band of rock can be identified as an individual lava flow; it is 26 feet wide across the outcrop, strikes north, dips 45 degrees west, and like the surrounding rocks has been much contorted. On the west, and upper, side the flow is in contact with slate. The contact is well exposed, and there is no evidence of any unconformity. The lava next the slate is thinly flow-textured and highly amygdaloidal, with the small, closely spaced amygdules arranged in strings, and many drawn out into flattened forms. Five or 6 feet from the contact the flow bands become wider and the amygdules larger; and the lava contains many fragments of original crust broken up by flow movements. The flow textures continue to within 6 feet of the base of the flow, where they begin to fade and disappear; and the lowermost 3 or 4 feet consist of massive lava, with neither amygdules nor flow textures.

Very like the chlorite rocks of Warwick map-area though differing in some respects is a chlorite band in Disraeli map-area, traceable about 2 miles south from Belmina ridge. This rock was first studied by Knox (86) and was termed by him hornblendite; but this term is best applicable to the northern part of the body, where recrystallization by the heat of the intrusive peridotite has gone on. Farther to the south the rock is very fine-grained, soft, and dirty dark green in colour, and appears to consist entirely of chlorite. The band at its south end is only about 30 feet wide; at the road passing the north end of Breeches lake it is 250 to 300 feet wide; and it continues to widen to some 2,200 feet southwest of Belmina ridge. The latter figure, however, is due in part to folding, and the real thickness there does not probably exceed 600 to 700 feet.

The southern part, not recrystallized by heat, is well banded, in bands about an inch wide that parallel the bedding of the quartzites. The most careful study, however, failed to reveal any differences of composition either within individual bands or between one band and another; and the divisions between the bands appear to be paper-thin cracks filled with a whitish vein material. Except for the parallelism of the banding with the bedding of the quartzite, therefore, there is no evidence that the banding is original bedding.

The contact of this rock with the quartzite is visible in many places. It is usually sharp, and follows smoothly the bedding of the quartzite. In several places within the north-striking section of the hornblendite, bands of quartzite occur in it and are apparently interbedded conformably with it. In other places there are bands of intermediate composition that look like quartzites badly contaminated by additions of basic material.

The uniformity of composition of this rock, its conformability with the quartzites, the interbanding with quartzite beds, and the bands that appear to have been quartzite contaminated by basic additions, together with the lens-like shape of the mass as a whole, all point to its having been a basic lava or ash rock, more probably the latter, which has been thoroughly chloritized and sliced by the movements attending folding.

The study of this unusual rock is complicated by the occurrence, in two places, of basic intrusives in it. On the north side of the Breeches Lake road, Wolfestown tp., range V, lot 27b, there are excellent exposures of the "hornblendite" thus disturbed. The intrusive, a fine-grained basic material so altered that its original composition is indeterminable, is injected lit-par-lit between the "hornblendite" bands, which here are rather quartzitic. The bands of intrusive material vary from ¼ inch to 2 inches in width, and include very numerous slabs and fragments of the schist broken away during the injection. In places the bands expand and unite to form rounded lumps of intrusive a foot or more in diameter. Other portions of the intrusive form dykes that cut across the schistosity at varying angles. An extraordinary feature is that the more siliceous parts of the wall-rock continue into the dykes and, in places, nearly or even completely across them; so that the dyke materials at first sight appear to have a schistose structure crossing them. The only possible explanation of such an unusual structure would appear to be that injection occurred along some crack crossing the schistosity, from which crack the igneous material penetrated laterally into the schist, absorbing or melting the basic parts but leaving the more siliceous parts untouched, so as to yield a comb-like structure.

Between 1,400 and 1,700 feet from the Breeches Lake road, in the same lot, there outcrops a small knob of hornblende-rich rock, of the composition of a basic gabbro or diorite. The mass is about 300 feet long and 200 feet wide, with the greater diameter parallel to the north-northwest strike of the sediments. On the west side it lies directly against a quartzite heavily impregnated with some iron mineral for several feet from the contact; and the igneous rock is strongly flow-textured for 30 feet or more from the contact. Beyond this it becomes massive and medium-grained. On the east it is in contact with "hornblendite," and the most careful search failed to find a sharp contact. As the rocks are very rusty and lichen-covered, however, failure to find such a contact does not necessarily indicate its absence. The banding of the "hornblendite" seems to melt away as the massive igneous rock is approached, and within a distance of 10 or 15 feet it gradually becomes so indistinct as to be altogether lost.

These relations may be interpreted in two ways: (1) the igneous rock may be an intrusive that metamorphosed the "hornblendite" near the contact so as to destroy the banding; or (2), the igneous rock may be a lava, from the same source as the "hornblendite," which, as shown, is probably a tuff. As the banding of the "hornblendite" has been shown to be probably due to slicing under the stress of folding, its disappearance near the igneous rock could be considered due to an increase of hardness as the massive lava was approached. The fine-grained, flow-textured top of such a lava would be indistinguishable in composition from the tuff laid down above it; but it would shear much less readily, and slicing would probably be confined to a narrow zone near the edge.

The writer is inclined to favour the second possibility, for two reasons. The schistose quartzite on the west side of the igneous mass is not metamorphosed, beyond introduction of some iron minerals; whereas if the mass were an intrusive, hot enough to metamorphose the "hornblendite" over a width of 10 to 15 feet, some metamorphism might be expected in the quartzite also. Again, the igneous rock is much more basic than the near-by gabbro, and is in fact entirely unlike any other igneous rock in the district; but it is exactly the type that, crushed and altered, would yield a rock like the "hornblendite."

The "hornblendite" exhibits certain changes in mineral character and grain, with increasing nearness to the peridotite of Belmina ridge, which may here be mentioned in order to complete the description of this unusual rock. The changes begin to be evident about 1,300 feet from the peridotite, and become more and more pronounced as the contact is neared. The chloritic material is first recrystallized to acicular hornblende, the crystals of which become larger and larger toward the contact, until a grain of 1 to 2 mm. is attained. As this goes on the banding becomes less and less pronounced, until it either disappears altogether or is replaced by a poorly defined gneissic texture. These changes are accompanied by the injection along the banding of narrow veinlets of material as yet undetermined, which appear to be of a pegmatitic nature. Such veinlets become more and more numerous as the contact is approached, although their relative volume, even near the contact, is very small.

J. K. Knox (86, pages 56-8) states that the " hornblendite " near the peridotite contact is composed of 98 per cent green hornblende, with small amounts of interstitial orthoclase, hematite, titanite, white mica, chlorite, and pistacite. He also describes some varieties close to the contact as containing numerous scattered crystals of red garnet. The writer did not find the locality where the garnets occur.

Structure of the Bennett Schist

The structure of the Bennett schist is most complex, and a detailed study of it would undoubtedly result in obtaining valuable information on the structure of the area as a whole, and the behaviour of rocks in the zone of flowage in an area of close folding. As the writer's task has been primarily the study of the asbestos deposits, their origin and manner of emplacement, it has not been possible to devote the required time to the detailed study of the Bennett. The following remarks, therefore, discuss merely some of the phenomena encountered, without attempting any exhaustive analysis.

Throughout the greater part of the area occupied by the Bennett schist the original bedding of the rocks has been almost completely obliterated, so that structure observations must be confined to the schistosity. The schistosity of the central part of the area dips at low angles, and in places is practically flat. Throughout a band about 4 miles wide, beginning $1\frac{1}{2}$ to 2 miles from the southeastern border of the Bennett, these gentle dips are toward the northeast and southwest, or at right angles to the usual directions of dip throughout the region. South of this band the dips gradually become rather steep to the southeast, and the axes of cross folds in the schist plunge in the same direction. North of this band the dip averages about 50 degrees northwest, and the axes of the numerous cross folds in the schist plunge likewise northwest. So far as the schistosity is concerned, therefore, the structure is that of a broad, flat-topped anticline.

Bedding can be observed in a number of places. On the summit of the anticline it is not uncommon to find beds of pure quartzite which have suffered little metamorphism, and these lie fairly flat, paralleling the schistosity. On the flanks, particularly the wide northern flank, bedding can be observed in places, and where found the dip is northwest on the north flank, and southeast on the south flank. These facts, though not so numerous as might be desired, confirm the conception of the general structure gained from a study of the schistosity.

Both the schistosity and the bedding, where the latter can be seen, are commonly intensely plicated on the flanks of the anticline, although on the crest there is comparatively little plication. In the plicated areas it is generally easier, as well as more accurate, to determine the true dip by measuring the plunge of the axes of the numerous cross folds. Secondary folds, with axes parallel to the general strike, are likewise strongly developed in many places, and present very striking features. They are difficult to observe, however, in that they can be distinguished as a rule only where some feature like a cliff face or stream canyon affords a vertical section across the strike. In such places it can be seen that the schistosity has been dragged into a complicated series of recumbent folds, the axial planes of which are nearly parallel to the schistosity. Most of such observations made by the writer were on the northern flank of the anticline, and in all observed cases the axial planes of these drags dip northwest at low angles, indicating that the upper beds sheared over the lower, moving from the northwest toward the southeast. On the south flank of the anticline good cross-sections are rare, and not enough observations have been made to draw any general conclusion.

In Warwick map-area the southwesterly plunge of the anticline carries the schists beneath the upper beds of the Caldwell series; and, as the mapping shows, the individual beds here curve around the anticlinal nose. It can be seen here that the anticline is complex, as might be expected, with many subordinate folds. As the plunge of the nose is smaller than the dip of the strata on the flanks, the exposed width of the zone showing the change from schistose to non-schistose types is wider here than in Thetford area, and the change can be studied in more detail.

Although the Bennett schists constitute the Sutton range, the highest part of the region, they are not well exposed. They are fairly uniformly covered with soil ranging from a few inches to several feet in depth, judging from well borings and other data; so that they can be seen and studied only on particularly steep hill-sides, on the summits of the higher hills, and in stream beds. Quite commonly exposure is continuous in roadside ditches a few inches deep, but no rock is visible in the surrounding fields.

Veining

No description of the Bennett schists would be complete without reference to the numerous quartz veins that characterize it. In the area northwest of Thetford such veins literally swarm throughout the schists. Most of them have been injected between the leaves of the schist, but others cut across the schistosity. As a rule they are small, but in places, such as range XI, lot 8, Broughton tp., large ones may be seen. The number of veins in the schists decreases toward the southwest, and in the northeast corner of Disraeli map-area there are relatively few of them.

The age of the quartz veins was determined in range IV, lot 7b, Leeds tp., about 1½ miles southeast of Kinnear Mills. There the strata are black slates interbanded with quartzites, and strike north 30 degrees west, with an overturned dip of 70 degrees west. The beds are strongly drag-folded, and flow cleavage has developed in the slates at a considerable angle to the bedding. The cleavage planes are filled with quartz, yielding veinlets about three-fortieths of an inch thick. Evidently, therefore, this quartz was introduced after development of the flow cleavage, thus dating it as later than the post-Ordovician folding at least.

Further evidence is found just west of Clapham lake, in Thetford tp., range VIII, lots 17-19. There a crush breccia occurs, containing numerous fragments of schistose quartzite containing quartz veins that end sharply at the edges of the fragments. Vein formation, therefore, preceded fragmentation. It will be shown that the sharp bending of the strata at this point, which caused fragmentation, was due to injection of peridotite masses, which forced the sediments aside. It will also be shown that the peridotites were injected as sill-like masses into the already folded Caldwell and Beauceville strata, and also that the peridotites, at a later date, were folded with the sediments. Only two folding movements took place in this region, the post-Ordovician and the post-Lower Devonian. Thus the order of these events, starting with the oldest, must have been: (*a*) folding of the Caldwell and Beauceville series; (*b*) injection of quartz veins; (*c*) injection of peridotites, with fragmentation of the beds near Clapham lake; (d) post-Lower Devonian folding.

QUARTZITE

The Caldwell quartzites are white or light grey rocks, commonly massive, and composed principally of quartz with a few grains of feldspar, and accessory mica or chlorite, apatite, ilmenite, and zircon. Here and there beds containing considerable feldspar, up to 40 or 50 per cent, are found. The feldspar is usually altered largely or completely to epidote, sericite, and kaolin. The grain of the quartzite beds is normally rather fine; but in places, as in range X, lot 21, Thetford tp., beds contain quartz pebbles up to the size of beans. Beds vary in thickness from a few inches to 6 feet or more. Throughout the quartzite formation there are many beds of grey slate up to 6 inches thick, which, by the relation of the slaty cleavage to the bedding, enable the structure to be determined with certainty.

In many geological text books it is taught that sedimentary beds varying in grain from top to bottom commonly have the coarsest grain at the bottom, the finest at the top; and in many places where beds are steeply inclined or vertical this supposed relation is used to determine which side is the upper. In Thetford area it has been proved (35) that many of the quartzite beds are coarsest at the tops; so that the theory, even if true in many instances, is by no means certain in its application.

The contact between the normal quartzites and the underlying Bennett schists is a transition zone, in which bands of massive, pure quartzite alternate with bands of fissile schist. The transition is well exposed in range XI, lots 12 to 14, Broughton tp., and again, over a much wider zone, in the northwest corner of Disraeli map-area. In this transition zone apparently the purer quartzites resisted deformation more strongly, whereas the less pure were converted into sericite and chlorite-sericite schists. The apparently massive beds did not remain unscathed during deformation, however, for thin sections show that the original mineral grains were completely crushed and shattered. This probably accounts for the peculiar fact that most of the massive quartzite beds near the contact with the Bennett are very fine-grained.

Farther southeast, and 3 to 4 miles from the contact with the Bennett, there are places where, for a local reason, the quartzites have been subjected to unusual crushing and shearing, and converted into crumpled schists indistinguishable from those of the Bennett. This effect may be seen west of Clapham lake, in ranges VIII and IX, lots 19-20, Thetford tp., and again on Bécancour hills, west of Bécancour lake.

Very few quartz veins are found in the Caldwell quartzites, except near the contact with the Bennett schists, and particularly within a few miles of the town of Thetford. Within this area, and for distances up to a mile from the Bennett, the quartzite is apt to be rather badly fractured, and the fractures filled with quartz. In some places, as in lots 15-16, range V, Thetford tp., quartz veins are so numerous that it is difficult or impossible to determine the bedding planes. The veins, as might be expected in a massive quartzite, are narrow, crooked, and run in all directions.

The thickness of the quartzite formation above the Bennett schists cannot be measured with accuracy, because of the numerous drag-folds and small faults within it. The known dips and widths of outcrop, however, suggest a possible thickness somewhere between 2,000 and 2,500 feet.

LAVAS

Lavas are largely developed both in Thetford and Disraeli map-areas. Most of them are fine-grained, dark green basaltic types, commonly characterized by pillow structures. Being hard, tough, and resistant to erosion, they tend to form ridges, and some of the highest hills of the interior plateau are underlain by them.

Southwest of Thetford Mines the lavas are closely associated with gabbro, peridotite, and pyroxenite, a fact that led Dresser, in his reconnaissance of the region, to consider the lavas as intrusive in origin and forming an igneous sequence with the intrusives mentioned. East of Thetford Mines, however, the lavas continue for many miles without association with intrusives. Their pillow structures, amygdaloidal textures, and flow textures definitely prove them to be extrusives; they can be seen to be conformably interbedded with the Caldwell sediments, and hence must be of Caldwell age. The intrusives, as will later be shown, are all of later age; and it will also be shown that the close association of lavas and intrusives southwest of Thetford Mines is due purely to structural causes.

The lavas lie for the most part either at or near the top of the Caldwell quartzite. In some places they separate the quartzite from the overlying shale, at others some quartzite has been deposited on top of them. Commonly there is but one horizon of lavas, but in Thetford map-area there are two, separated by a few hundred feet of quartzite.

Starting from the western side of Disraeli map-area, west of Coulombe lake, the lavas form a band that can be traced northeast about 7 miles, and then passes beneath drift for about 2 miles, to reappear north of Disraeli bay where it underlies a fairly large area, due apparently to rather intricate folding. Passing around the southwestern end of Bisby ridge it is found here and there along the southeast side of the ridge, but the continuity of the band appears to have been broken by erosion, because in places the Beauceville series lies directly against pyroxenite or Caldwell quartzite. Coldstream hills, north of lake St. Francis, form another wide area of lava, which ends on the northeast against the base of the Beauceville series. On the north side of the main anticline passing through lac à la Truite, what is in all probability the same lava horizon again appears, and forms two wide bands, which the writer considers as the same set of flows repeated by folding. Between these bands are some outcrops that appear to belong to a second horizon. These lavas turn northward past Clapham lake, and have been traced for more than 15 miles around a series of complex folds. An irregular, detached mass, probably belonging to the same horizon, is found north and east of Black lake, and another west of Coleraine. No lavas were found in the eastern 4 miles of Thetford map-area, but MacKay (92) reports their occurrence in the Caldwell series on the east side of the Chaudière river.

Observed contacts between the lavas and sediments are rather rare, although in many places the contacts are hidden by only a few feet of drift. One excellent contact was seen in range VII, lot 12c, Thetford tp., in a cliff facing west toward a small creek. The succession from south to north at this place is: quartzite, pillowed lava about 12 feet thick, massive quartzite 15 feet, followed by lava. No break of any kind is visible at the contacts of the lava and sediments, and the planes of contact are parallel to the bedding of the sediments. A second excellent contact was seen in lot 25, range XI, Broughton tp., close to the Broughton-Thetford boundary. Its character is similar to that described in the previous paragraph.

North of East lake (Disraeli map-area, west half) a rather unusual development of acid lavas and tuffs is found in the Caldwell series. Elsewhere all the lavas are basalts or andesites; but on the 1,175-foot knob west of the lake, west of and stratigraphically above a considerable thickness of basalt, there occurs a fine-grained, light grey lava containing no visible quartz, which may tentatively be termed trachyte. The coarser basal part of the flow exhibits long, narrow, black phenocrysts, which may have been hornblende; but the whole rock is now altered to secondary minerals. Near the base this material has been sheared to resemble a light grey slate or slaty quartzite.

On the northwest side this lava displays beautifully developed pillow structures, and the shapes of the pillows indicate that the top of the flow strikes approximately north 25 degrees east and faces northwest. The upper parts of the pillowed zone contain numerous, rounded masses of white chert and some of red chert, a feature common to many trachytes. Above the pillowed zone there is a fairly thick series of beautifully banded, violently contorted red and grey cherts, interbedded in the lower parts with thin flows of the trachyte. A drift-filled valley about 1,000 feet wide follows, beyond which the more ordinary basaltic and andesitic lavas and tuffs again appear.

About a half mile north of the middle of East lake an unnamed hill rises to a height of 1,400 feet, whereon may be studied a magnificent development of the red and grey cherts and tuffs. The hill is the anticlinal crest of a large drag-fold, so that the cherts strike across it in a general east-southeast direction, and plunge northeast at about 30 degrees. Starting at the extreme south end of the hill, the succession begins with rather poor exposures of deeply weathered, acid pillow lavas. North of these are beds of coarse red tuffs or agglomerates, green agglomerate, red chert, and probably some thin lava flows, beautifully exposed, and extending about half the length of the hill. North of them again the beds change to a fairly uniform succession of grey cherts, or cherty tuffs, laid down in beds averaging perhaps an inch thick. The total width of the outcrop of the tuffs and cherts here is a little more than half a mile, indicating a thickness of about 1,300 feet if the rocks were not thickened by crumpling and faulting, but as crumpling has been intense, about half the above figure may represent the true thickness.

Scattered outcrops of the grey cherts were found along the northern flanks of the next ridge to the east, indicating that this band, though thinning, tends to pass round the nose of the main anticline which runs through Coleraine cemetery and passes about $\frac{1}{2}$ mile east of East lake.

Large bodies of coarse, volcanic agglomerate form part of the lava sequence on the knobs between 1 and 2 miles west of Coleraine village, on Oak hill and the outcrops south of it, around Coleraine itself, and on the large hill $1\frac{1}{4}$ miles to the northeast. Agglomerates occur in other places, also, although not in such large amount.

In the south corner of range III, Garthby township, and the adjoining part of range II N, about 2 miles north of Coulombe lake, a considerable thickness of rather thick-bedded, light grey argillite or slate outcrops just above the lavas. This argillite is quite different in composition and appearance from the fissile, thin-bedded, black slate of the Beauceville series forming the next outcrops to the east. Similar light grey argillites occur at the southwest end of Brousseau hill, about a mile north of Disraeli, where they lie between a thin band of volcanic breccia that flanks the gabbro and pyroxenite of the hill, and the Beauceville slates to the south. These argillites are more massive and the beds are thicker than in the normal grey slates of the Caldwell series; and this, together with their close association with the lavas, inclines the writer to the opinion that they are locally developed mud rocks resulting from heavy showers of fine volcanic ash.

LOWER GREEN SLATE

In Thetford map-area a rather thick series of grey and green slates conformably overlies the lavas and quartzites. For the most part it is in contact with quartzites, but in Thetford tp., ranges VI and VII, lot 12, and westward, it is in direct contact with the lavas. Metamorphism has not obliterated the bedding, which is usually easily visible on glaciated or other smooth surfaces and the beds are rarely more than 2 inches thick, with a perfectly developed slaty cleavage. Beds of quartzite, some of them 25 feet or more in thickness, are interbanded with the slates in places. As the slates flowed readily under pressure, they have been intricately folded in many localities, particularly near the crests of folds; and undoubtedly by these processes have been much thinned in some places and thickened in others. They have been further disturbed by a multitude of small faults, with displacements of a few inches.

The slates, on account of their softness, are rather poorly exposed, even where they form fairly high ridges. Large areas of slate are so uniformly covered with 2 to 4 inches of soil that it is difficult to obtain sufficient outcrop for determination. Almost all the larger areas of slate mapped as "outcrop" are of this character.

The poor exposures and the intricately folded and faulted nature of the slates make it impossible to secure accurate determinations of the thickness, but the general dip and the width of outcrop in range VII, lot 12, Thetford tp., suggest that it may be approximately 1,200 feet.

RED SLATE

The principal body of red slate in the district is a band about 7 miles long, with a maximum width of 1¼ miles, in ranges VII and VIII, Thetford township, and the adjacent part of Broughton township. It and the slates above and below were supposed by Dresser to be correlative with the Sillery slates in the neighbourhood of Levis. Except in colour, the red slates are in every way similar to the grey and green slates. Their thickness in the western end of the band may be about 600 feet. Toward the eastern end the band thins, and in its easternmost outcrop is only about 75 feet thick. Farther east the red slate was not found, suggesting that it may never have been deposited.

UPPER GREEN SLATE

The red slates in Thetford map-area are overlain in turn by a second series of grey and green slates. They are identical in every appearance with the lower grey and green slates, so that they can be distinguished from them only in ranges VII and VIII, lots 2 to 10, Thetford tp., where the red slates lie between.

STRUCTURE

The Caldwell series has been closely folded along axes that strike approximately north 50 degrees to 55 degrees east. The main anticline of the district runs through the area of Bennett schist in Thetford map-area, leaving the map-area about 2 miles northwest of East Broughton station, on the east, and about 1½ miles north of Trout lake, on the west. In order that the above precision of statement may not mislead, however, it should be added that the axial line is placed rather arbitrarily within the axial area, which is a band between 3 and 4 miles wide throughout which the schists strike northwest and dip at low angles to the northeast or southwest. From this axial band the general dip is southeast and northwest.

Northwest of the axial band nothing but the Bennett schist is found as far as the extreme northwest corner of Thetford map-area, although northwest of Kinnear Mills metamorphism has not been so great as to obscure the original bedding altogether. The writer has carried the geological examination a mile or so beyond the northeast corner of the map-area, through Inverness village, and found that the first rocks to outcrop above the schists are green and grey slates, petrographically similar to those of the Caldwell series in Thetford map-area. It would seem, therefore, that on the northwest side of the anticline the full thickness of the quartzite member of the Caldwell has been rendered schistose, whereas on the southeast side there is a zone of non-schistose quartzite a mile wide lying between the Bennett schists and the lower green slates. The reason for this peculiarity is not known.

On the southeast side of the main anticline the rocks dip away in a series of rolls to the first principal syncline which runs through the area of red slate previously described, and through the small, irregular syncline west of Coleraine. Southeast of the synclinal axis, the prevailing dip is again northwest for about 4 miles, to the second main anticline of the region. This leaves the east side of Thetford map-area about 5 miles from the northeast corner, runs southwest in a fairly straight line to pass through the middle of lac à la Truite, where a wonderfully exposed cross-section may be seen, then swings somewhat to the west to pass just south of Coleraine village and a short distance east of Breeches lake. In Thetford map-area, east of lac à la Truite, the quartzites south of this anticline dip southeast and pass beneath the Beauceville series. Southwest of lac à la Truite, a subordinate anticline develops, along the course of Bisby ridge.

An extraordinary twist in the structure occurs in Thetford map-area, around Clapham lake, where the beds have been bent at right angles to the normal northeasterly trend over a width of 3 miles. This violent bend is a purely local feature, for within a mile east of Clapham lake the bedding resumes its normal strike. Both to the north and to the south of the 3-mile band where the bending occurs the strata maintain normal strikes, without noticeable disturbance. A second violent twist of the same sort is found to the west of Coleraine, in Disraeli map-area. It is significant that the larger masses of ultrabasic intrusives occur within these sharply twisted areas.

As the strata of the sharply twisted area or areas have roughly the same dips as those outside these areas, it seems necessary to conclude that the twists were formed after the strata had been folded into their present steeply inclined positions, that is, either during the Devonian period of folding or at the very end of the post-Ordovician folding. The only process by which the strata could be thus bent within so local an area would seem to be the process of drag-folding. According to this conception, a tendency must have developed, late in the period of folding, for the block of territory on the southeast to move southwesterly past the block on the northwest; and the strains thus set up were relieved by the twisting of the strata within a 3-mile belt between the two blocks. The bending was facilitated and accentuated by the injection of the peridotite-pyroxenite magmas. These may be thought of as forcing themselves into the bending strata like a great wedge, and shoving them apart, particularly on the northeast and southwest, the directions of easiest relief; and thereby increasing the sharpness of the bends.

That the intrusives really forced their way into the folded sediments, driving them upwards and sideways in the process, is suggested by two pieces of evidence. The first is that the sediments near the intrusives are sharply domed, and dip away steeply from them over considerable widths both to the northeast and southwest. This sharp doming is a purely local structure, for to the northwest of Thetford, away from the intrusive masses, doming is very gentle indeed, and the plunges to the northeast and southwest, respectively, are rarely more than 20 degrees. The second piece of evidence was obtained at the southwest end of Brousseau hill, in Disraeli map-area. The hill is a mass of intrusive pyroxenite, standing 300 feet above the more easily eroded sediments, with patches of older rocks on its lower flanks. To the southwest the sediments plunge northeast at angles of 30 to 45 degrees, to within some 500 feet of the nose of the hill. Northwest of the hill, where observations are fairly numerous, the northeast plunge is maintained past the hill, almost as far as Coleraine village; and southeast of the hill the scattered plunges obtained are likewise northeast. On the southwestern nose of the hill itself, however, there is a patch of exposed strata in which the dip is steeply southwest. Such a purely local, and extreme, change in direction of plunge can only be explained by concluding that the intrusive body was driven upwards like a great punch, forcing the overlying sediments upward, and dragging upward the strata around the margins.[1]

BRECCIAS

Breccias are of common occurrence in the region under discussion. They are mainly associated with the Caldwell series, hence their description is inserted here; but many of them present features of such peculiar complexity and interest that it seems best to devote a separate section to them.

Many breccias are associated directly with the lavas of the Caldwell and later series. They are of the two common types, flow breccias and explosive breccias or agglomerates. They exhibit no features not common to similar rocks elsewhere, and hence do not merit any special description.

Breccias are also common in the slate areas of the Caldwell series. They consist of fragments of slate in a structureless or slaty matrix. In many places there is sufficient outcrop to demonstrate that such breccias form near the summits of folds, where intense drag-folding first crumpled the strata into very short folds, and then, continuing, broke them into fragments. As such breccias are not unusual in closely folded areas, no further description of them will here be given.

Injection breccias, consisting of fragments of country rock in a matrix of later intrusive material, occur at a few points and will be described in the section devoted to "Intrusive Rocks."

Just west of Clapham lake, in range VIII, lots 17 to 19, Thetford tp., four knobs of breccia occur along an east-west line three-quarters of a mile long. The breccia consists of fragments of somewhat schistose quartzite up to 3 feet in diameter, embedded in a matrix of sand and grit that is clearly crushed quartzite. A few boulders are slate, and a few others are quartz. Many boulders both of quartzite and slate contain quartz veins ending at the margin of the boulder. All the boulders are angular or subangular.

At this locality the strata have been bent sharply through a right angle; and it is inferred that the sharp flexing has caused the brecciation described. That such bending will produce the observed effects is clear, for about a mile farther south, in range X, lot 17a, Thetford township, the quartzites are sharply bent into a series of small folds up to 15 feet across, and certain of the beds, presumably the more brittle, have been crushed to yield breccias identical with those described in the previous paragraph.

[1]For a detailed discussion of this question, *See* "The Mode of Emplacement of the Ultrabasic Rocks of Thetford District, Quebec"; Trans. Roy. Soc. Canada, 1935, sec. IV.

At this place all stages of the brecciation can be observed, from the initial fragmentation with but little matrix to the final stage in which 30 per cent or more of the rock is crushed to sand and grit; and in one place the fragments from a bed of distinctive grain and colour could be traced through a body of breccia. The bodies of breccia thus formed are 10 to 15 feet wide and up to 100 feet or more in length.

Similar breccias have been found in several other places, as on Morin hill, near the northwest end of lots 8 and 9, range VI, Coleraine tp., and near the southeast end of lots 41 and 42, range II, Wolfestown tp. A curious feature of many of them is the tendency of the fragments to form almost cubical blocks, 6 or 8 inches to the side. As the quartzites are almost invariably quite schistose, fragmentation might be expected to yield a predominance of platy fragments, but this is never the case. The outcrops in lots 8 and 9, range VI, Coleraine tp., throw light on this peculiarity. Between 200 and 300 feet uphill from the western side of the outcrop the schistose quartzite is not completely brecciated, but includes some large masses that show its condition just prior to complete fragmentation. In them the schistosity is violently contorted into strong drag-folds, the axial planes of which strike north 20 degrees east, dip westward at a low angle, and plunge about 30 degrees south. Numerous joints cut across the schistosity, making angles of 70 to 80 degrees with it; so that very little further movement would be required to produce a breccia of almost square blocks.

Still other breccias, whose origin is most difficult to explain, occur in at least three localities. The most accessible is at Coleraine village. Behind the cemetery on the southwest side of the village there is a large outcrop (Figure 1) composed of a most extraordinary mixture of materials. There are pebbles and boulders of red and grey lavas, some of which exhibit amygdaloidal and flow textures; red, grey, and white banded tuffs and cherts; more or less schistose quartzites easily recognizable as belonging to the Caldwell quartzites; and gabbro. The gabbro fragments include both normal fine- and coarse-grained varieties, very coarse pegmatitic types, and types so high in pyroxene as to be practically pyroxenite.[1] The various fragments are mostly fairly well rounded, though some are subangular to angular. They vary in size from 6 inches diameter downwards, though a few pieces of larger size are present; and are embedded in a greyish or reddish, gritty to gravelly matrix. Pebbles of the volcanic materials, lavas, tuffs, and cherts, predominate largely, but in some places pebbles of gabbro are almost equally numerous.

A rock of the type described might be: (1) a volcanic breccia, in which case it would be necessary to explain the presence of the gabbro and quartzite pebbles; (2) a crush breccia, in which case the same explanations would be required; or (3) a conglomerate, which because of its content of gabbro pebbles would have to be much younger than any other rock of the neighbourhood. Consequently, its structure and method of occurrence would have to be elucidated.

To determine which of these alternatives was correct, an intensive examination of the near-by outcrops was made. At locality "A" tuffs and

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[1]For a full description of the petrography of the gabbro and its internal and external relations, *See* this report, pp. 53 to 59.

breccias occur with a crude banding striking north 40 degrees east and dipping 60 degrees northwest. Some narrow bands are fairly fine-grained, like a sand, and grey in colour; but the common rock is a coarse breccia consisting of large lumps of lava, up to a foot in length, in a matrix of small, angular, grey and red fragments. The large lumps of lava are mostly dark red, with a hardness of 5 to 6, and very fine-grained. A few of them contain numerous, small, bubble-like cavities, and others exhibit a banding of dark red, pale red, and grey or greenish grey materials. This banding is very irregular in shape, width, and direction, and was accordingly interpreted as flow texture. In addition to the lava fragments, a few small pebbles of gabbro and quartzite are present.

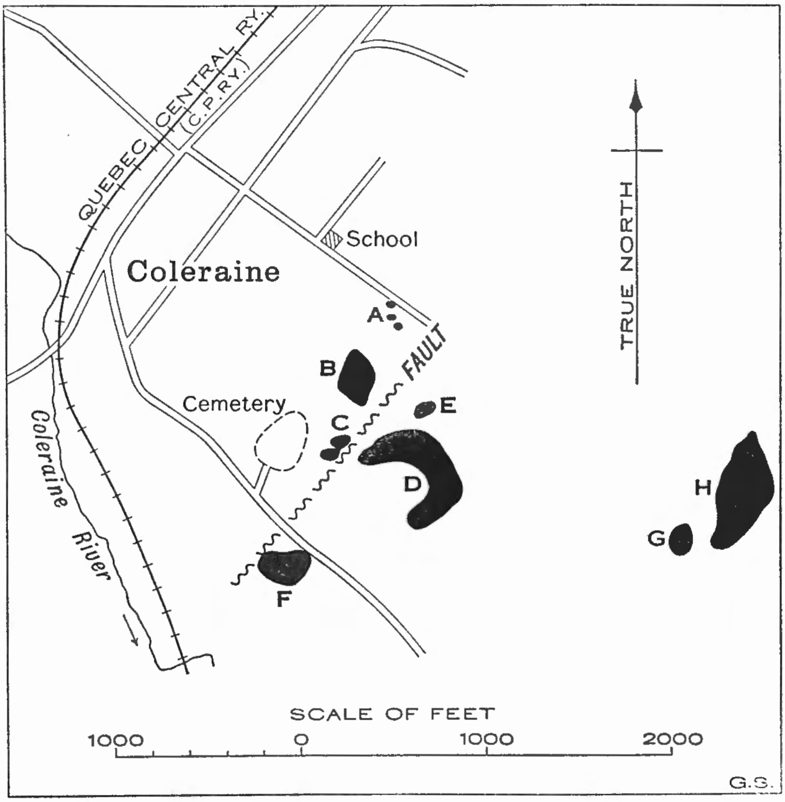

Figure 1. Outcrops near Coleraine village, Quebec. Outcrops shown in solid black.

The outcrops at " B " are more informative. Much of the rock, again, consists of large lumps of red lava embedded in a reddish, finely fragmental matrix which composes about half the total bulk; but the lumps of lava are larger, up to several feet in length, and most of them are sharp-angled. Accompanying the coarse material are bands, or fragments of bands, of finely fragmental red or grey rock. The different bands vary in grain from a fine sandstone or greywacke to a coarse grit. Their thicknesses, which are fairly uniform for as far as they can be traced, vary from a few inches for some bands to 2 or 3 feet for others. Traced along the strike these bands exhibit numerous sharp contortions. The character of the bands themselves, and the parallelism of their contortions, indicate that they are true sedimentary beds that have been violently folded, and to a considerable extent broken by folding. From the drag-folds it was determined that the true strike of the beds is north 45 degrees to 50 degrees east, the true dip is to the northwest at a low angle, perhaps 10 degrees or 15 degrees, and the plunge is southwest at about 20 degrees.

The general flatness of the dip, and the intensity of drag-folding, suggest that this area lies on or close to the crest of a fold. This conclusion is confirmed by the geological examination of the district as a whole, which proves that the area under discussion is part of the rather broad top of one of the main anticlines of the region. Anticlinal crests in general throughout this district, and this anticline especially, are characterized by intense drag-folding and crumpling.

At "C" the materials of the rock are somewhat more varied and more conglomeratic in appearance. Pebbles of red lava are somewhat less numerous than before, and those of grey lavas more numerous. Pebbles of white chert, up to 6 or 8 inches long, are fairly common; a few fragments of schistose quartzite are present, and quite a number of gabbro pebbles, most of them less than an inch in diameter. Most of the fragments have one or more sharp angles. The southwest end of this outcrop is broken off to give a steep overhanging face 4 or 5 feet high; and the two outcrops shown at "C" are separated by a vertical fissure about 3 feet wide and 15 to 20 feet deep. On these vertical faces it can be seen that the rather thick bands of breccia described are underlain, or interbanded with, bands of other materials, such as reddish quartzites or fine tuffs, fine greyish tuffs, and cherts. The strike of such bands here is north 80 degrees east, the dip is southward, varying rapidly within short distances between 20 degrees and 60 degrees.

Outcrop "C" is separated from outcrop "D" by a drift-filled gully about 50 feet wide, striking approximately north 40 degrees east. As the character of the rocks of "D" is very unlike those of "C," it was concluded that the gully is the locus of a fault. For reasons developed later, it was concluded that the southeast side of this fault is upthrown. The fault separates the outcrops at "A," "B," and "C" from those at "D," "E," and "F," and the determinations of structure already given, coupled with those about to be given, indicate that it developed either on or very close to the anticlinal axis.

The outcrops at "F" are mainly coarse agglomerates, made up largely of fragments of greyish lavas together with a number of fragments of quartzite and gabbro. Interbanded with the coarse materials are beds, or fragments of beds, of finer materials. Nearest the fault these beds strike north 60 degrees west, or almost at right angles to it, and dip southwest; and between this point and the southeast side of the outcrop the strikes become successively north 80 degrees west, north 80 degrees east, and finally north 60 degrees east, the dip being always south.

At the extreme southeast side of this series of outcrops there is a most interesting situation. A large proportion of the rock here is banded white and grey chert, such as forms many pebbles in the rock elsewhere. Closely examined, it is seen that these cherts formerly were a series of parallel beds, and that the parallelism is still maintained to a great extent. They have, however, been intensely drag-folded, and greatly stretched in the process. As a result, what was formerly a bed of chert is now, on the limb of a fold, in places a fairly continuous band, in others a linear succession of lenses separated by gritty matrix. Passing round the nose of the drag-fold the bed is more intensely broken into small bits, separated from one another by several inches, perhaps a foot or more, of gritty matrix. It is abundantly clear, in this locality, that brecciation has occurred by intense distortion.

In the area " D " the rock is, as already mentioned, entirely different from that in " C." Fragments of red lava, so numerous in " C," are entirely absent; and red chert fragments, also numerous in " C," are very scarce. Gabbro fragments are much more numerous, and constitute between 20 and 25 per cent of all the pebbles. Most of the remainder are grey or brownish grey lavas, with a few of schistose quartzite. In one or two places there are remnants of thin bands of slate and white chert, intensely contorted and broken into plate-like fragments.

Remnants of bedding in this area exhibit the same relations as described in area " F." Close to the fault the strike is north 50 degrees west, the dip about 40 degrees southwest. Farther southeast the strike swings until it is northeast, with a dip to the southeast.

In the outcrops at " E," which, if the structure has been correctly determined, are stratigraphically the lowest of those described, the breccias contain a still larger proportion of gabbro, and a great deal more quartzite. About 40 per cent of the fragments here are gabbro; and although the quartzite fragments are not numerically numerous, they are large, one measuring 5 feet in length by 3 feet in width. The remaining fragments, as before, are chiefly grey lavas.

As to the possible origins of these rocks it has been shown that they lie on the crest of one of the principal anticlines of the district, a most unlikely place, structurally, for the occurrence of a later conglomerate. The only conditions under which a conglomerate could be found in such a place would be, that it should have been deposited in a valley eroded along the anticline, after the older series had been folded and deeply dissected by erosion. If this were so the younger rock should be either undeformed or much less deformed than the surrounding rocks; but it is as intensely deformed as the surrounding rocks. It is, therefore, impossible for these rocks to be younger conglomerates.

A second possibility is that they are tuffs and agglomerates of volcanic origin. Very thick, coarse agglomerates form part of the lava series both northeast and southwest of the area under discussion; but they differ from the rocks described in containing only pebbles of lavas—no cherts, no quartzites, no gabbros. The lavas, in forcing their way to the surface, might have torn away and carried up fragments of rocks through which they passed, thus accounting for the presence of quartzite fragments; but ordinarily no such explanation could be given for the presence of fragments of gabbro, an intrusive younger than the lava; or of fragments of cherts, which were mainly deposited toward the end of the extrusive period.

Eliminating these possibilities, it would seem that these rocks must be crush breccias, formed by the intense crumpling of pre-existing beds at the summit of the anticline. Regional work shows that the volcanic rocks overlie quartzites, and are separated from them in this district by a sill of gabbro. Violent crumpling and flowage, such as are known to occur at the summit of this anticline, and may be directly observed in outcrops B, F, and D, could, therefore, have produced breccias of the type observed, by breaking up the gabbro sill and mixing fragments from it with fragments of the overlying lavas and tuffs and the underlying quartzites. That mixing of the various materials took place here mainly by the means outlined is further suggested by the relations found in outcrops "G" and "H", about 2,000 feet southeast of the anticlinal axis. Outcrop "G" is a knoll of coarse breccia, the northwest side of which consists of fragments of quartzite, gabbro, and lava, whereas the southeast side, in addition, has many fragments of banded red and grey cherts. The northwest side of outcrop "H" shows a sill of gabbro striking north 50 degrees east and dipping 65 degrees southeast, parallel to the sediments. The sill is overlain on the southeast by a rather thick succession of red and grey bedded cherts. The northwest side of the gabbro sill is badly brecciated. Thus, away from the crest of the anticline the sill, as might be expected, is only partly brecciated, whereas on the crest it appears to have been completely brecciated.

However, although this theory seems adequate for the explanation of the Coleraine breccia, and much of that breccia was undoubtedly formed by mashing and flowage, certain facts indicate that mashing and flowage were not the sole agencies of their formation. One fact is the discovery of a granite pebble in outcrop "E". No other pebbles were found, as might be expected if a sill or dyke had been fragmented; and in any case all the known granites of the region are later than the folding. The presence of the granite fragment thus remains unexplained. Another fact is the occurrence of similar breccias in at least two places where drag-folding and mashing are not intense enough to explain the observed relations.

One of these localities is near the town of Asbestos, in the southwest corner of Warwick map-area. A gabbro-lava contact, with associated breccias, was found near the reservoir about half a mile southeast of the town, and was traced southwest more than 2 miles, beyond the limits of the map-area. It is best exposed on the crest of Burbank hill, about 1½ miles southwest of the town. The sill of gabbro occupies the northwest side of the hill, and is in contact, on the north, with pyroxenite. The southeast part of the gabbro is fine-grained over a width of at least 200 feet, and is badly brecciated. The breccia consists of fragments of fine-grained gabbro cemented by a small amount of matrix consisting of crushed gabbro. No other fragments are present in it. South of the contact is a series of thick bands or beds of coarse breccia, made up of angular and subangular fragments of lava and gabbro. The gabbro fragments vary in grain from very fine to very coarse, and from fairly basic to quite feldspathic in composition. Interbanded with the breccias is a flow of basic lava, the grain of which is coarsest on the north and becomes gradually finer toward the south, indicating that the flow faces southward. The lava contains no fragments of gabbro. Above the lava there are more bands of breccia identical in composition with those below, and these are succeeded in turn by well-banded, red and grey cherts. Farther to the southeast the cherts can be seen to be succeeded by softer, more slaty types, and then by true slates. All these rocks strike about north 60 degrees east, dip vertically or steeply southeast, and seem to follow one another with perfect conformity. The cherts are rather badly crumpled by folding, and have been broken up to some extent thereby.

The difficulty of finding an adequate explanation for these phenomena is great. On the one hand, the gabbro is known to be an intrusive rock injected after the lavas were laid down, hence there would seem to be no way of producing a breccia of gabbro and lava fragments except by movement after the gabbro was consolidated; and that such movement took place is shown by the brecciation of the gabbro itself, and the crumpling and partial brecciation of the overlying chert beds. Opposed to this view are the facts: (1) that the chert beds, though crumpled and to some extent broken, are not crushed to fragments and those fragments mixed with other materials; so that movement was not extreme, and transfer of material from one horizon to another was not great. (2) The fragments of gabbro in the breccias vary widely in grain and composition, although the nearby top of the sill itself is fine-grained. The known composition, if caused by movement, would necessitate very great transfers of material, because fragments such as found could come only from the interior of the sill. It would be necessary to conclude, therefore, that the zone of fracturing cuts across the strike or dip of the contact at a small angle, and that the coarse-grained fragments were moved considerable distances from their point of origin to their present positions. This is a far-fetched conclusion, in view of the evidence afforded by the cherts. (3) The breccias occur in thick bands; no banded structure could have been produced by brecciation, but on the contrary original banded structures would have been destroyed. (4) A lava flow is interbanded with the breccias, but exhibits little or no crumpling or fracturing. Movement sufficient to form beccias like these would probably have destroyed the flow. In fact, great amounts of flow material must have been destroyed, under the hypothesis of movement, to supply the lava fragments in the breccias. (5) The breccias above the lava flow are identical in composition with those below it. Whence could these breccias have derived their gabbro fragments? (6) The succession of bands of breccia, with the interbanded lava, followed by normal sedimentary beds, cherts, and slates, in perfect parallelism, suggests a sedimentary succession.

The preponderance of this evidence, therefore, is against the conclusion that the breccias were formed by movement, even while admitting that some were formed thereby, and is in favour of their origin as beds. The gabbro sill, however, is known to be later than, and intrusive into, the lava; and if the breccias and lava are essentially contemporaneous, *the sill must also be later than and intrusive into the breccias.* In other words, the gabbro fragments in the breccias cannot, except to a minor extent, have been derived from the sill.

We must conceive, therefore, of a body of gabbro magma rising by successive stages, with long halts, and probable freezing of its upper parts during these halts. At the end of the first stage of which we have record, the magma must have halted in its rise, and the upper parts solidified to a gabbro of much the same composition as the sills. Renewed activity then caused fracturing and formation of volcanoes, from which explosions hurled the mixtures of gabbro and lava fragments that now form the bands of breccia. Occasional fragments of foreign materials, such as granite, might be expected in aggregate thus formed, and are actually found. At times quiet extrusions of lava from the volcanoes took place, forming flows interbanded with the breccias. The close of this phase of activity was marked by the release of heated waters, which deposited the chert beds. After another period of quiescence of unknown length there was a further rise of gabbro magma, which rose as far as the hard lava bands and there spread into the flat sheets or sills.

The probable correctness of the hypothesis advanced can be checked by the descriptions of two other localities. About half a mile southeast of Asbestos the section differs from that described, in that the breccia in direct contact with the gabbro sill is composed entirely of fragments of lava, and this is succeeded on the south by breccias of gabbro and lava fragments, in which two fragments of granite were noted. The outcrops in this locality are scattered, so that a continuous section cannot be obtained.

About a mile southwest of Coleraine village, along the north side of an east-trending ridge (Garthby tp., range II, southeast ends of lots 41 and 42) there are excellent exposures of breccia. Structurally, the area lies on the northwest flank of the main anticline passing near Coleraine village. The ridge itself consists of gabbro, the north side of which is fine-grained over widths of 100 to 200 feet. It is also rather badly brecciated, though less so than the gabbro on Burbank hill. In the main, brecciation has merely fractured the rock rather badly, without crushing much of it to powder; so that true breccias composed of gabbro fragments in a paste of powdered gabbro are found only in a few small areas close to the north margin.

At the westernmost exposure of the upper contact, the gabbro is in direct contact with a breccia composed almost wholly of gabbro fragments, with a few of quartzite and quartz. The gabbro fragments are not fine-grained like the adjacent sill material, but exhibit the same variety in grain and composition as those on Burbank hill. The contact for 10 or 15 feet was stripped of moss, and proved to be highly irregular. It was found later that similar irregularity, both on a large and a small scale, prevails wherever the contact can be seen. The breccia made up almost wholly of gabbro fragments is only about 2 feet thick. Above this, quartzite pebbles increase rapidly in numbers, until they form perhaps 80 per cent of the volume of the breccia, the remainder being gabbro. Most of the fragments are less than 6 inches in diameter, though they attain much larger sizes in a few places, and large numbers of them have one or more sharp angles. About three-quarters of the quartzite fragments are more or less schistose, the rest massive. Many of them are traversed by quartz veins which end at the margins. The fragments are cemented by a very small amount of fine-grained, yellowish matrix, that to the eye exhibits no trace of fragmental texture. Some of the fragments are cracked, and the matrix material, or what appears to be it, has penetrated the cracks, even when these are very narrow. In one place, on a very clean, glaciated surface, reaction seemed to have taken place between the matrix material and the gabbro fragments, for the latter are somewhat bleached around the rims throughout widths of one-fortieth to one-twentieth of an inch. The effect is best seen in the smaller fragments, about one-quarter inch in diameter, many of which have been about one-half converted into the lighter coloured material. This effect, together with the character of the matrix, suggests either that the matrix material was itself a liquid, or that it was permeated by gases or vapours that exercised an alterative effect.

About one-quarter mile east of the locality described the more or less brecciated gabbro is in direct contact with a lava of medium to acid composition. The contact is very irregular. The lava is flow textured at the contact, and passes into flow breccia above. A drift-filled depression perhaps 100 feet wide separates this outcrop from the next on the north, which consists, on the south side, of moderately basic lava carrying numerous fragments of gabbro of all types. The gabbro fragments are very numerous in the upper and lower horizons of the flow, but relatively few over a width of about 10 feet in the middle. The upper foot or so of the lava, which may be tuff or ash, contains fragments of quartzite in addition to those of gabbro. This rock is overlain by a breccia consisting almost wholly of quartzite fragments, many of them 3 or 4 feet in length. Large fragments of the quartzite have sunk into the lava or tuff beneath them, for distances up to a foot, so that they now lie across the contact; and there is no evidence of movement having taken place since they were laid down.

Much more space could be devoted to the description of these extraordinary rocks, but enough has been said to bring out: (1) the banded nature of the breccias, (2) their highly irregular contacts with the gabbros, (3) the lack of evidence that much brecciation occurred in place, except near Coleraine village, (4) the occurrence of gabbro fragments both in the ordinary breccias and included in lavas, and (5) the impossibility of deriving the fragments from the adjacent sill. The evidence afforded by these breccias, therefore, strongly supports the hypothesis that they originated by volcanic explosions by which the then-existing rocks, including some pre-formed mass of gabbro, were broken down and hurled out on the surface. The numerous quartzite fragments in the breccias in the last locality described add strong support to this conclusion, as the nearest quartzite that could have supplied them now lies stratigraphically beneath the gabbro sill. The highly irregular contacts, and the manner in which gabbro is found here in contact with breccia, and there in contact with lava, both combine to indicate the probable intrusive character of the sill.

It is concluded, therefore, that the gabbro and lavas belong to one general period of igneous activity with several episodes. The first was the injection, deep below the surface, of a magma that solidified to a gabbro like the present sill. Renewal of igneous activity caused the breaking out of volcanoes, which not only emitted lavas, but in which gas explosions brought up fragments of the underlying gabbro and quartzite, and ejected them to form the existing breccias. More magma was then injected, which spread into sills beneath the lava-breccia cover. Finally, the whole series was intensely folded, with further brecciation of the gabbro sill and the chert beds, and some mixing of the different bands where crumpling was particularly great, as on the anticlinal axis near Coleraine.

BEAUCEVILLE SERIES

By T. H. Clark

The Beauceville series forms a band about 5 miles wide that runs southwest through the southeast part of Thetford map-area and the middle of Disraeli map-area into the southeastern corner of Warwick map-area. In 1932 Cooke traced the band eastward to Chaudière river, and thus proved it to be continuous with what MacKay had previously termed the Beauceville series (92, page 4). Accordingly, the name Beauceville was extended to the areas here treated.

In Thetford area the Beauceville series consists mainly of black slates with a basal conglomerate and some interbedded, impure quartzite or greywacke. These continue southwestward into Disraeli map-area, bounded on the north by the Caldwell series, supposedly Cambrian, and on the south in Disraeli map-area by the Devonian. South of the Devonian, and faulted against it, is a band of lavas followed by sediments whose fossil content indicates their age as Ordovician. Petrographically these rocks are entirely unlike the Beauceville series to the north, and it has not been found possible to determine the relations of the two, even in the northeast beyond the Devonian beds, where the two groups adjoin, because there the contact is hidden by wide areas of drift. In these circumstances it seems best to differentiate the two Ordovician groups and accordingly in subsequent pages the sedimentary rocks of the southern band are termed the St. Francis series. The boundary between the two has been indicated on the map as closely as the widely scattered outcrops will permit. It may possibly be a fault. If this is true the fault must be pre-Devonian, as the Devonian beds run across it unbroken.

The Beauceville series is made up of three fairly distinct lithological types or phases, which are separately described below although they have not been differentiated on the accompanying maps. These are, in descending order:

Slate, quartzite, and conglomerate
Slate
Basal conglomerate

BASAL CONGLOMERATE

Along the contact with the underlying Caldwell formation the basal Beauceville beds are conglomeratic. North and northeast of Disraeli village there are large outcrops of pebbly slate that may be the upper part of the basal conglomerate. In most places the basal conglomerate consists of pebbles, mainly of quartzite, in a slaty matrix. This fact for some time caused doubt as to its true nature, because similar rocks might be formed by folding and brecciation of thin, alternating bands of quartzite and slate. The doubt was finally removed by the discovery of two or three localities where there had been little or no shearing, so that the rock could be definitely established as a true conglomerate. One such place is near the northeast ends of lots 34 and 35, range XIV, Adstock tp., where conglomerate lies directly upon Caldwell quartzite, and dips southeast in what appears to be a small syncline. At the contact itself the conglomerate is much sheared, but about 1,200 feet to the southeast, presumably near the axis of the syncline, the shearing dies out completely. At this point the rock is made up of pebbles of quartzite and slate, embedded in a matrix of grit and small slate fragments. The pebbles are numerous, of all sizes up to 2 inches, and subangular to moderately rounded. The slate fragments are soft, not far removed from shale, and very noticeably less slaty than the existing slates of either the Caldwell or Beauceville series, indicating that they had been broken away before the Caldwell series was metamorphosed to the extent it now is. Black slate, grey and whitish slate, dark quartzite, light grey quartzite, coarse quartzite, and fine quartzite, were identified among the pebbles, all of which can be matched with the underlying Caldwell rocks. Some parts of the conglomerate are made up entirely of slate fragments rather loosely cemented.

At another locality in Adstock tp., range V, lot 34, the conglomerate is but slightly sheared, and, in addition to the usual type consisting of quartzite and slate fragments, a new type appears, made up almost wholly of quartzite fragments. In this rock the pebbles are crowded together, and cemented with a small quantity of gritty matrix. The pebbles are nearly all quartzite, with a very few of slate, and are of all sizes up to 2 feet in diameter. The edges and corners are somewhat rounded, but otherwise the pebbles do not exhibit pronounced wear, so that they were evidently not subjected to long-continued abrasion. The quartzites are of the various types found in the underlying Caldwell series.

At the most northerly point of lake St. Francis, where Coldstream brook enters the lake, there is a development of this basal conglomerate. There the matrix and fragments are almost entirely slate, but with some fragments of quartzite, grit, and limestone. The matrix is dark, almost black, whereas the fragments are flakes of lighter, almost white slate for the most part less than an inch across. Here and there are pebbles that look as if they might have come from the greenish lava of the Caldwell. Almost perfect parallelism between the cleavage of the rock and the cleavage of the fragments obtains here.

SLATE DIVISION

The common rock of the Beauceville series is a dark grey or black slate, impregnated in places with cubes of pyrite or crystals of carbonate. The slates are evenly and thinly bedded, the beds varying from 1 to 2 inches in thickness, and characterized by an excellent secondary cleavage. The metamorphism causing cleavage has obliterated the bedding in some places producing a fissile slate or schist; but for the most part the bedding is still readily discernible wherever a clean, relatively smooth surface can be obtained. In places, innumerable tiny pyrite cubes are crowded in the sandier interbeds, the intervening argillaceous beds being comparatively free. This abundance of pyrite leads to local rustiness.

In three localities, namely, at the four corners 2 miles west of St. Gerard, 1½ miles northeast of Garthby, and north of Ste. Praxede, the beds transitional from the slate division to the overlying slate and quartzite are visible. They form a succession of alternating dark and light bands about an inch thick, very evenly bedded; with an occasional bed of quartzite up to a foot thick. The light bands seem slightly harder than the dark bands, and on casual inspection might be taken for fine-grained quartzite, but more careful examination shows them to be predominantly argillaceous, and not very different from the darker bands.

UPPER DIVISION: SLATE, QUARTZITE, AND CONGLOMERATE

The uppermost part of the Beauceville series consists of alternating beds of quartzite or greywacke, and slate, the beds ranging from ½ inch to 3 or 4 inches in thickness. The quartzite beds are lighter in colour than the slates, so that the formation may resemble that described in the previous paragraph; in fact it is difficult, where the two are in contact, to draw a definite line between them. The upper division was distinguished as such in the field only where the light-coloured beds could be determined as definitely arenaceous. The bedding of these rocks is remarkably even, so that where on edge they outcrop as a succession of parallel ribbons of perfectly uniform width.

In places, particularly in the upper horizons, beds of conglomerate are interbanded with the slates and quartzites. Such beds range from 1 to 30 feet in thickness, and are composed of pebbles or boulders 2 to 6 inches in diameter, fairly well rounded, and in some places closely packed. The formation of these beds is rather difficult to explain, as they are in sharp contact both above and below with the well-bedded, quite undisturbed slates and quartzites. An excellent place to observe these relations is on Garthby peninsula, about 1½ miles due east of Garthby village. Here the conglomerate consists of pebbles ranging from 2 to 6 inches in diameter, the majority of which are either quartz or quartzite, though there may be some rhyolite pebbles among those classed as quartzite. The remaining pebbles are mainly chert and slate; none of granite was seen. The slate pebbles are apt to be irregular and slab-like in shape, but those of the harder rocks are fairly well rounded. The matrix is a greywacke in which quartz, mica, and feldspar are visible to the eye. It is identical in composition with the sandstone beds interbedded with the conglomerate.

In places, as at St. Peter point, lake St. Francis, where the division was first studied, and also about 5 miles southeast of Disraeli, the formation has been intruded by a granite dyke or dykes and strongly metamorphosed to nearly black, hornstone-like rocks with development, in places, of minerals like sillimanite or andalusite. Half a mile west of the west end of Lambton lake the formation has been crumpled to form a breccia.

RELATION TO CALDWELL SERIES

The strata of the Beauceville series parallel those of the Caldwell series fairly closely, indicating that no important folding of the Caldwell took place before the Beauceville was laid down upon it.

That a considerable period of erosion, probably accompanied by a little folding, intervened between deposition of the two series, is proved by a number of facts. The basal conglomerate of the Beauceville is made up of fragments from the underlying Caldwell series. The base of the Beauceville is not in contact with the upper, slaty horizons of the Caldwell, but is, stratigraphically, close to the boundary between the quartzites and the lower green slates. This fact, together with the great abundance of slate fragments in the Beauceville conglomerate, points to the conclusion that the intervening period of erosion was long enough to cut away the full thickness of Caldwell slates. A third and indubitable proof of unconformity is afforded by the regional mapping, which brings out the fact that the base of the Beauceville lies in some places on Caldwell slate, in others on quartzite, in still others on lava. The only manner of attaining these relationships is by erosion of a folded series prior to deposition of an overlying series.

Some folding of the Caldwell before deposition of the Beauceville is also indicated by the nature of the slate pebbles in the undeformed conglomerate of lot 34a, range XIV, Adstock tp. Although many of these pebbles are rather dull and earthy in appearance and might properly be classed as lithified shale or even fissile shale, most of them have a well-developed cleavage, with smooth, shining cleavage faces. Such cleavage can only have been formed by metamorphism during folding. The direction of cleavage in one pebble has no relation to that in another pebble, but in the jumble of pebbles the cleavages lie at all angles; indicating that the cleavage was not impressed on the rock after the conglomerate was deposited, but must have been a property of the slates before they were eroded and brought into their present positions. The softness of the slate pebbles, however, and the presence of many that are merely hard shale, show that the folding and metamorphism were not extreme.

It may, therefore, be concluded that the Caldwell series was moderately folded, and then subjected to erosion for a time sufficiently long to permit of the almost complete removal of the various Caldwell slates, before deposition of the Beauceville began.

RELATION TO LAKE AYLMER SERIES

There is little doubt, from the evidence of the basal conglomerate of the Lake Aylmer series (page 43), and from the great petrographic differences between the two series, that the Lake Aylmer series overlies the Beauceville series disconformably. Lack of outcrops, however, makes good evidence difficult to obtain and the relations are still further obscured by the occurrence of conglomerate in the upper part of the Beauceville series, stratigraphically contiguous to the Devonian basal conglomerate. During the earlier part of the field work all these conglomerates were ascribed to the Devonian; but this gave rise to an impossible situation, for, if true, it then had to be concluded that the interbedded shales were also Devonian, and likewise the whole series of Beauceville slates, as no line can be drawn between the two divisions. The possibility was considered that the whole Beauceville series might be Devonian; but this proved untenable because the Devonian proper cuts across the contact between the Beauceville and St. Francis series. Thus the conclusion seems inescapable that there are actually two conglomerates, rather alike but of different ages, one just above, and the other just below, the Ordovician-Devonian contact.

Although it is undoubtedly difficult to differentiate the two conglomerates petrographically, the writer believes that with care it may be done. The Devonian conglomerate contains an abundance of well-rounded pebbles and boulders up to 30 inches in diameter, many of which are granites, rhyolites, and similar resistant rocks. The conglomerate is made up of thick beds, some of which contain numerous large boulders, whereas others are made up mainly of smaller pebbles; and the boulders or pebbles are crowded together with a minimum of matrix. The matrix is gritty or sandy rather than muddy, so that the rock is clean looking. In the upper Beauceville conglomerates the pebbles are smaller and less well rounded, there is a larger proportion of matrix, and the matrix is apt to be muddier, so that it was often referred to in the field as a "dirty" conglomerate. Stratification is rarely seen in it. In spite of these general differences, however, there are many places where petrographic differences fail; and in general the two were separated according to whether they were associated with the distinctive Beauceville strata or with the characteristic Devonian strata.

AGE

Cooke (33, page 45) in 1932 considered that he had fixed the age of the Beauceville series as Ordovician through the discovery of Ordovician graptolites in lots 11 and 12, ranges VIII to IX, Adstock tp. Subsequent work indicates that these fossiliferous strata fall into the St. Francis series rather than the Beauceville series, hence the age of the Beauceville series is not definitely known.

It has been shown, however, that the Beauceville series overlies the Caldwell series with unconformity, and the Caldwell series is almost certainly to be correlated with rocks in the Memphremagog district which underlie, with unconformity, fossiliferous Middle Ordovician slates, and which are, therefore, either Cambrian or Lower Cambrian, or both. The Beauceville series underlies, with unconformity, the Lake Aylmer series, the fossils of which indicate its age as Helderberg. For the time at least, therefore, the Beauceville series is considered to be Ordovician, and to have a rough contemporaneity with the known Ordovician strata of the St. Francis series.

ST. FRANCIS SERIES

By T. H. Clark

A line drawn from lac Rocheux in Adstock township to Elgin lake in Stratford is approximately the northern boundary of the St. Francis series. It underlies all of Disraeli map-area southeast of this line, except the parts underlain by the Winslow granite and the Lake Aylmer series; in all, somewhat more than 100 square miles. There are large areas of outcrop, so that the rocks can be termed well exposed.

The St. Francis series is made up of two members, a group of lavas and a formation consisting mainly of impure quartzite and graywacke.

The lavas have commonly been considered older by earlier workers. The southeastern quarter of the Eastern Townships map (1875) represents them as Precambrian, along with the Bennett schists. Burton (20), under the name Weedon schists, correlates them with the lavas of the Caldwell series (called by him the Gagne Brook series). Evidence obtained by the writer seems to indicate, however, that neither of these classifications is correct.

LAVAS

The lavas form a band that runs from lake Elgin, on the south border of Disraeli map-area, northeastward for about 10 miles. At lake Elgin the band is about 2 miles wide, and it narrows on the northeast to a point. Its western boundary is the great fault, termed by Burton the Weedon thrust, which has brought it into contact with the Devonian; this fault cuts across its strike at a small angle, accounting for the decreasing width in the northeast. On the east the lavas are in contact with the St. Francis sediments, except on mount Aylmer where granite is injected between them. An excellently exposed cross-section of these rocks can be seen along the road running northwest from the village of Stratford Centre, and the upper horizons are beautifully displayed on the northwest flank of mount Aylmer.

The northwesternmost outcrop on the cross-section mentioned is the flow-textured top of a lava flow. This is followed on the southeast by ash beds, in which two bands of white chert, each 2 to 4 inches thick, were observed. The ash beds are highly ferruginous, and weather deeply to a soft red material. A flow, not well exposed, follows; then a second, rather acid lava, near rhyolite in composition. The latter has a massive base, 50 to 60 feet thick, grading on the southeast into flow-textured material which becomes more and more finely laminated as the southeast edge is approached. It is thought that the lamination has been accentuated by shearing. Ten to 15 feet from the margin numerous, red, cherty nodules appear in the lava, filling what appear to be amygdules. These are of all sizes up to 4 or 5 inches long and 1 or 2 inches wide. The strike of the margin of the flow is north 20 degrees east, the dip about 60 degrees east; and the observed relations indicate that the top faces east.

Overlying the flow, thin-bedded, rather soft tuffs occur, containing large, elongated nodules of the red, cherty material.

The next outcrop to the southeast displays more basic lava, near andesite in composition. It contains a series of flows, some of which are not more than 6 to 10 feet thick. These are flow-textured throughout.

Similar basic lavas continue across the section to Stratford Centre. Some of them exhibit pillow structures, others flow breccias; and there are many beds of coarse agglomerate or tuff. One excellently exposed band of flow breccia is made up of non-amygdaloidal fragments of lava in a highly amygdaloidal matrix. Interbanded with these basic lavas are two bands of fine-grained, glassy rhyolite carrying a few phenocrysts of white feldspar about 1 mm. in diameter. The bands are about 25 feet wide, and one of them directly overlies the pillowed top of the basic flow beneath. There is here no good evidence to indicate whether these bands are flows or dykes.

The outcrops on the northwest flank of mount Aylmer display the uppermost horizons of the lavas. The best section is obtained by starting opposite the road between lots 10 and 11, range VI SW., Stratford tp., and angling across the strike in a northeasterly direction. The rocks for some distance from the road are mainly andesitic lavas, exhibiting very well-developed flow structures and some excellent pillow structures. The general strike is north 35 degrees east, the dip about 60 degrees southeast, and the flows face southeast. A good many bodies of rhyolite also occur with the lavas. Some of them form elongated lenses or nodules of all sizes from 5 to 100 feet or more in length, lying parallel to the bedding of the basic lavas. Others cut across the bedding of the lavas at angles of about 45 degrees. One of the latter, seen in lots 5-6, has the same composition as the porphyry northwest of Stratford Centre, suggesting that the latter is likewise a dyke.

Near the top of the hill, in the vicinity of the Stratford pyrite deposit, the flows become thinly banded, due to flowage; this suggests that the individual flows are probably thin. Interbanded with the flows is material that appears to be of sedimentary origin, fine-grained tuff with some chert, and much of this has been altered to carbonate. The "limestone" described by Burton (20, page 117) as a part of the Disraeli series is an isolated outcrop of this carbonated tuff. Similar carbonated material is found at the Stratford pyrite deposit, and may be responsible for the precipitation of pyrite there.

The uppermost horizons of the lavas consist of a succession of thinly banded, siliceous rocks that appear to be silicified and recrystallized tuffs. On the southeast flank of the hill in lot 4, range VII SW., Stratford tp., these rocks are in conformable contact with recrystallized greywackes and slates, filled with needles of altered andalusites. Among these beds a single thin bed of impure limestone was observed. A wide drift-filled gap separates these rocks from the nearest outcrop of rocks definitely determinable as belonging to the St. Francis sediments.

Age

The lavas are petrographically quite unlike the lavas of the Caldwell series. The difference is difficult to describe, but is readily discernible by anyone studying them in the field. In part at least it is one of structure. H. C. Cooke has traced the Caldwell lavas for nearly 60 miles along their strike, and within this distance they are prevailingly massive, dark green flows, with distinctly minor amounts of breccia and tuff. The St. Francis lavas outcrop less than 7 miles across the strike from the nearest outcrops of the Caldwell lavas, and, therefore, in view of the uniformity displayed by the latter, might be expected to be similar to the Caldwell if of the same period of extrusion. On the contrary, however, the St. Francis lavas consist in large part of strongly flow-textured lavas, flow breccias, and tuffs, indicating that the flows were less fluid and thinner than the Caldwell flows, and also more gassy, resulting in numerous volcanic explosions.

Throughout the whole width of the lava band all the structure determinations obtained indicated that the flows face toward the southeast. Unfortunately, these determinations were all obtained near the northwest edge and within a half mile of the southeast edge, so that there is a width of about a mile in the centre of the band from which no determinations were obtained. It is possible, therefore, that an undetected fold in the succession exists. If this is not the case, the thickness of the lavas must be in excess of 8,000 feet.

As the flows face southeast at their southeastern edge, however, the St. Francis sediments still farther southeast must overlie them, unless a fault of which there is no evidence lies between. As the strike of the lavas is parallel to that of the sediments, there is no reason for assuming that an unconformity exists between them. If the recrystallized sediments in lot 4, range VII SW., Stratford tp., belong to the St. Francis sediments, recrystallized by the nearby granite of mount Aylmer, there can be no doubt as to the conformity of the lavas with the sediments.

On these grounds the writer has classed, tentatively, the lavas with the sediments of the St. Francis series. Extension of the geological work to the south may prove this classification incorrect; but the data at hand appear to justify it.

ST. FRANCIS SEDIMENTS

The St. Francis sediments lie east of the lavas, and extend beyond the eastern border of the Disraeli and Thetford map-areas. They consist mainly of impure quartzite and greywacke, but in addition there is a considerable amount of argillite or slate, and a minor amount of limestone. Pure quartzite was not seen, nor any conglomerate or beds on the borderline between conglomerate and sandstone. The exposures near Stratford Centre contain rather more slate than those farther east.

Slate

The argillaceous rock shows few inherent characteristics that are noteworthy, and is nearly always in thin beds up to 2 inches thick, although in a few places beds have widths up to 30 feet. No original minerals are visible. The slate commonly contains rhombs of siderite or other ferruginous carbonate, usually less than $\frac{1}{8}$ inch in diameter, but in places up to $\frac{1}{4}$ inch. Some beds contain from 2 to 5 per cent of these rhombs, which weather out to ochreous depressions, although a few inches from the surface the carbonate is fresh or nearly so. All the slates have good secondary cleavage.

One slab, found loose at Lambton, showed obscure traces of graptolites, and another unmistakable algal fossils. No fossils were found in place, however, in spite of diligent search.

Quartzite and Greywacke

All gradations occur between the true argillaceous and typical arenaceous rocks. Thus by far the greater part of the St. Francis sediments consist of fine- to medium-grained greywackes and impure quartzites. Most of these rocks are grey, some nearly black, but a few of the quartzite beds are dull pink or buff. There is little difference between the quartzites and greywackes. Both consist predominantly of quartz grains, with a maximum of perhaps 10 per cent of feldspar fragments and a little detrital mica. The difference lies wholly in the large amount of muddy matrix in the greywackes. The grain ranges from about one-sixteenth inch down to extremely fine, and no coarse grits or conglomerates occur. The beds range from several inches to several feet in thickness. No ripple-marks were seen, but crossbedding is common. In some places the crossbedding is so extreme as to make interpretation difficult, but usually, by the exercise of some ingenuity, its significance can be determined.

Near the Winslow granite these rocks are commonly baked to a sort of hornstone, heavier and more compact than the unaltered rocks. Commonly the quartz grains in them are rendered more prominent, apparently by the fusing of the remainder of the rock.

Secondary minerals in the greywackes include siderite, pyrite, and sericite. The amount of siderite is much less than in the slates. Pyrite is common, and forms cubes up to ¼ inch in diameter.

Calcareous Beds

Calcareous strata appear at several localities; namely, 1 mile south of Lake Aylmer corner; along the western shore of lake St. Francis 1½ miles northeast of Indian River bridge; along the shore and on islands ¾ mile north of Indian River bridge; along the road 1 mile west of Lambton, and again about 2 miles north of Lambton; 1¼ miles northwest of Cranberry lake; Stratford Centre; etc. In all cases the beds deserve to be called calcareous sandstones or calcareous shales rather than limestones. They range in colour, when fresh, from buff to dark grey. Weathered, the sandy types become light brownish grey, with a sandy surface, and the shaly, a deep brown, almost black. Where the latter are exposed at a road cut in a bend of the road a mile west of Lambton they contain half-inch shiny streaks that may have been graptolites, but unfortunately no structures of organic significance can be made out. Weathering has reduced the upper parts of this shale to a soft, earthy mass, whereas in the calcareous sandstones weathering is never more than skin deep.

The calcareous sandstones are well exposed along the first road to the northwest of Lambton, where roadside excavations have provided a great deal of fresh material. The "limestone" is in beds from ½ inch to 6 inches thick, and as might be expected has not had cleavage impressed upon it, in spite of the fact that it has been considerably folded. Specimens showing two or three open folds in a square foot are common.

About a mile east of mount Aylmer (Stratford tp., range VIII SW., lots 1 and 2), and again on the shore of lake St. Francis, one-half mile northeast of Indian River bridge (Price tp., range II, lot 9) calcareous sandstones are interbedded with shales, and the calcareous beds have yielded to distortional stresses in a way that has shortened them along their strike and thickened them across it, *with little or no distortion of the bedding planes above and below.* The two occurrences are found on opposite sides of the mass of Winslow granite, and close to it; and it is thought that in some way the pressure of the granite magma during injection must be responsible for the structures; but the mechanics of the process are not understood.

Structure

Everywhere the beds of this series are folded, and save for the calcareous sandstone they are everywhere cleaved. Throughout the area the prevailing strikes are about north 40 degrees east, the chief exceptions being around the outcrop of Winslow granite. Flow cleavage in the slate approximates that direction, but fracture cleavage in the quartzite is nearly everywhere north 28 degrees east. Folding has been close and the axial planes are somewhat overturned towards the west, so that the vast majority of the dips are easterly.

Unusual cleavage-bedding relationships occur about 2 miles north of Lambton in outcrops 1,000 feet from the road. The beds of greywacke there alternate several times in dip from about 60 degrees to nearly vertical. Cleavage is nearly vertical in the beds that dip about 60 degrees, and is about 60 degrees where the bedding is vertical. The relationships suggest a fan fold on a small scale.

The general structure of the St. Francis series has been fairly well worked out in the southeasterly parts of Disraeli map-area, where outcrops are abundant; but elsewhere it can only be guessed. Even though the positions of the axes have been thus satisfactorily determined, it is still impossible to make satisfactory estimates of thickness, because the numerous minor folds and drag-folds make the estimated thickness much greater than the true thickness. In general, it is known that the folded beds are dipping southward, because calcareous beds that appear northwest of Lambton are not found in the exposures to the southeast. It is impossible, therefore, to say more than that the series is several thousand feet thick; probably more than 5,000 feet, and possibly as much as 10,000 feet.

Age

Unsatisfactory as is the prospect of unravelling any stratigraphic succession, nevertheless there is no doubt whatever regarding the age of at least a part of the series, for in the northern area south and southeast of lac Rocheux, fossils were found in the St. Francis series, in 1932, by H. C. Cooke's assistants, M. S. Hedley and A. R. Byers. The fossils, mostly graptolites, occur in several places along the strike of some beds of fine-grained, blackish sandstone in lots 11 and 12, ranges VIII to IX, Adstock tp., about half a mile south of lac Rocheux. They were submitted to Dr. R. Ruedemann of the New York State Museum for examination. Dr. Ruedemann reported as follows:

"The faunule from Adstock township, Beauce county, Quebec, seems to consist of only one species, presenting various shapes by compression in different angles. It is not very well preserved, but in its dimensions and thecal aspect is best comparable with *Diplograptus (Glyptograptus) euglyphus* Lapworth which occurs in our Normanskill shale. It is, however, also possible that the form is a narrow type of the *Diplograptus recurrens* Ruedemann, occurring in our Lorraine. The concavo-convex cross-section of some specimens is especially suggestive of the latter species which resembles a narrow *D. amplexicaulis* (*See* Bull. 262, p. 57). It also agrees with this species in the close arrangement of the thecæ (11-12 in 10 mm.)."

Dr. Ruedemann's determinations, therefore, place the formation either in the Middle Ordovician (Normanskill, Chazy), or in the Upper Ordovician (Lorraine).

The present writer made further collections from the same locality, and is of the opinion that the fossils should be identified definitely as *Diplograptus euglyphus* Lapworth, thus fixing the age of the series, in part at least, as Normanskill.

LAKE AYLMER SERIES

By T. H. Clark

The Lake Aylmer series is a band of Devonian strata that strikes southwesterly across Disraeli map-area from the eastern to the southern boundary. The name, Lake Aylmer, was given to it by Burton, who at first included only the calcareous shales and limestones (20, page 118), but later decided to bring in the conglomerate at the base (21). The Lake Aylmer series is one of a number of downfolded Devonian remnants found here and there from lake Memphremagog to Chaudière river and beyond.

The first mention of these rocks in the literature was by Logan in 1848. In describing the exposures along lake St. Francis he evidently included in his Devonian a good deal of the upper part of the underlying Beauceville series. In the 1863 report, page 436, Logan says that "Most of them [the limestones and shales] appear to be Devonian; but *Halysites catenulatus* and *Syringopora compacta,* which are supposed to be found there, have not been hitherto recognized higher than the Lower Helderberg group [supposed at that time to be Silurian]. These facts seem to indicate that a portion of these fossiliferous strata may belong to the summit of the Gaspe limestones, or perhaps represent the base of the Gaspe sandstones". Later, Ells (58, page 7J) traced these rocks southwest through Weedon to Dudswell, and referred the series to the Silurian.

The band of Lake Aylmer series is about 3 miles wide at the south boundary of Disraeli map-area. To the northeast it narrows, but again widens as it continues into Forsyth township to a breadth of more than a mile. The northwest boundary of the band is the unconformable contact with the Beauceville series; the southeast boundary is a large fault, termed by Burton the Weedon thrust. The series has been folded to about the same degree as the underlying Caldwell and Beauceville series, so that the beds now stand at moderately high angles. Slaty cleavage is found in the argillaceous beds, and the limestones are in part recrystallized.

The base of the series is a conglomerate, which includes more or less interbedded shale. The remainder of the series is a succession of calcareous shales, with occasional lenses of conglomerate and one or more beds of fairly pure limestone.

CONGLOMERATE AND INTERBEDDED SLATE

The conglomerate has its most extensive exposure on the south flank of mount St. Peter, in Price township. Elsewhere it is restricted, so far as known, to two outcrops, one 2½ miles south-southwest of Garthby in lot

17, range B, Garthby tp., and the other on a hill a mile southwest of the first. In the latter outcrop there is little that is remarkable save the presence of granite boulders some 4 feet in diameter.

The outcrop in lot 17, range B, Garthby tp., is worthy of detailed description. At the west end of the outcrop the conglomerate is in contact, over a length of about 50 feet, with dark grey slate like the Beauceville slate. The bedding is almost vertical, but the cleavage-bedding relationships in the slate indicate that the upper side faces southeast, so that the conglomerate overlies the slate. The material directly in contact with the slate is a band of grit or fine conglomerate, 6 feet wide at the west end of the outcrop, thinning to 3 feet where the slate disappears on the east beneath drift. This band is not uniform throughout, but is made up of layers and long, narrow lenses of materials differing in coarseness. The common phase consists of angular, subangular, and rounded small fragments of cherty and granitic rocks, with many chips of slate, most of them quite thin and less than an inch long. The slaty chips have a sub-parallel arrangement, dipping 75 degrees northwest, whereas the slightly overturned contact dips 86 degrees to 88 degrees northwest. In addition to these chips, the grit surrounds and includes some larger fragments of slate, most of them 5 to 6 inches long, and one 4 to 5 feet long and 1 foot thick. The slate appears identical with the dark grey slate beneath the grit bed. These larger fragments of slate become particularly numerous near the top of the grit bed where there are quite a number of flat plates of slate up to 15 inches long, and rarely more than an inch thick.

Above the grit bed is a boulder bed 12 feet thick, made up of well-rounded boulders up to a foot in length, crowded together. Most of them are a cherty material, probably fine-grained rhyolite or trachyte. Granitic and syenitic boulders are fairly common, and there are some of quartz, impure quartzite, and slate. The slate pebbles are mostly small, and fairly numerous.

Next comes a 7-foot bed of grit containing scattered boulders and lenses and strings of boulders. One of the boulders is 2 feet long and 7 inches in maximum thickness. Then follows another band of heavy boulder conglomerate 160 to 170 feet thick, similar in composition to that previously described. It is followed in turn by 100 to 110 feet of grit, containing numerous fragments of slate and some pebbly bands with pebbles about an inch in diameter. Beyond the grit bed there are no more outcrops, but some of the upper beds of grit have a honeycombed surface, as if due to weathering out of carbonate crystals; so that it is suspected that the next overlying beds may be the limy shales. Thus about 290 feet of conglomerate can be seen here.

More extensive outcrops can be seen on both sides of the Disraeli-Lambton road as it descends the south flank of mount St. Peter. With one or two unimportant exceptions to the southwest, all of these outcrops occur within Price township. Areal distribution and rock structure show that there are two bands of conglomerate, practically identical, separated by a belt of slaty shales and sandstones. The whole is folded into one or more southwest-plunging folds. Although drag-folds complicate the structure to some exent, it can nevertheless be utilized to make some rough estimates of thickness, particularly of the interbed of slate. Along the north limb of the syncline the slate, which is everywhere well bedded and displays fairly good cleavage, outcrops continuously over a width of 2,000 feet, with dips that vary from 87 degrees south to 70 degrees south. These figures yield a calculated thickness of 1,997 to 1,879 feet, depending on the figure used for the dip, and it seems reasonable to assume that the true figure lies between these limits. The width of the shale along the axial plane of the fold is approximately 3,465 feet, and the plunge ranges from 30 to 45 degrees. From these figures the thickness can be calculated as lying between 1,732 and 2,450 feet, figures probably somewhat high as there is generally flowage of slate into the nose of a fold. Probably, therefore, the original thickness of the slate bed was somewhat less than 2,000 feet. The conglomerate that overlies the slate exhibits few dips, but from comparative breadths of outcrop its thickness should be somewhat more than half the thickness of the slate, perhaps about 1,250 feet. The conglomerate beneath the slate displays rather wide variations in dip, rendering estimates of its thickness even more uncertain; but again using comparative breadths of outcrop it should be half as thick again as the slate, or about 3,000 feet. Because of the number of drag-folds this figure may well be reduced to 2,500 feet. Thus, in approximate terms, the formation in this locality is 5,750 feet thick.

The pebbles and boulders of the conglomerate in Price township show a moderate amount of rounding. Those with a diameter of about one inch appear to be the most nearly round. They are of granite, quartz porphyry, slate, quartzite, and grit, and nearly all are fresh, in contrast with the weathered appearance of most of the fragments in the Beauceville conglomerate. The matrix appears to be made up of smaller particles of the same rock types, together with small grains of quartz, mica, etc. In one or two places it is black, on account of the great amount of triturated slate present, but usually it is dark green.

The interbedded shales and sandstones are not remarkable in any particular. They are known in abundance only south of mount St. Peter, though at other localities the formation consists of irregularly stratified conglomerate with thin partings of shale. The shales are nowhere so fine-grained that they do not show detrital mica grains, and the sandstones, medium grey, contain quartz, feldspar, mica, slate, and other fragments, a typical greywacke. Cleavage is developed in both types, fairly well in the shale, poorly in the sandstone. The shale and the sandstone are closely interstratified, the beds of each ranging up to 10 feet in thickness. Pyrite is rare, and nowhere are there any rhombs of carbonate in the shales.

Wherever this formation is known to occur it outcrops in topographic prominences. It is, relatively speaking, more resistant than either the Beauceville rocks to the north or the calcareous shales to the south. Hence its patchy outcropping is good evidence of patchy distribution.

It has not been found either east of lake St. Francis or along Third Range brook. Where the road leading southeast from Garthby crosses Third Range brook, the drift-covered gap between outcrops, within which the conglomerate must lie if present, is less than half a mile wide. The same conditions obtain on Garthby peninsula. These facts, coupled with the lack of topographic expression, indicate that the conglomerate in these localities is either thin or entirely absent; so that conglomerate deposition must have been due to local causes.

What these causes were may perhaps be inferred. As the conglomerates are directly overlain by marine sediments, they were probably either marine or shore accumulations. Although granite and rhyolite pebbles are numerous, neither rock occurs nearby in place, thus precluding the possibility that the conglomerates were cliff derivatives. The local accumulation of coarse materials brought in from a distance, therefore, seems to demand but one explanation, namely, that they are deltaic deposits formed at the mouths of fairly rapid streams. If so, they must be contemporaneous with the lower beds of limy shale formed where the conglomerates are absent.

It has not been found possible as yet to trace the sources of most of the boulders in the conglomerates. Some quartzite boulders strongly resemble Caldwell types, and the occasional greenstone boulder may be Caldwell lava. The rhyolite and quartz porphyry boulders so numerous in the conglomerate of lot 17, range B, Garthby tp., strongly resemble the rhyolites of the St. Francis series, outcropping 3 miles to the southwest in Stratford tp., range V SW., lots 16-19, and, together with the presence of so many granite pebbles, suggest that the source of the materials may have been to the southeast. The conclusion is supported to some extent by the almost entire lack of boulders of the basic extrusives and intrusives lying to the northwest.

CALCAREOUS SHALE AND INCLUDED MEMBERS

The bulk of the Lake Aylmer series consists of calcareous shales, with a little purer limestone and some conglomerate lenses. The shales are nowhere found in contact with the underlying conglomerate, and no overlying rock is known. Fossils are abundant in one or two places, and indicate the age of the formation as Lower Devonian.

The calcareous shales were mixtures of fine-grained argillaceous and calcareous sediment, deposited in fairly quiet water. Occasionally the supply of mud waned, and limestone was formed. Ordinarily, however, carbonate and mud came down together in varying proportions. In several places the shales seem to contain limestone pebbles, but in almost all such cases it can be proved that these were formed by disruption of thin beds of limestone. Curiously enough, no beds of sandstone have been found anywhere between the conglomerate and the overlying shale, as if some quite sudden physiographic change had put an end to the deposition of conglomerate.

The shales are usually dark grey to black on fresh surfaces, but weather to light grey and brownish tints. They are not much metamorphosed except near Stratford, where the limestone is recrystallized and sericite is abundantly developed in the shales. The metamorphic changes were probably caused by the Weedon thrust which brought the St. Francis lavas into contact with the Devonian.

The shales are well exposed north of St. Gerard, on Long point, and in a few localities west of lake St. Francis. East of that lake outcrops are abundant near Lambton lake, on islands in lake St. Francis, and along the road separating Forsyth and Lambton townships. Everywhere the shales have a fairly well-developed cleavage, but stratification is rather obscure in places.

Around Lambton lake the shales are folded into a syncline plunging northeast. Presumably, however, this plunge is not maintained far, for observations on exposures near the boundary of the map-area indicate a southwesterly plunge. The attempt was made to follow the Devonian band eastward beyond the limits of the map-area, but no further outcrops of it could be found. Hence it is believed that the Devonian syncline must end not far from the boundary of the map-area.

Grey limestone was seen only near St. Gerard and northwest of Stratford Centre. Near St. Gerard, in Weedon tp., range VII, lots 22 and 26, it has been quarried for lime. It ranges in colour from light grey or white to dark grey, and in composition varies from a moderately pure carbonate to a rock that lies upon the border-line between limestone and shale. The following section can be seen at the quarries south of the road at Weedon, range VII, lot 22. The bedding is practically vertical. The thicknesses are those of Burton (21).

	Feet
Calcareous shales, thickness not measured	
Light grey limestone, with abundant Favosites of two or more species, trails, algæ, Stromatoporids, etc. Considerable sericite on fracture surfaces...............................	50
Brown-weathering, calcareous shale with fragments of limestone, which may well be disrupted limestone beds..............	25
Medium- to dark-coloured limestone in places fine-grained, in others conglomeratic, containing fossils of Helderberg age..	50
Calcareous shales, thickness not measured.	

The discontinuous nature of the component parts of the lower limestone, and the low lime content of the upper band doubtless combined to render the quarry unprofitable. Burton (21) records the $CaCO_3$ content of the upper beds as 88·02 per cent; of the lower beds 57·35 per cent. More recently Goudge (69, page 249) gives 87·87 per cent as the amount of calcium carbonate in a sample taken from both limestone bands. Other localities in the vicinity of St. Gerard contain 87·93 per cent, 88·04 per cent, and 51·87 per cent $CaCO_3$. In spite of the rather low calcium content, the stone, if abundant enough and continuous, would be suitable for agricultural purposes.

The limestone outcrops for a mile or more northeastwards, where it is uniformly medium grey, and in many places fossiliferous, the fossils being crinoid stems or corals (Favosites).

A band of conglomerate is interbedded with the calcareous shales about a mile south of the west end of Lambton lake. It occurs about 500 feet northeast of the road, on the axis of a northeasterly plunging syncline, and appears to be about 700 feet thick. The rock is very poorly stratified, and consists (in order of abundance) of pebbles of limestone, slate, quartz, and quartzite. One pebble of granite was observed. The pebbles rarely exceed a few inches in diameter, though one or two of a foot or more were noted. The limestone pebbles are grey, and resemble the limestone at St. Gerard. Many of them are fossiliferous, and the fossils, by field identification, are the same as those in the latter beds. The shale pebbles are black, never weather rusty, and have good cleavage. They are, therefore, interpreted as fragments of the underlying Beauceville and to that formation probably belong the small pebbles of quartzite. The absence of pebbles of Lake Aylmer shale is probably due to the tardiness with which that rock became lithified. The one pebble of granite shows that the agencies building the conglomerate tapped a source outside the formations at present known.

The thickness of this conglomerate can be determined with a fair degree of probability. The outcrop along the axis of the syncline is about 2,000 feet wide. At the lower contact the plunge is 20 degrees northeast, at the upper contact, 24 degrees. The thickness, calculated for each angle of plunge, is 684 and 817 feet, respectively. As the lower figure is probably the more reliable, the thickness may be considered as about 700 feet.

A second occurrence of what is probably the same conglomerate is in Forsyth tp., range III, lot 3. The conglomerate is much like the one described, except in containing an abundance of pebbles of light-coloured talcose shale or slate, similar to the Caldwell grey slates.

Two other occurrences lie in Stratford tp., range I SW., lot 26, and range V SW., lot 3. Both occurrences are apparently part of a band of schistose, small-pebble conglomerate following the southeast side of a strong limestone band and are rather poorly exposed. The largest observed pebbles were about 3 inches long, and much of the pebbly material is less than an inch in diameter. Shearing has obliterated the original character of most of the softer pebbles. Most of those remaining are rather hard, light grey, and fine-grained, like a rhyolite or very fine-grained quartzite. Other pebbles included at least one of granite, and one of some kind of slate or schist. The low, dirty outcrops made identification of pebbles very difficult.

RHYOLITE DYKES

Very fine-grained, light-coloured sheets of acid igneous rock, of the general composition of rhyolite, are found here and there in the Devonian sediments. They are commonly structureless, and parallel the bedding. They evidently were introduced into their present position before the last folding, as some of them are strongly sheared. The largest of these bodies is 2 miles northwest of Stratford Centre. It is a steeply dipping sheet, approximately 600 feet wide, which was traced along its strike about 2 miles. Similar sheets, too small to map, were seen in other places, as in the Beauceville conglomerate on Garthby Neck, and in the Lake Aylmer shale just south of the boundary of Disraeli map-area. The occurrence of these rocks in both the Devonian and the underlying Ordovician strata indicates that they are intrusives, and post-Lower Devonian in age. They may be contemporaneous with the rhyolite dykes that cut the St. Francis lavas. As they parallel the bedding fairly closely, and were evidently injected before the sediments were folded, they must originally have formed flat sills. Both their composition and their age combine to suggest that they may represent the preliminary manifestation of the igneous activity which culminated in the injection of the Mount Aylmer and other Devonian granites.

STRUCTURE

In general, the Devonian rocks form a complex syncline let down into rocks of the Beauceville series. Their border on the north is supposed to be a normal sedimentary contact, but on the south they are cut off by a great thrust that has brought the Ordovician slates and lavas up beside them. The fold axes are not horizontal, and changes in the plunge give canoe-shaped ends of folds.

Actual contact between the Lake Aylmer and Beauceville series is seen only southwest of Ward bay, in lot 17, range B, Garthby tp. The Beauceville slate there is very poorly stratified, but the conglomerate is well, if coarsely, bedded. The basal sandy bed of the Lake Aylmer series wedges out remarkably, suggesting that the beds were rapidly accumulating on an old surface.

The fault that bounds the Lake Aylmer series on the south is inferred from a variety of evidence, for the southern contact is everywhere hidden by drift. Although conglomerate marks the northern contact in several places, there is no conglomerate anywhere along the south boundary, nor any other evidence that strata appearing on the north side of the band are repeated on the south side. At the one locality near the south side where good bedding was obtained (Stratford tp., range V SW., lot 5, along road) the beds dip steeply southeast, instead of northwest as might be expected. They are also sliced into sheets from ¼ inch to 1 inch thick, with the slicing striking north 34 degrees east, and dipping 70 degrees southwest. Southeast of this locality, towards the contact, the rocks become more and more intensely sliced. The lavas just south of the contact, as shown on a previous page, face southeast, away from the Devonian rocks, instead of toward them as they would at a synclinal contact. Traced northeast, the south contact cuts across the Devonian folds at lake St. Francis, so that at the lake the formation almost disappears. At a point 5½ miles north-northeast of Lambton the Devonian limestones dip beneath the slates of the St. Francis series, an arrangement inexplicable except by faulting or overturned folding. Outcrops of the St. Francis lava in lot 29, ranges I to III NE., Stratford tp., and continuing along range line VII-VIII of the same township, are more sheared than elsewhere. Thus all the evidence points to the existence of a large thrust fault.

The internal structure of the Devonian band is thus that of a compound syncline, the south side of which has been cut off by a thrust fault. The structures of the remaining part can best be observed south of mount St. Peter, and south of Lambton lake. Both these localities have already been described in some detail, so that it is unnecessary to repeat the descriptions here.

THICKNESS

The thickness of the Lake Aylmer conglomerate has already been estimated at about 5,750 feet. These strata, as the map shows, are thrown at lake St. Francis into complex folds plunging southwest, and there can be little doubt that the folds must continue some distance southwest before dying away, even if the whole band is not thus folded. Lack of outcrops makes it impossible, however, to trace the folds southwest, or even to determine if they exist. Under such conditions, any attempt to estimate the thickness of the calcareous shales is mere guesswork. About all that can be said, in view of the width of exposure, is that they are probably some thousands of feet thick.

PALÆONTOLOGY

No fossils have been found in the Lake Aylmer conglomerate, but good collections have been made from several localities in the Lake Aylmer calcareous shales and limestones. These are described in detail below. In the lists of forms obtained from Weedon tp., range VII, lot 22 (two localities) and from Stratford tp., range II S., lot 28, the writer has quoted freely from his report published by Burton (20, pages 118-20). A few new identifications are included in the present lists, which represent the results of considerable intensive collecting. Crystallization has unfortunately made identification of the species of the corals and stromatoporoids almost impossible.

(1) Fossils from the old lime quarry, Weedon tp., range VII, lot 22. The fossils from the east and the west sides are not here separated.

Corals

Streptelasma sp. or *Zaphrentis* sp. The preservation is too poor to determine the genus with accuracy. Both occur in the Devonian, and as a rule the species are not highly diagnostic.
Favosites sp., probably *F. helderbergiae* Hall.
Favosites sp. One of the ramose types which do not appear as a rule until the Onondaga.
Favosites sp. A species with very small corallites.
Halysites sp., probably *H. catenulatus* Linné. The writer has collected this coral from two other localities in Quebec, where, as at this one, it is associated with Devonian fossils. One of these localities is on the east shore of Memphremagog lake, the other is St. Joseph tp., range St. Thomas, into Cranbourne tp., ranges IV and V. There can be no doubt as to its extension into the Devonian in southern Quebec.
Stromatocerium sp.

Brachiopods

Leptaena rhomboidalis Wilckens; ranges from Ordovician to Carboniferous.
Meristella n. sp. Close to *M. bella* Hall from the Helderberg.
Meristella sp.

Pelecypods

Conocardium sp. A dwarf species. The genus ranges from the Ordovician to the Permian.

Gasteropods

Loxonema sp. Probably two species.
Diaphorostoma sp.

Cephalopods

Orthoceras sp. Too poor to identify.

Trilobites

Ceratocephala sp.

Ostracods

Beyrichia sp. This genus ranges from the Ordovician to the Carboniferous, but is pre-eminently a Silurian genus. Only five species are at present recognized from the Devonian of North America, and of these but one from the Helderbergian.
Kloedenia sp. Two or possibly three new species of this genus. All are very closely related to the species described by Ulrich from the Helderberg of New Brunswick.
Kloedenia manliensis Weller; Helderberg.
Pachydomella sp. In North America this genus is restricted to the Devonian.

(2) Fossils from the old lime quarry, Weedon tp., range VII, lot 26.

Corals

Favosites sp., probably *F. helderbergiae*.
Crinoids, columnals are common.

(3) Fossils from outcrops at Stratford tp., range II S., lot 28.

Corals

Favosites sp. Probably two species, one somewhat like *Favosites cervicornis* (de Blainville), but not co-specific with it. It is in all probability a new species, and most closely resembles other species of the Onondaga epoch.

(4) Fossils from the brown-weathering calcareous shale east of Lambton lake, Lambton tp., ranges V, VI, lots 17-18.

Corals

Zaphrentis sp.
Amplexus sp.
Favosites sp. Two or three species.
Heliolites sp.

Crinoids

Columnals abundant.

Brachiopods

Strophonella geniculata (Hall); Helderberg.
S. punctulifera (Conrad); Helderberg.
Gypidula galeata (Hall); Helderberg.
Camarotoechia litchfieldensis (Schuchert); Helderberg.
Atrypa reticularis (Linné); Silurian-Devonian.
Atrypina imbricata (Hall); Helderberg.

(5) Rolled fragments in the conglomerate south of Lambton lake. Lambton tp., range IV, lot 20.

Corals

One or two species of corals, too poorly preserved to identify.

Thus it can be seen that there are but two localities where fossils occur in a sufficiently well-preserved condition to be diagnostic. At both of these localities the evidence for the Helderberg age of the shales and limestones is incontrovertible. In northeastern North America beds of Helderberg age occur in New Jersey-Maryland-Pennsylvania, in New York, at Montreal, in Gaspe, in New Brunswick, and in Maine. A tabulation of the species so far definitely identified with their occurrences elsewhere follows.

—	Gaspe including Dalhousie formation	Montreal	New Jersey, Maryland, Pennsylvania	New York, Helderberg	New York, Oriskany
Leptaena rhomboidalis	×	×	×	×	×
Strophonella geniculata	×	....	×	....	....
S. punctulifera	....	×	×	×	....
Gypidula galeata	....	....	×	×	....
Camarotoechia litchfieldensis	....	....	×	....	....
Atrypa reticularis	×	×	×	×	....
Atrypina imbricata	×	....	×	×	....
Meristella bella (cf. with *M.* sp.)	....	....	....	×	....
Kloedenia manliensis	×	....	×	×	....

A perusal of this table leaves no doubt as to the validity of the correlation of the Lake Aylmer series with the Helderberg beds of Gaspe (St. Albans, Bon Ami, and Grande Grève formations), the Dalhousie formation, and the Moose River formation to the northeast. Neither is there any doubt as to its equivalency with the Helderberg of New York, New Jersey, Maryland, and Pennsylvania to the southwest. Thus the existence of a seaway postulated by Clarke (29, page 153) stretching from Gaspe southwestward to New York and New Jersey receives substantial confirmation. The nearest already described Helderberg fauna is that from St. Helen island, Montreal, 100 miles to the west, but our beds and the limestone of that locality have but one diagnostic species, *Strophonella punctulifera,* in common. It is evident, therefore, that there could not have been open water connexion between the two localities. Clarke's contention that the Montreal occurrence "indicates the remnant of a backset along the St. Lawrence trough of these waters, rather than any connexion with New York through the Champlain trough" (29, page 162) is, therefore, substantiated.

There are other Devonian occurrences in eastern Quebec of closely similar strata. Some 40 miles to the northeast, near Chaudière river at range St. Thomas, St. Joseph township, the writer obtained in 1935 a collection of fossils of Helderberg age in collaboration with C. Tolman, who was mapping that area. Few species were common to the two faunas, but the Helderberg age is indubitable. Fifty miles southwest around Memphremagog lake are fossiliferous horizons that strongly resemble the present ones. Still farther southwest, Billings and Cleaves (11, page 419) have described an Oriskany fauna from Littleton formation, Littleton, N.H. It seems that in all these cases we have sediments deposited in an early Devonian trough and preserved as synclinal remnants. Billings and Cleaves also describe a Middle Silurian fauna from Littleton, and Raymond (72, page 289) has already recorded a Silurian faunule from Lake Memphremagog area. Evidently a seaway, beginning at least as early as Middle Silurian time, occupied this region and persisted to the Lower and probably Middle Devonian (28, pages 12, 13). No Upper Silurian formation has as yet been identified, nor is the structural relationship between the Middle Silurian and Lower Devonian clear. It is interesting to note that Logan (1863, page 429) in classifying the Lake Aylmer series with what he called the Gaspe series, plainly indicated the close stratigraphic relationship between the rocks of this area and the Devonian rocks of Gaspe, and antedated Clarke's more fully documented statement by nearly half a century.

INTRUSIVE ROCKS

The intrusive rocks of the region are gabbro, peridotite, pyroxenite, granite, and certain dykes composed mainly of albite or oligoclase albite, with or without quartz and (or) mica. The granites form more or less equidimensional stocks with satellitic dykes, the other intrusives, elongated sills, dykes, or laccolithic bodies. A few of the latter are very thick. It is common to find that intrusion of the basic rocks was controlled both by the pre-existing structure and by the competency of some of the older rocks to resist intrusion. Thus, they are found in anticlines rather than in synclines; and the lava horizon of the Caldwell series evidently resisted strongly any attempt to break through, forcing magmas to spread out beneath it in the form of sills. Accordingly we find gabbro commonly forming sheet-like masses directly beneath the lava horizon; then the peridotite or pyroxenite magmas rose to encounter a double barrier in the gabbro sill and the overlying lavas, and were forced again to spread out beneath the gabbro. Where these rocks occur together, as they do in many parts of the region, the almost invariable succession is peridotite or pyroxenite at the base, followed by gabbro and then by lava. This regularity, coupled with the almost entire lack of exposed contacts and the occurrence in the gabbro of a pyroxenite derivative, led Dresser to infer (54, pages 42-49) that the gabbro which he did not differentiate from the lava, the peridotite, and the pyroxenite are all derivatives of a common magma. More detailed examination has not only proved the gabbro to be younger than and intrusive into the lava, but has also discovered a sufficient number of contacts to prove that the peridotites and pyroxenites are later than and intrusive into the gabbro. The peridotites and pyroxenites, however, have been derived from a common magma and grade into each other in places, although the pyroxenite appears to have remained liquid somewhat longer than the peridotite, and forms dykes in it.

The larger bodies of granite are not associated with the other intrusives, and are commonly supposed to have been injected during the post-Devonian deformation. Some doubt is thrown on this conclusion, however, by the occurrence of large numbers of granite pebbles and boulders in the Lower Devonian conglomerate, and the entire lack of other granite bodies from which such pebbles might have been derived. Smaller granite bodies, and the acid dykes mentioned above, intrude the peridotites and pyroxenites, and may have originated from the same magma. The peridotites are known to intrude the Ordovician strata, hence they and the pyroxenites are of post-Ordovician age, and may have been injected during the Taconic, or post-Ordovician, period of folding. The gabbros are so closely associated with the lavas, as the discussion of the origin of the breccias indicates, as to suggest that they may be pre-Ordovician. They have never been found to intrude the Ordovician within the area studied, though this may be due to their being everywhere confined beneath the lava cover.

GABBRO

Occurrence

Little gabbro has been found in Thetford map-area except on mount Adstock, where the main body of the hill is composed of it. The lavas extending east of Thetford Mines for several miles have no gabbro beneath them, so that the centres of gabbro supply lay evidently to the southwest. Throughout Disraeli and Warwick map-areas gabbro follows the lower contact of the lavas, rising into them in places. West of Disraeli it is absent, apparently because never injected; in some other places its absence is evidently due to intrusion of pyroxenite, which destroyed it.

Petrographic Character

The normal gabbro is a rock of medium to coarse grain, composed of about equal parts of pyroxene and feldspar, and weathering to a greyish green colour. The proportions of the essential minerals vary somewhat from place to place, and the colour alters to lighter or darker accordingly. The average rock is massive and equigranular, with a grain of 1 to 2 mm.; but coarser varieties are not uncommon near the middle of large masses, and toward the contacts the rock chills to a fine-grained material almost indistinguishable from basalt. This makes mapping of gabbro-basalt contacts very difficult. In a number of places the gabbro exhibits flowage textures, indicating some movement in the later stages of consolidation.

The gabbro is highly altered almost everywhere. Commonly the augite is completely gone over to uralite, actinolite, and chlorite, although identifiable remnants are occasionally found, particularly in the coarser types. A little of the original feldspar still remains, and was identified as andesine, but most of it is converted into sericite, zoisite, and epidote. Ilmenite, now largely altered to leucoxene, is the principal accessory. Some carbonates and sulphides, including pyrite, chalcopyrite, and galena, occur here and there in veinlets and fine disseminations, but are probably not original constituents.

A peculiarity of the gabbro is the almost universal presence in it of numerous dykes varying from an inch to several feet in width. They occur so consistently wherever the gabbro is found, and in such numbers, that the observer presently accepts them as a characteristic part of the intrusive. They are limited to the intrusive and do not pass beyond its borders. Although this behaviour is similar to that of pegmatitic differentiates, they do not otherwise resemble such differentiates. F. R. Burton (21) has subdivided them into gabbro-diorite porphyry, quartz-diorite porphyry, and granite porphyry. The great majority of the dykes are of the first type, with a limited number of the second, and very few of the third. All the dykes are so highly altered to secondary minerals that their original compositions are largely inferential.

Differentiation

Some of the larger masses of gabbro have been differentiated in place to yield products that vary from pyroxenite at one end of the series to granite at the other. One of the best exposed sections showing these changes is found near Lemay hill, about 1½ miles southwest of Coleraine village. A narrow, steep-walled valley, apparently a fault line, separates Lemay hill from the ridge northeast of it, and the north wall of this valley affords almost continuous exposure across the gabbro sill. The north side of the sill, over a width of 200 feet or more, is fine-grained and more or less brecciated. It contains perhaps 50 to 60 per cent of pyroxene. Southward the grain gradually coarsens until it attains in places a size of 3 to 5 mm., but the composition remains about the same. Toward the base of the sill there is a tendency for the pyroxene grains to collect and form irregular masses of pyroxenite. These have no regular shape or size, and there is no sharp boundary between them and the ordinary gabbro, but the one grades into the other simply by diminution in the proportion of feldspar. Numerous basic dykes of the types described cut all the above types; and in addition there occur splashes, larger irregular masses, and dyke-like bodies of a sort of pegmatite. This material is a very coarse gabbro, with pyroxenes generally about ½ inch in length and in places much longer, and with a larger proportion of feldspar than the normal gabbro. These masses likewise have no sharp boundaries, but pass by a rapid gradation into the surrounding gabbro.

West of Lemay hill there are some exposures of granite in low ground. The granite, which is deeply weathered, appears to be made up of quartz and feldspar in nearly equal proportions. It is cut by numerous dykes like those found in the gabbro, and the strike of the dykes is north 45 degrees east both in the granite and the near-by gabbro. The nearest outcrops of gabbro, some 200 feet southeast, contain small dykes and irregular patches of similar granitic material, and other patches of intermediate composition, i.e., of coarse gabbro containing considerable quartz. For these reasons the granite is considered to be, probably, an acid differentiate of the gabbro magma.

No other bodies of probable granite differentiate have been identified in the region, though perhaps the mass about 2¼ miles north of Disraeli village may have originated in this way. Bodies of the pyroxenite differentiate are fairly common, however. Small masses of it have been found on mount Louise, in the gabbro northwest of Brousseau hill, and in other places; and a large mass of it occurs on mount Adstock, where it forms most of the hill above the 1,700-foot contour.

With practice the gabbro-pyroxenite is readily distinguishable in the field from the pyroxenite associated with peridotite. All the pyroxene of the gabbro-pyroxenite is dark green, and the rock weathers dark green. The pyroxene of the other pyroxenite, on the other hand, is mostly pale green to light grey, and the rock weathers to light tints or where iron is present to browns and reds. The gabbro-pyroxenite commonly contains a little feldspar, and where none can be detected with the eye it is rarely necessary to go more than a few tens of feet across the outcrop to come upon feldspathic varieties or pegmatitic phases. The other pyroxenite, on the other hand, never contains feldspar. The writer has examined many square miles of these rocks in detail and studied some thousands of fragments with the lens without detecting any feldspar in them, except in one doubtful instance.

In addition to these petrographic differences, the gabbro-pyroxenites always lie wholly within masses of the ordinary gabbro and grade into gabbro at the edges; whereas the other pyroxenites have no necessary association with gabbro, and where the two are in contact the relations are those of an intrusive to an older rock.

In the next subsection evidence will be presented to show that the gabbro is older than and intruded by the peridotites and their associated pyroxenites. It follows, therefore, that the gabbro-pyroxenite is also older than the pyroxenite associated with peridotite. The recognition of the existence of two pyroxenites of differing age and origin is of the greatest importance, for their non-separation both confused the igneous history of the region, and led to erroneous conclusions as to the petrography and origin of the later pyroxenite.

Relations to Older and Younger Formations

The peculiar habit of the gabbro of spreading into sheets directly beneath the Caldwell lavas, and its action then as a dam, forcing the later ultrabasic rocks to spread out beneath it again, leave it in contact in almost all places with lava and ultrabasic intrusive only. In the few places where the ultrabasic rocks do not occur beneath it, as east of Sunday lake, the contacts wherever crossed are covered with drift. Good contacts even with the lavas are difficult to obtain and interpret, because the similarity of composition makes it difficult to separate the two rocks on the ordinary weathered and lichened surface. The strong chilling of the gabbro as the contacts are approached, however, is good evidence of its intrusive nature. In Wolfestown tp., range III, lot 28, close to the Garthby line, good clean outcrops were obtained by stripping away large sheets of moss. It could then be seen that numerous stringers and small dykes of the gabbro intrude the Caldwell basalt so as to form a breccia of basalt fragments in a gabbro matrix. The intrusive nature of the gabbro is, therefore, established.

For the reasons already stated, the relations of the gabbro to the Beauceville series and the Lake Aylmer series can nowhere be directly determined. The brecciation of the gabbro already described indicates that it was intruded prior to the folding of the sedimentary and volcanic rocks, but as folding took place both after the Ordovician and after the Devonian, this does not help to place its age. The intimate relations of the gabbro and lava, as shown in the breccias, suggest that there may have been no great difference in age, but this can be no more than a suggestion. The peridotite and its associated pyroxenite are closely related in age and origin, as will be shown in the following section; and both intrude the gabbro. The evidence is as follows.

In Wolfestown tp., range V, lot 28, about a quarter of a mile from the Garthby-Wolfestown boundary and 500 feet from the road past the north end of Breeches lake, there is a contact between peridotite and gabbro on a low cliff forming part of the southwest face of Chalet hill. The gabbro, as in many places, exhibits pronounced flowage textures which here strike north 20 degrees west and dip 30 degrees east. The peridotite emerges at the foot of the cliff, its upper edge almost parallel to the flow texture in the overlying gabbro. It then turns sharply to a vertical position and cuts across the flow textures at an angle of 60 degrees (Figure 2). A little gully that cuts across the contact into the cliff yields a vertical cross-section about 8 feet long, on which the relations described are well displayed. A short distance south of the gully nearly all the vertically dipping peridotite has been removed by erosion. There still remain, however, a number of flat remnants or chips of peridotite adhering to the gabbro face. Both here and in the gully it can be seen that the contact cuts at a large angle across the original flow texture of the gabbro.

The point separating the two " legs " of Breeches lake is underlain by gabbro. A dyke-like mass of pyroxenite, now pretty well serpentinized, cuts through the gabbro of the south shore of the point, and presumably crosses the eastern " leg," as what appears to be its continuation is found on the eastern shore, cutting the Caldwell quartzites. In the gabbro it is a tabular vertical sheet about 100 feet wide, with gabbro on both sides; so that the areal arrangement is that of an intrusive dyke. The contacts are everywhere covered with drift and boulders, but in one place, on the north side, what appears to be a parallel offshoot about 6 inches wide cuts through the gabbro. In two places this throws off wedge-shaped apophyses into the gabbro, one of which is about 4 inches wide at the base and a foot long, the other about the same width at the base and 18 inches long.

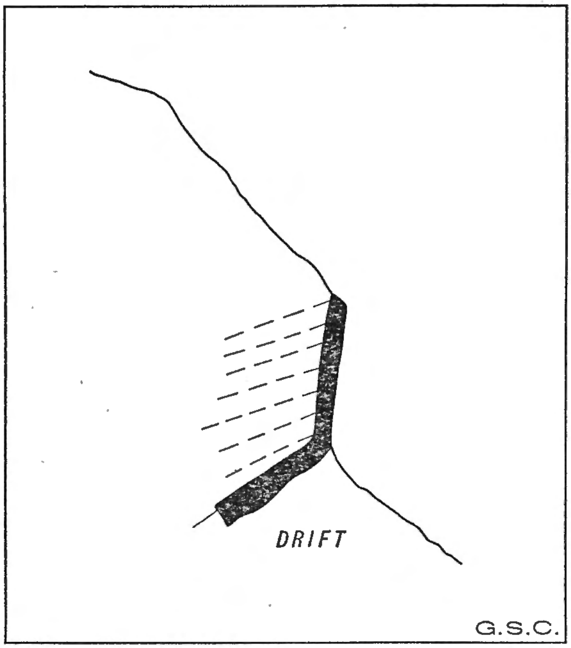

Figure 2. Cross-section showing relations of gabbro and peridotite on Chalet hill.

On the northwest slope of Nadeau hill (Coleraine tp., range IV, about middle of lot 8) a small mass of gabbro is in contact with pyroxenite. The place was burned clean of all vegetation, so that exposures were excellent. The contact is highly irregular and embayed. The pyroxenite is much finer grained close to the contact than farther away, but the gabbro remains coarse-grained to the contact. In some places crooked, fine-grained fingers of pyroxenite extend from the main mass into the gabbro; in others a little contact breccia, consisting of half a dozen fragments of gabbro in a matrix of pyroxenite, has been formed. The gabbro, as usual, is cut by many basic dykes; and although a few of these seem to cross the contact and run a few feet into the pyroxenite, others end at the contact and furnish fragments to the contact breccias. In the cases observed, the fragments trail southwards from the dyke whence they came, as if the pyroxenite magma at this point had a movement from north to south.

On the west flank of mount Adstock, about the 1,500-foot contour, a dyke of coarse pyroxenite cuts the gabbro of the hill. The dyke is about 8 feet wide, strikes slightly north of east, and dips almost vertically. The contact is sharp, but the pyroxenite for a few inches from the edge has been sheared to a white, featureless material.

On the south side of Nadeau hill pyroxenite is in contact with a large mass of gabbro, and is chilled over a wide zone. The exact width of the chilled zone was not measured, but is approximately 100 to 200 feet. As the contact is approached the pyroxenite becomes progressively finer in grain, forming a massive white or very light grey rock of striking appearance. The same change, on approaching gabbro contacts, was observed in pyroxenite on Lemay hill and on the ridge north of it.

At the south end of Brousseau hill gabbro forms a thin, steeply dipping sheet that runs around the hill paralleling the strike of the surrounding sediments. In two places the pyroxenite that forms the body of the hill breaks completely through this sheet of gabbro (*See* Map 418A).

At the west end of the hill on the south side of Little Lake St. Francis coarse gabbro is in contact with pyroxenite. The gabbro over a width of about 6 feet is fractured into blocks up to 2 feet in diameter. Fine-grained pyroxenite has penetrated the fractures to form a contact breccia of gabbro fragments in a rather scanty matrix of pyroxenite.

In the north part of Cloutier hills there are many inclusions of gabbro in pyroxenite and partly serpentinized pyroxenite. On the northwest edge of the outcrop pyroxenite composed of crystals about $\frac{1}{4}$ inch in diameter includes two roughly cubical lumps of gabbro, 18 to 20 inches to the side. Long slabs of fine-grained gabbro were observed in two or three places in the pyroxenite. Partly serpentinized pyroxenite surrounds one roughly triangular mass of gabbro about 10 feet to the side. The largest observed inclusion of gabbro is about 40 feet long and 15 feet wide. Both the long sides and one of the short sides of this inclusion are completely exposed, together with a part of the fourth side. Serpentinized pyroxenite surrounds it on all the exposures, and dips under the inclusion on two sides; and a fine-grained dyke of pyroxenite about 4 inches wide runs from the main mass into the inclusion.

On the northwest side of Brousseau hill the contact between pyroxenite and gabbro is well exposed, undeformed, and sharp. It was seen on the face of a 20-foot cliff. The gabbro at this point is moderately coarse-grained, and no change in grain takes place as the contact is approached. The pyroxenite, on the other hand, becomes gradually finer grained throughout a width of 20 to 30 feet from the contact; and the part next the contact, about a foot wide, is so fine that no perceptible grain shows on the weathered surface.

To summarize, the peridotites and their associated pyroxenites have been observed to break through the gabbro, across pre-formed flow structures and sills; to form dyke-shaped masses in it; to exhibit chilled contacts against it; to throw off stringers and apophyses into it; to cut off dykes that intersect it; and to include fragments both of the gabbro and of the dykes found in the gabbro. The conclusion is, therefore, indubitable that the pyroxenites and peridotites are later than the gabbro and intrude it.

Age of the Gabbro

As the gabbro intrudes the lavas of the Caldwell series, it is post-Caldwell in age; and as it is in turn intruded by the peridotites and pyroxenites it is older than these rocks which, as will be shown, were probably injected during the post-Ordovician folding. It may, therefore, have been injected: (*a*) during the period of gentle folding and uplift that followed the deposition of the Caldwell series; (*b*) at about the same time as the extrusion of the Ordovician lavas; or (*c*) during the post-Ordovician folding, before injection of the peridotites and pyroxenites. There are no data, as yet, to indicate which of these alternatives is correct, except that the close association of lava and gabbro, as seen in the gabbro-lava breccias, suggests that there may have been no great difference in age. If the fact is as suggested, injection of the gabbro probably followed closely the deposition of the Caldwell series.

PERIDOTITE AND PYROXENITE

The peridotites and pyroxenites form a series exhibiting all variations in composition from pure olivine rocks to rocks composed wholly of pyroxene. The main masses are distributed throughout two principal zones, which lie about equidistant from the Coleraine-Lac à la Truite anticline. In the southeastern zone the rock is principally pyroxenite, with a little pyroxene-rich peridotite along the northwestern flank. These rocks underlie Poudrier hill, Diamond hills, Cloutier hills, Nadeau hill, Bengel hills, and Brousseau hill. Farther southwest, the only intrusives in this zone are a narrow dyke about 1½ miles southeast of Breeches lake, another, in the gabbro, about ¾ mile south of Sunday lake, and the fairly large body of peridotite underlying Nicolet lake.

In the northwestern zone the rocks are mainly olivine-rich peridotites, with a narrow, southeastern margin of pyroxene-rich peridotite and pyroxenite. Into this zone fall the large mass of peridotite that extends from Thetford Mines southwest to underlie Reed hills, Murphy hill, Quarry hill, Caribou mountain, Oak hill, and Kerr hill; the Belmina Ridge mass; the elongated mass that underlies Breeches lake and extends past Sunday lake; and two or three small masses on the south side of mount St. Adrien, in Warwick map-area. The serpentine body on Trout brook, northeast of Richmond lake, the body at the town of Asbestos, and others known to occur in the unmapped western half of Warwick map-area, seem also to lie in this zone.

In addition to the bodies mentioned, a number of dykes, some very large, are found in various places. Starting from a point about 1½ miles north of Thetford Mines, what is here termed the Pennington dyke has been traced northeast for 14 miles. On this dyke there are nine pits that have yielded a considerable amount of asbestos in past years. One of them is still producing. None of the other dykes carries asbestos in economic amounts, but some have yielded considerable amounts of soapstone.

Although these dykes are mapped as if continuous between outcrops, they are not necessarily so. Thus in the Pennington dyke there is almost undoubtedly a gap in Broughton tp., range IX, lot 12; and other gaps are strongly suspected in the parts east and west of Rumpleville. The probability that gaps occur is increased by the known fact that the dykes vary greatly in width along the strike. In places, as at the Fraser mine and about 1½ miles west of Rumpleville, the width is 500 feet or more, and in other places, as in the southwest end of lot 12, range IX, Broughton tp., it is less than 10 feet. These facts, and the shapes of many of the larger bodies as shown on the maps, indicate that the peridotites tended to form stumpy lenses, rather wide in proportion to their length. The shapes suggest that the original magma must have been very viscous.

Petrography

The peridotites, characteristically, are composed of olivine crystals with varying amounts of pyroxene, usually about 10 per cent, and a little accessory chromite. They are massive rocks, dark grey or greenish grey on fresh surfaces, and weathering commonly to browns, red-browns, or yellow-browns. The bright colours of weathered surfaces make bare hills and cliffs strikingly prominent features of the landscape. The original olivine crystals averaged 3 to 4 mm. in diameter, attaining 6 mm. in places, and the pyroxenes, as a rule, were somewhat smaller. The peridotites are everywhere partly or wholly altered to serpentine. In the larger masses it is common to find 40 to 50 per cent of the rock consisting of serpentine, but the dykes, and certain zones in the larger masses, now consist wholly of serpentine with, in places, more or less talc.

Peridotite of the type described forms the greater part of the large Thetford-Black Lake mass and the other masses of the northwestern zone. Toward the northwestern edge of it there occur a few small and scattered masses of dunite, completely enclosed in peridotite. Two such bodies have been found and mapped by the writer, both of which are quite small and irregular in shape. The dunite consists wholly of olivine, with perhaps a little accessory chromite. The contacts between the dunite and peridotite, where observed, are not sharp lines, but the one rock grades rapidly into the other within a distance of 3 or 4 inches. One of the most accessible of such contacts lies between 100 and 200 feet north of the Bennett-Martin pit, within the town limits of Thetford Mines. The relations suggest that the dunite was segregated from the peridotite during cooling and consolidation, probably by aggregation of masses of olivine crystals.

The peridotite bodies maintain approximately the same composition across the greater part of their width until the southeast side is approached. There the proportion of pyroxene increases, at first gradually, then rapidly, and the rock passes first into pyroxene-rich peridotite and finally into pyroxenite. One of the best exposed sections showing the change is on Reed hill. The peridotite of which most of the hill is composed contains, it is estimated, between 10 and 20 per cent of pyroxene; and toward the south end the pyroxene content rises rapidly, and exhibits great variations within distances of a few inches. Peridotite containing about 20 per cent of pyroxene includes patches, inches or feet in diameter, carrying 50 per cent pyroxene. No sharp contact is found between the high-pyroxene patches and the surrounding rock, but the two grade into each other within a distance of about 3 inches. The extreme south end of the outcrop averages between 40 and 50 per cent of pyroxene. It is separated from the next hill to the south by a drift-filled gap about 300 feet wide, but the extreme north edge of the latter hill still has about the same composition, though it is succeeded quickly by fairly pure pyroxenite.

Pyroxenite, as the name implies, is rock composed almost entirely of pyroxene crystals. The pyroxenites associated with peridotites in the area under discussion consist largely of diallage and enstatite, with a little accessory chromite. In some places one of these pyroxenes is in excess, in other places the reverse is true. The pyroxenites, on the whole, are very coarse-grained rocks. The average rock has a grain diameter of about $\frac{1}{4}$ inch, although finer grained types are common, particularly near contacts, and much coarser types, made up of crystals an inch or more in diameter, are also commonly found. Unlike the gabbro-pyroxenite, which weathers dark green, these pyroxenites commonly weather to rather light grey or greenish grey tints, or even to almost pure white in the very fine-grained varieties. Where the pyroxenite contains some olivine, however, it weathers to bright browns and red-browns, as in the Red hills. The pyroxenites, except the finer grained varieties, are extremely tough rocks, so that collection of specimens is difficult; and the coarse grain appears to permit easy percolation of surface water, so that weathering is as a rule considerably deeper than in other rocks of the region.

The areas coloured as pyroxenite on the maps do not, however, consist wholly of pure pyroxenite, but include much pyroxene-rich peridotite. In the Red hills and the hill to the west perhaps half the rock contains more or less olivine. On Nadeau and Bengel hills there is more or less pyroxene-rich peridotite along the northwestern margin. In both places the pyroxene-rich peridotites form definite bands interbanded with each other and with pure pyroxenite. In the Red hills, where exposures are particularly fine, the bands run in long, gentle, sweeping curves, with sharp contortions in one or two places, the whole arrangement strikingly suggestive of flow movement in a partly differentiated magma just prior to consolidation. The banding likewise exhibits a unity and general parallelism over wide areas which indicates that it owes its existence to some general cause, such as widespread flow movement (Figure 3).

The banding was particularly studied on a steeply inclined clean exposure north of the Hall chrome pit, in the Red hills. At this point it strikes north 80 degrees west and dips steeply north. The individual bands, which consist of pyroxenite in a matrix of pyroxene-rich peridotite, attain widths of 8 inches, but the usual width is 2 to 4 inches. The total proportion of pyroxenite at this point was estimated to be 4 or 5 per cent of the volume of the rock. The bands are long, narrow lenses, which end as a rule by gradual thinning. A band 2 inches wide will be about 20 feet long. The width, though fairly uniform, varies somewhat, so that a band with an average width of 1 inch may have a maximum width of 2 inches, and may thin in places to $\frac{1}{2}$ inch. The edges are commonly linear and quite sharp, but in places they are irregular, with little bunches of pyroxene crystals off to one side in the pyroxene-rich peridotite. In places a band may be broken, and over a length of a few inches may consist of small bunches of pyroxene crystals embedded in pyroxene-rich peridotite.

In many cases, though not in all, the grain of the bands is roughly proportional to the width, i.e., coarser in the thicker bands and finer in the thinner. Cases were noted where the grain becomes finer at a constriction in the band, and coarsens at an expansion.

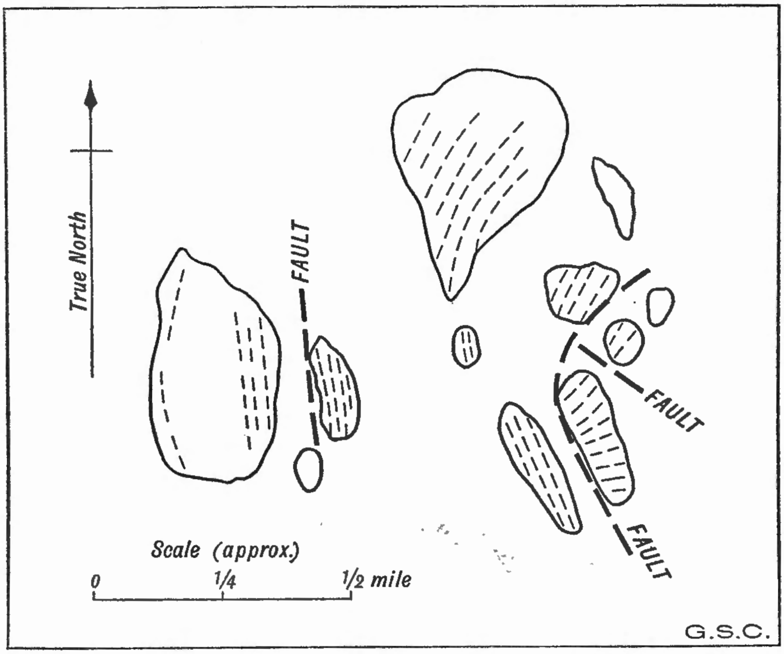

Figure 3. Red Hills area, showing directions of banding.

Here and there little stringers run off from a band of pyroxenite, or a band at its end may pass into a narrow stringer. In general such stringers parallel the general banding, but in some cases they cut across it at angles of 2 or 3 degrees. One of these, measured as accurately as possible, varied in width from one-twentieth of an inch to one-eighth, and was composed of minute pyroxenes, the largest about one-fortieth of an inch in diameter.

The interbanded pyroxenites and pyroxene-rich peridotites are cut by numerous dykes of somewhat younger pyroxenite, which break across the banding. In the locality last described such dykes strike north 40 to 50 degrees west and dip about 60 degrees northeast, thus crossing the banding at angles of 30 to 40 degrees. The dykes here vary from $\frac{1}{2}$ to 2 inches in width, and appear to be composed entirely of pyroxene. In other places the dykes exhibit less regularity and may run in all directions; and they may even become numerous enough to produce an injection breccia, in which blocks of interbanded pyroxenite and pyroxene-rich peridotite lie in a matrix of somewhat younger pyroxenite.

The dykes, like the bands of pyroxenite, usually end by thinning to a stringer. In many the grain seems roughly proportional to the width of the band, and becomes finer where the dyke thins. Some dykes are edged by very narrow bands of blackish material, which suggests chilled edges. The pyroxene of the dykes appears identical with that of the bands.

The very coarse pyroxenites, in which individual crystals have diameters of an inch or more, occur in roughly equidimensional masses some of which are very large. One, some hundreds of feet across, lies on the eastern flank of the Red hills, and others were noted on Nadeau and Bengel hills.

Pyroxenite dykes are also found everywhere throughout the ordinary peridotites. They vary in width from less than an inch to several feet, and are usually composed of fairly large pyroxene crystals, one-eighth to one-half inch in diameter. The boundaries, though definite, are not as clean-cut as if material had been injected into a crack in solid rock. On the other hand, many dykes fork, even quite small ones, so that it is difficult to avoid the conclusion that the peridotite must have been solid when they were formed. The very coarse grain of the pyroxenite, in dykes not more than an inch wide, the entire absence of chilled edges, and the lack of very clean-cut boundaries, combine to make the pyroxenite dykes resemble the final pegmatitic crystallizations of a magma rather than the result of injection after the peridotite was wholly solidified.

An interesting facies of the pyroxenite was found on the south side of Nadeau hill, toward the west end. The pyroxenite there, over a width of 100 to 200 feet from its contact with gabbro, is fine-grained, forming a pure white rock of striking appearance. A thin section showed it to consist entirely of secondary products. About half the section was uralite, apparently secondary after pyroxene; and the remainder consisted mainly of zoisite which, it was thought, may have been secondary after feldspar. This occurrence is the only one in which feldspar, or material that may have been feldspar, has been recognized in the ultrabasic rocks of the region.

Relations of Peridotite to Pyroxenite

The descriptions given show that the northwest side of the Thetford-Black Lake mass of peridotite consists of peridotite carrying little pyroxene, which acts as a matrix to small bodies of dunite in which there is no pyroxene. On Reed hill the proportion of pyroxene increases, and the material passes gradationally into pyroxene-rich peridotite, which is interbanded with pyroxenite in the Red hills. On Nadeau and Bengel hills the rock on the northwest side is pyroxene-rich peridotite interbanded with some pyroxenite, and the southeastern part, about three-fourths of the total width, is pure pyroxenite. The same type of areal relation prevails throughout the whole region. Thus pyroxenite is found on the south side of Caribou lake, on the extreme southeast edge of the peridotite; and on Oak hill, in the same relative position. Though no true pyroxenite, other than dykes, was noted on Belmina ridge, the eastern part of the mass is much more pyroxenic than the western. The peridotites of Breeches and Nicolet lakes have not been noticeably differentiated; but the mass at Asbestos exhibits the same relation, peridotite on the north, pyroxenite on the south. Pyroxenite likewise occurs as dykes, cutting both normal peridotite and the interbanded mixtures of pyroxenite and pyroxene-rich peridotite, indicating that some of the pyroxenite-forming fluid, or magma, must have remained liquid after the consolidation of the remainder. The character of some bands in the interbanded pyroxenites and pyroxene-rich peridotites also fits the conception that the pyroxenite bands may have formed by migration of pyroxenite-forming liquid into cracks or zones of easy access as the surrounding materials solidified. The irregular masses of very coarse pyroxenite found here and there are also strongly reminiscent of the coarse pegmatites related to granitic stocks.

These facts render necessary the following conclusions: (1) that the peridotite and pyroxenite are derivatives of a common magma; (2) that the pyroxenite-forming part tended to remain liquid longer than the peridotite-forming part; (3) that the magma differentiated to form pyroxene-poor peridotite with dunite inclusions on the northwest side, and pyroxene-rich peridotite and pyroxenite on the southeast side; (4) that as the peridotite is both somewhat heavier than the pyroxenite, and likewise crystallized first, the southeast side of these masses must have been the upper side. This conclusion is in harmony with the known regional structure.

Origin

Planimeter measurements give the area of the large Thetford-Black Lake peridotite mass as 20·5 miles, and that of the Belmina mass, which is probably connected with the former by a narrow neck, as 2·4 square miles. The total area of the pyroxenites and pyroxene-rich peridotites from Brousseau hill northeast to Red hills, assuming continuity throughout the drift-covered area between Red hills and Poudrier hills, is 13·86 square miles. The Red hills, of which about half or more is pyroxene-rich peridotite, have an area of about 2 square miles. If the volumes of these bodies are proportional to the exposed areas, which may or may not be true, it follows that the olivine-forming constituents of the original magma were to the pyroxene-forming constituents in the ratio of about 2 to 1.

Differentiation wholly in place, however, can hardly account for the existing areal arrangements. The maps and descriptions indicate that the northwestern Thetford-Black Lake intrusive consists of peridotite with a little pyroxenite on top; whereas the southeastern intrusive mass is mainly pyroxenite with a little pyroxene-rich peridotite at the base. The connecting neck through Red Hills area is a mixture of the two rock types, and is intensely flow-textured, with the flow lines indicating southward movement. It can hardly be assumed that differentiation of a uniform magma could yield this distribution, as this would imply that peridotite, as it separated from the southeastern mass, flowed back through the Red Hills neck into the northwestern reservoir, and at the same time the pyroxenite forming in the northwestern reservoir must have risen through the Red Hills neck into the southeastern reservoir. A better conception is that partial differentiation into an upper, pyroxenic part and a lower, olivinic part, took place in the original reservoir *before* the magmas rose into their present position. Subsequent rise of the whole body of magma would then result in the pyroxenic part being first injected, and occupying the upper horizons of the new position, whereas the olivinic part would occupy the lower horizons. The completion of the differentiation process in place would then yield arrangements like those found.

The writer is aware that in thus inferring the existence of liquid magmas of ultrabasic composition he is directly opposing the conclusions of many able petrographers and students of magmatic differentiation, of whose views N. L. Bowen[1] has perhaps been the chief exponent in recent years. These writers hold that liquids of essentially the same compositions as these basic rocks cannot exist, and in support of their conclusions they point out: (1) that lavas and *small* dykes of peridotite and pyroxenite are never found, though they should be if these rocks had once been fluid; (2) that the temperatures required to melt olivine and pyroxene are so high that liquids of corresponding composition should strongly metamorphose the country rock; but the country rock is rarely, if ever, thus metamorphosed; (3) that if the supposed ultrabasic magma contained sufficient volatile constituents to reduce its melting temperature to a point where it would not metamorphose the country rock, the volatile constituents would escape on cooling and cause great hydrothermal alteration of the surrounding rocks. No such hydrothermal alteration is found. In view of these facts, Bowen has concluded that the ultrabasic rocks were formed by fractional crystallization of gabbroic magmas, a conclusion supported by a wealth of evidence drawn from the experimental work of the Geophysical Laboratory at Washington, D.C., on the course of crystallization of controlled melts, and from petrographic studies of igneous rocks. He maintains that the olivine or pyroxene crystals that formed during the earlier stages of crystallization were separated from the remainder of the molten rock by sinking or other processes of aggregation, and that bodies of pyroxenite or peridotite not associated with more feldspathic types resulted from the further advance of the still liquid portions of the magma, and the draining or squeezing out of the liquid from the crystal masses by earth movements.

Nevertheless, in spite of Bowen's clear and convincing argument, the field facts in Thetford district seem to require the conclusion that the peridotites and pyroxenites actually were introduced into their present positions in the liquid form, with much the same compositions as they now possess. These may be summarized as follows:

Flow textures are prominent in the mixtures of pyroxene-rich peridotites and pyroxenites, and may also be detected in peridotite in many places by the linear arrangement of chromite grains or pyroxene crystals. The massive pyroxenites are roughly equigranular and do not exhibit flow texture. Flow textures indicate movement during consolidation of an igneous magma.

A process of squeezing residual magma from masses of already formed crystals, such as Bowen postulates, should likewise cause a good deal of crushing of the crystals. Such crushing might be hidden, in the peridotites, by serpentinization, but should be seen in the coarse pyroxenite; and it is not.

The Thetford-Black Lake peridotite mass, as described, contains small inclusions of dunite at the base, and graduates into pyroxene-rich peridotite at the top. The Nadeau Hill pyroxenite has pyroxene-rich peridotite at the base, which grades into pyroxenite above. These relations are characteristic of magmas that differentiate in place.

[1]Bowen, N. L.: "The Evolution of the Igneous Rocks; Princeton University Press, 1928; and other papers.

The pyroxenite dykes that cut the peridotites and the mixtures of pyroxenite and pyroxene-rich peridotite indicate that pyroxene-forming magma remained fluid after consolidation of these rocks. Many of the dykes are so narrow, and their grain is so coarse, that by no stretch of imagination can they be supposed to have been formed by injection of material already crystalline in large part, as Bowen's hypothesis would have it. Any such attempt would inevitably have resulted in the crystals jamming and blocking the narrow fissures.

In habit the pyroxenite commonly forms sill-like masses, some quite thin, spread out beneath the sheet of gabbro or in the sediments beneath. This behaviour indicates for the magma a degree of fluidity comparable with that of the gabbro magma itself. In addition, there is no feldspathic igneous material in the neighbourhood of such sills that might represent liquid squeezed out from them, as Bowen supposes. The breccias of gabbro fragments in a pyroxenite matrix, found near contacts, and the dykes and stringers of pyroxenite in gabbro, which have already been described, likewise indicate that the pyroxenite magma was quite fluid.

Perhaps the most convincing evidence, however, is afforded by the field inspection of the ultrabasic masses themselves. The largest peridotite mass is about 8 miles long, with a maximum width of 3 miles, and the main pyroxenite mass is 7 miles long, with a maximum width of nearly 2 miles. If these were masses of crystals from which feldspathic liquid had been squeezed out, one would expect to find many places where the feldspathic liquid had not been completely removed; and the surrounding rock should contain many dykes of olivine gabbro and more acid types. These relations actually obtain in the peridotites of the Hebrides, to the description of which Bowen devotes much space, and in other peridotites, but not in those of Thetford district. The great masses of this district have been traversed from end to end without finding a trace of feldspar, except in the one doubtful case already mentioned; and there are no dykes of more feldspathic composition in the rocks around.

It may possibly be argued, as some writers have done, that the feldspathic and granitic dykes associated with the peridotites represent an acid differentiate squeezed out during consolidation, and in some places the association between peridotite and the granitic types is so close as to suggest the conclusion strongly. If it were true, however, a more or less even distribution of granitic dykes throughout the peridotite might be expected, which is not the case. On the contrary, there is a great concentration of granite in the peridotite from Thetford to Black Lake, whereas very little is to be seen in the great mass of Caribou mountain or on Belmina ridge. Very little granite, also, is found with the pyroxenites, and that which occurs is mostly associated with serpentinized parts. Also, the granite and other acid dykes do not occupy irregular fissures of the nature of cooling cracks, but are found in sheared zones and in joints associated with them, indicating that the peridotites and pyroxenites were thoroughly consolidated before the granites were injected. The large dykes of serpentine in the northeastern part of Thetford map-area have no associated granite either in or near them, so far as observed. For these reasons it seems unlikely that the granites are magmatically related to the peridotites.

In a recent paper[1] H. H. Hess has advanced a suggestion that may reconcile the field facts with the objections advanced by Bowen. It has been pointed out that the peridotites of Thetford district are everywhere about half serpentinized, and the uniformity of this alteration suggests that it was probably caused by magmatic water. The amount of water required for this alteration would be between 5 and 10 per cent of the weight of the magma, according to the type of reaction that took place. The presence of this quantity of water would greatly lower the melting point, thus accounting for the lack of contact metamorphic effects; and as the water, instead of escaping during consolidation, united with the olivine to form serpentine, no hydrothermal alteration of the country rock need be expected.

Alteration of Peridotite

The dunites and peridotites have undergone a very general, though partial, alteration to serpentine, so that the larger bodies are now fairly uniformly serpentinized. The unpublished microscopic studies of R. Harvie indicate that 75 to 80 per cent of the original olivine and pyroxene of the rocks has been converted into serpentine during this alteration. The thin sections of samples taken by the writer suggest that this figure is perhaps too high, and that a 40 to 60 per cent serpentinization is perhaps closer to the average; but no attempt at exact estimation was made. This serpentinization seems to have been entirely independent of the presence of asbestos deposits.

Serpentine may be formed from peridotite by several possible reactions, of which the following equations indicate some of the more probable:

(1) Enstatite + forsterite + water = serpentine
$MgSiO_3 + Mg_2SiO_4 + 2H_2O = H_4Mg_3Si_2O_9$
(2) Forsterite + silica + water = serpentine
$3Mg_2SiO_4 + SiO_2 + 4H_2O = 2H_4Mg_3Si_2O_9$
(3) Forsterite + carbonic acid + water = serpentine + magnesite
$2Mg_2SiO_4 + CO_2 + 2H_2O = H_4Mg_3Si_2O_9 + MgCO_3$
(4) Fe-bearing forsterite = serpentine + magnetite
$3Mg_3FeSi_2O_8 + 6H_2O + O = 3H_4Mg_3Si_2O_9 + Fe_3O_4$
(5) Forsterite + water = serpentine + brucite
$2Mg_2SiO_4 + 3H_2O = H_4Mg_3Si_2O_9 + Mg(OH)_2$

Reaction (1) requires a peridotite containing approximately 40 per cent of pyroxene, and as most of the peridotites have only about 10 per cent, the reaction can account for a 25 per cent serpentinization, or at best about half that observed. Reaction (2) has been much favoured by many writers, of whom the latest is H. H. Hess (77, pages 651-2); but if the serpentinizing solutions were of magmatic origin, as both Hess and the writer have concluded, they could hardly have carried a large percentage of free silica, because this constituent would surely have combined with magnesia, during crystallization, to form enstatite, after which serpentinization would go on according to reaction (1). The writer, therefore, considers that little or no serpentine could have been formed in this way. In reaction (3) magnesite is formed as a by-product, in amount nearly one-third that of serpentine. As no magnesite is found in Thetford

[1]Phillips, A. H., and Hess, H. H.: Metamorphic Differentiation at Contacts between Serpentinite and Siliceous Country Rocks; Am. Miner., 21, pp. 333–362 (1936).

district, except in one spot south of Thetford Mines, where it appears to be a product of pre-glacial weathering, this reaction cannot have contributed to the general serpentinization. Reaction (5) requires the formation of brucite in the ratio of about 1 volume of brucite to 4½ volumes of serpentine. Although considerable brucite is found in the serpentine rims of asbestos veins, the writer has found none in the partly serpentinized peridotite, so that this reaction cannot have produced much serpentine. Reaction (4) yields serpentine and magnetite, the products actually present; this reaction, therefore, seems the most probable. Although the origin of the oxygen required by the equation is difficult to understand or explain, it is clear that some must have been available, because the ferrous iron of the olivine is oxidized to magnetite.

It would seem, therefore, that serpentinization must have gone on mainly according to reactions (1) and (4). In the pyroxene-rich peridotite, reaction (1) may have been dominant; in the pyroxene-poor peridotites, reaction (4) must have been the more important.

Attention has frequently been called to the large increase of volume that takes place when peridotite is altered to serpentine, and certain writers have concluded that the numerous faults and joints in the peridotite bodies have been caused by this expansion. It is, therefore, worth while to point out that if serpentinization, as supposed, was caused by magmatic water, no such expansion would take place, because the volume of the system as a whole would be about the same, or a trifle smaller, after serpentinization as before, as the following equations show. The assumption must, of course, be made that the specific volumes of the various substances at high temperatures have about the same proportion to one another as they have at low temperatures. Under this assumption, the relative volumes are, for reaction (1):

$$\begin{array}{l}\text{Enstatite} + \text{forsterite} + \text{water} = \text{serpentine}\\ 31{\cdot}3\text{ vols.} + 42{\cdot}4\text{ vols.} + 36\text{ vols.} = 107{\cdot}4\text{ vols.}\end{array}$$

making a total of 109·7 volumes of original constituents, reduced to 107·4 volumes by serpentinization. In reaction (4) we have

$$\begin{array}{r}\text{Fe-bearing forsterite} + \text{water} + \text{oxygen} = \text{serpentine} + \text{magnetite}\\ 277{\cdot}7\text{ vols.} + 108\text{ vols.} + ? = 322{\cdot}2\text{ vols.} + 45\text{ vols.}\end{array}$$

making a total of 385·7 volumes of original constituents (disregarding oxygen) which are reduced to 367·2 volumes after reaction.

Alteration of Pyroxenite

The pyroxenites in general look fairly fresh, but thin sections under the microscope show a good deal of alteration to chlorite and uralite, and whether this is due to weathering or not it is impossible at present to ascertain. The entire lack of prospect pits or other openings in the pyroxenites confines the collection of specimens to the weathered zone; and the coarse, loose texture of the pyroxenites permits water to penetrate them readily. All specimens collected by the writer had suffered more or less in this way.

Pyroxenite dykes cutting the peridotite of the asbestos pits at Thetford Mines are much less altered to chlorite and uralite. In places they are serpentinized, like the surrounding peridotite; but where this is not the case, the pyroxenes are commonly fairly fresh.

More exact information as to the freshness of the pyroxenite below the zone of weathering is highly desirable. If the pyroxenite was injected as a liquid magma, as the field evidence indicates, the liquid can only have existed by reason of a high content of volatile constituents, such as water; and these, on cooling, should attack and alter the pyroxene crystals. If the pyroxenes below the zone of weathering are not so altered, the problem of explaining the origin of the pyroxenite is rendered very difficult. The freshness of the pyroxenite dykes at Thetford Mines may be explained by the fact that the volatile constituents of the dyke magma would preferably attack and alter the surrounding peridotite rather than the pyroxene of the dyke.

Throughout the pyroxenite masses there are bands of pure serpentine, which weather to a light grey. In a few places such bands have been found with widths of only an inch or two, but more commonly their width ranges from 6 or 8 feet to 200 feet or more. Previous observers have considered them to be altered peridotites; but the following evidence proves conclusively that they are merely altered parts of the pyroxenites themselves, and that alteration probably took place by the entry of solutions along fault or other fissures. The question is of more than academic importance, as it is in these serpentine bands that chromite deposits commonly occur. To determine the origin of the chromites, therefore, one must first know the origin of the serpentine bands.

One of the best places to study the bands is the well-exposed area of the Red hills. Here the rocks possess various primary structures, namely, the interbanding of pyroxenite and pyroxene-rich peridotite already described, and the numerous later dykes of pyroxenite, most of them only a few inches wide, which intersect the banding. The serpentine bands cut indiscriminately across these primary structures, at all angles, and hence must have been formed after them. The bands are more or less tabular bodies, with steep to vertical dips; hence they must be either alteration products or dykes. If dykes, the edges should be sharp and fairly linear; but they are not, and it may, therefore, be concluded that they are alteration products, an inference that is amply confirmed by the following direct evidence.

The edges of those serpentine bands that cut across the primary banding have a saw-toothed contour, because the serpentine is much wider where it crosses the pyroxene-rich peridotites than where it crosses the bands of pure pyroxenite. This behaviour should be expected in an alteration product, as the peridotites serpentinize more readily than the pyroxenites.

The edges of the serpentine bands are not sharp, but the serpentine grades into the pyroxenite within an interval of about a foot. Within this distance all stages of the change can be studied. The following observations, which are typical of all contacts, were made on a 6-foot band of serpentine about $\frac{1}{4}$ mile west of the Hall chrome pit. The band is exposed over a length of 30 or 40 feet. On both sides of it the rock is pyroxene-rich peridotite, estimated to contain about 80 per cent of pyroxene, and weathering to a reddish tint. The extreme edge of the grey band contains as many and as large pyroxenes as the surrounding pyroxene-rich peridotite, but the matrix weathers grey instead of reddish. This material grades in turn into rock of a still greyer tint, in which the pyroxenes are approximately as numerous as before, but smaller, as if their edges had been attacked. At its inner edge this material passes rapidly into the featureless, grey serpentine which forms the middle part of the band. At the centre of the band is a fault that has sheared the serpentine over widths of 6 inches to a foot.

Where serpentine bands cut across dykes of the coarser varieties of pyroxenite, still better evidence of the nature of the bands is obtainable. The pyroxenite dykes are not cut off at the contact, as they would be if the material of the bands had been injected; on the contrary, the course of the dyke may be traced, in some places for scores of feet, through the grey, featureless serpentine. This is because the large pyroxenes of the dykes, though altered to bastite within the serpentine band, do not entirely disappear like the smaller ones of the surrounding rock, but enough of them retain their form so that on weathered surfaces the original course of the dyke may be followed.

The pronounced linearity of the serpentine bands and the manner in which they cut indiscriminately across older structures indicate that they have been formed by the entry of solutions along faults or other fissures. As serpentinization causes considerable expansion, it would result in closing the original fissures tightly; accordingly there are many bands having no trace of an original central fissure. Many others do have a fault at the centre, but as the serpentine walls of such faults are slickensided and rendered schistose, the faults are clearly later than the alteration to serpentine. Perhaps movement took place where it did because the earlier, pre-serpentine movement had created zones of weakness; or perhaps because the serpentine bands are less tough and resistant than the surrounding pyroxenites.

The reactions by which pyroxenite may be converted into serpentine are suggestive. Thus in the case of enstatite:

(1) Enstatite+water=serpentine+silica
$3MgSiO_3+2H_2O=H_4Mg_2Si_2O_9+SiO_2$

(2) Enstatite+magnesia+water=serpentine
$2MgSiO_3+MgO+2H_2O=H_4Mg_3Si_2O_9$

the equations make it evident that if water alone was the active reagent, some silica must be formed at the same time. If no silica is formed, it is necessary to conclude that magnesia was added, as in (2). The more common pyroxene, diopside or diallage, has the formula $MgSiO_3 . CaSiO_3$, indicating that it consists of the enstatite molecule plus the calcium silicate molecule. In the conversion of this substance into serpentine, the enstatite molecule would presumably behave as in the above equations. The lime of the calcium silicate molecule would either have to be replaced by magnesia, again indicating addition of magnesia, or all the calcium silicate would have to be driven out and carried away. Poitevin and Graham (102) have suggested that the dyke-like bodies of diopside, garnet, and vesuvianite so commonly associated with these serpentine bands have been formed by the action on granite dykes of solutions carrying lime silicate from the pyroxenite.

Age

The bulk of the peridotite and pyroxenite of the region lies entirely within areas underlain by Caldwell series, but between Thetford map-area and Chaudière area, mapped by B. R. MacKay (92), a large dyke of serpentine cuts the Beauceville series. The dyke ranges in width from 100 to 300 feet, and was traced by the writer more than 3 miles. For all this length it lies south of the Caldwell-Beauceville contact, at distances ranging between 500 and 1,600 feet from it. The peridotite is, therefore, post-Beauceville in age.

It is likewise obvious, from a study of the region, that intrusion was controlled by the folding. Nearly all the so-called dykes are really sills, controlled by and following the bedding, though cutting across it here and there. Further, there is a distinct tendency for the peridotites to occupy anticlines in preference to synclines, though in certain cases, as will be shown, the upthrust of peridotite or pyroxenite magma has made its own anticline. It will also be shown that the disturbance of the strata around Clapham lake must have been caused by the sidethrust of already folded strata by the peridotite injection. These facts indicate that injection must have taken place at some time after the post-Ordovician folding. The peridotites have, however, been more or less folded. This can best be seen in the Pennington dyke northeast of Thetford both at the Federal mine and in the pit at Rumpleville. At each place the north or foot-wall side of the sill is flexed, along with the surrounding sediments, into a drag-fold with a low, eastward plunge. Obviously, therefore, the sill must have been folded along with the surrounding sediments.

Two folding movements are known to have occurred in this region, one following deposition of the Beauceville sediments, the other after deposition of the Lower Devonian. As the peridotites were injected after one folding movement, and are themselves folded, it is evident that they must have been introduced during or shortly after the first folding. Evidence already given as to the age of the quartz veins in the Bennett schists (page 17) seems to place the peridotite injection at or near the very end of the post-Ordovician folding movement. This conclusion is in agreement with F. J. Alcock's determination of the age of the serpentines of mount Albert.[1]

J. A. Dresser expressed the opinion (54, pages 27, 51) that the serpentine dykes northeast of Thetford, which he terms the Broughton phase of the intrusions, may be older than the remaining parts, or Thetford phase. He based this opinion partly on the fact that the Broughton phase is much more serpentinized than the other, so that the original minerals are not now discernible, and partly on the fact that the Pennington dyke, the principal mass studied by him, is highly sheared, whereas the Thetford phase is not. The writer does not consider the conclusion justified. All the smaller bodies of peridotite in the region, wherever they are, are highly serpentinized, so that the lesser serpentinization of the larger masses seems to be a function of their size. The intense shearing of the Pennington dyke seems due, in large part, to the comparatively slight resistance to shearing stresses offered by serpentine, so that slip movement which, during folding, would normally be spread throughout a considerable thickness of strata, was concentrated in it. As a matter of fact the dyke is sheared throughout its whole width only where it is narrow. Where it is wider, as at the Fraser mine and in lot 5, range V, Thetford tp., shearing is confined to a zone 40 to 100 feet wide, and the remainder is as massive as

[1] Geol. Surv., Canada, Mem. 144, p. 38 (1926).

the serpentine elsewhere. The other large dykes that run northwest near the western side of Broughton township do not exhibit an unusual amount of shearing.

Mode of Intrusion

Exposed contacts between the ultrabasic rocks of Thetford district and the older rocks do not number more than half a dozen, and of these all but one are contacts of dykes or sills. The one exception, at the southwest end of Brousseau hill near Disraeli village (*See* Map 418A), is most informative. The hill is the southwest end of a ridge of pyroxenite known as Bisby ridge, and is itself an oval mass of pyroxenite somewhat more than half a mile long and one-quarter mile wide, rising some 300 feet above the more easily eroded sediments around it. Bisby ridge runs north 40 degrees east, approximately parallel to the general strike of the surrounding sediments.

The sediments have been closely folded, and for about 3 miles southwest of Brousseau hill the folds plunge northeast, except that about $1\frac{3}{4}$ miles from the hill the plunge is reversed for a short distance. The northeasterly plunge is maintained to within 500 feet of the contact with the intrusive. Passing across a narrow, soil-covered belt, the observer next comes to the nose of the hill, where sediments are exposed with a very steep dip to the southwest. Pyroxenite lies a few feet behind this exposure.

It may be that this change of plunge is one of the ordinary reversals characteristic of cross-folded sediments. If so, the narrow area between the sediments with the northeast, and those with the southwest, plunge must be the axis of a synclinal cross-fold, and it should be possible to trace this axis to the northwest and southeast. It has not been found. On the northwest, numerous observations on the plunge of the folded quartzites have been obtained, and all are northeast as far as Coleraine village. On the southeast observations have proved more difficult to obtain, but those that have been secured are likewise northeast for about 2 miles northeast of Brousseau hill.

It can only be concluded, therefore, that the sudden and violent reversal of plunge, a purely local feature found only at the pyroxenite contact, was caused by the pyroxenite intrusion; leading naturally to the conception that the pyroxenite plug was driven upwards like a punch, forcing its sedimentary roof ahead of it, and dragging it upward on the sides.

Turning now from this purely local feature to the district as a whole, a most unusual situation becomes evident. Although throughout the general region the sediments maintain a regular northeast strike, at Clapham lake the strike suddenly changes to a direction at right angles to the normal. This strike is maintained for some 3 miles southwest of Clapham lake as far as the border of the peridotite mass, and throughout this distance the dip is steeply northeast. At the southwest end of the main peridotite mass, in the area northwest of Coleraine village, the sediments dip away to the southwest, again steeply, over a width of more than a mile.

The sediments both northeast and southwest of the main peridotite mass thus exhibit a steep updoming in a direction at right angles to the regional strike. If this updoming were due to normal cross-folding, it should not be a wholly local feature, but should be found in the areas to the northwest and southeast, though it might be less accentuated farther away. The sediments to the northwest are most likely to exhibit this feature, because there are good outcrops within a mile of the peridotite mass; but they do not. Although the plunges of the folds indicate that there probably is an anticlinal cross-fold northwest of the main peridotite mass, the plunges are low, rarely more than 30 degrees, and commonly not more than 15 degrees. Nothing comparable with the steep dips at the ends of the peridotite mass is to be seen. It would seem, therefore, that these steep dips must be ascribed to the injection of the periodite rather than to normal cross-folding; so that we are again led to the conclusion that the peridotite mass was updriven like a plug, or punch, raising the overlying rocks and dragging upward the strata around the margins.

This conception affords a very happy explanation of several puzzling features of the structure of the district. One group of features most difficult to explain by other conceptions is the condition existing around Clapham lake. Not only do the strata strike at right angles to the normal direction of strike, as already mentioned, but west of the lake the hard, massive quartzites of the Caldwell series have been intensely metamorphosed and contorted, forming schists indistinguishable from the Bennett schists. East of the lake the Caldwell slates are intensely crumpled and disturbed over a width of about half a mile, beyond which zone they appear quite normal in strike and general appearance. Neither northwest nor southeast of the area of abnormal strike is the normal strike of the sediments disturbed in the slightest.

When the area was first studied, it seemed that these phenomena must be the effect of a drag movement between the area on the northwest and that on the southeast; that is, after the rocks had been folded along northeast axes a block to the southeast tended to move southwest, causing drag phenomena throughout a belt 3 miles wide between the northwest and southeast blocks. This hypothesis left much unexplained, however. If it was correct, it implied that the southeast block moved southwest almost 3 miles, relative to the northwest block; and with such a large movement it would seem that drag phenomena must appear in the soft slates for a long distance east of Clapham lake. The fact that they do not do so suggests that the hypothesis is incorrect.

If, however, we assume that some drag, not necessarily a great deal, took place in the 3-mile belt under consideration, the place where the drag was localized would be exactly where intrusion of igneous material would tend to occur. If now the intrusive, as suggested, was forced in, raising the overlying strata and no doubt also forcing them aside, both the elevating movement and the lateral thrust would result in shifting the strata farther and farther to the northeast, giving them, after erosion, their present northwest strike. The intense pressures developed by the lateral thrust would account for the unusual metamorphism of the quartzites, and the crumpling of the slates just east of Clapham lake. The soft slates east of Clapham lake would yield like putty under the lateral thrust, without transmitting it any great distance, and we would find, as we do, that beyond a relatively narrow belt of disturbance the bedding and other structures in the slates would resume their normal appearance.

Further, if the strata of the drag-fold were thrust sidewise in the manner outlined, they would probably be torn apart in places, and peridotite could enter the gaps thus formed. It is interesting to note that the smaller mass of peridotite around the town of Thetford Mines occupies a gap that may have been formed in this way; and that the large mass of peridotite south of Black Lake village seems to have thrust itself into another gap, forcing the broken ends aside, particularly those of the strata on the south.

Turning to the southwest end of the main peridotite body, another unusual structure is found. This is a small synclinal bowl of lavas and sediments, almost circular, between 2 and 3 miles in diameter, bordered on the north by the peridotites of Caribou mountain and Oak hill. The outer parts of the bowl are underlain by the quartzites and lavas of the Caldwell series, and the centre, about a mile in diameter, is occupied by black slates identical in appearance with the Beauceville slate. The peculiar shape of this synclinal mass, and the presence in it of possibly Beauceville rocks nearly 6 miles across the general strike from the main mass of Beauceville series, have been features for which no explanation was previously apparent. The conception of the peridotite masses being forced into the folded sediments, so as to drive them upwards and sidewise, now makes this structure clear. To the north of this bowl is the great main body of peridotite, to the west the smaller mass of Belmina ridge, to the south the small masses of Breeches lake and East lake, and to the east the mass of Bisby ridge. The upward drag of all these masses would give the basin between a synclinal structure, and their sidewise thrust would develop great lateral pressures, which might depress the base of the syncline sufficiently to permit of the inclusion and preservation of some Beauceville slate.

The structure around Bisby ridge, particularly at the southwest end, is extremely difficult to interpret without the aid of this hypothesis. The conception advanced as to the mode of intrusion of the ultrabasic rocks makes it possible to develop the clear and easily understood relations shown on the maps. The recognizable lava horizon crossing lake Aylmer, under this conception, continues smoothly northward to pass around the nose of the main anticline at Coleraine; but where the pyroxenite of Brousseau hill was injected it pushed up the lavas, which would otherwise have been covered by the Beauceville series, to form the secondary anticline of Brousseau hill, and to create a considerable exposed width of lavas on the northwest side of the hill. In addition, it may be concluded that this sharp and unnatural bending also caused fracturing of the lavas northwest of the hill, permitting intrusion of the body of granite in this locality.

On the south side of Bengel hill the pyroxenite changes suddenly in width from some 900 feet to about 2,200 feet. As pyroxenite resists erosion strongly and stands commonly as high ridges, it is assumed that the north side of the ridge indicates fairly closely the pyroxenite boundary, although outcrops of other rocks are lacking to prove this. If the assumption is correct, the widening of the pyroxenite must be responsible for pushing aside the lavas and sediments on the south side (*See* Map 418A), because these have been displaced to about the same extent as the pyroxenite has widened. A similar displacement of the sediments seems to accompany widening of the pyroxenites at the east end of Nadeau hill, and again just northeast of the pond named Clay lake.

The hypothesis outlined thus accounts satisfactorily for most of the puzzling structural peculiarities of the district, which in itself is good presumptive evidence of its correctness. If correct, two further conclusions may be drawn. The peridotite and pyroxenite must have been sufficiently fluid prior to injection to permit of being thrust into their present positions; and the manner in which they shouldered aside the country rocks suggests an entire lack of power to assimilate them or stope them down.

ACID INTRUSIVES

In Thetford map-area the only acid intrusives are small plugs and large dykes of granite within the peridotites, and various small dykes of alaskite and albitite, commonly highly altered, which are associated with the asbestos and chromite deposits. In Disraeli map-area the Winslow granite lies southwest of lake St. Francis, and extends beyond the southern limit of the map-area. This body measures about 6 miles from east to west, and 10 miles from north to south, of which the southernmost 3 miles lies outside the map-area. Two miles west of this body there is a smaller one forming mount Aylmer. It underlies a part of the map-area measuring $\frac{3}{4}$ mile from north to south and $1\frac{1}{4}$ miles from east to west. An irregular body of granite about a mile long lies about half a mile northeast of Disraeli bay; and in addition two small masses are known, one about 300 feet in diameter at the northeast end of Breeches lake, and the other about $\frac{1}{4}$ mile north of the east end of East lake. The latter, which appears to be a differentiation product of gabbro, has already been described. In the east half of Warwick map-area the only granites encountered are a long, sill-like mass on the east side of Nicolet lake, and a large dyke on the west side of Duck lake.

Petrography

The petrography of the acid dykes found in the asbestos and chromite pits has been the subject of careful study, both by the writer and by Poitevin and Graham (102); but no particular study has been made of the other granites of the region.

The Granite Hill plug, and the other granite bodies west of it, are composed of a light grey, massive mica granite. Quartz, orthoclase, acid plagioclase, and biotite are the chief constituents. Some parts contain much biotite, others little to none. The grain is moderately coarse.

The Mount Aylmer granite has been studied by F. R. Burton (21, page 189) who finds it composed of some 20 per cent quartz, 40 per cent microcline, 30 per cent oligoclase, and accessory muscovite, biotite, magnetite, apatite, and zircon. It is a medium-grained, light grey granite, weathering to a dull grey. Thin sections show the rock to be practically fresh, except for a slight sericitization of the feldspar.

The Winslow granite is the largest body of this rock in the region under discussion. It is an oval mass about 10 miles from north to south, and 6 miles from east to west. Where outcrops around contacts are numerous, its margin can be seen to be very irregular. The rock is a light grey mica granite of medium grain, with, in places, much visible hornblende. Thin sections show that it consists mainly of fresh feldspar, $Ab_{35}An_{65}$ to $Ab_{40}An_{60}$ in composition, with a little microcline, possibly 4 or 5 per cent of quartz, and about the same amount of biotite. Some hornblende is commonly present, and in some parts is present in large amount. Hornblende seems more likely to be found on the west side of the stock than on the east. The heat of this intrusive mass has recrystallized the Beauceville rocks for some hundreds of feet from the contacts into hornstones and tough quartzites.

Dykes of granite that have not been particularly studied occur at St. Peter point on the west shore of lake St. Francis, metamorphosing the neighbouring Beauceville rocks, and again south-southwest of Lambton lake, in the Lake Aylmer series. In the latter case the intrusion has broken off fragments of the surrounding shales, which are now embedded in the body of the dyke. This occurrence is of particular importance, as it is the only one seen by the writers of granite in actual contact with Devonian strata.

The large granite dyke about 1½ miles east of the middle of lake Aylmer, along range line IX-X of Stratford township, is a mica granite, much like that of mount Aylmer.

The Breeches Lake granite is likewise very similar. A thin section by Burton showed 35 per cent quartz, 30 per cent orthoclase, 20 per cent oligoclase, 7 per cent muscovite, and 3 per cent biotite, with accessory ilmenite and zircon. It is, however, much more altered. The oligoclase has largely gone over to sericite, together with much of the orthoclase; and the micas have been largely chloritized. The rock is fine- to medium-grained and massive, but passes at the north end of the outcrop into a porphyritic phase carrying phenocrysts of orthoclase up to half an inch long.

The mass of granite northeast of Disraeli bay is a white, rather coarse-grained rock showing much quartz. Thin sections described by Knox (86, page 49) contained about 20 per cent of quartz, 50 to 75 per cent of oligoclase, and the remainder mainly orthoclase with a very little ferromagnesian mineral. The small body of granite in the northwest corner of Disraeli map-area, between Belmina ridge and Caribou mountain, is stated by Knox to have a similar composition.

Acid Intrusives of the Asbestos and Chromite Pits

Localization and Shapes of Dykes. The dykes exposed in the open pits display extraordinary irregularities of shape, so much so as to preclude mapping. Most commonly they are found in sheared zones, and in such cases the smaller ones, those less than 3 or 4 feet wide, have rarely much continuity, but form a series of disconnected lenses strung along the line of shear. Other dykes follow joints developed presumably by the shearing stresses, and then have most irregular courses, according as one part or another of the joint system proved easiest to follow. A beautiful example of such irregularity may be seen at the entrance to the haulage tunnel of the Johnson mine. Here a dyke about 2 feet wide follows joints so as to box in on three sides a rectangle of peridotite some 30 or 40 feet to the side. Such irregularities make it impossible to forecast the position of a dyke beyond where it is actually visible.

The question whether the granite was injected into the sheared zones after their formation, or whether shearing went on after injection and broke the dykes into disconnected lenses was carefully investigated. The serpentine of the sheared zones is broken down completely to little disks about the size of a silver dollar, forming the so called "fish-scale" or "fishmeat" of the miners; and these disks themselves contain numerous subordinate planes of slip, so as to break readily into minute fragments bounded by slip faces. The dyke materials, even when only a few inches wide, rarely exhibit much fracturing beyond a slight amount of jointing or slicing. Thin sections show only very moderate amounts of granulation of the original minerals. It seems quite impossible that even a moderately soft rock like the serpentine could be so thoroughly broken down by shearing and leave thin dykes uncrushed; so that intrusion must have taken place after the greater part of the shearing was completed.

The shapes of the larger granite masses of Granite hill and eastward were also carefully investigated, as it was obviously important to determine whether they are definitely intrusive into the peridotite, or are differentiates of the peridotite magma. On Granite hill peridotite outcrops on all sides of the granite except at the northwest end, where the granite disappears beneath drift. The contact is almost everywhere covered by drift, but when followed on the steep hill-side it was traced down into gullies and other depressions, and up the hill again for 100 feet or more of vertical distance, without noticeable lateral deflexion. This condition obtains on all sides of the mass, and indicates conclusively that the dip of the contact must be nearly vertical, a conclusion corroborated by direct observation of the dip in a few places. The contact, where observed, is sharp, never gradational. The granite mass is, therefore, a steep-sided plug, intrusive into the peridotites, and there is no evidence to suggest that it may be a differentiate of the peridotite magma. As for the large, dyke-shaped masses to the east, their contacts can be seen in places, as at the Maple Leaf mine, to be sharp, and steep-dipping to vertical.

Composition and Alteration. The dykes found in the asbestos pits, though locally termed "granite," rarely have a granitic composition. The freshest consist mainly of oligoclase-albite feldspar, usually $Ab_{85}An_{15}$, although both slightly more sodic and slightly more calcic varieties have been observed. Orthoclase was noted in two sections, but is uncommon. Nevertheless, Eugene Poitevin, who has studied the mineralogy of the deposits for many years, is inclined to believe that the oligoclase albite is not an original mineral, but has been formed, in large part at least, by albitization of an earlier orthoclase. Practically the only ferromagnesian mineral of the dykes is a seal-brown biotite, which in thin section appears to be original. However, its distribution within the dykes is not uniform. Many dykes contain little or none, and where a good deal is present it is common to find it concentrated in bands in a marginal or near-marginal position, with the flakes oriented approximately parallel to the edges of the dyke. These facts suggest that it was formed by some secondary process.

Practically all the dykes have suffered alteration, over and above the possible preliminary albitization, and many are completely altered to aggregates of secondary minerals. Thin sections indicate that alteration was preceded by movement that cracked the dykes and granulated the feldspars to a greater or less extent. The first step in alteration was the entry of solutions that deposited fresh, clear albite and fine-grained quartz, together with a little white mica in a few places. In many dykes this is the sole change, save for some kaolinization and sericitization of the older feldspar. Alteration proceeds by continued kaolinization of the older feldspar, with development of some sericite, epidote, clinozoisite, and zoisite. As kaolinization nears completion, needles of tremolite, actinolite, and colourless pyroxene, probably diopside, make their appearance, at first in cracks, later spreading to form patches and masses. It is presumed that these minerals attack and replace the secondary albite and quartz, because where much of the pyroxene-hornblende mixture is found, the albite and quartz are absent.

Still further alterations, which have been the subject of special study by Eugene Poitevin, give rise to local development of unusual minerals in small amounts. One specimen taken from a dyke in the King mine proved to be almost wholly white garnet. Vug-like cavities in another specimen from the King mine are lined with mesolite.

Some of these dyke materials break down rapidly to clay when exposed to the atmosphere. They seem to be those that have suffered most severely from the primary crushing mentioned above, without too much subsequent alteration except kaolinization.

The original composition of the dykes in the chromite pits, and the course of their alteration, are much less well known, partly because they are fewer in numbers, partly because most of the chromite pits are now filled with water and inaccessible, and partly because most dykes are now entirely converted to masses of secondary minerals. So complete is this alteration in the majority of cases, that no proof of igneous origin remains, and some observers have accordingly doubted that these bodies were ever "granite." The existence, however, of some dykes in which alteration has not proceeded far enough to obscure the igneous origin, and the fact that the dykes in the chromite pits display all the peculiarities of structure that characterize the dykes of known igneous origin, leave little doubt that these bodies were originally "granites."

Diopside is perhaps the mineral most largely developed as an alteration product of these dykes. As a rough estimate, diopside forms perhaps half, or more than half, of the total volume of altered material. It commonly occurs in white, compact masses or in white or pale lilac, platy masses, according to Poitevin and Graham (102, pages 31-44). The white, compact masses consist of fairly large, interlocking crystals of diopside, with the interspaces filled with a granular aggregate of smaller crystals of the same mineral. The platy masses are composed of plates or blades intergrown in the form of an irregular network, intersecting one another at all angles. The interspaces are filled with crystals of pale green andradite and clinochlore, minute calcite prisms, and in places vesuvianite. Diopside also occurs as small, colourless, transparent crystals on the walls of fissures in the massive diopside rock, and in drusy cavities. An analysis of these crystals shows that their composition is very close to the theoretical diopside, $CaMg(SiO_3)_2$.

Graham and Poitevin state that the white, massive diopside occurs in narrow veins or dykes and along the edges of the larger ones, whereas the platy diopside is found in the middle of the larger veins, separated from the wall-rock by narrow zones of the massive diopside. From these relations they infer that the diopside masses were not formed by replacement of "granite" dykes, but by direct deposition from heated solutions that had extracted lime and magnesia from the surrounding pyroxenites. The white, massive diopside, in their view, originated by the more rapid chilling of these solutions at their contact with the cold walls, whereas the platy diopside developed by slower cooling and more leisurely crystallization.

The diopside dykes, where best developed at the Montreal chrome pits, are now entirely inaccessible to study, hence the writer has no direct evidence bearing on Poitevin and Graham's hypothesis. Graham and Poitevin did not recognize the fact, however, that the serpentine in which the dykes occur is an alteration product of pyroxenite, but, along with all other observers up to that time, they regarded it as altered peridotite. It, therefore, seemed quite possible to both of them that the elements of diopside could be carried out of the near-by pyroxenite, and that chilling against the cold peridotite could take place. The recognition that the serpentine is altered pyroxenite, of which the chief constituent was diopside, makes it necessary to reconsider both conclusions. Alteration of the pyroxenite to serpentine involves mainly the loss of lime, or lime silicate (page 70); and if the dyke materials were formed by direct deposition from the solutions carrying away the materials removed during serpentinization, they would be expected to be composed mainly of lime silicates, and not of diopside. Again, the fact that the serpentine is altered pyroxenite indicates that the whole body of rock was permeated by the serpentinizing solutions, and must have all been at the same temperature as the solutions, whatever that may have been. There would, therefore, be no reason for such parts of the solutions as seeped into cracks to be chilled against the walls. These considerations, therefore, render Poitevin and Graham's conclusions very doubtful.

Next to diopside, the mineral developed in greatest amount is the garnet grossularite, $Ca_3Al_2(SiO_4)_3$. A little andradite garnet, similar in composition except that iron replaces aluminium, is found at the Montreal chrome pit. The grossularite commonly forms compact, granular masses of small crystals replacing the edges of "granite" dykes. The masses are usually white, but in some cases are rose coloured or colourless. Cracks and druses in this material are commonly lined with beautifully crystallized grossularite. In places, as at the Hall chrome pit, the Caribou pit, and the Black Lake Chrome and Asbestos pit No. 18, some of the original granitic material of the dykes still remains, so that no question can arise as to the origin of the material by replacement.

The third mineral of common occurrence in these bodies is vesuvianite, another calcium aluminium silicate. It was found most largely at the

Montreal chrome pit, where a lilac vesuvianite forms compact, fine-grained crystalline masses, which may contain, in addition, a little interstitial diopside and garnet. An emerald-green vesuvianite is commonly associated with the massive diopside of this locality. Cracks and druses in the material are lined with beautifully crystallized specimens, some of which are wine-yellow. Massive vesuvianite has also been found in a number of the other pits; the occurrences are described in detail by Poitevin and Graham (102).

A number of other unusual minerals are also found in these altered dykes, but they are rare and may hence be considered mainly as mineralogical curiosities.

Significance of Dyke Alterations. The alteration of the dykes is intimately connected with the alteration of the surrounding country rock. This is best seen in the pyroxenite areas, because in them serpentinization is less general. The dykes within the areas of serpentinized pyroxenite are commonly the highly altered types just described, whereas dykes that cut the unserpentinized pyroxenites are comparatively unaltered. The same seems true in the asbestos pits, for the most highly altered specimens studied were obtained from greatly serpentinized zones, and dykes in the fresher, only partly serpentinized peridotite are only partly altered. It seems necessary to conclude, therfore, that the alteration of the dykes was effected by the agents causing serpentinization, or by interaction between the dyke materials and country rock through the medium of these agents, rather than that the dykes were altered by volatile constituents set free by their own cooling.

It will be recalled that the dykes in the asbestos pits are altered, first to kaolin, with development of pure albite and quartz, and then to tremolite and actinolite, with relatively small amounts of epidote, zoisite, and garnet. The composition of these substances is as follows:

Albite $Na_2OAl_2O_3.6SiO_2$
Anorthite $CaO.Al_2O_32SiO_2$
Kaolin $2H_2O.Al_2O_32SiO_2$
Tremolite $CaMg_3(SiO_4)_3$
Actinolite $Ca(Mg.Fe)_3\ (SiO_4)_3$
Epidote $H_2O.4CaO.3(Al,Fe)_2O_36SiO_2$
Garnet $3CaO.Al_2O_33SiO_2$

The principal, and in many cases the only, original mineral of the dykes was oligoclase-albite, $Ab_{85}An_{15}$, so that the dykes may be considered as consisting of 10·6 parts by weight of albite to 1 part of anorthite. Inspection of the formulæ shows that the change from anorthite to kaolin takes up water and sets lime free; and the change from albite to kaolin takes up water and frees soda and considerable silica. The preliminary alteration to kaolin, with accompanying deposition of albite and silica, could, therefore, have been effected by the action of hot water only. The decomposition of the oligoclase-albite could result in setting free a part of the albite that could crystallize as such, and the remainder of the albite, together with the anorthite, would be hydrated to form kaolin and set free silica which could crystallize as quartz. At the same time, soda and lime would go into solution and be available for later reaction.

Whether this reaction would sufficiently account for all the quartz found in the partly altered dykes, only careful quantitative studies can decide. If not, the solutions must have carried some silica. The writer's microscopic work leads him to conclude, however, that the solutions need have carried little or no silica, but that practically all the quartz observed can have come from the kaolinization of albite.

The next step in the alteration is the development of tremolite and actinolite, with small amounts of epidote and, in a few places, of garnet. Tremolite and actinolite, the formulæ show, are magnesian silicates mainly, with some lime and iron. The only source of magnesia is the surrounding peridotite; and it will be shown in a subsequent section that during serpentinization considerable quantities of magnesia were eliminated. Iron was also eliminated at the same time, so that the iron of the actinolite and epidote could have come from the same source. The peridotites contained very little lime, however, so that the amount of lime is hard to account for; but some could undoubtedly have been supplied from the anorthite of the dyke itself, and some may have come from the peridotite.

The final breaking down of the albite during replacement by tremolite, etc., would mean the complete elimination of soda; and it is significant that the very last substances formed during alteration are unusual soda-bearing minerals, such as mesolite, natrolite, and pectolite.

The facts observed, therefore, suggest that the dykes were altered by the agents that simultaneously effected the serpentinization of the peridotites. The chief agent was, apparently, water. On first entering the fissures in the dykes it caused partial decomposition of the feldspar, and recrystallized part of it to albite and quartz. Continued circulation of the solutions then brought in magnesia, iron, and perhaps some lime, which had been extracted from the surrounding peridotite during serpentinization, and resulted in formation of lime-magnesia-iron silicates. The soda set free from albite during this process eventually reacted with the older minerals to form a series of unusual soda-lime silicates.

The time when this took place must have been during the second period of serpentinization, when the asbestos veins were formed. It has been shown that the primary, general serpentinization of the peridotite probably occurred in the final stages of consolidation; and it will be shown that the dykes were injected some time after consolidation was complete. The dyke alteration, therefore, cannot have been associated with the earlier serpentinization.

If the hypothesis outlined is correct, the alteration of dykes in the serpentinized pyroxenite should exhibit differences from that in the peridotite, because the pyroxenite has a different original composition, and the substances carried out of it during serpentinization must likewise be different. This actually is the case. The principal secondary minerals in the dykes in serpentinized pyroxenite are diopside, grossularite garnet, and vesuvianite, the compositions of which are

Garnet $3CaO.Al_2O_3.3SiO_2$
Vesuvianite $Ca_7(OH)_2Al_4(SiA_4)_6$
Diopside $CaMg(SiO_3)_2$
Serpentine $H_4Mg_3Si_2O_9$

The principal mineral of the unaltered pyroxenite is diopside or diallage; and the mere inspection of the formulæ shows that to convert these substances into serpentine, all the lime must be eliminated. By the hypothesis, therefore, minerals high in lime should be the chief ones found in the altered dykes, as is actually the case. The occurrence of diopside among the alteration products indicates that some magnesia must also have been transferred by the solutions. The alumina, of which the altered products contain much, in part undoubtedly came from the feldspar of the dykes themselves; but some could have been brought in from the surrounding pyroxenite, as chemical analyses show the pyroxenite contains some 3 per cent of it, whereas serpentine commonly has less.

Alteration of Serpentinized Peridotite Near Dykes. The serpentine directly in contact with the dyke materials is commonly converted into talc. These talc rims are rarely more than one-quarter of an inch wide, but in two places, in the Bell mine, several inches of talc were found along the lower edge of dykes with low dips. Beyond the talc rim, for distances proportional to the width of the dyke and approximately equal to it, the peridotite is altered to black-weathering serpentine, which gives the rock the appearance of having been baked. That this effect is genetically related to the dykes, and is not in any way connected with the fissuring or other structure, is shown by an occurrence observed in 1931 in the Johnson mine, which has now unfortunately been removed by the mining operations. At that time, between the King and Johnson pits, there remained a tongue or promontory of rock, a part of the unremoved party wall. On the upper surface, from which all soil had been stripped, a sheared zone some 8 or 10 feet wide was visible, forming the long axis of the tongue. Dyke material had been injected into the sheared zone, forming a line of thick, stumpy lenses. One of these, some 8 or 10 feet wide and perhaps 25 feet long, was separated from the next by a gap of 30 to 40 feet. The usual zone of black-weathering serpentine, in this case about 6 feet wide, was developed next the dyke; and the significant fact was, that in the 30- to 40-foot gap the altered band swung across the schistosity, paralleling the boundary of the granite lens (Figure 4). Thus the black alteration is something genetically connected with the individual bodies of dyke rock, and is not due to solutions rising along the fissures into which the dykes have been injected.

At first sight the blackish alteration appears due to contact metamorphism of the surrounding rock by the heat of the dyke aided, perhaps, by solutions or vapours given off during cooling of the dyke magma; and the baked appearance of the altered rock assists to no small degree in suggesting the conclusion. Certain facts, however, are opposed to it. One is the comparatively wide, altered zones flanking rather narrow dykes, which can hardly be supposed to have had much metamorphic effect. Another is the lack of much blackening near certain large dykes of real granite in the Reed and Murphy Hills area. Such dykes, both because of their large size and their granitic composition, which implies that they were probably hotter when injected than the more aplitic types of the asbestos pits, should have had strong metamorphic effects, but do not. Another possibility, however, is suggested by the conclusion already reached that the dykes were altered by the solutions causing serpentinization. If solutions circulating from the peridotites into the dykes carried magnesia and other constituents into the dykes, the same waters should carry some of the dyke constituents out into the surrounding peridotite, thereby causing alteration. To investigate exactly what has taken place during blackening, the following chemical analyses were made:

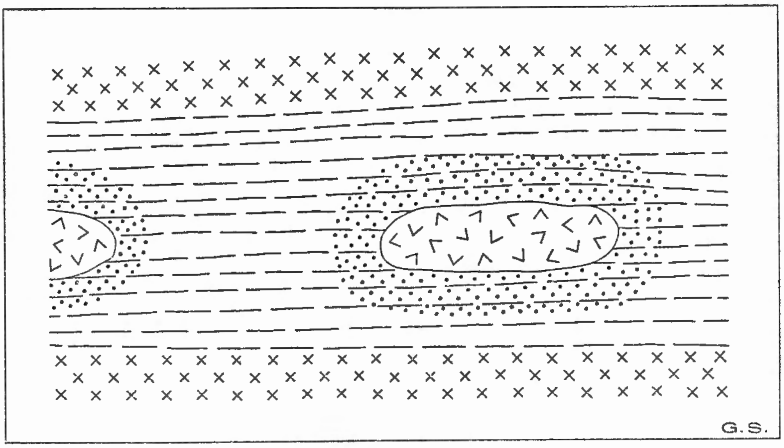

Figure 4. Relations observed on party wall between King and Johnson pits. Massive peridotite indicated by crosses; sheared peridotite by broken lines; blackened peridotite by dots; and acid dyke by pattern of angles.

TABLE I

Analyses Showing Alteration of Serpentine Close to Acid Dykes

—	1	2	3	4
SiO_2	34·40	40·42	42·05	43·48
Al_2O_3	0·50	2·24	Nil	1·41
Fe_2O_3	0·82	2·11	0·96	0·60
FeO	3·79	4·26	0·39	2·36
CaO	0·02	0·29	0·05	0·12
MgO	42·36	39·44	43·30	39·50
H_2O+	15·17	11·11	12·52	12·69
H_2O-	0·47	0·10	0·75	0·45
TiO_2	Nil	....	....	....
MnO	0·94	....	....	....
CO_2	0·38	....	....	....
Cr_2O_3	0·48	....	....	....
NiO	0·35	....	....	....
Total	99·68	99·97	100·02	100·61

1. Normal red-weathering serpentine, from chromite pit in northwest corner of lot 19 NW., rangeX, Coleraine tp.
2. Same material, blackened over a zone a foot wide, flanking a dyke about a foot wide.
3. Chrysotile asbestos. King mine.
4. Chrysotile asbestos, darkened and made brittle. In blackened zone close to acid dyke, Johnson mine.

The material for analysis No. 1 was taken from the serpentine just outside of the blackened zone, that for analysis No. 2 from about the middle of the zone. The two samples were only about a foot apart. Nos. 3 and 4 require a word of explanation. Asbestos veins entering the blackened zones surrounding a dyke undergo pronounced change. The soft, flexible fibre, pale green in the lump, becomes brown, harsh, and brittle. In extreme cases it becomes so hard that the vein material, when broken, forms glassy needles that tinkle when shaken together. Analyses 3 and 4 show what occurs during the change.

Both pairs of analyses show the same change. The materials of the blackened zones are much higher in silica, alumina, and iron, and slightly higher in lime, than the unaltered materials. The only source of the silica and alumina, and the possible source of the lime, was the material of the dyke; and we know that silica and alumina were both carried out of the dykes during their final stages of alteration. It seems reasonable to conclude, therefore, that the blackened zones are not contact metamorphic effects, but were produced by the same agents that formed the asbestos veins and altered the dykes. Why iron should have been concentrated in the blackened zones, the writer is unable to explain. Its source could not have been the dykes, and it must, therefore, have been brought in from the surrounding peridotite. Possibly on entering the zone where serpentine and chlorite were forming, the iron was readily taken into these combinations and thus got no farther. Certainly very little of the iron in the blackened zones occurs as magnetite; on the contrary, the amount of visible magnetite is much less than in the ordinary serpentines.

Age of the Granites and Acid Dykes

The acid intrusives of the region may be of more than one age. A small granite body somewhat north of the east end of East lake has been described as probably a differentiate of the gabbro, and if so must be of the same age, i.e., older than the peridotites, and possibly pre-Beauceville. Some of the other granites, such as the small body at the north end of Breeches lake and that northeast of Disraeli bay, may be of the same age and origin, though proof is lacking. That important bodies of pre-Devonian granite existed is shown by the occurrence of numerous granite boulders in the conglomerates of the Lake Aylmer series, though it has not yet been possible to identify such bodies.

The granites and the feldspathic dykes within the peridotite areas have commonly been assumed to be of one age, but this assumption has never been proved. If true, it is singular that these intrusives should form such different petrographic types. The granites, whether plugs or dykes, are ordinary quartz-bearing mica or mica-hornblende granites. The feldspathic dykes, on the other hand, never contain original quartz, and many of them have little or no mica, though others have much. Types of intermediate composition have not been found, although the problem has admittedly not been studied with the care it perhaps deserves; nor has any reason ever been advanced to account for the petrographic differences. It is, therefore, a possibility that the feldspathic dykes may differ in age and origin from the true granites.

The age of the feldspathic dykes can be determined only with reference to the peridotites and asbestos. They were injected into sheared zones that cut the peridotites and associated pyroxenites, hence are later than the consolidation and faulting. Few of them have been much granulated or fractured, hence movement was fairly complete when they were injected. It has been shown that the peridotites were probably intruded during the post-Ordovician orogeny, and that they were later folded, presumably during the Devonian period of disturbance. It seems probable that the intense faulting of the larger masses was caused, in the main, by the stresses that folded the smaller. This inference would place the intrusion of the feldspathic dykes toward the end of the Devonian folding movements.

Evidence that has been cited indicates that the feldspathic dykes were altered by the same solutions forming the asbestos veins. If the observations have been correctly interpreted, the dykes must be older than the veins.

The large bodies of granite in the south part of Disraeli map-area are generally considered Devonian in age, and correlated with similar intrusives throughout the Eastern Townships. Direct evidence of Devonian age is lacking, however, as the latest sediments cut by the granites are Ordovician. The only occurrence of granite cutting Devonian rocks is the dyke south-southwest of Lambton lake, which has already been mentioned.

The plugs and large dykes of true granite found on Granite, Reed, and Murphy hills, south of Thetford Mines, and in smaller amount elsewhere in the peridotite areas, seem very like the supposed Devonian granites in composition. It has been shown that the peridotites were probably injected in post-Ordovician time, and folded in post-Devonian time; and the granites rise through the peridotites with vertical or steeply dipping contacts, as if they had never suffered disturbance since intrusion. This suggests that intrusion occurred after, or near the end of, the Devonian deformation. Both composition and attitude, therefore, indicate that these granites may be similar in age and origin to the supposedly Devonian granites farther south.

BASIC DYKES

On Nadeau hill and on the west end of mount Adstock some basic dykes cut the pyroxenites, and are, therefore, among the latest intrusives of the district. They vary in width from a few inches to 3 or 4 feet, and dip almost vertically. Practically all trace of original composition is now lost. A thin section of one having the freshest appearance showed nothing but a felted mass of actinolite fibres, with a few grains of accessory magnetite.

CHAPTER IV

ECONOMIC GEOLOGY

The principal mineral of economic value in Thetford district is chrysotile asbestos. The output of this valuable product has varied in recent years from a high, in 1929, of 306,000 short tons with a total value of more than $13,000,000, to a low in 1932 of 123,000 tons valued at somewhat more than $3,000,000. Full statistics of production up to 1929 are given by J. G. Ross (106), and those of later years may be obtained from the annual reports of the Quebec Bureau of Mines. The only other product actively mined is soapstone, of which some $45,000 to $50,000 worth is produced annually by the Broughton Soapstone and Quarry Company from lot 12, range XI, Broughton tp. In 1933 two other soapstone deposits were opened, one on lot 11, range XI, Broughton tp., the other on lot 2, range V, Thetford tp., but no statistics of production are yet available. Chromite was mined during the late war from a number of properties in Coleraine township, but these all ceased production immediately afterward, as ore of as good or better grade can be obtained more cheaply from other parts of the world. Much chromite still remains in the deposits, however, and can be readily utilized should a shortage of this mineral again occur. On the north flank of mount Aylmer a small pyrite deposit was opened some years ago, and attempts were made to work it as a low-grade ore of copper. Northeast of Nicolet lake a number of old pits and shafts mark the site of a former deposit of antimony. Attempts at iron mining have been made in two or three places, particularly at the so-called "Leeds mine" in lot 7, range V, Leeds tp. Limestone has been quarried and burned in a few places, but the quality is poor, and no operations have been carried on for several years.

ASBESTOS

The term "asbestos" is derived from a Greek word meaning "incombustible." Mineralogically a number of different substances are termed asbestos, all of them characterized by a finely fibrous texture, and with the exception of chrysotile asbestos they are fibrous varieties of different amphiboles. Chrysotile asbestos is a fibrous variety of serpentine, and hence differs both chemically and mineralogically from the others. Economically it is much the most important, because the fibres are finer and softer, and hence more valuable for spinning purposes. All the asbestos of Thetford region is chrysotile asbestos. In this report it will be termed simply "asbestos."

Asbestos is of two types, cross fibre and slip fibre. Cross fibre occurs in veins with clean-cut walls, the fibres arranged parallel to one another at a large angle to the walls. Slip fibre, as the name implies, is found in highly sheared serpentine. The fibres, more or less matted together, lie lengthwise along the planes of slip. Most of the output of Thetford region is cross fibre.

The veins of cross fibre vary in width from a hair line to 3 inches, or in rare instances 4 or 5 inches. Fibre more than three-eighths of an inch in length is known as " crude asbestos," and this is subdivided into " Crude No. 1 " consisting of staple three-quarters of an inch or more in length, and " Crude No. 2" consisting of staple three-eighths to three-quarters of an inch long. To an outsider it seems puzzling and contradictory to apply the term "crude" to the finest grades produced. The term is used because the "crude" is hand selected, cobbed from the enclosing rock with hammers, and sold in the lump; whereas the shorter grades, known as " milled asbestos " have gone through a milling process whereby they are freed from enclosing rock, fibreized, and put on the market as purified asbestos wool.

The relative proportion of crude fibre is very small. In 1929 the total output of crude of all grades was 4,800 tons, and that of other grades of fibre, 306,404 tons. Thus crude formed only about 1½ per cent of the total. From this it may be seen that of the actual number of veins, more than 99 per cent must be less than three-eighths of an inch wide.

MINES AND MINING COMPANIES

Five companies carried on active mining operations during 1935. These were: the Canadian Johns-Manville Company, whose property is situated at Asbestos, Quebec; Asbestos Corporation, which in 1935 operated the King and Beaver mines at Thetford Mines, and the Vimy Ridge mine southwest of Black Lake; Bell Asbestos Mines, operating the Bell pit at Thetford Mines; Johnson's Company, whose main pit is at Thetford Mines, with a second pit and mill at Black Lake; and Quebec Asbestos Corporation, drawing rock at present from lot 13, range IX, Broughton tp. The product of the Quebec Asbestos Corporation is mainly slip fibre, that of the others mainly cross fibre. Nicolet Asbestos Mines, with property in lots 20 and 21, range VI, Tingwick tp., began operations early in 1930, and continued, with some interruption, for two years, since when the mine has been closed.

A large number of pits have been worked in the past, and with improved demand for asbestos many will doubtless be re-opened. Most of them are now the property of Asbestos Corporation. They include the British-Canadian Quarries, at Black Lake; the Maple Leaf mine, on lots 28 and 29, range VIII, Coleraine tp.; the Black Lake Consolidated property at Black Lake, which includes what were formerly known as the Union Asbestos pits, the Southwark pits, the Imperial pits, and the Black Lake Asbestos and Chrome quarries; the Bennett-Martin pit at Thetford Mines; and the Pennington, Federal, Kitchener, Fraser, and Boston Asbestos pits, all of which lie on the Pennington dyke northeast of Thetford Mines.

The fibre from the King, Johnson, Bell, and Beaver pits at Thetford Mines, and from the Canadian Johns-Manville pit at Asbestos, is pale green in the lump, and pure white when fibreized. It is very soft and flexible, producing a very high-grade spinning fibre. The various Black

Lake pits yield a fibre of similar appearance, but somewhat harsher, and in general more suitable for shingle stock. The Vimy Ridge fibre is brown and very harsh, and is hence peculiarly adapted for use as shingle stock. The various pits on the Pennington dyke yield mainly slip fibre.

HISTORY

Although asbestos was first found in the Des Plantes River region, between the villages of St. Joseph and St. Francis, as early as 1862, it was not until 1877 that deposits large enough to work were discovered in the serpentine hills of Thetford and Coleraine. "Mining operations on a small scale commenced in 1878, and in this year 50 tons were produced; but it was difficult to find a market. The quality of the fibre mined was excellent, and the width of the veins everything that could be desired, being from ½ inch up to 2, 3, and sometimes 4 inches. . . Shipments of the better grades to London created quite a sensation in the British market; hence extensive tests and investigations were made, with the result that, on account of its exceptional spinning qualities high prices were soon established, and the race for the acquisition of additional areas likely to contain the valuable mineral began. . . The principal areas in which the asbestos-bearing serpentines were found to occur were lots 26, 27, and 28, near the line between ranges V and VI of Thetford township, and in Coleraine township near Black Lake station, four miles southwest of Thetford station, in previously unsurveyed areas adjoining range B on the southwest; also on lots 27 and 28, range B; and on lot 32, range C. . . During the next twelve years a rapid development of the asbestos industry was witnessed. The mines were operated on a large scale; while prospectors were busy exploring the hills of the surrounding country for new deposits of the mineral. . . In 1885 it was reported that seven quarries were in operation, which produced during the same season an aggregate of about 1,400 tons of asbestos. The prices obtained for the various grades were: first quality, $80 per ton at the mines; second quality, $60; third quality, $40; and a lower grade, suitable only for pulp, $10.

"Dating from 1885 a gradual increase in the prices took place, especially for the first and second qualities. In 1900, about $300 was realized for the first quality. This and other economic features in connexion with the industry served to give a powerful impetus to the development of the existing asbestos resources: additional mines were opened; the demand for the mineral continued brisk for a time; and properties were sold at a high figure.

"But this state of affairs did not continue long; prices began to drop gradually, the demand slackened, and it was discovered that the prevailing methods of hand extraction were faulty, inadequate, and expensive, especially with regard to the lower grades. As a matter of fact, under prevailing price conditions, only those quarries which were working on rich ground, and had a large percentage of crude asbestos, had a chance to carry on operations at a profit. The natural outcome of these adverse conditions was obvious; many quarries producing only a very small percentage of the higher grades were forced to shut down and this, together with serious difficulties accentuated by overproduction and a consequent fall in prices, caused the industry to receive a severe set-back in the middle of the nineties " (106, pages 5, 6).

The result of the depression of the " nineties " was the rapid adoption of mechanical methods of treating the asbestos-bearing rock, with consequent economies of production. Experiments along these lines had begun as early as 1888, but had not been particularly successful in making a good separation of the fibre from rock particles and dust. About 1895, however, methods were sufficiently perfected to justify the adoption of machinery, and this accordingly was done throughout the camp. Since that time continual experiment has resulted in continuous improvement of the methods of extraction.

Briefly, milling is carried on as follows. The rock from the pits, which always contains some moisture, is first broken down by a jaw crusher, and then passed through dryers, which remove the bulk of the moisture. It is then passed successively through a series of crushers and beaters, perhaps eight or ten. As it leaves one of these, before entering the next it is passed over screens, through which the powdered rock, or sand, drops, and the fibre freed by the beating is lifted from the screen by overhead suction. The next crusher further pulverizes the material, and on passing to the next screen the sand and free fibre are again removed as before. The fibre obtained during the various operations is collected, graded by passing through another series of screens, bagged, and stored for marketing.

During the Great War there was an abnormal demand for asbestos, with consequent high prices, following which demand dropped greatly, and the industry passed through some lean years. The Canadian situation was further complicated by the entry into the market of large quantities of asbestos from Rhodesia in 1920, and from Russia and the Union of South Africa in 1925. In an attempt to better the situation, in 1926 twelve companies were combined, by merger or purchase, to form the Asbestos Corporation. Canadian production reached a high point of 306,000 tons in 1929, and then, in the stress of depression, fell to the lowest point since 1921. Depression, however, had its usual effect in forcing new economies of operation, of which probably the most interesting and important is the adoption, at the King mine, of the block-caving system of mining (107). By this system blocks of rock 160 feet square are completely undercut at the 500-foot level, permitting the whole block to sink bodily downward as rock is drawn off from beneath. The weight of the block as it drops crushes the rock, so that there are large savings in drilling and powder costs; and at the same time it is unnecessary to remove the drift at the top of the block, thus effecting other large savings. It seems probable that when other companies reach the depth limit of profitable open-pit mining this method will have to be generally adopted.

SLIP-FIBRE DEPOSITS

The principal slip-fibre deposits are those on the Pennington dyke. Fairly large bodies of this type have been mined at the Pennington, Federal, Kitchener, Fraser, Quebec Asbestos, and Boston Asbestos mines. As might be expected the deposits are sheet-like, with a steep dip to the south. In some places they occupy the full width of the dyke, as at the Pennington and Federal mines; in others the dyke is so wide that only a part of it is sheared, and then only the sheared part is mined, as at the Fraser mine and the present workings of the Quebec Asbestos Corporation. The fibreized zone varies in width from about 150 to 350 feet.

Operations on this type of deposit have not been particularly profitable, the writer understands, and the Quebec Asbestos Corporation property was the only one operated between 1930 and 1935. The steep dip, also, renders it impossible to carry open-pit methods to any depth. Consequently most of the operations ceased on attaining depths between 100 and 150 feet.

In the other mines of the region there are many zones of shear, and no doubt the milling of these yields a certain amount of slip fibre. No attempt is made, however, to segregate such areas in milling, and consequently it is impossible to determine how much slip fibre is actually produced. The proportion, however, must be quite small.

In slip fibre, as the name implies, the fibres lie flat along slip planes in the serpentine. Owing to their manner of occurrence the fibres may appear to have considerable length, but this is due to the matting together of overlapping fibres. In situ the fibre appears light green or white, but in milling it acquires a grey tint, which the binocular microscope shows to be due to admixture of much dusty magnetite. According to Ross (106, page 27) the product must be very harshly milled to free it from the rock, which renders it less desirable for certain uses.

It is not possible to secure pure slip fibre for chemical analysis, as it cannot be separated from other fibrous varieties of serpentine in the attempt to pick it out of the hand specimen. It is necessary, therefore, to use milled fibre, which contains more or less rock dust as well as the magnetite dust already mentioned. These impurities render it impossible to draw any conclusions concerning the true composition of the fibre itself. As the analyses, however, may have some value, two are herewith appended:

TABLE II

Analyses of Commercial Slip Fibre

—	5	6	—	5	6
SiO_2	34·67	38·45	MgO	43·03	41·18
Al_2O_3	0·39	0·14	H_2O+	11·78	11·86
Fe_2O_3	5·26	3·15	H_2O-	0·49	....
FeO	1·83	0·86	CO_2	2·26	4·45
CaO	0·09	....			
			Total	99·80	100·09

5. Commercial milled slip fibre, lot 13, range IX, Broughton tp. Analyst, R. J. C. Fabry, Geological Survey, Dept. of Mines and Resources, Ottawa.
6. Milled fibre, Quebec Asbestos Corporation, East Broughton, Que. Analyst, E. A. Thompson, Bureau of Mines, Dept. of Mines and Resources, Ottawa. From report by J. G. Ross (106, page 20).

If these analyses are recast, according to the known mineral composition, they yield the following results:

TABLE III

Analyses of Commercial Slip Fibre, Recast into Minerals

—	5	6	—	5	6
Magnetite	7·10	2·76	Talc	....	15·85
Hydromagnesite	6·24	12·25	Periclase	5·50	2·20
Chlorite	3·54	5·54	Brucite	0·12	....
Serpentine	77·50	61·40	Total	100·00	100·00

The wide variations in the composition of the material, thus shown, evidence its impurity. The most interesting point about the analyses, perhaps, is the amount of carbonate present, because carbonate, for practical purposes, is entirely absent from the vein deposits. Its presence may well be due to seepage of surface water carrying carbon dioxide through the permeable schist.

DESCRIPTION OF VEINS

A vein of cross fibre, in its simplest form, is a rather thin plate or sheet, which ends by narrowing gradually or rapidly to a point. It may have any dip, from vertical to horizontal, and any strike, although certain regularities exist, which will afterwards be described. As statistics of production show (page 87), more than 99 per cent of all veins are less than three-eighths of an inch wide, and it is rare to find a vein wider than 1½ inches. The length may vary from a fraction of an inch to several tens of feet, but as a rule individual veins do not go far without branching or meeting other veins so as to form a network. The total space occupied by the veins in the deposits may be estimated from the mill returns, which show that in the twenty years from 1910 to 1929 the fibre recovery was 5·68 per cent of the rock mined (106, page 60), and 7·01 per cent of the rock milled. Local portions of the rock contain much higher percentages of fibre. A rich block of ground on the boundary between the Bell and Johnson pits carries, the writer estimates, approximately 20 per cent of fibre; and measurements of the big ribbon veins of Vimy ridge show that the contained asbestos, in some cases, is as much as 45 per cent of the whole ribbon.

The edges of the veins are notably linear, and straight or gently curving. Certain writers who support a replacement origin for the veins have emphasized the irregularity of the edges, but the irregularity is minute, of the order of one-fortieth of an inch. In general, a straight edge can be laid along the veins and little divergence noted. Considering the dimensions of the veins, the straightness and regularity of the walls are outstanding features.

The material of the veins is a closely packed mass of parallel fibres oriented at a large angle to the walls. Text books have commonly taught that the fibres lie at right angles to the walls, but, in Thetford district at least, this is true only for veins that lie in nearly vertical or nearly horizontal positions. In other veins the fibres form an angle with the walls, which may be as small as 45 degrees. The position of the fibres is not a random one, however, but bears a constant relation to the dip of the vein. If a line is drawn at right angles to the plane of the vein, the direction of the fibres will be intermediate between it and a vertical line (Figure 5). This fact has a significant bearing on the origin of the veins.

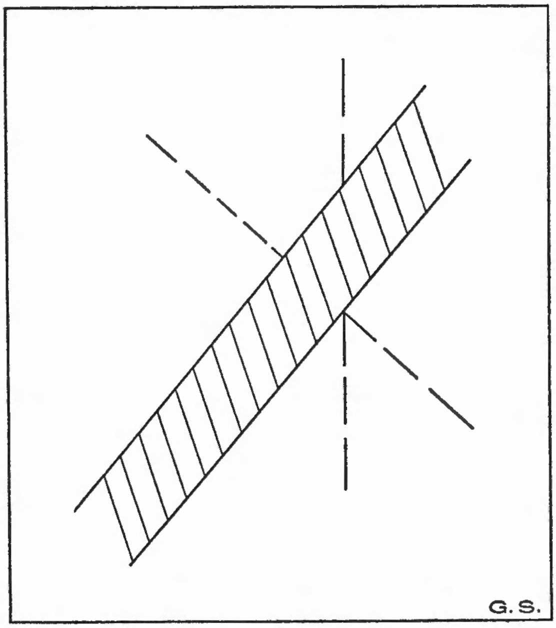

Figure 5. Direction followed by fibres in veins of asbestos.

The asbestos veins are of two distinct types, and these two types occur everywhere throughout the deposits in close proximity. Although this fact has been noted by other observers, it has not been emphasized, and its importance has apparently not been recognized. The two types may be termed 1-fibre veins, in which a single set of fibres runs from wall to wall unbroken except by occasional inclusions; and 2-fibre veins, in which the fibres from one wall extend only part way across, and are met at a central fissure or break by a second set of fibres attached to the opposite wall. At the junction the ends of the two sets of fibres may be pressed closely together, without cohering, or they may be separated by chips of serpentine or by magnetite. The great majority of all veins are of the 1-fibre type, but the 2-fibre veins are usually the larger, and hence have been those most generally described. The recognition of the two types is of the utmost importance for a correct understanding of the origin of the veins.

The veins may also be subdivided into simple veins and ribbon veins. The latter are mainly found in the Vimy Ridge mine, though they also occur here and there in other mines. Ribbon veins (*See* Plate I) are so called because a band or " ribbon " of rock from 2 inches to 3 feet wide has been sliced along closely spaced, sub-parallel lines, and the fractures filled with asbestos. The individual veinlets of asbestos vary in width up to an inch, but commonly average one-eighth to one-quarter inch; and they are separated by plates of serpentine of roughly the same widths. There is no relation, however, between the width of a serpentine plate and that of the vein of asbestos next it. The veinlets of asbestos are not parallel to the ribbon, but lie at a small angle to it. The fibre of the ribbon veinlets invariably runs across the veinlet without any break. It differs from the fibre of the simple veins in that the latter always separates readily from both walls, whereas that of the ribbon veinlets separates readily from one wall, but sticks rather tightly to the other. The wall to which it sticks is always that nearest the centre of the ribbon.

All the fibre of a ribbon vein was clearly developed at the same time. Wherever one veinlet runs into another, or a veinlet crosses the plate of serpentine between two other veinlets, the fibre of one never cuts or crosses the other, but the continuation is as shown in Figure 11A. It must, therefore, be concluded that the whole ribbon vein corresponds to one of the simple veins, and hence that the ribbon structure must be due to some peculiarity of fracturing prior to the introduction of asbestos. This may be related to some peculiarity in the rock itself, which causes it to fracture as it does, or, less probably, to some unusual type of stress.

The walls of a ribbon vein are broad bands of completely serpentinized rock, making the ribbon, considered as a whole, a large-scale replica of the individual vein elsewhere.

The central fissure of the 2-fibre veins follows a highly irregular course. Figure 6 is a drawing, made as carefully as possible, of the central fissure in a specimen. Irregularities such as those shown in the figure are by no means abnormal, but may be seen in the majority of specimens examined.

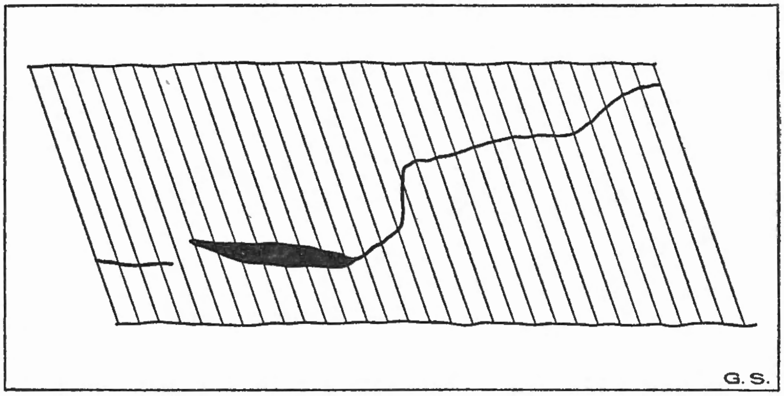

Figure 6. A 2-fibre specimen, two-thirds natural size, to show irregularity of central fissure; solid black area is a large chip of serpentine from wall.

The central fissure may contain nothing, or two types of material may be present, namely, chips of serpentine like the walls, and magnetite. In a few rare instances a pale green, translucent serpentine is present, which looks like serpentine deposited from solution. The magnetite has clearly been formed after the asbestos, though it is not thought that any great interval of time separated them. Veinlets of magnetite were observed in many places to follow one wall of a vein for some distance, then cut across the vein at a small angle to the other wall, which in turn was followed for some distance. Under the microscope the magnetite may be seen replacing the asbestos fibres, and penetrating them in highly irregular fashion, both across and lengthwise. The propensity displayed by the magnetite for occurring in the central fissure, as a rule, is considered due to two causes. The central fissure undoubtedly afforded a channel more easy of penetration than elsewhere by the magnetite-bearing agencies; and numerous observations suggest, though they do not prove, that the serpentine chips in the central fissure were a little more readily replaced than the asbestos itself.

At Thetford Mines the magnetite is largely confined to the central fissures and to the individual veinlets mentioned, and a relatively small proportion has penetrated the fibre to form long or short hairs of magnetite in it. Where these do occur, they are generally in the part close to the outer edges of the vein, or close to the central fissure. This limitation of occurrence suggests replacement working in from the ends of the fibres. The asbestos at Black Lake contains much more magnetite, not only in the central fissures, but as fibres and bundles of fibres running the whole width of the vein. The Vimy Ridge asbestos contains still more magnetite, so much that it took a long time to pick out sufficient uncontaminated material for analysis. All of the magnetite is in thin fibres or bundles of fibres paralleling the asbestos, and this relation seems to suggest intercrystallization. However, study under the binocular microscope shows that the asbestos close to a bundle of magnetite fibres is yellowish and rotted, instead of having the brown colour and silky lustre of good fibre; and when the fibre is pulled apart with tweezers to separate it from the magnetite, this yellowish, rotted material proves brittle and falls readily to powder, whereas the good fibre is tough and strong. These relations indicate that the magnetite is later than the asbestos, and that its introduction effected a change in the fibre that renders it brittle.

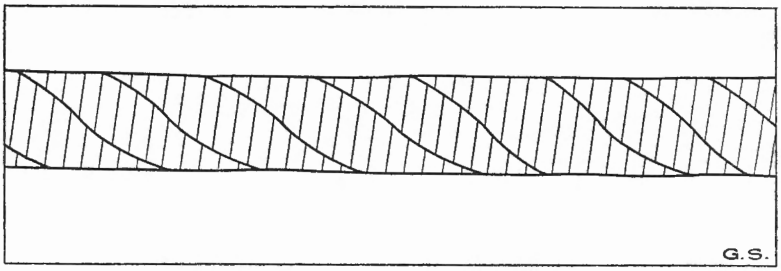

Figure 7. Lens structure, common in veins within picrolite bands; the asbestos lenses are separated by picrolite fibres.

Where veins have developed in shear zones in which some fibrous picrolite was formed during the shearing, it is not uncommon to find a structure like that illustrated in Figure 7. The lenses of fibre are separated by thin fibres of picrolite, about as thick as a piece of grocer's string; the fibres of asbestos may be variously oriented, from nearly perpendicular to the main walls, to nearly perpendicular to the picrolite fibres. Throughout any one vein, however, the fibres are parallel.

Where asbestos veins of the 2-fibre type are developed along one side of a shear zone containing much picrolite, so that one wall is picrolite, the other peridotite, it is usual to find the plate of fibre attached to the picrolite side very narrow in comparison with the plate attached to the peridotite side (Figure 8).

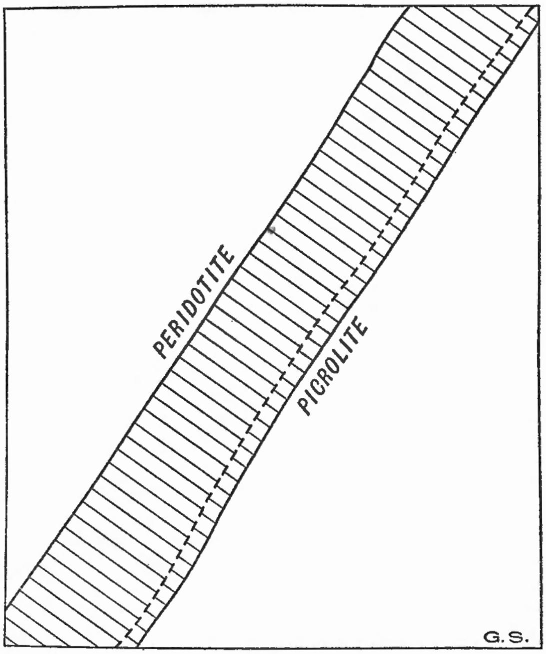

Figure 8. Asbestos 2-fibre vein lying between serpentinized peridotite and picrolite, along the edge of a fault. The thickness of the asbestos plate on the picrolite side is much less than on the other side.

Another structure common in veins is a change in the direction of the fibres, illustrated in Figure 9. In some cases there are several such bends, and the unequal reflection of light from the changes in direction of the fibres gives the material a banded appearance, like watered silk. The number of such bands is always an odd number. There is no break in the fibre at the bends, but individual fibres pass around the bends with perfect continuity and no apparent loss of strength. The bending is not caused by deformation of a pre-formed asbestos vein. There has been very little movement in the deposits since the veins were formed, and in the few cases observed the fibre was irregularly crushed down by the pressure, and bent sidewise by lateral movement, exactly as when a brush is pressed hard against a wall and pulled along it. The result is entirely different from the regular, even banding of the veins under consideration, in which a series of bands, in some cases not more than one-tenth of an inch wide, run along in perfect parallelism, with no indication of deformation whatever. It is quite clear that the banding is a peculiarity of growth.

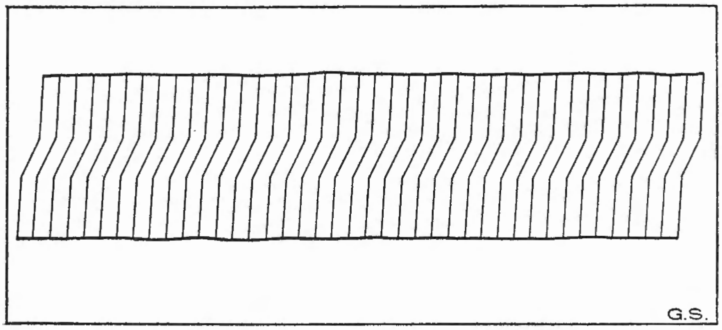

Figure 9. Change in course of fibre seen in many asbestos veins.

Where fissures containing asbestos meet and cross, it happens in very rare cases that the fibres of one vein cut those of the other (Figure 10). A few such cases have been observed in Thetford region. More commonly, almost invariably, in fact, the fibre follows around the corner of the wall at the junction, and mingles smoothly with the fibre of the other vein

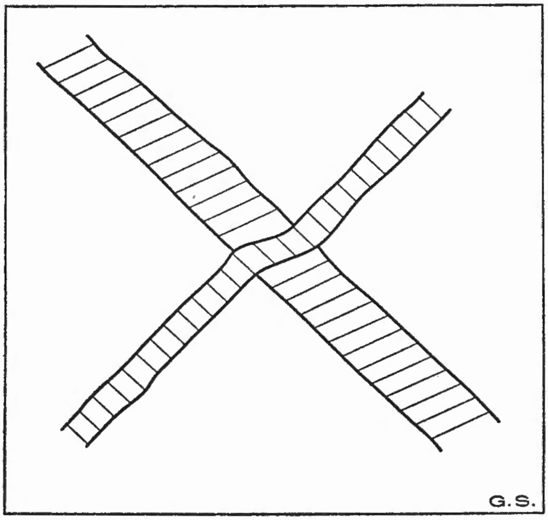

Figure 10. In rare instances one asbestos vein cuts directly across another.

(Figures 11A and B). Fibre grows around obtuse angles quite smoothly and easily; at right angles the growth is apt to be sparse, and the junction to be filled with a mass of serpentine chips, short fibres, and magnetite; and growth does not seem to follow around acute angles at all. Where the fibre of one vein thus swings around into the fibre of another, the two sets of fibres may be separated by a central fissure or break, which may run along for some distance or may shortly end; or, in other cases, no such break occurs (Figure 11). Such a break, when present, is commonly the locus of considerable magnetite.

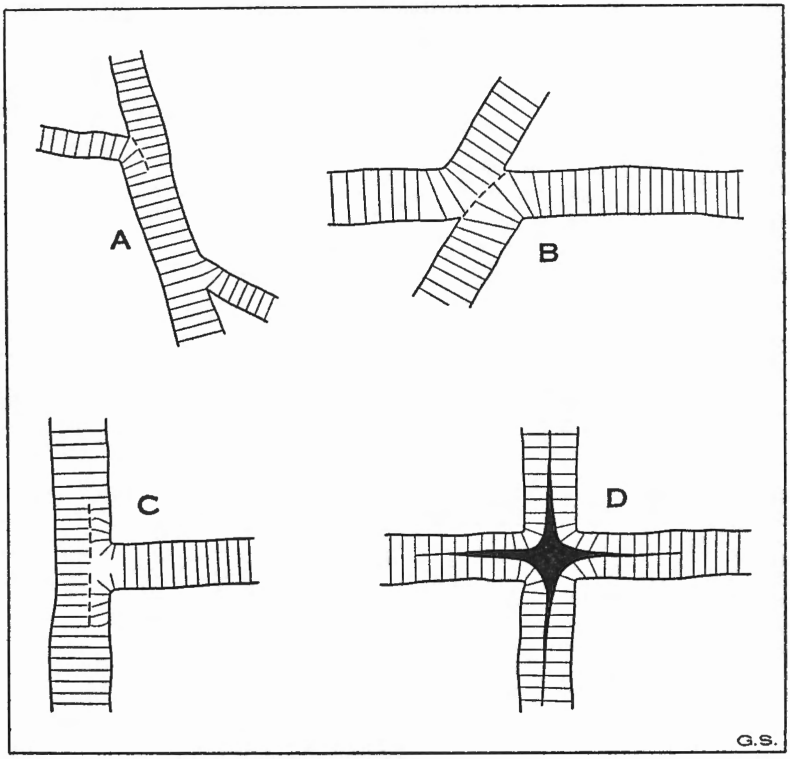

Figure 11. Usual types of vein junction.

The walls of veins, as already stated, are usually straight or smoothly curving. In rare instances, however, veins occupy irregular fissures (Figure 12). In such cases the irregularities of one wall match those of the other quite perfectly, and matching points occur at opposite ends of the same fibres.

In both 1-fibre and 2-fibre veins, the fibre is broken in many places by inclusions of serpentine from the walls. This is perhaps somewhat more common in the 1-fibre veins, because in the 2-fibre type most of the inclusions are concentrated in the central fissure. Although most of the inclusions are thin chips whose shape makes it impossible to determine their point of origin, many nevertheless can be found with characteristic shapes that can be matched on the walls whence they were torn (Figure 13). A large number of these were sought and studied, particularly in the 1-fibre veins, and it was found that approximately as many inclusions, in any vein, had been torn from one wall as from the other, regardless of the attitude of the veins. In most cases, though not invariably, recognizable points on the inclusions and corresponding points on the walls lie at opposite ends of the same fibres.

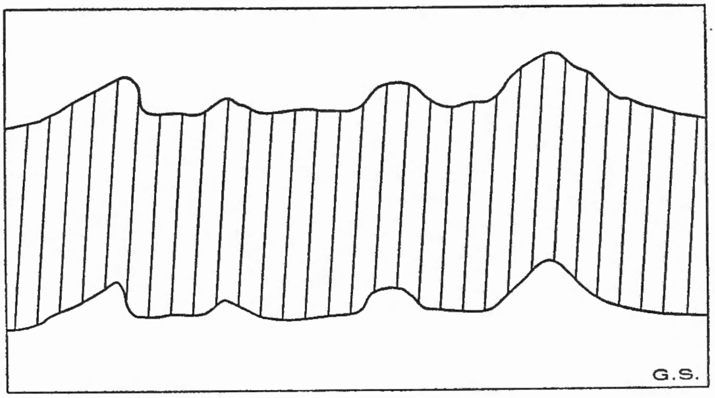

Figure 12. Asbestos vein filling irregular fissure, to illustrate matching of walls and occurrence of matching points at opposite ends of same fibres.

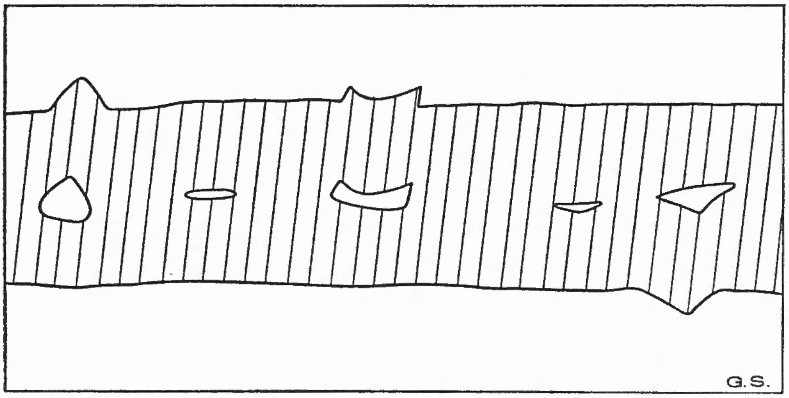

Figure 13. Diagram to illustrate manner in which some inclusions match irregularities of walls.

An important feature of many veins of the 1-fibre type is their occurrence in fissures *unconnected with any other fissures.* Great numbers of little veins are developed in bastite crystals, and end at the crystal boundaries. Such veins may be perhaps one-eighth of an inch long, and up to one-fortieth of an inch thick. From this upward, all sizes of lenses occur, up to several feet in length and normal widths. In them, characteristically, the asbestos ends in a sharp or blunt point, and the fissure in which it is found can rarely be traced beyond the end of the asbestos. The small size of great numbers of these veins, and the manner in which so many are confined to bastite crystals, makes it certain that the majority cannot be connected with cross fractures, as such fractures would be visible on some of the exposed faces, which is not the case. Lenses of asbestos thus entirely surrounded by massive rock have been termed by the writer *closed veins;* and the recognition of their occurrence is of great importance in considering theories of ore genesis.

COMPOSITION OF ASBESTOS

During the winter of 1934-5 the writer had analyses made of various types of asbestos and other fibres from the Thetford-Black Lake district of Quebec. One object of the investigation was to determine whether differences in composition were sufficient to account for the fact that some fibres are soft and others harsh. A second was to learn what differences exist between the asbestos fibres and the presumably related fibrous materials occurring in fault planes. Keep[1] has stated that in Southern Rhodesia brittleness of fibre is due to partial talcification, and it seemed desirable to know whether brittleness in certain of the Canadian chrysotiles is due to the same cause.

Various attempts have been made in the past to determine whether harshness in the Canadian fibres is a matter of chemical composition. Unfortunately, it has been the common practice to select for analysis lumps of fibre from suitable veins, without any painstaking attempt to separate impurities that may be present. In other words most of the analyses have illustrated the composition of commercial fibre, rather than of pure asbestos. As a result, no sound conclusion has been reached as to the causes of harshness or softness, because it was impossible to be certain whether variations in the analyses were due to presence of impurities or to variations in the composition of the asbestos itself.

To overcome this difficulty, the materials supplied for the following analyses were prepared with the utmost care. In the case of the asbestos analysed, specimens of the best long fibre available were first secured. These were then split into thin sheets with a knife, and the ends, to which more or less massive serpentine invariably adheres, were cut off with scissors. If the vein material had a central fissure, where there might be contamination with massive serpentine and magnetite, the sheets of fibre were broken along the fissure, and the central part also cut away with scissors.[2] The result of these preliminary operations was to yield a number of thin sheets of fibre averaging perhaps $\frac{1}{4}$ inch square. These were then placed in turn on a sheet of white paper in a strong light on the stage of a binocular microscope, and any large masses of magnetite or other impurity at once removed and discarded. The remaining fibre was then gradually crushed down, the fibres separated from one another with a fine-pointed tweezers, and all impurities discarded as they appeared. The sheet was then turned over, and the process gone over again. This painstaking examination was repeated until the writer was satisfied that not

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[1] Keep, F. E.: Geology of the Shabani Mineral Belt, Belingwe District; Geol. Surv. So. Rhodesia, Bull. 12 (1929).

[2] The use of scissors is itself a possible source of slight contamination of the material. In certain cases the cut ends of the fibre appeared to have a blackish stain, as if some of the iron of the scissors had been rubbed off on them during cutting. As the writer had no other means of cutting the fibres, however, and the possible contamination seemed very small, it was disregarded.

even the minutest grain of magnetite or other visible impurity remained. The final step was to view the purified material by strong transmitted light, as a check on the effectiveness of the earlier operations.

The progress of collecting material in this way was necessarily slow. In no case was a quantity sufficient for analysis obtained in less than two days, and with some fibres, such as those of Vimy ridge and Black Lake, where the amount of magnetite present is large, more than a week was required. The writer is confident, therefore, that the materials thus obtained are pure asbestos fibres, so far as human care can secure them; and that the analyses below display true differences in composition of the fibres. The only possible contaminator of the materials is brucite. This substance appears, particularly in the fibre from the Beaver mine, in exceedingly thin flakes between the fibres. The relative amount, in any case, is small, and the bulk of it was separated during the crushing; but a small amount undoubtedly still remained in the samples.

In making the analyses, it was decided not to determine the alkalis, partly because of the exceedingly small amounts present, and partly because of probable contamination due to the large amount of handling required in preparation. Particular care was given to the determinations of ferric and ferrous iron and of water. The analyses were made by Mr. R. J. C. Fabry, chemist, Geological Survey, Department of Mines and Resources.

The first group of analyses, all of asbestos fibres, includes the following:

3. From King mine, Thetford Mines, Quebec. The King, Bell, and Johnson pits at Thetford Mines are all developed on a single deposit of very high-grade fibre. The specimen is a representative sample from this group of pits.

7. From the Beaver mine, Thetford Mines, Quebec. This is likewise a very high-grade fibre, said to be even softer than that obtained from the King-Johnson-Bell group of pits.

8. From Deloro township, Porcupine district, Ontario. This fibre, analysis of which was made for comparative purposes, is said to have been some of the highest grade chrysotile ever mined in Canada. The deposit, unfortunately, was too small for profitable operation. The sample analysed is pale yellow, indicating presumably some oxidation of the contained iron. Descriptions of the deposit state that the fibre is green at depth.

9. From the British-Canadian pits, Black Lake, Quebec. This fibre, though pale green like the Thetford fibre, is somewhat harsher in texture.

10. From Vimy Ridge mine, 3 miles southwest of Black Lake, Quebec. This is a brown, very harsh fibre, used exclusively for shingle stock and the like.

4. From the Johnson mine, Thetford Mines, Quebec. Within the zone of dark serpentine that surrounds an acid dyke, asbestos veins are apt to be dark brown instead of green, and the fibres, instead of being soft and flexible, are harsh and brittle, so much so that in some cases they "tinkle" on being shaken together. This specimen is from an unusually large vein of this type. Its fibres are harsh, but not so brittle as some others of the type.

TABLE IV

Analyses of Pure Asbestos Fibres

—	3	7	8	9	10	4
SiO_2	42·05	41·13	42·40	41·80	42·95	43·48
Al_2O_3	Nil	0·80	0·14	0·64	Nil	1·41
Fe_2O_3	0·96	1·01	0·97	0·80	2·08	0·60
FeO	0·39	0·58	0·19	1·89	0·84	2·36
CaO	0·05	0·03	0·14	0·14	0·19	0·12
MgO	43·30	43·24	43·09	42·18	41·60	39·50
H_2O+	12·52	12·74	12·60	12·07	10·26	12·69
H_2O-	0·75	0·45	0·45	0·20	1·61	0·45
Totals	100·02	99·98	99·98	99·72	99·53	100·61

3. Chrysotile asbestos, King mine. High grade.
7. Chrysotile asbestos, Beaver mine. High grade.
8. Chrysotile asbestos, Deloro township, Ont. High grade.
9. Chrysotile asbestos, British-Canadian mines, Black Lake. Harsher fibre.
10. Chrysotile asbestos, Vimy Ridge mine, Coleraine tp. Very harsh.
4. Altered chrysotile asbestos, Johnson mine. Very harsh.

Eliminating the uncombined water from these analyses, and recalculating to 100 per cent, they become:

TABLE V

Analyses of Pure Asbestos Fibres, Recalculated to 100 Per Cent

—	3	7	8	9	10	4
SiO_2	42·36	41·32	42·59	42·00	43·87	43·41
Al_2O_3	Nil	0·80	0·14	0·64	Nil	1·41
Fe_2O_3	0·96	1·01	0·97	0·80	2·12	0·60
FeO	0·39	0·58	0·19	1·89	0·85	2·35
CaO	0·05	0·03	0·14	0·14	0·19	0·12
MgO	43·64	43·47	43·32	42·41	42·50	39·44
H_2O+	12·60	12·79	12·65	12·12	10·47	12·67
Totals	100·00	100·00	100·00	100·00	100·00	100·00

It is interesting to note how closely the analyses of the three high-grade fibres check with one another, although obtained from very different localities. Inspection of the two analyses of natural harsh fibres, 9 and 10, shows that each has a higher $\frac{\text{Silica}}{\text{Magnesia}}$ ratio, and a lower proportion of combined water, than the soft fibres; and that the harsher of the two, No. 10, has both these features more accentuated than No. 9. In both of these, also, the total iron (Fe) content is much larger than in the soft fibres, though only slightly greater (2·14:2·03) in No. 10 than in No. 9.

The harsh fibre No. 4, which may be considered as a fibre originally like No. 3 altered as described on pages 82, 83, exhibits the same relations, except that the water content was not reduced by the alteration. The silica-magnesia ratio has been greatly altered, so that silica is now very high relative to magnesia, and the iron content has been notably raised. The alumina content also has been raised considerably, though what effect this may have had on the quality of the fibre is unknown.

Further light may be thrown on the problem by recasting the chemical analyses into mineral form. This procedure has the effect of emphasizing small differences in composition, and thus brings to view facts that might otherwise escape notice. The method of recasting to be followed required careful consideration. It was obvious that, in view of the careful preparation of the material, the introduction of such substances as magnetite and limonite into the recast analyses would not paint a true picture. From the close mineralogical relationship of serpentine, chlorite, and talc, however, it seemed reasonable to assume that these three molecules might be present together, in varying proportions, in the asbestos fibre, and, accordingly, it was decided to calculate the composition on this basis. For this purpose, both alumina and ferric iron were calculated as chlorite of composition $4H_2O.5MgO.R_2O_3.SiO_2$ where R is Fe''' or Al; serpentine is calculated as $2H_2O.3MgO.2SiO_2$, and the FeO and CaO radicals are introduced into the serpentine, replacing equivalent amounts of MgO. Excess of silica or deficiency of water is considered as indicating the presence of more or less of the talc molecule. Excess magnesia is calculated as brucite, if enough water is present, and as periclase if it is not. The analyses used for recasting are those of Table IV, not Table V, and after recasting they were recalculated to 100 per cent. This procedure gives somewhat different results from those obtained if the analyses are recalculated to 100 per cent before recasting, presumably because the analyses are given to two decimal places only, and consequently the relative proportions, where two constituents are large and the rest small, are altered by recalculation. In the recast analyses, the total percentages of chlorite and serpentine, as above determined, are succeeded, in brackets, by the percentages of iron-chlorite and iron-serpentine, so called because Fe_2O_3 and FeO replace Al_2O_3 and MgO respectively.

TABLE VI

Analyses of Pure Asbestos Fibres, Recast into Minerals

—	3	7	8	9	10	4
Chlorite	3·70	8·22	4·47	6·57	8·16	9·90
(Iron-chlor.)	(3·70)	(3·88)	(3·70)	(3·07)	(8·16)	(2·26)
Serpentine	93·01	89·47	92·43	85·84	65·95	83·76
(Iron-serp.)	(0·67)	(1·00)	(0·27)	(3·26)	(1·47)	(4·05)
Talc	1·44	....	1·79	4·75	20·42	....
Brucite	....	0·47	....	....	....	2·02
Periclase	1·85	1·84	1·31	2·84	5·47	....
Silica	....	....	....	....	....	4·32
Totals	100·00	100·00	100·00	100·00	100·00	100·00

Table VI brings out a number of interesting points:

(1) The softest fibre, that from the Beaver mine, No. 7, contains none of the talc molecule whatever, but has a little brucite.

(2) The three high-grade fibres are all closely alike in the chlorite+serpentine percentage. Evidently the presence of chlorite up to 8 per cent does not cause brittleness.

(3) In what may be termed the naturally harsh fibres, Nos. 9 and 10, the chlorite+serpentine proportion falls off with increasing harshness, while the talc and periclase proportions rise.

(4) It is particularly interesting to contrast the naturally harsh fibres with No. 4, in which harshness has apparently been caused by alteration of an earlier vein of soft fibre like No. 3. Although in No. 4 the chlorite+serpentine proportion is closely the same as in the soft fibres, chlorite has increased largely at the expense of the serpentine, due to additions of alumina. No talc is present, but silica has been introduced to an amount in excess of the requirements for serpentine and chlorite.

The conclusions to be drawn from the figures depend largely on the weight given to No. 4. This analysis makes it clear that harshness may be due to high silica content, even though other constituents are present in the same proportions as in high-grade fibres.

Considering the other fibres without respect to No. 4, however, it is seen that they become progressively harsher with increase of the talc and periclase molecules, whereas the chlorite molecule merely varies irregularly within small limits. We are led to conclude, therefore, with Keep, that the principal cause of harshness is increase of the talc molecule.

It may also be noted that the sum of the iron-chlorite and iron-serpentine percentages is constant around 5 per cent in the better fibres, but rises to 6·33 per cent in No. 9, 9·63 per cent in No. 10, and 6·31 per cent in No. 4. This increase may also be a concomitant cause of harshness.

SERPENTINIZED WALLS OF VEINS

The walls of the asbestos veins invariably consist of serpentine, which at the edges farthest from the vein passes by a rapid gradation into the ordinary partly serpentinized peridotite. The serpentine is usually a mass of bladed antigorite crystals without uniform orientation; and in places, particularly at Thetford Mines, considerable brucite is likewise developed. Toward the outside of the serpentine zones the blades of antigorite are long, and appear to replace the mesh-antigorite of the partly serpentinized peridotite; but nearer the vein the blades become shorter and the grain finer, until the material becomes minutely granular and nearly isotropic. The outermost quarter or third of the altered zone consists of material not wholly altered to serpentine. The outer edges of the serpentine zones, except in rare instances, are linear and almost as regular as the edges of the veins themselves. These edges are sufficiently sharp to be lines of physical weakness, so that the rock splits rather readily along them.

The width of the serpentine zones has long been recognized as a characteristic feature. More than twenty years ago J. A. Dresser made a series of forty-nine measurements, mainly on the Black Lake veins, which showed that the combined width of the altered zones, together with that of the vein between them, averages 6·6 times the width of the vein alone. Casual observation shows, however, that the relationships can not be as simple as above stated, because many narrow veins have altered zones of far greater relative widths. It seemed worth while, therefore, to extend Dresser's observations further, and determine more precisely the relations existing.

To make these observations, however, proved a matter of some difficulty. Although individual measurements are easy to obtain, it was the writer's aim to obtain, if possible, sets of measurements on single veins, to determine the desired ratios for varying widths of asbestos. Undesired disturbances, however, are introduced by the numerous forkings and other junctions of veins; veins run beneath drift or other debris, or extend to unattainable places on the walls of the pits. In some pits only two or three really good sets of measurements could be secured. Still further, two or three years of weathering are required to make the altered zones stand out clearly, so that in the active pits, where the walls are most accessible, very few observations can be got. With these obstacles, it was found possible to obtain only 312 measurements, a considerably smaller number than hoped for.

Widths were measured precisely with a sharp-pointed pair of dividers, which were then applied to a scale graduated in fiftieths of an inch. Where veins contained a notable proportion of magnetite and other material at the centre, the width of this also was taken, to determine the net width of fibre. In measuring the ribbon veins of Vimy Ridge lines were ruled across the veins at right angles, and the width of the lowest veinlet taken with the dividers. The dividers were then lifted, without moving the points, and the forward point was placed on the lower edge of the next veinlet. The other point was then set firmly down, and the forward point moved to the upper edge of the veinlet. The distance between the points was then the sum of the widths of the first two veinlets. By repeating this process until all the veinlets were accounted for, a very accurate measure of the total width of fibre in the ribbon vein was obtained.

When a vein is traced to its end, it is noted that the altered zones do not narrow at the same rate as the vein, so that at the thin ends the altered zones are disproportionately wide. Here and there, particularly at Vimy Ridge, the altered zones extend for some distance past the end of the vein, as in measurement 132f of the following table. The table lists the widths of six veins, in each case from the greatest visible width to the least, together with the corresponding widths of the altered zones at each point of measurement. Nos. 132-5 illustrate the normal type of change as veins narrow. Nos. 136-7 are introduced to show that the change is not always perfectly regular, although the trend is always in the one direction. Numerous other sets of measurements were made, but the following suffice for purposes of illustration.

TABLE VII

Relation of Width of Altered uone to Varying Widths of Vein Materials

No.	Vein	Vein + altered zone	Ratio $\frac{\text{vein + altered zones}}{\text{vein}}$
	In.	In.	
132a	1·12	5·76	5·14
b	0·88	4·93	5·60
c	0·48	4·47	9·31
d	0·37	3·88	10·48
e	0·14	3·36	24·0
f	0·00	3·24	∞
133a	0·61	3·70	6·06
b	0·45	3·60	8·0
c	0·36	3·25	9·0
d	0·27	3·05	11·3
134a	0·89	5·57	6·26
b	0·84	6·33	7·53
c	0·62	5·64	9·10
135a	0·23	1·48	6·4
b	0·16	1·18	7·4
c	0·08	0·85	10·6
d	0·03	0·68	22·6
136a	0·34	2·00	6·0
b	0·26	1·73	6·6
c	0·20	1·28	6·4
d	0·15	1·10	7·3
137a	0·43	3·32	7·72
b	0·38	2·71	7·13
c	0·37	3·06	8·27
d	0·19	1·42	7·47
e	0·10	1·01	10·1
f	0·06	0·91	15·1
g	0·02	0·68	34·0

If only the wider parts of the veins are considered, it is found that throughout single pits or groups of pits the ratio $\frac{\text{vein+altered zones}}{\text{vein}}$ is fairly uniform, but that the ratio varies a good deal from one group of pits to another, as the following tables illustrate. In Tables VIII and IX, two measurements, marked respectively "To" (total) and "Fi" (fibre) are given in some cases, under vein width. In such cases the veins contained serpentine and magnetite at the centres in measurable amount. The ratios, in these cases, are always $\frac{\text{vein+altered zone}}{\text{“To”}}$. This was done because magnetite is a secondary mineral replacing asbestos and serpentine, and hence the magnetite has probably taken the place of some original fibre. In so far as the central material is serpentine, however, or magnetite that has replaced serpentine, the figure for total width is by that much too great, and the calculated ratio is too small. In all these cases it is probable that the true ratio lies between the figures $\frac{\text{vein+altered zone}}{\text{“To”}}$ and $\frac{\text{vein+altered zone}}{\text{“Fi”}}$.

TABLE VIII

Altred Zone—Vein Ratios, Beaver and Jacobs Pits

No.	Vein width	Vein + altered zone	Ratio
	Ins.	Ins.	
1	0·86	6·97	8·10
2	0·64	6·43	10·4
3	0·41	3·40	8·3
4	0·54	5·13	9·5
5	0·42	4·73	11·26
6	0·40	4·05	10·12
7	1·23	12·40	10·4
8	0·59	8·17	13·8
9	0·43	4·46	10·4
10	0·76	6·17	8·12
11	0·43	3·91	9·1
12	0·57	4·62	8·1
13	0·42	3·65	8·7
14	0·44	4·63	10·5
15	0·70	7·92	11·3
16	0·50	4·93	9·8
17	1·13 To 0·96 Fi	10·07	9·0
18	1·21 To 1·06 Fi	11·14	9·2
19	1·27 To 1·01 Fi	10·31	8·1
20	1·05 To 0·93 Fi	10·01	9·5
21	0·69 To 0·51 Fi	6·33	9·17
22	0.71 To 0·57 Fi	5·30	7·5
23	1·12 To 0·94 Fi	7·42	6·6
24	1·19 To 0·94 Fi	12·50	10·5
25	1·05 To 0·92 Fi	9·23	8·8
26	0·71 To 0·52 Fi	7·78	10·95
27	0·97 To 0·82 Fi	7·15	7·3
28	0·75 To 0·66 Fi	5·70	7·6
29	1·27 To 0·98 Fi	13·70	10·8
30	1·00 To 0·79 Fi	10·97	10·97
31	1·04 To 0·73 Fi	9·24	8·88
32	1·06 To 0·81 Fi	7·04	6·64

Average ratio, 32 determinations, 9·36.

TABLE IX

Altered Zone—Vein Ratios, Black Lake Pits

No.	Vein	Vein + altered zone	Ratio
	Ins.	Ins.	
33	1·25	5·80	4·64
34	0·99	6·93	7·00
35	0·83	5·82	7·00
36	0·73	4·59	6·3
37	0·64	4·36	6·8
38	0·43	3·67	8·53
39	0·52	5·22	10·04
40	0·91	5·97	6·56
41	0·57	4·21	7·38
42	0.89	5·57	6·26
43	0·84	6·33	7·53
44	0·62	5·64	9·10
45	0·80	5·41	6·75
46	0·66	5·24	8·0
47	0·48	3·06	6·37
48	0·58	4·13	7·12
49	0·58	4·48	7·72
50	0·63	3·82	6·06
51	0·93	6·16	6·62
52	0·55	4·84	8·80
53	0·53	4·65	8·77
54	1·36 To 0·96 Fi	6·98	5·13
55	1·57 To 1·14 Fi	6·58	4·20
56	0·88 To 0·57 Fi	5·51	6·26
57	0·67 To 0·33 Fi	3·21	4·80
58	0·53 To 0·27 Fi	4·09	7·5
59	0·74	5·11	7·0
60	0·83	5·48	6·60
61	1·64	10·02	6·1
62	1·74	9·40	5·40
63	2·33 To 1·00 Fi	9·07	3·96
64	0·47	4·18	8·9
65	1·58	6·59	4·17
66	0·88	4·93	5·60
67	1·12	5·76	5·14
68	0·48	4·47	9·31
69	1·13	6·21	5·50
70	0·84	4·62	5·50
71	0·75	5·21	7·0
73	0·43	2·57	6·0
74	0·55	2·91	5·3
75	0·53	2·85	5·37
76	0·97	8·40	8·66
77	0·86	5·50	6·4
78	0·55 To 0·49 Fi	2·96	5·4
79	0·68	3·21	4·72
80	0·93 To 0·65 Fi	3·30	3·54
81	0·44	1·82	4·14
82	0·83 To 0·70 Fi	3·65	4·4

TABLE IX

Altered Zone—Vein Ratios, Black Lake Pits—Concluded

No.	Vein	Vein+altered zone	Ratio
	Ins.	Ins.	
83	0·71 To 0·49 Fi	3·56	5·0
84	0·71 To 0·60 Fi	3·63	5·1
85	0·76 To 0·57 Fi	3·53	4·64
86	0·65	4·01	6·17
87	0·44	2·70	6·13
88	0·41	3·62	8·8
89	0·43	2·76	6·4
90	0·50	2·71	5·4

Average ratio, 58 determinations, 6·26.

TABLE X

Altered Zone—Vein Ratios, Vimy Ridge Pits

No.	Vein	Vein + altered zone	Ratio
	Ins.	Ins.	
91	0·45	3·60	8·0
92	0·61	3·70	6·06
93	0·46	2·85	6·2
94	0·46	2·60	5·65
95	0·42	2·90	7·0
96	1·25	6·05	4·84
97	1·20	5·63	4·70
98	0·96	4·80	5·0
99	0·88	4·75	5·4
100	0·95	4·63	4·87
101	0·85	4·30	5·06
102	1·10	4·80	4·36
103	1·15	5·10	4·43
104	2·25	10·15	4·51
105	1·70	8·95	5·26
106	1·90	8·40	4·42
107	1·82	8·50	4·60
108	1·68	8·75	5·20
109	2·08	9·10	4·37
110	1·84	10·45	5·68
111	1·53	9·85	6·43
112	1·34	6·80	5·07
113	1·45	6·33	4·30
114	1·13	5·50	4·87
115	0·80	4·50	5·82
116	0·80	3·64	4·05
117	0·74	3·01	4·07
118	0·46	1·85	4·02
119	1·82	10·60	5·82
120	1·90	10·90	5·73
121	1·75	10·95	6·27

Average ratio, 31 determinations, 5·23.

Other observations were taken in the Bell and Johnson pits, and around the Bennett-Martin pit, at Thetford, but as they correspond fairly closely with those made in the Beaver and Jacobs pits they are not introduced here. With regard to the Black Lake figures, Nos. 33-77 were obtained from the Union Asbestos pits at the summit of Murphy hill, Nos. 78-85 from the main pit of the Standard Asbestos Company, Black Lake, and the remaining five determinations from a small pit at the southwestern edge of the town, opening off the highway through a short tunnel beneath the railway. Of the Vimy Ridge figures, Nos. 91-99 are observations taken on simple veins, and the remainder on the compound, ribbon veins.

In addition to the asbestos veins, there are other veins that likewise are flanked by serpentinized zones. Such veins have been observed on the west side of Reed hill, at the old Lambly mine at the south end of Kerr hill, and in the pits at the south end of Belmina ridge. The veins are rather narrow bands of black serpentine, some of which have a very little asbestos developed along the extreme outer edges. The central vein of serpentine (or serpentine and asbestos) is flanked by serpentine zones, exactly like the asbestos veins; and the similarity of appearance is so great that they are sometimes termed "painted veins", because they look like true veins but contain no asbestos. The relations between these veins and their altered zones is shown in the following table.

TABLE XI

Altered Zone—Vein Ratios, Painted Veins

No.	Vein	Vein + altered zone	Ratio
	Ins.	Ins.	
122	0·25	0·64	2·56
123	0·48	1·52	3·16
124	0·71	2·09	2·94
125	0·38	0·91	2·4
126	0·27	1·01	3·7
127	0·21	0·79	3·76

Average ratio, 6 determinations, 3·08.

In the above tables it will be noted that some of the ratios depart considerably from the average. Some of the variations, of the order of one unit or thereabouts, are due to local variations in the width of the vein. Thus, Nos. 17 to 20, Table VIII, are all measurements made on different parts of one vein; the vein exhibits a maximum variation of 20 per cent, whereas the altered zone varies only 11 per cent. These differences cause a ratio variation of 8·1 to 9·5. Again, Nos. 79 and 80, Table IX, lie on the same vein, No. 80 being a short expansion; and it will be observed that the altered zone maintains nearly the same width, is in fact a little narrower, where the vein is wider. In general, the tendency is for the altered zone to be smoother in outline than the asbestos vein, so that the ratios vary somewhat, depending on the point of measurement.

Still larger variations occur, in a few places, which are not so simply explained. In some of them the altered zone is abnormally narrow, in others abnormally wide. Four abnormally narrow altered zones are listed in the following table.

TABLE XII

Abnormal Ratios

No.	Vein	Vein—altered zones	Ratio
	Ins.	Ins.	
128	1·04	2·84	2·73
129	0·63	2·23	3·54
130	0·57	1·49	2·62
131	1·34 To 1·26 Fi	5·84	4·36

Of the above, Nos. 128-130 are from the Union Asbestos pits at Black Lake, where the average ratio is 6·26, and No. 131 is from the Bell pit at Thetford, where the average ratio is 9·36. In addition to these, such veins as Nos. 23, 32, 33, 55, 57, 63, 65, 79, 81, 82, and 85 in the preceding tables may also be considered anomalous in lesser degree.

It may also be mentioned that the above anomalies are not due to local rock differences. The veins displaying them occur in the asbestos pits, in rock no different from that bearing ordinary veins, and surrounded by veins having normal altered zones.

Altered zones of unusual width are commonly found in fault fissures. It is easier to observe this fact qualitatively than to secure reliable measurements, partly because of the broken nature of the rock, and partly because the asbestos is apt to form a multitude of anastomosing veinlets and threads difficult to measure with accuracy. One measurement was made at the Union Asbestos pit, on a slip containing two narrow bands of cross fibre. The combined widths of fibre was 0·12 inch, and the width of the veins and altered zone was 6·36 inches, yielding a ratio of 53. This ratio is between two and five times as large as that for ordinary veins of the same width.

The significance of the varying widths of the altered zones will be discussed in the section discussing the origin of the asbestos.

Another characteristic of the altered zones is illustrated in the cross-section, Figure 14A. The zones are crossed at right angles by joints, which are widest next to the vein and end in a point at the outer edge. The joints are filled with chlorite or some whitish material. If the asbestos is stripped away so as to expose an area of the vein wall, the joints are seen to have a reticulating pattern, like the cracks in dried mud. At the big end, the joints average about one-fortieth of an inch in width, though they have been observed to attain double that width. They are spaced about an inch apart. In one place where they were few in numbers and fairly large, measurements were made to determine the area of the joints relative to that of the cross-section of the altered zone. It was found to be 0·8 per cent.

The existence of these joints appears to indicate that the formation of the serpentine zones was accompanied by a slight contraction in volume. They were not formed by any regional stress, as the relations in Figure 14B show. If they had been formed by cooling of the rock there is no reason for their ending at the border of the altered zones, as they invariably do. The fact that they are widest where alteration has been most extreme, that they narrow as alteration becomes less, and end where alteration ceases, proves definitely that their formation was controlled by the degree of alteration.

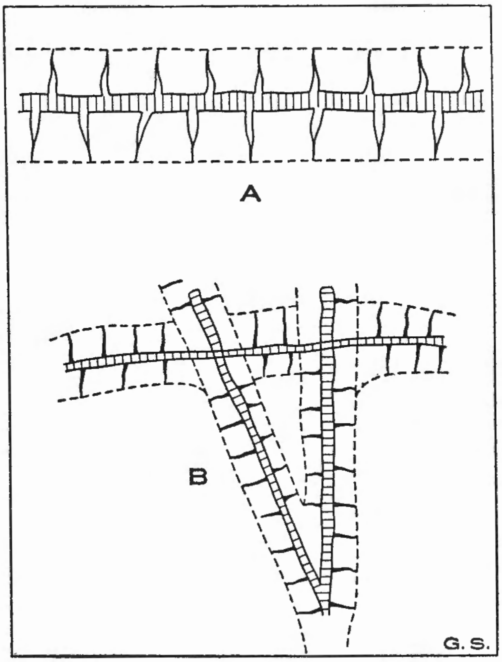

Figure 14. A, contraction fissures in serpentine zones flanking asbestos vein. Width of fissures is exaggerated. B, sketch of vein arrangement, Black Lake pit, showing that contraction fissures are related to individual veins, and are not a result of general stress.

A characteristic of many, though by no means all, vein walls is slickensiding. This is more commonly found in the walls of the larger veins, and particularly in the walls of veins that have a central fissure. It is due, quite evidently, to slight fault movement prior to vein formation. In many the movement was sufficient to develop some picrolite or other fibrous materials (Figure 15) like those developed regularly in the larger faults and this now forms one wall of the vein. In other places the drag of one wall on the other has formed little tension cracks, now filled with asbestos, running off from the vein (Figure 16). The asbestos fibres abut directly on the slickensided surfaces, from which they separate very readily. These facts, to which attention has never been previously called,

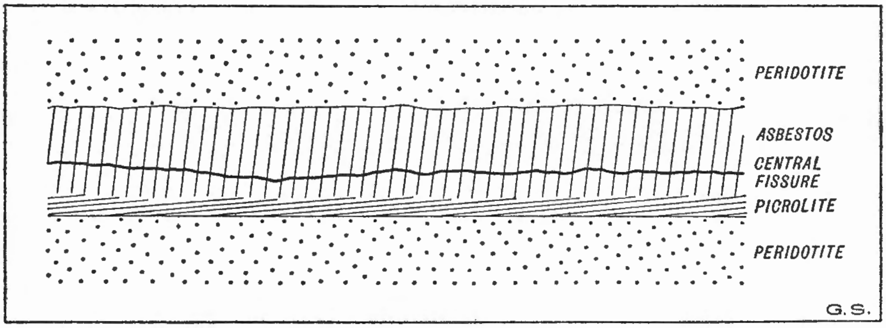

Figure 15. Picrolite, developed by pre-vein faulting, forming one wall of asbestos vein.

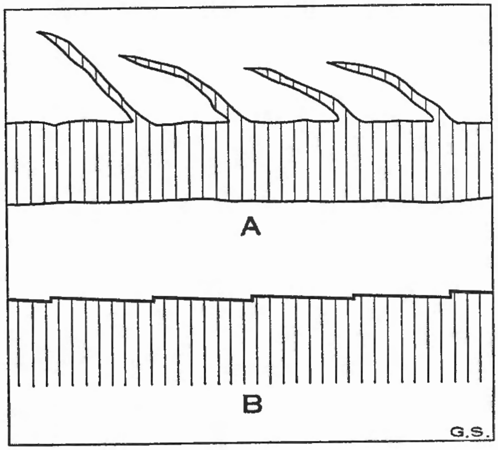

Figure 16. A, tension cracks filled with fibre running off from a vein of type shown in Figure 20. B, corrugated surface of a slab of fibre such as A, when broken out of the rock.

are of the utmost importance in considering the genesis of asbestos, for they indicate that *the original walls of the fissures have not been destroyed,* as they would have been had the asbestos formed by replacement, or had asbestos-forming agents caused solution of the walls.

The chemical changes that took place during serpentinization of vein walls are shown in the following analyses:

TABLE XIII

Analyses, Serpentinized Walls of Veins

—	11	12	13	14
SiO_2	39·66	40·72	40·11	37·42
Al_2O_3	1·84	1·01	0·18	0·34
Fe_2O_3	4·07	4·07	3·05	1·79
FeO	3·92	0·63	4·46	3·00
CaO	1·52	0·32	0·03	tr.
MgO	39·96	39·30	43·43	43·27
Na_2O	0·29	0·09	n.d.	n.d.
K_2O	....	....	n.d.	n.d.
H_2O+	7·51	13·41	7·52	13·51
H_2O-	0·38	0·43	0·22	0·29
CO_2	....	....	....	....
S	0·05	0·10	....	....
NiO	0·24	0·30	0·09	0·05
MnO	....	....	0·09	0·12
Cr_2O_3	0·13	0·42	0·36	0·39
Total	99·57	100·80	99·54	100·18
Sp. gr.	2·90	2·57	2·91	2·67

11. Partly serpentinized country rock, Vimy Ridge mine. R. J. C. Fabry, analyst.
12. Completely serpentinized vein wall, Vimy Ridge mine. R. J. C. Fabry, analyst.
13. Partly serpentinized peridotite, Bell pit, Thetford Mines. R. J. C. Fabry, analyst.
14. Completely serpentinized vein wall, Bell pit, Thetford Mines. R. J. C. Fabry, analyst.

Eliminating the water given off below 105° C. (H_2O–), and recalculating to 100 per cent, these analyses become:

TABLE XIV

Analyses, Serpentinized Walls of Veins Recalculated to 100 per cent

—	11	12	13	14
SiO_2	39·99	40·57	40·39	37·46
Al_2O_3	1·86	1·01	0·18	0·34
Fe_2O_3	4·10	4·05	3·07	1·79
FeO	3·95	0·63	4·50	3·00
CaO	1·53	0·32	0·03	tr.
MgO	40·29	39·16	43·72	43·32
Na_2O	0·29	0·09	n.d.	n.d.
H_2O+	7·57	13·35	7·57	13·53
S	0·05	0·10	....	....
NiO	0·24	0·30	0·09	0·05
MnO	....	....	0·09	0·12
Cr_2O_3	0·13	0·42	0·36	0·39
Totals	100·00	100·00	100·00	100·00
Sp. gr.	2·90	2·57	2·91	2·67
Vol., 100 g.	(cc.) 34·48	38·91	34·36	37·45

The final figures of the above tables give the volumes of 100 grammes of each rock analysed, as determined from its specific gravity, and it will be noted that the volume of a given weight of serpentine is considerably larger than that of the same weight of peridotite. The data given in a preceding paragraph have shown, however, that there is little or no change in volume during the serpentinization; in other words, that 34·48 cc. of rock of composition like No. 11 alter to 34·48 cc. or slightly less, of rock with composition like No. 12. Similarly, for the other pair of analyses, 34·36 cc. of material like No. 13 changes to 34·36 cc., or slightly less, of rock like No. 14. To find what has occurred during serpentinization, therefore, it is necessary to recalculate the figures of analyses Nos. 12 and 14 so as to obtain the weights present in 34·48 cc. and 34·36 cc., respectively. When this is done, the figures become:

TABLE XV

Analyses, Serpentinized Walls of Veins, Recalculated to Corresponding Volumes

—	11	12	Loss	13	14	Loss
SiO_2	39·99	35·96	4·03	40·39	34·38	6·01
Al_2O_3	1·86	0·90	0·96	0·18	0·32	0·14[1]
Fe_2O_3	4·10	3·59	0·51	3·07	1·64	1·43
FeO	3·95	0·56	3·39	4·50	2·75	1·75
CaO	1·53	0·28	1·25	0·03	....	0·03
MgO	40·29	34·70	5·59	43·72	39·75	3·97
Na_2O	0·29	0·08	0·21	....	....	....
H_2O—	7·57	11·83	4·26[1]	7·57	12·42	4·85[1]
S	0·05	0·09	....	....	....	....
NiO	0·24	0·27	....	0·09	0·05	....
MnO	....	....	....	0·09	0·11	....
Cr_2O_3	0·13	0·37	....	0·36	0·35	....
Totals	100·00	88·63	....	100·00	91·77	....
Vols. (cc.)	34·48	34·48	....	34·36	34·37	....

[1]Gain.

In determining the specific gravities of the rock specimens, Nos. 13 and 14 were boiled for some hours before determining their weight in water, and the determinations are, therefore, fairly accurate. It is not known whether specimen 12 was similarly treated, and, if not, the specific gravity is probably a little low. This, if true, would make the figures for loss of material somewhat too high, and the figure for gain of water too low. However, an error of this sort, though it would change slightly the figures, would not alter their relative proportions, except the proportion of water to the others.

According to these figures, therefore, serpentinization of the edges of the veins was accompanied by addition of water, and removal of considerable amounts of all other constituents. The first pair of analyses indicates that in serpentinizing 100 grammes of the Vimy Ridge peridotite, 4·26 grammes of water was added, and 15·94 grammes of other materials removed. The second pair indicates that in serpentinizing 100 grammes of Thetford Mines peridotite, 4·85 grammes of water was added and 13·19 grammes of other constituents were removed. As the bulk of the material removed in both cases is magnesia, silica, and iron, doubtless much of it went to form the asbestos and the magnetite of the vein.

AGE OF ASBESTOS VEINS

The asbestos veins are developed in the partly serpentinized peridotites, and cut across pyroxenite dykes. Where masses of chromite are found, asbestos veins may be observed in places to cut through the chromite. Mr. E. Poitevin, mineralogist to the Geological Survey, Bureau of Geology and Topography, has in his collection a large specimen of massive chromite cut by an asbestos vein of the 1-fibre type. Undeformed veins of asbestos may everywhere be observed filling joints and faults, and enclosed by picrolite and other types of fibrous material developed during faulting. More rarely, asbestos veins may be seen to angle across the crushed zones of faults. Asbestos is, therefore, younger than the peridotite and pyroxenite, the chromite deposits, and the faulting.

Direct evidence of the relative age of the feldspathic dykes and the asbestos is almost lacking. In 1930 the writer observed, in the Bell pit, a somewhat sliced dyke containing the sliced and shattered remnants of a serpentine inclusion through which ran asbestos veinlets with a continuity that pointed to their being formed after the serpentine had been brought into its present condition and position. Another dyke in the Bell mine, on the south side of the incline connecting the present upper and lower levels, has a 6-inch zone of talc developed along its lower edge, through which run asbestos veins not altered to talc. It would seem that the asbestos must have been developed after talcification of the surrounding serpentine. Again, at the extreme south side of the Thetford map-area, near Beebe brook, the writer's assistant, M. S. Hedley, found a dyke of medium-textured granite containing a number of inclusions of serpentine. A vein of fine, silky cross fibre, some 3 feet in length, with a maximum width of ¾ inch, ran out from one of these inclusions into the surrounding granite.

This rather meagre direct evidence is strongly supplemented by the facts discussed in the section devoted to the granitic dykes. It is there shown that the alterations of the dyke materials and those of the surrounding peridotite combine to suggest that the asbestos-forming waters tended to carry magnesia from the peridotite into the dykes, and silica and alumina from the dykes into the peridotite. This, if correct, requires the conclusion that the dykes were injected before asbestos was formed.

It is also shown, in the section describing the granites, that they were probably injected during the post-Lower Devonian period of deformation. If so, the asbestos must likewise have been formed toward the end of the same period. The correctness of this conclusion is further indicated by the fact that the veins have suffered no deformation since they were formed. Had they passed through the Devonian deformation, much faulting and crushing might be expected, but nothing of the sort is found.

FAULTS AND THEIR RELATIONS TO ASBESTOS VEINS

Faults are very numerous throughout the peridotite masses, both where there is asbestos and where there is none. They are of all sizes, from simple fractures on which there has been only a little movement to wide zones of shearing within which the serpentine is crushed into little imbricating disks, forming what the miners term "fishmeat." Though displacement along such sheared zones was undoubtedly large, its magnitude is impossible to determine, on account of the lack of recognizable horizon markers, such as dykes. It is known, however, that considerable widths of the brittle peridotite and serpentine may be crushed by comparatively small movements. Small horizon markers of various sorts were distinguished during the study of the Vimy Ridge pit; and it was there proved that displacements of an inch or two will produce beautifully slickensided surfaces, with a good development, in some places, of fibrous materials (not asbestos) between them; and that displacements of 6 inches may reduce a 4- to 8-inch band of peridotite to "fishmeat."

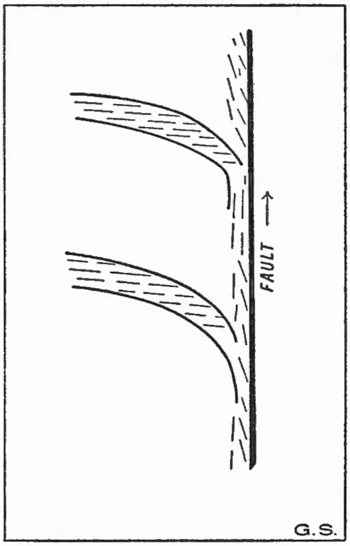

Figure 17. Vertical section, east end of Vimy Ridge pit, June 25, 1934; shows two ribbon veins branching from fault; broken lines are asbestos.

The strains set up during faulting have had other, highly important effects on the brittle peridotite. Numerous tension cracks were formed in the fault walls, running off at angles of 20 to 40 degrees (Figure 21); and where asbestos occurs, these cracks become filled with it (Figure 17). Near small faults, a strained condition was set up throughout considerable thicknesses of rock. This is manifested by the development of little asbestos veins in the pyroxene or bastite crystals (Figure 18). Such veins run through the bastites, and either end sharply at their margins, or run into the peridotite for some such distance as one-twentieth of an inch. It is noticeable that these veinlets are nearly all parallel to one another, regardless of the attitude of the bastite crystals, *and that they are likewise parallel to the tension cracks running off from the fault.* The arrangement is not regional, however, but very local. Perhaps 20 feet away, in the zone of influence of a neighbouring fault, the veinlets in the bastite will have an entirely different orientation, which is parallel to the tension cracks of that fault.

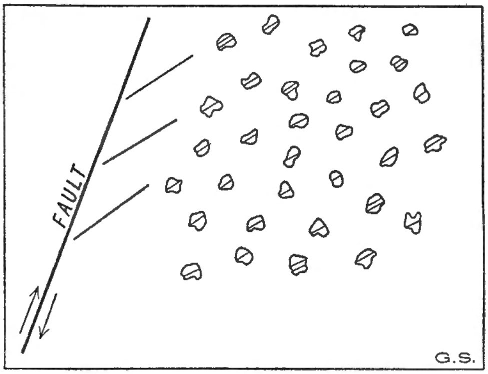

Figure 18. Development of asbestos veinlets within bastite crystals, parallel to tension cracks of a neighbouring fault.

Larger faults set up more intense strains, resulting in the formation of longer fractures (Figure 19). Most of these, as the figure shows, are likewise parallel to the tension cracks running off from the fault; but there are a few that cross the main direction almost at right angles.

Under still more intense stresses very regular fracture systems are set up. Figure 20, a drawing of a part of the north wall of the Johnson pit, illustrates this. The individual veins of such fracture systems are apt to have slickensided walls, indicating a little movement along the fractures before they were filled with asbestos.

Although all types of faults are found in the pits, the great majority are thrust faults, and the veins, as a rule, tend to occur beneath them. This seems to be due to the differing effects exerted by drag on the two sides of any fault. In Figure 21 the drag of one wall on the other wall of the fault AB would *tend* to form tension cracks in each (indicated by the dotted lines), but this tendency would meet with more resistance on the upper side than on the lower. On the lower side, the frictional pull is upward, and as relief is possible in this direction, tension cracks could readily develop. On the upper side of a thrust the frictional pull is downward, thus compressing the rocks, so that cracks of any sort would be less likely to form.

A beautiful example of the above relationship is afforded by a small asbestos deposit just west of Black Lake village. The pit is approximately 200 feet long and 30 to 40 feet wide, and is entered from the provincial

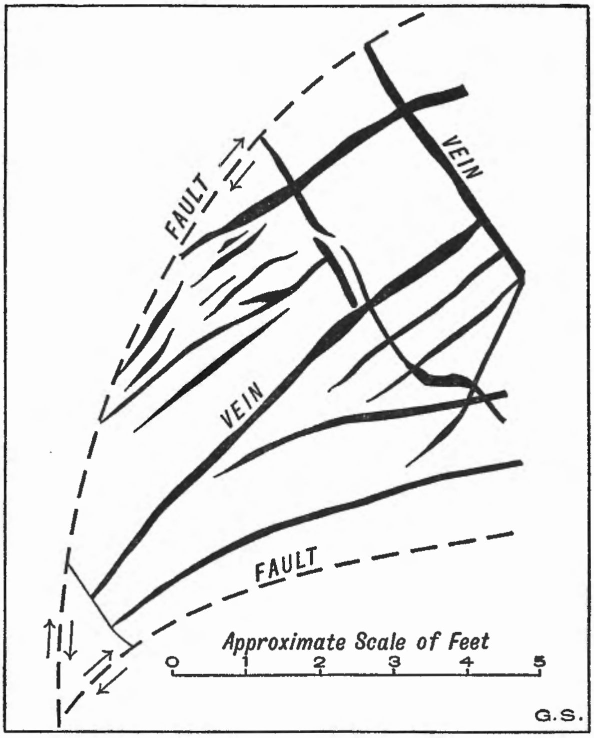

Figure 19. Part of south face, Johnson pit, Thetford mines. Solid black areas are asbestos veins.

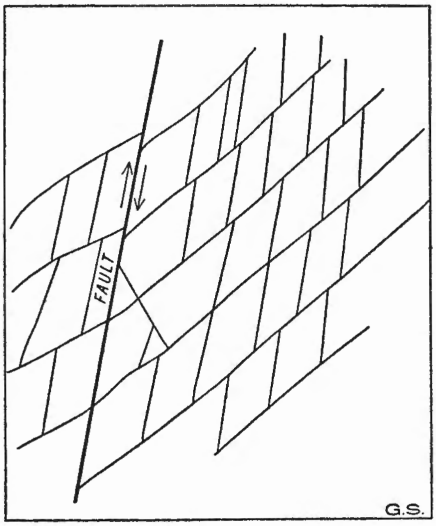

Figure 20. Part of north face, Johnson pit, Thetford mines, illustrating regularity of vein system. The thin lines are asbestos veins.

highway through a short tunnel beneath the railway track. The pit trends northwesterly along a somewhat S-shaped curving course. The northeast side is bounded by a single thrust fault, and the boundaries of the pit follow faithfully the curves of the fault. The fault is a thrust, and dips northeast, so that the deposit occurs on the lower or downthrow side. The uniform width of the deposit, its limitation to the downthrow side, and the manner in which it follows the curves of the fault, all combine to prove the control exercised on deposition by the faulting; and the absence of any nearby fault that might complicate the relationships makes the locality almost a laboratory illustration.

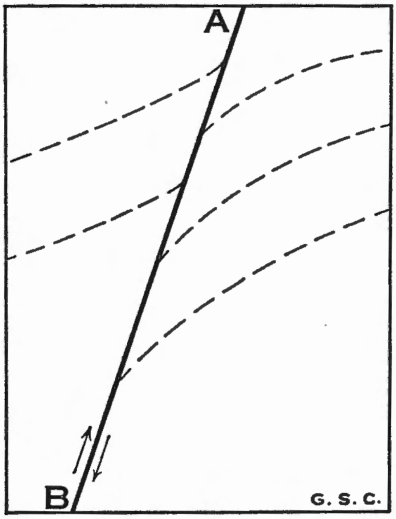

Figure 21. Development of tension cracks in walls of a fault.

The asbestos deposits, considered as a whole, are of three structural types. There are those which, like that just described, are genetically related to a single fault or to a series of more or less parallel faults. It is obvious that such faults would have to be fairly closely spaced to produce a deposit large enough for profitable and long-continued working. Some of the Black Lake deposits appear to be of this type, though more detailed work must be done on them before a positive statement can be made. A second structural type is that occurring between faults that converge downward, thus forcing upward a conical block of ground. The upward-moving block is badly shattered, as a rule, yielding ideal conditions for the deposit of asbestos. The large block of asbestos-bearing ground at Thetford Mines, on which the King, Johnson, and Bell pits are situated, is of this type, as is also the smaller block of the Beaver mine. The third structural type occurs between faults that converge upwards. The Vimy Ridge mine, and the Canadian Johns-Manville deposit at Asbestos are of this type.

FIBROUS MATERIALS IN FAULTS

Fibrous materials are almost universally developed along fault planes in the peridotites and serpentines, and are of several types. The first type, here termed " slip serpentine", can not be recognized as a fibre without the aid of a glass. It appears on fault faces as a translucent, pale green or yellow-green coating, one-fortieth to one-twentieth of an inch thick, and particularly on the individual disks composing the sheared masses called " fishmeat." The surface of such disks is very smooth and slippery and viewed through a thin edge the coating appears massive or glassy. When efforts are made to chip it off, however, it is found to be composed of layers of fibres parallel to the slip plane and to each other. The material is close to serpentine in composition, and is, therefore, presumably serpentine rendered fibrous by shearing stresses. It is, perhaps, the first step toward formation of slip-fibre asbestos, but lacks its fineness and strength. To trace the successive steps between this material and true slip fibre would be a most interesting subject for investigation.

Slip serpentine contains much magnetite, and in places minute veins of cross-fibre asbestos have developed between the layers of slip serpentine fibres. The material analysed (Table XVI) was first carefully chipped from the surfaces of slickensided blocks, and each chip was then examined under the binocular microscope both by direct and transmitted light, so that all magnetite, and as far as possible all asbestos, could be removed. The analyses, therefore, represent fairly closely the composition of the slip serpentine alone.

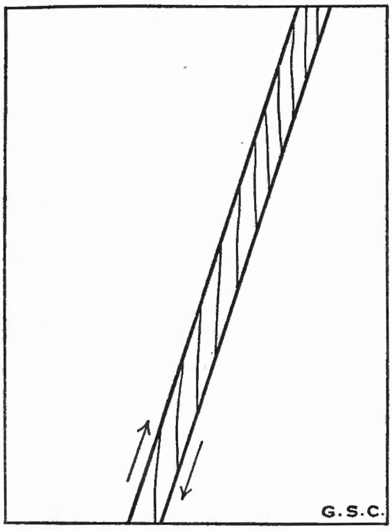

Figure 22. Cross-section of pre-asbestos fault, showing direction of fibres.

A second type of fibrous materials, varying in composition between wide limits, is commonly found in those faults that have not crushed a wide zone of rock, but in which displacement has been along a single fissure.

The fibres may vary from 1 to 10 inches in length; in some cases they are tough and stringy, in others fairly brittle. The fibres commonly lie at an angle to the fault plane (Figure 22); and by checking carefully, in many places, the direction of movement as determined by the displacement of some recognizable band or dyke, it was established that the orientation of the fibres bears the same relation to the direction of movement as does flow cleavage. Thus the direction of fault movement may be determined from the position of the fibres in the fault plane, when other data are absent. Care must be used in applying this method, however, where the fibres are nearly parallel to the fault plane, as small bends in the latter readily give rise to erroneous interpretations (Figure 23).

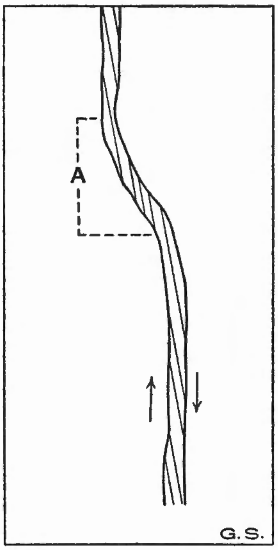

Figure 23. Where fibres are nearly parallel to fault plane, observations made at small bends (section marked A) will yield erroneous results.

The composition of these fibrous materials varies from nearly pure serpentine to practically pure brucite. Nearly all the soft, stringy varieties, with rather talcose feel, contain much brucite, but both the more serpentinous and the more brucitic types have fairly stiff, harsh fibres. In Table XVI are given the analyses of three of these, showing the wide variation occurring. Other analyses would doubtless reveal the existence of intermediate types. In preparing the materials for analysis, they were broken into thin chips, studied under the binocular microscope, and all visible impurities removed. However, as these fibres, with the exception of the brucite, are not translucent, it is not possible to be as certain of their purity as in the case of the translucent varieties.

A third type of fibrous material found in fault planes is the brittle, coarse-fibred serpentine termed picrolite. It also forms veins of cross fibre, exactly like asbestos, and in places, where tension cracks run into the rock from such a fault, the picrolite of the fault may be observed to pass without break, and with perfect parallelism, into cross-fibre picrolite in the tension crack (Figure 24). In many cases the fibrous tendency of the cross-fibre veins is but weakly developed, and the cross-fibred material grades into pale green, fine-grained serpentine without any fibrous structure, likewise occupying a vein fissure.

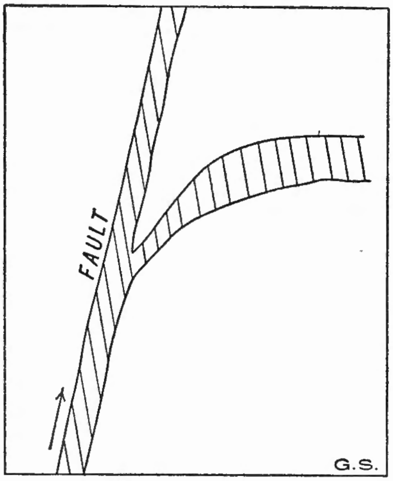

Figure 24. Relation between picrolite fibres in fault and those in vein satellitic to fault.

Analyses of the picrolites were made (Table XVI) partly to compare their compositions with those of other fibrous materials analysed, partly for comparison with the Rhodesion picrolites described by Keep (80, pages 94-5). One analysis is of the fibrous type found in faults, the other is of the cross-fibred picrolite of a vein, just where it grades into non-fibrous serpentine.

For purposes of comparison, the analysis of the dark serpentine vein material at the centre of one of the "painted veins" (page 109) is also included.

TABLE XVI

Analyses of Fibres in Fault Planes, and of Material of "Painted Vein"

—	Slip serpentine 15	Slip serpentine 16	Fault fibre 17	Fault fibre 18	Fault fibre 19	Picrolite 20	Picrolite 21	22
SiO_2........	42·45	39·24	40·61	14·97	0·59	42·16	40·63	36·61
Al_2O_3.......	Nil	0·03	0·49	1·58	0·57	0·41	2·27	Nil
Fe_2O_3......	0·56	1·13	1·49	1·61	0·93	1·99	1·78	12·63
FeO........	1·13	0·55	1·07	2·61	6·09	1·72	2·53	3·29
CaO.......	0·09	0·07	trace	0·07	0·19	0·09	0·32	0·07
MgO.......	42·78	42·93	42·31	56·69	62·01	40·00	39·88	36·69
H_2O+.....	12·98	14·20	13·27	22·46	28·76	12·08	12·47	10·33
H_2O-.....	0·39	0·36	1·36	0·76	0·14	0·37	0·47	0·65
MnO.......	....	....	....	....	0·32	....	....	....
NiO........	....	....	....	....	....	....	....	....
TiO_2.......	....	....	....	....	....	....	....	....
CO_2........	....	1·49	....	....	....	0·47	....	0·10
Total.	100·38	100·00	100·60	100·75	99·60	99·29	100·35	100·37

15. Slip serpentine, from broad fault zone, drift 505X, King mine, Thetford Mines, Quebec.
16. Slip serpentine, from fault zone, drift 504X, King mine.
17. Tough, stringy fibre from a fault, drift C502E, near D505X, King mine.
18. Soft fault fibre, drift 304, King mine.
19. Fault fibre, Beaver mine, Thetford Mines, Que.
20. Green, fibrous picrolite from fault plane, 300-foot level, King mine.
21. Semi-fibrous picrolite, filling veins, 300-foot level, King mine.
22. Serpentine vein, centre of "painted vein", Lambly mine, near Coleraine village, Quebec.

The analyses in Table XVI are recast into mineral form in Table XVII, using the same methods as in the case of the asbestos fibres. Magnetite is shown in No. 19, although the material submitted for analysis, being transparent, could be seen to contain none, because the analysis does not show enough silica to calculate the ferric iron as chlorite. In No. 22 the microscope shows considerable magnetite present, and this is accordingly shown in the recalculation.

TABLE XVII

Analyses of Fibres in Fault Planes, and of Material of "Painted Vein," Recast into Minerals

—	Slip serpentine 15	Slip serpentine 16	Fault fibre 17	Fault fibre 18	Fault fibre 19	Picrolite 20	Picrolite 21	22
Chlorite..........	2·14	4·56	8·42	14·65	1·82	9·92	19·12	20·37
Serpentine........	96·72	88·23	88·70	23·95	....	80·35	77·73	57·70
Talc.............	....	....	....	....	....	7·94	2·23	8·87
Brucite...........	0·59	3·06	2·71	57·61	95·41	....	....	....
Periclase.........	0·55	....	0·17	3·79	1·42	0·46	0·92	2·14
Hydromagnesite.	....	4·15	....	....	....	1·33	....	0·29
Water...........	....	....	....	....	....	....	....	....
Na_2O+K_2O.....	....	....	....	....	....	....	....	....
Magnetite........	....	....	....	....	1·35	....	....	10·63
Totals........	100·00	100·00	100·00	100·00	100·00	100·00	100·00	100·00

If the large amount of magnetite in No. 22 is thrown out, to make the analysis comparable with Nos. 20 and 21, and the analysis is then recalculated to 100 per cent, it becomes:

	22
Chlorite	22·79
Serpentine	64·57
Talc	9·95
Brucite	....
Periclase	2·39
Hydromagnesite	0·30
	100·00

so that the composition is not unlike that of No. 21, although the larger amount of talc and periclase points to a material originally less aqueous.

The picrolite analyses have a special interest, because of the differences between them and the picrolites found in the Rhodesian asbestos deposits (80, pages 94-5). The latter contain 5 to 8 per cent of alumina, yielding 30 to 43 per cent of chlorite in the recast analyses. Keep, who described the Rhodesian deposits, is inclined to consider the large alumina content as the reason why picrolite forms instead of asbestos. The small percentages of alumina in Canadian picrolites—No. 20 has no more than most varieties of asbestos—indicate that Keep's hypothesis cannot be true, and that the cause of picrolite formation must be sought elsewhere.

LOCALIZATION OF ASBESTOS DEPOSITS

The deposits of cross fibre, from which the main production comes, have one feature in common in that all are situated comparatively near the northwest side of the peridotite intrusive. The King-Johnson-Bell group of pits at Thetford Mines is ½ mile from this contact, and the Beaver mine about the same; the width of the intrusive here is somewhat more than 1½ miles. The Maple Leaf mine is about 900 feet from this contact. The Black Lake group of pits varies from about ¼ mile, for the pit nearest the contact, to ¾ mile for the farthest, and the total width of the intrusive is about 2 miles. The Vimy Ridge deposit lies between one-quarter and three-eighths of a mile from the contact. In one or two places pits have been opened at greater distances from the contact, as in the case of the Edith mine, seven-eighths of a mile away, but the amount of fibre found has been small. The Johns-Manville deposit at Asbestos likewise lies on the northwest side of the intrusive, but the latter is only about half a mile wide, and the deposit occupies the greater part of this width.

Pits have also been opened, close to the contact in each case, at the Lambly mine, south end of Kerr hill, and at the north and south ends of Belmina ridge. None of these produced much asbestos, but they illustrate nevertheless the localization of such asbestos as does occur.

No asbestos has been found in the peridotite masses of Breeches and Sunday lakes, of Nicolet lake, or in the small serpentine masses west of Nicolet lake as far as the Nicolet Asbestos mine 6 miles northeast of Asbestos. This last-mentioned mine lies within a heavily drift-covered area, so that its position with regard to the boundaries of the peridotite is unknown.

These facts seem to point to the conclusion that the asbestos-forming agent entered the peridotite masses from outside, rather than originating within the peridotite itself, as most writers have supposed; and, if so, the agents or solutions must have originated to the northwest of the present peridotite boundary. Further, the distribution of deposits from northeast to southwest indicates that there must have been two centres from which such solutions originated, one of which produced the Thetford-Black Lake-Vimy Ridge group of deposits, the other the Johns-Manville and Nicolet Asbestos deposits, leaving the intervening areas of peridotite barren.

ORIGIN OF ASBESTOS

The facts given in the preceding pages afford the necessary data for a discussion of the origin of asbestos. It has been shown that the asbestos deposits always occur relatively near the margins of the larger peridotite masses, and, further, that where there is little asbestos, any small deposit that occurs is very close to the margin, whereas the larger deposits may be as much as half a mile from the margin. These facts are interpreted to mean that the asbestos-forming agent entered the peridotite from without. Where the quantity of the agent was small, it did not get far within the margin before reacting to form asbestos; where large, it could penetrate farther. Possibly, also, the initial temperature of the solutions, as well as their volume, may have influenced the depth of penetration before they commenced to form asbestos.

Again, it has been shown that asbestos deposits are confined to faulted areas. The asbestos is found both in the faults themselves and in tension cracks running off the faults. The fault zones are serpentinized over far greater widths than their asbestos content alone would justify. It seems evident, therefore, that the faults formed the main channels of entry for the agents of serpentinization and asbestos formation.

The nature of the asbestos-forming agent may be inferred from the composition of the fibrous materials found in the fault zones, which have been shown to vary between almost pure serpentine and almost pure brucite. To convert non-fibrous serpentine into a fibrous form need not have required anything but a shearing action. If any solution were present, its action must have been merely that of a lubricant or catalyser. The more brucitic fibres, however, indicate the presence of an active agent. These fibres may have been formed by alteration of a first-formed fibre of the composition of serpentine, or else the serpentine of the wall-rock may have been dissolved in part and redeposited with its present composition. In either case, the alteration requires the addition of water to serpentine, and the removal of silica. Thus the agent passing through the faults must have been a dilute, highly aqueous solution of some kind, one that was able to give up water freely, and take considerable amounts of silica readily into solution.

It should be noted, moreover, that the asbestos veins occur *on* and *throughout* the fibrous fault materials and in the tension cracks running off the faults, so that the same dilute aqueous solutions must have been responsible for the formation of the asbestos. This conclusion is directly opposed to that of many previous workers, who have supposed that the asbestos-forming agents were silica-bearing solutions; but the analytical results appear to demand it. It is further supported by the evidence afforded by the alterations of the feldspathic dykes, which, as shown, seem mainly due to solution of some dyke constituents and their removal to the surrounding peridotite, and, vice versa, to solution of some constituents of peridotite, which were carried into the dykes where they were deposited. The conclusion is again supported by the action of the asbestos-forming solutions on the vein walls; as has been shown, this action was again one of solution, by which all constituents of the peridotite were in part dissolved and carried away, while water was added.

How did the asbestos-forming agents reach the fissures in which asbestos was deposited? The existence of the " closed veins " affords an answer to this question. It has been shown that thousands of veins exist that have no connexion with any other fissure through which a supply of asbestos-forming solution might have been introduced. The only alternative, therefore, is to conclude that the agent must have entered through the pores and other submicroscopic openings of the rock itself.

If the rock were thus drenched with the fluid, or vapour that caused serpentinization and vein formation, it may reasonably be asked why serpentinization should be confined to the walls of the veins, instead of being uniform throughout the body of the rock. It can hardly be supposed that the composition of the vein walls was originally different from that of the rock a little farther away; the only existing difference was the presence of a fissure here and not there. Hence we are forced to the conclusion that *it was the existence of the fissure that caused selective serpentinization.* There may be more than one reason why this should be so; but as material was dissolved out of the walls, and other material was deposited in the fissures, it seems probable that the walls alone suffered serpentinization *because the existence of the fissure afforded the opportunity for reaction to go on.* Without the opportunity for expansion that the fissure afforded, little reaction took place, and, equally, as soon as deposition ceased in the fissure, alteration of the walls would likewise have to cease. This conception accounts for the general correspondence in width between the asbestos veins and the surrounding altered zones, a fact long known but never satisfactorily explained.

It has been shown that two types of veins exist throughout the deposits in close juxtaposition, the so-called 1-fibre veins, in which the fibres run unbroken from wall to wall; and the 2-fibre veins, which display two irregular plates of fibre, one attached to each wall. Most of the 1-fibre veins are of the " closed " type, and most of the 2-fibre veins are larger veins found in fault planes, although exceptions to both these generalizations are found. Why should two types occur? The presence of the numerous 2-fibre veins is readily explained as due to the fibres commencing growth from each wall of an ordinary fissure, and growth continuing until the fissure was filled; such is the ordinary process of fissure filling; but it leaves unsolved the riddle of the 1-fibre veins. Why should these lack the central break? The only possible answer seems to be, that their original fissure was so narrow, its walls so tightly pressed together, that the first-formed needles of asbestos completely bridged it. In this way the final vein, however wide, would never have a central break.

If the deduction is correct, the type of vein formed is dependant on the character of the original fissure. Fissures originally tight, with close-fitting walls, yielded the 1-fibre vein, whereas more open fissures, which the first-formed fibres of asbestos could not bridge, gave rise to the 2-fibre type.

A test of the accuracy of this hypothesis is afforded by the 2-fibre veins themselves, for in any open fissure, at depth, there must be places where the walls touch. At such places, under this hypothesis, the first-formed fibres could have bridged the fissure, giving places in the veins where the fibres pass without break from side to side. Such places are not uncommon in the 2-fibre veins.

From the above conclusion, two further inferences flow logically and necessarily. First, the junction of the fibre with the wall must have been where growth occurred, so that the central part of each fibre must be the oldest, the part next the wall the youngest. This condition is the opposite of that occurring in ordinary fissure filling. Second, since many fissures were originally tight and are now filled with fibre, *outward movement of the walls must have taken place as the fibre grew,* and this movement must have been accurately adjusted to the rate of growth, or the fibre would display breaks or crumpled parts, which it does not.

Taber (124) has argued that the pressure of the growing fibres must have forced the walls apart, and, in a way, this must be true, as no other explanation of the accurate adjustment between wall movement and fibre growth seems possible. That much force was involved in this process, however, the writer does not believe. Had the rocks been under high compression when the veins were formed, the cracks found in the serpentine walls of the veins (Figure 14) could never have formed; even moderately high pressures would have caused the soft, incompetent serpentine to flow and thereby erase such openings. Obviously, therefore, the rock must have been in a state of balance, probably because the recent faulting had set up tensions not yet completely adjusted, so that the comparatively small force exerted by the growing fibres could push aside the walls sufficiently to adjust these tensions.

Such a modification of Taber's idea affords an excellent explanation of the small size of the asbestos veins. It has been shown that less than 1 per cent of all the asbestos produced is more than half an inch in length, and this means that only a small fraction of one per cent of the veins have more than this width. If the growing asbestos actually had the power to force the vein walls apart against the normal resistances encountered at depth, there should be no limit to the possible widths except the limitation of supply of vein-forming solution. The supply of solutions, in the big deposits, must have been abundant; therefore the fact that no veins are very wide, and that so few exceed half an inch, suggests that they could not force the walls apart, but that as soon as the tensional slack, so to speak, was taken up by vein growth, and further growth would be opposed by compressive stress, development was forced to cease.

Previous Theories

Before delving further into the origin of the veins, it seems well to consider the previously held theories of origin, as the objections to these yield valuable evidence in favour of the theory advanced. Three alternatives have been advanced to account for the asbestos veins, and these will be discussed in turn.

Replacement Theory. The replacement theory seems to have been originated about 1910, when several writers appear in support of it. It is perhaps best developed by J. A. Dresser (54, pages 61-66, 1913), who may be quoted in part as follows:

"All considerations of the origin of asbestos resolve themselves into two classes:

"(*a*) Those that regard the veins as originally open fissures which have been filled by material brought from without. . .

"(*b*) Those that regard the asbestos veins as crystallized parts of the serpentine, the fibres being considered to have grown outward from a central fracture or crevice. . .

"The position, size, and number of asbestos veins in rich ground make it inconceivable that the spaces they now occupy were once open fissures, and especially that many of them were open at the same time. Open fissures up to 2 inches in width, running in all directions from vertical to horizontal, extending 100 feet or more in length, and occupying in places as much as 10 per cent of the entire rock, would be a mechanical impossibility. . .

"It is, therefore, concluded that the veins are crystallized portions of the serpentine walls, and that the crystals (fibres) have grown outwards from the original crevices which are now represented by partings of iron ore found near the centre of the veins. In cases where there is no such parting the growth of the crystals has taken place on one side of the fracture only. In most cases, however, there has been crystallization on both sides of the fracture, thus leaving a parting in the vein."

The writer admits both the facts as given by Dresser, and his conclusion that open fissures were impossible; but the alternative that the veins must have, therefore, been formed by replacement is no longer the only possibility. On the contrary, many facts prove that replacement did not take place. Replacement veins have irregular edges, caused by parts of the rock being more easily and extensively replaced than others, and the vein materials pass by a gradation into unaltered country rock. The asbestos veins have straight or smoothly curving edges, and there is a sharp break between the vein material and the enclosing rock. Replacement veins contain partly replaced inclusions of country rock. Asbestos veins contain many inclusions of wall material, but these have clean-cut edges, like the walls, and display no evidence of partial replacement by asbestos. In addition to these general considerations, the following pieces of direct evidence seem conclusive.

In the chrome pit of the Vanadium Company at the west end of Caribou lake, small asbestos veins cross the chromite bands in several places. The chromite bands have widths up to ½ inch, and consist of small chromite grains thickly scattered in a serpentine matrix. The asbestos veins have their customary altered zones. The bands of chromite grains continue unchanged into and through the altered zones as far as the edge of the asbestos, where the chromite stops abruptly, to continue on the other side. Not a single grain of chromite was seen in the asbestos veins. Where the chromite bands pass through the altered zones of the veins, the matrix of the chromite grains is darkened in colour, apparently through more complete serpentinization.

The manner in which the chromite passes unchanged through the serpentine zones shows that it will not itself alter to serpentine; and it may be added that at no place in the region is there any evidence that chromite can be replaced by serpentine. If the asbestos were a replacement, therefore, the chromite grains should continue through the asbestos veins. As they do not do so, it must be concluded that no replacement took place.

In all pits, and particularly in those at Thetford Mines, it was observed that *the walls of many veins are slickensided surfaces.* As the fibre is not distorted, the slickensiding was evidently produced by movement before the asbestos was deposited. This conclusion is additionally proved by the presence of little tension cracks filled with fibre (Figure 16A), cutting through the slickensided walls into the rock beyond. The slightest movement after deposition of the fibre would have broken off these offshoots. *Had the fibre been formed by replacement of the original walls, these slickensided surfaces would have been destroyed;* hence replacement did not take place.

Further evidence, if this is necessary, is afforded by veins of the type shown in Figure 17. If asbestos had been formed by replacement, the threads of picrolite between the asbestos lenses could probably not have survived, and, if they did, should exhibit irregularities of width according to the varying extent of the replacement. No such irregularities, however, can be seen.

Fissure-filling Hypothesis. The theory of fissure filling by the ordinary process of injection of vein-forming solutions and subsequent crystallization was naturally the first advanced for the asbestos veins. It has recently been revived by S. B. Keith and G. W. Bain (2) and Keep (80, pages 101-2) also favours a modified form of the hypothesis. The latter considers that the Rhodesian asbestos veins fill contraction cracks that formed as the dunite magma cooled, and that growth of the fibre continued as long as the surrounding rock continued to cool and contract. No such conclusion is applicable to the Canadian deposits, which, as shown, were not formed until long after the peridotite had consolidated.

Those who support the fissure-filling hypothesis in recent years—and their number included the writer in the early years of this study—have done so mainly because: (*a*) the straight, clean-cut walls of the veins are obviously not of the type produced by replacement; and (*b*) they did not consider the force of growing crystals adequate to push vein walls apart, as Taber advocated. In addition, Keith and Bain (2), from their work on the New Hampshire deposits, have advanced direct evidence to prove that the fibres did not push walls apart. They point out that if the walls were driven aside by the growth of the fibre, irregularities in one wall should *always* match those in the other, and the corresponding irregularities should invariably be found at opposite ends of the same fibres. Similarly, if an inclusion can be matched with the point in the wall whence it was torn, as many can, corresponding points on the wall and the inclusion must lie at opposite ends of the same fibres. They point out that with some inclusions this is not the case, but that the inclusion has been moved sidewise from the position it should occupy according to theory; and they infer, therefore, that Taber's theory cannot hold, but that open fissures were filled with a serpentine solution, in which such sidewise movement was possible.

The reasoning seems irrefutable, unless some as yet undetermined cause for the sidewise movement of inclusions can be found; and it must be admitted that at Thetford, as in the New Hampshire deposits, occasional instances of sidewise movement have been noted. On the other hand, the objections to the hypothesis of fissure filling are so numerous and insuperable as to compel the conclusion that some cause for sidewise movement, though undetermined, must exist. These objections are:

(1) The impossibility that open fissures so numerous and with such aggregate volume could have co-existed, as Dresser has pointed out. Yet the manner in which the vein matter behaves at vein junctions (Figure 11) shows that they must have co-existed, if the fissure-filling hypothesis is correct.

(2) Fissures filled by ordinary methods display a much greater range of widths than is found in the asbestos veins, which, as shown, are mostly less than half an inch wide. If veins were formed by fissure filling, why should they not range up to several feet in width?

(3) In all veins formed by fissure filling, growth invariably commences at the walls and continues toward the centre. This process, therefore, could yield only veins of the 2-fibre type, and fails utterly to explain the occurrence of the 1-fibre type.

Attempts have been made, both by the proponents of this theory and by those of the replacement theory, to explain the 1-fibre veins as due to growth from one wall only. Why the fibres of some veins should have done so, when in adjoining veins, under otherwise identical conditions, they grow from both walls, they do not attempt to explain. Their assumption can be checked by field observations, however, and was so checked by the writer in some hundreds of veins. Many of the numerous inclusions in the veins have distinctive shapes that can be matched with corresponding indentations in the walls, so that it can be known from which wall they have been torn away; and from this study it became evident that approximately as many have been torn from one wall as from the other. Growth of fibre from both walls, therefore, went on in the 1-fibre veins exactly as in the 2-fibre veins.

The various growth peculiarities noted at vein junctions, and illustrated in Figure 11, cannot be explained by any hypothesis of growth from one wall only. A study of the diagrams will make this abundantly evident.

Taber's Hypothesis. In 1916 Dr. Stephen Taber, in endeavouring to formulate an explanation of the fibrous structure of asbestos and other minerals, advanced an hypothesis of vein formation radically different from those previously considered. It was, approximately, the same as that to which the facts at Thetford point. He supposed that vein-forming fluids or vapours, penetrating the pores of the peridotite, carried serpentine into tight fissures, where it began to crystallize as asbestos. As the fibres grew they were supposed to push the wall apart to the width of the existing veins. Doubt of the adequacy of the force of growing crystals to accomplish the required results made geologists and others chary of accepting his conclusions, but the difficulties facing both the alternative hypotheses have gradually caused it to be received with more favour.

As shown in preceding pages, the writer's conclusions are essentially those of Taber. Taber's main difficulty, the great force supposed to have been exerted by the growing fibres, has been met by finding facts that show that no great force was necessary, nor appears to have been applied. Again, the entry of the asbestos-forming agents through the pores of the rock was, with Taber, merely a probable inference, and the conclusion that the walls were pushed apart was likewise an inference drawn from certain structures (Figures 9, 13) in the fibres themselves. The existence of closed veins, as described, proves definitely that the solutions must have been introduced through the pores of the rock, and that the vein walls must have moved apart as the fibres grew, so that the hypothesis is thus placed upon a firmer basis.

The recognition of this sequence of events makes it easy to explain nearly all the structural peculiarities found in veins. It has been shown that in many veins the fibre occupies a position between the vertical and the normal to the plane of the vein (Figure 5). Any force tending to push apart the walls of a fissure dipping, say, at 45 degrees, would oppose two forces, gravity, acting vertically downwards, and the resistance of the rock to compression, acting in a horizontal plane. Of these, the force of gravity was undoubtedly the smaller; and, consequently, movement of the walls would not be at right angles to the plane of the vein, but in some direction closer to the vertical. The fibre would, of course, be elongated in the direction of movement.

In many veins the fibre displays bends, as illustrated in Figure 9. These bends record changing directions of wall movement as the fibres grew, but cannot be satisfactorily accounted for by any other hypothesis of vein development.

All the peculiarities of growth found at vein junctions, Figure 11, are readily explained by the hypothesis outlined, but not by any other.

The irregularity of the central fissure (Figure 8) in those veins that possess it, is one of the most difficult features to explain under this or any hypothesis. Taber appears to believe that it is due to the unequal speed of growth, the more rapidly growing fibres slipping on those of slower growth; for he writes (123, page 1990):

"The inequality in the length of fibres is due to the more rapid growth of those fibres that are most favorably situated for receiving additions of new material. The stresses resulting from unequal growth are relieved by slipping along cleavage planes and prism boundaries, and this tends to accentuate the development of the fibrous structure."

So far as the writer has been able to observe, there are no data to prove this point, and hence any conclusion must be largely a matter of opinion. However, as the fibres are closely packed together, so that there would have been much frictional resistance to slippage between them, the writer strongly doubts that any occurred, and is inclined to suppose, rather, that fibre growth did not necessarily commence simultaneously and evenly over the whole surface of the fissure, but may have begun at various spots where it obtained quite a start before any growth appeared in the intervening parts. Thus, under Taber's hypothesis, the form of the central fissure might change during growth of the vein; under the writer's, its form was fixed after uniform growth from both walls began.

Thus far, Taber's theory and the writer's merely demand a simple transfer of material throughout a distance of an inch or two, from the wall to the vein. The factor conditioning the reaction was, in all probability, the state of tension prevailing in the rock, whereby open fissures tended to form. Reaction between a particle of olivine and one of water to form serpentine results in expansion, whereby a high local pressure would momentarily be set up. This would facilitate removal of material to a point of less pressure, and such a place was only to be found in the vein fissure, where the regional forces were approximately balanced. Thus the complementary processes of wall alteration and asbestos deposition would go on as long as the state of tension prevailed, and no longer. As soon as the general pressure became equal to the pressures set up by serpentinization of olivine particles, no further material could be transferred into the fissures, and the vein would cease to grow.

However, veins exhibit a number of peculiarities that indicate that the transfer of material from the walls to the fissures may have been more complex than yet suggested. The most widespread and general of these characteristics is the difference in the ratio $\frac{\text{altered zone}}{\text{vein}}$ displayed in different parts of the same vein. Numerous measurements have shown that where veins narrow the altered zones do not narrow proportionately, so that the above ratio may be several times as great in the narrow parts as in the wide parts. Thus material removed from the walls, during serpentinization, must have moved laterally along the vein before crystallizing as asbestos. The same conclusion is indicated by the occasional occurrence of asbestos veins in chromite.[1] The chromite contains none of the constituents of asbestos, hence the latter must have entered laterally along the vein fissure. Again, veins such as those shown in Figure 7 imply lateral movement of solutions. The threads of picrolite on which the asbestos veins have grown are incapable of supplying the necessary material, partly because of their small size, partly because they show no sign of having suffered either solution or replacement. Their sole function, therefore, must have been to act as floors along which solutions could run, and to which asbestos fibres could anchor.

Veins like those shown in Figure 8 seem also best explained by lateral movement of solutions. The picrolite bounding one side of the veins could have supplied no material to them, since, as shown, to do so would require solution of the picrolite and its recrystallization as asbestos, which did not take place. The material for the asbestos growing on the picrolite side, therefore, must have come either through the picrolite, from the other side of the fault, or from the peridotite side through the asbestos vein. In either case there must have been considerable movement of solutions; and, also, the necessary materials must have been supplied much more slowly to the picrolite side of the fissure, so that growth on that side was sparser.

[1]In the collection of Mr. Eugene Poitevin, mineralogist to the Geological Survey, Bureau of Geology and Topography, there is a fine specimen of an asbestos vein running through massive chromite. The vein is of the closed type, with fibres running unbroken from wall to wall. Other examples were observed by the writer in the field.

Such observations suggest that the asbestos-forming agent, supposedly mainly water, arriving through the pores and other microscopic openings of the rock, entered the minute fissures that later became the veins laden with the constituents of asbestos, and then, before crystallizing, had time to run along and fill the vein fissure, even where it ran through chromite, serpentine, picrolite, or other substances that could supply no material to it. It seems, further, that even after the first plate of asbestos had formed, solutions must have continued to creep along the walls and supply the growing fibre, because many of the veins in chromite, picrolite, etc., are of considerable width.

Ribbon Veins

The ribbon type of vein, found mainly in the Vimy Ridge mine, is very difficult to account for under any hypothesis, but seems to find its best explanation by the hypothesis advanced. It has been shown that the fibres of the individual veinlets of the ribbons stick fairly tightly to one wall, but are easily separated from the other. In simple veins the fibre separates with equal ease from either wall, and it has been shown that in such veins the fibre has also grown from both walls. It seems reasonable to conclude, therefore, that the opposite behaviour of the ribbon fibre is due to its having grown from one wall only, namely the wall from which it separates most easily; and that wall, it has been shown, is always the wall nearest to the outside of the whole ribbon.

The individual veinlets of the ribbon, it was shown, do not parallel the ribbon, but lie at a small angle to it; and this position always has a definite relation to the movement causing the original fissuring (Figure 17). The whole block of rock composing the ribbon seems to have been placed under tension, chiefly along its length, as the parts of the veins lying at a large angle to the general strike are always the widest (Plate I).

The connexion between the ribbon veins and faulting is well shown by occurrences like those illustrated in Figure 17. Why a band of rock should be thus affected, instead of stress being relieved along a single line of fracture, is not known. However, a multitude of closely spaced fractures having thus been formed, the whole series obviously acted as a single fracture, and material started to move inward from the surrounding walls, which at the same time underwent serpentinization. In the individual veinlet, therefore, growth would occur only on the side from which material was being brought in, namely the side nearest the outer edge of the whole ribbon. On the other side, the fibres would jam tightly against the wall, and, undoubtedly, enter any pore, crack, or other minute opening larger than the individual fibre, thereby bolting themselves, as it were, to the wall, so that there is now more or less difficulty in breaking them away. Part of the asbestos of a veinlet would undoubtedly come from the immediately adjacent plate of rock, and the remainder would be brought in from the wide serpentinized zone that bounds the whole ribbon. The latter contribution would be variable, so that no uniform relation need exist between the width of the individual veinlets and that of the adjoining plates of rock.

Various writers, in discussing asbestos veins, have assumed growth from one side of the vein only, to account for various features, such as the lack of a central fissure. The ribbon veinlets yield a criterion for determining whether growth actually was of this type, for in such cases the fibres should stick more tightly to one wall than to the other.

Ultimate Causes of Differences in Grade of Asbestos Fibres

The analyses of fibres given in Table V, page 101, have shown that the more brittle fibres of Vimy Ridge are higher in silica and iron, and lower in magnesia and water, than the soft, flexible fibres of Thetford Mines. The figures given in Table XV, page 114, show that during the serpentinization of 100 grammes of the peridotite of the vein walls, 15·94 grammes of material were removed and 4·26 grammes of water added at Vimy Ridge, and 13·19 grammes of material removed and 4·85 grammes of water added at Thetford Mines. Tables VIII and X, however, show that the relative widths of the altered zones at Vimy Ridge and Thetford Mines are, approximately, 5·23:9·36; so that to obtain the relative amounts of material removed from and added to the altered zones in the two places, the above figures for Thetford Mines should be multiplied by $\frac{9\cdot36}{5\cdot23}$. Thus multiplied, the latter become 23·7 grammes of material removed, and 8·68 grammes of water added.

The asbestos-forming solutions were thus able to dissolve more of the rock constituents at Thetford than at Vimy Ridge. Their greater solvent power may have been due either to their being more aqueous or hotter. It is probable that some temperature difference existed, because at Thetford most of the magnetite is concentrated in veinlets either at the centres of the asbestos veins, or cutting through them, whereas at Vimy Ridge the magnetite appears to have merely replaced individual fibres and groups of fibres; so that the solutions at Thetford may have been somewhat hotter than those at Vimy Ridge. It is improbable, however, that such temperature difference could have been great, because both magnetite and asbestos were being formed in both places; hence the Thetford solutions were probably more aqueous than those at Vimy, or, in other words, the Vimy Ridge solutions carried more mineral constituents in solution, at the time asbestos was formed, than did the Thetford solutions.

Taking the "Loss" columns of Table XV, multiplying the Thetford figures by $\frac{9\cdot36}{5\cdot23}$, and converting all the iron present into Fe_2O_3, for easier comparison, the principal constituents become:

—	Loss, Vimy Ridge	Loss, Thetford	Ratio, Thetford / Vimy Ridge
SiO_2	4·03	10·7	2·64
Fe_2O_3	4·28	6·0	1·4
MgO	5·59	7·0	1·25

From this it is evident that the solvent activity at Thetford, compared with Vimy Ridge, was relatively greatest for silica, next for iron, and least for magnesia. As it has been shown that the Vimy Ridge solutions probably contained more dissolved mineral constituents than those at Thetford, the above results suggest that these constituents were mainly silica, with less amounts of iron, and still less of magnesia. As the conclusion, however, rests on the evidence of only two analyses, it cannot be considered as more than tentative.

Nevertheless, the conclusion is fairly in accord with the evidence afforded by the composition of the fibre itself. The supposedly cooler solutions of Vimy Ridge, partly saturated with silica and iron, might reasonably be supposed to yield a fibre higher in those constituents than the fibres of Thetford Mines; their greater concentration might also, at the same time, make them less apt to give up water, and thus yield a fibre with less water than the Thetford fibre.

Still further evidence to the same effect is afforded by the "painted veins" (page 109). These veins present some curious and interesting

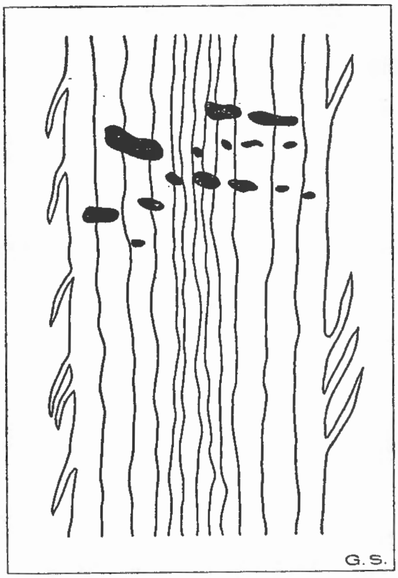

Figure 25. Sketch of a part of the serpentine central vein portion of a "painted vein". Edges display numerous little tension cracks filled with vein serpentine, running off as illustrated. The slightly wavy lines paralleling the walls are serpentine bands, 0·02 mm. wide, of slightly lower birefringence than the rest of the vein material. A few black dots and needles are introduced to illustrate the relation of magnetite to the rest of the vein material.

features. As described, they are rather narrow veins of dark serpentine, flanked by altered zones like the veins of asbestos, but the altered zones are much narrower in proportion to the width of the veins. Under the microscope it is seen that little tension cracks filled with vein material run off into the wall, as in Figure 25; and the serpentine of the vein has a well-defined banding parallel to the walls. Much magnetite is present, and the magnetite mainly forms narrow needles that cut across the banded structure at right angles to the walls. Many veins contain inclusions of the wall materials, exactly like asbestos veins; and it is common to find a string of such inclusions occupying the centre of a vein. This is taken to indicate that growth went on from the two walls, exactly as in the asbestos veins.

The localization of the painted veins is interesting and significant. They are found at the old Lambly mine, near Coleraine, and at the south end of Belmina ridge; in both cases close to the edge of the peridotite mass. They are also found at Reed hill, between ½ and ¾ mile southeast of the Maple Leaf mine, just beyond the edge of the zone of asbestos formation. Smaller veinlets of dark serpentine, similar in their internal structure to the painted veins, but apparently without the altered zones, were found, cut by asbestos veins on the north side of the Bell pit beyond the outer edge of the main asbestos deposit; and in many places in the Vimy Ridge mine, both cutting asbestos veins and cut by them. The apparent lack of altered zones may be due to the fact that the surrounding rocks are fairly thoroughly serpentinized, so that altered zones, if they once existed, would now be obscured.

The occurrence southeast of the Maple Leaf mine indicates strongly that veins of this type must be formed when the solutions became too cool to deposit asbestos. The other occurrences are in line with this conclusion, but discussion of them is deferred until the next characteristic of the painted veins is discussed.

Many of the painted veins contain a little true asbestos, and where this occurs the asbestos always forms a pair of narrow stringers along the *outside edges* of the central vein of serpentine. This arrangement is most significant. It has been inferred that the painted veins, identical in structure and mode of origin with asbestos veins, are serpentine because their temperatures of formation were too low for asbestos to crystallize. The appearance of fibre along the outer rims, therefore, must mark a rise in temperature. The only source of the necessary heat was the solutions themselves; and it must, therefore, be concluded that the solutions were hotter than the peridotites, so that their continued accession raised the rock to the asbestos-forming temperature.

These conclusions elucidate the relations found at the Bell and Vimy Ridge mines. It would be natural for serpentine veinlets to form, in the Bell mine, at the edge of the deposit, where the asbestos-forming solutions were first chilled by contact with the colder rocks beyond the deposit; and continued access of solutions could warm these marginal rocks until asbestos veinlets could crystallize. The occurrences in the Vimy Ridge mine are similar except that there are a few serpentine veinlets that cut the asbestos veins. These were probably formed by a small amount of solution that remained or was introduced after the rock had cooled below the temperatures for crystallization of asbestos.

Temperatures of Asbestos Deposition, How Attained

Magnetite, which is everywhere associated with the asbestos veins, and was deposited after the asbestos, is a mineral commonly formed only at high temperatures. Lindgren[1] estimates its temperature of formation, for the most part, at above 300° C. As asbestos is a mineral containing water, it would be unlikely to form in the higher temperature ranges, so that the temperature at which the veins formed was probably near the lower limit for magnetite, namely 300° C. The solutions may, of course, have been much hotter when first injected.

Even very hot solutions, however, if injected into a cold rock and forced to pass through its pores and other submicroscopic openings like the asbestos-forming agents, would be instantly chilled below the temperature of asbestos deposition. It has in fact been shown that some chilling apparently took place, so that little serpentine veinlets were formed before the asbestos; but such veinlets were very small, and their distribution local, so that the amount of chilling could not have been great. It may, therefore, be inferred that when the solutions were injected the peridotites themselves were fairly hot, probably nearly at 300°C.

In the eastern United States, the average rise of temperature with depth is about 7°C. a thousand feet. At this rate of increase, to attain a temperature of 300°C. the peridotites must have lain at a depth of 43,000 feet, or about 8 miles, approximately. At this depth the overlying rocks would exert a pressure, roughly, of 24 tons a square inch. It is highly unlikely that any such depth prevailed at Thetford, because under such pressures the soft, incompetent, serpentinized peridotites would have deformed by flowage rather than by fracture as they did; and also because such hydrostatic pressures would at once have corrected the tensional conditions prevailing when the veins were formed. It must, therefore, be concluded that the peridotites lay much closer to the surface, and accordingly, that the thermal gradient from the surface down was much greater than 7° a thousand feet.

Places where the downward thermal gradient is high, such as the mercury mines of Idria, Austria, where it is 29° a thousand feet, are usually areas of recent igneous activity. Thetford district was a centre of igneous activity from the late Cambrian, when the Caldwell lavas were extruded, to the Devonian, when granites were injected. Much heat was also undoubtedly produced by friction during the folding movements that followed the Ordovician and Devonian depositions. It seems probable, therefore, that a high thermal gradient existed. Proof of this is afforded by the occurrence of asbestos, both cross fibre and slip fibre, in the Pennington dyke. The dyke lies miles away from any visible heating agent, such as a granite stock or dyke, so that unless there is some nearby intrusive that does not outcrop, the dyke must have been warm enough for the mere injection of solutions to raise it to the temperatures required for asbestos deposition. The intense fracturing and shearing of the dyke, of course, would allow solutions to penetrate rapidly every part, and thus facilitate the heating operation.

The Pennington dyke, however, is a relatively small mass. In the larger peridotite bodies, where the mass of rock is greater, and accession of solutions must have been slower, because of less intense fracturing, it is noticeable that asbestos formed comparatively close to the margins,

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[1]Mineral Deposits, 4th ed., pp. 637, 640-41 (1933).

except under special conditions to be discussed later; and in these marginal deposits the asbestos is small in quantity, with many "painted veins" in which dark serpentine appears instead of asbestos. Serpentine veins, as described, have also been found around the margins of commercial asbestos areas. Consequently, it must be concluded that the general rock temperature, though high, was yet below that required for asbestos deposition, and, except under special conditions, sufficiently below to chill the solutions so that they became comparatively ineffective.

There are, however, four localities where asbestos veins and deposits are found up to distances of half a mile or more within the margins of the main peridotite masses. These are, at Thetford Mines itself, in the 3-mile stretch between Granite hill and Black Lake village, at Vimy Ridge, and at Asbestos. In each area, *but not elsewhere,* there are numerous acid dykes, plugs, and irregular masses. It is difficult to avoid the conclusion that these dykes must have acted as local heaters, by which the temperature of the surrounding peridotites was raised to the point, or nearly to the point, at which asbestos could form. The hot solutions themselves could apparently raise the temperatures of insufficiently heated rocks, as shown by the deposits of the Pennington dyke, and by the character of many "painted veins" (page 109); but undoubtedly their efficiency in producing asbestos would be greatest where the dykes had already raised rock temperatures so high that the heat of the solutions would not be required for this purpose.

The above conclusion affords an explanation of many facts, hitherto puzzling. It accounts for the general association of dykes and asbestos crisply expressed by the miners' proverb, "No granite, no mine." It explains the presence of serpentine veinlets around the margins of deposits, where they might be expected because the present margin would be the limit of the heated area. It gives a reason for the common occurrence of very rich ground in the general neighbourhood of large granite masses. One of the best examples of such occurrence is found in the former Jacobs pit, now a part of the Beaver mine. This rich block of ground, some 600 feet in diameter, contained numerous wide veins of very high-grade fibre, and is still being mined for crude fibre. It is notable for the number of dykes present; and the bottom of the old pit, some 300 feet in depth, is a network of irregular granite masses that almost form a floor, the heating effect of which must have been very great.

It seems probable, also, that the quality of the fibre is closely tied with the heating effect of the dykes. At Black Lake the quality of fibre is poorer than at Thetford Mines, and dykes, though numerous and many of them large, are less closely spaced than at Thetford. At Vimy Ridge, where the hardest fibre is obtained, the dykes in the pit are few and small, though larger masses are known to exist in the neighbourhood. The effect of cooling on the incoming solutions would be to lessen their ability to take materials into solution, thus producing the effects discussed on a preceding page (pages 134, 135).

A peculiar feature of the Vimy Ridge mine not previously mentioned is the presence, at the east end, of a body of high-grade, green fibre entirely unlike the harsh brown fibre that surrounds it. A possible explanation of the occurrence is that the body of green fibre was a more highly heated area than the remainder of the pit. This might be because of the presence at no great distance of some body of intrusive; or the green part may have been a central channel of entry for solutions, which lost their heat as they spread out.

If the conclusions thus reached are correct, it will be difficult to foretell the depth to which any given deposit may extend. The granitic dykes pinch, swell, and change direction both in strike and dip with such irregularity that their behaviour beyond the point of observation cannot be predicted. It seems probable, therefore, that deposits will prove to be pod or lens shaped, their occurrence depending on the fortuitous association of a sufficient number of intrusive bodies. It seems reasonable to suppose that such pods or lenses may occur at any depth, and that many may never reach the present surface.

General Summary of Genesis of Asbestos

Folding and deformation toward the close of the Ordovician period were accompanied, in southern Quebec, by injection of masses of peridotite and pyroxenite. Some of these formed dykes roughly paralleling the bedding of the sediments, others are large plugs or laccoliths. Further folding, apparently in the Devonian period, was accompanied by injection of granites and related rocks. Indirect evidence suggests that the numerous acid dykes and plugs intruding the peridotites were injected at this time.

The peridotites have suffered a general alteration by which about half of the original olivine and pyroxene is converted into serpentine. Where "peridotite" is used in this report, this partly serpentinized material is commonly meant. It is believed that the general serpentinization was caused by water present in a peridotite magma reacting with the mineral constituents in the later stages of crystallization.

A second, more local alteration was caused by the injection of the heated waters or vapours producing the asbestos veins. These waters or vapours entered along faults, the walls of which they converted into serpentine. Longer continued action, in many cases, converted fibrous materials formed in the fault planes into brucite. From the fault fissures the waters penetrated all the pores of the rock, and wherever they encountered an incipient fissure they reacted with the peridotite to convert the walls of the fissure into serpentine, and to carry some of the excess material into the fissure, where it was deposited as asbestos. The process seems to have been conditioned in part by temperature, and in part by the state of strain induced in the rocks by faulting; and it went on either until temperatures dropped below the reaction point, or until the strain was removed by deposition of asbestos, and equilibrium was attained. Various lines of evidence indicate that this second alteration took place after injection of the acid dykes, and hence, quite probably, toward the end of the Devonian deformation.

The asbestos-forming waters were undoubtedly hot, as one of the last products deposited was magnetite, a mineral formed almost wholly at high temperatures. Where the mass of peridotite encountered was small, as in the case of the Pennington dyke, the excess heat of the waters seems to have been sufficient to raise the rock temperature to a point at which asbestos could form. Where they encountered larger masses of peridotite this could not take place, and in such cases, where sufficient additional heat was not furnished by granitic dykes, asbestos formed only close to the edge of the peridotite mass. In these cases, also, the amount of asbestos is commonly small, and many veins are the so-called "painted veins," with vein material wholly or largely of dark serpentine.

In four localities the process of vein formation is carried for half a mile or more into the edge of the peridotite, and each of these localities is also a place where acid dykes are numerous. Beyond this general areal relation there appears to be no connexion between the occurrence of granite and that of asbestos; and the hypothesis is advanced that the dykes acted solely as heaters, by which the temperature of the peridotite was raised sufficiently to prevent undue chilling of the incoming solutions, and thereby permit reaction to go on. The conclusion is considerably strengthened by the fact that serpentine veinlets, indicating chilled conditions, are numerous around the margins of deposits, but tend to be few or lacking within the body of a deposit.

The asbestos deposits are all localized along the northwest side of the main peridotite mass, and the asbestos-forming agents, therefore, must have entered from that side.

If the preceding conclusions are correct, as the writer believes them to be, any yet undiscovered deposits of asbestos must lie within areas of peridotite that contain considerable numbers of acid dykes, as in no other manner could the larger bodies of peridotite have been heated sufficiently to permit reaction with asbestos-forming solutions. The most likely areas for further prospecting, therefore, according to data on hand, appear to be: (1) the strip of peridotite about ½ mile wide, measured from the northwestern contact, lying between Granite hill and Black Lake village; and (2) the drift-covered area, likewise within the half-mile from the contact, between Black Lake and the Vimy Ridge mine.

The facts and conclusions given in the preceding pages thus indicate that three factors were required to produce an asbestos deposit in Thetford region: (1) faulting, to break up the rock and permit ingress of solutions; (2) an adequate supply of the necessary solutions; and (3) injection of acid dykes, in sufficient numbers to raise the temperature of the serpentine to a point where it would react readily with the solutions. Lack of any one of these factors would prevent formation of a deposit, even if the other two were present.

CHROMITE

GENERAL HISTORY

Chromite is a mineral that has come into use only within the last century. The metal chromium was not discovered until 1797, and for years the expense of bringing its ores from the Ural mountains to Europe greatly restricted its economic use. Not until chromite was discovered near Baltimore, Maryland, in 1827, did it begin to be extensively employed in the arts. The Turkish ores were discovered in 1846, and from 1860 to 1896 dominated the markets of the world because of their excellent quality and comparative cheapness. Their average annual output up to 1929 was about 12,000 long tons, and the amount since 1929 has largely increased.

About 1896 Russia and New Caledonia began to produce such large amounts that Turkey fell into third place as a world producer. Russia, with an annual production of some 20,000 tons, maintained first place until 1902, after which New Caledonia took that place. About 1906 the great ore-bodies of Southern Rhodesia were opened, and by 1910 their production equalled that of New Caledonia. From 1910 to 1920 Southern Rhodesia alternated with New Caledonia as the world's leading producer, except in 1918 and 1919; but in 1921 the production of Southern Rhodesia began to rise so rapidly that it easily held first place up to 1931, and in 1929 it yielded almost as much as all the rest of the world. In 1933 and 1934 it was, however, surpassed by both Russia and Turkey.

World production of chromite in 1903 was approximately 61,000 long tons. Between 1904 and 1915 it fluctuated from 101,000 tons in 1905 to 186,000 tons in 1914. War needs brought production up to 325,000 tons in 1918, after which it fell off to 128,000 tons in 1921. In the following years tonnage rose by leaps and bounds to 587,000 tons in 1929, but depression brought great restriction of use, to a low point in 1932 of 294,000 tons. Since that year a gradual increase has taken place.

USES OF CHROMITE

About half the chromite mined is used in alloys of various kinds, chiefly with steel. Used either alone or with other substances such as carbon, silicon, and nickel, chromium imparts to the steel increased hardness, resistance to wear, and resistance to corrosion. The alloys are finding a constantly increasing number of uses along these lines. High-speed tools, safes and burglar-proof bars, automobile engine valves, bearings of all kinds, furnace tubings, armour plate, gun barrels, acid tanks, and a thousand other articles requiring the above qualities are now manufactured, using different alloys. Stainless steels are alloys containing 9 to 16 per cent of chromium with less than 0·70 per cent of carbon.

About two-fifths of the chromite produced is used for refractories, chiefly as furnace linings. It is either utilized in the crude form as it comes from the mines, or is ground and moulded into bricks. Its value for this purpose is due to a combination of properties. At high temperatures it remains hard and resistant to abrasion, does not melt, crack, or spall, is not much affected by sudden temperature changes, and is not attacked by acids, fused ore, or slags. As it is a neutral refractory it is specially useful where basic or acid refractories are undesirable. Its melting point has been determined as varying between 1,450° and 1,850°C., according to composition (2,600° to 3,200° F.).

Within recent years experiments have been directed to preparation of a satisfactory mixture of chromite and magnesite for refractory purposes. The expansion of a suitable mixture of these substances, on heating, is practically nil, so that it is particularly valuable as a converter lining. A mixture of chromite and silica has proved more useful for certain purposes than pure silica brick.

The remainder of the chromite mined, about one-tenth of the annual production, is absorbed by the chemical trades. A great variety of dyes is prepared from the salts; in fact, the metal derives its name from the Greek word Chroma, meaning colour. Chromic oxide, Cr_2O_3, has a beautiful green colour, and is the main constituent of many green paints, such as chrome green, emerald green, and Cassal's green. It is also used for glazing and colouring in the manufacture of enamels, pottery, and glass. Chromates of lead yield various yellows, such as chrome yellow, lemon yellow, Paris yellow, and royal yellow; and the basic chromates of lead are the base of chrome orange, chrome vermilion, and other red tints. Manganese chromate is brown; and tin oxide with a little chromic oxide affords certain crimson and pink colouring matters.

Chromium salts are also used to a large extent in the dye industry as mordants for fixing coal tar dykes in wool, silk, and certain printed cottons. They are used in dying khaki materials. Chrome leather, tanned with chromium salts, is unusually tough, resistant to heat and moisture, and capable of being dyed. These qualities make it particularly suitable for fine shoes and gloves, and for such articles as high-speed belts. Bichromates are powerful oxidizing agents, and hence are used for bleaching oils and fats, in the preparation of some aniline dyes, in certain galvanic cells, and in various laboratory processes. A mixture of potassium dichromate and gelatin becomes insoluble when exposed to light, and this behaviour renders dichromate useful in colour printing, block printing, photolithography, and similar processes. Chromium compounds are employed in making safety matches and a variety of minor purposes.

COMPOSITION

Though a considerable number of minerals containing chromium are known, the only ore of this metal is the mineral chromite. Theoretically a chromate of iron, $FeCr_2O_4$, or, as more commonly written, $FeO.Cr_2O_3$, no chromate of that composition has ever been actually found, the natural mineral always contains more or less magnesia and alumina, which replace the iron and chromium. As a consequence, the percentage of chromium may vary from nil to more than 60 per cent. This behaviour is due to the fact that the chromites form part of an isomorphous series of minerals, the spinels, all of which have the general composition $R''O.R'''_2O_3$, where R'' may be one or more of the metals magnesium, ferrous iron, zinc, and manganese, and R''' one or more of the metals aluminium, ferric iron, and chromium. Those in which chromium is an important part of the base, however, never seem to contain zinc or manganese.

The simpler members of this series are

Spinel	$MgO.Al_2O_3$
Chromite	$FeO.Cr_2O_3$ theoretically
Hercynite	$FeO.Al_2O_3$ (Iron spinel)
Magnetite	$FeO.Fe_2O_3$

In addition, there are a number of minerals of intermediate composition, among which should be mentioned picotite, or chrome spinel, the formula of which is generally written $(MgFe)O.(AlFeCr)_2O_3$. Among the picotites are classed those members of the series that contain less than 10 per cent of chromium. All these minerals crystallize in the isometric system, and the common form is the octahedron.

Poitevin[1] has found it useful to study the chromites as if they were mixtures of the four compounds $MgO.Al_2O_3$, $MgO.Cr_2O_3$, $FeO.Cr_2O_3$, and $FeO.Fe_2O_3$. Although such a classification may be purely artificial, it has many advantages for comparison purposes.

It is easy to see that, with a mineral of such variable composition, the value of a deposit will not only depend on the proportion of chromite in the deposit, but also on the percentage of chromium in the kind of chromite composing the deposit. The variable composition of the chromite has been a common source of misunderstanding and even serious financial loss to operators accustomed to dealing with minerals of fixed composition such as chalcopyrite or galena. With deposits of the latter type, when the percentage of copper or lead is too low, it is known that some other mineral is present, and that if this can be removed the grade will be improved. This is not necessarily true in the case of chromite; for the low grade may be due to a low percentage of chromium in the mineral itself; and obviously no process of purification can raise the chrome content of the ore above what it is in the chromite itself.

Chromite is an iron-black to brownish black mineral, with a metallic to sub-metallic lustre. In thin section it is opaque as a rule, but very thin edges are slightly translucent and have a yellowish to reddish colour. Some varieties are feebly magnetic. The hardness is 5·5 on the ordinary mineralogical scale, or slightly softer than orthoclase feldspar, and the specific gravity 4·3 to 4·6. It is readily distinguished from magnetite, the mineral with which it is most likely to be confused, by the colour when finely powdered, commonly termed the streak. The streak of chromite is brown, whereas that of magnetite is black. Another readily applied means for distinction is to test with a weak magnet, which attracts and holds grains of magnetite but not of chromite.

Chromite for market purposes is usually required to contain at least 50 per cent chromium, and much of that now sold is of even higher grade. At times, however, as during the late war, 40 per cent or even 25 per cent material has been marketed. The increased use of chromite has introduced still other requirements. Chromite for making ferro-chrome is more valuable if low in iron and high in magnesia and alumina, because the latter substances are slagged off during smelting. Consequently, for this use the principal matter of importance is that the ratio of iron to chromium in the ore should be low. When the chromite is to be used as a refractory, on the other hand, the proportions of iron and magnesia are of little importance, but the proportion of alumina should be low, because this constituent renders the chromite more fusible.

PRICES

Prices of chromite have fluctuated widely in the last forty years, making mining hazardous except where supplies are large and cheaply obtained. Thus ore containing 50 per cent of chromic oxide sold in 1895 for $15.50 a ton; in 1900, for $16; in 1905, for $12; in 1909, for $10.50; in 1914, for $14.50. During 1917-18 the price rose enormously, so that in August 1918, 50 per cent ore sold for $80 a ton, and ores containing as

[1] Poitevin, Eugene: Geol. Surv., Canada, Sum. Rept. 1930, pt. D, pp. 15-21.

little as 25 per cent of chromic oxide were being marketed. Prices of 48 per cent ore at the present time (March 1934) are $20 to $21 in London and about $18 in New York.

CHROMITE IN THE EASTERN TOWNSHIPS OF QUEBEC

The first discovery of chromite in Canada is attributed to Sir William Logan, who in 1842 is said to have found some loose blocks near lake Memphremagog. Later, in the course of a systematic examination of the Eastern Townships region, he noted the common occurrence of the mineral as scattered grains in the serpentines. The first discovery of an economic body, according to Logan's report for 1846, appears to have been made by Mr. Batchelder of Troy, Vermont, on lot 23, range VIII, Bolton tp., near the west shore of lake Memphremagog. This discovery, however, lay virtually untouched until 1918, when a little work was carried on. No actual mining was done until 1861, when Major R. G. Leckie took out some 10 tons of ore from lot 4, range II, South Ham tp. About 1886 several tons were mined from lot 24, range III, Wolfestown tp. In 1887 Dr. James Reed shipped to Philadelphia 54 tons of ore mined from lot 1, range X, Leeds tp., as well as 4 or 5 tons of lower grade from lot 16, range IV, Thetford tp. He also sent specimens to the Antwerp exhibition, where they attracted much attention. Obalski states that, as a result, offers to purchase lots of as much as 2,000 tons were received, but had to be refused because the known deposits were neither large enough nor rich enough to be profitably worked. Nevertheless, he kept the possibilities before the attention of prospectors, in view of the strong probability of the discovery of larger bodies. When, therefore, Mr. Provencal of Black Lake discovered an important body of ore in April 1894, he was able almost immediately to get in touch with purchasers and begin mining. Other discoveries soon followed, and shipments of about 1,000 tons were made that year. From that date there was a fairly steady production of chromite until 1910, when the competition of the ores from Rhodesia and New Caledonia became too strong, and production ceased. The war both interfered with foreign shipments and increased the consumption of the mineral, so that in 1915 operations were resumed and continued until 1921. Since that time a few tons of chromite have been shipped from time to time, but no large-scale mining has been carried on.

More than one hundred individual occurrences of chromite in the Eastern Townships are known, although the majority, of course, are of minor importance. Excellent descriptions of all those of importance have recently been published by B. T. Denis (42) rendering it unnecessary to give them here. Attention will, therefore, be confined to descriptions of the geologic relationships.

Situation of Chromite Deposits

Chromite deposits have been found both in the peridotites and in the pyroxenites. Of these, the bulk are in the peridotites, but at least one large deposit, the Montreal chrome pit, and one of lesser size, the Hall deposit, occur in pyroxenite. Of the former, some are found in comparatively small bodies of peridotite, such as the chrome body in the Beaver mine, at Thetford Mines, and the bodies in the peridotite between Breeches and Sunday lakes. Those found in the large mass of peridotite extending from Granite hill to Caribou mountain appear to be concentrated within a band about a mile wide, along the southeast side of the mass. This arrangement may have some genetic significance not yet recognized.

The deposits found in pyroxenites occur, without exception, in parts of the rock that have been thoroughly converted into serpentine. Most of the occurrences, including the two larger mentioned above, are found within a few hundred feet of the margins of the intrusive; but some, like the pits of the American Chrome Company on lots 6 and 7, range B, Coleraine tp., are somewhat farther. Production from pits farther within the intrusive, however, has been small.

The peridotite surrounding chromite masses, likewise, appears in general to be pretty thoroughly converted into serpentine. However, this is not invariable, as thin sections through small veins from some of the pits exhibit peridotite not more serpentinized than the average of the general mass.

Nature of Chromite Masses

It has long been recognized that chromite is one of the essential constituents of peridotite and dunite, and scattered grains of the mineral may be found in almost any hand specimen. In places it may be observed that a number of such grains are arranged in a straight or gently curving line, and as such lines are usually parallel to strings of pyroxene crystals, the arrangement may perhaps be due to flow movements in the cooling magmas.

Larger concentrations of chromite are of two types, disseminated and massive. In the first, grains of chromite are scattered fairly evenly throughout a matrix of serpentine, and the chromite-serpentine mixture occurs in bands, usually ½ inch to 1½ inches in width, which run in straight or gently curving courses parallel to one another and to flow textures, if any, in the surrounding peridotite. The chromiferous bands are separated by bands of pure serpentine containing no chromite, and usually of about the same or slightly lesser width. The distribution of chromite within the chromiferous bands is fairly uniform, although there is a slight tendency toward bunching of crystals. As a rule, the chromite grains constitute between 15 and 20 per cent of the volume of a band, the writer estimates; but in some cases their concentration may be considerably greater, sufficiently so for the band to approach massive chromite. The chromiferous bands end, usually, by gradual wedging.

Chromite bands of this type appear to be confined to the peridotites. They are found in Red Hills area, but there seem restricted to serpentine derived from pyroxene-rich peridotite. None has been recognized in serpentine derived from pure pyroxenites, or in fresh pyroxenites. Further, where a pyroxenite dyke or its serpentinized equivalent cuts across such bands, the chromite invariably stops at the margin of the dyke, and continues on the other side; it never runs through the dyke. It is known that the pyroxenites solidified very soon after the peridotites; so that chromite bands must have had their present form very early in the magmatic history; in fact, taking into consideration their parallelism to flow textures, it is reasonable to conclude that they are original differentiates of the peridotite magma.

The second type of chromite occurrence differs in every way from that described. The chromite grains, instead of being disseminated through serpentine, are closely packed together; and in places, in thin section, the masses of grains surround small remnants of serpentine in a way that suggests replacement. In places the chromite forms vein-like masses that ramify through the rock following irregular courses, and varying greatly in width. Such " veins " do not seem to follow any pre-existing fissure, and are apt to display discontinuities. The bulk of the massive chromite, however, does occur in pre-existing fissures that may be either faults or, more commonly, the tension cracks running off from faults. The following descriptions of individual occurrences will illustrate what was observed in a great many places.

In the eastern end of the Hall chrome pit (northeastern end of lot 16, range A, Coleraine tp.) the rock is serpentinized pyroxene-rich peridotite cut by a small fault that strikes east and dips 55 to 60 degrees north. Though little chromite occurs in the fault, numerous, short, vein-like bodies project from it into the hanging-wall, and one was observed to project into the foot-wall. One projection into the hanging-wall was seen to tail into the fault fissure, as in Figure 26A. Each chromite vein has an edging of light green serpentine somewhat softer than normal serpentine, and perhaps, therefore, containing some talc or chlorite. These edgings vary from one-sixteenth to one-eighth of an inch in thickness, and grade outward into the darker serpentinized peridotite.

At the northeast end of lot 17, range A, Coleraine tp., a chromite pit was being worked in 1933 by E. T. Gray, of Thetford Mines. The country rock is pyroxene-rich peridotite containing numerous chromite bands of the flow type, which strike north 70 degrees east. A fault that strikes north 10 degrees west and dips 70 degrees east has much massive chromite in and near it. No constituent other than chromite could be detected in the ore with a lens; the ore has vein-like forms with sharp, clean-cut walls; the veins cut the rock in various directions, and tail into thin stringers.

The fault also contains irregular masses of light-coloured rock consisting mainly of vesuvianite, which presumably are the altered equivalents of an acid intrusive. Mr. Gray kindly donated a specimen showing a slab of chromite about an inch thick lying entirely within the vesuvianite. The vesuvianite breaks through the chromite in a number of places, so that the chromite is clearly the older.

In the Caribou chrome pit near the northwest shore of Caribou lake the rock is normal olivine-rich peridotite cut by parallel faults spaced 20 to 30 feet apart. They strike north 80 degrees west and dip northward at angles varying between 35 and 60 degrees. Thick, irregularly shaped, vein-like masses of massive chromite are found in the shear zone of each fault.

The northernmost fault visible in the pit displays some interesting relations (Figure 26B). The country rock is crushed to a sandy gouge over a width of about 2 feet. Two veins of chromite, each about 2 inches wide, run through this gouge, cutting across the schistosity at an angle of some 20 degrees in the central part, and parelleling it near the edges. Obviously the chromite must have been introduced after the faulting.

About half-way between Breeches and Sunday lakes, Disraeli map-area, the rock is a normal olivine-rich peridotite with flow textures, as

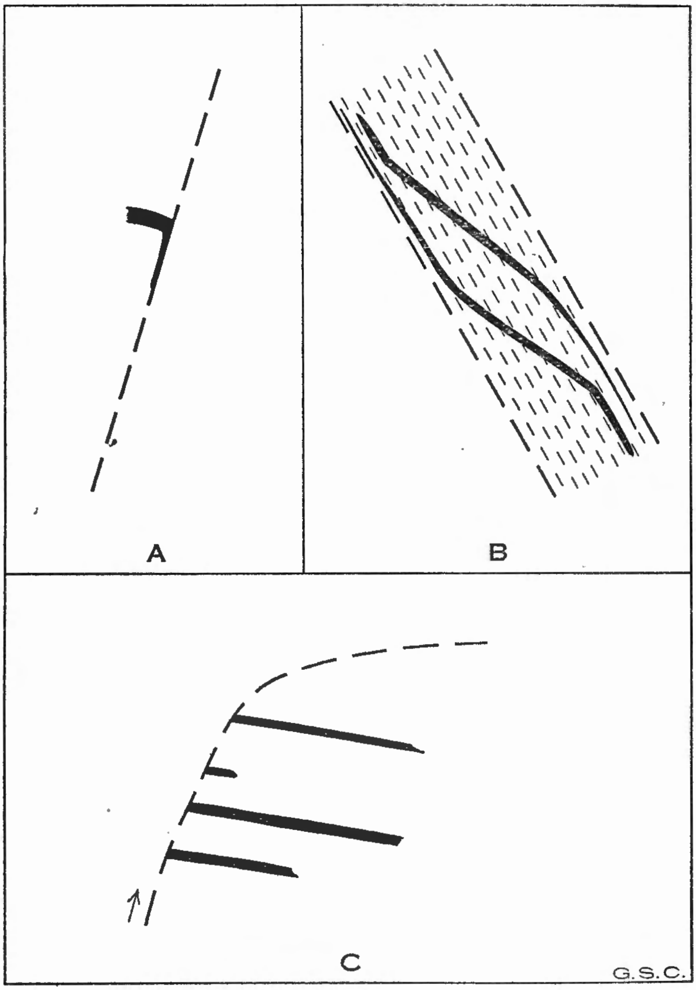

Figure 26. Chromite veins at: (A) Hall chrome pit; (B) Caribou chrome pit; (C) pits south of Breeches lake.

determined in several places from strings of chromite grains, striking north 10 degrees west and dipping about 60 degrees west. The rock is badly broken by faults, only the oldest of which have any connexion with chromite deposition. One such fault strikes approximately east. The dip, which is southward, rolls from 65 degrees south at the bottom of a shallow pit, to horizontal about 6 feet above. The fault is a thrust, and the rock of the elbow (Figure 26C) is much fractured by joints more or less parallel to the horizontal part above. No chromite was found in the main fault, though it may have been removed by the miners; but the joints and little subordinate faults contain plates of chromite. The writer pried off a plate about 1½ square feet in area and ¼ inch thick from the face of one of the subordinate faults.

The chromite of these veins is hard and massive, with no other constituent visible under the lens; and the veins are flanked by bands of light green serpentine about one-twentieth of an inch wide.

Additional facts of the same sort were obtained from the examination of other pits, but need not be detailed here. In every pit where massive chromite was found, except one, there is evidence that it is of the later, vein type. The exception is the Belanger pit (controlled by the Vanadium Corporation), at the west end of Caribou lake, where bands of disseminated ore pass in places into bands of massive ore, by increase in the proportion of chromite to serpentine.

The facts thus show that the peridotites are cut by faults that cross primary textures in the peridotites, such as flow textures. The faults are, therefore, later than the solidification of the peridotites. The chromite fills the fault fissures, appears in places to replace parts of the walls, and in one place cuts across the schistosity of a fault zone. It is, therefore, later than these faults. Other faults occur, to which the chromite displays no relationships, and these are presumably later than the chromite deposition.

It is necessary to conclude, therefore, that the chromite of Thetford district is of two different ages and origins. The bands of disseminated chromite appear to be original magmatic constituents, formed by magmatic differentiation, the present form of which is due to flowage in the cooling magma. The massive chromite of the faults is undoubtedly later, and formed by introduction of chromite-bearing material into faults and associated fissures. The writer can advance no suggestion as to how a mineral so insoluble and so heat-resisting could have been carried; but that it was so carried appears indubitable.

Age

The age of the disseminated chromite has already been indicated, from its various relationships, as the same as the age of the peridotite itself. The massive chromite, on the other hand, is later than the peridotite, but some facts enable it to be fixed more accurately.

The massive chromite has been seen in many places to be cut by veinlets of asbestos. In a few places the asbestos veins are as much as ¼ inch wide, but mostly they are mere stringers. The chromite is, therefore, pre-asbestos in age.

The chromite is also cut by the altered products of acid dykes, as in the case described from Gray's chrome pit. Similar relations may be seen in many places. There seems no reason to believe that vesuvianite, garnet, and diopside of these masses represent anything but altered dyke material; and if so, the chromite must be older than the dykes. The conclusion is supported slightly by one already drawn, and which appears to rest on good evidence, namely, that there was probably little difference in age between the asbestos veins and the dykes.

In the pyroxenite masses no chromite is found except in the parts completely altered to serpentine; and all the chromite so occurring is in faults and associated fissures that cut this serpentine. The chromite must, therefore, have been introduced after the serpentinization was complete. Acid dykes occupy the same fissures, and appear to be somewhat later than the chromite ore; and it has been shown (page 81) that the serpentinization, in part at least, probably took place after injection of the dykes. The sequence of events must, therefore, have been:

1. Injection and consolidation of pyroxenite.
2. Faulting, followed by serpentinization.
3. Further faulting of serpentinized rock.
4. Introduction of chromite.
5. Injection of acid dykes.
6. Serpentinization, alteration of dyke materials.
7. Formation of asbestos veins.

The last two events were probably synchronous, or nearly so.

Most writers have supposed that the introduction of the chromite probably followed fairly closely the consolidation of the peridotite and pyroxenite, and there is nothing in the above sequence to contradict the conclusion. Equally, however, there is nothing to support it; and the possibility should, therefore, not be overlooked, that the chromite filling fissures is considerably later.

SOAPSTONE

Soapstone has been quarried sporadically from pits in the district for many years, but the chief, and for many years the only, producing pit was that of the Broughton Soapstone and Quarry Company, in lot 12, range XI, Broughton tp. In 1933 two other deposits were opened, one on lot 11, range XI, Broughton tp., and the other on lot 2, range V, Thetford tp.; but no statistics of production are yet available. The great part of the soapstone produced is sold as blocks for furnace linings, but of late years some has been utilized for making stoves, clock cases, ash trays, and other articles of use and ornament. The finer grades have pale green tints, mottled and streaked with grey or brown, and when polished make an attractive stone. The value of the rock produced fluctuated for some years between $45,000 and $50,000, but in 1935 was only $32,000[1].

All the soapstone of Thetford district is an alteration product of peridotite dykes. It has been thought that soapstone was mainly an alteration product of pyroxenite, as serpentine is of peridotite, but the writer has found no evidence supporting this conception.

SITUATION OF DEPOSITS

Soapstone is found at several places along the Pennington dyke, namely at the Federal mine, Thetford tp., range V, lot 9, in lots 5, 6, and 7 of the same range, and at the Kitchener pit, lot 2. The pit of the Broughton Soapstone and Quarry Company, in Broughton tp., range XI, lot 12, is probably a part of the same dyke, which apears to have been separated from the rest by faulting or movement of some sort. Farther east, soapstone is found at the Fraser mine, Broughton tp., range VII, lot 14, on what

[1]Preliminary statement, Bureau of Mines, Quebec.

appears to be a continuation of the Pennington dyke. The two dykes that run northwest through ranges X and XI of Broughton township are partly or thoroughly converted into soapstone in places, although none of it has yet been mined. Pits have been worked on what appears to be a parallel dyke about a mile north of Pontbriand, in ranges II and III, lot 12, Thetford tp. Soapstone has been found in drill cores near the eastern edge of the Thetford body of peridotite, on the property of Asbestos Corporation.

In addition to these, Wilson[1] also mentions occurrences in Inverness tp., range 1, lot 1; Ireland tp., range VII, lot 2; Wolfestown tp., range II, lot 20; and Ham tp., range I, lots 22 and 25 (old numbers, 43-44 and 49-50). These were not examined by the writer.

All the occurrences on the Pennington dyke, except two, are found on the north or foot-wall side of the dyke; and in those at the Federal and Kitchener pits, the only ones where mining has gone far enough to expose the structure, it is evident that the *only parts of the dyke converted into soapstone are those that have been drag-folded into a nearly horizontal position.* Where the wall of the dyke dips steeply, no alteration to soapstone has occurred. It is strongly suspected that the soapstone at the Fraser mine lies in a similar drag-fold, because of the unusual width of the outcrop at this place. The exceptions mentioned above are found in Thetford tp., range V, lots 5 and 6, where the south or hanging-wall is converted into soapstone; and the pit of the Broughton Soapstone and Quarry Company, where the dyke is only 50 or 60 feet wide and is entirely converted into soapstone.

The two dykes running northwest through ranges X and XI of Broughton township have low dips, paralleling the schistosity of the sediments; and the parts most thoroughly converted into talc are the south ends, where dips are almost flat. The pits north of Pontbriand are not worked deeply enough to expose the structure well, but the little data at hand suggest a drag-fold like those at the Federal and Kitchener pits. The soapstone in the drill holes near Thetford Mines was all found near the margin of the peridotite.

WALLS AND WALL-ROCK ALTERATIONS

The wall-rocks of all the known soapstone occurrences are siliceous quartzites or schists. All the dykes are injected into the Bennett schists, which are mainly schistose quartzites of varying degrees of purity. For distances of a few feet from the margin of the soapstone, these schists are converted into a mass of dark green chlorite, commonly termed "blackwall." In this they resemble closely the soapstone deposits of northern Vermont.

The following analyses of the country rock and "blackwall" at the Federal mine are taken from a paper by A. H. Phillips and H. H. Hess[2], and show the nature of the alteration:

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[1]Wilson, M. E.: Talc Deposits of Canada; Geol. Surv., Canada, Ec. Geol. Ser. No. 2 (1926).

[2]Phillips, A. H., and Hess, H. H.: Metamorphic Differentiation at Contacts between Serpentinite and Siliceous Country Rocks; Am. Min., 21, p. 340 (1936).

TABLE XVIII

Analyses of Unaltered Schist and "Blackwall" Walls of Soapstone Deposits

—	Unaltered schist	Blackwall
SiO_2	63·14	27·18
Al_2O_3	16·46	18·91
Fe_2O_3	0·93	2·76
FeO	4·61	16·28
MgO	2·60	20·76
CaO	0·87	0·98
Na_2O	0·55	0·38
K_2O	4·35	0·24
H_2O+	2·82	10·55
H_2O-	0·14	0·21
TiO_2	0·78	0·98
P_2O_5	0·07	0·27
MnO	0·98	0·28
CO_2	....	....
C	1·65	....
Totals	99·65	99·78

Analyst, A. H. Phillips.

Thus the alteration of siliceous schist to chlorite rock involves a large loss in silica and the alkalis, and great increases in magnesia, iron, and water, with a small increase in alumina.

ALTERATION OF SERPENTINE TO SOAPSTONE

No analyses to illustrate this change were made for the writer, but the following analyses from various sources will illustrate the nature of the change:

TABLE XIX

Analyses of Serpentine and Soapstone

—	a	b	c	d	e	f
SiO_2	34·40	40·08	37·66	59·62	54·88	59·66
Al_2O_3	0·50	2·11	1·61	1·40	3·59	1·67
Fe_2O_3	0·82	1·13	6·15	1·21	1·44	0·37
FeO	3·79	1·70	1·87	4·25	4·63	4·12
CaO	0·02	0·20	tr.	....	1·10	....
MgO	42·36	37·90	38·66	28·49	27·22	29·26
H_2O+	15·17	13·89	12·49	4·61	5·86	4·90
H_2O-	0·47	1·35	0·75	....	....	....
CO_2	0·38	....	....	....	1·52	....
Minor	1·77	0·10	0·20	....	....	....
Totals	99·68	98·76	99·61	99·58	100·24	99·98

a. Red weathering serpentine, this report, No. 1, Table I.
b. Serpentine near Black Lake station. J. A. Dresser, Geol. Surv., Canada, Mem. 22, p. 29. Analyst, M. F. Connor.
c. Serpentine, lot 40, range II, Garthby tp. J. A. Dresser, loc. cit.
d. Soapstone, lot 9, range V, Thetford tp. H. S. Spence, Mines Branch, Dept. of Mines, Canada, 1922, p. 43.
e. Soapstone, lot 7, range V, Thetford tp. H. S. Spence, loc, cit.
f. Soapstone, lot 5, range V, Thetford tp. H. S. Spence, loc. cit.

Although these analyses are not exactly comparable, as they do not show the same rocks before and after alteration, they do indicate in a general way that the alteration of peridotite to soapstone must have involved important additions of silica and losses of magnesia and water. Nothing can be said as to the changes in the minor constituents; to determine them, analyses across the zones of alteration must be made. It will be noted, however, that these alterations are the exact opposite of those found in the alteration of the wall-rock. In changing to soapstone, the peridotite gained much silica, whereas the wall-rock lost silica and was altered to chlorite. The peridotite lost magnesia during the change, and the wall-rock gained it.

ORIGIN OF SOAPSTONE

To account for the above changes, and others of a higher temperature type found in Vermont but not in Thetford district, Phillips and Hess[1] have advanced an hypothesis similar to that offered by the writer to account for the alteration of the feldspathic dykes at Thetford Mines. They have supposed that the solutions causing the alteration rose from depth, because it is mainly the foot-wall sides of dykes that have suffered alteration, and in many places alteration is confined to places where such solutions would be ponded, as beneath drag-folds. The solutions probably contained little but water, because very little actual addition of material seems to have taken place. The hot waters, saturating all the pores of the rocks, took into solution whatever minerals they touched; whereupon an interchange naturally began, with the constituents of the siliceous schist drifting into the peridotite, and those of the peridotite into the siliceous schist. As a result, for several feet on each side of a contact the peridotite is silicified and converted into soapstone, and the schist took on magnesia and was converted into chlorite. The hypothesis appears to account for all the observed phenomena, which is strong presumptive proof of its correctness.

AGE

In places, veins of picrolite or asbestos may be found within the soapstone bodies, altered to talc; and at the Kitchener pit Hess, in company with the writer, traced asbestos veins from the serpentine into the soapstone body, and found them altering to talc, though retaining the cross-fibre structure. From such data Hess has concluded that the soapstone was formed after, "and probably long after," the formation of the asbestos veins. It cannot be denied that the soapstone was formed after the asbestos; but the writer believes that the two processes followed each other closely, and were both effects of the same injection of solutions. Several pieces of evidence in favour of this contention are at hand. In both processes the solutions have been inferred to be mainly water, which, if the processes were separated by a time interval, would be an unlikely coincidence. Again, the asbestos originated after the Devonian deformation, since which time there is no evidence of igneous intrusion, vein formation, or other source of waters for forming soapstone. Thirdly, it will be noted that soapstone could not form in any peridotite body until all the peridotite was converted into serpentine, because so long as any original olivine remained, water would react with it to form serpentine rather than with

[1] Loc. cit.

serpentine to form talc. With the exception of the small amount of soapstone near Thetford Mines, where a wide margin of serpentine surrounds the central peridotite, it is noticeable that all the soapstone deposits are found in the serpentine dykes, and that thorough conversion to soapstone occurs only where the dykes are unusually narrow. Such relations are exactly those that would be found: (*a*) where the quantity of solution was in excess of that required to serpentinize the rock completely, while forming asbestos; and (*b*) where the body of rock was small enough for the incoming solutions to heat it to the point where reaction could take place. In larger bodies of peridotite the quantity of solutions was not sufficient to serpentinize it wholly, nor could they raise its temperature to the reaction point; hence soapstone could not form.

ANTIMONY

In South Ham tp., range I, lot 56, considerable work was done many years ago on an occurrence of antimony. At the present time nothing is visible except the mouths of the old shafts, and even the dumps are badly overgrown. The following description is that given by Dresser (54, page 95):

" The ores are native antimony, with less amounts of stibnite, kermesite and valentinite. The deposit is said to have been found in 1863, and to have been soon after developed and equipped with a mining and concentrating plant. After a time the works closed, and the property passed into the hands of the late owner (Dr. James Reed, Reedsdale, Que.) to whose estate it still belongs.

" The development, so far as could be made out in the present state of disrepair, consisted of four shafts. An adit, which could not be entered at the time of our visit, starts at a lower level some 300 feet from the main shaft, and is said to reach it at a depth of 100 feet. Considerable drifting is reported to have been done along the length of the ore-body.

" *Character of Deposit.* This is a contact deposit, in which the ores occur in schists along their contact with an intrusion of diabase and serpentine. The schists strike N. 50° E. magnetic, and have a vertical dip. A serpentine ridge runs east and west. The serpentine just north of the main shaft is exposed for about 150 feet in length, east and west, and has a breadth of 75 feet. It is bordered by diabase on the west and northwest sides; but on the southwest comes directly in contact with the slates, of which it contains fragments. The principal workings are at the south contact of the serpentine with the schists, with one small shaft on the northwest side of a similar hill about 1,000 feet east of the mouth of the adit. As these two intrusions of serpentine are doubtless connected at no great distance beneath the slates it is not improbable that antimony may be found in the intervening distance. On the other hand, this structure lessens the probability of the deposit continuing to a great depth.

" No distinct veins of any considerable width could be found in the present state of the workings, but the principal amount of ore seems to be in flakes along the cleavage planes of the schists. The proportion of ore becomes greater as the contact is approached.

"Two samples of antimony ore from this property which have been assayed for gold by Mr. H. A. Leverin of the Mines Branch yield only a trace."

COPPER AND PYRITE

Small bodies of pyrite carrying low values in copper are found in a few places in Disraeli map-area. The most important are: the Stratford pyrite deposit, on the south flank of mount Aylmer, which was discovered in 1910 and mined in a small way in 1914-15; and the Coulombe mine, beside the highway just west of lake Coulombe, Garthby tp., range I, lot 22. As these properties have recently been described in detail by Burton (20, pages 133-142), and are unimportant from a mining standpoint, the descriptions will not be repeated here.

PLATE I

A.

B.

A and B. Asbestos, ribbon fibre, Vimy Ridge pit.

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