THE GENESIS OF ASBESTOS IN ULTRABASIC ROCKS

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ABSTRACT

The asbestos and picrolitic veins of the asbestos deposits in the Thetford-Black Lake District are very similar in structure and tend to grade into one another. Field and laboratory evidence suggests that the original vein serpentine was in an amorphous or nearly amorphous state, and that the veins are in many cases of a composite nature, resulting partly from fissure-filling and partly from wall rock replacement. It is proposed that the picrolite and asbestos were derived through crystallization of this vein material, and that two stages of crystallization were involved such that a first stage gave rise to picrolite and a second resulted in the conversion of picrolite to asbestos.

INTRODUCTION

During the past seven years the writer has had the opportunity of examining in some detail the asbestos deposits and their environs in the Thetford-Black Lake District of Quebec. In the course of the field work and laboratory investigation it became evident that none of the existing theories concerning the genesis of chrysotile asbestos were reconcilable with the conditions that pertain in this region. The purpose of this paper is to outline the various characteristics of vein serpentine and, in particular, those of chrysotile asbestos veins, and endeavor to draw certain conclusions as to the manner of formation of asbestos veins and asbestos fiber.

The writer wishes to express his gratitude to Dr. M. Archambault and Mr. Fernand Claisse of the Quebec Department of Mines for their X-ray and thermal analyses, and to the Deputy Minister of Mines, Quebec, for permission to publish this paper. He is especially indebted to Dr. J. E. Gill of McGill University for his advice and encouragement during the preparation of this paper.

VEIN SERPENTINE

The material of the veins that occur in the host rocks of the Thetford-Black Lake asbestos deposits displays a great variety of form, color, hardness, and texture. From a study of numerous hand specimens and thin sections of vein serpentine it is believed that most of it is fibrous. Certain varieties, that appear to be massive in the hand specimen, often grade into columnar material, and under the microscope, although some of this material appears to be amorphous, much of it has a fibrous form.

A description follows of the main types of vein serpentine considered to be peculiar to the host rocks of the asbestos deposits and to the late stage of serpentinization associated with the formation of these deposits. These include asbestos veins, picrolite veins, and serrated veins.

1 Numbers in parentheses refer to References at end of paper.
Asbestos Veins

Most of the asbestos veins in the Thetford-Black Lake area are composed of cross-fiber; however, a good deal of slip-fiber may occur in conjunction with the cross-fiber or in zones where the deformation has been more intense.

The characteristics of the cross-fiber veins are tabulated below for purposes of easy reference. These data are based on the observations of Cirkel (2), Dresser (4), Graham (7), Harvie (6) and Cooke (3), as well as on those of the writer:

(a) *Widths*—range up to four inches; however these are rare and most veins are under three-eights of an inch.

(b) *Form*—minute gash veins, or lenses, or persistent veins up to several tens of feet in length. They may be straight, curved or irregular. They may intersect, branch or have minor offshoots.

(c) *Color*—normally shades of apple-green to dark green and olive-brown, which is generally constant across the width of the vein, and commonly approaches the color of the wall rock.

(d) *Fibers*—silky and soft, to harsher varieties that generally have a higher content of iron and lower content of water (3). They are parallel, and may lie normal to the walls of the vein or occupy any position between this and parallel to the plane of the vein, but generally lie somewhere between vertical and normal to the vein wall. They are rarely perfectly straight, and normally display minute corrugations, some of which may be pronounced. These corrugations may be persistent along the vein but individually may fade out to be replaced by others, or may coalesce; they give the vein a banded appearance (Fig. 4).

(e) *Partings*—one or more may be present and are generally parallel to the vein but are commonly irregular. The orientation of the fibers is generally the same on either side of a parting.

(f) *Magnetite*—occurs along the partings as fine grained sheets or lenses. These are seldom continuous, normally display extreme irregularities, and may occupy any position in the vein, although they tend roughly to parallel the walls. Some disseminated grains may be present, and strings of magnetite in places are parallel to the fibers. Magnetite is usually abundant in the wall rock immediately adjacent to the vein, and in inclusions.

(g) *Walls*—are commonly sharply defined; minute irregularities are normal. Some veins have distinctly crenulated margins suggestive of some replacement. Major irregularities in opposing walls can normally be matched. In some cases one wall may be slickensided and coated with picrolite. Vein material may separate more readily from one wall than the other.

(h) *Inclusions*—of wall rock take the form of thin selvages or angular fragments. Many, although not all, of these match irregularities in the wall. Some have evidently been displaced along the vein. Inclusions of picrolite may be present; some of these may run oblique to the vein, which is thus broken up into a series of en echelon lenses.
(i) **Intersections**—the fibers of both veins may tend to coalesce, or there may be a confused mixture of magnetite, picrolite, and asbestos. Cross-cutting veins are extremely rare. Junctions are commonly marked by the presence of much magnetite. At some intersections the fiber of the marginal portion of one vein may be seen to swing around the corner to merge with the fiber of a similar portion of the other vein.

(j) **Displacement**—post-asbestos faulting is not common, and is generally very local.

(k) **Gradations**—asbestos may give way to picrolite either laterally, or along the length of the vein, and in places appears to lens out (Fig. 12). Veins may terminate abruptly, or fade out into wall rock, without any gradual decrease in width.

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**Figure 1.**

**Differential Thermal Analysis of Asbestos and Picrolite from the same vein**

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**Picrolite Veins**

A common variety of fibrous material that occurs along fault planes, and particularly in those associated with the blocky type of ground in which asbestos veins so often occur, is slip-fiber picrolite. This material is made up of bundles and sheaves of coarse fibers that lie roughly parallel to the plane of the fissure. It is generally soft, and white to pale yellowish green in color, and has a splintery fracture. The fibers separate with difficulty, and
generally break easily. This material grades into apple green and darker shades of a harsh, compact, brittle form that, nevertheless, may be seen to be fibrous when observed in thin sections.

A cross-fiber variety of picrolite is found in the form of compact veins that have a banded structure parallel to the walls and a columnar structure normal to the walls. These veins range in size from microscopic veinlets up to as much as several inches in width. In some cases they are dark green, or assume the olive brown color so typical of the serpentinized host rock. They generally have a waxy luster, and although some are quite hard and compact, others are surprisingly soft, and may be mistaken for talc. The softer varieties appear to have a high content of uncombined water, since they tend to lose weight and crumble after brief exposure to the atmosphere.

These banded veins are associated with fault planes, and many other fissures similar to those with which asbestos is normally found. Cooke (3) referred to them as “painted veins” because of their similarity in appearance to asbestos veins, for which they may at first be mistaken.

In polished specimens the delicate bands paralleling the walls are mostly only a small fraction of a millimeter in thickness but may reach as much as several millimeters (Fig. 3). The parting between successive bands is generally sharp and the banding is further emphasized by slight differences in color. The bands are rarely perfectly straight, but reflect the irregularities in the vein wall and are slightly corrugated or wavy. The banding does not in all cases extend across the full width of the vein, and may be confined to the margins of the vein, or to one margin only.

In thin sections individual bands may be seen to have more or less simultaneous extinction (Fig. 5), and appear to be composed of transverse, parallel
fibers that occupy a position anywhere from normal to noticeably oblique to the margins of the band. The position of extinction, which differs in alternate bands, is evidently due to slight differences in the orientation of the fibers in successive bands. In some bands, sweeping extinction occurs transverse to the band and is apparently due to curvature of the fibers within a band. In some cases the fibrous structure may be continuous across several bands, whose

Fig. 3. Delicately banded wall rock portion of a composite picrolite vein; black bands are mainly magnetite (reflected light, X 18).

Fig. 4. Delicate banding in an asbestos vein (natural size).
Fig. 5. Banded portion of the same vein as Fig. 3. Vein margin fades out into nearly isotropic serpentine (right). Note the fibrous structure transverse to banding. The original compositional partings between bands are emphasized by what are probably discontinuities or sharp flexures in the fibrous material (X Nicols, X 18).

Fig. 6. Composite picrolite veins cut serpentinized dunite. The primary veinlets terminate in the marginal banded portions (white), which are evidently replaced wall rock in contrast to the central portions (gray), which are probably fissure-filling. The center of each vein carries a string of magnetite. The material of the veins is fibrous with a common orientation in the banded portions (X Nicols, X 60).
apparent margins are marked by what are presumably sharp kinks in the fibers. In one unusually compact specimen of banded vein material, individual bands were distinct between crossed nicols and appeared to be composed of cryptocrystalline serpentine with slightly coarser and more birefringent material along the partings, suggesting an early stage in the evolution of the more crystalline fibrous varieties.

The structure of these veins may be emphasized by the yellowish cloudy character of certain bands, or by the presence of a little fine grained brucite in some bands, and its absence in others. Furthermore, they commonly display a composite form (Fig. 6) wherein the banding is confined to the walls, and the central portion stands out in sharp contrast. The outer margins of the banded portions tend to fade out into the wall rock, which may be composed of relatively unaltered olivine, but, in the case of the larger veins, is composed of isotropic serpentine with abundant disseminated magnetite. The whole of the central and banded portions is composed of transverse fibers, but there is often a marked difference between the orientation of the fibers in the central portion and those in the margins. The orientation in the marginal zones is generally common to both sides of the vein. An almost continuous string or sheet of magnetite generally occupies the center of the vein, and lenses sometimes occur within the banded portion.

Where the veins cut the primary or autometasomatic serpentine veinlets, the latter fade out within the banded margin (Figs. 6, 7). Where two composite veins cross one another the banded portions of the two veins merge at the junction, whereas the central serpentine portions are broken up into a number of irregular fibrous segments. It is evident, therefore, that the banded portions represent replacement of the walls whereas the central portion is probably "fissure-filling."

Not all of the fissure-fillings are accompanied by banded margins. Some grade along their length into amorphous serpentine or material that is slightly but irregularly anisotropic and probably cryptocrystalline. Many of the smallest veins, none of which have the banded margins, are composed of amorphous serpentine. Other veins have the normal central portion of transverse fibers accompanied by amorphous margins, which appear to be replacement of the original walls.

The margins of those veins, which are composed of amorphous serpentine, or banded fibrous serpentine grading into amorphous serpentine, suggest a form of colloidal "replacement," and it is evident, from the amorphous nature of some of the vein-fillings, that these probably resulted from colloidal deposition. The cloudy nature of some of the vein-fillings and bands is thought to be due to the deposition of iron from a colloidal stage. Furthermore, analyses show that the content of uncombined water in these veins is considerably higher than that of the normal wall rock serpentine (3).

Both the compact slip-fiber and cross-fiber varieties of picrolite may be found in the same vein. A thin section containing both these materials, when observed in ordinary light, was completely featureless, and the difference in form was only revealed between crossed nicols. The slip-fibers form a twisted mass, more or less, parallel to the vein walls in contrast to the transverse structure in the banded portion.
The various characteristics of these picrolite veins suggest that they probably had a colloidal origin, that the initial solid phase was amorphous or cryptocrystalline, and that, at some later stage in the process of their evolution, this material, in most cases, assumed a fibrous form.

Fig. 7. Picrolite veins cut partially serpentinized olivine. The primary veinlets fade out in the banded marginal portion of the later larger veins. Black material in the larger veins is magnetite which is mostly confined to the central portions (X Nicols, × 60).

Fig. 8. Fibrous (to bladed) serpentine in serrated replacement veins; the fibers (or blades) extend outward from minute, irregular fractures (X Nicols, × 18).
Serrated Veins

In thin sections of the host rocks a fibrous variety of serpentine may be observed on either side of a central fracture. This fibrous growth is roughly normal to the plane of the fracture and produces a microscopic vein with sharply serrated margins (Fig. 8). A proportion of the vein material may appear to have a bladed form, and in some cases this variety seems to be the sole constituent. The fibers are not always perfectly parallel, but have more or less simultaneous or sweeping extinction along the length of the vein. The fractures, associated with these veins, are mostly irregular, and it is evident from the relationships to be found that the fibrous, or bladed, serpentine has replaced the walls. Some of the fractures may have a thin filling that is composed of serpentine, of a very low birefringence, and a little magnetite.

Not uncommonly this vein material has a noticeably high birefringence and it is possible that some of it is actually chrysotile. Successive veining is common and in some cases the fractures may be sufficiently closely spaced to have allowed for almost complete replacement of the original material of the rock. Branching and intersecting veins produce an effect somewhat similar to a dendritic pattern.

ORIGIN OF ASBESTOS VEINS

The hypotheses advanced to explain the origin of asbestos veins fall into two main groups, those in each group differing from one another on minor points only. One hypothesis is that the fibers have grown between the walls of the original rock fracture; Taber (13), Keith and Bain (11), Keep (10), and Cooke (3) have supported this view. The other is that the fibers grew at the expense of the walls of the original fracture; Dresser (4) and Graham (7), (8) are the chief proponents of this view.

The process involving growth of asbestos fibers between the walls of the fissure, as generally accepted, requires that the fissure walls separate as the fiber grows. This hypothesis could only be satisfied by a gradual separation of the walls. It might be expected, however, that this movement, in most cases, would be rapid or sudden, such that the walls would have assumed their present position immediately the rock fractured. The only other alternative, therefore, would be for the asbestos fibers to have grown outward into the open space from one or both walls. Split cross-fiber veins are common; however, if growth had occurred simultaneously and independently from both walls it seems improbable that the fibers on both sides would have assumed the same inclination to the vein walls, which is the rule, except for minor corrugations. If the original fibers are to be envisaged as having grown perpendicular to both walls, then later deformation would have to account for the deviations that occur, and certainly there is little evidence in these compact veins which would support this view.

The theory that postulates the formation of asbestos exclusively beyond the walls of the fissure would require that the fissure was never open, or, at least, that the opening was only microscopic. Again this is contrary to what might be expected to occur in the case of normal fracturing associated with faulting.
Although many fissures might remain closed, it seems inevitable that the majority would produce openings. This situation would almost certainly develop as a result of movement along an irregular fault plane.

Fig. 9. Asbestos vein with what appear to be "ghosts" of the wall rock structure preserved along the upper margin. Note also the "matching" irregularities in either wall, and the faint central parting—or what may represent the position of the original fracture (X Nicols, X 18).

Fig. 10. Asbestos vein (central band at tip of compass arm) and marginal zones of serpentinized wall rock.
The general characteristics of the asbestos veins, enumerated earlier, suggest that fissure-filling has occurred. In places, minor unmatched irregularities in the walls, and the presence in the vein margins of what appears to be relict wall rock structure (Fig. 9), would indicate that there has been some growth at the expense of the walls. It seems probable, therefore, that both processes...

Fig. 11. Composite asbestos vein. Fibers in the broad central portion lie at a flat angle with the walls, whereas those in the banded margins are less oblique and the orientation is similar on either side (X Nicols, × 60).

Fig. 12. Polished section of a part of a composite serpentine vein. Asbestos (white) is bounded on either side by slip fiber picrolite. The upper delicately banded, marginal portion is composed of cross-fiber picrolite. The cross-fiber structure of the asbestos has been masked by polishing (× 2).
have been involved and that one or other may predominate in any particular vein.

One of the commonest characteristics of the asbestos veins is that, in many places, they may be seen to be composed of both picrolite and asbestos, and the relationships are distinctly gradational (Fig. 12). Pure asbestos veins do not necessarily lens out, but rather fade out into an intimate mixture of the two vein materials. Where asbestos does not occupy the entire space between the vein walls, the asbestos vein, itself, is commonly extremely irregular in outline. These conditions have been observed by the writer in the process of logging many thousand feet of vein-bearing drill core, and it is common knowledge to those who have been confronted with the task of assessing the asbestos content of the rock, that such relationships pose one of the most difficult problems.

It is evident from the character and relationships of the asbestos veins that they are the latest product of serpentinization, and that the asbestos was formed, for the most part, after all of the adjustments associated with this process had been completed. In view of the fact that the asbestos veins grade into picrolite veins and contain inclusions of picrolite, these two minerals might be presumed to be contemporaneous. However, these two products differ markedly in their physical properties and it seems more probable that they were formed under different conditions of temperature and pressure. One must therefore have been formed prior to the other, or one may have been derived from the other. The latter assumption is accepted as a basis for the hypothesis of asbestos genesis set forth in the following pages.

GENESIS OF ASPBESTOS

Source of Vein Material.—The relationship between breadth of serpentinized vein margin and width of serpentine vein would suggest that the magnesia and a part of the silica¹ of the vein material were probably derived from the wall rock. That the vein material has largely been derived from the immediate walls is borne out by the fact that the composition of the picrolite and asbestos veins generally reflects the wall rock composition. This is particularly noticeable in the harsh dark-green to dark-brown fibers found in the serpentinized aureoles adjacent to the acid intrusives, where the content of iron is abnormally high. The gradual decrease in asbestos, and high content of quartz, in the asbestos veins that enter syenite bodies, also bears evidence to the influence of the immediate wall rocks as a source of the magnesia for the vein filling. The transporting power of the solutions was weak in the case of magnesia, for although some talcification of the quartzite has occurred over a narrow zone of a few inches beyond the contact, and serpentine and talc may be found over somewhat greater widths in the contact slates, these materials are virtually absent in the country rocks beyond the immediate contact, where, however, large quartz veins are numerous.

The process of serpentinization of the immediate wall rock of the fissure evidently involved, in some cases, successive advancing waves of replacement

¹ Assuming that the serpentinisation involved no change in volume, silica would be removed in addition to magnesia in the ratio of between 1:3 and 1:4.
by colloidal material. Removal of magnesia and some silica would accompany this process and the general serpentinization of the outer wall rock. It is suggested that this leached material accumulated in the fissures and in the final stages was deposited along with additional silica to form an amorphous vein-filling.

Commencing with this composite form of vein material, including part fissure-filling and part wall-rock serpentine, the successive steps leading to the formation of asbestos are postulated below.

**Crystallization—1st Stage.**—This stage involved the formation of cross and slip-fiber picrolite. Crystallization of the banded material of the wall rock probably preceded that of the vein-filling, as a sharp boundary invariably exists between the margins of the two, at which the transverse fibers terminate. During the crystallization of the serpentine of the amorphous banded wall rock, and of the fissure-filling, iron was thrown out. The tendency of magnetite to occupy the center of the vein would suggest that the fibers of the vein-filling, in most cases, grew inward from the original fissure walls. The concentration of magnetite in the wall rock beyond the banded portion would suggest that the iron in this case was either driven out during the initial period of serpentinization, or by the crystallization of this portion.

Although the fibrous material would tend to crystallize with its long axis normal to the vein wall (13), the direction would be influenced by vertical relief of stress and the position assumed might be expected to be somewhere between the vertical and normal to the vein wall. Small components of stress parallel to the plane of the vein would account for the deviation from layer to layer and within any one layer of the banded wall rock. The general attitude of the fibers in the central portion of the vein coincides with that of the fibers in the margins and it may be assumed that their growth was influenced in the same manner. Shearing stresses along the vein have resulted in the formation of a confused and twisted mass of fibers roughly parallel to the vein. This latter development, in places, is confined to one margin of the vein, to the center, or occurs in several portions of the vein. Alternatively, small oblique shears have given rise to fibrous growth parallel to these planes, which has tended to split the vein into a series of overlapping lenses.

**Crystallization—2nd Stage.**—Turkevich and Hillier (14) and others (1), through the use of the electron microscope, have illustrated the fact that chrysotile asbestos is probably tubular in form. It is not known whether picrolite exhibits the same characteristics; however it is clearly evident that these two products have very distinctive physical properties, the chief of these being the marked difference in tensile strength. Selfridge (12) has classified picrolite as a variety of antigorite; however powder X-ray photographs of the picrolite vein material from Thetford are closely similar to those of asbestos. Differential thermal analyses, on the other hand, do show a distinction between these two materials such that both the endothermic and exothermic reactions are noticeably more pronounced for picrolite in contrast to those of chrysotile asbestos (Fig. 1).

It is assumed, for lack of adequate evidence to the contrary, that the picrolite does not have the tubular structure attributed to chrysotile asbestos,
and that, therefore, an asbestos fiber would tend to occupy a somewhat greater volume than that of an equivalent fiber of picrolite. It is suggested, therefore, that the conversion from picrolite to asbestos would involve an overall increase in volume, and that such a change of state would be favored by conditions of tensile stress.

There is some evidence to show that the formation of asbestos veins was favored by tensile stresses. Cooke (3) has described the presence, in the serpentinized wall rocks, of tension cracks that are approximately normal to the plane of the asbestos vein. In the vein margins it is quite evident that serpeninization has worked outward from the walls, and, although the outer boundary is normally sharp in outline (Fig. 10), weathering of these margins reveals that the complete serpeninization fingers out into the partly altered rock (Fig. 2).

Cooling of the vein and walls would induce contraction; tension cracks in the walls would tend to follow the lines of weakness engendered by the alteration, such that the maximum strain developed roughly parallel to the plane of the vein. On the other hand, relief of stress within the vein itself could have been accomplished by the conversion of the picrolite to chrysotile.

The fibrous form of the serpentine in the composite picrolite veins would tend to lend itself readily to conversion into asbestos cross-fiber. The formation of asbestos would, therefore, merely involve some recrystallization and growth of the existing fibers across the full width of the vein or a part thereof. The minute corrugations, so frequently found at the margins of asbestos veins (Fig. 11) and over much of the widths of some veins (Fig. 4), are no doubt derived from the slight changes in orientation that prevailed in the original fibrous material in the adjacent layers of the wall rock (Fig. 2). The formation of slip-fiber asbestos from the slip-fiber picrolite, formed originally through shear stresses, would be accomplished at the same time and in the same manner as the formation of the cross-fiber asbestos.

The absence of asbestos in many of the picrolite veins, particularly around the margins of the deposits, could be interpreted on the basis that the initial temperatures were insufficient to cause the necessary stress conditions that prevailed within the main body of the deposit during cooling. It is apparent from the measurements, obtained by Cooke (3), of the serpeninized margins of these barren veins, that the conditions were not the same at the extremities of the deposit, and that serpeninization of the walls was noticeably less intense. The comparative absence of picrolite, particularly in the larger veins, and the absence of large picrolite veins, may be accounted for by the fact that circulation of solutions within the larger veins has been much greater than in the smaller. Consequently, the temperature would have been appreciably higher in the wall rocks of the larger veins, and the stress conditions would be much more favorable to the complete conversion of picrolite to asbestos.

It may be generally stated that the high temperatures that prevailed at the culmination of vein deposition, and the low confining pressures that existed during the cooling period, were the chief factors favoring the formation of asbestos. The presence of the larger bodies of acid intrusive, chiefly in the form of granite, has no doubt been to a large extent responsible for the higher
temperatures. In the absence of such bodies, the presence of through-going structures that served as main trunk conduits for the heat-bearing siliceous solutions has served a similar purpose.

SUMMARY

Brecciation of the host rocks produced the many fissures through which siliceous solutions circulated and caused serpentinization of the wall rocks. The wall rock in some cases was converted into colloidal serpentine over narrow widths. The magnesia and silica, removed during this process, was deposited in the fissures in combination with more silica in the form of colloidal serpentine. All of this colloidal serpentine later crystallized to form picrolite, largely transverse to the direction of the vein.

Chrysotile asbestos was derived from the picrolite of the preformed composite veins, as a result of recrystallization during the cooling stage subsequent to the formation and primary crystallization of these veins. These successive stages of crystallization would have served to mask the effects of successive fracturing and vein formation that inevitably occurred during the initial period of any fissure-filling that took place.

Heating of the fissure walls and host rock generally has been an important factor insofar as asbestos formation is concerned. Where temperatures were adequate to induce sufficient contraction during the cooling period, stress conditions were favorable for the recrystallization of the picrolite into asbestos.

The serrated veins are believed to be composed of antigorite, and were probably formed through replacement of the original serpentine of the host rock under conditions of dynamothermal metamorphism as proposed by Du-Rietz (5) and Hess, Smith and Dengo (9).

THERFORD MINES, P. Q.,
March 9, 1954

REFERENCES