QUARTZ VEINS FORMED BY METAMORPHIC DIFFERENTIATION OF ALUMINOUS SCHISTS

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ABSTRACT

Quartz veins in staurolite schist are believed to have formed by metamorphic differentiation. As silica was removed from the wall rock to form the veins, micas, staurolite, and accessories were concentrated in the schist bordering the veins. The inner part of this border zone is composed of staurolite prophyroblasts arranged in a thin layer against the quartz veins. Out beyond the staurolite layer is a wider layer of quartz-poor schist composed almost entirely of mica but devoid of staurolite. The differentiation is believed to have operated according to the concretion and solution principles but differential compression, due principally to folding, is considered to have played an important role. Vein formation continued over an extended period but the veins ceased growing just before the staurolite layer formed.

INTRODUCTION

The writer was first impressed by the occasional discovery of numerous large quartz veins in schist while mapping the bedrock geology in western New Hampshire in 1937. The most striking feature about these veins appeared to be the concentration of large staurolite crystals in the schist along the vein walls. Zones, one to two inches wide and commonly composed almost entirely of staurolite crystals apparently identical with the porphyroblasts of the enclosing schist, were noted in several localities. It was concluded (Chapman, 1946) that the veins influenced the localization of staurolite in the schist walls by transporting components essential to the formation of this mineral. More recent studies show that the problem is much more complicated than was formerly thought. Field work has shown that these veins, with associated staurolite zones, are not rare but are widely distributed through the staurolite schists of the region.

The most detailed studies were made of the veins in the Claremont quadrangle in western New Hampshire (Figure 1). The best examples noted are on the west slope of Croydon Mountain (Blue Mountain) within the boundaries of the Blue Mountain Forest Association (formerly called Corbin Park). Persons unable to obtain permission to enter this private game reserve may see very fine exmaples of these veins along the road just west of Perry Mountain in the town of Charlestown.

It is hoped that this paper will further stimulate interest in the study of analogous veins in other regions and in other rock types that such studies may result in a clearer understanding of the problems involving transfer of material during metamorphism.

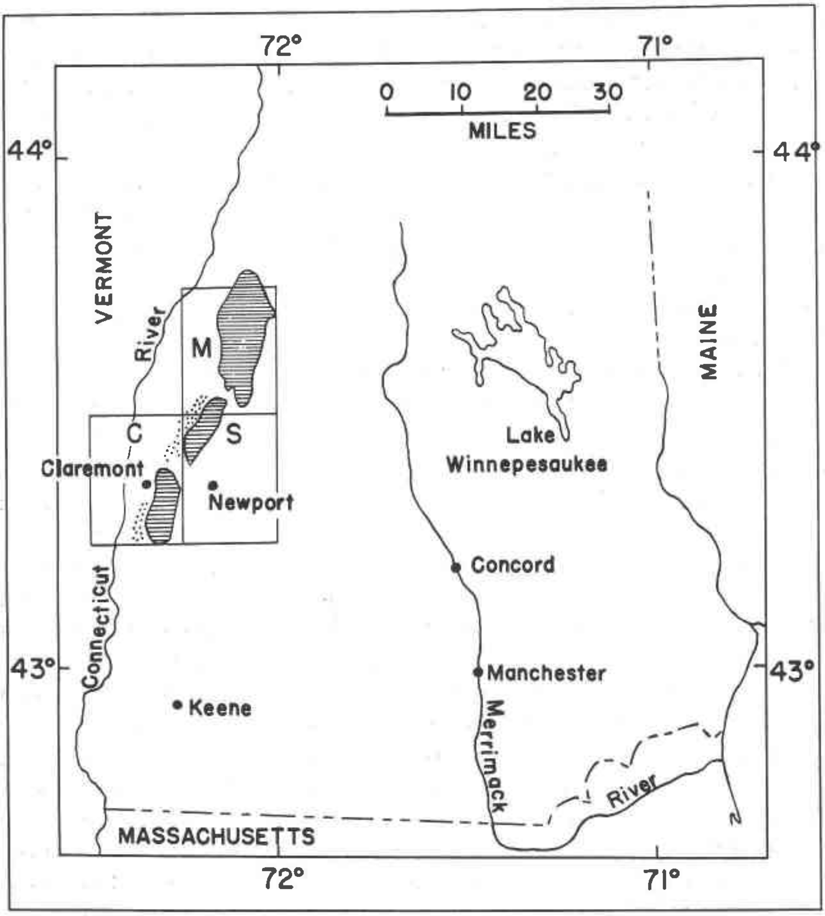

FIG. 1. Index map of southern New Hampshire. Areas where quartz veins were studied—stippled. Domes of the Oliverian magma series—ruled. Claremont quadrangle—C. Mascoma quadrangle—M. Sunapee quadrangle—S.

FIELD RELATIONS AND PETROGRAPHY

General Statement. The rocks considered in this paper occur within a belt of schist which constitutes part of the Littleton formation (lower Devonian) of west-central New Hampshire. This belt lies within the middle-grade zone of metamorphism and extends roughly NNE–SSW along the west flanks of the numerous domes of the Oliverian magma series (Chapman 1939 and 1942). See Fig. 1. The rocks consist chiefly of fine- to medium-grained mica schists, most of which contain prophyroblasts of biotite, garnet, and staurolite; and are believed to have been derived from shale, sandy shale and impure sandstone. A marked schistosity and generally pronounced lineation are characteristicallydeveloped. The general distribution and relative abundance of rock types within the formation are well understood and the detailed petrography has already been worked out (Chapman 1939 and 1942).

Petrography of the Schist. For the present study only the following rock types need be considered; mica schist, quartz-mica schist, and staurolite-mica schist. Staurolite-mica schist is perhaps the most abundant, but it should be noted that these divisions are purely arbitrary and all three types are gradational. For convenience, these schists will be referred to as representing the normal schist type.

In each of the three rock types quartz and plagioclase (oligoclase) occur as elongate or polygonal-shaped grains averaging 0.1 millimeter across. Mica and chlorite may either be scattered through the quartz-feldspar mosaic or concentrated in thin layers. Most of the muscovite occurs as flakes 0.1 to 0.3 millimeters long and is generally oriented parallel to the foliation of the rock. Red-brown biotite is found most commonly as porphyroblasts one to two millimeters across and oriented at various angles to the schistosity. Garnet is not an abundant constituent. It occurs somewhat sporadically as anhedral to subhedral grains up to one or two millimeters across and incloses quartz poikiloblastically. Staurolite occurs as porphyroblasts, up to four or five inches long, which inclose quartz grains or small patches of the groundmass. In most of the staurolitic rocks these porphyroblasts average one to two inches long and locally may be confined to certain layers. Where this difference in stauorlite content is obviously related to bedding, it is believed to be due to differences in chemical composition of the original sedimentary rocks. For the most part the individual porphyroblasts have been completely altered to a fine aggregate composed mostly of sericite with some chlorite. Where alteration has not been so intense, only a shell of sericitic material surrounds a relatively fresh core of staurolite. Most of the chlorite in these rocks is pseudomorphic after biotite, whereas minor amounts only have formed from garnet. The minor constituents of the schists include brownish green tourmaline, zircon, apatite, sphene, ilmenite, pyrite, and magnetite. In Table 1, modes 1 to 5 inclusive represent several varieties of the schist.

Quartz Veins. Quartz veins are numerous in the schists of the Littleton formation. They range up to about two feet in thickness and many tens of feet in length. On outcrop surface they may appear as simple, clean-cut bands or they may grade into highly irregular and anastomosing vein-complexes. Some are sharp, straight veins whereas others are curved, folded, irregular, lenticular or pod-like. The pinch-and-swell type of structure is not uncommon. For the most part the veins follow the schistose structure of the rock, particularly where schistosity and bedding are parallel. Where bedding is folded and schistosity cuts it, as at the noses of folds, the quartz veins generally wrap around with the bedding. This relationship is well shown in Fig. 2 and its significance will be considered later. Even where bedding and schistosity are parallel a few veins have been observed cutting both structures at 10–25 degrees.

Petrographically the veins are composed of very coarse-grained glassy quartz which in thin section shows strong stain shadows and highly sutured borders. Minor constituents of the veins are, in order of decreasing abundance; feldspar, staurolite and mica. Feldspar is a common constituent and generally occurs in masses up to one inch or so across. It is very commonly abundant near the margins of veins. A two foot vein was observed to contain 10 per cent feldspar in irregular masses about four inches across. Most of these masses were clustered in a small section of the vein about two feet by one foot. In this concentration the feldspar made up 50 per cent of the vein material giving the rock a typical pegmatitic appearance. Feldspar is probably much more abundant than one would at first suspect because careful examination of many veins shows that much feldspar has been removed by weathering at the surface of the vien, leaving epimorphs in the quartz. These small cavities become favorable loci for lichens and are eventually almost completely obscured. In thin section some of the more granular aggregates of feldspar show a medium- to coarse-grained, granablastic texture. The feldspar is oligoclase and much is slightly sericitized. Albite twinning is fairly conspicuous and occasionally both albite and Carlsbad twinning are seen. A few of the large grains show marked zoning. Isolated crystals of staurolite, unassociated with schist and wholly enclosed by the quartz veins, were not commonly observed. Staurolite within the veins is generally unaltered or at least less altered than that in the adjacent schist. In areas where staurolite crystals show outer zones of alteration products, the zones are much thinner for those crystals enclosed by quartz veins. Most staurolite crystals in the veins are well formed with $\{110\}$, $\{001\}$ and $\{010\}$ universally present. Several small veins were observed to contain tiny grains of fresh-looking staurolite, and in one vein these grains were scattered in two thin layers about one-half inch from either vein wall. Small grains of staurolite in the viens may be much more common than surface exposures would indicate; because, as in the case of feldspar, close examination shows that many small grains have been partially or completely weathered out of the vein rock. Micas, independent of schist inclusions, appear to be very uncommon in the quartz veins. Flakes of muscovite and some biotite, scattered through the vein quartz, show up clearly in thin section but these are not readily detected in the field.

Border-Zone Rocks. Between the typical quartz vein and the normal schist is a border zone of characteristically different rock. At the inner part of this border zone, adjacent to the quartz vein, is a relatively thin layer of staurolite. Between the staurolite layer and the normal schist the border zone rocks are extremely rich in mica. The four rock types, therefore, form a distinct zonal arrangement. In passing outward from the quartz vein one traverses, first, a thin staurolite layer and then a somewhat thicker layer of mica-rich schist before reaching the normal schist. Some of the one inch viens, for example, have border zones ranging between one-quarter and one-half inch thick. For veins up to one or two feet wide the border zone ranges up to about six inches in thickness.

The staurolite layer is usually one inch or less in thickness and may be somewhat discontinuous along the vein wall. In places only scattered crystals of staurolite occur in contact with a quartz vein whereas but a few inches or a few feet farther along the contact staurolite may be so abundant as to form a compact layer between the quartz vein and adjacent rock. Masses up to many inches across composed almost entirely of staurolite are commonly encountered. Field studies show that in general the larger quartz veins are accompanied by a greater concentration of staurolite than are the smaller veins. Both megascopic and microscopic examination of the material in these staurolite layers from numerous localities was undertaken. The size of the staurolite crystals in the border-zone rocks at any particular locality is ordinarily the same as that of the staurolite porphyroblasts in the adjacent schist. In most localities studied these border-zone crystals range from one-half to two and one-half inches long, and are generally well developed against the quartz vein.

The mica-rich schist of the border zone possesses an unusually brilliant to silky luster and the finer-grained varieties are phyllitic. This rock differs from the normal schist in two other respects. It is generally coarser grained and is relatively richer in nearly all mineral constituents except quartz and staurolite. The mica-rich schist layer is more persistent than the staurolite layer; and where the latter is somewhat discontinuous or absent, the mica-rich schist comes in direct contact with the vein wall. Away from the vein the mica-rich schist is gradational into the normal schist, but in general the layer is several inches wide. As a rule the mica-rich schist layer is thickest where associated with the larger quartz veins and thinnest about the smaller veins. A three inch vein, for example, might have a layer of mica-rich schist one inch thick whereas the layers associated with somewhat larger veins may range up to four inches or more in thickness.

The gradational character of the outer boundary of the border zone is well illustrated by three modes shown in Table 1. Mode 5 is for a specimen taken 12 inches from the vein wall, mode 6 is for a specimen taken four inches from the same vein wall, and mode 7 is for a specimen taken one inch from the same vein wall. This series shows a marked decrease in

TABLE 1. MODES OF THE NORMAL SCHIST AND MICA-RICH SCHIST*

	1	2	3	4	5	6	7	8	9	10	11	12
Quartz plus Feldspar	55	56	64	65	74	66	1	3	1	7	2	30
Biotite	15	14	15	16	10	13	32	28	41	52	58	2
Muscovite	12	19	12	9	14	20	64	67	53	39	38	65
Staurolite	17	3	7	8	1	0	0	0	0	0	0	0
Garnet	1	7	1	1	tr.	tr.	1	1	3	tr.	0	1
Tourmaline	tr.	tr.	tr.	tr.	tr.	tr.	0.9	0.5	0.4	0.2	0.3	0.3
Opaques	0.5	0.4	0.2	0.2	0.3	0.5	1.0	1.0	1.0	1.3	1.3	1.0

1. Staurolite-mica schist, normal schist type.
2. Staurolite-mica schist, normal schist type.
3. Staurolite-mica schist, normal schist type.
4. Staurolite-mica schist, normal schist type.
5. Staurolite-mica schist, normal schist type, 12 inches from quartz vein.
6. Quartz-mica schist, four inches from quartz vein.
7. Typical mica-rich schist, one inch from quartz vein.
8. Coarse porphyroblastic mica-rich schist, one inch from quartz vein.
9. Very coarse porphyroblastic mica-rich schist, one inch from quartz vein.
10. Typical mica-rich schist, one-half inch from quartz vein.
11. Typical mica-rich schist, one-half inch from quartz vein.
12. Phyllite from mica-rich schist layer, 2 inches from quartz vein.

* For simplicity, percentages are given to the nearest unit except for tourmaline and opaques which are expressed to nearest tenth. Chlorite (altered from biotite, staurolite and garnet) is assigned to those respective minerals in the table.

amount of quartz+feldspar toward the vein and an increase in amount of micas. Modes 8, 9, 10, and 11 are quite typical of the inner part of the mica-rich schist layer, whereas mode 12 is somewhat richer in quartz.

Much of the biotite has been partially or completely chloritized, and biotite and chlorite are as large flakes commonly one to two millimeters long. Many of these large flakes are believed of late development, because they appear to cut off, interrupt and penetrate muscovite-rich layers in a fashion which partially obliterates an earlier crinkled structure. A few biotite plates over 12 millimeters across were noted. In general the cross-micas (biotite) are larger and more abundant nearer the quartz veins, the greatest size and abundance being attained in the inner part of the mica-rich schist layers. In the more extreme cases the individual crystals have developed as long blades rather than as spindles as in the normal schists. In some of the coarser varieties of mica-rich schist, these biotite porphyroblasts are extremely abundant as blades two millimeters wide and 15 millimeters long. Accessory minerals are more abundant and in somewhat larger grains than those of the normal schist.

Inclusions. Inclosed by many of the larger quartz veins are numerous masses of staurolite-rich and mica-rich rocks. These masses appear as stringers, lenses and irregular bodies ranging up to a few feet in length and several inches across. For the most part they are composed of schist not unlike that of the mica-rich schist layer of the border zone. The outer portion (that next to the quartz vein) of many of these inclusions is rich in staurolite and corresponds to the staurolite layer of the border zone. In some of the larger masses the central part is composed of the normal schist with a few staurolite porphyroblasts. This central mass is surrounded by a layer of mica-rich schist which in turn is rimmed by a more or less continuous staurolite layer. The petrographic relationships within the inclusions are, therefore, the same as those for the extra-vein rocks. Numerous stringers and elongate clusters of staurolite crystals within quartz veins are commonly observed on outcrop surfaces. These aggregates, however, are usually associated with minor amounts of mica-rich schist, and they probably represent staurolite layers around tabular inclusions of schist which have scarcely been exposed or which have all but been destroyed by erosion.

Genesis and Significance of Vein Complexes

Age of Veins and Border-Zone Rocks. The quartz veins and staurolite layers cannot logically be considered pre-metamorphism in age because the staurolite must be younger or essentially contemporaneous with the porphyroblasts of staurolite in the adjacent normal schist. The vein complexes are probably not post-metamorphism because they show a marked preference to follow bedding rather than schistosity, where these two structures are not parallel. Figure 2 shows that the quartz veins follow folds in bedding. On the nose of folds the schistosity, which is parallel to that of the region, cuts across the bedding at large angles. These folds and probably the veins as well formed before the final schistosity in this locality. If the veins are neither distinctly pre-metamor-

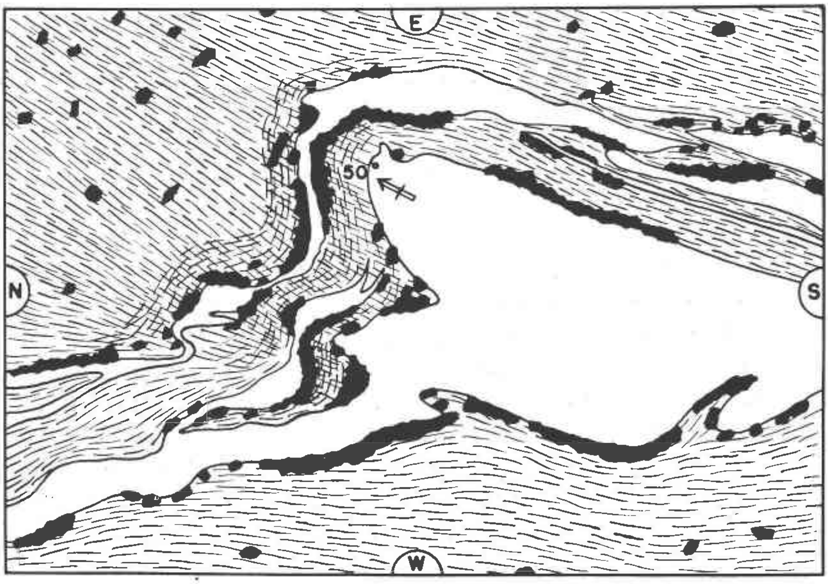

Fig. 2. Map of quartz veins in schist showing staurolite layers. West slope of croydon Mtn. in Croydon, New Hampshire. Area about three feet by four feet. Staurolite—black, quartz veins—clear, schist—lined. Arrow shows attitude and plunge value of folds. Intersecting lines show regional schistosity cutting bedding.

phism nor post-metamorphism in age they may be considered to have formed during metamorphism. Several observations further substantiate this conclusion.

Crinkled structures believed due to relatively late metamorphic processes are much more perfectly formed and better preserved in the mica-rich schist than in the normal schist. This tendency for schistose micaceous rocks or layers to exhibit more perfect crinkled structures than mica-poor rocks or layers is a common observation in metamorphic study. The micaceous portions are weaker and much more sensitive to the forces causing crinkling; and by virtue of their more perfectly developed schistose structure, the micaceous rocks retain and better reveal these small-scaled features. Therefore, the mica-rich schist layer must have existed, in part at least, prior to crinkling.

Microscopic study of certain specimens, however, shows that the minutely crinkled layers of micaceous material in the border-zone rocks (particularly the inner part of the mica-rich schist layer) are more or less obliterated by the great number of large biotite flakes and porphyroblasts which have replaced the rocks. This would indicate, therefore, that some recrystallization (particularly biotite) took place in the border-zone rocks after the crinkles formed. In one vein, near the contact with border-zone rocks (mica-rich schist), biotite occurs as long, slender blades. These blades are all elongated parallel to each other and to the blade-like porphyroblasts of biotite in the adjacent border zone. The mica blades in the vein so closely resemble those of the border-zone rocks that it is concluded that the former represent relicts of the wall rock which were completely inclosed and isolated as the growing vein developed. Some of the quartz veins, therefore, must have continued to grow even after some of the larger porphyroblasts of biotite had formed. These apparently contradicting observations may be reconciled if one pictures the veins and border-zone rocks as forming over a more or less extended period of time during the processes of metamorphism.

Origin of Vein Complexes. It seems logical to exclude an igneous theory of origin for these quartz veins on the grounds that evidence of igneous activity in the vicinity is lacking and the mineral assemblages of the veins and wall rocks are not characteristically hydrothermal. Perhaps even a better reason for excluding this theory is that the data are so compelling in favor of a metamorphic origin for these features. It is unreasonable to assume that these chemically different rock types could have formed through simple recrystallization of originally chemically different sedimentary layers. The existence of such abnormal sedimentary types in such intimate relationship is extremely doubtful. In preference to starting with such intimately mixed and chemically different sedimentary rocks and metamorphosing them into the contrasting rock layers as we now see them, the writer would prefer to start with a more normal and more homogeneous series of shales and sandy shales and obtain the same results through differential movement of material during metamorphism. Evidence which has led the writer to this conclusion, that metamorphic differentiation best explains the quartz vein phenomena, will now be considered.

Perhaps the most convincing evidence that the quartz veins themselves were derived by secretion from a rock of the normal-schist type is the petrographic character of the border-zone rocks. If the veins have formed by extraction of silica from the wall rocks, then we would expect to find an impoverishment in silica in the border-zone rocks and an enrichment in all other constituents. This is exactly what field and laboratory studies show. A brief study of the modes in Table 1 shows that the amount of quartz+feldspar decreases, to practically nothing, as one approaches the vein. Micas, on the other hand, increase proportionally toward the vein where they make up more than 90 per cent of the rock. Even accessories like tourmaline and opaque minerals are relatively more abundant in the inner part of the border zone than in the normal schist. Garnet is as sporadic in the border-zone rocks as it is in the normal schist. The distribution of staurolite is not clearly shown in the table because all border-zone rocks represented there were taken from the mica-rich schist layer where staurolite is virtually absent. Staurolite in the border zone, it will be recalled, is confined to the vein contact in the form of a thin layer where it commonly excludes nearly all other mineral grains. A clearer picture of mineral variation is shown by the generalized curves of Fig. 3. It is apparent that in the mica-rich schist layer the curves for quartz, staurolite, and feldspar are sympathetically related but antipathetic to the curve for mica. Near the boundary of the staurolite layer quartz and feldspar are virtually absent but the staurolite curve rises abruptly as the mica curve drops. An even sharper break is noted at the vein contact where staurolite disappears and quartz makes up most of the vein.

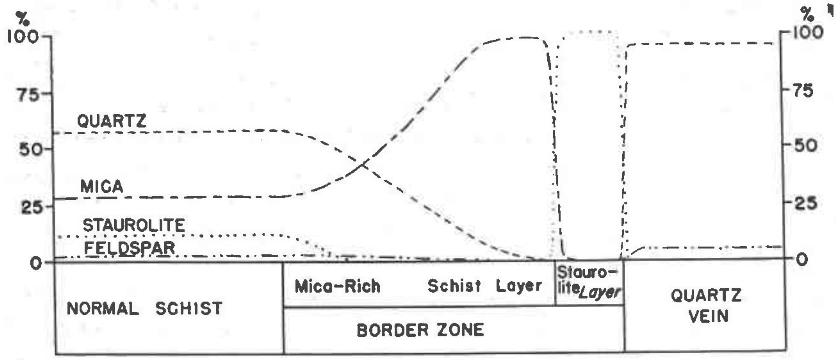

FIG. 3. Variation in mineralogy of the vein complexes.

An attempt was made to check the secretion theory by determining the relative volume of quartz vein, staurolite layer and mica-rich schist layer in a small space and comparing these values with the relative amounts of quartz, staurolite and micas in the normal schist. It was soon realized, however, that a quantitative check could not be very accurate for several reasons. The staurolite layer is somewhat discontinuous along the vein wall. The mica-rich schist is gradational toward the normal schist; and it is difficult, therefore, to set a limit for the thickness of this layer and to determine its average composition. Furthermore, the width of the mica-rich schist layer is somewhat variable. To be accurate, the method would require careful sampling at a very great number of points and it is questionable whether this would be practical.

Quantitative estimates were made and appear to be in harmony with the theory of metamorphic differentiation. Figure 4 is a sketch of a quartz vein complex about three feet by ten inches in which half the area is composed of quartz veins and half of border-zone rocks. No normal schist is shown. The total amount of staurolite in this area is about the same as would appear in an equal area of the adjacent normal schist. Furthermore, the amount of quartz in the veins plus the small amount estimated in the border-zone rocks here totals roughly that of the average normal schist.

Another quantitative estimate may be made by study of Fig. 2. About 200 staurolite crystals occur within the area occupied by the quartz veins and associated border-zone rocks. The average cross-section of these crystals, as exposed, is one-half a square inch. There are exposed,

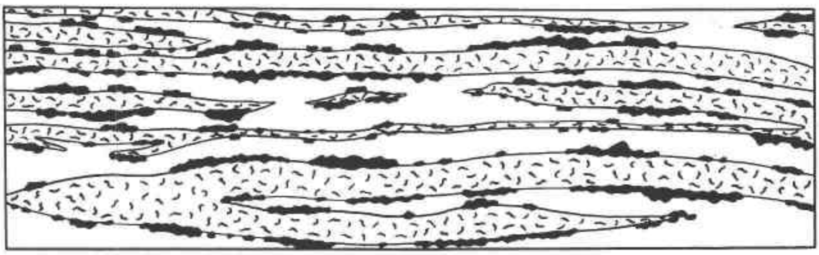

FIG. 4. Map of quartz veins with staurolite layers in mica-rich schist. Near road west of Perry Mtn. in Charlestown, New Hampshire. Area about three feet by ten inches. Staurolite—black, quartz vein—vermiculated, schist—clear.

therefore, about 100 square inches of staurolite within an outcrop surface of about 1150 square inches. Staurolite thus constitutes about 8.7 per cent of the outcrop surface. A similar calculation, on a smaller scale, on the normal schist of the vicinity indicates about 10 per cent staurolite. Two similar but large scale calculations in other parts of the formation show 10 per cent and 13 per cent staurolite, respectively. Estimates at numerous localities in the field and even data from thin sections indicate that the staurolite content of these schists is around 10 per cent. It seems reasonable, therefore, that the amount of staurolite (8.7 per cent) in the quartz-vein complex could have segregated during metamorphic differentiation of the normal schist.

Origin of the Staurolite Layer. It is not sufficient to say that while the quartz veins grew the staurolitic material was left behind to form the staurolite layers. Several observations must be explained such as why staurolite is so abundant next the quartz veins and why the mica-rich schist is nearly devoid of staurolite. Other minerals besides staurolite were "left behind" but these are not confined to the walls of the quartz veins; staurolite, when present, always intervenes.

The following explanation is offered. The veins started to develop in the earlier part of metamorphism, while the adjacent rocks were being metamorphosed, and continued to grow for some time. Staurolite had not yet formed but staurolitic components as well as components for other minerals (except quartz and feldspar) were becoming enriched in the rocks immediately adjacent to the growing veins. Perhaps micas had already formed; and as more silica moved inward to enlarge the veins, the existing micas near the veins were in part replaced and the components moved outward to the gradually retreating and widening border zones which were becoming richer in those minerals not forming the veins. By the time the veins had grown to nearly their present size, the concentration of staurolitic components in the border zones was great (several times that of the normal schist). When conditions were suitable staurolite started to grow in regions of highest concentration, namely at the walls of the quartz veins. The initial loci of the large crystals were established, therefore, as a result of concentration. The crystals in the staurolite layers appear identical with the staurolite porphyroblasts of the normal schist because they all formed under essentially the same conditions. The higher concentrations of staurolitic material in the border zones resulted in closer spacing of crystals in the staurolite layers. Rapid crystal growth tended to deplete the inner part of the border zones of material to form new crystals and diffusion of staurolitic components toward the vein walls resulted. In effect, staurolitic material was "drawn" for some distance toward the vein contacts and precipitated there as staurolite crystals; this left the mica-rich schist layers devoid of staurolitic material for distances up to, perhaps, a foot from the quartz veins. Beyond this distance staurolitic material was "drawn" outward toward the growing staurolite porphyroblasts of the normal schist. All except the innermost part of the border zone was thus sapped of staurolitic material. The strong power of staurolite to form porphyroblasts explains why nearly all other crystals were excluded from the staurolite layer.

Had not the staurolite grown late in the history of the vein, we would have expected staurolite porphyroblasts scattered widely as inclusions and relicts throughout the vein. Such crystals are rare. Evidence of vein widening against mica-rich schists has already been given. Had the veins grown much after the staurolite layers formed, however, many crystals of staurolite would have been cut off (replaced) by the veins or else segments of staurolite layers would have been surrounded and included in the veins. Such relationships were not observed. Had the staurolite crystals formed early in the history of the quartz veins, they would have been dissolved and re-precipitated time and again until the veins reached their present size. This process would afford no means of cleansing the mica-rich schist layers of the growing porphyroblasts of staurolite. It seems evident, therefore, that the veins received their initial development in the earlier stages of metamorphism, and that they were nearly completely formed before staurolite crystallized.

This theory equally well explains two other observations; (1) why some smaller veins located close to larger veins never developed staurolite layers, and (2) why some small veins developed staurolite layers to an extent disproportionate to their size. These two relationships are illustrated by Fig. 5. Suppose the large vein *A* of Fig. 5 is to grow to form

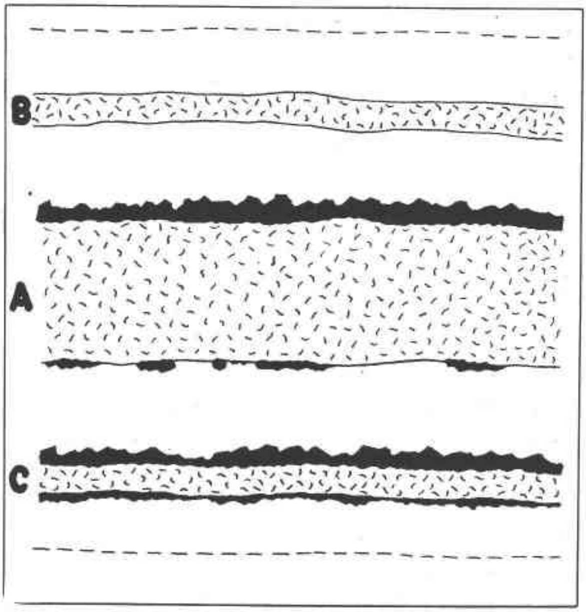

Fig. 5. Idealized sketch showing inconsistencies in thickness of veins and associated staurolite layers. Staurolite—black, quartz vein—vermiculated, schist—clear.

a staurolite layer on either side and that the staurolitic material is drawn from the region between the two dashed lines. The dashed lines represent the outer limits from which staurolitic material moves toward the vein. Suppose a second vein *B* starts to form after vein *A* has attained nearly its maximum size. Before this smaller vein can build up a fair concentration of staurolitic material near its borders, this material will be robbed by the growing staurolite layer of the large vein. Vein *B* will be left without a characteristic staurolite layer. Vein *C*, on the other hand, might develop sufficiently early to build up a rich concentration of staurolitic material near its borders where crystallization would start before staurolite forms at the walls of vein *A*. Once started, the staurolite layer bordering vein *C* could continue to draw additional material, made available by formation of vein *A*, from the zone within the dashed line. Vein *A* is thus robbed of much staurolite, whereas vein *C* develops a staurolite zone out of proportion to its thickness. Some veins may grow largely from one side so the staurolite layers become thicker on one side of the vein than on the other. This may account for certain large veins with little or no staurolite on one side whereas the next adjacent vein possesses a normal amount. This gives but three examples of the complexity of the problem. The reader will undoubtedly see others, too numerous to consider here. These three examples are sufficient to explain why some discontinuous staurolite layers may form, why the thickness of a staurolite layer may vary along a uniformly thick vein, and why the thickness of a staurolite layer may be out of proportion to the size of its associated vein.

So far the writer has tried to simplify the problem by considering movement of material essentially perpendicular to vein walls. When it is realized that material must have migrated for some distance parallel to vein walls as well, even greater variations are expected. Some variation in amount of staurolite along veins must, of course, be attributed to irregular distribution of staurolite components in the original sedimentary rocks.

Origin of Inclusions. The inclusions and septum-like masses of mica-rich schist rimmed by layers of staurolite and enclosed by quartz veins are considered to have originated in essentially the same manner as the border-zone rocks. Many of these sheets of included material probably formed while two or more parallel veins widened themselves by addition of silica from the gradually dwindling, intervening layers of schist. They represent, therefore, relicts of the country rock deprived of its quartz and are so differentiated that each possesses its own staurolite layer. This is further substantiated by the observation that the schistosity and lineation of the isolated masses are respectively parallel to the schistosity and lineation of the nearby schist. Furthermore, there are all gradations between inclusions and well defined septa or inter-vein layers.

Longitudinal Migration. The problem of longitudinal migration (parallel to vein walls) of mineral components can not be ignored. Not all irregularities and inconsistencies in the staurolite and mica-rich schist layers can be attributed to such factors as original composition and interference of one vein by another. Some of the more radical variations indicate that longitudinal migration of mineral components took place.

One isolated quartz vein, one to three inches wide and exposed for 15 feet, cuts sharply across bedding and schistosity. The vein strikes N 15 W and dips 75 degrees SW; the bedding and schistosity strike N-S and dip 30 degrees E. In the north half of the vein staurolite crystals form continuous layers along either vein wall. These layers range up to two inches thick. To the south the vein contacts are sharp and not much staurolite is found near the walls. A little further to the south staurolite is again found concentrated at the vein contacts. There appears to be no relation between the amount of staurolite along the vein walls and the staurolite content of the different beds transected by the vein. The staurolite layers are continuous and quite uniform in thickness regardless of whether they cross staurolite-rich or staurolite-poor beds. This strongly suggests longitudinal migration for distances of several feet at least. Furthermore, the same vein shows fresh grains of staurolite (average one millimeter across) distributed in two thin layers parallel to vein walls and located about one-half inch from either wall. These relationships indicate that the staurolite was deposited as a thin layer on either wall of the growing vein. The vein is, without doubt, of the filled-fissure type and indicates longitudinal migration of perhaps many yards.

At another locality several veins up to one inch appear to fill fissures parallel to schistosity. They pinch and swell slightly but do not branch or die out suddenly as do most of the veins. It was noted, furthermore, that they are associated with neither a staurolite layer nor a mica-rich schist layer; and yet, if traced several yards along the strike their thickness increases to two inches and thin border zones are apparent. From here they may be traced to the larger quartz veins with typical border zones. The thinner portions of these veins carry numerous staurolite grains and coarse flakes of biotite and muscovite a few millimeters across. Tiny epimorphs, probably after feldspar, are present. These relationships indicate that some of the segregation veins gradually pass into filled-fissure veins whose components were transported longitudinally.

The occurrence of feldspar in large masses comprising 50 per cent of a vein within an area two feet by one foot has already been described. Such a concentration without longitudinal migration seems very unreasonable in view of the low feldspar content of the normal schist.

Mica-rich schist layers, whose thicknesses are inconsistent with those of the adjacent quartz veins, have been described. Where these occur on both sides of a vein, longitudinal migration of silica may have played an important role. Where the mica-rich schist layer is abnormally thin, it is probable that the associated quartz vein derived much of its silica by longitudinal migration. Where veins are abnormally thin for their border zones, a large percentage of silica may have been removed by longitudinal migration.

Mechanics of Vein Formation. It seems fitting to inquire further into the cause of quartz vein formation. It is conceivable that the well-known concretion principle (Eskola 1932b) could have been operative during metamorphism of the Littleton formation thereby causing the more siliceous layers to become still richer in silica and the alumina-rich layers to be still further enriched in alumina. Such a process would in general promote the formation of relatively thin but uniform quartz layers or veins alternating with micaceous layers. Such features, moreover, would generally be widely distributed provided the original rocks were essentially uniform over great areas. Under what conditions were the quartz veins formed, therefore, that they should be so erratically distributed and vary so greatly in thickness and extent? Why should the segregation of quartz be on such a large scale locally and practically inconspicuous in much of the adjacent schist?

Another question to be answered is why the quartz should segregate in the first place. It is generally agreed that the degree of mobility (solubility) of silica is high but its power of segregation is low for it rarely shows porphyroblastic form. It would seem, therefore, that the role of silica in the formation of these veins was a passive one; and that silica was probably forced into new positions. The precipitation of quartz at the corners of "eyes," developed around porphyroblasts of garnet, magnetite, and biotite, and the quartz fillings in small tension fractures of stretched and broken crystals and pebbles are but a few examples illustrating the tendency for quartz to seek regions of low pressure. The writer does not mean to imply that the concretion principle is ineffective. It is admitted that metamorphic banding in pelitic schists may be due to a higher segregation power of micas, etc., which causes these minerals to concentrate into layers and exclude the quartz which is forced out form to alternating parallel layers. It does not seem, however, that large scale transfer of these materials perpendicular to bedding, due to high power of segregation (the concretion principle), would take place for distances much exceeding one or two inches; and transfer would very commonly be limited to distances of less than one-half inch. Again it seems some additional factor must be considered to account for the distances involved in transfer of material in the formation of the vein complexes.

The solution principle (Eskola, 1932b) must have been operative. It is suggested that during folding, which accompanied metamorphism, potential openings developed parallel to bedding, particularly at the noses of folds. The most mobile materials (silica) flowed from the flanks of the folds to the crests or troughs where pressure was at a minimum. Accompanying the deformation by folding, fractures must have formed. The more open of these must have been filled with quartz. Limited amounts of feldspathic, staurolitic, and micaceous material moved along with the silica into the growing filled-fissure veins. Examples of filled-fissure veins passing into segregation veins have already been given. Squeezing on fold limbs must have been somewhat irregular causing the solution, migration, and deposition of quartz (and some staurolite) along bedding planes to be somewhat uneven. This may partly explain the interrupted staurolite layers as well as the inconsistencies in thickness of the mica-rich schist layers and associated quartz veins.

In summary, it is advocated that, accompanying changes involving the concretion principle, there was differential movement and slipping along bedding surfaces during folding with the result that the more mobile (soluble) substances (quartz and feldspar) were transferred from points of high pressure (on fold limbs) to points of low pressure (at crests and troughs and along tension joints) thereby impoverishing certain layers of the schist in these mobile substances and enriching these layers in less mobile constituents. The quartz, for example, was filter-pressed out of the schist leaving a quartz-poor or mica-rich rock.

Comparison with Other Areas. Read (1933) has made an excellent study of somewhat analogous vein complexes in the metamorphic rocks of Unst, Shetland Islands. Here are quartz-kyanite veins which he attributes to metamorphic differentiation. The features of these quartz-kyanite rocks differ slightly from those of the quartz-staurolite rocks from New Hampshire.

In the first place, Read found kyanite intergrown with quartz along vein walls as well as concentrated in what the present writer would term the border zone. Moreover, kyanite was an important constituent of some of the simple veins. In the New Hampshire rocks, however, staurolite is generally absent from the quartz veins and confined to the inner parts of the border zones.

In the second place, Read considered the vein formation due to lateral secretion, but it is not clear how much, if any, longitudinal migration has taken place during vein growth. In the New Hampshire veins, it is believed that some longitudinal migration was essential.

In the third place, Read considered the concentration of kyanite at the borders of the veins due to impoverishment of the marginal zones in silica. Whereas this is believed to be largely the case with staurolite in the New Hampshire rocks, it has already been shown that some migration of staurolite toward the vein has taken place. It is apparent from Fig. 3 that staurolitic components have evacuated the mica-rich schist and presumably joined similar components in the staurolite layer. This migration across bedding and foliation amounts to nearly a foot in some cases.

In a classical paper by Eskola (1932*a*) brief consideration is given to staurolite porphyroblasts in mica schist in Karelia. His sketch (Eskola 1932*a*, p. 58) showing two small quartz veins roughly parallel to schistosity with staurolite porphyroblasts concentrated at their margins, might easily pass as one representing veins from the New Hampshire locality. Eskola's description of these veins appears in harmony with the ideas and theory advanced in the present paper.

REFERENCES

CHAPMAN, C. A. (1939), Geology of the Mascoma quadrangle, New Hampshire: *Geol. Soc. Am., Bull.*, **50,** 127–180.

CHAPMAN, C. A. (1942), Intrusive domes of the Claremont-Newport area, New Hampshire: *Geol. Soc. Am., Bull.*, **53,** 889–916.

CHAPMAN, C. A. (1946), Staurolite zones along quartz veins in schist: *Geol. Soc. Am., Bull.*, **57,** 1186 (abstract).

ESKOLA, P. (1932*a*), Conditions during the earliest geological times: *Acad. Sci. Fenn., Ann.*, Ser. A, **36,** No. 4.

ESKOLA, P. (1932*b*), On the principles of metamorphic differentiation: *Comm. géol. Finlande, Bull.*, **97,** 68–77.

READ, H. H. (1933), On quartz-kyanite rocks in Unst, Shetland Islands, and their bearing on metamorphic differentiation: *Mineral. Mag.*, **25,** 317–328.