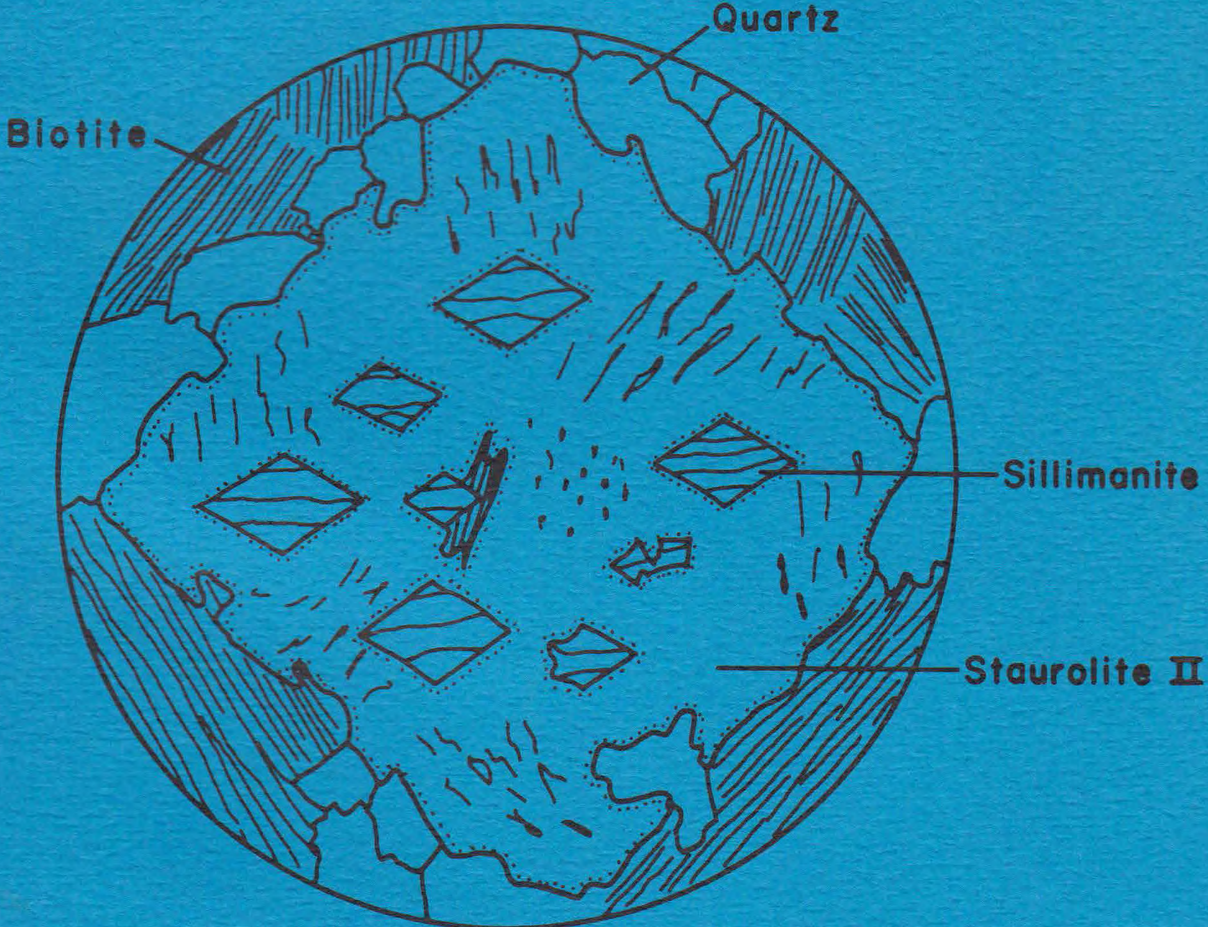
PETROLOGY AND CONTACT EFFECTS OF THE HATFIELD PLUTON OF BELCHERTOWN TONALITE IN THE WHATELY-NORTHAMPTON AREA

WESTERN MASSACHUSETTS

BY PENELOPE LOUISE STOECK



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OF THE

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TABLE OF CONTENTS

Page

ILLUSTRATIONS

Abstract: Although its eastern border is obscured by overlying Triassic sedimentary rocks, the exposed Hatfield Pluton appears to be zoned, with a wide outer zone of tonalite and an inner zone of granodiorite, and with minor amounts of hornblendite, breccia, and felsic dikes. Both tonalite and granodiorite contain plagioclase with an anorthite content of 33 percent and hornblende with a Mg/(Mg+Fe) ration of .74. The granodiorite contains hornblende as the major mafic mineral, while biotite is slightly more abundant than hornblende in the tonalite. The similarity of plagioclase and hornblende compositions in the two rocks cannot be explained by simple fractional crystallization. Since the outer tonalite zone appears to be more hydrated than the granodiorite zone, it is concluded that the zoned nature of the pluton is the result of an introduction of water and possibly K_2O from the wallrocks.

The Whately Schist of Devonian age was intruded and contact metomorphosed by the Hatfield Pluton within a setting of intermediate grade regional metamorphism. The paragenetic sequence of andalusite $\longrightarrow$ staurolite II (containing minute rods of quartz) $\longrightarrow$ kyanite $\longrightarrow$ sillimanite is best explained by an increase in pressure as well as in temperature during contact metamorphism. Staurolite II, kyanite, and sillimanite are found in pseudomorphs of andalusite. Within 15 feet of the contact the relative scarcity of muscovite or equivalent potassic feldspar and the abundance of aluminous minerals suggests that potassium was dissolved or melted out of the schist and carried

toward the magma. As the pluton crystallized and temperatures declined, potassium that had dissolved out of the schist further from the contact and which had not migrated into the intrusion, reacted with remaining andalusite to form coarse muscovite rims around staurolite II.

The quartz rods in the staurolite II pseudomorphs after andalusite probably were produced because andalusite is more siliceous than staurolite:

$$9Al_2SiO_5 + 4FeO + 2H_2O \longrightarrow 2Fe_2Al_9Si_{3.75}O_{22}(OH)_2 + 1.5SiO_2$$

This was accompanied by the substitution of Al in the tetrahedral Fe-site coupled with a corresponding substitution of Al for tetrahedral Si.

The Hatfield Pluton was intruded into the Whately Schist after an episode of deformation that folded the schist and produced a foliation subparallel to the bedding but before development of a slip cleavage. Both deformations are considered to be Devonian; thus the Hatfield Pluton must be Devonian in age.

INTRODUCTION

The Hatfield Pluton of the Belchertown Tonalite is located in the Whately-Northampton area, western Massachusetts, and is included within the Williamsburg and Easthampton 7 1/2-minute quadrangles of the U.S. Geological Survey. This intrusive was called Belchertown Tonalite because Emerson (1898) believed it to be related to the Belchertown Tonalite in Belchertown, Massachusetts (Fig. 1).

The Hatfield Pluton occurs on the border between the Berkshire Plateau and the Connecticut Lowland of the New England province (Thornbury, 1965, p. 167). It is separated from the tonalite in Belchertown by the Connecticut lowlands, which are underlain predominantly by Triassic sedimentary and volcanic rocks. No outcrops of a Belchertown-type rock are known to occur in the Connecticut Lowland between the twc bodies, although other pre-Triassic rocks do crop out (Fig. 1).

The exposed area of the Hatfield Pluton (Plate 1) is approximately 6 miles long and 2 miles wide. It is bounded on the west by the Williamsburg Granodiorite (Willard, 1956) and the Whately Schist (W. Trzcienski, oral commun.). On the east, the pluton is unconformably overlain by the Sugarloaf Arkose (Willard, 1956; Bazakas, 1960).

The Hatfield Pluton is a light gray, mesocratic, medium- to coarse-grained foliated rock. Many dikes and stringers of the Williamsburg Granodiorite intrude the southern portion of the pluton. Two inclusions of the Whately Schist several hundred feet long are located in the northern tip of the intrusive (Plate 1). Along the

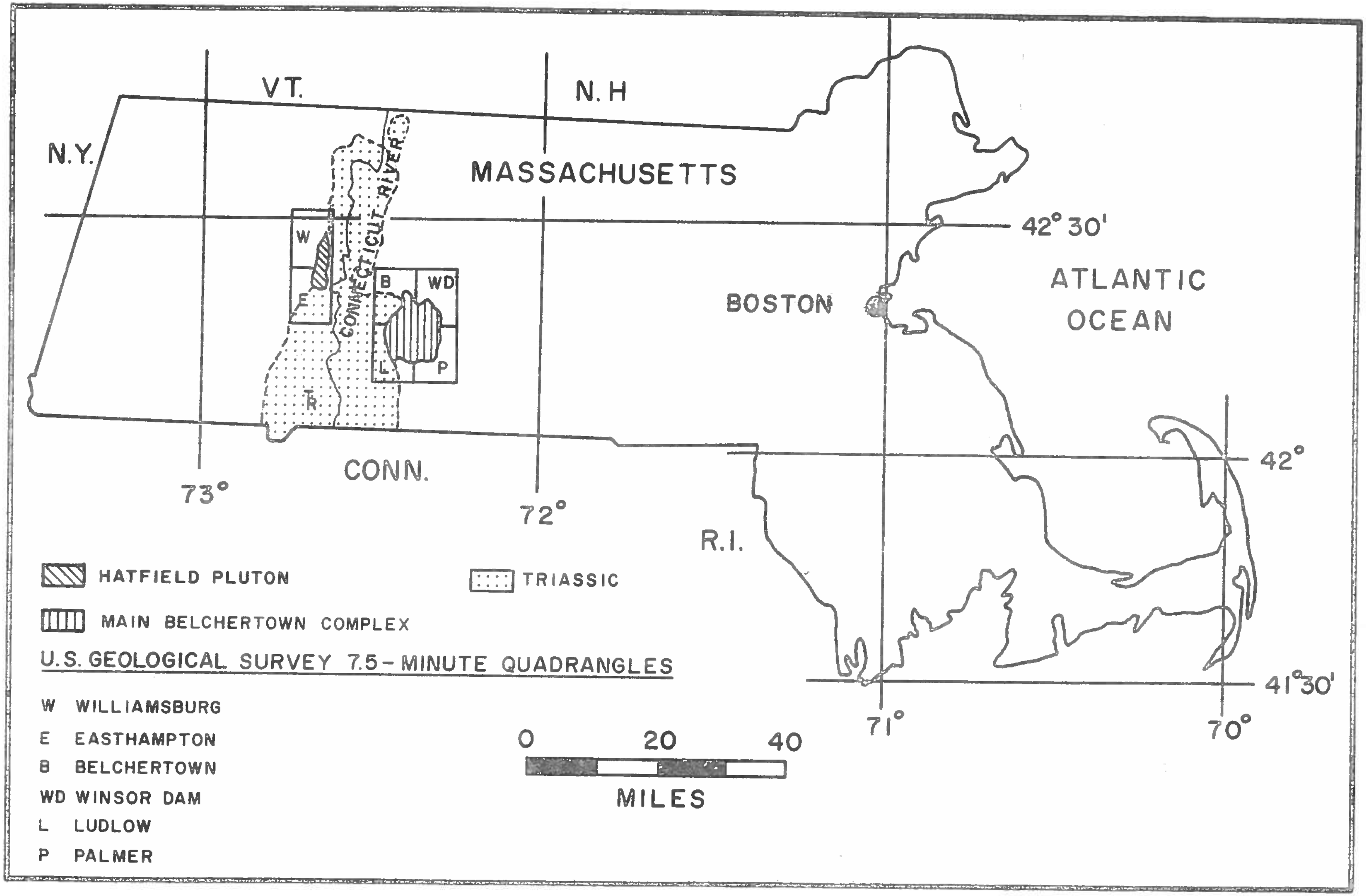

Figure 1. Index map of Massachusetts showing location of the Hatfield Pluton.

eastern bluffs near the intersection of Pantry Road and Routes 5 and 10, the pluton is cut by galena- and barite-bearing ore veins which are Triassic in age (Emerson, 1898).

The area underlain by the Hatfield Pluton is heavily mantled by glacial deposits which obscure approximately 90 percent of the pluton. Furthermore, the Hatfield Pluton is more hydrothermally altered than the main Belchertown Complex (Emerson, 1898; Guthrie and Robinson, 1967).

Topography and drainage

The area underlain by the Hatfield Pluton is on the western edge of the Connecticut Valley. It is topographically higher than the flood plain but lower than the adjacent metamorphic terrain. The eastern edge of the Hatfield Pluton rises abruptly from the floor of glacial Lake Hitchcock and the Connecticut River flood plain in 50- to 100-foot bluffs. The maximum topographic relief on the pluton is 350 feet; the lowest point is at an elevation of 150 feet on the eastern edge, and the highest points are from 450 to 500 feet on the western edge where the Hatfield Pluton abuts the metamorphic rock.

The topography is characterized by rounded hills somewhat elongated in a north-south direction. The elongation of the hills probably reflects glacial modification.

Three streams drain the area; West Brook in the north, Running Gutter and its tributaries in the central area, and Broad Brook and its tributaries in the south. All three systems drain from west to east, having their source areas in the metamorphic highlands west of the pluton. Broad Brook drains into Running Gutter, and Running Gutter and West Brook flow into the Mill River which empties into the Connecticut River. Many swamps occur adjacent to the streams in the area.

Methods of study

Field work was done during June, July, and August of 1969, with various checks throughout the Fall of 1969 and the Spring of 1970. Essentially, the field work consisted of checking the contacts of the Hatfield Pluton mapped by Trzcienski (oral commun.) in the Williamsburg quadrangle; refining the contacts of the pluton with the country rocks in the Easthampton quadrangle, previously mapped by Bazakas (1960); and most importantly, collecting representative samples of the entire Hatfield Pluton, inclusions, and the adjacent metamorphic rocks. A Brunton compass was used to measure foliations in the Hatfield Pluton. Some joints in the pluton were also measured.

Mapping and station location were done at a scale of 1:24,000 on 7 1/2-minute quadrangle maps. A 1:12,000 scale blowup of the relevant parts of the topographic sheets was used for locating each sample.

Approximately 200 samples of the Hatfield Pluton and country rocks were taken. In the pluton, samples were taken based on available outcrop and variation of rock type. Samples of the Whately Schist were taken in traverses perpendicular to the contact with the

Hatfield Pluton (Plate 2).

Laboratory techniques

Seventy-one uncovered thin sections commercially prepared from the above samples included 45 sections of the Hatfield Pluton, five sections of the Williamsburg Granodiorite, and 21 sections of the adjacent Whately Schist. All sections of the Hatfield Pluton were etched with hydrofluoric acid and stained with a saturated solution of sodium cobaltinitrite in order to facilitate the identification of potassium feldspar. All sections were etched, stained, and covered by the author.

The thin sections were used for mineral identification, determination of textures, and modal analysis. Modal analyses of sections of the Hatfield Pluton were made with a Leitz micrometer stage attachment with a point spacing equal to the approximate average grain size of 1 mm. One thousand points were counted for critical samples. Once the two rock types were established, i.e., granodiorite and tonalite, classification of the remaining slides was based on estimated percent of stained potassium feldspar, since the granodiorite contained greater than 10 percent and the tonalite less than 6 percent and usually less than 4 percent.

Approximate compositions of the plagioclase, hornblende, and biotite in the Hatfield Pluton were determined by matching pertinent indices of refraction in oil immersion mounts. The indices of the oils were checked with an Abbe Refractometer immediately after a match was obtained.

In the set of oils used, the interval of refractive index was .002. For every increase in refractive index of .001, the anorthite content of plagioclase increases about 2 percent. Therefore the composition of the plagioclase in the pluton was determined to be 33 ± 2 weight percent anorthite (Chayes, 1952).

Identification of minerals in all sections was based on microscopic determination of optical properties in plane-polarized light and under crossed nicols. Several staurolites from the Whately Schist were x-rayed with Mn-filtered radiation using the 57.3 mm diameter Norelco powder camera in an attempt to identify an included wormy mineral. Pure samples were obtained by scraping a minute amount of the staurolite out of the specimen. Although the wormy mineral is suspected to be quartz, the principal x-ray diffraction line of this mineral was not recorded on the film, nor were any other spurious lines. Apparently the amount of wormy mineral was insufficient to be recorded.

ACKNOWLEDGMENTS

The author wishes to thank Professor Howard W. Jaffe, chairman of the thesis committee, for his direction and help, Professor Peter Robinson for his advice on aspects of metamorphism, Professor Leo M. Hall for his many helpful suggestions, and Professor Joseph H. Hartshorn for his thoughtful editing of the manuscript. Discussions with David J. Hall and Walter Trzcienski concerning aspects of this project were particularly useful. I would especially like to thank David F. Charter whose assistance with the field work was invaluable.

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STRUCTURAL GEOLOGY

Regional setting

The Hatfield Pluton is located on the eastern limb of the Berkshire anticlinorium. This region consists predominantly of metamorphosed Lower and Middle Paleozoic volcanic and sedimentary rocks (Willard, 1956; Hatch, 1968). In the Williamsburg-Easthampton quadrangles regional metamorphism reaches kyanite grade (Thompson and Norton, 1968; Willard, 1956; Hatch, 1968).

Unfortunately, details of the structural history in the Williamsburg-Easthampton area are not well established. A structural analysis of the eastern limb of the Berkshire anticlinorium 20 miles west of this area (Fig. 2) by Hatch (1968) indicates four periods of deformation. These include: 1) a pre-Silurian, probably Taconic deformation, producing tight northwest-trending folds, 2) a major deformation, probably Acadian, which formed north- to northeast-trending isoclinal folds in Devonian and older rocks, 3) a less severe but probable Acadian deformation which caused a northeast-trending, northwest-dipping slip cleavage, and 4) a north-trending open folding (Hatch, 1968).

Areas east of that studied by Hatch, including the Williamsburg-Easthampton area, have not been structurally analysed in detail. Possibly the rocks in the Williamsburg-Easthampton area have been affected by the same episodes of deformation as in the area studied by Hatch (1968).

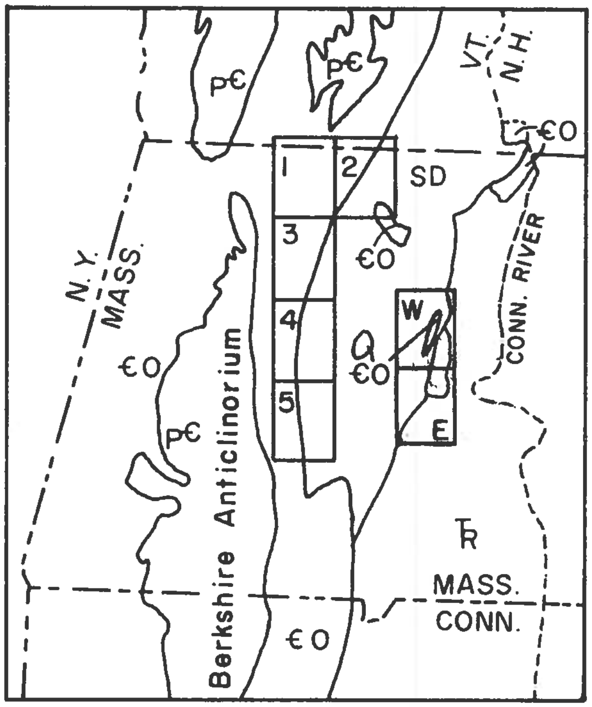


Figure 2. Generalized geologic map of western Massachusetts and vicinity. Numbered and lettered 7 1/2-minute quadrangles: 1. Rowe; 2. Heath; 3. Plainfield; 4. Worthington; and 5. Chester; W. Williamsburg; E. Easthampton. Quadrangles 1-5 studied by Hatch. (Modified from Hatch, 1968)

Correlation and stratigraphy of the schists adjacent to the Hatfield Pluton present some problems. Willard (1956) called these schists the Conway Formation and the Leyden Argillite. However, the area adjacent to the Hatfield Pluton in the Williamsburg quadrangle has been remapped by Trzcienski (Plate 1) (oral commun.) who shows that some Ordovician Partridge Formation is overlain by a small lens of Clough Quartzite. A volcanic unit considered to be the Erving Formation overlies the Partridge and Clough Quartzite. Graded bedding in the schists above the volcanics shows that these units are stratigraphically right side up. Based on lithology, Trzcienski concluded that the unit above the volcanics is the Waits River Formation. The schist unit in contact with the pluton lies stratigraphically above the Waits River Formation and is apparently local in extent. This unit has been called the Whately Schist by Trzcienski (Plate 1) (oral commun.).

Contact relationships

The Hatfield Pluton comes in contact with three units: the Whately Schist, the Williamsburg Granodiorite, and the Sugarloaf Arkose (Plate 1). The Hatfield Pluton is intrusive into the Whately Schist, crosscutting bedding and containing two large inclusions of folded Whately Schist in the northern tip of the intrusion (Plate 1). The contact between the pluton and the Whately Schist is exposed for only a few feet, southwest of where a telephone line crosses the contact (Plate 1). A thin section taken across the contact shows the pluton cutting across the bedding and the foliation parallel to the bedding in the Whately Schist. No chill zone in the pluton is evident at the contact.

The contact between the Hatfield Pluton and the Williamsburg Granodiorite is nowhere exposed but is placed approximately between known outcrops of the two bodies. The Williamsburg Granodiorite is intrusive into the Hatfield Pluton. Dikes of the Williamsburg are common in the southern portion of the pluton. Contact relationships between the Hatfield Pluton and dikes of Williamsburg Granodiorite clearly show the dikes truncating foliation in the Hatfield Pluton. No chill zone is evident in the dikes of Williamsburg Granodiorite, perhaps indicating that the Hatfield Pluton was still hot when the granodiorite was emplaced.

The contact between the Hatfield Pluton and the Sugarloaf Arkose likewise is not exposed. A few outcrops of Sugarloaf Arkose are found along Chestnut Plain Road, south of Whately (Willard, 1956), but further south the Sugarloaf Arkose is covered. The contact between the Triassic Sugarloaf Arkose and the Hatfield Pluton is drawn at the break in slope between the Connecticut River valley on the east and the western highlands on the west. The Sugarloaf Arkose overlies the Hatfield Pluton unconformably (Segerstrom, 1956; Willard, 1956).

Shape of the Hatfield Pluton

The shape of the Hatfield Pluton is uncertain. At the western contact, steep cliffs of Whately Schist stand above the pluton. If these cliffs were produced by a more rapid erosion of the pluton than of the schist, it may be assumed that the western contact with the schist dips steeply. The nature of the eastern contact is unknown. Possibly the Hatfield Pluton was originally part of the main Belchertown Complex that has since been separated by faulting during the Triassic. It is also possible that the Hatfield Pluton was a smaller offshoot at depth of the main Belchertown magma. In this case, the pluton may be in contact with metamorphic rocks on the east also, this contact being obscured by Triassic sediments. In the main Belchertown Complex (Guthrie and Robinson, 1967), the breccia and hornblendite inclusions are located along the northern contact of the batholith with the country rock. By analogy, the occurrence of breccia and hornblendite inclusions near the eastern edge of the exposed Hatfield Pluton (Plate 1) may indicate that this edge lies close to a buried contact with metamorphic rocks.

Structural features in the Whately Schist

Work on the metamorphic rocks adjacent to the Hatfield Pluton was confined to contact relationships and contact metamorphism. Samples of the schist were taken at and proceeding away from the contact for the specific purpose of determining the extent of the contact effects of the Hatfield Pluton.

A few structural features, probably related to regional metamorphism and deformation, are obvious both in outcrop and in thin sections of the Whately Schist. These are bedding, foliation, and a slip cleavage. The foliation is subparallel to the bedding, and is deformed by a slip cleavage, which causes crinkle folds. The slip cleavage strikes northeast and dips steeply. Possibly it is related to the third deformation described by Hatch. The structural features in the Whately Schist within 2,000 feet of the Hatfield Pluton contact are complex and deserving of much more detailed work than could be accomplished in the present study.

The two inclusions of Whately Schist in the northern end of the pluton are foliated and folded. The folds in the inclusions seem to be disoriented from those in the wallrock (Willard, 1956). Axial planes of small folds in bedding in the southern inclusion trend northeast parallel to the general trend of foliation in the wallrock.

Structural features in the Hatfield Pluton

Foliation. Foliation is obvious throughout the Hatfield Pluton. It is the result of alignment of plagioclase laths and discontinuous streaks of hornblende and biotite. The plagioclase, hornblende, and biotite are usually bent and broken in such a manner as to align the crystals more perfectly.

In general, the foliation strikes north-northeast and dips steeply, apparently parallel to the west contact of the intrusion. It also corresponds to the direction of the slip cleavage in the Whately Schist. Willard (1956) concluded that the foliation was a primary igneous structure. It may be possible that the foliation is primary and that the pluton was partially crystalline when intruded, thus causing deformation of the crystals. It is also possible that the foliation is the result of a primary igneous structure intensified by metamorphism. In other words, during the regional deformation causing the late slip cleavage, the igneous foliation was intensified as crystals were bent and broken when forced into stronger alignment. It is also possible that the foliation is entirely metamorphic. In either of the last two cases, the pluton would have had to be intruded prior to the development of the northeast-trending slip cleavage.

Jointing. The Hatfield Pluton is highly jointed. Many outcrops show two and sometimes three joint sets. Seventy-six joints measured by Bazakas (1960) in the southern part of the pluton reveal two major joint systems in the southern half of the pluton; one striking N. 50° W. and the other striking N. 60° E. (Bazakas, 1960). Joints in the northern half of the pluton, measured by the author, agree with these findings.

Faulting. Many minor faults occur throughout the Hatfield Pluton. Felsic dikes are offset a few inches in places and slickensides are common on "joint" planes. A sheared zone occurs in the quarry on Route 5 and 10 in the Easthampton quadrangle (Plate 1). The rock in this zone is severely crushed, appears flinty, and slickensides are numerous. Thin sections of the rock show that it is mylonitized and highly altered. The mafic minerals have been totally replaced by epidote and chlorite.

Bazakas (1960) located two other faults. He suggested that these faults are part of the "Western Triassic Border Fault". However, Willard (1956) and Segerstrom (1956) concluded that the contact between the Triassic Sugarloaf Arkose and the Hatfield Pluton is an unconformity rather than a fault.

PETROGRAPHY OF THE HATFIELD PLUTON

General

The Hatfield Pluton is not a homogeneous rock mass but rather is composed of several rock types. Point-counted modes (Tables 1 and 2), plotted on a quartz-plagioclase-orthoclase triangular diagram (Fig. 3), clearly indicate that most of the pluton is divided into two rock types designated Group A and Group B on Figure 3. According to Johannsen's classification (1931), half of Group B would be tonalite and the other half granodiorite. However, since Group B is obviously distinct from Group A, for the purpose of simplification 12 percent orthoclase rather than 5 percent will be used as the boundary between granodiorite and tonalite in this study. Therefore granodiorite will be used to refer to Group A rocks and tonalite will be used to refer to Group B rocks.

Both the granodiorite and tonalite are gray, medium- to coarse-grained, foliated rocks that contain blebs or pods of hornblende. These aggregates of hornblende are elliptical with smooth boundaries and are elongated parallel to the foliation. They range in size from 1/4-10 inches in length and 1/8-4 inches in width. The hornblende in the blebs is finer grained than the hornblende in the groundmass, and a rim of coarse hornblende commonly occurs at the bleb-groundmass interface.

In addition to the granodiorite and tonalite, two other rock types are found in the pluton. These are a more mafic phase of the pluton, designated hornblendite, which ranges in composition from

Table 1. Point-counted modes of the granodiorite

Specimen	W31	W65	W72	W80	W82	W90	E82	Ave.
Quartz	17.8	10.7	10.0	16.2	9.2	13.8	13.6	13.0
Plagioclase[1]	40.4	45.8	36.6	41.4	36.2	39.4	44.8	40.6
Microcline[2]	15.2	12.4	10.8	13.6	12.4	13.0	16.2	13.3
Myrmekite	1.4	+	+	+	.2	+	.2	.4
Diopside	+				+	+		
Hornblende[3]	11.6	17.7	13.6	14.8	24.2	18.6	10.0	15.7
Biotite[4]	11.0	8.1	20.0	9.4	12.6	12.0	12.6	12.2
Epidote	+	.6	3.4	+	+	+		.6
Allanite	+	.2		+	.2	.2	+	.1
Sphene	.8	2.8	2.8	2.0	2.6	1.8	1.0	1.9
Apatite	1.6	1.0	.6	2.0	2.0	.6		.6
Zircon	.2	.4	1.2	.6		.6		.6
Chlorite[5]	+	+			+			
Prehnite[5]	+	+		+		+	+	
Total	100.0	99.7	99.0	100.0	99.6	100.0	98.4	99.0
Color Index	22.6	23.8	33.6	24.2	36.8	30.6	22.6	27.7
Ave. grain (mm)	2.0	1.8	2.2	2.0	1.7	1.5	2.2	1.8

	W31	W65	W72	W80	W82	W90	E82
1. Mole % An	33	n.d.	33	32	n.d.	33	35
3. Mg/(Mg+Fe)	.74	n.d.	.75	n.d.	n.d.	n.d.	.74
4. Color	G+B	B	R	B	G	B+G	B+G

1. Mole % An (see above)
2. Microcline includes some sanidine.
3. Mg/(Mg+Fe) (see above)
4. Color (see above)
   G = green; B = brown; R = reddish-brown.
5. Secondary minerals.

(See Plate 2 for sample locations)

Table 2. Point-counted modes of the tonalite

Specimen	W32	W42	W85	E25	W56	E81	Ave.
Quartz	20.0	25.6	17.6	15.6	18.0	17.4	19.0
Plagioclase[1]	46.8	55.0	52.0	49.6	53.8	42.6	50.0
Microcline[2]	6.0	6.3	4.4	5.4	1.8	1.8	4.2
Myrmekite	+	+	+	+	+	+	
Hornblende[3]	10.6	6.3	11.2	10.0	11.6	16.6	11.0
Biotite[4]	13.4	5.0	11.6	16.4	11.4	17.4	12.5
Epidote	.2	.4		.8	.6	+	.3
Allanite	.2	+			.1	+	.1
Sphene	2.2	1.0	1.2	1.2	.8	2.8	1.5
Apatite	.4	.4	1.4	.4	1.3	1.4	.9
Zircon	.2	+	.4	.4	.4	+	.3
Chlorite[5]	+	+					
Prehnite[5]	+	+	+	+	+	+	
Total	100.0	100.0	99.8	99.8	99.8	100.0	99.8
Color Index	24.0	11.3	22.8	26.4	23.0	34.0	23.6
Ave. grain (mm)	1.5	1.8	2.0	2.1	2.2	1.8	1.9
1. Mole % An	35	33	31	n.d.	33	33	

2. Microcline includes some sanidine.

3. Mg/(Mg+Fe)	.74	n.d.	.74	n.d.	.75	.74
4. Color	G	G	G+B	B G	G B	G

G = green; B = brown.

5. Secondary minerals.

(See Plate 2 for sample location)

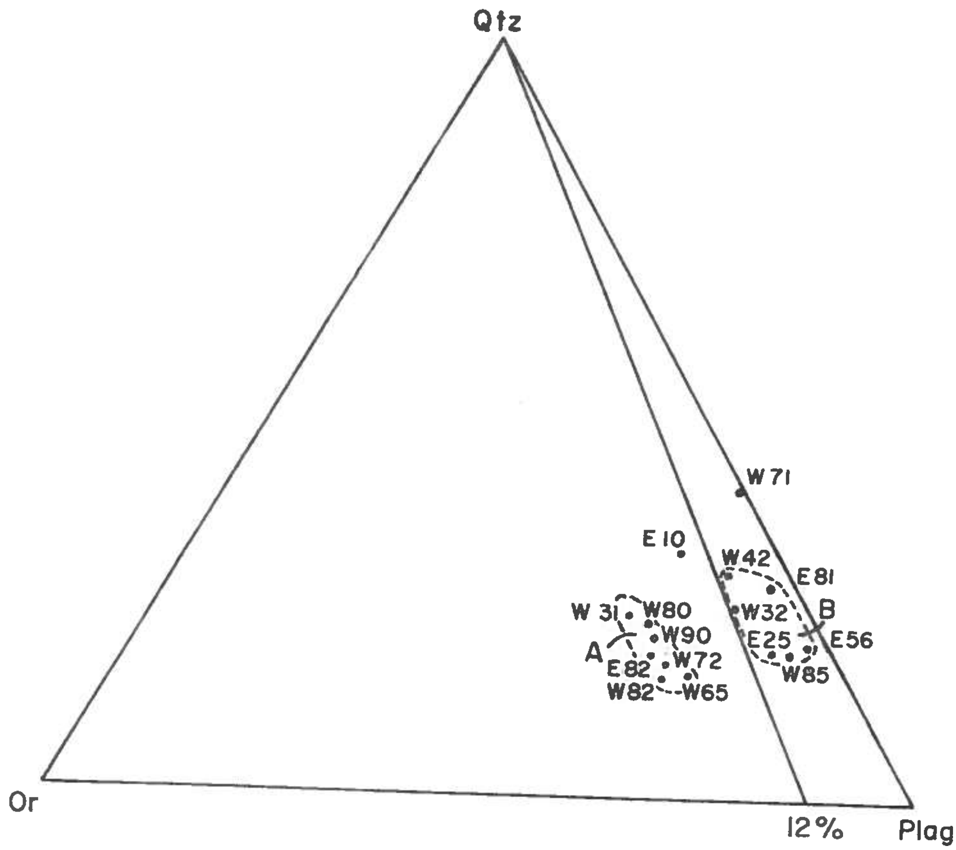


Figure 3. Ternary plot of modes from Tables 1 and 2. E10 is breccia matrix (Table 3), W71 is contact tonalite (Table 3). Group A is designated as granodiorite, Group B as tonalite.

hornblendite to meladiorite, and a breccia (Table 3). These two are only minor constituents of the intrusion (Plate 1). The hornblendite occurs both as inclusions in the pluton and as angular to partially resorbed blocks in the breccia. Small felsic dikes also occur in the pluton.

In the field, the granodiorite and tonalite cannot be differentiated. The contact between the two rock types (Plate 1) was located approximately, based on thin-section identification (Plate 2). In the southern part of the intrusion along Coles Meadow Road, breccia grading into rock rich in inclusions is common. Since the groundmass of the breccia is granodiorite (Table 3, E10), this portion of the pluton was mapped as granodiorite.

Later alterations

Several features seemingly unrelated to the formation of the Hatfield Pluton are observable in the pluton. These include silicified zones, ore veins, epidote veins, and secondary minerals. The silicified zones, first noted by Emerson (1898), appear to be zones of fracture along which siliceous solutions have crystallized. Bazakas (1960) reports two silicified zones in the Easthampton quadrangle. His thin sections of one of these zones showed quartz in comb structure surrounding lenticular masses of fine-grained untwinned plagioclase. Another silicified zone occurs in the gravel pits a quarter of a mile north of Linseed Road in the Williamsburg quadrangle (Plate 1). This zone appears to be an area of partially dissolved plutonic rock. Apparently the zone was riddled with fractures,

Table 3. Miscellaneous point-counted modes

	Breccia Matrix Granodiorite E10	Contact Zone Tonalite W71	Hornblendite H4*
Quartz	26.2	26.1	+
Plagioclase[1]	46.0	38.3	15
Microcline[2]	10.2		+
Myrmekite	+		
Diopside			+
Hornblende[3]	5.5		80
Biotite[4]	8.8	32.3	5
Epidote	1.2	.6	+
Allanite	.1		+
Sphene	.5	.4	+
Apatite	1.0	.4	+
Zircon	.3	1.8	+
Chlorite[5]	+	+	+
Prehnite[5]	+		
Total	99.8	99.9	100
Color Index	14.3	32.3	85
Ave. grain (mm)	2.5	1.5	10
1. Mole % An	31	35	n.d.
2. Microcline includes some sanidine.			
3. Mg/(Mg+Fe)	n.d.		.80
4. Color	B	R	

B = brown; R = reddish-brown.

5. Secondary minerals.

* Estimated mode of thin section provided by Allen Ludman, Smith College.

(See Plate 2 for sample location)

breaking the rock into pieces a few inches in diameter. Solutions moving along these fractures dissolved the blocks of igneous rock, rounding them and leaching out the mafic constituents. The rounded blocks are surrounded by a matrix of vuggy quartz. The former blocks of igneous rock are recognizable as such because of a remnant foliation reflecting the original foliation of aligned plagioclase and streaks of mafic minerals. This zone is about 6 feet wide and is exposed for about 30 feet in the gravel pit. Small quartz veins, 1-3 inches wide, commonly are found throughout the Hatfield Pluton.

A galena-barite-quartz vein occurs west of Route 5 and 10, a quarter of a mile north of Rocks Road (Plate 1). This vein has been described by Emerson (1898) and by Willard (1956). The vein is about 4 feet wide and was mined at one time. Along the bluffs of The Rocks, on either side of this vein, very fine quartz veins can be seen. Some of these veins contain galena, but pyrite is more common. These smaller veins are no doubt associated with the large vein. Similar galena-bearing veins can be seen in a small pit in the Williamsburg Granodiorite south of the Hatfield Pluton, just east of Chestnut Street (Plate 1).

The Hatfield Pluton is also riddled by tiny veinlets or fissures along which the mafic minerals in the pluton have been replaced by epidote and chlorite. These veins are abundant near the eastern border of the pluton and disappear to the west.

Chlorite and prehnite occur as secondary minerals in most sections of the Hatfield Pluton. Chlorite occurs as a replacement of hornblende and biotite, and prehnite occurs in biotite.

All of the above are probably related to events in the Triassic (Emerson, 1898; Willard, 1956).

Distribution of rock types

Although the locations of the eastern and southern borders of the pluton are uncertain, the intrusion appears to be zoned to some extent. The outer zone, which comprises the majority of the exposed body, is tonalite; the inner zone is granodiorite (Plate 1). The breccia occurs along the eastern edge of the exposed pluton, and is gradational into the surrounding pluton. Contacts between breccia and the surrounding intrusion are placed approximately. The breccia occurs as small masses up to about a quarter of a mile in diameter, and comprises only a small portion of the entire complex (Plate 1). The hornblendite occurs only as blocks in the breccia and as inclusions in the pluton. Some inclusions are up to 100 feet across (Plate 1). Inclusions of hornblendite are most numerous near the eastern edge of the exposed intrusion and disappear to the west. Felsic dikes are common but not abundant near the eastern and southern edges of the pluton.

Mineralogy

All of the rock types in the Hatfield Pluton contain the same mineral assemblages, but the amounts of the minerals vary from rock type to rock type. This section is devoted to the variations in chemical compositions of the major rock-forming minerals as inferred from their pertinent optical properties.

Quartz. The quartz in all thin sections of the pluton is highly strained. Optic axis figures with a 2V of about 5° were observed on some grains.

Potassium Feldspar. Two types of potassium feldspar are present in the Hatfield Pluton. A clear untwinned variety with a small 2V of 20° to 30° was identified as sanidine, containing on the order of 20-30 percent of the albite molecule in solid solution (Deer and others, 1966). The other variety has a large 2V, between 80-90°, and exhibits the tartan pattern of twinning characteristic of microcline. Neither variety is peculiar to the granodiorite or the tonalite. However, the sanidine generally occurs near the contact while the most prominently twinned microcline occurs in the interior of the body.

Since the more disordered sanidine is concentrated in the tonalite, it is probable that this rock crystallized at a higher temperature than the granodiorite. The sanidine may also indicate that the magma at the contact cooled quicker than that in the interior. Slower cooling in the interior allowed the sanidine to invert to microcline, while at the contact sanidine persisted due to faster cooling.

A few grains of microcline exhibit exsolution lamellae in their cores, indicating unmixing at even lower temperature. The potassium feldspar in several slides exhibits a patchy extinction, possibly indicating that some sanidine has not fully inverted to microcline.

Plagioclase. The composition of the unaltered plagioclase in the granodiorite, tonalite, tonalite at the contact with the Whately Schist, and in the breccia groundmass, is andesine, $An_{33 \pm 2}$ (weight percent). The original composition of the plagioclase in the hornblendite is unknown because it is totally altered in available specimens.

The composition of the unaltered plagioclase was determined by matching the alpha index in oil immersion mounts. The α index of refraction of unaltered plagioclase from 20 specimens of granodiorite and tonalite varied within the narrow range of 1.542 to 1.547 $\pm$ .001, indicating an essentially constant An content. Bazakas (1960) reported that the plagioclase composition varied from albite to andesine in the southern part of the Hatfield Pluton. Willard (1956) reported that the plagioclase in the northern part of the pluton was oligoclase. Neither author reported his method of determining the composition of plagioclase. Perhaps the discrepancy between the present work and earlier work can be explained by assuming that the above-mentioned workers used a twin-method for determining the plagioclase composition. Twin-methods are less reliable than the oil immersion method (Deer and others, 1966). Furthermore, most plagioclase grains are bent and broken, creating a curved extinction, and thus making a twin-method even more uncertain.

Much of the plagioclase is highly altered to fine white mica, prehnite (?), and epidote. The plagioclase in the granodiorite is more highly altered than that in the tonalite. The plagioclase in the hornblendite is totally altered.

Diopside. The diopside is light green and not pleochroic in thin section. It has an estimated $2V_Z = 60°$ and a β index of refraction = 1.683, indicating a ratio of Mg/(Mg+Fe) = .90 (Hess, in Deer and others, 1966). The extinction angle is about 46°.

Hornblende. Two highly magnesian hornblendes are present in the Hatfield Pluton. The hornblende that occurs in the granodiorite and tonalite is optically negative and does not vary detectably in composition, having a ratio of Mg/(Mg+Fe) = .74 (Deer and others, 1966) based on the γ index of refraction of 1.662 measured in immersion mounts. It is strongly pleochroic. In a {100} section, the center of the grain is green, while at the borders of the grain the color is slightly bluish green, indicating some chemical zonation.

The hornblende in the blebs and in the hornblendite is slightly more magnesian, Mg/(Mg+Fe) = .80 (Deer and others, 1966), than that in the groundmass, based on a γ index of refraction of 1.655. Perhaps this indicates that the hornblende in these rocks crystallized earlier from the same magma that later produced the hornblende in the groundmass. The hornblendite and bleb hornblende are slightly pleochroic and commonly have colorless border zones. Both hornblendes are twinned on {100}.

Biotite. Both green and brown biotite are found in the pluton. The brown biotite has a γ index of refraction of 1.638, indicating a ratio of Fe/(Fe+Mg) = .46 (Wones, 1963). The green biotite has a γ index of refraction of 1.600 and is probably rich in ferric iron.

A reddish-brown biotite that occurs in the pluton at the contact with the Whately Schist probably contains titanium (Deer and others, 1966).

Accessory Minerals. Epidote, allanite, sphene, apatite, and zircon are accessories. Epidote and allanite are found in most thin sections while sphene, apatite and zircon are found in all sections. In a few sections the epidote is slightly pleochroic in yellow-green.

The allanite is yellowish brown to bright orange in thin section. Many grains are slightly metamict, with typical cracks radiating from the allanite grain out into the surrounding grains. Most grains are surrounded by epidote.

The sphene has a normal, small, optically positive 2V and is pleochroic in brown red, probably indicating that a rather high dosage of U and Th produced high radiation damage (H.W. Jaffe, oral commun.).

Zircon is particularly abundant at the contact with the Whately Schist. It occurs as larger metamict grains that are almost isotropic and have low birefringence.

Secondary Minerals. The major secondary minerals are chlorite and prehnite. Chlorite occurs in most sections as borders and bands in biotite and sometimes as rims on hornblende. The chlorite has a small 2V, positive sign, and is length-fast, indicating that it is magnesian chlorite (Deer and others, 1966).

Prehnite occurs as "bow tie" reniform masses inside biotite grains and as "beads" along biotite grain boundaries.

Granodiorite

The central zone of the exposed pluton is composed of granodiorite (Table 1, Plates 1 and 2). Plagioclase is the most abundant constituent. The plagioclase occurs in large crystals about 2 mm long. Grains of plagioclase are subhedral and exhibit combined albite, Carlsbad, and pericline twinning. The plagioclase where unaltered is andesine, $An_{33\pm2}$. Many of the plagioclase grains, however, show cores that are more highly altered than in the plagioclase of the tonalite. Myrmekite occurs as quartz vermicules in plagioclase grains at the contact of plagioclase and microcline, but is not common.

Both orthoclase and microcline are present in the granodiorite. They occur as large subhedral grains 1 mm across, and in some cases poikilitically enclose rounded grains of plagioclase and hornblende. Potash feldspar grains are smaller than the plagioclase grains. Microcline and sanidine occur together in most slides. Specimen 72, near the western contact with tonalite, contains only sanidine. Where sanidine occurs with microcline, the former exhibits patchy extinction, probably indicating that it has not completely inverted to microcline. Some grains of microcline exhibit very fine exsolution lamellae, probably of an albitic plagioclase.

Remnant diopside can be seen in the centers of some hornblende grains (Fig. 4). Other hornblende grains contain irregular grains of quartz in the cores. These minute quartz grains probably indicate that the hornblende replaced diopside (Emerson, 1898). Because

Figure 4. Diopside core of hornblende grain. Specimen W82. Length of view is 2 mm.

Figure 5. Hornblendite breccia. Note that some blocks are angular whereas others grade into the groundmass. Location near Specimen E10.

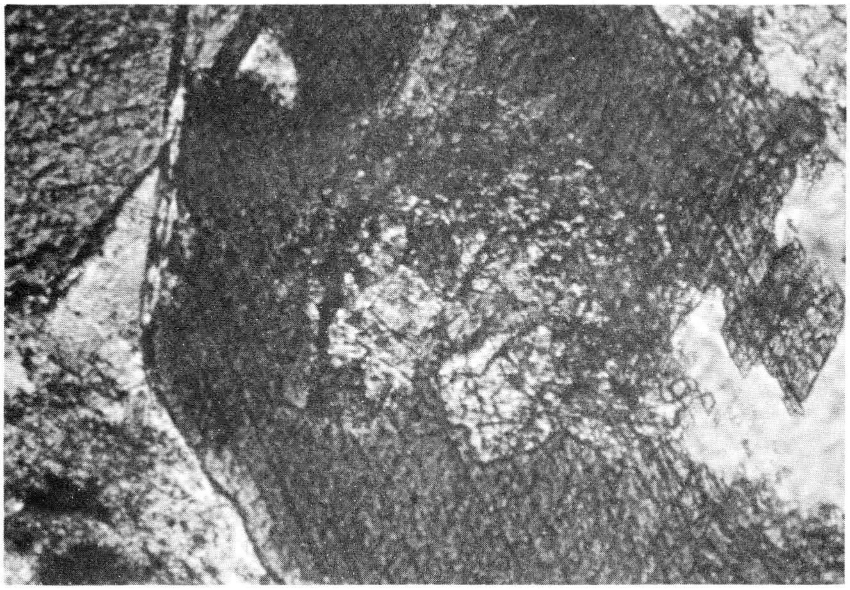


Figure 4

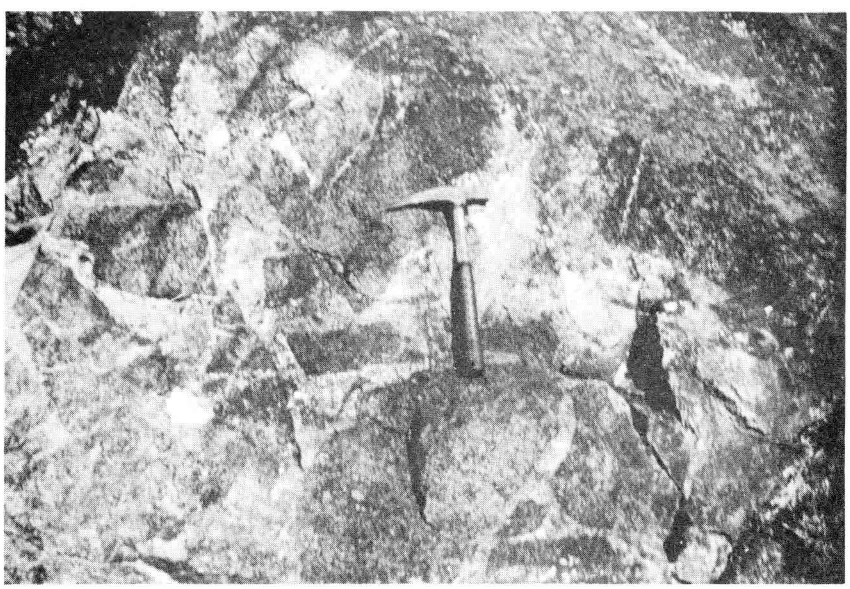


Figure 5

diopside is richer in silica than hornblende, the conversion of pyroxene to amphibole would produce excess quartz.

Hornblende is the dominant mafic mineral in the granodiorite. Hornblende grains are subhedral and are about 1.5 mm long. The hornblende occurs in elongated aggregates with biotite. These aggregates partially define the foliation. Biotite penetrates and borders the hornblende.

Green and brown biotite occur in the granodiorite, the brown variety being somewhat more abundant. The green biotite occurs as subhedral grains while the brown biotite is usually poikilitic. Pleochroic haloes around inclusions of zircon, apatite and sphene are common. Prehnite occurs as a secondary mineral along biotite boundaries and as "bow ties" up to .25 mm in diameter within biotite grains. Most biotite is partially replaced by chlorite.

Sphene occurs as large anhedral grains associated with hornblende and as elongated grains parallel to the cleavage in biotite. Sphene seems to be more abundantly associated with green biotite, probably indicating a low titanium content in that biotite. Titanium for the formation of sphene apparently was derived from the brown biotite during its conversion to green biotite at a late stage.

Allanite is usually surrounded by epidote. Epidote occurs as large grains with biotite near the western border with the tonalite. Zircon and apatite occur abundantly associated with hornblende and biotite. Apatite is usually small but may be up to .25 mm long.

Tonalite

The tonalite is very similar to the granodiorite in texture and mineralogy. However, the tonalite has less potash feldspar and hornblende and more biotite and quartz than the granodiorite (Tables 1 and 2).

As in the granodiorite, the quartz in the tonalite is interstitial, and highly strained. A few grains of myrmekite are also present in most tonalite slides.

Both sanidine and microline are found in the tonalite as small interstitial grains. Specimens from near the contact with the Whately Schist contain only sanidine. Most tonalite sections contain microcline and potash feldspar with patchy extinction, which probably has not fully inverted from sanidine to microcline.

The plagioclase in the tonalite is more deformed and less altered than that in the granodiorite. The unaltered plagioclase is $An_{33\pm2}$.

Hornblende is subordinate to biotite in the tonalite, and no diopside is present. The hornblende is subhedral and interpenetrated by biotite.

Green biotite is slightly more abundant in the tonalite than brown biotite.

The tonalite at the contact with the Whately Schist apparently has reacted with the schist to some extent. The tonalite contains no hornblende or potash feldspar, but does contain abundant biotite and quartz (See WM 71, Table 3). The biotite is reddish brown, indicative of a high TiO_2 and low Fe_2O_3 content. Perhaps this zone was enriched in potassium and silica as well as H_2O from the adjacent schist.

Hornblendite

Rocks called hornblendite are really gradational from true hornblendite to meladiorite. This is also the case in the main Belchertown Complex (Guthrie and Robinson, 1967). In any event, rocks called hornblendite are much more mafic than the enclosing tonalite and granodiorite.

The hornblendite is composed chiefly of hornblende with some biotite, diopside, and plagioclase (see H4 of Table 3). Several specimens of this rock from Belchertown contain more than 50 percent diopside (Guthrie and Robinson, 1967). One specimen (E23) from the Hatfield Pluton contains aggregates of subhedral diopside grains. However, in most hornblendite inclusions, diopside occurs only at the cores of a few hornblende grains. Numerous grains of hornblende also contain minute grains of irregular quartz in their cores, probably indicating that hornblende replaced diopside (Emerson, 1898).

The hornblende in the hornblendite is slightly more magnesian than that in the enclosing granodiorite and tonalite but has the same Mg/Mg+Fe = .80 ratio (Deer and others, 1966) as the hornblende in the hornblende blebs which occur throughout the pluton. The hornblende in the hornblendite occurs in large subhedral crystals up to 1 cm across. The large hornblende crystals are surrounded by interstitial to subhedral plagioclase, small grains of hornblende, and a few grains of biotite, microcline, and quartz. Biotite also occurs inside hornblende grains, probably indicating partial replacement of hornblende by biotite.

The composition of the plagioclase could not be determined from the samples available because the plagioclase is totally altered to fine mica.

Accessory minerals are apatite, sphene, allanite, and epidote. The apatite, in grains as much as 2 mm long, is more abundant and much coarser grained than in the surrounding tonalite and granodiorite. Secondary brown carbonate (siderite?) occurs poikilitically in a few of the hornblendite inclusions and is probably a product of alteration during the Triassic.

Small veins, 1 mm wide, of pure microcline can be seen cutting across the hornblendite in some specimens.

Breccia

The breccia consists mostly of blocks of hornblendite in a matrix of granodiorite that is similar to the granodiorite described above. Blocks of schist and of earlier solidified plutonic rocks also occur. Hornblendite blocks are several inches to tens of feet across. Schist inclusions and blocks of coarse-grained plutonic rock are usually smaller than 1 foot across. Contacts between the hornblendite blocks and the groundmass are usually sharp but some are gradational as if the hornblendite were partially resorbed (Fig. 5). Some blocks of hornblendite have been deformed. Hornblende in the hornblendite breccia blocks is sometimes colorless in the outer zone of the grains. This colorless amphibole rim on hornblende grains is probably tremolitic and may have to do with Triassic retrograde alteration.

The schist blocks are probably pieces of the wall rock. This may indicate that the contact between the Hatfield Pluton and the metamorphic rocks is buried by Triassic rocks but is approximately located at the eastern edge of the exposed pluton.

The groundmass granodiorite contains quartz, microcline, subhedral plagioclase, hornblende, sphene and epidote. Where breccia grades into inclusion-rich plutonic rock, biotite is also abundant (E10, Table 3). The plagioclase in the groundmass is highly altered to fine mica. Microcline occurs as large grains as much as 2 mm across, poikilitically enclosing plagioclase. Hornblende is not abundant and is much finer grained than the hornblende in the rest of the intrusive rocks. In general the granodiorite breccia matrix is less mafic than the corresponding granodiorite in the center of the intrusion. Very thin, dark pink dikes of microcline are common in the breccia.

Felsic Dikes

There are two varieties of pink dikes. The most common consist of plagioclase and microcline but are depleted in mafic minerals. These are similar to the breccia groundmass. The plagioclase is subhedral and highly altered; the microcline is poikilitic. Hornblende grains are small and subhedral and are strongly aligned. These dikes are light pink in color and are up to 1 foot wide.

The other type of pink dike consists entirely of large pink microcline crystals up to 2 mm across. These dikes are most common in the breccia but also occur elsewhere. They are dark pink and never exceed 2 inches in width. Most of them are less than one-half inch wide.

PETROLOGY OF THE HATFIELD PLUTON

General

Before discussing the crystallization history of the Hatfield Pluton, its relationship to the main Belchertown Complex east of the Triassic rocks in the Connecticut lowland (Fig. 1) should be considered.

Both intrusions are zoned plutons, each having a principal outer zone of tonalite and an inner zone of granodiorite. Both contain breccia, inclusions of hornblendite, and small hornblende blebs (Bazakas, 1960; Guthrie and Robinson, 1967; Guthrie, 1971; D.J. Hall, oral commun., 1970). The Belchertown Batholith also has a core of granodiorite that contains diopside and hypersthene (D.J. Hall, oral commun., 1970). The exposed Hatfield Pluton does not contain this hypersthene-diopside granodiorite; however, remnant diopside in hornblende is present in several granodiorite samples. Similarly, diopside in hornblende is present in a zone surrounding the hypersthene-diopside granodiorite in the Belchertown Batholith (Guthrie and Robinson, 1967; Guthrie, 1971).

The plagioclase composition in the Belchertown Batholith varies somewhat and has an average An content of about 33 percent (Guthrie, 1971; Guthrie and Robinson, 1967; D.J. Hall, oral commun., 1970), which is very similar to the plagioclase found in the Hatfield Pluton.

Geophysical studies indicate a gravity high extending from the vicinity of the Hatfield Pluton across the Connecticut Lowland toward the Belchertown Batholith (Bromery, 1967). A gravity study of the Belchertown Batholith indicates a northwest-trending high in that body (D.J. Hall, oral commun., 1970). Whether or not this gravity high indicates a connection between the two bodies at depth is purely speculative. Metamorphic rocks are exposed in the Amherst area in the position of the gravity high, and there are no exposures of Belchertown-type rocks. However, Emerson (1917) shows a narrow band of Belchertown Tonalite along the Triassic border fault as far north as the town of Montague and Peter Robinson (oral commun.) has seen a few isolated outcrops in this general vicinity.

The numerous similarities between the two Belchertown bodies suggest that they are related and have had similar crystallization histories.

Crystallization history

The Hatfield Pluton is composed of granodiorite and tonalite with minor amounts of hornblendite, breccia, and felsic dikes. Several peculiar aspects of the granodiorite and the tonalite preclude a history of simple magmatic differentiation according to Bowen's reaction series (Bowen, 1928). If the granodiorite and tonalite had differentiated from the same magma, under the same conditions, it would be expected that the plagioclase would be more calcic and the hornblende more magnesian in the tonalite than in the granodiorite, which is not the case. Since water concentrates in the liquid as crystallization proceeds (Kennedy, 1955), it would also be expected that the earlier formed tonalite would contain the diopside and hornblende with little biotite, whereas the granodiorite would be expected to contain the more hydrous biotite as the principal mafic mineral, rather than hornblende. Quartz would also be expected to be more abundant in the later differentiated granodiorite, but instead it is more abundant in the tonalite.

The origin of the hornblendite presents another problem. Does the hornblendite represent inclusions of some country rock or is it a product of the intruded magma? Since the hornblende in the hornblendite is more magnesian yet optically similar to that in the granodiorite and tonalite, a genetic relationship is suggested. Furthermore, the presence of diopside in the hornblendite and in the granodiorite seems more than a coincidence. Since the two rocks are chemically related and no source of a hornblendite is known to exist in the country rock, an igneous origin for the hornblendite will be assumed. However, it is difficult to visualize a primary accumulation of hornblende since the intrusion would have been largely crystalline when hornblende began to crystallize, making crystal settling of the hornblende impossible.

Emerson (1898) considered the Belchertown Tonalite bodies to originally have been a "diallage-biotite-gabbro". He noted that in the Belchertown Tonalite "diallage" (pyroxene) crystals were often rimmed by hornblende. He concluded that the "diallage" went to hornblende (Emerson, 1898, p. 338). If the hornblendite is related to the Belchertown bodies, it seems plausible that the original Belchertown magma was more mafic, as Emerson concluded (1898), possibly dioritic.

On one hand we observe two end members of a magmatic differentiation, the early-formed diopside-bearing hornblendite and the residual felsic dikes. On the other hand the two intermediate rock types which comprise the vast majority of the complex, the granodiorite and the tonalite, do not fit a differentiation model.

The main differences between the granodiorite and the tonalite are in their amounts of quartz and potassium respectively. The modes in Tables 1 and 2 show that the amount of biotite in the two rock types is practically equal while the amount of orthoclase in the granodiorite is three times that in the tonalite. Thus potassium is far more abundant in the granodiorite than in the tonalite. The potassium in the magma must have concentrated in the center of the intrusion, thus changing the bulk composition of the central liquid. Therefore the central liquid may have followed a different path from the surrounding outer liquid. If we assume that the original tonalite and granodiorite liquids contained approximately the same percents of quartz, plagioclase, and potash feldspar as in the average mode of granodiorite (Table 1) and tonalite (Table 2) respectively, it can be seen that the two liquids would have followed different crystallization paths (Fig. 6). The tonalite (T) liquid

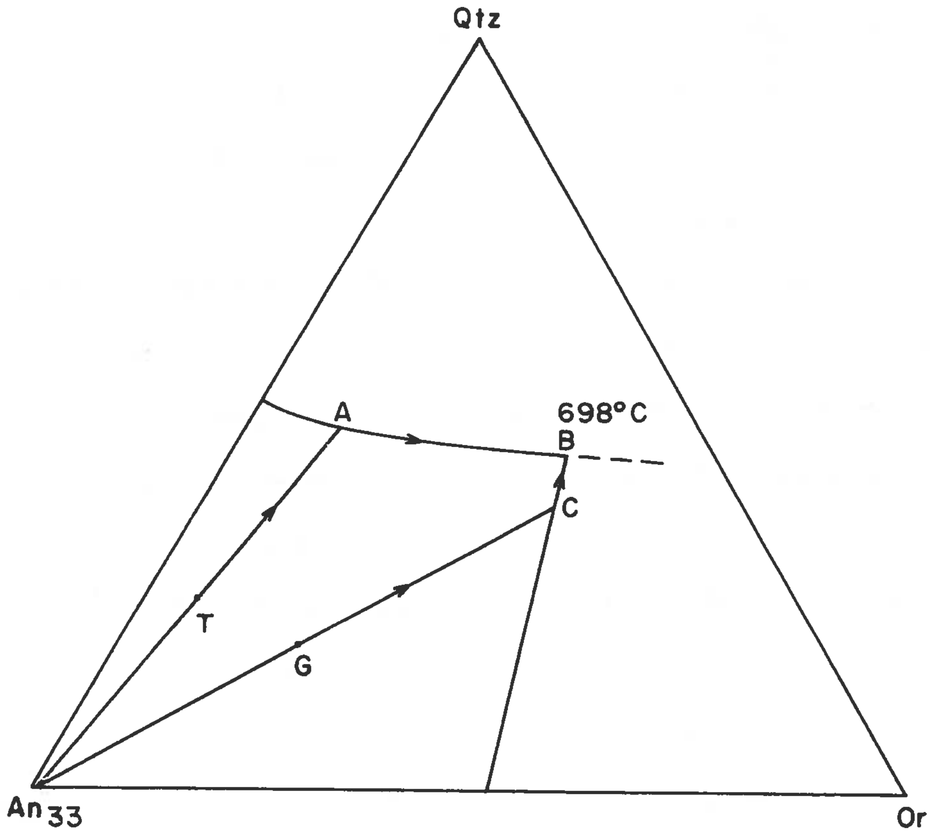


Figure 6. Approximate projection of the system Qtz-Or-An_{33} at P_{H_2O} = 2 kb. Point T is the average composition of the tonalite samples from Table 2. Point G is the average composition of the granodiorite samples from Table 1. (after von Platen, 1965)

would crystallize plagioclase until the plagioclase-quartz cotectic (A) was reached, and quartz would begin to crystallize. Following the cotectic, plagioclase and quartz would crystallize together. Potash feldspar would not crystallize until the eutectic (B) was reached. The granodiorite liquid (G), however, would reach the plagioclase-potash feldspar cotectic (C) first, thus precipitating plagioclase and potash feldspar together until the eutectic (B) was reached and quartz began to precipitate.

These two paths of crystallization are supported by textural evidence in the two rock types. The tonalite has more quartz than the granodiorite, indicating the earlier appearance of quartz. The small amount and interstitial form of potash feldspar in the tonalite reflect the fact that potash feldspar did not precipitate until the eutectic was reached. The granodiorite, on the other hand, has large subhedral potash feldspar crystals and a smaller percent of quartz which occurs interstitially, indicating the earlier appearance of potash feldspar; quartz did not appear until the eutectic was reached.

The concentration of potassium in the granodiorite is a real problem since it is obvious that the granodiorite could not have fractionated from the tonalite. A clue to this problem may be the fact that the dominant mafic mineral in the tonalite is biotite, whereas hornblende is dominant in the granodiorite. This indicates that the activity of water was greater in the tonalite than in the granodiorite. Normally, water concentrates in the liquid as crystallization of a magma proceeds, thus later formed rocks contain more hydrous minerals than early formed rocks. Since the tonalite comprises the outer zone of the intrusion, it is probable that the intrusion was enriched in water from the intruded wallrock. In part, the Hatfield Pluton intrudes pelitic schists which contained both pore water and hydrous minerals. The water in the schist would be heated by the intrusion, causing water pressure in the schist to rise rapidly at the contact. Thus the water pressure in the schist would be greater than that in the magma and water would enter the magma (Kennedy, 1955). The movement of water into the Hatfield Pluton from the schist is supported by the presence of tonalite (W59) adjacent to the southern schist inclusion in the north end of the intrusive, while slightly away from the inclusion the pluton is granodiorite (W58). Contact metamorphism of the schist caused some potassium and possibly some silica to dissolve in the heated water and be carried into the intrusion with the migrating fluid, enriching a narrow border zone in potassium and silica (W71). At depth, where the temperature was probably higher, the magma would have been more enriched in potassium from the wallrock. This deeper liquid could then have intruded the tonalite liquid, producing the granodiorite core of the body. In this manner an originally homogeneous liquid could have produced the tonalite and the potassium-enriched granodiorite.

According to this hypothesis, a homogeneous, relatively dry dioritic magma began differentiating at depth. First diopside would crystallize and accumulate along the walls and in aggregate meshes within the magma. Any water in the magma would have migrated to the cooler wall zone. The aggregated diopside would then react with the water-enriched interstitial liquid to form the magnesian hornblende. Plagioclase and possibly hypersthene were also crystallizing. Part of the magma would then be intruded into its present position. Water and potassium from the adjacent schist enriched the narrow border zone, causing abundant biotite to crystallize. Farther into the pluton, hornblende and then brown biotite were crystallizing in a normal crystallization sequence. Then the deeper part of the magma which had been enriched in potassium from the schist wallrock was intruded as crystal mesh containing diopside plagioclase and probably hornblende into the overlying tonalite, producing the granodiorite. The diopside-hornblende rock along the chamber walls was brecciated and included by the granodiorite liquid, producing the breccia and numerous inclusions in that body. Thus the second pulse of magma, enriched in potassium, would follow a different crystallization path from the tonalite, producing abundant microcline. As water from the wallrock penetrated the pluton, the secondary green biotite formed from the primary biotite and hornblende. Similarly the diopside aggregates in the magma were converted to magnesian hornblende, producing the hornblende blebs.

A metamorphic hydration may have produced the mineralogical zoning in the Hatfield Pluton. Fox and Moore (1969), in their detailed study of the Adamant Pluton, British Columbia, contend that an igneous body was totally recrystallized by introducing H_2O and varying the P_{O_2}. They concluded that the Adamant Pluton was an originally homogeneous pyroxene monzonite which was emplaced as a plastic solid. Later, water introduced into the pluton from the wall rocks caused recrystallization, proceeding inward, at a temperature of about 600°C. Anatexis in the peripheral zones produced late stage felsic dikes which cut the already zoned pluton.

The potash feldspar, which exhibits patchy extinction, and the outer more hydrous zone of the Hatfield Pluton are similar to features in the Adamant Pluton. According to this metamorphic hydration hypothesis, the Hatfield Pluton would have originally crystallized as a pyroxene-hornblende-biotite granodiorite with an early differentiated pyroxene rock. Then it would be plastically intruded, causing the foliation and deformation of crystals and breaking up and including blocks of the pyroxene rock. The introduction of water from the wall rocks would then hydrate the pluton progressively inward. Diopside in the blocks of pyroxene rock and in the pluton would recrystallize to hornblende, possibly with a recrystallization of the plagioclase which would homogenize the plagioclase crystals, obliterating any igneous compositional zoning. Eventually the second green biotite would form from the brown biotite and hornblende. Peripheral anatexis would produce the felsic dikes which cut across the main body. In places, the movement of this liquid would break up and include the pyroxene-hornblendite as well as the tonalite and granodiorite, thus producing the breccia. Either the exposed Hatfield

Pluton no longer contains an anhydrous core of the original rock type, or it is not exposed. However, the Belchertown Batholith does contain a core of water-poor hypersthene-diopside-biotite granodiorite (Hall, oral commun.).

The similarities between the Hatfield Pluton and the Adamant Pluton are evident. A temperature of 600°C, as suggested by Fox and Moore (1969), would also be plausible for hydration of the Hatfield Pluton since sillimanite is found in the schist wallrock, indicating a minimum temperature of 622°C (Richardson and others, 1969). However, not all aspects of the two bodies are correlative. For example, Fox and Moore (1969) report orthoclase in the central zone and microcline in the outer zone, with a transition zone of potash feldspar which exhibits patchy extinction between the two. In the Hatfield Pluton the best microcline occurs primarily in the center and the best sanidine occurs on the periphery. The most difficult feature to explain by a metamorphic process is the bulk concentration of potassium in the granodiorite. It is this feature that makes it most probable that the zoned nature of the Hatfield Pluton is a primary feature and the result of two pulses of intrusion, the second being enriched in potassium from the wallrocks at depth prior to emplacement.

CONTACT METAMORPHISM OF THE WHATELY SCHIST

General

The intrusion of the Hatfield Pluton caused contact metamorphism of the Whately Schist. This contact metamorphism was superimposed on regional metamorphism, and the contact metamorphism was, in turn, affected by a later slip cleavage.

The Whately Schist is well bedded, with interbedded quartzose and micaceous layers. Graded bedding can be observed in both thin section and hand specimen. At the contact with the Hatfield Pluton, recrystallization has destroyed the finer characteristics of bedding, but the interbedded quartz and micaceous layers are still observable.

In most areas away from the Hatfield Pluton, the Whately Schist is metallic gray to black and has a phyllitic sheen. It is well-foliated subparallel to the bedding, and most samples exhibit small scale crinkle folds having amplitudes of about 3 mm, caused by slip cleavage oblique to the foliation.

Composition of the Whately Schist prior to contact metamorphism

The mineralogical composition of the Whately Schist prior to contact metamorphism is not at all obvious. All of the schist adjacent to the Hatfield Pluton was probably affected by that intrusion or by the later intrusion of the Williamsburg Granodiorite on the west side of the schist unit (Plate 1).

It probably can be assumed that prior to contact metamorphism the Whately Schist was a quartz, biotite, muscovite schist, possibly containing sparse small staurolite I and garnet porphyroblasts. However, it would appear that the contact metamorphism of the Whately Schist was not isochemical, since specimens within 15 feet of the contact contain abundant aluminum silicates, specimens 100 feet from the contact contain no aluminum silicates, and specimens more than 1,000 feet from the contact show no evidence of ever having contained an aluminum silicate, even though the entire area is regionally in the kyanite zone. Thus it appears that the schist at the contact was enriched in aluminum.

At temperatures in the vicinity of 600°C and pressures around 6 kb., water present in the schist would have been heated above the critical point. Supercritical water has considerable solvent ability and may well have dissolved potassium and silica (Krauskopf, 1967) from the schist, thus leaving the schist at the contact rich in aluminum. Partial melting of the schist by the intrusion may also have contributed to aluminum enrichment of the schist at the contact.

Porphyroblast Minerals

Sillimanite, kyanite, andalusite, staurolite, garnet, biotite, muscovite, quartz, and opaques are found in the Whately Schist. Minerals considered to have grown due to contact metamorphism are: sillimanite (Sill), kyanite (Ky), andalusite (And), staurolite (St), garnet (Gar), and coarse muscovite (Mus_c). It is possible that one type of staurolite and some garnet were present as small porphyroblasts prior to contact metamorphism; however, both garnet and staurolite grew during contact metamorphism (Table 4).

Sillimanite. Sillimanite occurs at the contact in very coarse euhedral grains and as fibrolite (Fig. 7). Coarse sillimanite is as much as 4 mm long. It occurs as individual long blades cutting across bedding and in aggregates of grains in rectangular augen. These

Table 4. Estimated modes of Whately Schist

	Edge of aureole			50-1000 ft. from contact					50 ft. from contact	5-10 ft. from contact				At contact		Inclusion
Assemblage	1			2					3	4				5		6
Specimen	W98	W99	W103	W36	W64	W100	W101	W102	W97	W69	W73	W76	W92	W68	W75	W61
Qtz	45	50	60	45	50	58	50	50	44	35	50	40	55	33	40	68
Bio	25	26	12	22	16	18	20	20	20	24	20	15	18	20	20	12
Mus_f	15	10	8	19	23	15	18	13	16	3	10		13			1
Gar	4	4	2	+	3		1	+	+	5		10	+		3	4
St I	1	3	10	1	6	4	6	5	1	5	+	3	+	2	10	
St III														10	+	
Fib											5	12		+	+	
G+I	5	2	1	1	2	2	2	2	5	3	2	3	2	3	5	+
And pseudomorphs =				12		3	3	10	12	20	10	15	12	30	20	15
And									60							+
St II				15		30	20	30	30	80	40	95	35	90	98	
Ky										+	+	+	+			
Sill										18	+	+	+	10	2	50
Mus_c				85		70	80	70	10							50
Qtz															2	
Fib															+	

Figure 7. Coarse sillimanite and fibrolite associated with quartz and biotite. Specimen W69. S, sillimanite; F, fibrolite; B, biotite; Q, quartz. Length of view is 2 mm.

Figure 8. Kyanite apparently replacing staurolite II. Specimen W73. K, kyanite; St, staurolite II; M, muscovite. Length of view is 2 mm.

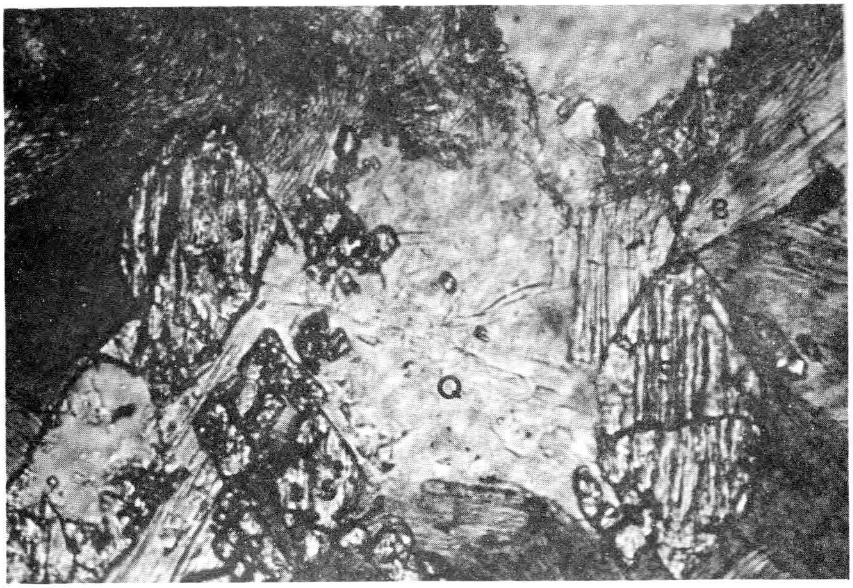


Figure 7

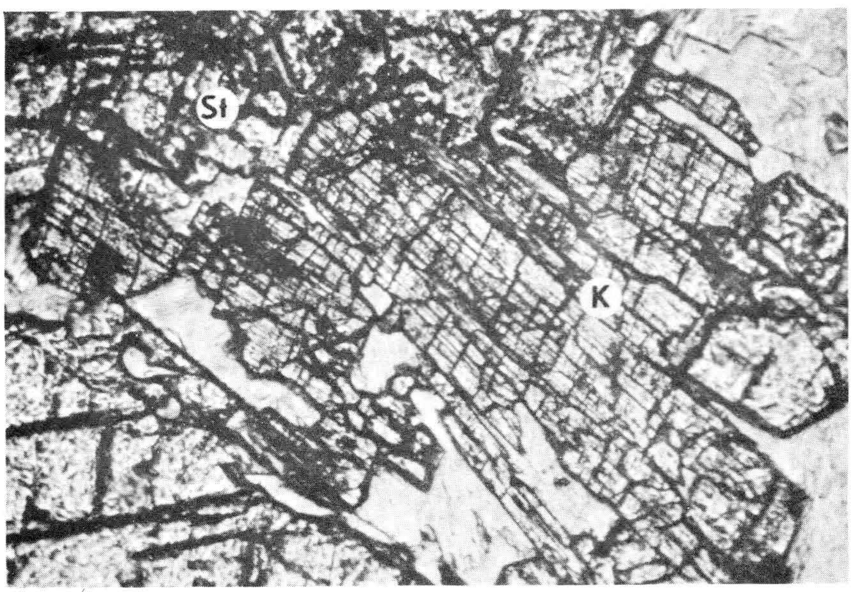


Figure 8

appear to be replacements of andalusite. Fibrolite occurs as dense mats of needles and as individual needles in quartz and muscovite.

Kyanite. Only a few grains of kyanite occur within 5 to 10 feet of the contact. They are small bladed crystals 0.5 mm across. The kyanite (Fig. 8) is usually associated with staurolite containing quartz rods within rectangular augen.

Andalusite. The andalusite occurs as large euhedral porphyroblasts up to 2 cm long. In thin section some prismatic sections have pink pleochroic cores, α = pink, $\beta = \gamma$ = colorless. Most grains also contain chiastolite crosses.

Staurolite. Three types of staurolite are present in the contact zone: I, yellow euhedral staurolite containing many inclusions; II, very pale to colorless staurolite with sectors containing a wormy pattern of quartz; and III, small pale yellow staurolite which is clear of inclusions. Staurolite I is present in most sections of the schist and may be due to previous regional metamorphism. These grains are pleochroic and are commonly twinned. Prismatic sections exhibit the sectoral zoning described by Hollister and Bence (1967), and commonly exhibit a chiastolite-like cross of opaque inclusions and small round quartz grains. Staurolite I often includes the foliation (Fig. 10).

Staurolite II was first described by Emerson (1898, p. 209-210). Sections cut perpendicular to the c-axis have a central zone of colorless staurolite with patches of wormy quartz and a narrow border zone of yellow pleochroic staurolite. The inner zone corresponds to the

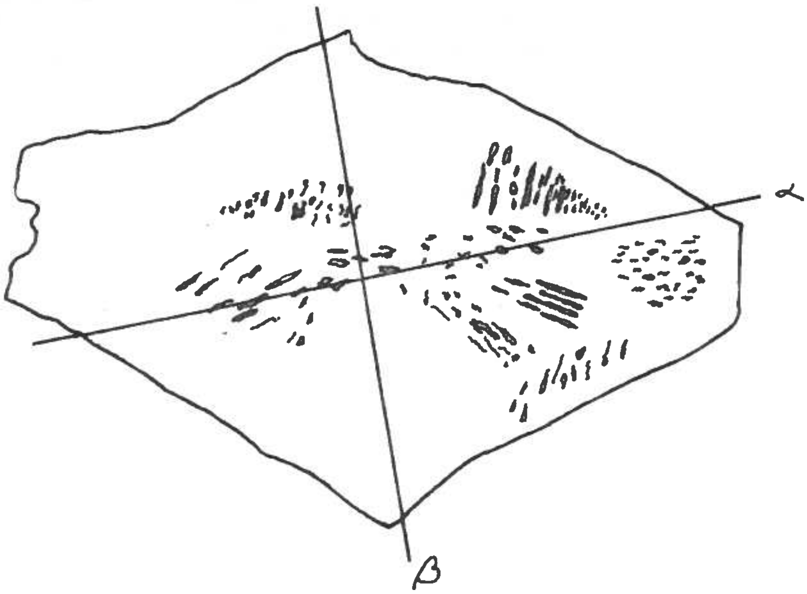


Figure 19. Sketch of Staurolite II showing different orientations of quartz rods in sections of the crystal. Length of view is 2 mm.

Figure 10. Staurolite I, including foliation. Note also the sectoral zoning described by Hollister and Bence (1967). Specimen W64. Length of view is 2 mm.

Figure 11. Grain of pale nonpleochroic staurolite III from slide at contact containing interfingering schist and intrusion. Specimen W74. St, staurolite III; B, biotite; M, muscovite; Q, quartz containing fibrolite. Length of view is 2 mm.

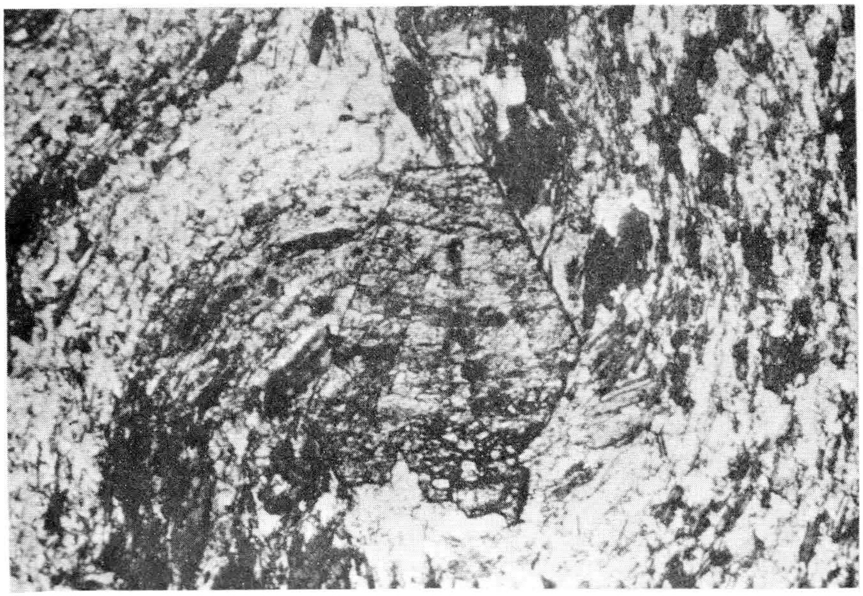


Figure 10

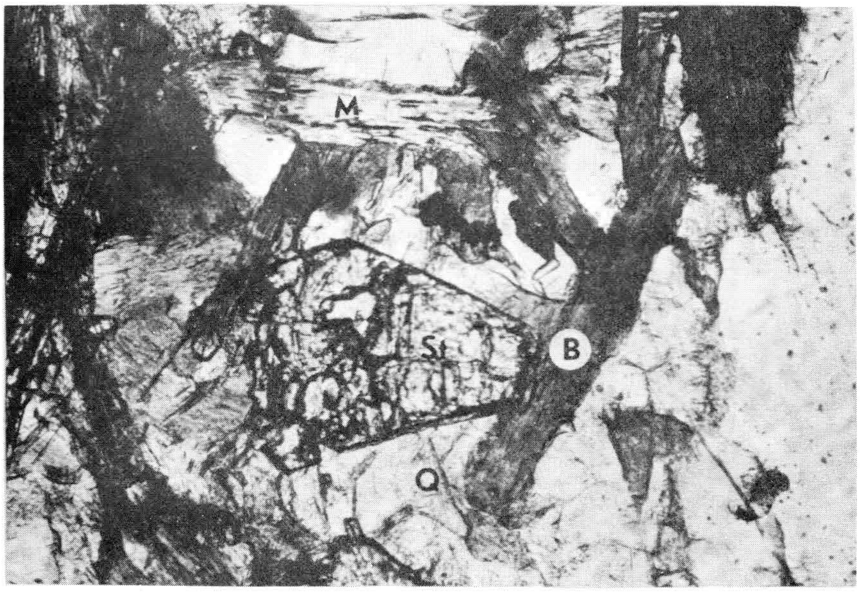


Figure 11

{001} sector and the outer zone corresponds to the {110} and {010} sectors defined by Hollister and Bence (1967). The quartz rods occur in patches in the {001} sector. Within each patch all rods are elongated in the same direction but the direction of elongation differs between patches (Fig. 9). Emerson (1898) suggested that the elongation of the quartz rods reflected crystallographic directions. Staurolite II occurs in grains up to 5 mm across and is always found in pseudomorphs of andalusite.

Staurolite III occurs only at the contact. These grains are not pleochroic, are less than .25 mm across (Fig. 11), and are anhedral in shape.

Garnet. Most sections of schist contain garnet. The garnet is usually poikilitic, containing numerous grains of quartz. At the contact, garnets are up to 1 cm across while one-third of a mile away from the contact the garnets are only 1 mm across.

Muscovite. Coarse muscovite flakes up to 1 mm long occur in "shimmer aggregates" around staurolite II and andalusite.

Groundmass Minerals

Biotite. Biotite is light reddish brown. It is pleochroic; α = pale reddish brown, $\beta = \gamma$ = reddish brown. Near the contact some grains of biotite are pleochroic to colorless; however, grains with a different index of refraction were not found in immersion mount.

Biotite is less abundant but coarser grained near the contact.

Muscovite. The groundmass muscovite is fine grained (Mus_f) and subordinate to biotite. However, neither this groundmass muscovite nor the "shimmer aggregate" muscovite is found at the contact.

Feldspar. Very little feldspar is present in thin sections of the schist. A few grains of oligoclase were observed, but no potash feldspar was identified.

Quartz. Quartz is abundant in all sections but increases in quantity away from the contact. Near the contact, the quartz often contains fine needles, probably fibrolite. All grains of quartz are strained.

Chlorite. A green pleochroic chlorite with anomalous blue interference colors occurs in a few slides. However, it was formed after the foliation and slip cleavage and thus was not involved in contact events.

Zircon, tourmaline, and opaques are accessory minerals. Zircon occurs in biotite and is most abundant at the contact. Tourmaline occurs in a few slides as small olive-green zoned grains. Opaques, which are abundant in all slides, are probably graphite and ilmenite (G+I).

Petrography of the Whately Schist

Several assemblages of minerals are found in the Whately Schist at varying distances from the contact with the Hatfield Pluton.

Assemblage 1 - staurolite I, biotite, fine muscovite, garnet, quartz, graphite, and ilmenite - represents little or no contact metamorphism (Specimens W98, W99, W103). This rock is a phyllite with sparse porphyroblasts of garnet and staurolite I up to 1 mm across (Table 4). Assemblage 2 - staurolite I and II, biotite, coarse and fine muscovite, garnet, quartz, graphite, and ilmenite ± fibrolite - is found closer to the contact (Specimens W36, W64, W100, W101, W102) and resembles the above rock except for the addition of staurolite II and coarse muscovite pseudomorphs after andalusite (Table 4).

Approximately 50 feet from the contact, Assemblage 3 - andalusite, staurolite I and II, biotite, coarse and fine muscovite, quartz, graphite, and ilmenite - is found (Specimen W97). The schist is more micaceous here. Andalusite and staurolite II occur in augen up to 5 mm across. The numerous augen are surrounded by "shimmer aggregates" of coarse muscovite (Fig. 12; Table 4).

Assemblage 4 - sillimanite, fibrolite, kyanite, staurolite I, II, and III, garnet, biotite, coarse muscovite, quartz, graphite, and ilmenite - occurs within 5 to 10 feet of the contact (Specimens W76, W69, W92; Table 4). Sillimanite, kyanite, and staurolite II occur together in andalusite pseudomorphs surrounded by a thin rim of coarse muscovite. Sillimanite, staurolite I and III, garnet, and a minor amount of kyanite occur as individual porphyroblasts. Poikilitic garnets are up to 1.5 cm across. Fibrolite occurs as mats in the matrix and as fibrous masses around biotite in quartz. Porphyroblasts are abundant and in general the rock is coarser-grained than rocks farther from the contact.

At the contact, Assemblage 5 - sillimanite, fibrolite, staurolite I, II, and III, garnet, biotite, quartz, graphite, and ilmenite - occurs (Specimens W68, W75; Table 4). No muscovite or kyanite is found at the contact. About 25 percent of the rock is composed of sillimanite-staurolite II pseudomorphs after andalusite up to 1 cm long. Individual coarse sillimanite needles up to 5 mm long cut across the matrix.

Assemblage 6 - sillimanite, andalusite, garnet, biotite, coarse and fine muscovite, quartz, graphite, and ilmenite - is found in the southern inclusion of Whately Schist (Specimen W61). This inclusion appears to be very quartzose and contains less mica than the schist wallrock. Sillimanite and andalusite occur together in rectangular augen surrounded by coarse muscovite flakes (Fig. 13). Small garnets occur individually (Table 4).

Actual grains of aluminum silicates are found only within 50 feet of the contact. Staurolite II + muscovite pseudomorphs after andalusite are found as much as one-fifth of a mile from the contact. Beyond that, only staurolite I and garnet are found, and these grains may have formed during regional metamorphism prior to contact metamorphism.

Relationships between the Aluminum Silicates and Staurolite

Staurolite II, sillimanite, $\pm$ muscovite; or sillimanite, kyanite, staurolite II and muscovite; or staurolite II, andalusite, and muscovite; or staurolite and muscovite occur together in rectangular augen as pseudomorphs of andalusite. The staurolite-muscovite pseudomorphs after andalusite were first described by Emerson (1898).

These pseudomorphs of andalusite can be seen in several stages of development. At the contact, large grains of staurolite II, which

Figure 12. Coarse andalusite containing several grains of staurolite II in similar orientations. The central staurolite grain, as well as the andalusite, is cut by a small fault which accompanied the development of the northeast slip cleavage. Staurolite on left also deformed. Note fine mica replacement of andalusite. Specimen W97. A, andalusite; St, staurolite II. Length of view is 2 mm.

Figure 13. Sillimanite after andalusite. Andalusite partially replaced by muscovite. Note rim of fine muscovite. Specimen W61. A, andalusite; S, sillimanite; M, muscovite. Nicols crossed. Length of view is 2 mm.

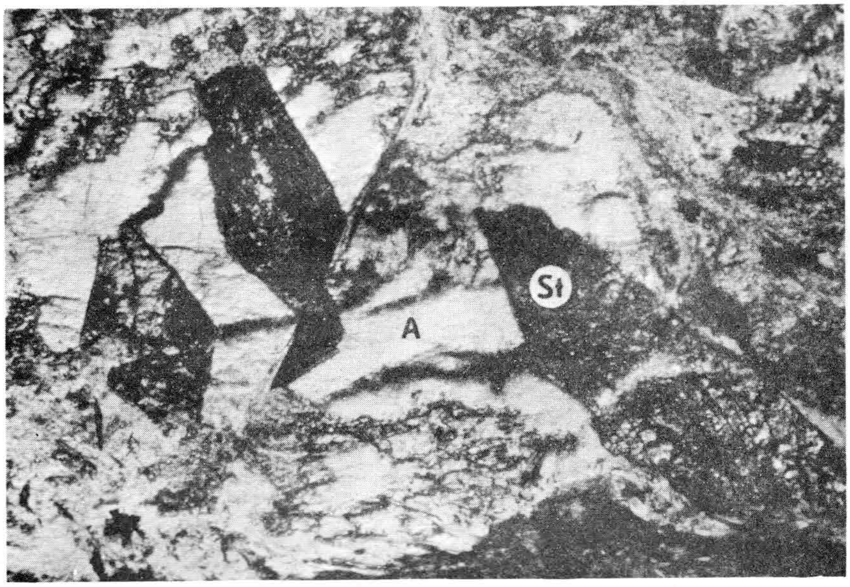


Figure 12

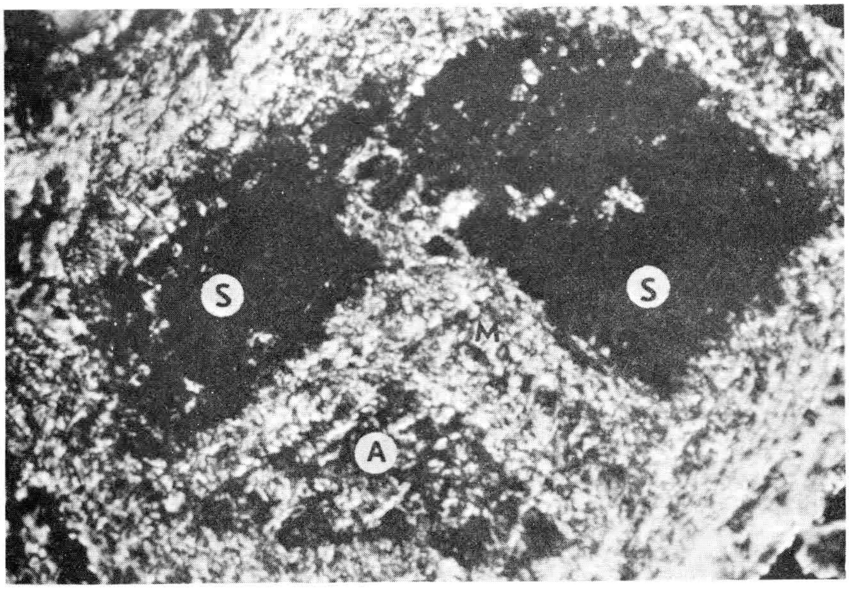


Figure 13

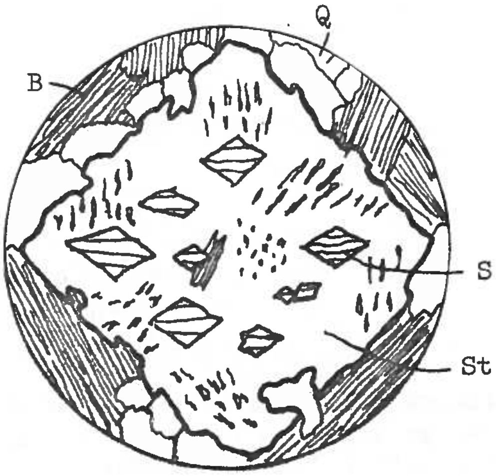
contain several smaller grains of sillimanite (Fig. 15), have totally replaced the original andalusite grains (Specimens W68, W79). These pseudomorphs are not rimmed by coarse muscovite (Fig. 14a).

Staurolite II, containing grains of sillimanite and rarely kyanite (Fig. 16), occurs 5 to 10 feet from the contact (Specimens W69, W76, W92). These pseudomorphs are rimmed by coarse muscovite (Fig. 14b). A little farther from the contact, specimen W97 exhibits grains of staurolite II inside andalusite porphyroblasts (Fig. 12), which are surrounded by a narrow rim of muscovite (Fig. 14c).

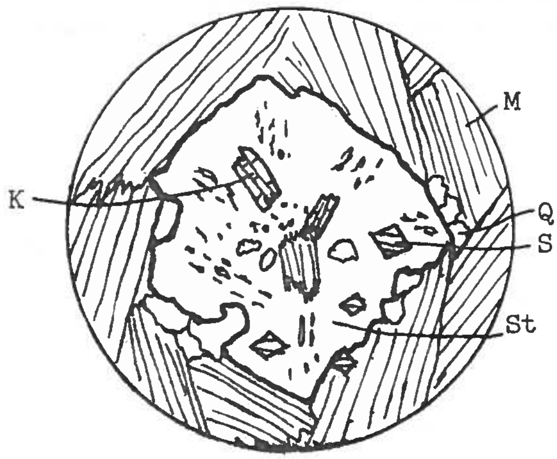
Farther from the contact, specimen W102 contains rectangular augen of coarse muscovite enclosing staurolite II (Fig. 17). Many of these augen contain a chiastolite-like cross of inclusions which begins at the four corners of the auge, and crosses in the center. The staurolite and muscovite that replaced the andalusite preserved the cross (Figs. 17, 18). Pseudomorphs after andalusite can be found as much as one-fifth of a mile away from the contact.

Pseudomorphs after andalusite are common. In cases where the replacement of andalusite by staurolite II was not complete, remaining andalusite was later partly or completely replaced by coarse muscovite, which is abundant in the pseudomorphs away from the contact. In specimen W97, not all of the andalusite was replaced by muscovite. Textural relationships indicate that kyanite and sillimanite appeared after staurolite II.

The relationship between kyanite and sillimanite is not certain. One grain was observed to be half kyanite and half sillimanite a.



b.



c.

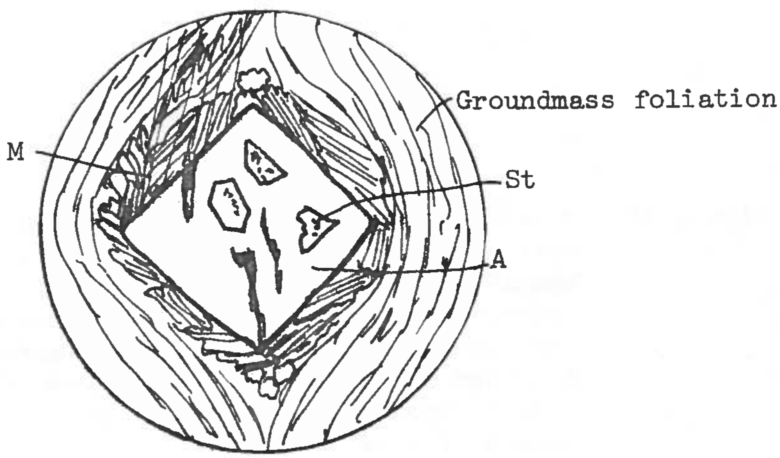


Figure 14. Andalusite pseudomorphs. a. Andalusite totally replaced by staurolite II + sillimanite, biotite rim; b. Staurolite II, sillimanite, and kyanite surrounded by muscovite; c. Staurolite II replacing andalusite, narrow muscovite rim. S, sillimanite; K, kyanite; A, andalusite; St, staurolite II; M, muscovite; B, biotite; Q, quartz. Length of view is 2 mm.

Figure 15. Sillimanite replacement of staurolite II. Note that coarse sillimanite crystals are all in the same orientation within the staurolite II grain. Specimen W68. S, sillimanite; St, staurolite II; B, biotite; Q, quartz containing fibrolite. Length of view is 2 mm.

Figure 16. Aluminum silicate grain which is half kyanite and half sillimanite, in staurolite II. Probably the kyanite partially inverted to sillimanite, but the reverse is also possible. Note the narrow rim of staurolite free of quartz rods surrounding the aluminum silicate grain. Specimen W76. S, sillimanite; K, kyanite; St, staurolite II; F, fibrolite. Length of view is 2 mm.

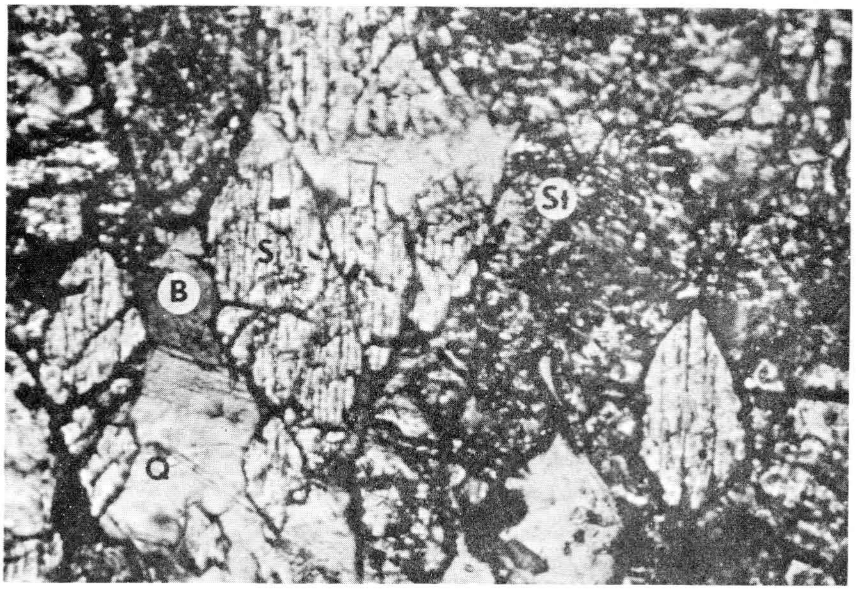


Figure 15

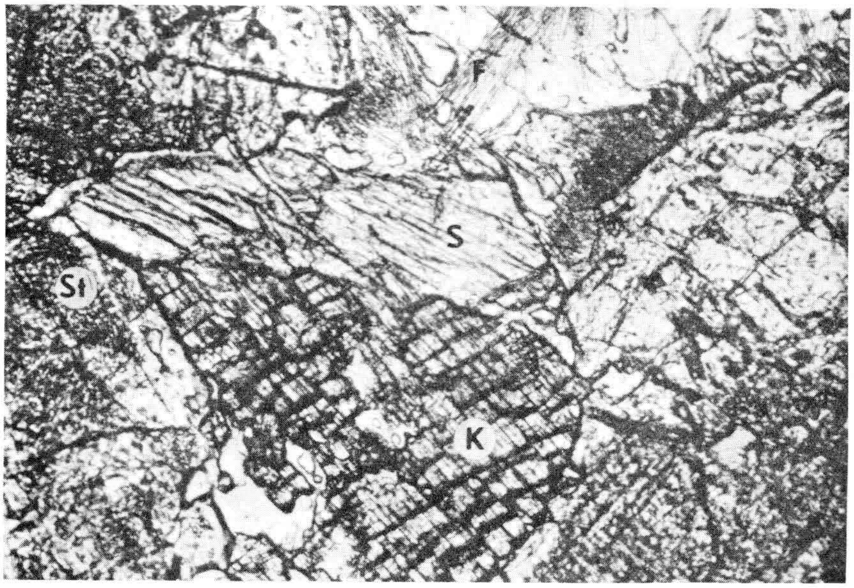


Figure 16

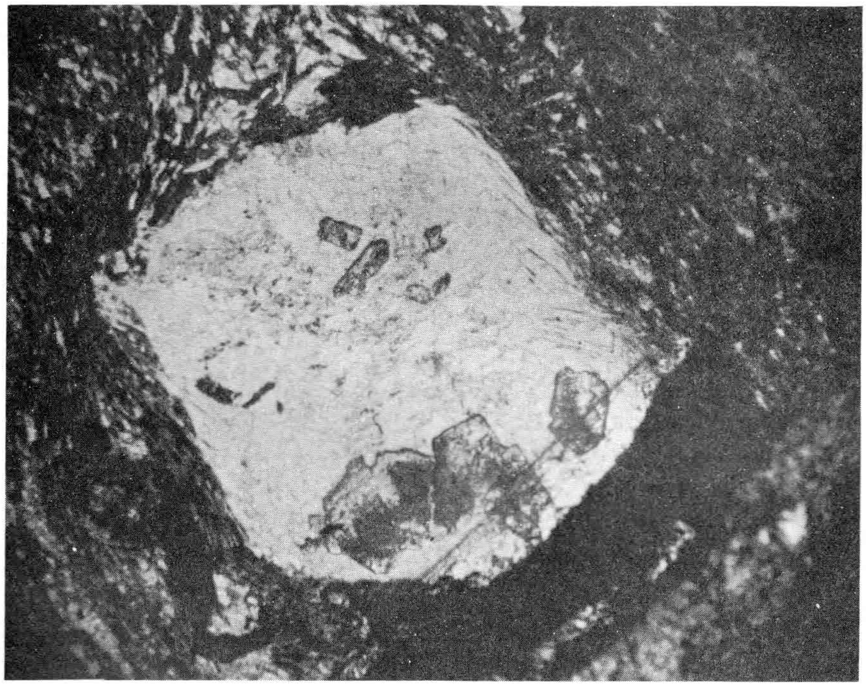


Figure 17. Staurolite II plus coarse muscovite pseudomorph of andalusite. Remnants of chiastolite cross of the former andalusite are visible. Note how the foliation bends around the andalusite pseudomorph. Specimen W102. Length of view is 7 mm.

Figure 18. Enlargement of thin-section W102. Staurolite II plus muscovite pseudomorphs of andalusite are numerous. Chiastolite crosses of former andalusite crystals are visible in many pseudomorphs. Foliation is parallel to the bedding. Graded bedding is also obvious. Slip cleavage cuts bedding and foliation at an angle. 3.5 cm in length.

(Fig. 16). Based on the abundance of sillimanite and the paucity of kyanite, it would appear that the kyanite was inverting to sillimanite. In other words, kyanite probably formed before the sillimanite. However, it may also be possible that the kyanite was formed during a later episode of metamorphism and was not a product of contact metamorphism.

Based on textural relationships, it can be concluded that: 1) andalusite formed, 2) staurolite II totally or partially replaced andalusite, 3) a few grains of kyanite began to replace staurolite, then sillimanite began to replace staurolite II and kyanite, and 4) muscovite partially or totally replaced the remaining andalusite.

Contact Metamorphic Reactions

If the schist had been a muscovite-biotite-quartz-ilmenite-graphite schist, potassium would have to leave the system in order to produce the aluminum silicates and no orthoclase. Essentially, these reactions would be dehydrations, using up muscovite and to a lesser extent, biotite.

To form andalusite:

1. Mus $\longrightarrow$ And + Qtz + K_2O + H_2O

To form staurolite:

2. a) And + Bio $\longrightarrow$ St II + Gar + Qtz + K_2O

   b) Mus + Bio $\longrightarrow$ St + Gar + Qtz + K_2O + H_2O

   c) Mus + FeO $\longrightarrow$ St + Qtz + H_2O + K_2O

To form sillimanite (kyanite, fibrolite):

3. a) St + Qtz ⟶ Sill (Ky) + Gar + H_2O (Hollister, 1969a)

   b) Mus ⟶ Sill + K_2O + H_2O + Qtz

   c) And ⟶ Ky ⟶ Sill

To form coarse muscovite:

4. And + K_2O + H_2O ⟶ Mus

The liberated H_2O and K_2O migrated out of the schist and into the Hatfield Pluton. At the contact, the destruction of muscovite must have been complete, since none is now present. An increase of potassium at the border of the Hatfield Pluton is suggested, since the contact rock contains over 30 percent biotite (Table 3). If potassium was being dissolved out of the schist and carried with the water toward the intrusion as the pluton crystallized and temperatures declined, potassium dissolved from schist away from the contact which had not entered the intrusion would react with remaining andalusite to form the coarse muscovite "shimmer aggregates" (Reaction 4 above) around the staurolite II pseudomorphs after andalusite.

Paragenesis of the Aluminum Silicates and Staurolite

Based on the textural relationships of the aluminum silicates, it appears that: 1) andalusite crystallized, 2) the andalusite was largely replaced by staurolite II, and 3) sillimanite and kyanite partially replaced the staurolite II. Garnet, staurolite III, and possibly staurolite I grew with staurolite II. Finally, at the end of crystallization of the Hatfield Pluton: 4) coarse muscovite replaced most of the remaining andalusite.

The sequence andalusite $\longrightarrow$ staurolite II $\longrightarrow$ kyanite plus sillimanite suggests increasing temperature, and probably increasing pressure, during contact metamorphism. There are four possible ways to explain the above observations:

Case 1. Impurities in the andalusite stabilized it in the kyanite field (Hollister, 1969a).

Case 2. Andalusite formed metastably in the kyanite stability field (Hollister, 1969a).

Case 3. Both the temperature and the pressure were increasing during contact metamorphism.

Case 4. Kyanite was not a product of contact metamorphism but formed later during regional metamorphism.

Since the andalusite in question is pleochroic in pink, it is likely that it does contain impurities (Case 1). A sample of pink pleochroic andalusite from the Burke Area, northeastern Vermont (Woodland, 1963), was studied by Albee and Chodos (1969). It was found to contain very slightly more iron than coexisting kyanite and sillimanite. It is possible that the iron impurity may cause the pink pleochroism. Furthermore, the iron impurity may also have contributed slightly to the replacement of andalusite by staurolite II. In thin section, the andalusite showing strongest pink pleochroism contains no grains of staurolite. The andalusite that surrounds grains of staurolite is not pleochroic.

However, whether or not the impurity is sufficient to stabilize andalusite in the kyanite field is dubious. Albee and Chodos (1969) concluded that impurity differences were not significant. Metastable persistence at pressure-temperature conditions close to the triple point was the most likely explanation (Strens, 1968). Persistence of andalusite near triple-point conditions does not explain replacement of andalusite by staurolite II, which is in turn partially replaced by kyanite and sillimanite.

The metastable formation of andalusite in the kyanite field (Case 2) was proposed by Hollister (1969a). According to this hypothesis, all three aluminum silicates can be formed by increasing the temperature but keeping the pressure constant. This sequence would follow a path similar to Path 1 on Figure 19. As the temperature begins to rise, andalusite forms metastably. When point a is reached at the boundary of the staurolite stability field, staurolite II begins to replace andalusite, as in Reaction 2a above. At point b, the kyanite field is entered, thus some kyanite forms, partially replacing staurolite II by Reaction 3a. Since kyanite never seems to have been abundant, probably only a corner of the kyanite field was crossed. At point c, fibrolite and perhaps sillimanite began to form. When point d is reached, the staurolite field is left and sillimanite forms at the expense of staurolite II by reaction 3a. In Hollister's study (1969a) it was not clear whether staurolite II replaced andalusite or kyanite. In the case of the present study, however, staurolite II clearly replaced andalusite.

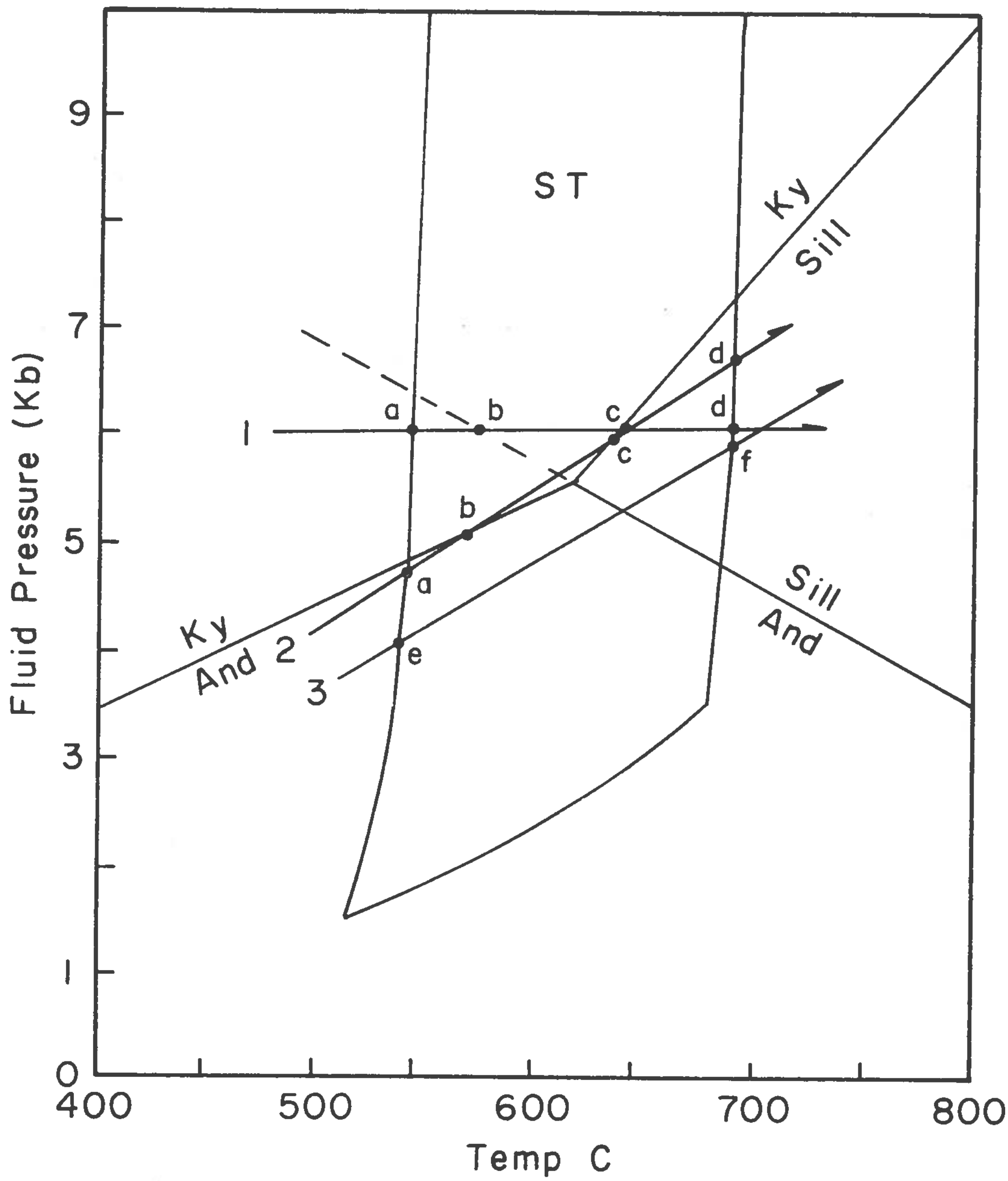


Figure 19. Al_2SiO_5 phase diagram with superimposed stability field of pure Fe-staurolite (Richardson, 1968) showing possible paths of observed aluminum silicate transitions. Sill, silimanite; Ky, kyanite; And, andalusite; St, staurolite.

Since there was a temperature gradient in the schist, the highest temperature being at the contact, the grade of metamorphism at the contact would be in the high-temperature region beyond point d. Ten feet from the contact, where kyanite and sillimanite occur, would probably be a point c. The area between points a and b represent Assemblage 3 - andalusite, staurolite II, biotite, coarse and fine muscovite, quartz, graphite, and ilmenite. Farther from the contact where staurolite and garnet occur but no andalusite was formed, the schist probably was not aluminous enough or the temperature was not high enough to form andalusite.

If, however, both the temperature and pressure increased during contact metamorphism (Case 3), the crystallization sequence may have followed path 2 on Figure 19. Of course, path 2 need not be a straight line but may curve or may be a wavy line if temperature or pressure declined and then increased again. The same events would take place at points a, b, c, and d along path 2 as along path 1, except that andalusite would crystallize stably rather than metastably. In the schist inclusion (Assemblage 6), no kyanite or staurolite are found. Quite possibly the pressure on the inclusion was less because of its position in the magma; thus it followed path 3 (Fig. 14) missing the kyanite field. The inclusion is very quartzose with little mica. Possibly there was not sufficient iron to produce staurolite so that the andalusite inverted directly to sillimanite (Fig. 13).

Hollister (1969a) chose metastable formation of andalusite as the best explanation for his observations in the Kwoiek Area, British Columbia, because the geologic setting showed no evidence of regional deformation. However, evidence of deformation in the Whately Schist is abundant. Pressure could have increased during contact metamorphism due to regional deformation, regional sinking, or burial by overfolded nappes, for which there is considerable evidence on a regional basis (Thompson and others, 1968). Furthermore, the inversion of andalusite directly to sillimanite with no evidence of kyanite ever being formed in the inclusion makes it very difficult to understand why andalusite would form metastably. If the pressure was slightly lower on the inclusion than on the wall-rock, metamorphism in the inclusion may have followed a path very similar to path 2 only at slightly lower pressures, thus missing the corner of the kyanite field (path 3, Fig. 19).

It is also possible that kyanite was not involved in the contact metamorphism (Case 4). If only sillimanite and andalusite formed due to contact metamorphism, possibly Path 3 (Fig. 19) was followed. First, andalusite formed. At point _e_ staurolite II would begin to replace andalusite, and at point _f_ sillimanite would partially replace staurolite. Thus the kyanite field would not be entered. Again, as temperatures declined, andalusite would be repalced by muscovite. Later, an episode of regional metamorphism, possibly the episode that produced the northeast slip cleavage in the schist, caused some kyanite to form. However, no kyanite is found at the contact or at a distance from the contact in the Whately Schist.

Kyanite does occur in the Conway Formation (Willard, 1956) about two miles west of the Hatfield Pluton. It may be possible that away from the pluton the Whately Schist was not aluminous enough to form kyanite. However, it seems odd that kyanite is found 10 feet from the contact where a few grains occur, but not at the contact with the Hatfield Pluton where sillimanite is abundant.

Based on the abundance and positions of the aluminum silicates with respect to the contact it seems most likely that both temperature and pressure increased during contact metamorphism of the Whately Schist (Case 3). This conclusion is further supported by evidence of regional and local metamorphism (Thompson, Robinson and others, 1968).

Structural Relationships between Staurolite and the Aluminum Silicates

Several authors have noted that a pattern of wormy quartz exists in staurolite that has replaced an aluminum silicate (Emerson, 1898; Hollister, 1969a, 1969b). To make staurolite from an aluminum silicate by diffusing iron into the aluminum silicate:

$$9Al_2SiO_5 + 4FeO + 2H_2O \longrightarrow 2Fe_2Al_9Si_{3.75}O_{22}(OH)_2 + 1.5SiO_2$$

Excess quartz is produced and forms the wormy rods in the staurolite. The staurolite no doubt contains some magnesium substituting for iron. Since the staurolite is clearly replacing the andalusite, it would seem that iron would have to diffuse into the andalusite structure. If the andalusite contained some iron as an impurity, the impurity may have acted as a nucleation center. Biotite probably supplied most of the iron that diffused into the andalusite structure (reaction 2a).

As stated previously, the patterns of wormy quartz occur in the {001} sector of the staurolite. Hollister (1970) analyzed several staurolites by sectors and found that the {001} sector is higher in aluminum and lower in silicon than the other sectors. Hollister also noted that if an aluminum "settles in an Al(3B) site, a potential excess charge of (-1) will be needed on both the O(3) atoms, but this excess charge can be eliminated by 2Al instead of 2Si going into the connecting tetrahedral sites" (1970, p. 761). In this way, more Al is concentrated in the {001} sector and Si is partially replaced by Al, thus producing even more excess quartz in that sector. However, Hollister assumes that the Fe-tetrahedral position is filled by Fe and Mg, based on similarities between the iron-bearing layer in staurolite and hercynite. Since Fe would have to diffuse into the andalusite structure, and Al is already abundant, it may be possible that some Al enters the Fe-site with a consequent substitution of Al in the Si-site. In this manner, a very aluminous staurolite would be formed, again producing excess quartz. Smith (1968) concluded that this paired substitution was probable, based on his refinement of the staurolite structure. He assigned up to 1.71 Al in the Fe-site and .51 Al in the Si-site. Substitution of Mg, Mn, and Ti into the staurolite structure would also help provide charge balance. Substitution of Al for Fe may also be responsible for the pale color and absence of pleochroism in the {001} sector of the wormy staurolite since iron is considered to cause pleochroism.

Staurolite and the aluminum silicates are also structurally related. Staurolite contains a kyanite-like layer (Naray-Szabo and Sasvari, 1958; Smith, 1968) that consists of aluminum octahedra and silicon tetrahedra. Thus, staurolite is very similar to kyanite, and has chains of aluminum octahedra in common with the other two aluminum silicates.

Based on the optical orientation of a staurolite crystal enclosed in an andalusite crystal and the optical orientation of the enclosing andalusite, it was possible to obtain an approximate angle of rotation between the a-axis of the staurolite and the b-axis of the andalusite. That angle was measured to be 63°. By rotating the a-axis of the staurolite structure 63° from the b-axis of the andalusite structure, the aluminum octahedra are in the same orientation in both minerals, except for the central octahedron in the andalusite (Fig. 20).

Sillimanite also seems to be structurally dependent on the host staurolite. The sillimanite grains within a given wormy staurolite II crystal have the same orientation and lie primarily along the chiastolite cross of the former andalusite crystal. Structural relationships between staurolite and kyanite could not be determined because of the very few grains of kyanite present.

Hollister (1970) also noted that the surface of one mineral could act as the nucleant for another. By exchange of the cations, the new mineral might grow without significant reorganization of the anions. Thus, staurolite would begin to replace andalusite by

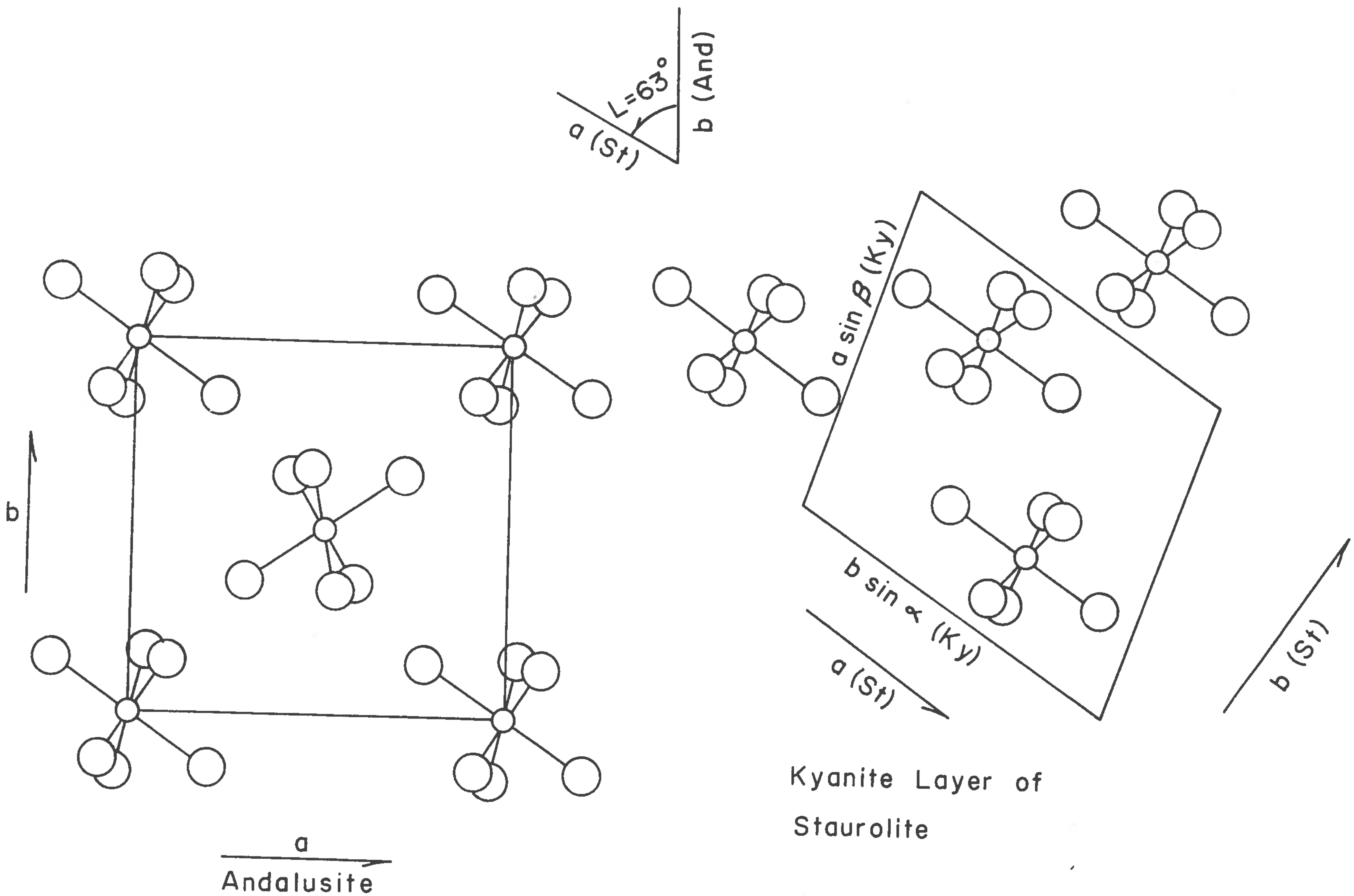


Figure 20. Sketch diagrams showing the orientation of Al-octahedra to crystal axes. By rotating the a-axis of staurolite ≈ 63° from the b-axis of the andalusite, the octahedra in both minerals are in the same orientation except for the central octahedron in the andalusite. St, staurolite; Ky, kyanite; And, andalusite.

the replacement of some aluminum by iron. Since the {001} face of the andalusite has an anion arrangement similar to the {001} sector of staurolite, staurolite would nucleate on that surface. Furthermore, the {001} layer of the staurolite is denser than the {001} layer of the replaced andalusite. Staurolite probably replaced andalusite by the reaction:

$$13Al_2SiO_5 + 3KFe_3AlSi_3O_{10}(OH)_2 \longrightarrow$$

$$3Fe_2Al_9Si_{3.75}O_{22}(OH)_2 + Fe_3Al_2Si_3O_{12} + 7.75SiO_2 + 1.5K_2O$$

with K_2O leaving the system. Of course the staurolite and biotite contain some Mg, and the garnet probably contains some Mn. Based on densities, it is obvious that the right side of the equation is favored by pressure. It is therefore suggested that the replacement of andalusite by staurolite proceeds due to an increase in pressure. If this is the case, it would indicate that pressure as well as temperature increased during contact metamorphism (Case 3).

AGE OF THE HATFIELD PLUTON

The oldest rock unit intruded by the Hatfield Pluton is the Whately Schist of Devonian age (Trzcienski, oral commun.). The Hatfield Pluton can be seen to cut the bedding and foliation of the schist. Furthermore, the large inclusions of Whately Schist must have been folded prior to being included since the surrounding pluton is not folded. The Hatfield Pluton must have been intruded after the folding and the development of the foliation in the Whately Schist. However, sillimanite and staurolite plus muscovite pseudomorphs produced due to contact metamorphism are deformed by the northeast-striking slip cleavage (Fig. 18). Therefore, the pluton must have been intruded before the episode of deformation causing the slip cleavage. Since the metamorphism is believed to be Acadian it can be concluded that the Hatfield Pluton is Devonian in age.

SUMMARY OF GEOLOGIC HISTORY

The Partridge Formation, Clough Quartzite, Erving Formation, Waits River Formation, and the Whately Schist were deformed, probably during the Acadian orogeny, causing a north-to-northeast fold system. The bedding in the Whately Schist generally parallels the fold axis. In conjunction with this episode of folding, the foliation subparallel to the bedding in the Whately Schist was developed. The Hatfield Pluton was intruded into the already deformed wallrocks. Pelitic schists probably were also present on the east side of the pluton at the time of intrusion. After the Hatfield Pluton had solidified and contact metamorphism had ended, a northeast trending slip cleavage developed, cutting the foliation in the schist and deforming andalusite pseudomorphs in the schist. Either prior to or after the development of the slip cleavage, the Williamsburg Granodiorite was emplaced.

After an ensuing episode of erosion, the Sugarloaf Arkose was unconformably deposited on the Hatfield Pluton during the Triassic, obscuring the eastern contact of the pluton.

REFERENCES CITED

Albee, A.L., and Chodos, A.A., 1969, Minor element content of coexistent Al_2SiO_5 polymorphs: Am. Jour. Sci., v. 267, p. 310-316.

Bazakas, P.C., 1960, Bedrock geology of the Easthampton quadrangle, Massachusetts: M.S. thesis, Univ. of Massachusetts, Amherst, Mass.

Bowen, N.L., 1928, Evolution of the igneous rocks: New York, Dover Publications, Inc., 333 p.

Bromery, R.W., 1967, Simple Bouguer gravity map of Massachusetts: U.S. Geol. Survey Geophysical Investigations Map GP-612.

Chayes, Felix, 1952, Relations between composition and refractive index in natural plagioclase: Am. Jour. Sci., Bowen vol., 85 p.

Deer, W.A., Howie, R.A., and Zussman, J., 1966, An introduction to the rock-forming minerals: New York, John Wiley and Sons, 528 p.

Emerson, B.K., 1898, Geology of Old Hampshire County, Massachusetts, comprising Franklin, Hampshire, and Hampden Counties: U.S. Geol. Survey Mon. 29, 790 p.

_______, 1917, Geology of Massachusetts and Rhode Island: U.S. Geol. Survey Bull. 597, 289 p.

Fox, P.E., and Moore, J.M. Jr., 1969, Feldspars from Adamant pluton, British Columbia: Canadian Jour. Earth Sci., v. 6, p. 1199-1209.

Guthrie, J.O., 1971, Geology of the north portion of the Belchertown intrusive complex, Belchertown, Massachusetts: M.S. thesis, Univ. of Massachusetts, Amherst, Mass.

_______, and Robinson, Peter, 1967, Geology of the northern portion of the Belchertown intrusive complex, in Robinson, Peter, ed., Guidebook for field trips in the Connecticut Valley, New England Intercollegiate Geological Conference, 59th annual meeting, p. 143-153.

Hatch, N.L. Jr., 1968, Isoclinal folding indicated by primary sedimentary structures in Western Massachusetts: U.S. Geol. Survey Prof. Paper 600-D, p. D108-114.

Hollister, L.S., 1969a, Metastable paragenetic sequence of andalusite, kyanite, and sillimanite, Kwoiek Area, British Columbia: Am. Jour. Sci., v. 267, p. 352-370.

Hollister, L.S., 1969b, Contact metamorphism in the Kwoiek Area of British Columbia: An end member of the metamorphic process: Geol. Soc. America Bull., v. 80, p. 2465-2494.

_______, 1970, Origin, mechanism, and consequences of compositional sector-zoning in staurolite: Am. Mineralogist, v. 55, p. 742-766.

_______, and Bence, A.E., 1967, Staurolite: sectoral compositional variations: Science, v. 158, p. 1053-1056.

Johannsen, Albert, 1939, A descriptive petrography of the igneous rocks, Vol. 1: Chicago, University of Chicago Press, 318 p.

Kennedy, G.C., 1955, Some aspects of the role of water in rock melts: Geol. Soc. America Special Paper 62, p. 489-504.

Krauskopf, K.B., 1967, Introduction to geochemistry: New York, McGraw-Hill, 720 p.

Naray-Szabo, and Sasvari, K., 1958, On the structure of staurolite, $HFe_2Al_9Si_4O_{24}$: Acta Crystallographica, v. 11, p. 862-865.

Platen, H.v., 1965, Kristallisation granitisher Schmelzen: Beitr. Mineralogie u. Petrographie, v. 11, p. 334-381.

Richardson, S.W., 1968, Staurolite stability in a part of the system Fe-Al-Si-O-H: Jour. Petrology, v. 9, p. 467-488.

_______, Gilbert, M.C., and Bell, P.M., 1969, Experimental determination of kyanite-andalusite and andalusite-sillimanite equilibria; the aluminum silicate triple point: Am. Jour. Sci., v. 267, p. 259-272.

Segerstrom, Kenneth, 1956, Bedrock geology of the Shelburne Falls quadrangle, Mass.: U.S. Geol. Survey Geol. Quad. Map GQ-87.

Smith, J.V., 1968, The crystal structure of staurolite: Am. Mineralogist, v. 53, p. 1139-1155.

Strens, R.G.J., 1968, Stability of Al_2SiO_5 solid solutions: Mineralog. Mag., v. 36, p. 839-849.

Thompson, J.B. Jr., and Norton, S.A., 1968, Paleozoic regional metamorphism in New England and adjacent areas, in Studies of Appalachian Geology: Northern and Maritime, E-An Zen, White, W.S., Hadley, J.B., and Thompson, J.B. Jr., eds.: New York, Interscience Publishers, p. 319-328.

Thompson, J.B. Jr., Robinson, Peter, Clifford, T.N., and Trask, N.J. Jr., 1968, Nappes and gneiss domes in West-Central New England, in Studies of Appalachian Geology: Northern and Maritime, E-An Zen, White, W.S., Hadley, J.B., and Thompson, J.B. Jr., eds.,: New York, Interscience Publishers, p. 203-218.

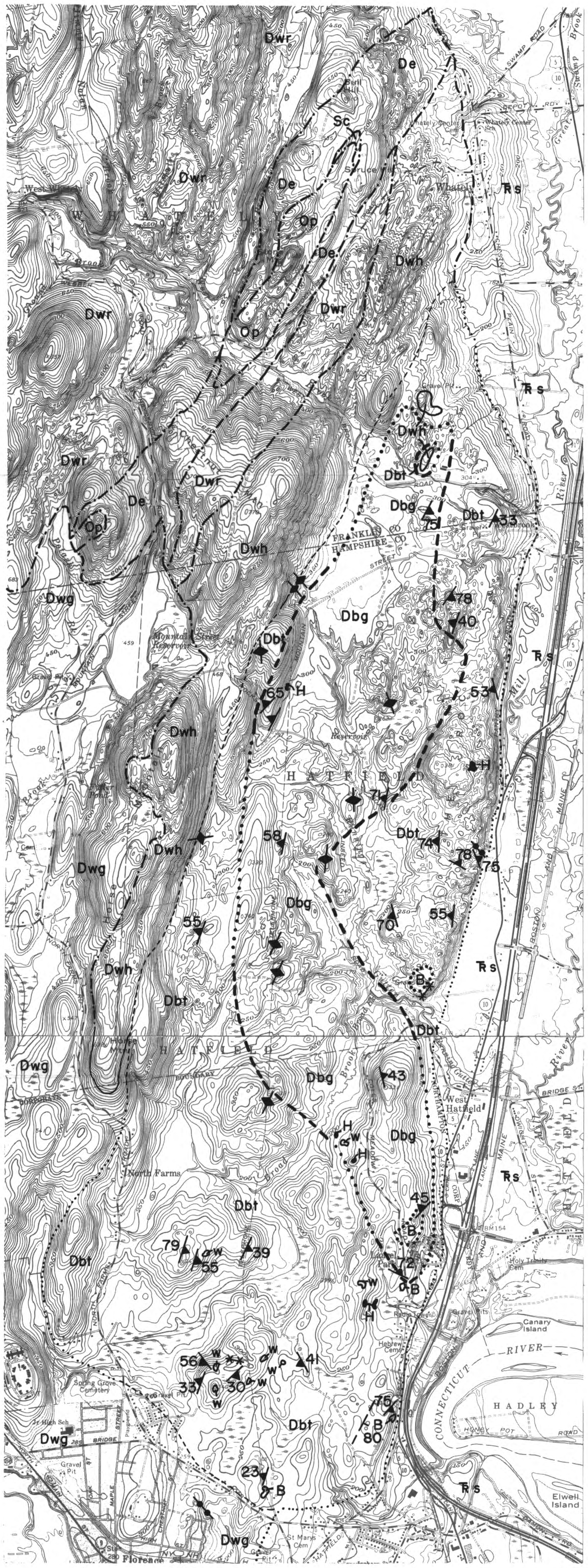
Thornbury, W.D., 1965, Regional geomorphology of the United States: New York, John Wiley and Sons, 609 p.

Willard, M.E., 1956, Bedrock geology of the Williamsburg quadrangle, Massachusetts: U.S. Geol. Survey Geol. Quad. Map GQ-85.

Wones, D.R., 1963, Physical properties of synthetic biotite on the join phlogopite-annite: Am. Mineralogist, v. 48, p. 1300-1321.

Woodland, B.G., 1963, A petrographic study of thermally metamorphosed pelitic rocks in the Burke area, Northeastern Vermont: Am. Jour. Sci., v. 261, p. 354-375.

PLATE I GEOLOGIC MAP OF THE HATFIELD PLUTON OF BELCHERTOWN TONALITE



EXPLANATION

Triassic

- Vein containing quartz, barite, galena and pyrite
- Silicified zone
- Ꞧs — Sugarloaf Arkose

Devonian

- Dwg — Williamsburg Granodiorite
- Ꞡw — Dikes (?) of Williamsburg Granodiorite in the Hatfield Pluton
- Dbt, Dbg, H, B — Hatfield Pluton of Belchertown Tonalite; Dbt, tonalite; Dbg, granodiorite; H, hornblendite; B, breccia
- Dwh — Whately Schist
- Dwr — Waits River Formation
- De — Erving Formation

Lower Silurian

- Sc — Clough Quartzite

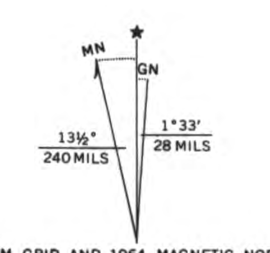
Middle Ordovician

- Op — Partridge Formation

- Contact
- Contact Approximately Located
- Contact Location Inferred
- Gradational Contact
- Inferred Gradational Contact
- Contacts Mapped by Trzcienski (1966-1967)
- 78 — Strike and Dip of Foliation
- Strike of Vertical Foliation

Key to Geologic Mapping

- W — Williamsburg Quadrangle
- E — Easthampton Quadrangle
- A — Mapped by Trzcienski (1966-67) and Stoeck (1969)
- B — Mapped by Bazakas (1960) and Stoeck (1969)



UTM GRID AND 1964 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24 000

1 MILE — 1000 0 1000 2000 3000 4000 5000 6000 7000 FEET — 1 KILOMETER

CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL

PLATE 2
LOCATION OF THIN SECTIONS