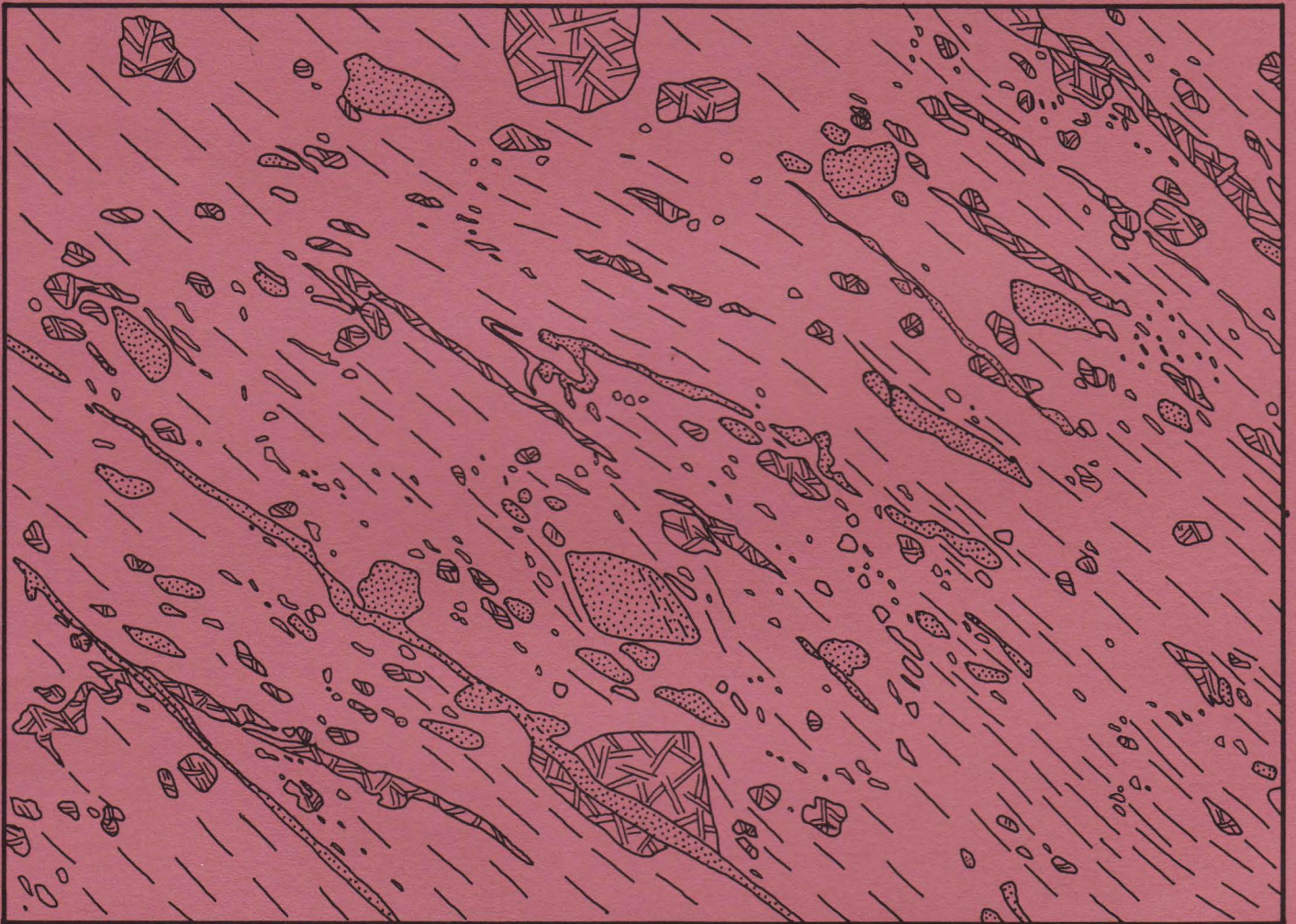


TECTONIC BRECCIA OF METAMORPHOSED INTRUSIVE IGNEOUS ROCKS IN AN ACADIAN SHEAR ZONE, BROOKS VILLAGE, NORTH-CENTRAL MASSACHUSETTS

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(M.S. Thesis)

by

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In Pocket

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ABSTRACT

The study area is located along Massachusetts Route 2 in north-central Massachusetts on the eastern margin of the Hardwick Tonalite pluton. It lies on the western limb of the Merrimack synclinorium, a major tectonic zone extending from central Maine through New Hampshire and central Massachusetts into Connecticut. The rocks in the area consist of the Silurian-Devonian sillimanite schists of the Rangeley and/or Littleton Formations and Devonian intrusive rocks comprising the Hardwick Tonalite, an associated tonalite sill, and subordinate granite and pegmatite. They have been deformed in the Devonian Acadian orogeny, here divided into an early nappe-stage, a backfold-stage, and a late dome-stage of deformation.

The Route 2 road cuts 0.6km north of Brooks Village in the Templeton Quadrangle expose a 120-meter-thick north-trending tonalite sill that is similar to the biotite-muscovite tonalite of the Hardwick Tonalite, and is separated from it by approximately 270 meters of country rocks. A breccia zone approximately 5-12 meters thick transects this sill. The breccia consists of angular to rounded ellipsoidal fragments of fine-grained gray tonalite and pegmatitic granodiorite in a biotite-muscovite tonalite matrix. Elsewhere in the area, early pegmatites are concordant with early nappe-stage foliation, and are folded by the backfold-stage folds. They are interpreted to be equivalent in age to the pegmatitic clasts in the breccia.

The breccia is interpreted to have formed as the result of the brittle behavior of early tonalite and pegmatite dikes while the mica-rich tonalite sill was behaving ductilely at the time of regional mylonitization that occurred late in the backfold-stage of Acadian deformation. Clasts that are still attached to one another and clasts with tails provide evidence that the tonalite sill was intruded by dikes that were subsequently brecciated, and they provide evidence that the breccia is not of primary igneous origin, as previously proposed.

A later generation of pegmatite dikes cuts across the breccia zone. These dikes are folded into asymmetric minor folds with axial planes parallel to a late foliation that is interpreted to have formed in the dome-stage. Because these dikes were not affected by the brecciation, but were folded during the dome-stage, the breccia forming process definitely predates the dome-stage. A later generation of 3-4cm thick granite sills concordant with the dome-stage foliation are apparently undeformed.

INTRODUCTION

Statement of the Problem

Road cuts on Massachusetts Route 2 near Brooks Village expose a tonalite sill that is apparently an offshoot of the Hardwick pluton. Transecting this sill is a breccia zone consisting of a tonalite matrix similar to the tonalite of the sill, containing rounded to angular ellipsoidal fragments of fine-grained gray tonalite and pegmatitic granodiorite. This breccia, unique in its appearance in central Massachusetts, has been variously interpreted as a sedimentary conglomerate, an intrusive breccia (Shearer, 1983), and a fault breccia. The purpose of this study is to provide outcrop and thin section petrographic descriptions of the rocks encountered, to identify the distinct phases and styles of deformation, to place them in chronologic order, to explain the origin and deformational history of the breccia, and to tie the sequence of events into the regional framework.

Location

The study area is located in the Templeton 7.5 minute quadrangle in north-central Massachusetts. The study is focused on the structural geology exposed in a road cut approximately 300m long on Massachusetts Route 2, 0.6km north of Brooks Village in the town of Templeton, east of the Phillipston town line. Route 2 is a divided highway at this point, so that bedrock is exposed on both sides of both the east-bound and west-bound lanes, as well as in an extensive strip between the two lanes.

The area immediately surrounding the cuts is rural farm country. The land in between the few farm fields is relatively flat and forested, and is covered with a mixture of deciduous and coniferous trees and assorted shrubbery.

Regional Setting

The area of this study is located on the western flank of the Merrimack synclinorium of north-central Massachusetts (Figure 1), a region that, with the Bronson Hill anticlinorium to the west, is analogous to the Pennine Zone of the Swiss Alps (Robinson, 1979; Robinson and Hall, 1980). It is generally agreed that these features are the product of Lower to Middle Devonian continental collision (Robinson, 1979; Robinson and Hall, 1980; Bradley, 1983), possibly between two parts of a previous single plate (Robinson and Hall, 1980).

The Merrimack synclinorium is a zone of metamorphosed Middle Ordovician, Silurian, and Lower Devonian, sedimentary and volcanic rocks that have been folded into a series of complex folds in the Devonian Acadian orogeny (Dixon and Lundgren, 1968; Thompson *et al.*, 1968; Robinson, 1979). Several syntectonic concordant to quasi-

concordant plutonic sheets, including the Hardwick pluton, were intruded into the area near the beginning of Acadian deformation (Robinson, 1979).

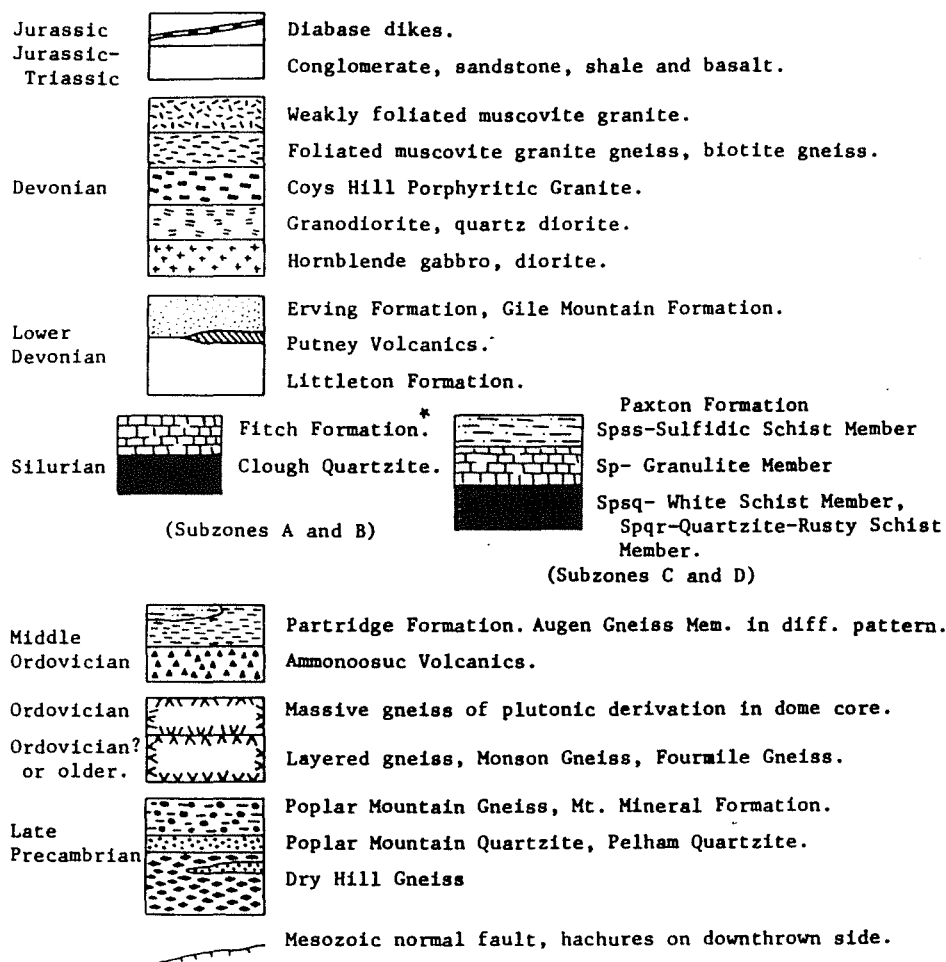
The Bronson Hill anticlinorium lies immediately to the west of the Merrimack synclinorium. This stratigraphic-tectonic zone consists of a north-south trending chain of en echelon mantled gneiss domes that span northern and western New Hampshire, central Massachusetts, and central Connecticut (Thompson et al., 1968). The oldest rocks in the area are Late Precambrian gneisses, quartzites, and schists, that are exposed in the core of the Pelham dome. The remainder of the rocks exposed in the cores of the domes consist of feldspathic gneisses ranging from tonalite to granite in composition, and the mantling strata include a variety of metamorphosed Middle Ordovician, Silurian, and Lower Devonian strata, that have been deformed in the Acadian orogeny.

Previous investigators have identified three distinct phases of the Acadian orogeny in central Massachusetts. They are an early nappe-stage, producing west-directed nappes with amplitudes of tens of kilometers, a subsequent east-directed backfold-stage, and finally a gravitationally induced dome-stage (Robinson, 1967a, 1967b; Thompson et al., 1968; Field, 1975; Tucker, 1977; Robinson, 1979; Robinson and Hall, 1980; Hall and Robinson, 1982). The regional foliation is interpreted as a nappe-stage structural feature. In this region, on the western limb of a foliation arch, the nappe-stage foliation typically has a moderate dip to the west (Tucker, 1977; Robinson, 1979).

Previous Work

Emerson (1917) described the "Hardwick granite" as a series of intrusive sheets composed primarily of "black granite" gneiss. He described the country rock bordering on the Hardwick granite as the Carboniferous Brimfield schist, a uniform coarse red-brown muscovite schist containing much biotite, fibrolite, graphite, and pyrite. Robinson assigned the country rocks in the area of this study to the Devonian Littleton Formation (Robinson and Tucker, unpublished data, 1976), an assignment adopted by Zen et al. (1983) on the compilation of the new Bedrock Geologic Map of the state of Massachusetts.

Shearer (1983) studied the petrography, mineral chemistry, and geochemistry, of the Hardwick Tonalite and other associated igneous rocks. He briefly discussed the breccia zone and presented a thin section mode and whole rock analysis for the tonalite breccia matrix. Shearer concluded that brecciation associated with intrusion of a small tonalite sill associated with the Hardwick Tonalite resulted in incorporation of an earlier generation of pegmatite and fine-grained granite.

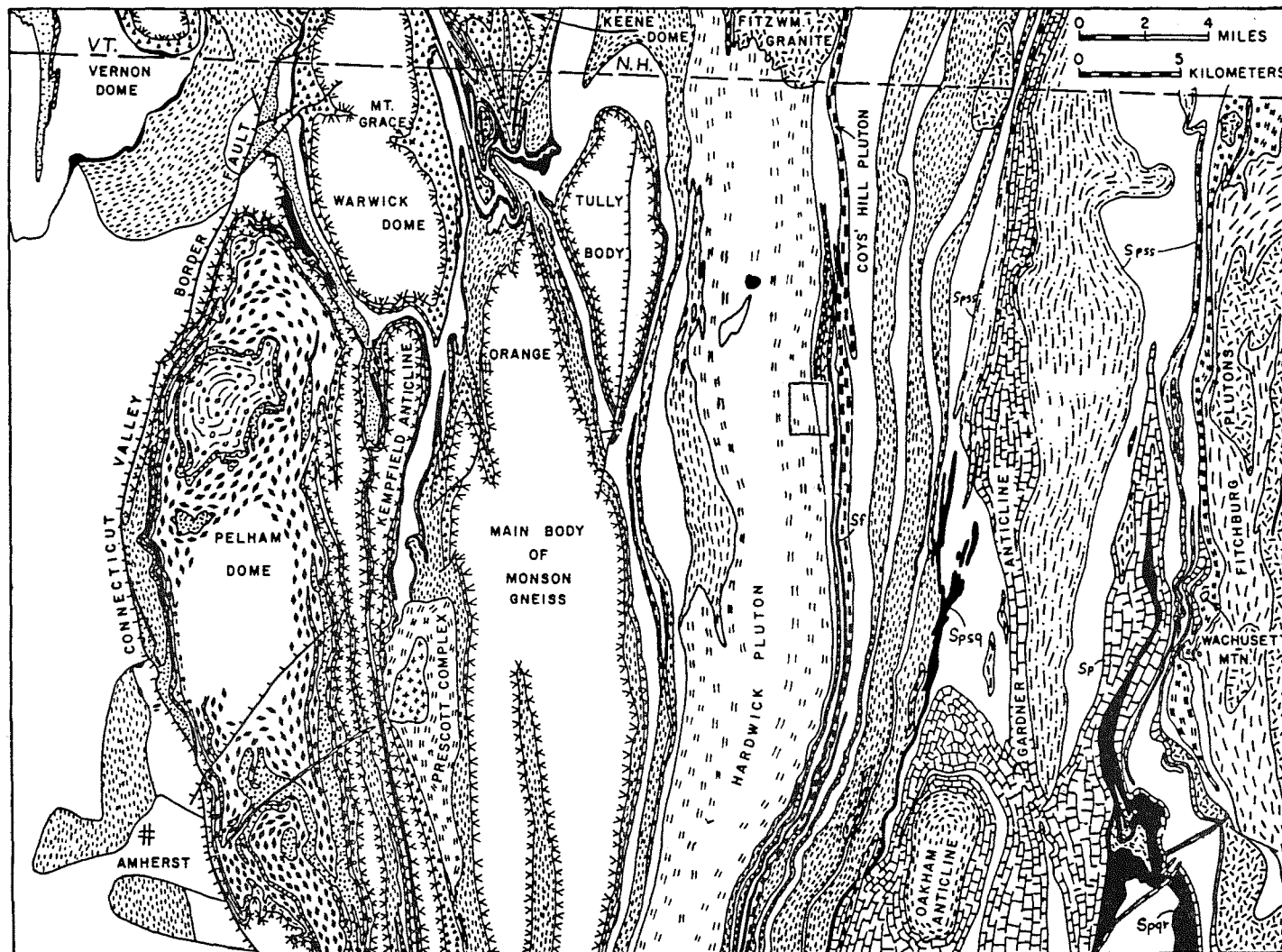


* Fitch Formation shown solid black in Subzone B.

Figure 1. Generalized bedrock geologic map of north-central Massachusetts modified from Robinson (1979). Rectangle denotes approximate boundaries of study area.

BRONSON HILL
ANTICLINORIUM

MERRIMACK SYNCLINORIUM



Field Methods

Field work for this project was carried out in the summers and falls of 1982 and 1983. The road cuts north of Brooks Village were studied extensively. Photographs of both of the north-facing exposures were made and pieced together in a panorama fashion. Structural features observed in the rock were drawn on transparent overlays of the photographs. Enlargements were made of photographs of several areas that best exemplify the structural features observed, and contacts were traced on transparent overlays. A geologic map of the immediate area of the cuts was made at a scale of 80m to the inch on an enlarged section of the Templeton 7.5-minute quadrangle. The bedrock geology of an area of approximately six square kilometers around the cuts has been mapped directly on the Templeton sheet in order to fit the geology exposed in the cuts into the regional framework. Stations in the field were located on the topographic map, using a Brunton compass, and a pocket aneroid altimeter. Attitudes of planar and linear structural features were measured with the Brunton compass. Some unpublished outcrop data of Robinson and Tucker (1976) has also been incorporated into this work.

Acknowledgments

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DESCRIPTION OF ROCK UNITS

The rocks of the study area can be subdivided into two distinct groups; the country rocks that consist of Silurian-Devonian sillimanite schists, quartzites, and calc-silicate rocks, and the Devonian intrusive rocks that include the Hardwick Tonalite, the associated Brooks Village tonalite sill, and miscellaneous granites. The schists that are in contact with the sill were previously interpreted as Devonian Littleton Formation (Zen *et al.*, 1983), but during this study rocks at two localities were found to have characteristics of the Silurian Rangeley Formation. In addition, a large (map-scale) inclusion within the main body of the Hardwick Tonalite has been identified as the Silurian Paxton Formation (Figure 4) and is of a

lithic type that probably correlates with the Silurian Madrid Formation of western Maine (Robinson, personal communication, 1984). Tables 1 and 2 present estimated modes of samples of the country rocks and the intrusive rocks, respectively.

In the five thin sections of schists studied there is both sillimanite and orthoclase indicating at least sillimanite-orthoclase-muscovite grade of metamorphism. There are traces of muscovite which could represent either the last remnants of muscovite in a transition to the sillimanite-orthoclase zone, or muscovite of a secondary nature. No cordierite has been found in the rocks, but there are a few grains that resemble the yellow pinite alteration of cordierite. If these were originally cordierite, then metamorphism in the sillimanite-orthoclase-cordierite zone is indicated. An outcrop 3km south of the road-cut has been reported to be in the sillimanite - K-feldspar zone (Robinson *et al.*, 1982, trip P-3), but may actually be in the garnet - cordierite - sillimanite - K-feldspar zone (Robinson, personal communication, 1984). Rocks in road cuts along Route 2, 7km to the east, and rocks exposed along Massachusetts Route 122 in the Athol quadrangle 6km to the west have been reported to be in the sillimanite - muscovite - K-feldspar zone (Robinson, 1979).

Rangeley Formation

There are two localities in the area of study where rocks distinctive of the Silurian Rangeley Formation have been identified. One is on the resistant knob at the eastern end of the northernmost Route 2 cut. The rock type is a very resistant, gray, medium-grained, quartz-biotite-garnet-sillimanite gneiss with elongate calc-silicate lenses and riddled with quartz veinlets. Foliation defined by the biotite is fairly well developed. Analysis of the rock in thin section (Table 1, Sample RT 40) shows quartz, biotite (with zircon inclusions), sillimanite, garnet, orthoclase, and plagioclase, and traces of apatite. Trace amounts of opaque minerals, ilmenite, pyrrhotite, chalcopyrite, and graphite, were identified in polished section. Quartz is anhedral, ranging in diameter from 0.25mm to 1.5mm. Biotite is red-brown, indicating a moderately high Ti/total Fe ratio (Hayama, 1959). Needles of sillimanite, typically 0.5mm to 1mm in length, describe a lineation parallel to the direction of foliation. Many of the larger sillimanites have a classic recrystallization texture, marked by the marginal development of ragged edges and smaller crystals of sillimanite, an indication that the rock has undergone shearing (Figure 2). Garnet in subhedral crystals, typically 0.5mm to 1mm in diameter, but locally up to 3mm, commonly has inclusions of quartz and biotite. Orthoclase occurs in subhedral crystals up to 1mm in diameter. It has a 2V of approximately 45 degrees, suggesting that it may have formed at high temperature as the result of the breakdown of muscovite (Tracy, 1978). Plagioclase is interstitial and ranges in diameter from 0.3mm to 1mm.

The Rangeley Formation also crops out in the woods approximately 250m south of Route 2, where the contact is exposed between the main body of the Hardwick Tonalite to the west and sillimanite schist (Table 1, RT 55B) and quartzite (Table 1, RT 55A) to the east. The schist is a blood-red sillimanite-garnet-quartz-biotite schist. There are some bluish patches in the rock that resemble cordierite in hand specimen, but thin section petrography failed to confirm this.

Analysis of one thin section, (Table 1, Sample RT 55B), shows the rock to consist of quartz, biotite (with zircon inclusions), sillimanite, plagioclase, and garnet, with traces of apatite and opaque minerals (ilmenite, pyrrhotite, and chalcopyrite, observed in polished section). Quartz occurs in anhedral crystals up to 0.5mm in diameter. Some of it occurs in polycrystalline aggregates, in which the individual grains show undulose extinction indicating that they have been strained. Biotite in flakes up to 1.5mm in diameter defines a foliation. It is red-brown indicating a moderately high Ti/total Fe ratio. Acicular sillimanite in discrete needles and clusters of needles, 0.25mm to 1mm in length, is characteristically aligned parallel to the direction of foliation. These also exhibit granulated and recrystallized texture (Figure 2) indicating that they have been subjected to shearing. Plagioclase occurs in subhedral grains up to 2mm in length, with 0.5mm being typical. Garnet, in subhedral crystals up to 0.5mm in diameter, carries inclusions of quartz and biotite. A few grains traversed by a fine-grained, fibrous, yellowish, alteration product, may represent a replacement of cordierite, a mineral that could not be identified. A myrmekitic pocket of quartz and plagioclase occurs adjacent to a large garnet grain in the thin section of sample RT 55B (Figure 3).

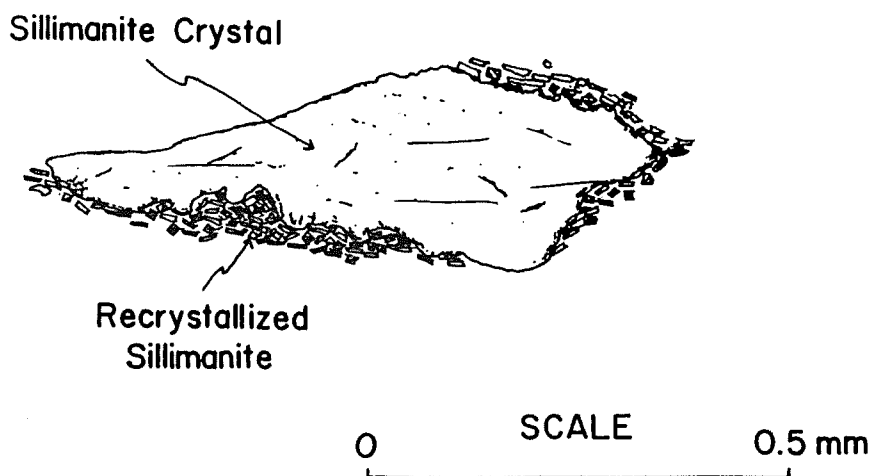


Figure 2. Sillimanite porphyroblast exhibiting recrystallized texture, suggesting that it has been subjected to shearing.

Table 1. Estimated modes for samples of country rocks.

	<u>Rangeley Formation</u>				<u>Paxton Formation</u>
	<u>RT 40</u>	<u>RT 55B</u>	<u>RT 55A</u>	<u>PMS 1</u>	<u>RT 54A</u>
Quartz	68	47	78	76	53
Plagioclase	2	10		Tr	25
(mol. % An)	(29)	(37)			(58)
Orthoclase	3				
Garnet	5	3	1	3	1
Biotite	15	25	15	15	20
Muscovite			Tr	Tr	
Sillimanite	7	15	5	5	
Apatite	Tr	Tr	Tr	Tr	Tr
Allanite					Tr
Zircon	Tr	Tr	Tr	Tr	Tr
Tourmaline					Tr
Ilmenite	Tr	Tr	1	Tr	1
Pyrrhotite	Tr	Tr		1	Tr
Chalcopyrite	Tr	Tr		Tr	
Graphite	Tr			Tr	

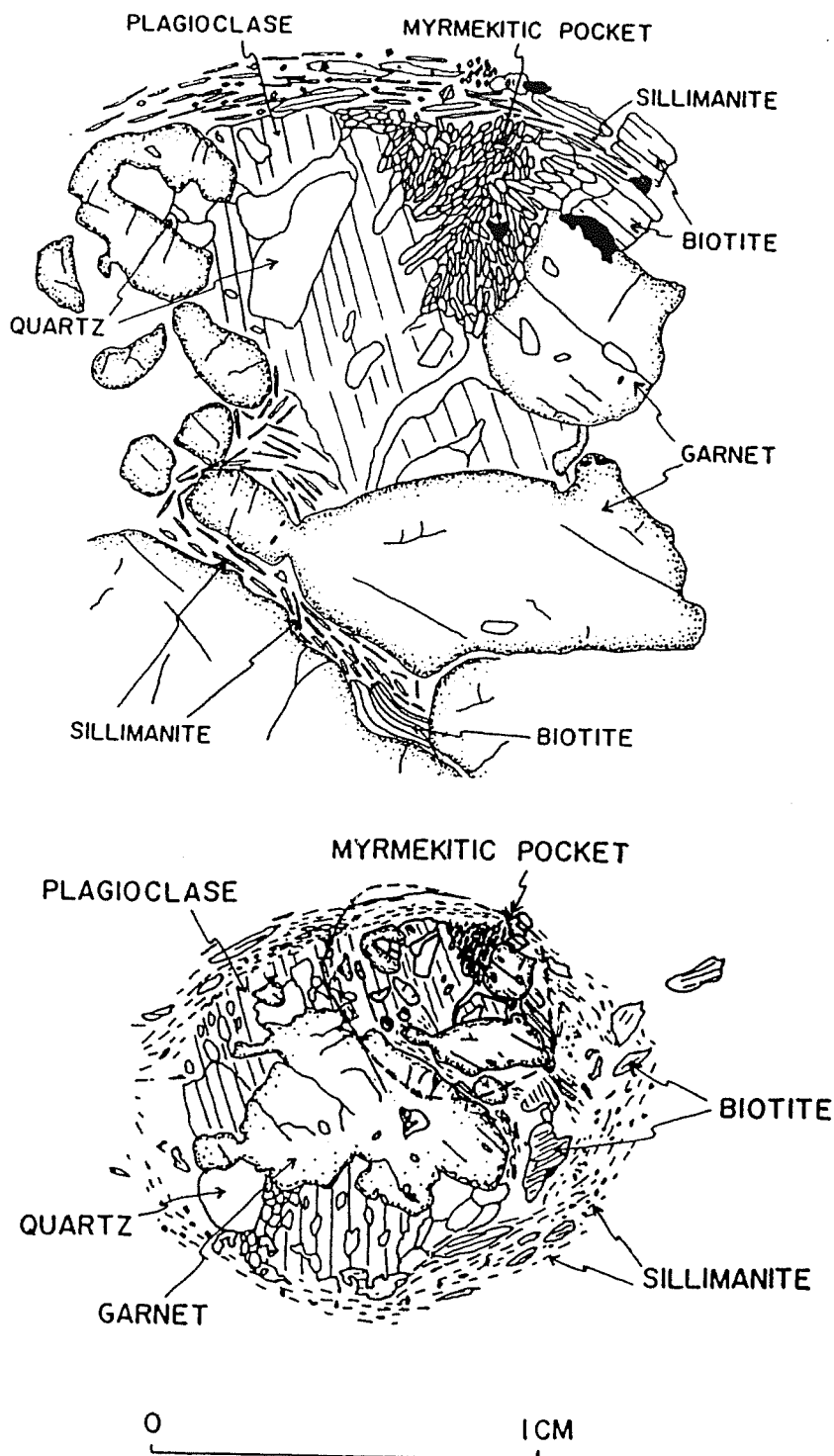


Figure 3. Myrmekitic pocket in garnet "pressure-shadow". Dashed line indicates area of close-up as shown in upper drawing.

This could be the product of eutectic crystallization out of a pocket of melt that was trapped in a pressure shadow next to the garnet (Robinson, personal communication, 1984).

The second specimen is a massive, medium-grained, gray quartzite, with visible biotite, garnet, and sillimanite. An analysis of one thin section (Sample RT 55A) shows the rock is composed of quartz, biotite (with zircon inclusions), sillimanite, garnet, and opaque minerals (ilmenite observed in polished section), with traces of apatite and muscovite. Quartz occurs in anhedral crystals that appear very strained. Crystal edges are ragged, the grains have undulose extinction, and some of the grains appear to have been on the verge of breaking up into smaller grains. Red-brown biotite appears as randomly oriented flakes, 0.5mm to 1mm in diameter. Sillimanite occurs in needles and clusters of needles from 0.25mm to 1mm long, with a strong preferred orientation. Some of the sillimanite exhibits recrystallized texture. Garnet occurs in subhedral crystals from 0.5mm to 1mm in diameter. The nature of the strained quartz grains, some of which appear to have been breaking up, and the recrystallized texture of the sillimanite, indicate that the rock has undergone shearing during its metamorphic history.

Because two localities previously assigned to the Littleton Formation (Zen *et al.*, 1983) have been reinterpreted as Rangeley Formation, the rest of the sillimanite schist country rocks in contact with the Brooks Village sill have also been interpreted as Rangeley. The schist in contact with the sill is a medium-grained, garnet-sillimanite-biotite-quartz schist. It is gray on a fresh surface, but is rusty weathering due to the presence of oxidized pyrrhotite. Analysis of one thin section (Table 1, PMS 1) shows the rock is composed of quartz, biotite (with zircon inclusions), sillimanite, garnet, and opaque minerals (pyrrhotite, ilmenite, graphite, and chalcopyrite, observed in polished section), with traces of muscovite, plagioclase, and apatite. Quartz occurs in subhedral crystals or "leaves", typically 0.5mm to 1mm long, that are flattened in the plane of foliation. Red-brown, titanian biotite, in flakes typically 0.5mm-1mm in diameter, defines the foliation. Sillimanite occurs in needles typically 0.5mm long. Garnet, in subhedral crystals up to 2.5mm in diameter, contains inclusions of quartz and biotite. There is a trace of muscovite, but it is difficult to determine whether it is primary or secondary. The texture of the rock section indicates that it has undergone shearing; sillimanite grains exhibit a recrystallized texture, and a few narrow zones of fine-grained (.1mm diameter) recrystallized sillimanite and biotite appear to be incipient mylonites.

Paxton Formation

A map-scale inclusion of Silurian Paxton Formation has been identified within the main body of the Hardwick Tonalite (Figure 4). It is a fine-grained, massive, gray granulite, with a rather distinctive purplish hue in outcrop. There are some small calc-silicate lenses

within this unit, and bedding has been identified. A minor fold appears within the Paxton with very delicate graded bedding indicating that tops are originally to the east on the long limb of this fold if the interpretation of the grading is valid.

Analysis of one thin section (Table 1, RT 54A) shows that the rock is composed of quartz, plagioclase, biotite (with zircon inclusions), garnet, and opaque minerals (ilmenite and pyrrhotite observed in polished section), with traces of apatite, allanite, and tourmaline. Quartz occurs in subhedral grains and interstitial fillings with 0.25mm-0.5mm diameter being typical. The edges of the grains are typically ragged. Plagioclase with well developed albite twinning occurs in subhedral crystals typically 0.5mm in length. Red-brown, titanian biotite, in flakes typically 0.25mm-0.5mm in diameter, defines a marked foliation. Garnet up to 0.5mm in diameter occurs in subhedral crystals with quartz inclusions.

Coys Hill Granite

A small sill of Coys Hill Granite, roughly 3 meters thick, is exposed near the eastern end of the road-cuts. It is granite porphyry containing phenocrysts of microcline (up to 10cm long) in a finer-grained matrix of quartz, plagioclase, and biotite. The main body of the Coys Hill Granite occurs roughly 1km east of the study area.

Hardwick Tonalite

The eastern contact of the main body of the Hardwick Tonalite is located west of the road cuts (Figure 3). The rock type here is biotite tonalite (Shearer, 1983, sample ST2). In outcrop, it is a medium-grained, gray, quartz-feldspar-biotite gneiss. Some of the quartz and feldspar appear as phenocrysts within a biotite-rich matrix. The rock is well foliated, with biotite defining the foliation. Analysis of one thin section (Table 2, PMN 6) shows the rock is composed of plagioclase, biotite (with zircon inclusions), quartz, orthoclase, and sphene, with traces of allanite, apatite, zircon, muscovite, and opaque minerals (ilmenite and pyrite observed in polished section, Shearer, 1983). The rock is classified as a quartz diorite gneiss based on the IUGS classification scheme (Streckeisen, 1973). The plagioclase occurs in subhedral crystals typically 1mm long but locally up to 2.5mm. Some of the plagioclase grains show marginal myrmekitic texture whereas other grains are entirely myrmekite. Biotite in flakes from 1mm up to 3mm in diameter shows a yellow-brown to brown color, indicative of a low to moderate Ti/total Fe ratio. Quartz is anhedral to subhedral, occurring in crystals typically 0.5mm in diameter, and also in aggregates of smaller crystals. Quartz exhibits undulatory extinction. Orthoclase occurs in subhedral crystals typically 0.5mm to 1mm in diameter, with a 2V of approximately 75 degrees. Sphene and allanite occur in subhedral crystals typically 1mm in diameter. The minor amount of muscovite occurs in close association with the biotite and appears to be primary. This

could be primary igneous muscovite, or muscovite that formed during peak metamorphic conditions. The apatite occurs in euhedral crystals .1mm in length.

Brooks Village Tonalite

The Brooks Village road cuts expose a tonalite sill that is mineralogically and texturally fairly similar to the biotite tonalite and biotite-muscovite tonalite units of the Hardwick Tonalite (Shearer, 1983). The shortage of outcrops in the fields and forests to the north and south of the cuts has made it impossible to determine how or if the sill connects to the main body of the pluton, but because of its proximity and similarity to the Hardwick, it is assumed that it does connect, at least at depth.

Samples PMS 3, PMS 4, and PMS 5 (Table 2), are from the southern face of the road cuts. They represent the eastern part of the sill, the central part, and the western part, respectively. The westernmost sample from the sill (PMS 5) has roughly 10% more biotite and less quartz than the eastern two samples. The muscovite in the sill appears close to the edges, and dies out towards the center of the sill. Estimated modes show the sill to consist of from 26-46% quartz, roughly 33% plagioclase, 30% biotite (with zircon inclusions), with traces of orthoclase, muscovite, garnet, apatite, zircon, and opaque minerals (ilmenite and pyrite observed in polished section). The quartz occurs in subhedral crystals typically 1-2mm in diameter, but locally up to 4mm diameter. Plagioclase occurs in subhedral crystals typically 0.5mm-1mm long. Red-brown, titanian biotite, in flakes typically 0.5mm-2mm in diameter, defines a foliation. The rock is classified as a tonalite gneiss based on the IUGS classification scheme (Streckeisen, 1973).

Breccia Matrix

Shearer (1983, sample ST3) presented a thin section (point-count) mode for the tonalite matrix of the breccia. The matrix (Table 2, ST3) is composed of plagioclase, biotite, quartz, orthoclase, muscovite, apatite, sphene, opaque minerals (ilmenite and pyrite observed in polished section), and calcite. It is equigranular, with grain sizes ranging from 0.1mm to 1mm. Plagioclase forms subhedral, equant, well twinned grains. Biotite is yellow-brown to red-brown indicating a moderately high Ti/total Fe ratio, and it defines the foliation. Quartz occurs as anhedral grains or as polycrystalline clusters. Orthoclase is anhedral and interstitial and is perthitic. Muscovite occurs in close association with the biotite. The apatite occurs as equant crystals. Another thin section from the matrix of the breccia zone (Table 2, PMS 2) shows a trace of allanite and no orthoclase, but the rock would still be classified as a muscovite-biotite tonalite gneiss, based on the IUGS classification scheme (Streckeisen, 1973), and is similar to the biotite-muscovite tonalite unit of the Hardwick Tonalite (Shearer, 1983).

Table 2. Estimated modes for samples from intrusive rocks. Samples ST 2 and ST 3 were point-counted by Shearer (1983).

	<u>Hardwick Tonalite</u>		<u>Brooks Village tonalite sill</u>			<u>Breccia</u>		<u>tonalite clast</u>	<u>pegmatite clast</u>	<u>late granite sills</u>
	<u>ST 2</u>	<u>PMN 6</u>	<u>PMS 3</u>	<u>PMS 4</u>	<u>PMS 5</u>	<u>matrix</u>		<u>PMS M2</u>	<u>PMS F2</u>	<u>PM 100</u>
						<u>ST 3</u>	<u>PMS 2</u>			
Quartz	13.7	9	44	39	26	21.1	25	44	50	50
Plagioclase	41.1	45	31	36	36	40	40	50	40	15
(mol. % An)	(45-36)	(38)	(34)	(35)	(29)	(33)	(32)	(38)	(36)	(35)
Orthoclase	5.5	5			tr	3				
Microcline									5	30
Biotite	32.6	40	25	25	35	31.8	34	5	1	1
Muscovite		tr	tr		3	2.5	1	1	4	3
Garnet					tr					
Apatite	2.2	tr	tr	tr	tr	tr	tr	tr	tr	tr
Zircon	0.2	tr	tr	tr	tr	tr	tr	tr	tr	tr
Allanite	0.2	tr					tr			
Rutile							tr			
Sphene	3.7	1				0.3				
Ilmenite	tr	tr	tr	tr	tr	tr	tr	tr		
Pyrite	tr	tr	tr	tr	tr	tr	tr			
Fe-chlorite					tr					
Epidote									tr	
Calcite						0.2	tr	tr		1

Tonalite Clasts in Breccia

One of the two distinct rock types that occurs as clasts in the breccia zone is fine-grained gray tonalite. It is massive in texture, and only locally does it exhibit a weak foliation. Quartz, feldspar, and biotite, are visible in hand specimen. Analysis of one thin section (Table 2, PMS M2) shows the rock is composed of plagioclase, quartz, biotite, and muscovite, with traces of apatite, calcite, and opaque minerals (ilmenite observed in polished section). The rock is equigranular, with grain size ranging from approximately 0.1mm to 1mm. Plagioclase occurs as equant grains with fairly abundant albite twinning. Quartz occurs in subhedral grains. Red-brown, titanian biotite is present. Muscovite occurs in grains which appear to be primary. Apatite occurs in euhedral crystals approximately 0.1mm in length. Calcite occurs as interstitial fillings between grains, and is probably secondary. The rock does not show evidence of shearing as do most of the other rocks in the area. It is classified as a leucotonalite. It is a far more leucocratic rock (color index approximately 5) than all of the other tonalites in the area due to the low proportion of biotite.

Pegmatite

The other rock type observed as clasts in the breccia is pegmatite. It is white to light-gray, with grain size up to 1cm diameter. Quartz and feldspar, as well as very minor amounts of garnet and biotite are visible in hand specimen. Analysis of one thin section (Table 2, PMS F2) shows the rock is composed of quartz, plagioclase, microcline, muscovite, and biotite (with zircon inclusions), with traces of garnet, calcite, tourmaline, sericite, epidote, and opaque minerals (pyrrhotite and chalcopyrite observed in polished section). Quartz occurs in subhedral crystals up to 1cm in diameter. Plagioclase occurs in equant, subhedral crystals up to 2mm in diameter, some of which is altered to sericite and epidote. Microcline displays "gridiron" twinning, and occurs in subhedral crystals up to 2.5mm in diameter. Muscovite and biotite occur in flakes up to 1.5mm in length. Garnet occurs in subhedral crystals up to 1mm in diameter. The one tourmaline crystal observed is euhedral and 0.2mm long. The rock is classified as a pegmatitic granodiorite. The mineralogical similarities between the pegmatitic clasts and the light-gray tonalite clasts could be explained if the pegmatite sills were intruded into the tonalite of the sill under water-rich conditions. Subsequent devolatilization, releasing water pressure and raising the temperature of the solidus, could have caused any remaining melt to crystallize rapidly to fine-grained (aplitic) tonalite.

There are also pegmatites present outside the breccia zone and at least two, and probably three, generations have been identified. Early pegmatite occurs as sills concordant with the early foliation. A later generation of pegmatite cuts across early foliation.

Late Granite

The youngest rocks seen in the area are a late generation of 3-4cm thick granitic sills that are concordant with the late foliation. The granite is a medium-grained light-gray rock. Quartz, feldspar, and a minor amount of biotite are visible in hand specimen. Analysis of one thin section (Table 2, PM 100) shows the rock to consist of quartz, microcline, plagioclase, muscovite, biotite (with zircon inclusions), and calcite, with a trace of apatite. Quartz occurs in subhedral crystals typically 2-3mm in diameter. Microcline occurs in subhedral crystals typically 1-2mm in diameter with "gridiron" twinning well developed. Plagioclase occurs in subhedral crystals 1mm long. Muscovite occurs in flakes typically 0.5-1mm in diameter. Biotite occurs in flakes from 0.1mm to 1mm in diameter, and is red-brown indicating a moderate Ti/total Fe ratio. Calcite is interstitial and appears to be secondary. The rock is classified as a granite under the IUGS classification scheme (Streckeisen, 1973).

STRUCTURAL GEOLOGY

Introduction

The rocks in this area were subjected to regional metamorphism and three phases of deformation during the Devonian Acadian orogeny, and a post-metamorphic, probably Mesozoic, period of brittle deformation. A regional period of mylonitization has been identified as occurring in the second phase of deformation (Robinson, 1979). The sequence of Acadian deformation in this region of Massachusetts as it is presently understood has been worked out by a number of investigators (Robinson, 1967a, 1967b; Thompson *et al.*, 1968; Field, 1975; Tucker, 1977; Robinson, 1979; Robinson and Hall, 1980; Hall and Robinson, 1982).

The first phase of Acadian deformation that has been identified in the region was the nappe-stage, producing west-directed regional nappes with amplitudes of tens of kilometers. The nappe-stage folds are responsible for the repetition of stratigraphic units throughout the region. Several concordant to quasi-concordant plutonic sheets including the Devonian Hardwick pluton were intruded into the region no later than this stage, since they bear evidence of nappe-stage structural features. A Rb-Sr whole rock age for the Kinsman Quartz Monzonite in New Hampshire, that is equivalent to the Coys Hill Granite, is 402 ± 19 m.y. (Lyons and Livingston, 1977), providing a maximum age for the nappe-stage of deformation. Sm-Nd ages from three whole rocks and four garnet separates from the same unit yield an age of 413 ± 5 million years (Barreiro, 1985).

The next phase of deformation was the backfold-stage, with the axial surfaces of the early nappes having been backfolded towards the east with amplitudes of tens of kilometers accompanied by longitudinal flow of gneissic basement rocks. The later part of the backfold-stage was punctuated by a regional period of mylonitization, and a strong

set of E-W trending mineral lineations and minor fold axes appear to have formed during this phase.

The third phase of Acadian deformation was the dome-stage, involving the formation of mantled gneiss domes by gravitationally induced upwelling of low density basement rocks into the denser overlying strata. A strong set of NE-SW trending mineral lineations and minor fold axes is attributed to this phase of deformation. The gneiss domes of the Bronson Hill anticlinorium formed during this phase.

General Structure of the Brooks Village Area

The eastern contact with the main body of the Hardwick Tonalite occurs along the western edge of the study area (Figure 4). The contact strikes roughly due north. The tonalite sill that is exposed in the road cuts north of Brooks Village has a strike that is roughly parallel to the Hardwick, but shortage of outcrop to the north and south of the cuts has made it difficult to trace the sill for any distance. The breccia zone that transects the sill strikes approximately N10W (Figure 5). The other units that have been identified in the area strike roughly north-south. The majority of the foliations measured in the area also strike in a northerly direction, with moderate to steep westward dips. A smaller percentage of the foliations measured dip steeply to the east. Locally minor folds are observed, but no map-scale folds were found in the area.

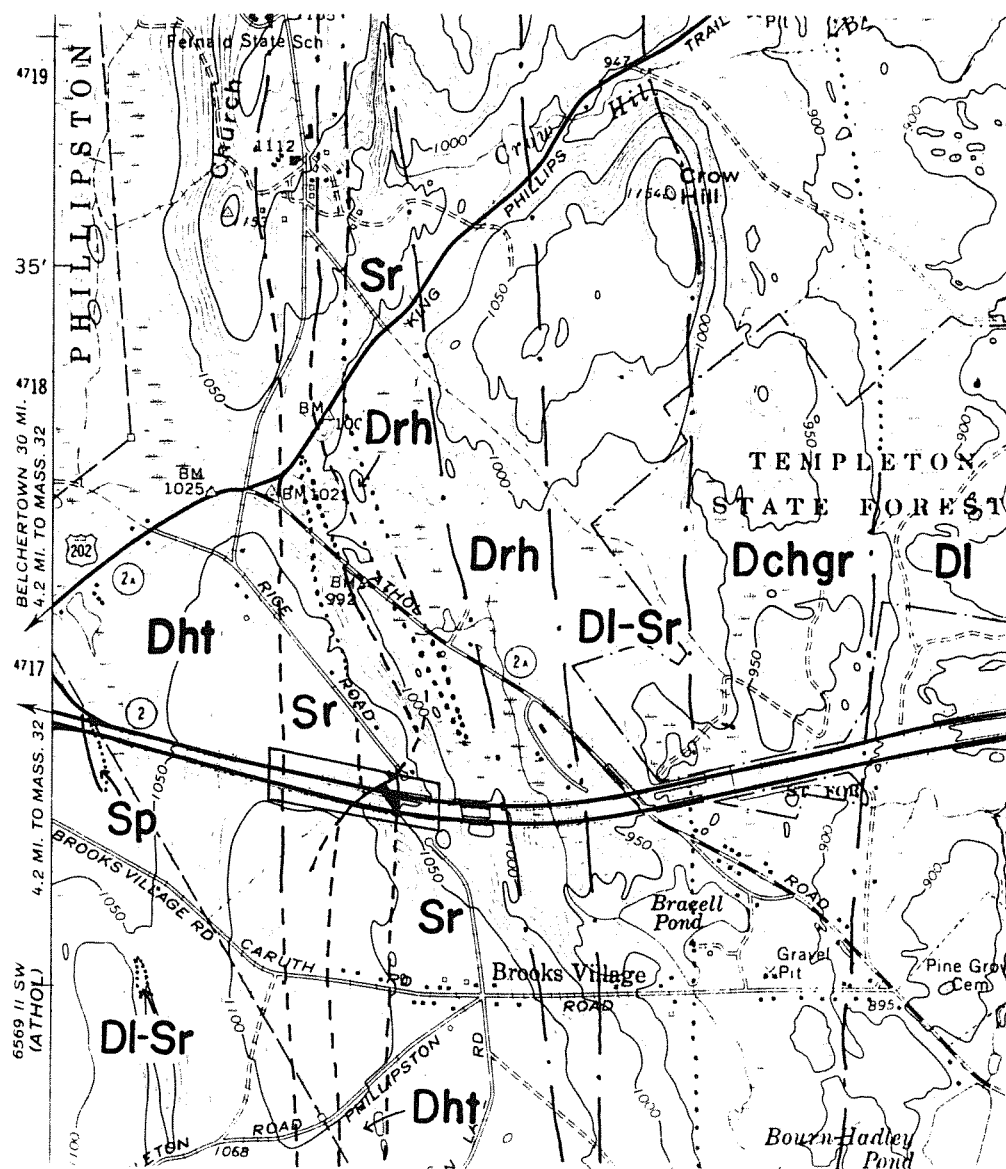
Field Relations of Brooks Village Sill and the Breccia

The breccia zone (Figure 5) is 5-12 meters thick. Where it is exposed in the southernmost of the road-cuts, it is in direct contact on the east with sillimanite schist country rocks. In the exposure on the northern cut, there is approximately 50 meters of tonalite in between the breccia and the schists to the east. The sill strikes approximately N-S, and the breccia strikes approximately N10W.

In outcrop, the breccia has a similar appearance to a sedimentary conglomerate. Most of the clasts are angular to rounded and ellipsoidal in shape, with a smaller percentage having very irregular shapes. The clasts range from 1cm to 1.5m long, with 15cm being typical. The contacts between the clasts and the matrix are sharp. The pegmatitic clasts outnumber the finer-grained clasts by approximately a 2:1 margin. An outcrop count of the clasts in an area of approximately 24 square meters in three of the breccia exposures showed 412 clasts of the pegmatitic variety versus 201 clasts of the fine-grained tonalite.

Minor Structural Features

Bedding. Primary bedding is the oldest structural feature observed in the area. It has been identified in three localities, two



SCALE 1:24 000	
1	5
0	1 KILOMETER
EXPLANATION	
DI	<u>Silurian-Devonian Strata</u> Littleton Formation
DI-Sr	Undifferentiated strata
Sp	Paxton Formation
Sr	Rangeley Formation
Dht	<u>Intrusive Rocks</u> Hardwick Tonalite
Drh	Ragged Hill gneiss
Dchgr	Coys Hill Granite
/	Contact, accurately located
- - -	Contact, approximately located
...	Contact, inferred
- . -	Contact, inferred mapping incomplete

Figure 4. Bedrock geologic map of area surrounding road-cuts. Outlined area shows location of Figure 5.

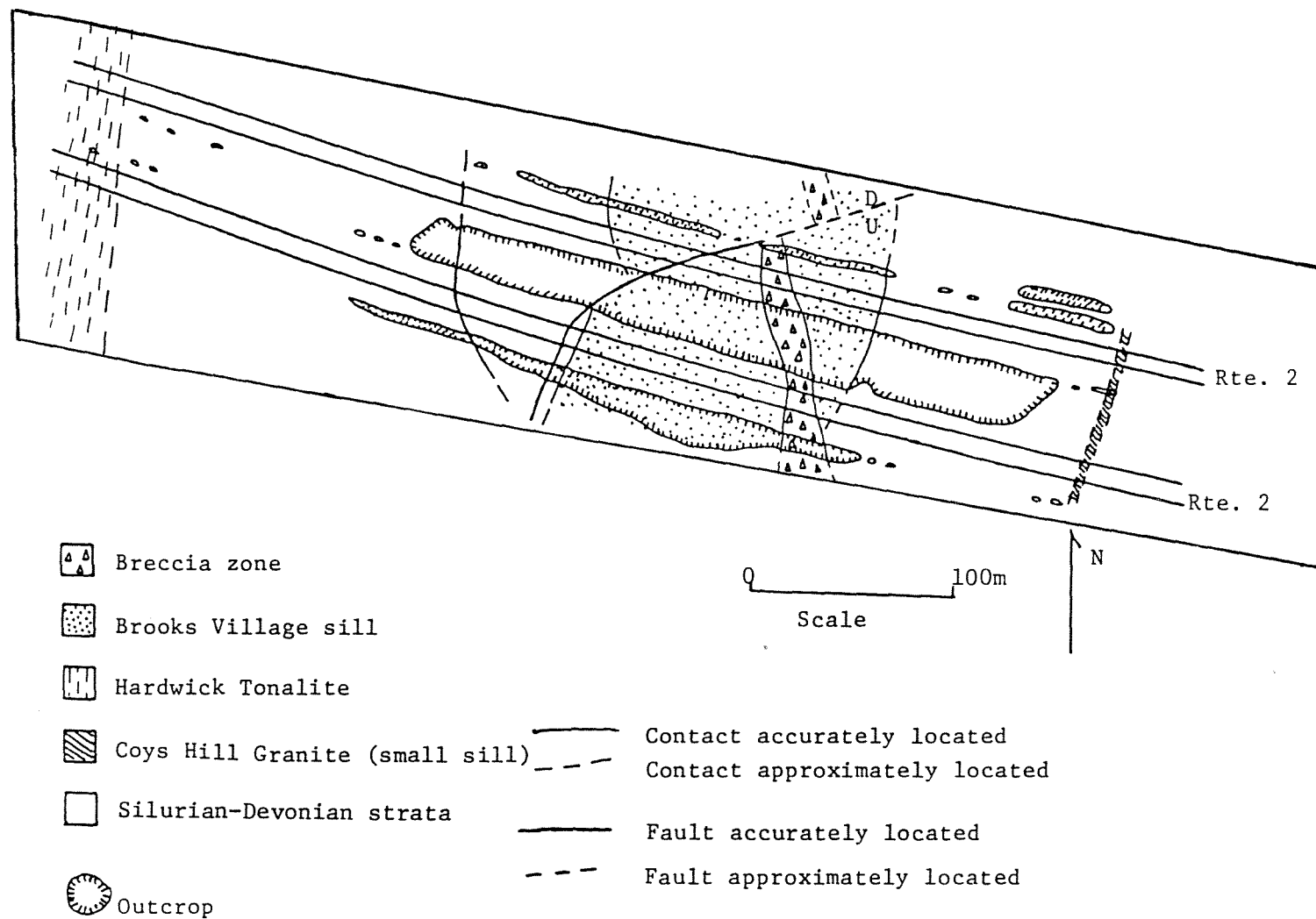


Figure 5. Geologic map of area of Brooks Village road-cuts.

of which are the outcrops identified as Rangeley Formation, and the other being in the Paxton Formation that occurs as an inclusion within the main body of the Hardwick Tonalite. In the Rangeley outcrops, well defined layering of quartz, garnet, and thin calc-silicate horizons, seem to be indicative of bedding. In the Paxton locality, the rock is a fine-grained biotite-quartz granulite, and bedding is well defined.

Foliation. Two generations of foliation are evident in the Brooks Village area. Both generations of foliation act as the dominant foliation locally, and both are clearly exposed in the road cuts (Plate 1). Parallel arrangement of biotite defines both foliations. Some of the quartz grains are flattened with their long axes in the plane of foliation.

The older foliation, interpreted as a nappe-stage structural feature, is deformed by folds with axial planes parallel to the younger foliation, interpreted as a dome-stage feature. The orientation of the older foliation is generally within 10 degrees of due north, and it dips fairly steeply to the east or west. Where bedding has been identified, it is subparallel to this foliation.

The younger foliation typically strikes N12W and dips 35 degrees to the west. It is the dominant foliation in the breccia zone.

It is only possible to identify definitely which generation a foliation is which when both are present together, as in the road cuts. There are probably outcrops in the surrounding area where single foliations have been misidentified as nappe-stage or dome-stage.

Mineral lineation. There are two generations of mineral lineation evident in the area, defined by the long axes of sillimanite crystals, quartz and feldspar rods, and clusters of biotite crystals.

One group of lineations falls in a cluster with a gentle plunge to the southwest. This is interpreted as being the younger group, attributed to the dome-stage of deformation. There is scanty evidence for an older group of lineations, but six measured orientations have been classified as an older group, because they have much more scatter and do not fall within the cluster of southwest-trending lineations. These lineations are interpreted as backfold-stage structural features. In the Barre area, roughly 15 km to the south, two generations of mineral lineations have been identified (Tucker, 1977), and further east of the area there are two strong sets of mineral lineations (Robinson, 1979, Stop5), so it seems reasonable that there are two sets present in the area. Further west, the older group of lineations, identified as features of the backfold stage, appear to have been overprinted completely by features of the dome-stage (Robinson, 1979), so the area of this study appears to be located where the backfold-stage lineation is present, but weak.

Minor folds. There are two generations of minor folds identified in the area. They are attributed to the backfold-stage and dome-stage of deformation. Both generations of folds deform the nappe-stage foliation and concordant pegmatite sills. The dome-stage folds also fold a later generation of pegmatites that are undeformed by backfold-stage folds.

There are no folds in the area that are interpreted as nappe-stage features. There are few examples of the backfold-stage folds. The majority of the minor folds seen in the area are interpreted as dome-stage features.

The few examples of the backfold-stage folds have amplitudes up to 5cm. They fold an earlier foliation, and locally they are deformed by folds assigned to the dome-stage. The presence of these folds, though few in number, is important, because they provide evidence that the early foliation is a nappe-stage feature.

There are many examples of the dome-stage minor folds, including the vast majority of the folds seen in the road-cuts. The dome-stage foliation is the axial plane foliation of these folds, and the folds range in amplitude from a few centimeters to a few meters. The fold axes are parallel to the dome-stage mineral lineation, and plunge gently to the southwest.

Mylonite and shear zones. There is one locality within the main body of the Hardwick Tonalite where mylonitic rocks have been identified, in a field immediately south of the Route 2 interchange by the Templeton-Phillipston town line. At this locality, the early foliation with associated pegmatite sills is deformed by minor folds associated with the backfold-stage of deformation. The limbs of these folds are truncated by mylonite zones approximately 3cm wide. The mylonite zones are thin planar zones of grain size reduction, and are called mylonites based on the Penrose conference definition of "mylonitic rock" (Tullis et al., 1982). These are zones of concentrated deformation, associated with faulting or shearing.

The other locality where mylonitic texture has been identified is in the Coys Hill Granite where it crops out in the road cuts. Around the margins of the Coys Hill, the large phenocrysts of microcline are fractured and reduced in size to a typical 1 to 2cm length, and the matrix also exhibits marked grain size reduction. These zones are roughly 0.5m wide.

Although these are the only mylonitic rocks seen in the area, many of the rocks in thin section show evidence that they have undergone shearing. The sillimanite in the schists identified as Rangeley Formation exhibits recrystallized texture, and some of the quartz grains are very strained and on the verge of breaking up into smaller grains. Both of these textures indicate that the rocks have been subjected to shearing.

There is also evidence at outcrop scale that the rocks have undergone shearing. In two localities in the road cuts, there are concentrated zones of plagioclase megacrysts with minor orthoclase that are concordant to the early foliation (Figure 6). In these zones, there are also small relict fragments of pegmatite. The zones are interpreted as the remains of early pegmatite sills that have behaved in a relatively brittle manner during the process of shearing.

Features peculiar to the breccia zone. The dome-stage foliation, with an approximately 35 degree dip to the west, is the foliation seen in the breccia zone. The elongate clasts in the breccia have a preferred orientation such that their long axes tend to be subparallel to the foliation (Figure 7).

Most of the clasts are massive in texture and show little evidence that they are deformed. A few of the tonalite clasts, however, exhibit a weak foliation around the edges, which is parallel to the late foliation that dominates the breccia zone.

In the southern cut, all of the breccia clasts are unattached to one another, and completely separated by the tonalite matrix. In the northern cut, however, some of the clasts are not entirely separated, and still have boudin necks between them. Some of the clasts have tails, which are folded into minor folds with axial planes parallel to the late foliation. A few of the tails are attached to clasts at both ends. Small quartz veins are present in a few of the pegmatite clasts.

The later generation of pegmatite is also present in the breccia zone. The pegmatite dikes, typically 3-4cm wide, cut across at a small angle to the dome-stage foliation. These dikes are folded into minor folds with axial planes parallel to this foliation.

The youngest feature identified in the breccia zone is the late granite, which occurs as concordant sills within the dome-stage foliation. These sills are typically 2-4cm wide, and are apparently undeformed.

Evidence for Sequence of Deformational Features in Study Area

There are several localities in the area that provide evidence for the sequence of deformational events, where all or most of the phases are exhibited together. Figures 8 and 9 illustrate two such localities. The nappe-stage foliation, a product of the earliest phase of deformation identified, is deformed by two subsequent phases of folding. Evidence for the first phase of minor folds, interpreted as backfold features, is scarce, but a few such folds have been identified. Figure 8 illustrates a locality where the axial plane of a backfold is deformed by a fold with the axial plane parallel to the dome-stage foliation, indicating that the fold interpreted as a backfold is older than the subsequent dome-stage folding. Another such locality

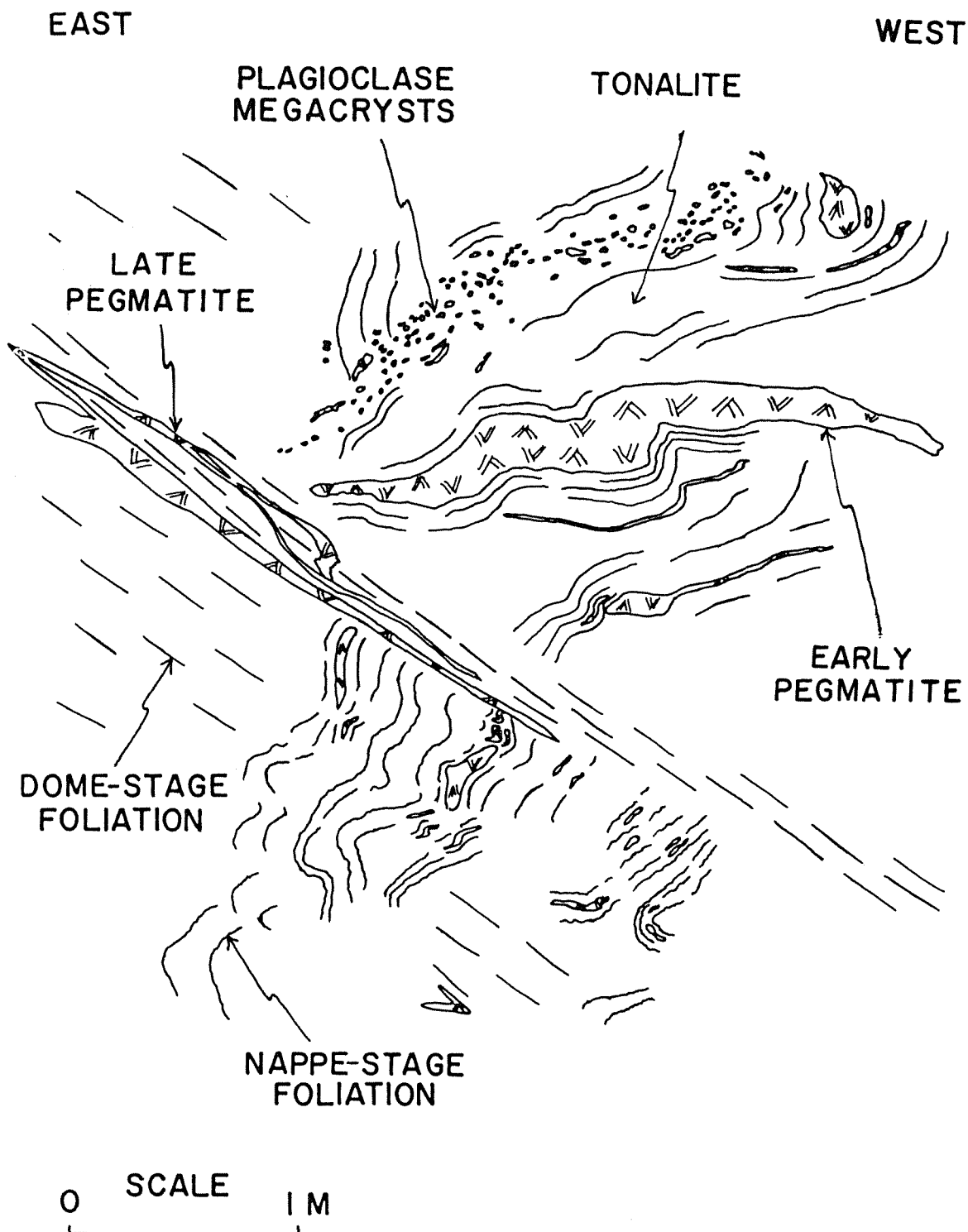


Figure 6. Locality in Brooks Village road cuts where sheared plagioclase megacrysts occur. The shear that produced this feature is also seen to deform the nappe-stage foliation. The age relation of the late pegmatite is ambiguous.

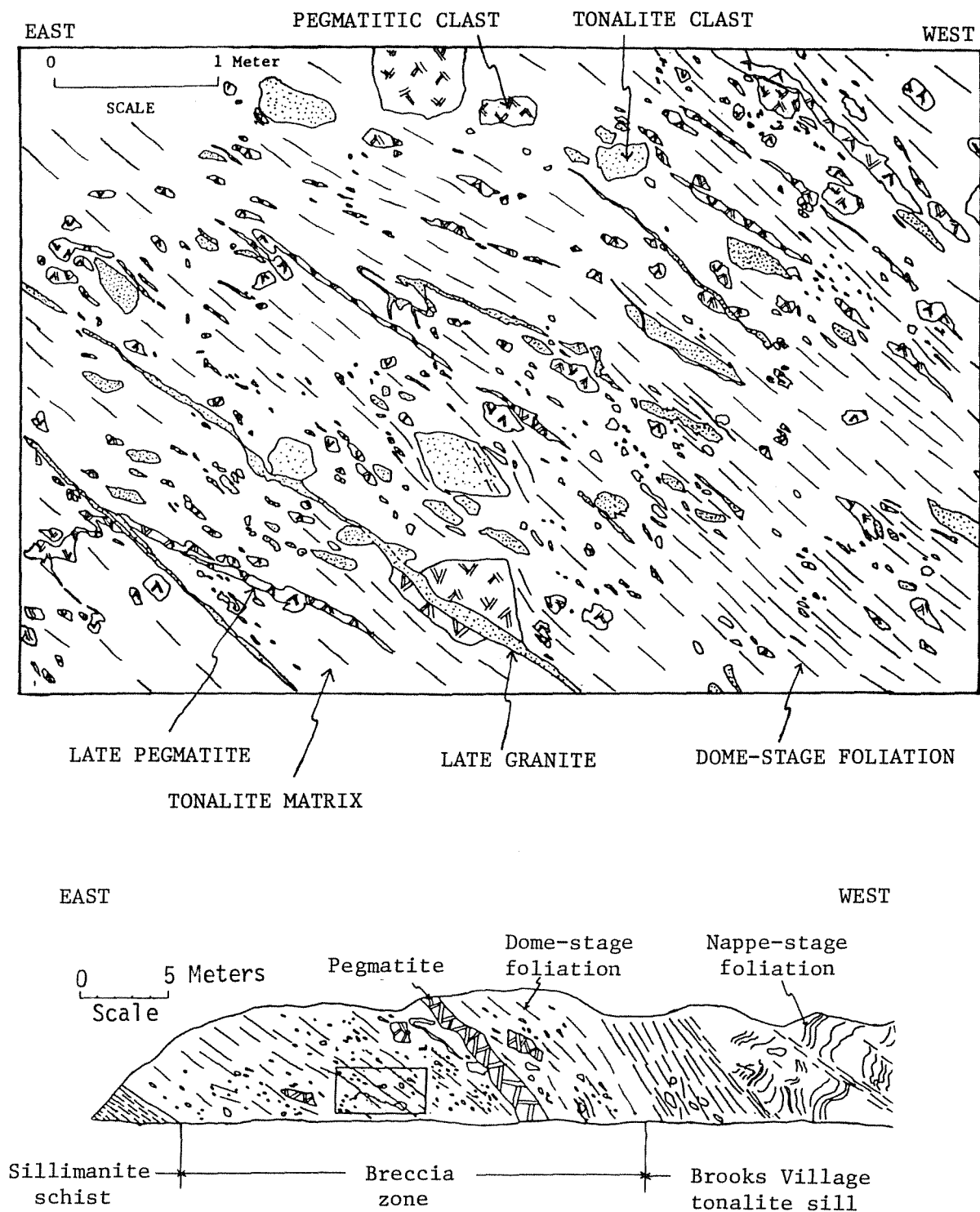


Figure 7. Bottom figure shows breccia zone as it is exposed on the south side of Route 2. Upper diagram shows close-up of the breccia.

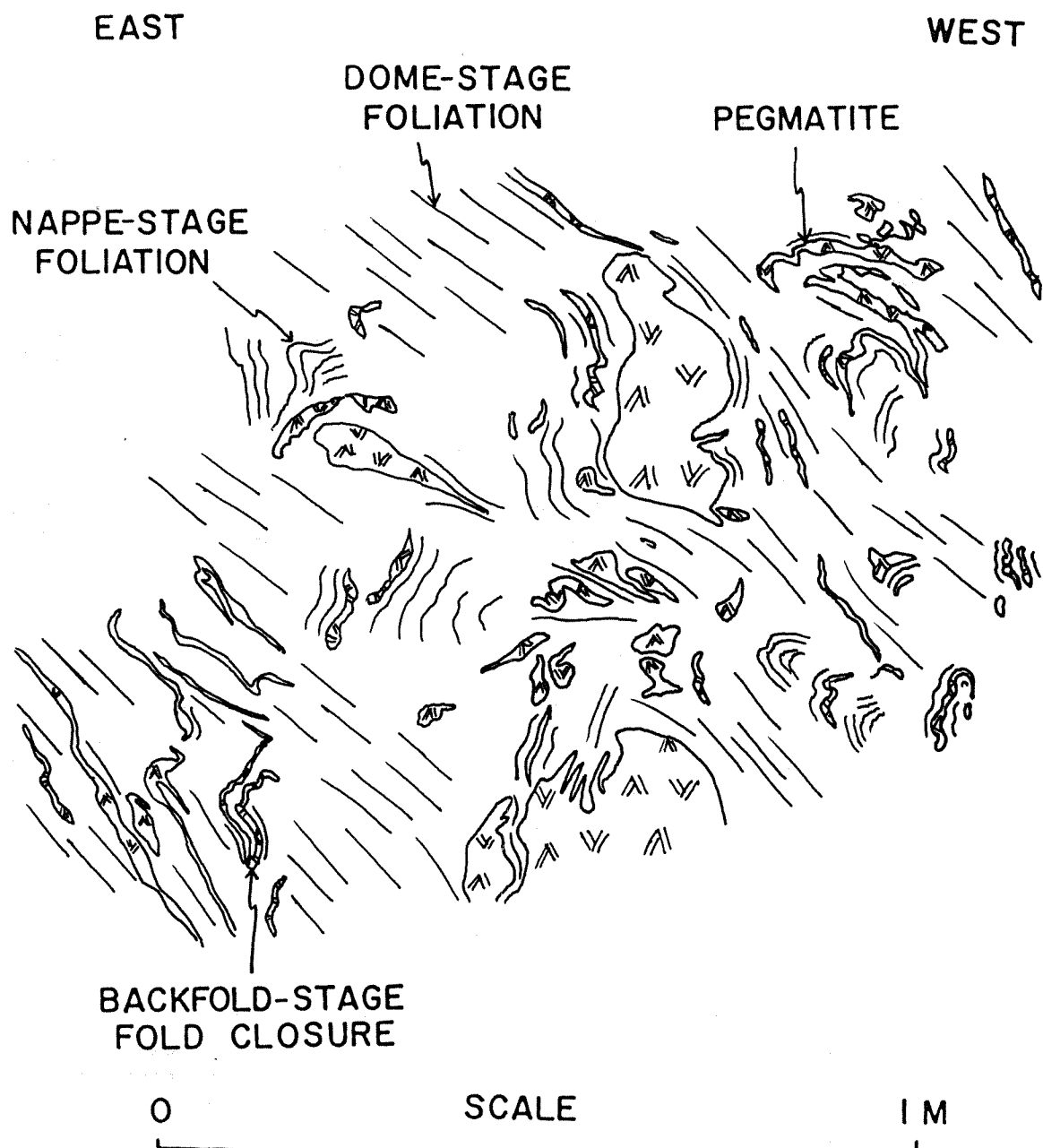


Figure 8. Backfold-stage fold closure exhibited in sillimanite schists west of the Brooks Village tonalite sill.

(Figure 9) is the locality within the main body of the Hardwick Tonalite where mylonites were also seen. Here, the nappe-stage foliation (with concordant pegmatite sill), is folded into minor folds interpreted as backfolds. The limbs of the backfolds are truncated by 3cm thick mylonite zones, indicating that the mylonitization post-dated the backfolding. A later generation of pegmatite dikes occurs within the mylonite zones. These dikes are not deformed by the backfolding. It appears that they may have undergone some shearing, so that they may have been intruded before or during the mylonite formation. Elsewhere in the area (Figures 7,12), the later generation of pegmatite dikes is deformed by dome-stage folds, indicating that the later dikes were intruded after backfolding, but prior to dome-stage folding.

There are two generations of mineral lineations identified in the area. While there is much scatter and scarce data ($n=6$), the backfold-stage lineations roughly define a great circle on the equal-area net (Figure 10b). This indicates that the backfold-stage lineations have been deformed by folds during the subsequent dome-stage of deformation.

Nappe-stage Structural Features

Foliation. The earliest phase of deformation that is identified in the area produced the early foliation that is present. Since the Acadian orogeny in this region has been divided into three phases, and the early foliation is deformed by two subsequent phases, the foliation is interpreted as being a nappe-stage foliation, probably axial planar to nappe-stage isoclinal folds. In the Barre area to the south, the dominant foliation is believed to be the axial plane foliation of the early nappes (Tucker,1977), but in the area of this study, no nappe-stage folds have been identified.

The nappe-stage foliation is clearly exposed in the road cuts north of Brooks Village (Plate 1). It is steeply dipping to the east or west and is deformed by folds with axial planes parallel to the late foliation. While there is much scatter in the data because of two subsequent phases of folding, a great circle on the equal area net can be roughly drawn through the poles to the early foliation and poles to primary bedding (Figure 10a), with the pole to the circle falling in the southwest quadrant amidst the cluster of late mineral lineations and minor fold axes (Figure 11b), indicating that they have been deformed by dome-stage folds. The amount of scatter can be attributed to the fact that the nappe-stage foliation was deformed by two subsequent phases of folding.

Pegmatite intrusions. Pegmatite sills classified with the early generation of pegmatites are concordant to the nappe-stage foliation. These sills were emplaced prior to the subsequent backfold-stage, since they are folded by folds interpreted as backfold-stage features, and possibly as early as the nappe-stage of deformation.

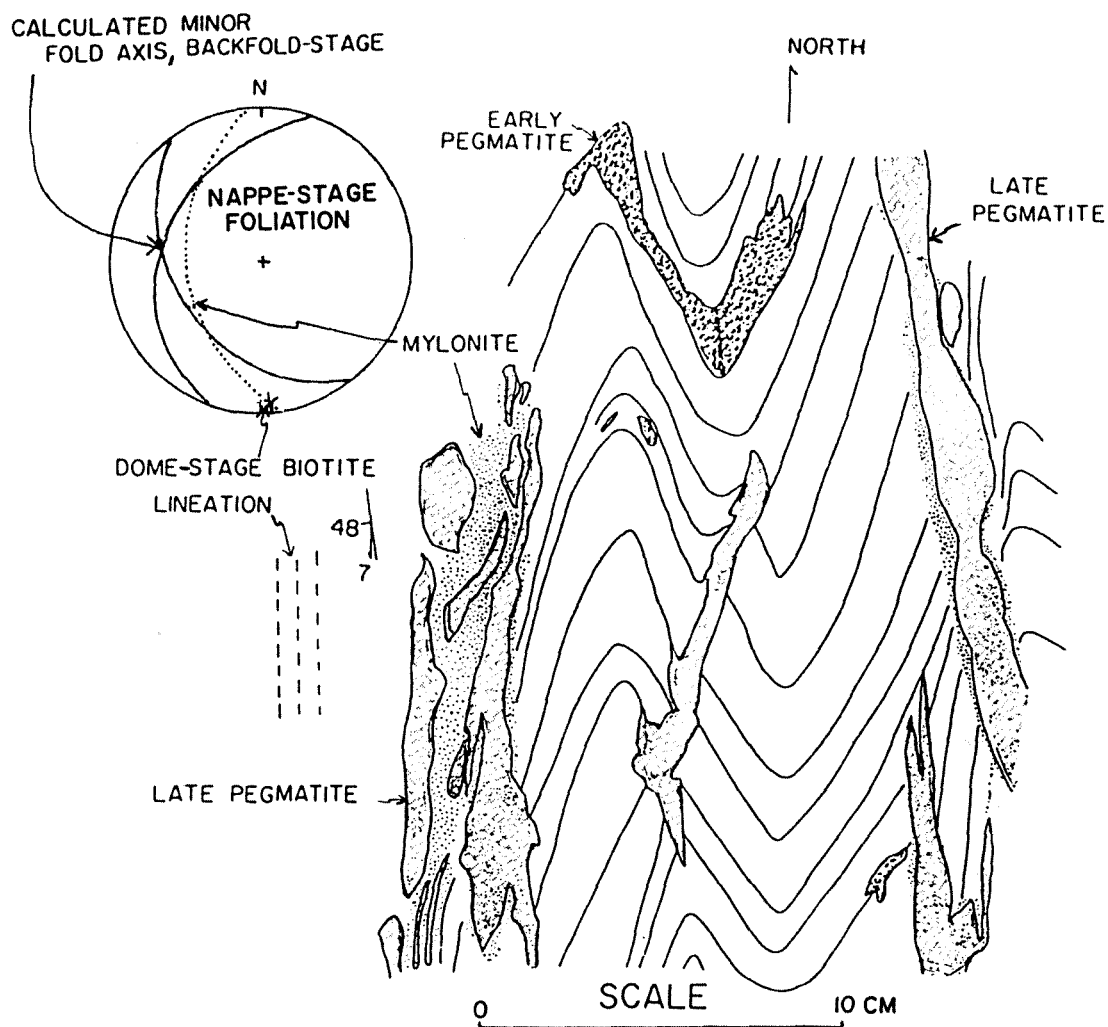


Figure 9. Locality within Hardwick pluton where nappe-stage foliation is deformed by folds interpreted as backfolds. Limbs of backfolds are truncated by mylonite. Dome-stage biotite lineation is present on a nearby foliation surface.

Backfold-stage Structural Features

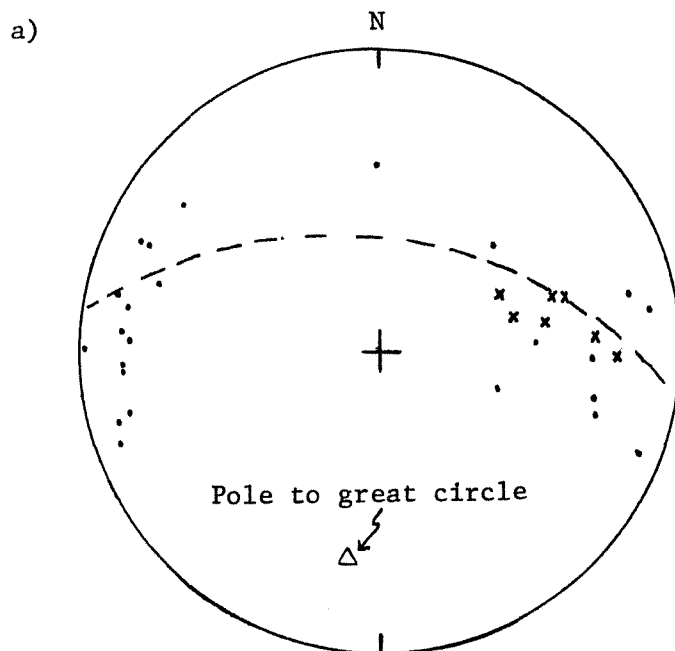
The second phase of deformation identified in the area is attributed to the backfold-stage of the Acadian (Robinson, 1979). This phase is Phase 2A as described in the Barre area (Tucker, 1977) and the Quabbin Reservoir area (Robinson, 1967, a, b). Several minor folds and mineral lineations in the study area are classified as backfold-stage features.

Minor folds. The minor folds of the first type described (Figure 8), that fold the nappe-stage foliation, and are, in turn, folded with axial planes parallel to the late foliation, are attributed to the backfold-stage. The fact that these folds deform features attributed to the nappe-stage of deformation, and are deformed by those of the dome-stage, is evidence that they developed during the intermediate backfold-stage. The westerly trend of the one backfold axis measured (Figure 9) fits into the regional pattern of E-W trending backfold features.

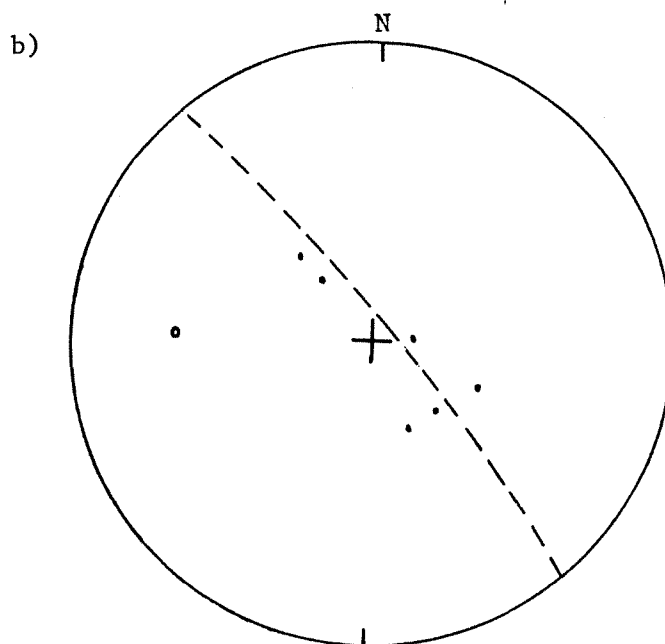
Mineral lineation. The older generation of mineral lineations in the area are believed to have formed in the backfold-stage (Figure 10b). Regionally, no nappe-stage lineations have been identified, but a pervasive backfold-stage lineation is identified in a broad area to the east (Robinson, 1979). While there is not enough data to have ample control, a great circle on the equal area net passes roughly through the backfold-stage lineations (Figure 10b), indicating that they have been folded by a mechanism of passive slip during the dome-stage of deformation.

Mylonite. A regional period of mylonitization developed in the later part of the backfold-stage (Robinson, 1979). The mylonites at the locality within the Hardwick pluton truncate the limbs of minor folds identified as backfolds, indicating that the mylonites formed after the backfolding (Figure 9). In Route 2 road-cuts 7 km to the east, and in the Barre area to the south (Tucker, 1977), the mylonites are deformed by the dome-stage folding. The mylonite in the study area (Figure 9) does not show evidence of dome-stage folding, but a dome-stage mineral lineation has been identified on a nearby foliation surface.

Pegmatite intrusions. A later generation of pegmatite occurs along the mylonite zones. These pegmatites are not deformed by the backfolds, but are deformed by subsequent dome-stage features. While the evidence is ambiguous, these pegmatites appear to show some effects of shearing, indicating that they were intruded prior to or during mylonitization. The late pegmatite dikes that cut across the breccia zone and are deformed by dome-stage minor folds show no evidence of shearing, so they were probably intruded after the mylonites formed, but before the dome stage of deformation.



- Poles to nappe-stage foliation
- x- Poles to bedding



- Backfold-stage mineral lineation
- Backfold-stage minor fold axis

Figure 10. Equal-area plots of nappe-stage and backfold-stage structural features.

Dome-stage Structural Features

The late foliation and mineral lineation identified in the area are attributed to the dome stage of Acadian deformation (Robinson, 1979). This corresponds to Phase 2B in the Orange and Quabbin areas (Robinson, 1967a, 1967b), and in the Barre area (Tucker, 1977).

Foliation. The foliation that is oriented parallel to the axial planes of folds interpreted as dome-stage folds is also a dome-stage feature (Figure 11a). This foliation has fairly consistent orientation, typically striking N12W and dipping 35 degrees to the west, and is not visibly deformed. This appears to be the foliation that is present in some of the clasts in the breccia.

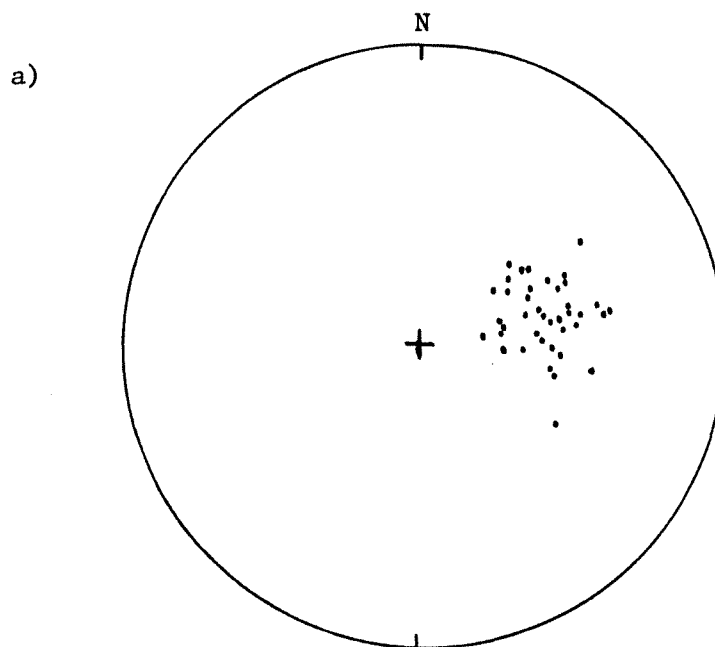
Minor folds. The majority of the minor folds seen in the area are attributed to the dome stage of deformation. The orientation of the nappe-stage foliation is a result of the dome-stage folding. Where fold axes have been measured, they fall amidst the cluster of late mineral lineations, with a gentle plunge to the southwest (Figure 11b).

The later generation of pegmatite dikes is deformed by these folds (Figures 7, 12). One such fold exhibits a rectangular quartz vein across the nose of the fold, with an orientation that is roughly perpendicular to the foliation (Figure 12). This is interpreted as the result of an extension fracture opening in the nose of the fold, allowing aqueous fluids to flow into the incipient void and precipitate quartz. This is evidence that, late in the dome stage of deformation, the late pegmatite was behaving in a brittle manner while the biotite-rich tonalite was flowing in a ductile fashion. The few quartz veins in the pegmatite clasts in the breccia are believed to have formed in a similar fashion.

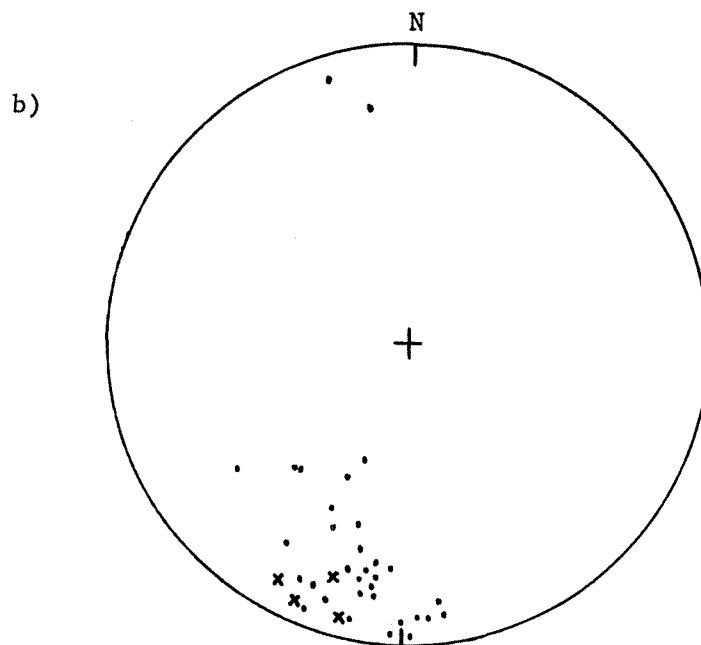
Mineral lineation. The late southwest trending set of mineral lineations is interpreted as a dome-stage feature (Figure 11b). It is composed of the long axes of sillimanite crystals, quartz and feldspar rods, and clusters of biotite crystals. The dome-stage lineation has a fairly consistent orientation, with a typical trend of S12W and a plunge of 22 degrees. This orientation is consistent with that of dome-stage mineral lineations identified elsewhere in the region (Tucker, 1977; Robinson, 1979) where they are also parallel to the axes of the identified dome-stage minor folds.

Post-Metamorphic Structural Features

A few post-Acadian, probably Mesozoic, brittle fractures were also identified in the area. Several joints and two normal faults occur in the road cuts. Where the normal fault that displaces the breccia zone (Figure 3) hits the southern cut, it strikes N17E and dips 52 degrees northwest. Where the fault cuts through the northern side of the center cut, it strikes N65E and dips 58 degrees northwest (Figure 13).



• - Poles to dome-stage foliation



• - Dome-stage mineral lineation

x - Dome-stage minor fold axis

Figure 11. Equal-area plots of dome-stage structural features.

Slickensides on this face trend N15E and plunge 51 degrees northwest. Offset of the western contact of the Brooks Village sill indicates that the north side of the fault moved down relative to the south side. The slickensides indicate that there was also a small component of right-lateral movement. Where the fault cuts through the center cuts, there is abundant fault gouge composed of uncemented soft white clayey substance, obscuring the Acadian structural features present in the rock.

Towards the western end of the center cut, there is another fracture in the country rocks with a zone of fine-grained breccia approximately 1 meter wide, striking due north and dipping 65 degrees to the west. This is also interpreted as being a fault, although rock types match across the breccia and no sense of relative movement can be determined.

These brittle, post-metamorphic fractures, are interpreted as being Mesozoic features, in keeping with the regional picture (Tucker, 1977; Robinson, 1979). The fault gouge that is present is characteristic of other known Mesozoic faults (Robinson, 1979). The faults are the youngest structural features identified in the study area.

INTERPRETATION OF BRECCIA-FORMING PROCESS

Introduction

At a cursory glance, the breccia looks like a sedimentary conglomerate. The intrusive nature of the breccia matrix discounts this possibility. It has also been proposed that the breccia is an igneous intrusive breccia, in which the intrusion of the Brooks Village sill broke up and incorporated dikes of pegmatite and tonalite already present in the country rocks (Shearer, 1983). There are several structural features within the breccia zone that are contrary to the intrusive breccia hypothesis.

Structural Features in Breccia

General. The fact that there are no breccia clasts composed of the sillimanite schists that make up the country rocks in the area argues against the idea of an intrusive breccia. If the tonalite sill were incorporating earlier dikes into it when it was intruded, it might also be expected to have incorporated some of the country rocks that these dikes were intruded into, and this is not the case. The only clasts seen are of leucotonalite and pegmatite.

The abundance of biotite in the Brooks Village sill indicates a high Fe+Mg content and probably a higher melting temperature than rocks with less iron and magnesium. This suggests that the intrusion of the biotite-rich sill could have melted the leucotonalite and pegmatite if they were already present when the sill was intruded. This provides additional evidence contrary to the intrusive breccia

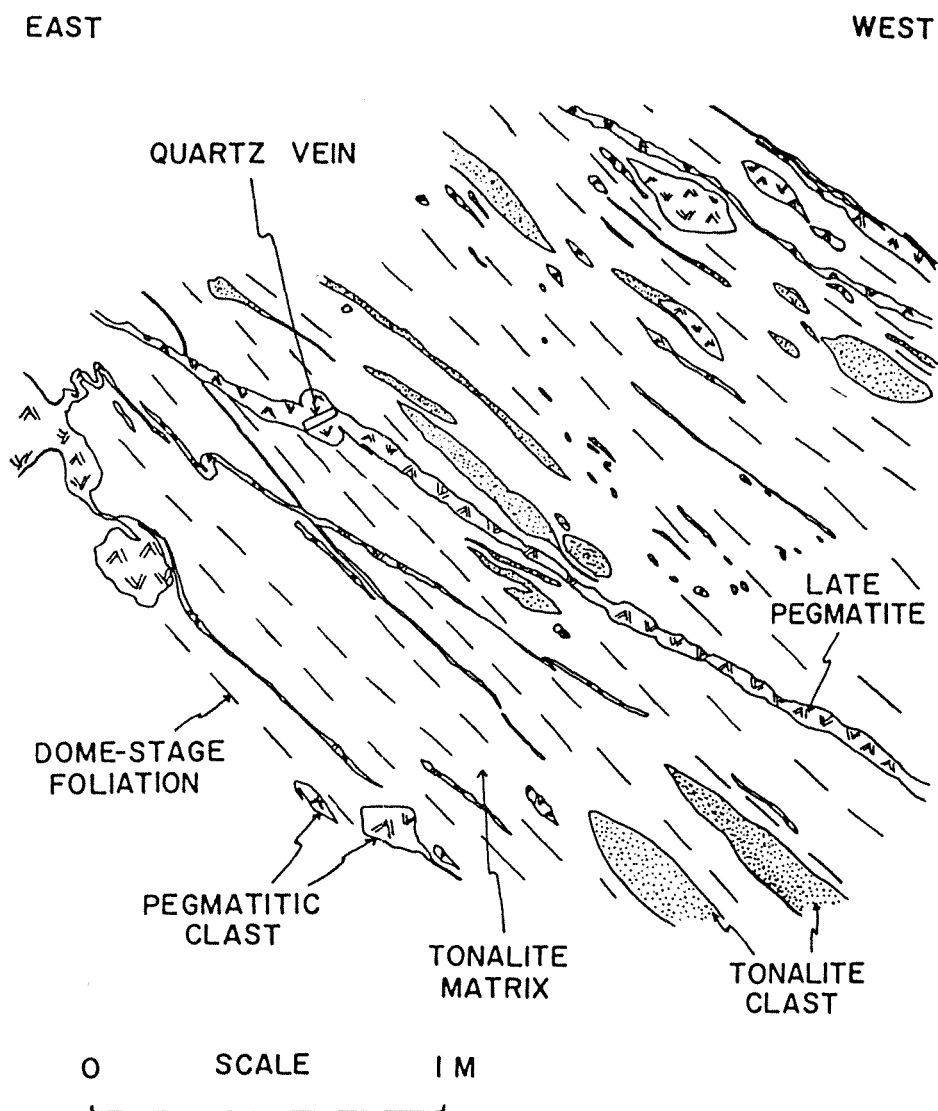
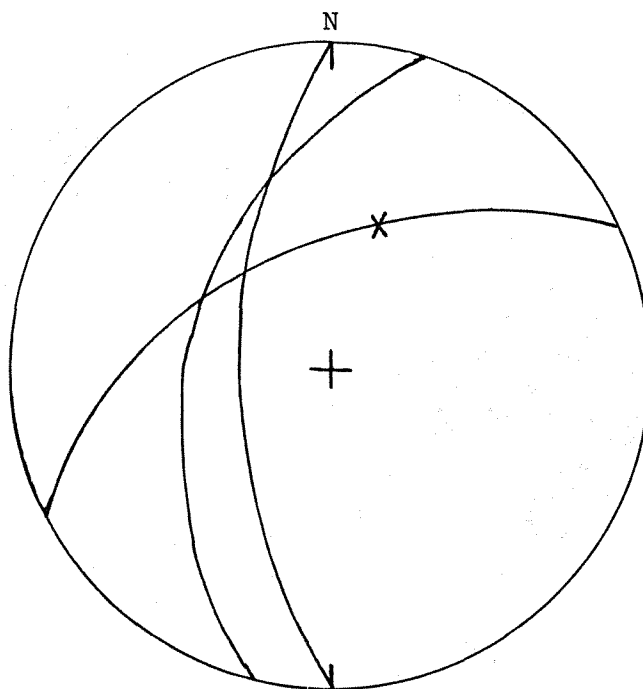


Figure 12. Dome-stage minor fold in late pegmatite dike cutting breccia. The minor fold is crosscut by a quartz vein suggesting brittle behavior of late pegmatite during dome stage of deformation.



X - Trend and plunge of slickensides

Figure 13. Equal-area plot of post-metamorphic normal faults in Route 2 road cuts.

hypothesis (Robinson, personal communication, 1985).

Another argument against an intrusive breccia origin is the way in which the breccia zone transects the Brooks Village sill. Where it crops out in the northern road cut, there are approximately 50 meters of tonalite between the breccia and the country rock contact to the east. If the breccia occurred only along the margin of the sill as it does in the southern cut, this would lend credence to the intrusive breccia idea. The breccia, however, cuts across the sill and is not a contact phenomenon.

Boudinage. The boudinage features in some of the breccia clasts in the northern cut provide further evidence against the intrusive breccia model (Figure 14). Boudins form where there is a difference between competency of layers. The majority of authors who have discussed boudinage agree that it is caused by elongation and extension of competent or more brittle layers between incompetent or more ductile layers (Cloos, 1947). When subjected to extensional forces, the more competent layers become thinned and exhibit "pinch-and-swell" structure. If the rock undergoes further extension, rupture occurs, and the competent layer becomes separated into a number of long, cylindrical pieces (Ramsay, 1967).

If the ductility contrast is great, the initial failure of the more competent layers is usually by well defined cross joints without any development of necks. The "pinch-and-swell" structures in some of the clasts in the northern exposure of the breccia are evidence for a moderate ductility contrast between the breccia clasts and the matrix (Ramsay, 1967).

The clasts that are present in the breccia that have tails, some of which connect to clasts at both ends (Figure 15), provide evidence that the Brooks Village sill was present and was then intruded by early pegmatite and tonalite dikes. These clasts are interpreted as being analogous to the clasts with boudin features, having started out as dikes and undergone subsequent deformation.

The boudins that are parallel to the dome-stage foliation (Figure 14) may have formed as the clasts were flattened during the dome-stage of deformation. The clasts with tails deformed by dome-stage folds (Figure 15) indicate that much of the boudin formation occurred prior to the dome-stage.

Quartz veins. The few quartz veins that are seen in some of the pegmatite clasts and one of the late pegmatite dikes provide evidence that the pegmatites were still behaving in a brittle manner relative to the tonalite matrix during the dome stage of deformation. Extension fractures opened up in the pegmatite dike, allowing aqueous fluids in the rock to precipitate quartz in the incipient void, while the biotite-rich tonalite of the sill was flowing in a more ductile fashion.

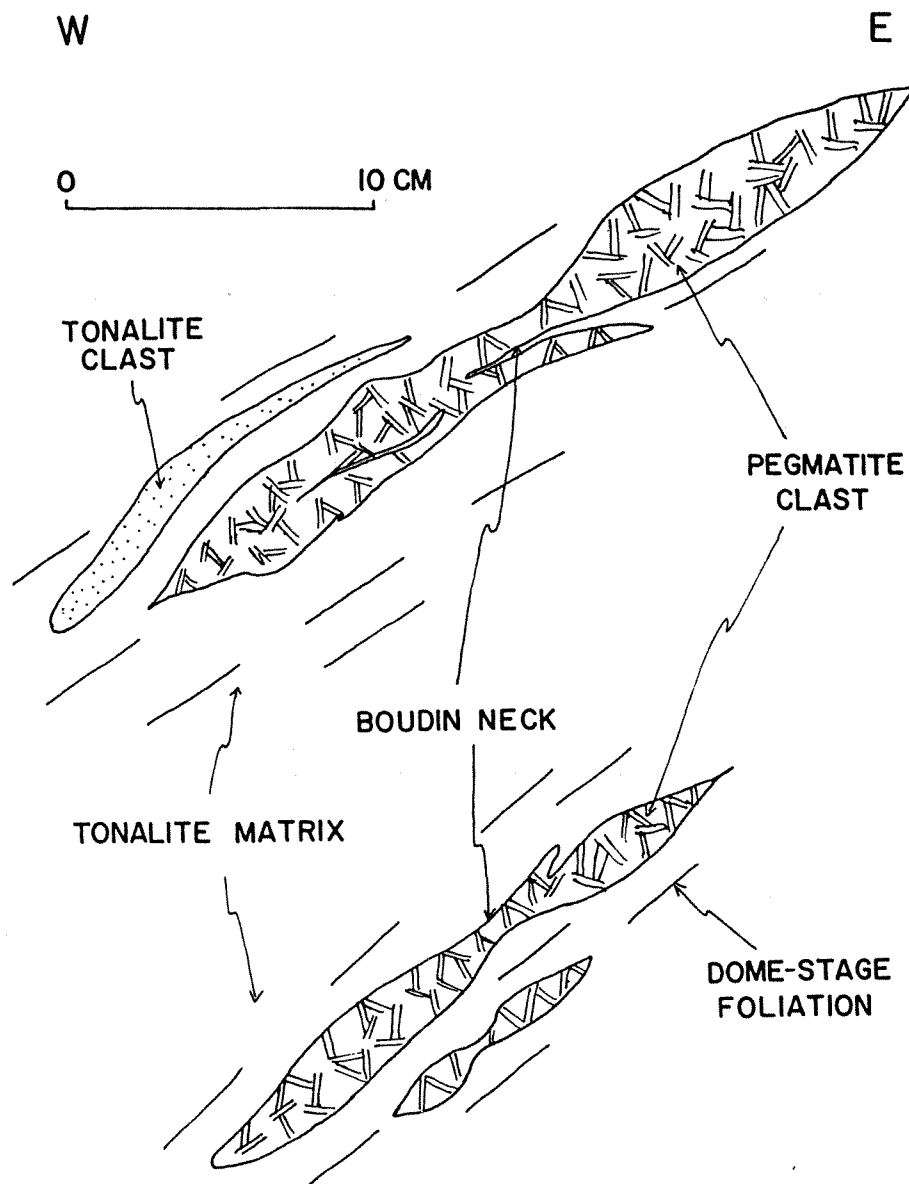


Figure 14. Locality in breccia zone where clasts exhibit "pinch-and-swell" structure.

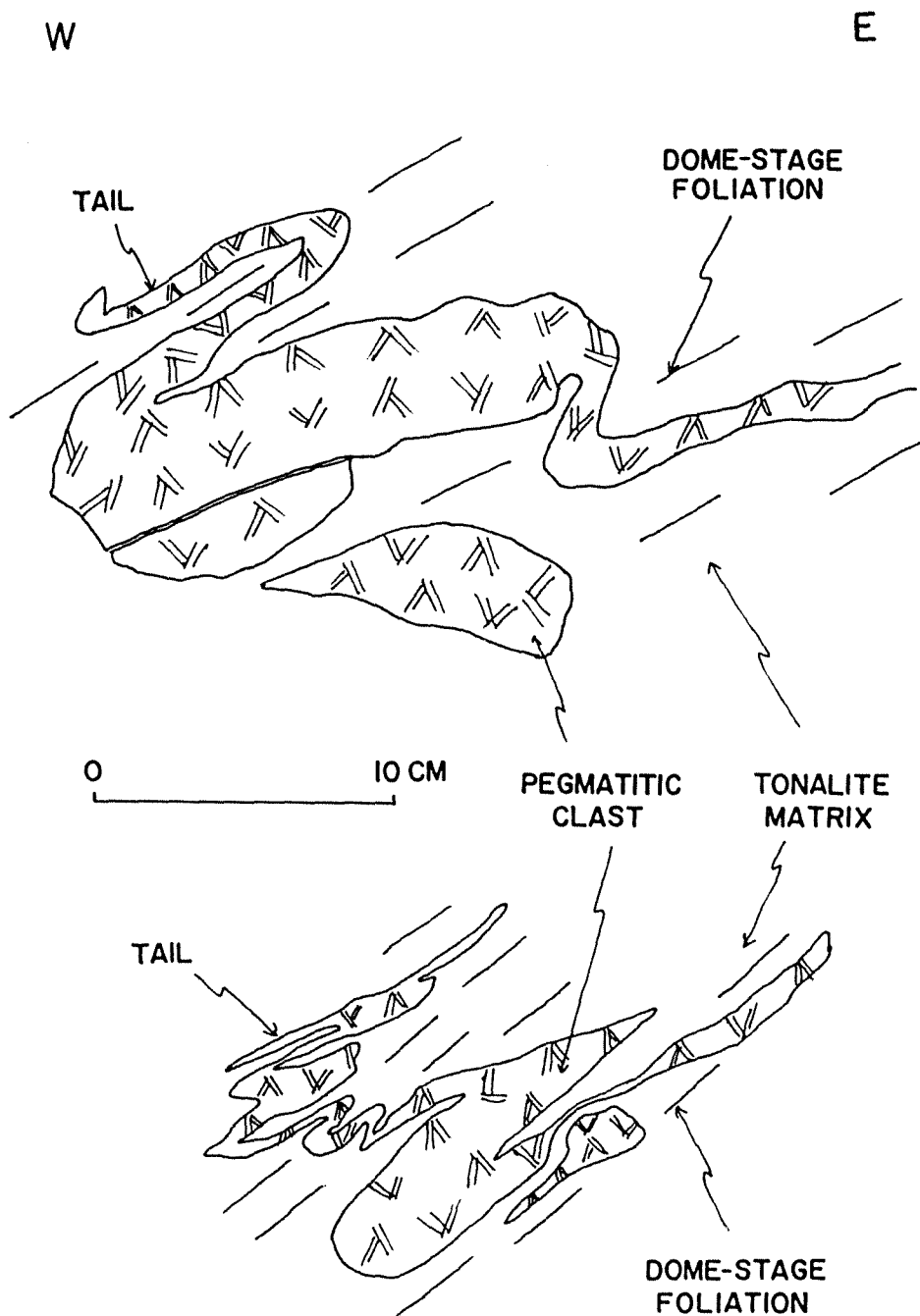


Figure 15. Clasts with "tails" deformed by folds with axial planes parallel to dome-stage foliation.

Model for Breccia Formation

The exposure of the breccia in the northernmost Brooks Village road cut provides good evidence for how the breccia formed. The process of brecciation in this location does not appear to be so advanced as it is in the other exposures, and demonstrates what the breccia looked like at intermediate stages.

The boudin features and the clasts with tails indicate that the clasts are the remains of dikes that were intruded into the tonalite of the sill. Lenticular boudins develop by a complete necking down during ductile stretching, prior to separation of the individual boudins (Ramberg, 1955). Wegmann (1932) showed that boudins may be deformed into entirely disconnected lenticular "pebbles" in extremely mobile areas. Some "pseudoconglomerates" described elsewhere are actually products of transposition and boudinage of alternating quartzite (brittle) and shaly (ductile) beds (Turner and Weiss, 1963). This is the proposed model for breccia formation, with the mica-rich tonalite of the Brooks Village sill (roughly 35% mica) behaving ductilely while the mica-poor dikes (roughly 5% mica) were deformed in a brittle manner.

Timing of Breccia Formation

The brecciation had to have occurred after the intrusion of the Brooks Village sill, assumed to be synchronous with the intrusion of the Hardwick Tonalite, and also occurred after the sill was intruded by the early pegmatite and tonalite dikes. Elsewhere in the area, early pegmatites are seen to be concordant to the nappe-stage foliation, and to be deformed by backfold-stage folds (Figures 6, 8, and 9), so they were intruded prior to backfolding, but no earlier than the nappe-stage of deformation. This provides a maximum age for the breccia-forming process.

A minimum age of brecciation can also be defined by the later generation of pegmatite dikes. These dikes cut cleanly across the breccia zone and are not affected by the brecciation, indicating that they are younger. These dikes are folded into minor folds with axial planes parallel to the dome-stage foliation, providing evidence that the dikes and hence the breccia formation are both older than the dome stage of deformation.

Thus, breccia formation occurred sometime after the nappe stage of deformation with its associated pegmatite sills, and before the dome stage of Acadian deformation. While it cannot be proven, it seems likely that the breccia formed during the regional period of shearing and mylonitization late in the backfold stage of deformation.

GEOLOGIC HISTORY OF AREA

The sequence of Acadian deformational events and associated intrusives is summarized in Table 3 and Figure 16. The earliest recognizable geologic events in the Brooks Village area were the deposition of the quartzose sandstones and shales of the Rangeley and Paxton Formations in Silurian-Devonian times (Figure 16a). In the Devonian, the sediments were metamorphosed and deformed in the Acadian orogeny. The Acadian in the area occurred in three phases. The earliest phase of Acadian deformation produced west-directed nappes with tens of kilometers of overfolding (Figure 16b). The early foliation that is present locally in the Brooks Village area is a product of the nappe-stage of deformation. Several sheet-like intrusive bodies such as the Hardwick Tonalite and Coys Hill Granite were intruded into the Silurian-Devonian country rocks before or during this stage.

The axial surfaces of the early nappes were subsequently backfolded to the east with amplitudes of tens of kilometers during the backfold-stage of deformation (Figure 16c). Late in the backfold stage there was a regional period of mylonitization. A few mineral lineations and minor folds in the study area are attributed to the backfold-stage. The mylonites and other evidence of shearing seen in the area formed during this regional period of mylonitization. The breccia zone near Brooks Village is interpreted to have formed during this period because pegmatite and tonalite dikes behaved in a brittle manner as compared to the ductile behavior of the enclosing biotite-rich tonalite of the Brooks Village sill (Figure 16d).

The final phase of Acadian deformation was the dome-stage, brought about by the gravitationally induced upwelling of lower density basement rocks into the denser overlying strata in the Bronson Hill anticlinorium immediately to the west. The late foliation and the majority of the minor folds in the Brooks Village area formed at this time (Figure 16e). The late mineral lineation with a gentle SW plunge is also a dome-stage feature.

A post-metamorphic, probably Mesozoic, period of brittle deformation is the youngest phase of deformation identified.

	STRUCTURAL FEATURE	INTRUSIVE
DOME-STAGE	Minor folds with axial plane foliation and strong SW plunging mineral lineation	Granite sills concordant to dome-stage foliation
BACKFOLD-STAGE		Pegmatite dikes (cutting across breccia zone)
	Mylonites truncate backfolds (breccia forms)	Pegmatites along mylonite zones
	Minor folds and mineral lineation	
NAPPE-STAGE	Foliation	Leucotonalite dikes (now fragments in breccia) Pegmatite concordant to nappe-stage foliation Hardwick Tonalite

Table 3. Summary of Acadian deformational history with associated intrusives, from oldest at bottom through youngest at top.

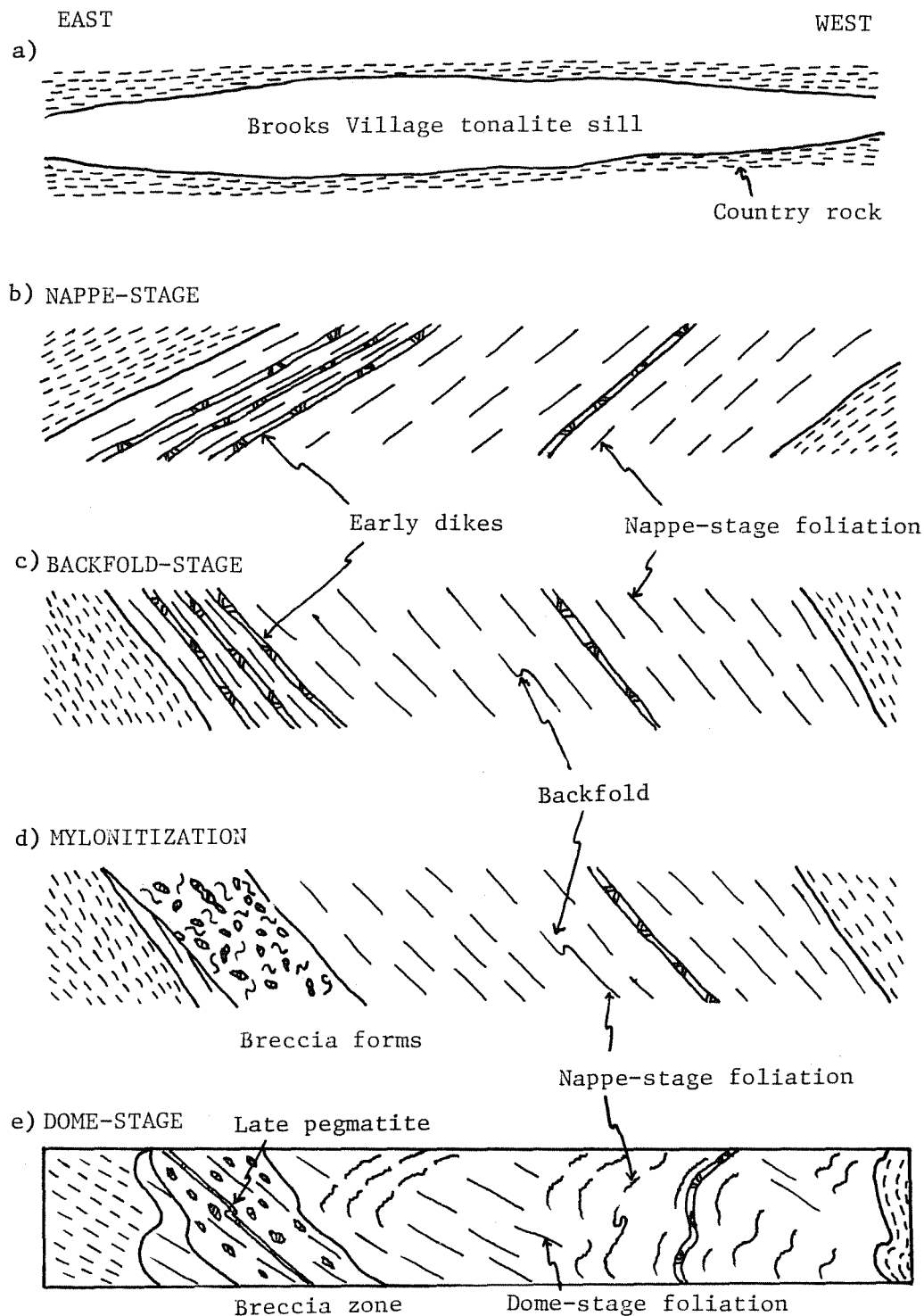


Figure 16. Schematic diagram showing Acadian Deformational history and breccia formation, from oldest at top through youngest at bottom.

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PLATE I FENCE DIAGRAM OF BROOKS VILLAGE ROUTE 2 ROAD CUTS

