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Bedrock Geologic Map of the Montpelier and Barre West Quadrangles, Washington and Orange Counties, Vermont

By Gregory J. Walsh, Jonathan Kim, Marjorie H. Gale, and Sarah M. King

Pamphlet to accompany

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)

Bedrock Geologic Map of the Montpelier and Barre West Quadrangles, Washington and Orange Counties, Vermont

By Gregory J. Walsh,[1] Jonathan Kim,[2] Marjorie H. Gale,[2] and Sarah M. King[2]

Introduction

The bedrock geology of the Montpelier and Barre West quadrangles consists of Silurian and Devonian metasedimentary rocks of the Connecticut Valley-Gaspé synclinorium (CVGS) and metasedimentary, metavolcanic, and metaintrusive rocks of the Cambrian and Ordovician Moretown and Cram Hill Formations. Devonian granite dikes occur throughout the two quadrangles but are more abundant in the Silurian and Devonian rocks. The pre-Silurian rocks are separated from the rocks of the CVGS by the informally named "Richardson Memorial Contact" (RMC), historically interpreted as either an unconformity (Cady, 1956; Doll and others, 1961) or a fault (Westerman, 1987; Hatch, 1988).

Previous mapping in the area includes the earliest work by Richardson (1916) in the towns of Calais, East Montpelier, Montpelier, and Berlin. Cady (1956) mapped the 15-minute Montpelier quadrangle, and his work represents the first published geologic map on a topographic base in the capital region (fig. 1). Unpublished mapping by Richard Jahns from 1937 to 1940 in the 15-minute Barre quadrangle (fig. 1) was subsequently described in Currier and Jahns (1941) and White and Jahns (1950) and used by Doll and others (1961) on the State geologic map. An unpublished reconnaissance map of the 7.5-minute Barre West quadrangle dated 1984 by Norman Hatch contained compilation information that was subsequently published in a regional paper on the CVGS (Connecticut Valley trough of Hatch, 1988).

Mapping in adjacent areas includes preliminary 1:24,000-scale work in the Northfield (Westerman, 1994) and Middlesex quadrangles (Gale and others, 2006) (fig. 1). Murthy (1957) and Konig (1961) mapped the adjacent East Barre and Plainfield 15-minute quadrangles, respectively (fig. 1).

The results of this report represent mapping by G.J. Walsh, Jonathan Kim, and M.H. Gale from 2002 to 2005. S.M. King assisted Kim and Gale from 2002 to 2003. A.M. Satkoski (Indiana University) assisted Walsh, and L.R. Pascale (University of Vermont) and C.M. Orsi (Middlebury College) assisted Kim and Gale as summer interns in 2003. This study was designed to map the bedrock geology in the area. This map supersedes a preliminary map of the Montpelier quadrangle (Kim, Gale, and others, 2003). A companion study in the Barre West quadrangle (Walsh and Satkoski, 2005) determined the levels of naturally occurring radioactivity in the bedrock from surface measurements at outcrops during the course of 1:24,000-scale geologic mapping to identify which rock types were potential sources of radionuclides. Results of that study indicate that the carbonaceous phyllites in the CVGS have the highest levels of natural radioactivity.

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Stratigraphy

The metamorphic and igneous rocks in the Montpelier and Barre West quadrangles range in age from Cambrian to Cretaceous. Cambrian and Ordovician metasedimentary, metavolcanic, and metaigneous rocks of the Cram Hill and Moretown Formations are exposed west of the Richardson Memorial Contact (RMC), an unconformity that separates pre-Silurian rocks to the west from Silurian and Devonian rocks to the east (fig. 2). Rocks east of the RMC occur in the Connecticut Valley-Gaspé synclinorium (CVGS) and include the metasedimentary Shaw Mountain, Northfield, Waits River, and Gile Mountain Formations (fig. 3). The metamorphic rocks are cut by Devonian granite dikes and quartz veins and Cretaceous diabase or lamprophyre dikes.

Rocks of Pre-Silurian Age

The Moretown and Cram Hill Formations occur west of the RMC (fig. 2). In southeastern Vermont, metasedimentary and metavolcanic rocks of the Moretown Formation are cut by calc-alkaline arc-related tonalite and trondhjemite gneisses that yield Cambrian and Ordovician U-Pb zircon ages of about 496 to 462 Ma (mega-annum) (Ratcliffe and others, 1997). The Late Cambrian to Middle Ordovician ages obtained from the intrusive rocks provide a minimum age for deposition of the metasedimentary and metavolcanic rocks of the Moretown Formation, and here we assign a Cambrian and Ordovician age to these rocks, in accordance with the time scale of Gradstein and others (2004). In Springfield, Vt., the Cram Hill Formation

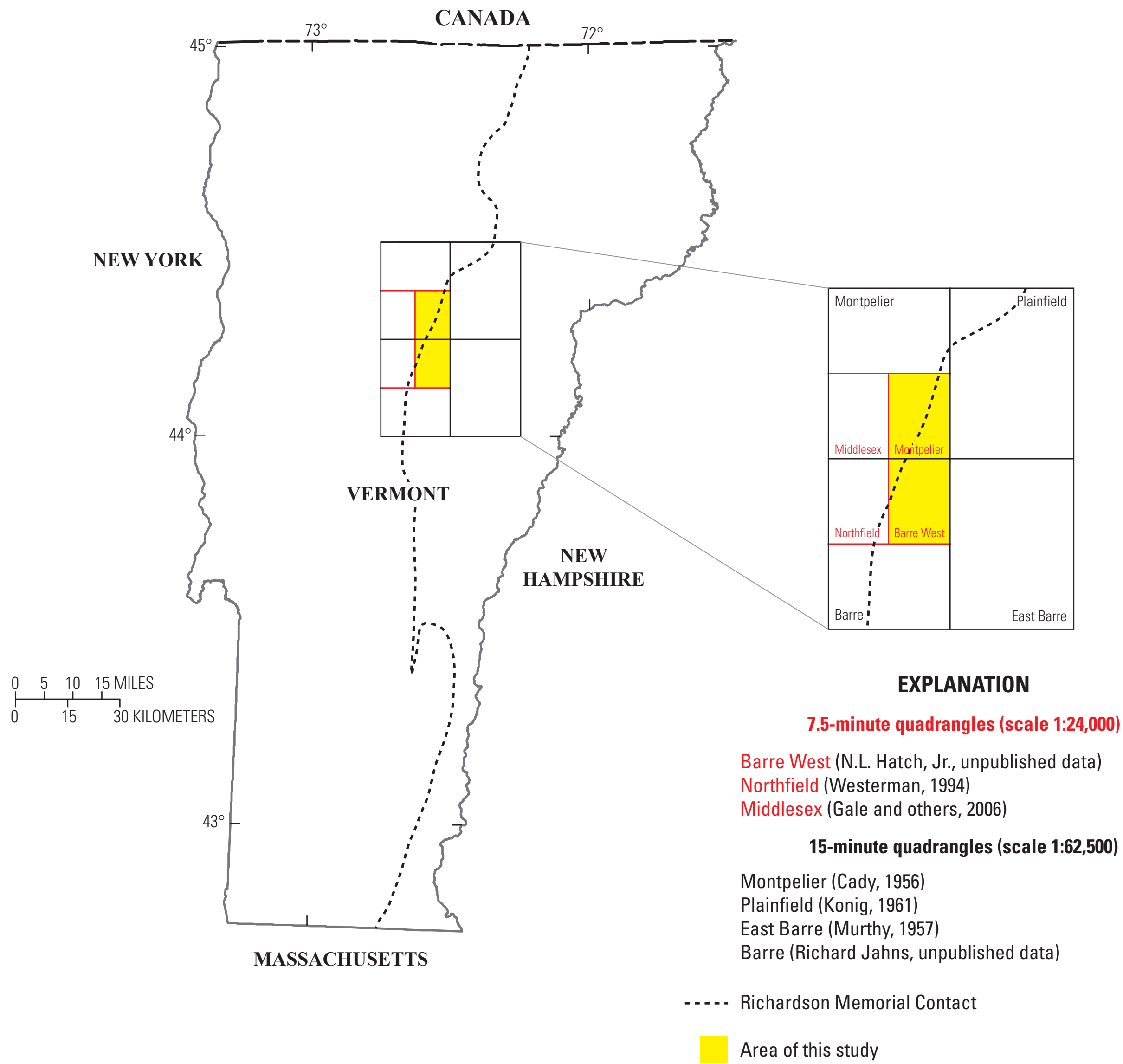


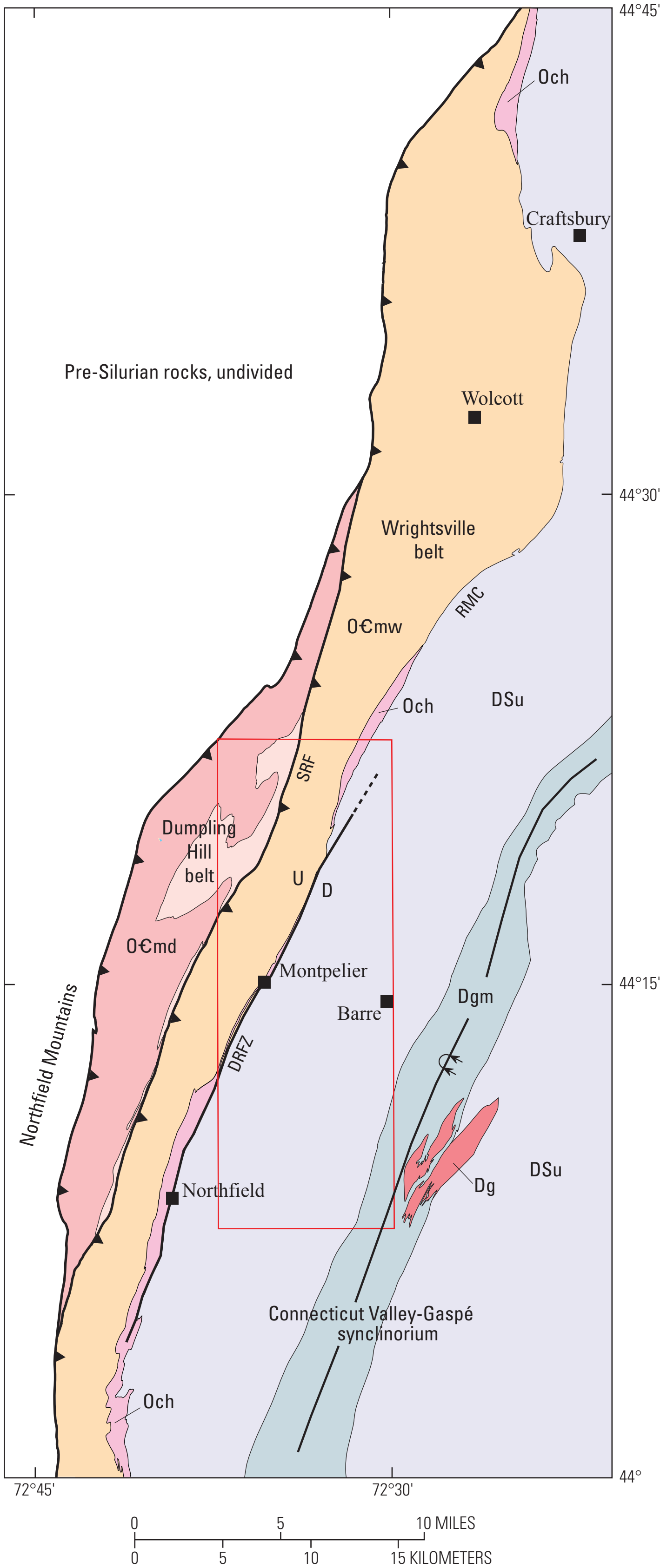
Figure 1. Index map of quadrangle-scale bedrock geologic mapping in the area of the Montpelier and Barre West quadrangles, central Vermont. Area of this study shown in yellow.

contains felsic volcanic rocks that yield an Early Ordovician U-Pb zircon age of 484±4 Ma (Ratcliffe and others, 1997); thus we assign an Ordovician age to these rocks.

The pre-Silurian metasedimentary and metaigneous rocks of the Moretown and Cram Hill Formations, and their along-strike correlatives, extend from northern Vermont to southern Massachusetts and are considered part of the lithotectonic Rowe-Hawley belt (RHB) of Stanley and Hatch (1988). In most recent tectonic models, the RHB represents lithologies juxtaposed in an arc-trench environment (for example, Stanley and Ratcliffe, 1985; Kim and Jacobi, 1996). In Massachusetts, where the RHB was defined, the Rowe, Moretown, and Hawley, respectively, represent the accretionary wedge, forearc, and western limit of a Taconian (Ordovician) arc. In central and northern Vermont, the Rowe is equivalent to the Ottauquechee and Stowe Formations, and the Cram Hill Formation is equivalent to the black slates in the Hawley Formation.

Moretown Formation (Cambrian and Ordovician)

Cady (1956) first assigned the metasedimentary rocks (granulite, quartzite, phyllite, and slate) on the eastern side of the Northfield Mountains in central Vermont (fig. 2) to the Moretown Formation. In his report, the Moretown Formation had a dominant quartz-albite-sericite-chlorite granulite unit and a carbonaceous slate and phyllite unit. Doll and others (1961), however, considered the Moretown as a member of the Missisquoi Formation. Currier and Jahns (1941), Cady (1956), and Doll and others (1961) suggested an Ordovician age on the basis of stratigraphic position of the Moretown



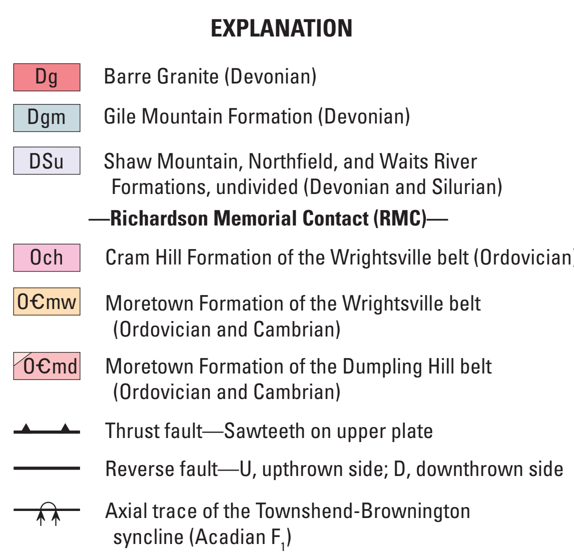


Figure 2. Simplified regional geologic map showing the setting of the Montpelier and Barre West quadrangles (outlined). DRFZ, Dog River fault zone; RMC, Richardson Memorial Contact; SRF, Shady Rill fault.

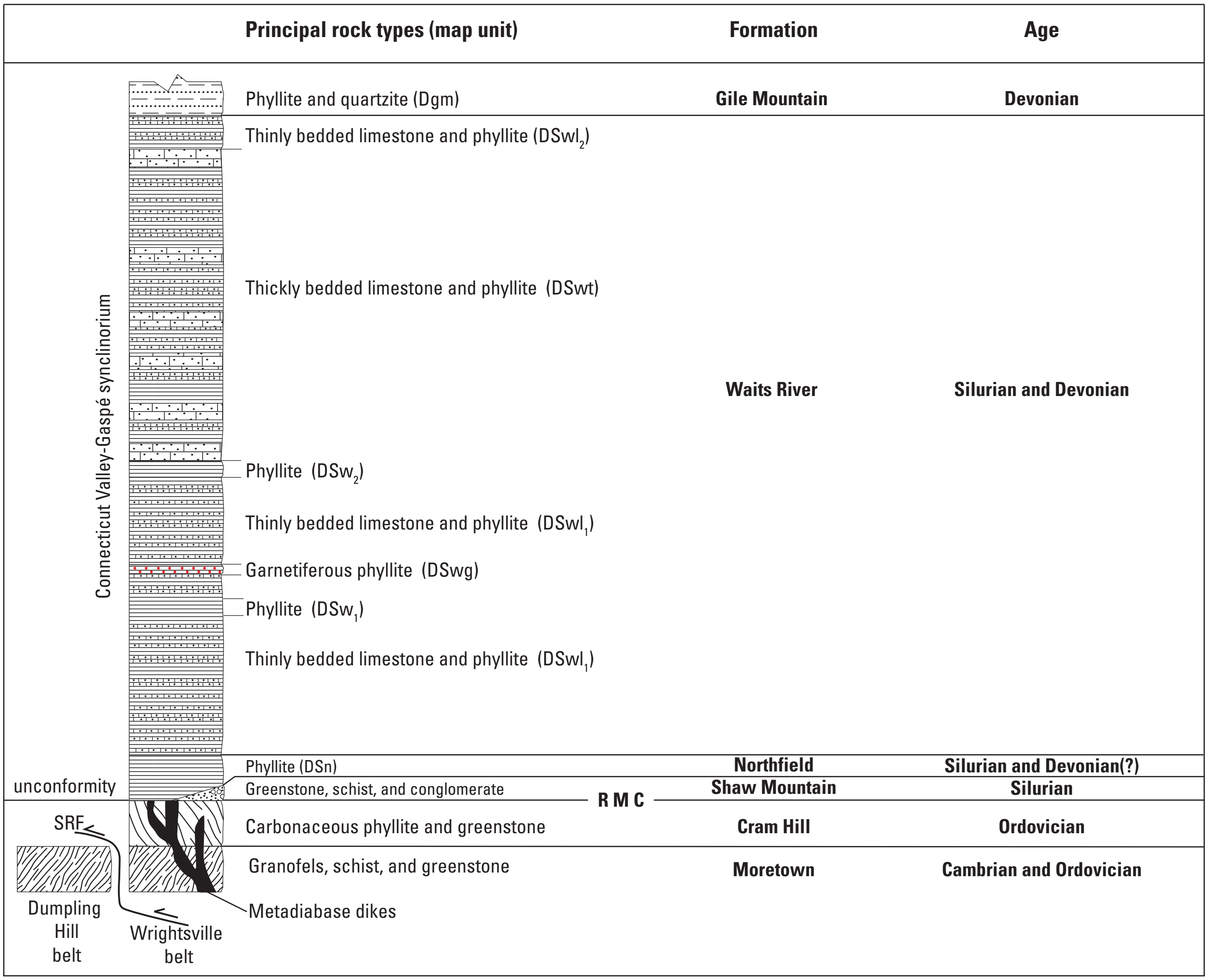


Figure 3. Simplified stratigraphic section for the Montpelier and Barre West quadrangles. RMC, Richardson Memorial Contact; SRF, Shady Rill fault.

Formation rocks in an east-facing homoclinal sequence beneath the Silurian and Devonian lithologies of the CVGS. The Moretown Formation extends into northernmost Vermont where it is truncated by the Acadian Coburn Hill thrust fault (for example, Gale, 1980; Kim, Coish, and others, 2003) and into south-central Massachusetts where it is cut out along the Acadian Prospect Hill thrust fault (Zen, 1983; Stanley and Hatch, 1988).

In the northwestern half of the map, the Moretown Formation occurs in the Wrightsville and Dumpling Hill belts (fig. 2). The Wrightsville belt also contains the Cram Hill Formation and is bounded to the east by the RMC-Dog River fault zone and to the west by the Shady Rill fault. The Moretown Formation contains similar metasedimentary rock types in both the Dumpling Hill and Wrightsville belts, with the exception that mafic rocks were not observed in the Dumpling Hill belt. Two types of mafic rocks occur in the Wrightsville belt: (1) greenstone and ankeritic greenstone interpreted as metamorphosed extrusive volcanic or volcaniclastic rocks interbedded with clastic rocks and (2) metadiabase and greenstone intrusive dikes or sills. In the field, however, it is not always possible to separately map greenstone and metadiabase or to see features that would conclusively demonstrate extrusive versus intrusive origin. Mafic rocks with a diabase texture (metadiabase) are locally in contact with finer grained greenstones that lack plagioclase porphyroclasts and a diabase texture. Such contacts appear gradational, and crosscutting relations are not always visible, suggesting that the protoliths of these rocks represent (1) basaltic rocks cut by diabase dikes, (2) basaltic flows with textural variability, or (3) diabase dikes with textural variability. Regardless of the difficulties in interpreting possible protoliths, we show the mafic rocks in the Wrightsville belt three ways on our map: (1) as separate map units—greenstone (OЄmg) interbedded in the Moretown

Formation or as younger metadiabase dikes (SOdg), (2) as point symbols showing locations of greenstone or metadiabase too small to map as separate units at 1:24,000 scale, and (3) as a subset of 1 and 2 showing geochemistry sample locations of Twelker (2004). Previous workers in this and adjacent areas also recognized both older greenstone layers and younger greenstone or metadiabase dikes in the eastern part of the Moretown Formation (Cady, 1956; Cua, 1989; Westerman, 1987, 1994).

In the pre-Silurian section of the Montpelier 15-minute map, Cady (1956) mapped two metasedimentary units in the Moretown Formation: (1) Om, quartz-albite-sericite-chlorite granulite with "greenstone beds" in the eastern part and (2) Omsp, carbonaceous slate and phyllite. Both units were intruded by metamorphosed mafic sills and dikes (metadiabase and greenstone) in areas designated by a green-stippled pattern on his map. The dominant map-scale structure shown by Cady (1956) in this area is an isoclinal fold defined by the carbonaceous slate and phyllite. The mafic dikes were interpreted to postdate this fold because he mapped them across its eastern limb. While we do not agree with the way Cady (1956) showed the folding of the carbonaceous rocks, especially because he did not describe multiple folding events, we do agree that the dikes cut a period of folding (F_2) in the Moretown Formation. In this report, we subdivide the Moretown Formation of Cady (1956) into several new map units that define a more complex map pattern than was previously recognized.

We found that the two Moretown Formation units, defined by Cady (1956) as non-carbonaceous (Om) and carbonaceous (Omsp) end members, actually could be subdivided into units containing greater or lesser amounts of the end members. Our mapping of Cady's carbonaceous slate and phyllite in the northwestern part of the 7.5-minute Montpelier quadrangle shows that parts of the formation are exclusively gray and black phyllites with interlayered quartzite (O€mdh). Other parts are gray and black phyllites that contain interlayered green phyllite and green granofels (O€msr); these latter non-carbonaceous green rocks are absent from O€mdh. In addition, we subdivide some areas previously mapped as homogeneous quartz-albite-sericite-chlorite granulite (granofels in our terminology) into two map units composed of green phyllite and granofels (O€mpb and O€m) and two units of green phyllite and granofels interlayered with grayish-black phyllites (O€msr and O€mw). On this map, the Dumpling Hill belt is divided into three units: O€mpb, O€msr, and O€mdh; the Wrightsville belt is divided into four units: O€m, O€mw, O€mg, and O€mq. Our map reflects the relative amounts of carbonaceous (gray to black) versus non-carbonaceous (greenish) rocks and the distribution of mafic rocks. Like Cady (1956), we find that the metadiabase dikes and greenstones are geographically restricted to the eastern outcrop belt of the Moretown Formation and the entire Cram Hill Formation in an area that we define as the Wrightsville belt.

In contrast to Cady (1956), we found that the metadiabase and greenstone dikes and interbedded greenstone layers are absent west of the inferred Shady Rill fault. This fault separates gray and black phyllites and quartzite (O€mdh) of the Dumpling Hill belt to the west from interlayered gray and black to green phyllites and granofels (O€mw) and green phyllite and granofels (O€m) of the Wrightsville belt to the east. Although Cady (1956) shows that the dikes cut across a map-scale isoclinal fold structure, our mapping suggests that this early structure is truncated along the Shady Rill fault and that rocks previously mapped within the eastern limb of this structure are actually part of the Wrightsville belt. As we map it, the inferred Shady Rill fault separates units that contain mafic rocks to the east from those that do not contain mafic rocks to the west, but it is also a boundary that divides rocks that preserve the oldest composite map-scale fold structures (F_1/ F_2) in the area (Dumpling Hill belt) from those that have been strongly overprinted by F_3 folds (Wrightsville belt) (see discussion below in Structural Geology section). Although we cannot rule out the possibility that the absence of mafic rocks in the Dumpling Hill belt is related to some fundamental change in the original depositional setting of the rocks, we prefer a fault model because older structures in the quartzite-rich Dumpling Hill belt are preferentially preserved, and the mapped boundary is sharp and parallel to a zone of penetrative foliation with consistent northwest-trending lineations.

In the Wrightsville belt, the most abundant unit of the Moretown Formation is O€m, which consists of grayish-green to green and silver schist, phyllite, and granofels and quartz-rich "pinstripe" granofels. Metadiabase and greenstone bodies are abundant and are locally mapped separately (see discussion above). Locally, O€m contains layers of small-pebble conglomerate (O€mq). In the central one-third of the map area there are two separate stratigraphic belts of O€m, a wide belt west of and a narrow belt east of the Cram Hill Formation, whereas in the northern half of the map area, there is one belt. This narrow belt of the Moretown Formation, east of the Cram Hill, is interpreted as a repeated part of the section about an early fold (F_1? or F_2 as shown on the map) of the Cram Hill Formation, based largely on the symmetrical distribution of Cram Hill rocks mapped west of the Dog River fault zone and south of Interchange 8 on Interstate 89 (I–89), and on the lithologic similarity to rocks found farther west. This inferred early fold of the Moretown and Cram Hill Formations is not continuous, however, and depending on the latitude, either the Ochr unit of the Cram Hill Formation or O€m is adjacent to the RMC-Dog River fault zone, and the early fold is truncated. Alternatively, the Moretown Formation rocks we map to the east of the Cram Hill Formation may be part of the Shaw Mountain Formation exposed above the pre-Silurian section without any fold repetition. The lack of repetition and symmetry in the northern part of the Montpelier quadrangle may support this alternate explanation. Locally O€m displays characteristic magnetite octahedra, especially along I–89 and U.S. Route 2 between Montpelier and Middlesex. Excellent exposures of O€m are located in the Green Mountain Cemetery in Montpelier, in the North Branch River in Putnamville, and on the northern side of State Route 12 in Berlin, west of the railroad bridge.

In the northern one-third of the map, grayish-green granofels and "pinstripe" granofels are interlayered with gray, dark-gray, green, and black phyllites that, together with largely unmapped but abundant mafic rocks, constitute the O€mw unit of the Moretown Formation. The contact between O€m and O€mw is gradational by intercalation and, therefore, interpreted to be stratigraphic. The O€mw unit is present in the northern part of the field area to the west of O€m and terminates along the trace of the inferred Shady Rill fault towards the south. Good roadcuts of O€mw occur on both sides of State Route 12 in Putnamville.

Cram Hill Formation (Ordovician)

The Cram Hill Formation occurs as discontinuous belts of rock east of the main belt of the Moretown Formation and west of the RMC; these belts extend from the northeastern corner to the west-central part of the map. The Cram Hill Formation was first described by Currier and Jahns (1941) in central Vermont as greenish-gray and black phyllites and slates interlayered with mafic metaigneous rocks on the western side of the RMC. Although Currier and Jahns (1941) indicated that the Cram Hill Formation extended 2.5 miles (mi) north of Montpelier, Cady (1956) and Doll and others (1961) considered these lithologies to be part of the Moretown Formation. On the State map (Doll and others, 1961), the "Cram Hill member of the Missisquoi Formation" was abruptly terminated south of Montpelier probably because Cady (1956) did not map this unit. On the basis of lithologic similarity, Currier and Jahns (1941) correlated the Cram Hill Formation with the fossiliferous Middle Ordovician Magog Group black slates of southern Québec. Recent bedrock geologic maps from southern Vermont (for example, Armstrong, 1994; Ratcliffe and Armstrong, 2001; Walsh and others, 1996a,b) and northern Vermont (for example, Hoar, 1981; Gale, 1980; Kim, 1997) demonstrate that the Cram Hill Formation extends the entire length of Vermont, albeit discontinuously. The black phyllite of the Cram Hill Formation also can be mapped continuously into the "Ohb" unit of the Hawley Formation (Hatch and Hartshorn, 1968; Kim and Jacobi, 1996) in northwestern Massachusetts.

The dominant lithology in the Cram Hill Formation is a gray to black carbonaceous phyllite interlayered with gray phyllite and quartzite (Ochr). Mafic rocks, including greenstone and metadiabase, are abundant in the Cram Hill Formation. Most mafic rocks in Ochr appear to be intrusions (see separate section below on metadiabase dikes). Extensive exposures of the Ochr unit are found on the northern side of I–89 just south of Interchange 8 and in Hubbard Park in Montpelier. Ochr is bounded to the east by the RMC-Dog River fault zone and to the west by the interlayered unit of the Cram Hill Formation (Ochi). Near downtown Montpelier, however, a coticule-bearing unit (Ochc) bounds Ochr to the west. South of Montpelier, a thin belt of grayish-green granofels, phyllite, and greenstone mapped as Moretown Formation (O€m) occurs between Ochr and the Dog River fault zone in an inferred early fold of rocks exposed farther west. Interlayered gray and green phyllites, quartzite, and granofels are the main rock types of the Ochi unit of the Cram Hill Formation. Subordinate lithologies include quartz-pebble conglomerate, quartzite, and mafic metaigneous rocks (greenstones and metadiabases). Ochi is the transitional unit between Ochr (Cram Hill Formation) and O€m (Moretown Formation) in the Wrightsville belt. This transitional contact is gradational by intercalation and is presumed to be stratigraphic. Typical outcrops of Ochi are located on the eastern side of Long Meadow Hill in Calais, on the northern side of I–89 just southeast of Interchange 8, and in Hubbard Park in Montpelier.

The coticule-bearing unit of the Cram Hill Formation (Ochc) (fig. 4) was mapped in the central part of the map area in the vicinity of Montpelier. Ochc consists of gray phyllite and granofels with conspicuous, 2- to 5-mm-thick, pale-pink, disarticulated layers of coticule (fine-grained quartz-spessartine rock); this unit occurs in contact with massive greenstone (with phenocrysts of plagioclase) and metadiabase. On the basis of the presence of abrupt and crosscutting contacts with the surrounding metasedimentary rocks and the presence of chilled margins, we believe many of these mafic metaigneous rocks are intrusions but cannot rule out the possibility that some of the massive rocks are flows. Well-exposed outcrops of Ochc are found on the southern side of U.S. Route 2, several hundred meters east of Montpelier High School, and in Hubbard Park.

Metadiabase and Greenstone Dikes (Ordovician? and Silurian?)

Cady (1956) showed generalized areas on the 15-minute Montpelier quadrangle where he found "metamorphosed mafic sills and dikes" in the pre-Silurian rocks. We observed massive metadiabase and finer grained greenstone intrusions only in the Wrightsville belt between the Shady Rill fault and the Richardson Memorial Contact (RMC)-Dog River fault zone. Although most contacts between these intrusions and the surrounding metasedimentary rocks of the Moretown and Cram Hill Formations are subparallel to the dominant foliation, there are some locations where the contacts cut this foliation at an angle (fig. 5). The dominant foliation, in most cases, is presumed to be the Taconian (Ordovician) S_2. Because of the ductility contrast between the metadiabases and the surrounding metasedimentary rocks, the metadiabases, which are typically 0.3 to 3 m wide, are locally boudinaged. Individual dikes are not traceable along strike from outcrop to outcrop. Thicker metadiabase bodies frequently have chilled margins. Petrography by Cua (1989), Twelker (2004) and Twelker and others (2004) show these metadiabases are quartz-epidote-chlorite-albite±actinolite rocks with secondary calcite that contain intergrown plagioclase and epidote-actinolite pseudomorphs after pyroxene indicating a relict diabase texture. Two of the best locations for observing these intrusions are (1) outcrops in the North Branch River in Putnamville (near the intersection of State Route 12 and Norton Road) and (2) at the intersection

A

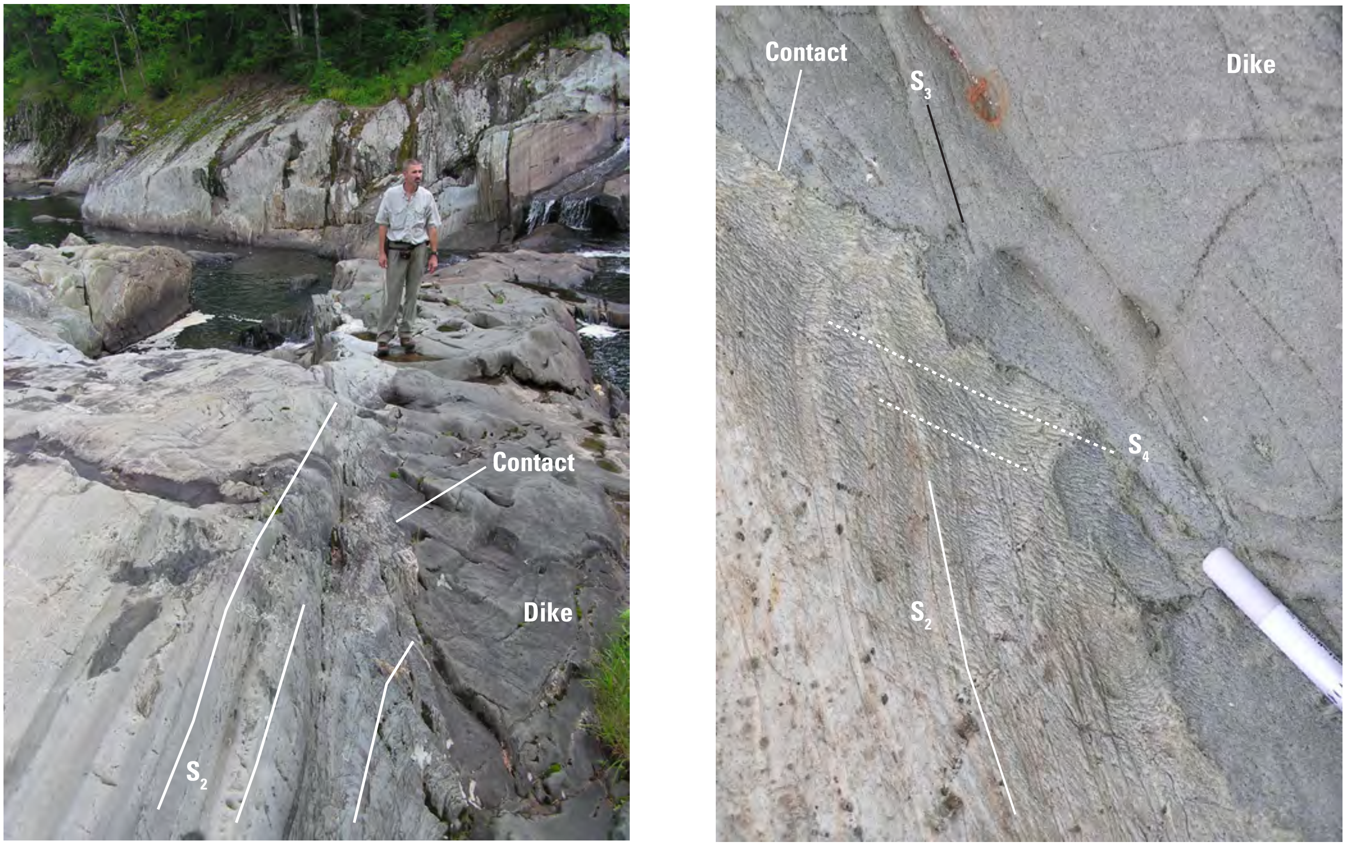
B

Figure 4. Photographs of coticule in the Cram Hill Formation. *A*, Thin resistant layers form ridges of tightly folded coticule in an outcrop in Hubbard Park in Montpelier. Coticule layers are deformed by F_2 and F_3 folds. *B*, Steeply north-plunging coticule rods observed in an outcrop just south of Memorial Drive in Montpelier. These rods are near the Richardson Memorial Contact-Dog River fault zone and are colinear with F_3 fold axes.

of Ledgewood Terrace and Terrace Street in Montpelier (street names not on base map). On the map we show the dikes as separate map units only where we observed crosscutting relations indicating an intrusive origin.

Although the isotopic age of the metadiabase dikes has not been determined, most dikes are pre-Acadian (Devonian) because their contacts with the host metasedimentary rocks are clearly folded by the first deformational event (S_3) to affect Silurian and Devonian rocks, and the dikes are absent in the CVGS, above the Silurian unconformity. The dikes may be correlative in age with similar mafic dikes found in the Comerford Intrusive Suite on the eastern side of the CVGS (Rankin and others, 2007). Gabbrodioritic rocks in the Comerford Intrusive Suite are dated at 419±1 Ma (Rankin and others, 2007). Biotite-hornblende monzodiorite of the Braintree pluton in central Vermont has the same age (419.26±0.39 Ma, Black and others, 2004) and appears to have the same relative age of the dikes in the Montpelier area but differs petrographically and chemically from the greenstones and mafic dikes in the Moretown Formation (Ratcliffe and Aleinikoff, 2000; Ratcliffe, 2006).

Trace and rare-earth element geochemistry of these intrusions indicate a backarc basin tectonic setting that was subject to varying amounts of suprasubduction zone metasomatism (Cua, 1989; Twelker, 2004; Twelker and others, 2004). On a regional scale, these metadiabases are possibly correlative with those in the Mount Norris Intrusive Suite of northern Vermont (Kim, Coish, and others, 2003), the Charlemont Mafic Intrusive Suite of northwestern Massachusetts (Kim and Jacobi, 1996), or mafic dikes in the Comerford Intrusive Suite in northeastern Vermont and northwestern New Hampshire (Rankin and others, 2007). Within the Rowe-Hawley lithotectonic belt of New England, many metadiabase dikes that are geochemically and petrographically similar to those in the Montpelier and Barre West quadrangles have been reported in northern Vermont (Stanley and others, 1984; Kim, Coish, and others, 2003), central Vermont (Cua, 1989; Martin, 1994), southern Vermont (Armstrong, 1994; Walsh and Ratcliffe, 1994a,b; Ratcliffe, 1997; Ratcliffe and Armstrong, 1999, 2001), and northwestern Massachusetts (Kim and Jacobi, 1996).



A *B*

Figure 5. Photographs of a metadiabase dike at Putnamville, Vt. *A*, Dark-gray-weathering metadiabase dike (SOdg) on the right side of the photograph shows a crosscutting intrusive contact with "pinstripe" granofels of the Moretown Formation (OЄm) on the left. The dike is approximately 3 m thick. Truncated planar layering in the Moretown Formation is parallel to S_2. *B*, Close-up photograph of the contact between the metadiabase dike and the granofels of the Moretown Formation. The dike cuts the dominant S_2 foliation at an angle, but the contact is deformed by F_3 folds and crosscut by an S_4 crenulation.

Rocks of the Connecticut Valley-Gaspé Synclinorium

The age of the metasedimentary rocks in the Connecticut Valley-Gaspé Synclinorium (CVGS), also called the Connecticut Valley trough (Hatch, 1988, 1991), is based on limited fossil and isotopic evidence. The stratigraphic sequence, from oldest to youngest, includes the Silurian Shaw Mountain, the Silurian and Devonian Northfield Formation, the Silurian and Devonian Waits River Formation, and the Devonian Gile Mountain Formation (fig. 3). Information on fossil localities from the CVGS is discussed by Hueber and others (1990).

Silurian (Llandoverian) fossils in the Shaw Mountain Formation, at the base of the CVGS, provide a lower age limit for the CVGS sequence (Boucot and Thompson, 1963; Boucot and Drapeau, 1968; Doll, 1984). Early Devonian (Emsian) plant fossils from the Compton Formation in Québec, the northern correlative of the Gile Mountain Formation, provide age control for the upper part of the CVGS (Hueber and others, 1990).

The age of the Waits River Formation is less well constrained and is assigned an age range of Silurian to Devonian. Aleinikoff and Karabinos (1990) and Hueber and others (1990) reported a conventional U-Pb zircon age of 423±4 Ma from a felsic rock from the Waits River Formation in Springfield, Vt. The sample is from a 50-cm-thick, light-gray, fine-grained epidote-chlorite-albite-quartz granofels layer within a coarser grained sequence of phenocrystic feldspathic schist and granofels. Aleinikoff and Karabinos (1990) interpreted the layer as a dike but left open the possibility that it was a volcanic layer. Walsh and others (1996a) and Armstrong and others (1997) interpreted the layer as a bed because of the lack of unequivocal crosscutting relations and the presence of many similar, yet thinner, layers within a felsic volcaniclastic map unit. The Silurian date either provides the age for the deposition of the felsic unit at that locality, and therefore the age of the Waits River there, or a minimum age.

Cady (1950) reported the occurrence of cup corals from several localities within the Waits River Formation in the 15-minute Montpelier quadrangle and suggested a Middle Ordovician age for these fossils. Cady (1956) changed the age of the Waits River from Ordovician to Silurian on the basis of regional correlations with fossiliferous rocks reported by Boucot and others (1953) in southern Vermont and Massachusetts. Only Cady's (1950, p. 492) locality no. 7 could be confirmed during our mapping, and the location is shown on the map. In our opinion, this locality contains what appear to be fossil fragments in a pebbly horizon at the base of a graded bed of phyllite, despite the fact that Hatch (1988, p. 1056) and Hueber and others (1990, p. 363) reported that, on the basis of a study of slides and slabs by William A. Oliver, Jr., "None of the specimens at hand appear to be corals and none have any markings or structure that suggest an organic origin, although this is a possible origin of the objects." This locality has yet to be re-examined by a paleontologist. Initial reports of Ordovician graptolites from Berlin Corners by Bothner and Berry (1985) and Bothner and Finney (1986) were re-evaluated by Hueber and others (1990) and reported to be plant fragments and not graptolites. Hueber and others (1990) also collected crinoid and echinoderm fragments from the Berlin Corners exposure, but the fragments did not provide specific age constraints. Plant fossil fragments without specific age constraints also were reported at the Catholic cemetery and Sabin's quarry localities in Montpelier (Hueber and others, 1990). The upper age limit of the Waits River Formation is probably Early Devonian because it is conformably overlain by the Early Devonian Gile Mountain Formation.

Shaw Mountain Formation (Silurian)

The Shaw Mountain Formation consists of a number of discontinuous lenses of metasedimentary quartz-rich rock, quartz-pebble conglomerate, and ankeritic greenstone and green schist located along the RMC in the northern part of the Montpelier quadrangle. The most conspicuous lithology in the Shaw Mountain Formation is a rusty-weathering, locally sulfidic quartz-pebble conglomerate. Although the clasts are dominantly composed of vein quartz, foliated clasts of rocks that resemble those found in the Moretown Formation are locally present. The conglomerate (Ss) in the Montpelier quadrangle occurs as lenses within a heterogenous unit (Ssg) consisting largely of ankeritic greenstone and calcarous green schist; in the absence of the quartz-pebble conglomerate, it is difficult to separate these lithologies from rocks in the underlying Moretown or Cram Hill Formations.

The Shaw Mountain Formation was first defined by Currier and Jahns (1941) in central Vermont as an east-facing succession of massively bedded quartz-pebble conglomerate, platy soda rhyolite tuff, and crinoidal limestone. In the 15-minute Montpelier quadrangle, Cady (1956) also recognized the quartz-pebble conglomerate and limestone and included a calcite-chlorite-albite schist unit above the Moretown Formation and beneath the quartz-pebble conglomerate unit. In the Montpelier 7.5-minute quadrangle we observe that the calcareous schist (Ssg) in the Shaw Mountain Formation is not just beneath the quartz-pebble conglomerate but above it as well, and that the conglomerate occurs as discontinuous lenses within our ankeritic greenstone and green schist unit (Ssg). Other exposures of calcareous greenstone occur within the Moretown or Cram Hill Formations. We also note that the "crystalline limestone" reported by Cady (1956), "a little northwest of a sharp bend in Long Meadow Brook," is simply a punky-weathering ankeritic chlorite-muscovite-albite-quartz granofels with abundant post-tectonic carbonate porphyroblasts. In southern Vermont, similar units containing ankeritic greenstone and calcareous quartzite have been mapped as either unnamed rocks (unit DScv of Ratcliffe, 2000b) or as part of the Northfield Formation (unit DSng of Ratcliffe and Armstrong, 2001). In northern Vermont, Konig and Dennis (1964) describe the Shaw Mountain Formation as dominantly crystalline limestone, calcareous metaquartzite, and phyllite but with subordinate amounts of greenstone and calcareous quartz-pebble conglomerate.

Konig and Dennis (1964) reported that bryozoans, brachiopods, corals, and echinoderm debris were found in the crystalline limestone of the Shaw Mountain Formation in the 15-minute Hardwick quadrangle and that the analysis of the fossil age ranges suggested a Silurian to Early Devonian age. Other work on the Shaw Mountain Formation fossils (for example, Boucot and Thompson, 1963; Doll, 1984; Westerman, 1987) indicates a Middle Silurian age.

Numerous Late Silurian along-strike correlatives to the Shaw Mountain Formation are well exposed in southern Québec, where the Acadian deformation is less intense than in Vermont, and stratigraphic relations are clearer. Lavoie and Asselin (2004) group these Silurian units of southern Québec into autochthonous and allochthonous categories depending on whether the units are found in the pre-Silurian (Dunnage or Internal Humber) or CVGS tectonic provinces. The autochthonous units, which are directly correlative with the Shaw Mountain Formation in Vermont, comprise the St. Luc, Cranbourne, and Lac Aylmer Formations and the Glenbrooke Group. These units grade upward from basal quartz-pebble conglomerate that unconformably overlies pre-Silurian terranes of the Dunnage and Internal Humber zones to sandstone and siltstone and finally to fossiliferous limestone (Lavoie and Asselin, 2004). The Late Silurian (Pridolian) ages of these units are based on fossils primarily found in the limestone. Although all autochthonous units clearly exhibit unconformable bases, some (for example, Lac Aylmer Formation) may also be cut on one side by a Devonian fault.

Northfield Formation (Silurian and Devonian?)

The Northfield Formation consists of dark-gray phyllite (DSn) that contains thin layers (≤20 cm) of micaceous quartzite and rare matrix-supported conglomerate (DSnc). The Northfield Formation occurs at the base of the CVGS and crops out continuously, although with variable thickness, through both quadrangles. Currier and Jahns (1941) and Cady (1956) mapped these rocks as the Northfield slate, and Doll and others (1961) established the name Northfield Formation.

Thin impure limestone beds are very rare but increase in abundance at the eastern contact with the Waits River Formation ($DSwl_1$), confirming reports by other workers (Currier and Jahns, 1941; Doll, 1951; Cady, 1956; Hatch, 1988). Hatch (1988) reported that graded bedding in the Northfield

Formation indicated that it was stratigraphically above the Waits River Formation. Due to the lack of definitive topping criteria in the Northfield Formation in the map area, we cannot confirm or refute Hatch's findings. The phyllite is well exposed in roadcuts east of Interchange 8 on I–89 and in outcrops in the Dog River located east of State Route 12 and the railroad tracks approximately 2.4 km south of the Montpelier-Barre West quadrangle boundary. In the northern part of the study area, the Northfield Formation is in sharp contact with the Shaw Mountain, Cram Hill, and Moretown Formations to the west and is in gradational contact with the Waits River Formation to the east. South of Horn of the Moon Pond, we map the sharp, western contact of the Northfield Formation as a fault.

The conglomerate near the base of the Northfield Formation (DSnc) was seen at one place along the Dog River in the Barre West quadrangle. This matrix-supported conglomerate occurs within the Northfield Formation, not at the contact between the Northfield and Cram Hill Formations. Although poorly exposed, the rock was described and seen elsewhere by Currier and Jahns (1941). In fact, the outcrop on the Dog River was photographed and appears as figure 1 in Currier and Jahns (1941, p. 1494). The outcrop is overgrown now, but tectonically elongated clasts are still visible in the phyllitic or slaty matrix. Currier and Jahns (1941) report that the clasts consist of rocks found in the Cram Hill and Shaw Mountain Formations. Along the Dog River, the conglomerate occurs as an approximately 2- to 3-m-thick layer within the phyllitic matrix. A second exposure in the Barre West quadrangle described by Currier and Jahns (1941, p. 1502) could not be confirmed by our mapping.

Waits River Formation (Silurian and Devonian)

The Waits River Formation consists dominantly of interbedded phyllite and impure limestone or marble (DSwt, $DSwl_1$, and $DSwl_2$), with minor amounts of phyllite (DSw), garnetiferous phyllite (DSwg), and quartzite (DSwq). The Waits River Formation occupies the majority of the Barre West quadrangle and the eastern half of the Montpelier quadrangle. The most distinctive aspect of the Waits River Formation is the presence of metamorphosed impure limestone or marble. Historically, workers have used both the terms "marble" and "limestone." White and Jahns (1950, p. 187) noted that the term "limestone" was "long-established local usage." Cady (1956, footnote 1) provides a possible explanation as follows: "Though the crystalline limestones are strictly marbles, the geologists who have studied these rocks have long referred to them as limestone rather than marble, probably because of their poor commercial qualities compared to the marbles of western Vermont."

Doll and others (1961) also used the term "limestone" on the State map, and we continue the traditional usage here. The limestone is typically bluish gray and weathers to a punky brown, earthy crust. The limestone is considered siliceous and impure because it typically contains 60 to 80 percent calcite, 20 to 40 percent quartz, and less than 5 percent muscovite and (or) biotite. The protolith of this rock was probably sandy limestone, according to the classification of Williams and others (1954) and Compton (1962).

The interbedded phyllite and limestone units (DSwt, $DSwl_1$, and $DSwl_2$) are the three main map units in the Waits River Formation (fig. 6). These map units are separated on the basis of bed-thickness of interbedded limestone. To the west, limestone beds generally are 0.2 to 3.0 m thick and locally as much as 5.0 m thick in the thinly bedded unit. Phyllite beds in $DSwl_1$ and $DSwl_2$ are generally less than 1 m thick, but their thickness is often difficult to determine because bedding planes are transposed, folded, and difficult to see. Bedding in the phyllite in all three units is locally defined by layer-parallel oxidized pyrite concentrations. The pelitic rocks are phyllitic in the biotite zone, schistose in the garnet zone, and locally calcareous. To the east, limestone beds generally are 1.0 to 5.0 m thick and locally as much as 9.0 m thick in the thickly bedded unit DSwt. Phyllite beds in DSwt are generally less than 1 m thick and locally are as much as 3 m thick. Like $DSwl_1$ and $DSwl_2$, the thickness of the phyllite beds is often difficult to determine because bedding planes are transposed, folded, and difficult to see. In a detailed survey over a 58-m-thick section of $DSwl_1$ at Interchange 7 on I–89 in the Barre West quadrangle (Walsh and Satkoski, 2005), phyllite beds range from 0.15 to 3.3 m thick and average 0.9 m thick. Limestone beds at Interchange 7 range from 0.3 to 8.6 m thick and average 1.8 m thick. At Interchange 7, a single limestone bed measured 8.6 m thick, and it is shown on the map as DSwt. The next thickest limestone bed measured 4.7 m thick. The Interchange 7 locality is one of only a few places in the $DSwl_1$ unit where a limestone bed greater than 5 m thick was seen, and in these places we map the units as DSwt. The thickly bedded unit (DSwt) is well exposed at Interchange 6 on I–89, at quarries north and south of State Route 63 just east of Interchange 6, along State Route 63 near the junction with Miller Road, at the falls on the Stevens Branch in South Barre, and below the dam on the Winooski River in Barre at an elevation of 600 feet. The thinly bedded unit ($DSwl_1$) is well exposed in roadcuts on I–89, 0.5 km south of the bridge over State Route 12, at Interchange 7, and at the overpass, 0.5 km west of Berlin Corners. Unit $DSwl_2$ is well exposed in Cold Spring Brook.

Graded bedding in the Waits River Formation was rarely seen, but the majority of observed topping criteria suggest that the Waits River is steeply overturned toward the east-southeast. Graded beds in the limestone are less common than those in the phyllite and consist of 2- to 4-cm-thick horizons of coarse- to very coarse sand-size grains or rare pebbles of quartz, rock and (or) fossil fragments. Graded beds in the phyllite contain relatively coarse-grained bases dominated by quartz and feldspar and rare conglomeratic horizons with very coarse sand-size grains or rare pebbles of quartz, and very rare rock or fossil fragments. On the map, locations where graded beds were observed are shown with a special strike and dip symbol. Four fossil localities within the Waits River Formation are shown with an open diamond and are summarized as follows:

A

B

Figure 6. Photographs of the Waits River Formation. *A*, Thinly bedded unit ($DSwl_1$) shows interlayered brown-weathering impure limestone and more resistant gray slate on the east side of Irish Hill, about 2 km west of Interchange 6 on I–89. *B*, Thickly bedded unit (DSwt) shows unweathered limestone and slate and phyllite at Interchange 6 on I–89, at the start of the northbound offramp.

U.S. National Museum locality number	Location	UTM Northing (NAD 27)	UTM Easting (NAD 27)	Reference
14293	Sabin quarry	4902748	694760	Hueber and others (1990).
14294	Catholic Cemetery	4903754	694473	Hueber and others (1990).
14300	Roadcut near Berlin Corners	4898005	693031	Hueber and others (1990).
	Locality no. 7	4908010	698274	Cady (1950).

The dominantly pelitic units (DSw, DSw_1, and DSw_2) occur throughout the Waits River Formation. They consist largely of dark-gray slate, phyllite, or schist without appreciable interbedded limestone. Very thin (<20 cm) limestone horizons may be present in the DSw units, but they are rare. Generally two large pelitic units were mapped in the area. The first (DSw_1) occurs in the western (lower) part of the Waits River Formation within the $DSwl_1$ unit along the crest of Paine Mountain to Irish Hill, and the second (DSw_2) occurs between the thinly and thickly bedded limestone units ($DSwl_1$ and DSwt, respectively). In the central part of the Barre West quadrangle, the eastern (upper) DSw_2 unit is repeated by folding. On our map we show the axial traces of F_3 folds (Acadian F_1) where we interpret the map distribution to reflect such folding. In places where we do not show axial traces, we interpret the map units as facies changes within the Waits River Formation. Small units mapped simply as DSw are interpreted as limestone-poor facies. Good exposures of the pelitic map unit are located on West Hill in Barre and at a roadcut along State Route 63, approximately 1.2 km east of Interchange 6 on I–89.

The garnetiferous phyllite (DSwg) occurs as a single map unit within the thinly bedded Waits River Formation. The garnetiferous phyllite is a distinctive nonsulfidic rock that contains abundant millimeter-scale garnet porphyroblasts. To the south on the eastern slopes of Paine Mountain, DSwg is thicker than to the north and can be mapped by the occurrence of several closely spaced across-strike outcrops in a zone several hundred meters wide. North of Berlin Corners, DSwg is generally restricted to only one or two outcrops in a zone approximately 150 m wide. In the Montpelier quadrangle, the zone narrows to less than or equal to 100 m wide at the Montpelier-East Montpelier town line, before we map it discontinuously to the north. A typical exposure of the garnetiferous phyllite is located in Berlin under the powerlines along Berlin Street (name not on map), approximately 300 m northwest of the Armory in the Barre West quadrangle. The garnetiferous phyllite does not contain interbedded limestone. The DSwg unit marks the westernmost occurrence of almandine garnet in the area and coincides with the mapped Acadian garnet isograd. The mapped garnet isograd is a function of bulk composition as DSwg is probably more aluminous than adjacent nongarnetiferous phyllite. Immediately east of the DSwg unit, in the garnet zone, nongarnetiferous dark-gray phyllite occurs in the Waits River Formation, providing evidence for minor differences in bulk composition. Within the garnet zone, garnetiferous phyllite or schist occurs sporadically in other places, and almandine garnet becomes more abundant towards the east, but the relatively greater abundance of garnet in the eastern part of the Waits River Formation makes it difficult to separate map units solely on the presence of garnet porphyroblasts. On the map in the garnet zone, we show locations where conspicuous garnet porphyroblasts were seen at outcrops in the eastern part of the Waits River Formation, east of the DSwg unit. West of the isograd and west of the RMC, the dominant assemblage in the pelitic rocks is quartz-chlorite-muscovite±biotite.

Quartzite of the Waits River Formation (DSwq) is a minor unit and is shown in three places in the Barre West quadrangle. At two places (Stations 1266 and 1321 in the database), the map unit shows the location of single 0.5- to 2.0-m-thick quartzite beds, and the third location (Station 1271) shows thinner interbedded quartzite, phyllite, and limestone layers, generally less than 30 cm thick. The quartzites at these three locations consist mostly of quartz (75–90 percent) with variable amounts of calcite, plagioclase, muscovite, and trace pyrite and graphite. Depending upon which of these secondary minerals is the second most abundant, the rocks can either be called calcareous, feldspathic, or micaceous quartzite. Protoliths for these rocks probably ranged from arenite to calcareous sandstone to wacke according to the classification of Williams and others (1954) and Compton (1962).

Contacts between the thinly and thickly bedded Waits River units ($DSwl_1$, $DSwl_2$, and DSwt) are mapped on the basis of limestone beds greater than or equal to 5 m thick. Contacts between the phyllite unit and the limestone-bearing units are gradational. Contacts between the garnetiferous phyllite and adjacent units, although not completely exposed, are sharp and occur within a distance of approximately 1 m. Contacts for individual quartzite layers are typically sharp except where graded bedding was observed.

Most workers in central Vermont have named these rocks the Waits River Formation (Currier and Jahns, 1941; White and Jahns, 1950; Konig, 1961; Ern, 1963). In the East Barre 15-minute quadrangle, however, Murthy (1957) called these rocks the Barton River Formation and suggested that they were older and stratigraphically beneath the Gile Mountain Formation and Waits River Formation. Doll and others (1961) used the name Barton River member of the Waits River Formation for the belt of rocks west of the Gile Mountain Formation and suggested in their correlation of map units that it was laterally correlative with the Waits River rocks east of the Gile Mountain Formation. In fact, the State map (Doll and others, 1961) uses the same pink color for Waits River Formation and Barton River member of the Waits River but uses different map unit designators, “Dw” and “Dwb,” respectively. Our findings combined with regional fossil evidence (Hueber and others, 1990; Lavoie and Asselin, 2004) suggest that the Waits River Formation in the Montpelier and Barre West quadrangles is stratigraphically beneath the Gile Mountain Formation, in agreement with most workers. Thus Murthy’s stratigraphic assessment appears invalid. Our mapping also agrees with more recent stratigraphic work in the Connecticut Valley rocks, placing the Waits River Formation below the Gile Mountain Formation in the Townshend-Brownington syncline (Fisher and Karabinos, 1980; Hatch, 1988).

Gile Mountain Formation (Devonian)

The Gile Mountain Formation consists largely of interbedded phyllite and quartzite (Dgm), with minor amounts of calcareous phyllite (Dgmcp) and impure limestone (Dgml). The Gile Mountain Formation occurs only in the southeastern corner of the Barre West quadrangle. Bedding in the interbedded phyllite and quartzite unit (Dgm) generally ranges from 10 to 30 cm thick. Graded bedding is locally preserved and generally indicates that the beds are steeply overturned to the southeast. The interbedded sequence of phyllite and quartzite probably represents a sequence of turbidites. The phyllite and quartzite unit is well exposed in Cold Spring Brook above the 1,100-foot elevation. At several locations along McGlynn Road (name not shown on map), dark-brown-weathering, gray calcareous phyllite layers, 30 to 40 cm thick, occur within the phyllite and quartzite unit and are mapped separately as Dgmcp. Similar calcareous phyllite layers occur throughout the Waits River Formation but are not mapped separately. At one location near McGlynn Road, a single ~50-cm-thick layer of impure siliceous limestone occurs in the phyllite and quartzite unit, and it is mapped separately as Dgml. This location marks the only observed occurrence of limestone within the Gile Mountain Formation in the map area. Similar limestones occur throughout the Waits River Formation but are not mapped separately.

The contact between the Gile Mountain Formation and underlying Waits River Formation, although not entirely exposed, is generally gradational over a distance of tens of meters. The number of limestone layers in the Waits River Formation decreases towards the contact with the Gile Mountain Formation, while the number of thin 10- to 20-cm-thick quartzite, micaceous quartzite, and feldspathic quartzite layers increases towards the contact with the Gile Mountain. The upper, or easternmost, part of the Waits River Formation contains thinly interbedded phyllite and limestone ($DSwl_2$) below the contact with the Gile Mountain Formation. This part of the Waits River Formation contains thinner and fewer limestone beds than the underlying thickly bedded phyllite and limestone unit (DSwt), suggesting a progressive decrease in limestone upsection towards the Gile Mountain Formation.

Doll and others (1961) and Konig (1961) mapped these rocks as Gile Mountain Formation, but Murthy (1957) called these rocks the Westmore Formation and suggested that they might be correlative with his Gile Mountain Formation exposed in the southeastern corner of the East Barre 15-minute quadrangle. The Gile Mountain Formation, as we map it, generally supports Hatch's (1988, p. 1045) assignment to the rhythmically bedded "RQM" unit in the core of the Townshend-Brownington syncline, the western limb of which is exposed in our study area.

Igneous and Metasomatic Rocks

Granitic Dikes (Devonian)

Granitic dikes in the area range in composition from trondhjemite to granodiorite to muscovite-biotite granite. The dikes are part of the Devonian New Hampshire Plutonic Suite. Although not dated in the map area, similar correlative rocks occur throughout Vermont. A U-Pb zircon age determined by sensitive high resolution ion microprobe (SHRIMP) for the nearby Barre Granite (Murthy, 1957) is 368±4 Ma (Ratcliffe and others, 2001). Ratcliffe and others (2001) report a similar U-Pb zircon age of 366±4 Ma for the Black Mountain Granite in southern Vermont. Structurally, the dikes cut the bedding in the Silurian-Devonian rocks and generally intruded subparallel to the dominant foliation (S_3 or Acadian S_1; see discussion below) in these rocks. Locally the dikes contain the S_3 foliation, especially in thin bodies or along the margins of larger dikes, suggesting that some might predate or be synchronous with foliation development. Other dikes without a foliation postdate the S_3 foliation but may have experienced subsequent flattening along their margins during continued regional deformation. The generally massive texture of the dikes makes it difficult to assess whether they predate or postdate the weakly developed S_4 (Acadian S_2) cleavage in this area. Under the microscope, however, the granite in the core of the dike at Crosstown Road contains no foliation or even preferred fracture orientation, suggesting that it either postdates both S_3 and S_4 or was insulated from the deformation due to the massive texture of the rock. The structural relations combined with the regional zircon ages and similar regional $^{40}Ar/^{39}Ar$ metamorphic ages (Laird and others, 1984, 1993; Spear and Harrison, 1989) clearly suggest that the granites are related to Acadian deformation and metamorphism.

Although some of the larger granite bodies in the northeastern part of the Montpelier quadrangle have elliptical shapes and crosscut the dominant foliation, most are thin elongate bodies that are parallel to the S_3 (Acadian S_1) foliation. Quarries are found in many of the largest granite bodies near the town of Adamant. Because most granite bodies intruded parallel to the dominant foliation, they are considered sills sensu lato. When viewed in three dimensions, however, some granite bodies parallel the dominant foliation in one part of an outcrop but crosscut the same foliation in other parts of the outcrop.

Quartz Veins (Devonian)

Quartz veins crop out in the two quadrangles, and the locations of larger veins are indicated either as map units (Dq) where they are large enough to map or with symbols. A strike and dip symbol represents the average orientation of the generally tabular bodies, and point symbols show locations where orientations could not be determined. The veins are folded in places and generally predate the regional S_4 (Acadian S_2) cleavage. Late tabular quartz veins postdate all the deformation and have either a late-metamorphic origin or a post-metamorphic igneous or a metasomatic origin. Anderson (1987) studied similar veins in north-central Vermont and concluded that most of the veins have a metamorphic origin and that some veins (especially those in northeastern Vermont) have a metasomatic origin related to New Hampshire series plutons. The veins are assigned a Devonian age. Small, unmapped, highly folded and disarticulated quartz veins in the Moretown and Cram Hill Formations may be related to Taconian (Ordovician) metamorphism.

Lamprophyre or Diabase Dikes (Cretaceous)

Lamprophyre or diabase dikes occur as tabular steeply dipping, outcrop-scale dikes throughout the two quadrangles, and their locations and orientations are shown by strike and dip symbols. Eleven dikes dip greater than or equal to 74° and have a preferred east-west strike (fig. 7), generally parallel to the major joint trends (see Brittle Structures section).

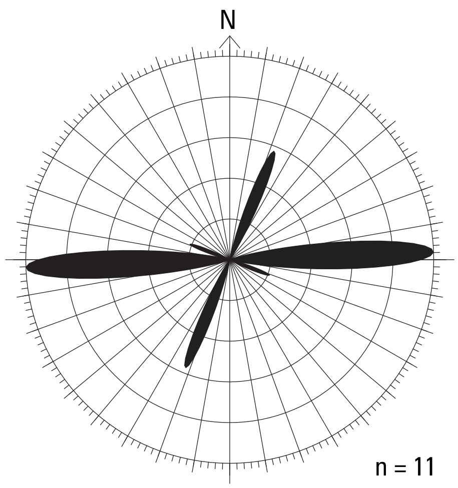


Figure 7. Rose diagram showing the strike of 11 steeply dipping Cretaceous dikes. Data are plotted using Structural Data Integrated System Analyser (DAISY 4.01) software by Salvini (2004). North is marked by "N," and the number of data points is indicated by "n."

The dikes are assigned a Cretaceous age on the basis of the 122.2±2 Ma age of the intrusive complex at Ascutney Mountain (Foland and others, 1985) and on a regional summary by McHone (1984) for similar dikes throughout New England and Québec.

Economic Geology

A number of quarries, both active and abandoned, exist in the Montpelier and Barre West quadrangles. Most granite quarries in the area are inactive. A number of granite quarries in the Adamant area were active in the late 1800s to 1900s (Dale, 1909, 1923; Cady, 1956). In Adamant, the Lake Shore granite quarry opened in 1902 (Dale, 1909) and was abandoned prior to 1915 (Dale, 1923). The Patch granite quarry was opened around 1893 (Dale, 1909) and was active at least until the 1950s when Konig (1961) mapped the 15-minute Plainfield quadrangle. Abandoned granite quarries in Berlin south of Crosstown Road were operated in the 1870s (Collier, 1872). The Berlin quarries, which have no formal name in the literature, were owned by C.M. Ayers and opened sometime after 1858 according to records of the Berlin Historical Society (Richard Turner, written commun., 2006). Unpublished documents on file at the Vermont Geological Survey indicate that the quarry also went by the name of "S. Fruchter quarry." The Berlin granite quarries were abandoned by the time of Richardson's mapping in 1914 to 1915 and probably sometime before then as Dale (1909) did not include them in his study. Abandoned slate quarries are found throughout the Waits River Formation in the two quadrangles. In downtown Montpelier, the Langdon quarry and Sabin quarry were abandoned prior to Richardson's (1916) study. Richardson (1916) mentions two abandoned quarries in the Montpelier quadrangle, which were not visited in our study: the Cutler quarry and an unnamed quarry on the road from Montpelier to Adamant. Other small, unnamed, abandoned quarries or prospects occur in quartzite of the Cram Hill Formation and in quartz veins.

Currently, there are three active slate and crushed stone quarries in the Waits River Formation. Black Rock Coal, Inc., received a permit in 2002 for a new quarry in Calais southwest of Bliss Pond for slate and granite extraction. Brousseau, Inc., operates a quarry in Berlin just southeast of Interchange 6 on I–89, and Lague, Inc., operates a quarry in Berlin along State Route 62, just uphill of the junction with U.S. Route 302. The locations of all identified quarries and prospects are shown on the map and are included in the GIS database section of this report.

Structural Geology

Ductile Structures

Five generations of ductile deformation and associated structures are recognized in the area. The five generations are designated D_1 through D_5, and their associated fabrics are summarized in table 1. The oldest two periods of deformation (D_1 and D_2) are interpreted to be the result of the Ordovician Taconian orogeny and the youngest three periods of deformation (D_3–D_5) the result of the Devonian Acadian orogeny because D_1 and D_2 occur only in the pre-Silurian rocks, and D_3 is the oldest fabric in the CVGS.

The distribution of deformational fabrics is not uniform across the map area (fig. 8*C*). For discussion, the area is divided into three structural zones: Zone I is the Dumpling Hill belt of the Moretown Formation, Zone II is the Wrightsville belt of the Moretown and Cram Hill Formations, and Zone III is the CVGS (figs. 2, 8, and 9). The zones divide the map area into three structural domains, which reflect the dominance of Taconian structures (Zone I), an overlap domain (Zone II), and Acadian structures (Zone III), respectively.

Schematic diagrams in figure 8 show the evolution and distribution of the five deformational fabrics across the map area. The area is complexly deformed, and, because the three oldest deformational events (D_1–D_3) produced variably penetrative coplanar fabrics and associated tight to isoclinal folding, it is often difficult to determine the absolute ages

Table 1. Regional correlation of Taconian and Acadian deformational fabrics, central Vermont.

[NA, not applicable]

This study								
	Deformation	**Foliation**	**Relative timing of Paleozoic intrusive rocks**	**Kim and Gale (2004)**	**Walsh and Falta (2001)**	**Ratcliffe (2000a,b)**	**Walsh (1998)**	**Offield and others (1993); Woodland (1977)**
D_5	Weak dome-stage cleavage	S_5 (Acadian S_3)		NA	S_5	F_4 and F_5	S_3	F_3
D_4	Northeast-striking/northwest-dipping and lesser northwest-striking/northeast-dipping cleavage and folds	S_4 (Acadian S_2)	Granite dikes	S_3	S_4	Acadian F_2	S_2	F_2
D_3	Dominant schistosity with tight-isoclinal folding in Devonian and Silurian rocks Cleavage to fault-related fabric along Dog River fault zone	S_3 (Acadian S_1)	Metadiabase and greenstone dikes	S_2	S_3	F_3 or Acadian F_1	S_1	F_1
D_2	Dominant schistosity and "pinstripe" in Moretown Formation, to relict foliation where overprinted by Acadian S_1	Taconian S_2		S_1	S_2	F_2	NA	NA
D_1	Relict layer-parallel foliation in Moretown and Cram Hill Formations	Composite Taconian S_1/S_0			S_1	F_1 Taconian(?)	NA	NA

of fabrics in the field. In such instances, our map shows the dominant planar fabric with an undetermined relative age of "Sn" in the pre-Silurian rocks because the dominant foliation is not the same absolute age across the map area. The orientation of planar features is reported in right-hand rule here and in the accompanying GIS database.

First-Generation Foliation—S_1

The oldest foliation in the area is a relict layer-parallel tectonic schistosity (S_1) observed primarily in Zones I and II. It is best preserved in Zone I, especially on the western side of Dumpling Hill. The relict fabric is characterized by a lepidoblastic texture of aligned micas that is subparallel to compositional layering in these rocks. The compositional layering appears to be bedding. Definitive folds associated with this oldest relict fabric were not seen at the outcrop but appear to be responsible in part for the map pattern seen in the Dumpling Hill belt (fig. 9). There, the green and dark-gray carbonaceous phyllite unit (O€msr) is interpreted to define a refolded fold pattern whose axial surface (F_1) generally trends northwest-southeast and is deformed by upright second-generation folds (F_2) (fig. 9). Definitive F_1 fold axes and mineral lineations were not positively identified in the field, so this earliest phase of deformation is largely based on interpretation of the map pattern. This relict period of deformation (D_1) is attributed to the Taconian orogeny.

Bed-parallel foliation defined by aligned quartz and mica is present in the Silurian and Devonian rocks, especially as thin laminations in the impure siliceous limestone or marble (fig. 10*D*). This fabric is not tectonic but rather diagenetic (Passchier and Trouw, 2005), as there are no axial planar folds associated with these laminations and they are deformed by the first period of folding recognized in these rocks (D_3). These laminations are, therefore, considered primary (S_0) with enhancement due to subsequent growth of metamorphic minerals.

Second-Generation Foliation—S_2

The second-generation foliation (S_2) is generally the dominant planar fabric in the pre-Silurian rocks of Zones I and II. In Zone I, bedding (S_0) and S_1 are folded by steeply west-dipping, steeply plunging asymmetric isoclinal folds (F_2) with associated axial planar schistosity (S_2). Second-generation (F_2) fold axes are parallel to downdip mineral "aggregate lineations" (Piazolo and Passchier, 2002; Passchier and Trouw, 2005), such as quartz rods (L_2). These downdip F_2 and L_2 lineations show a mean trend of 350°, 72° in Zone I and 359°, 65° in Zone II (fig. 11*A,B*). The phyllitic units contain a well-developed closely spaced schistosity, and the granofelsic rocks locally contain compositionally segregated bands of alternating micaceous and quartzofeldspathic material that give the rocks a "pinstripe" appearance. This "pinstripe" texture is typical of the Moretown Formation, and, because it is observed to postdate bedding, it is a tectonic fabric produced by metamorphic differentiation and is not bedding. Bedding is typically transposed by the S_2 foliation, especially along the limbs of F_2 folds, but is locally preserved in F_2 hinges and in massive quartzites. Zone II is bound by the Shady Rill fault (west) and the RMC (east) or Dog River fault zone (fig. 9). The dominant foliation in Zone II is the S_2, or, locally the S_3 foliation, and relict S_1 is locally preserved in F_2 or F_3 fold hinges. Locally, in Zone II, S_2 is overprinted by S_3 especially towards the Dog River fault zone, where the dominant fabric is controlled by S_3 (fig. 8).

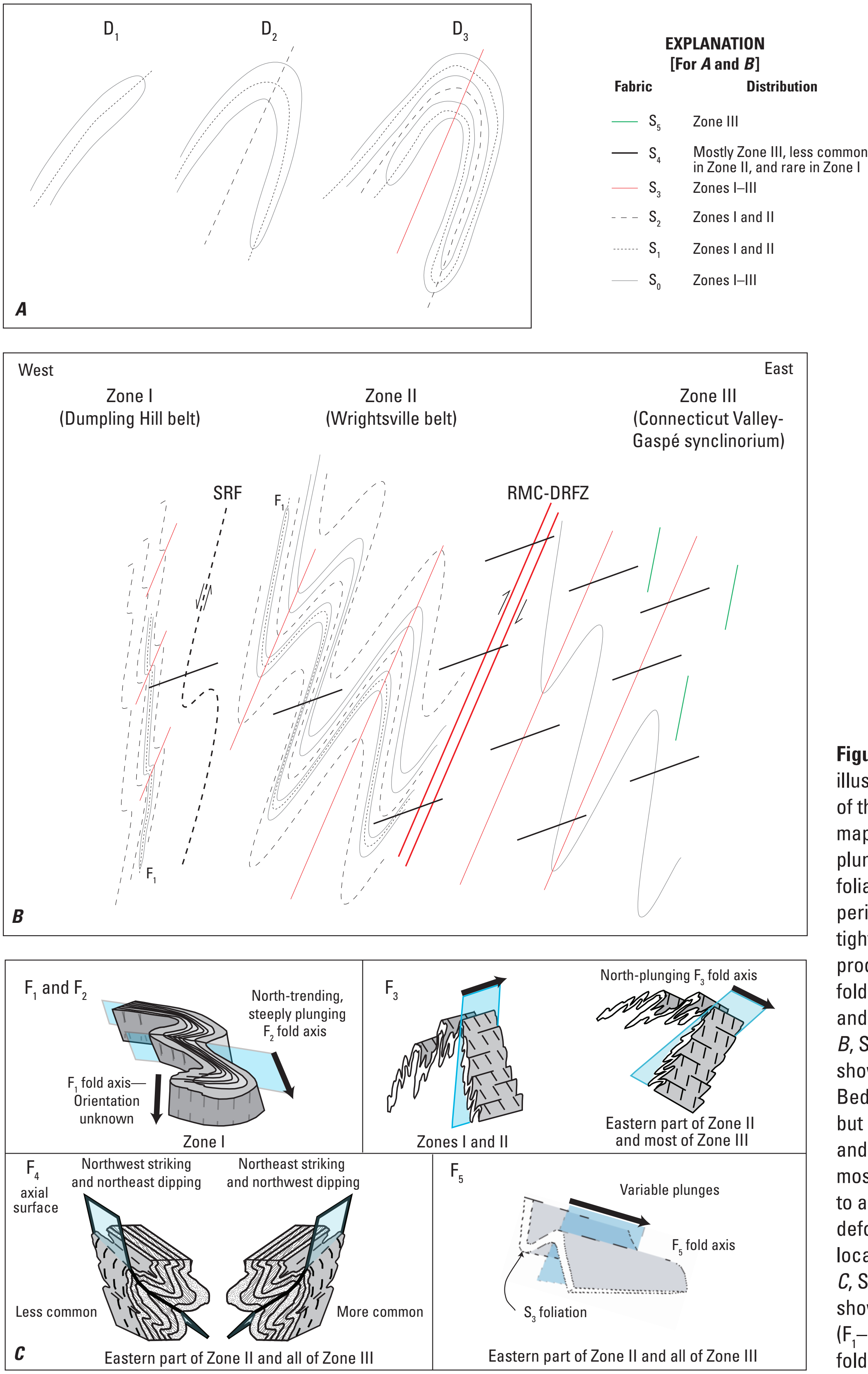
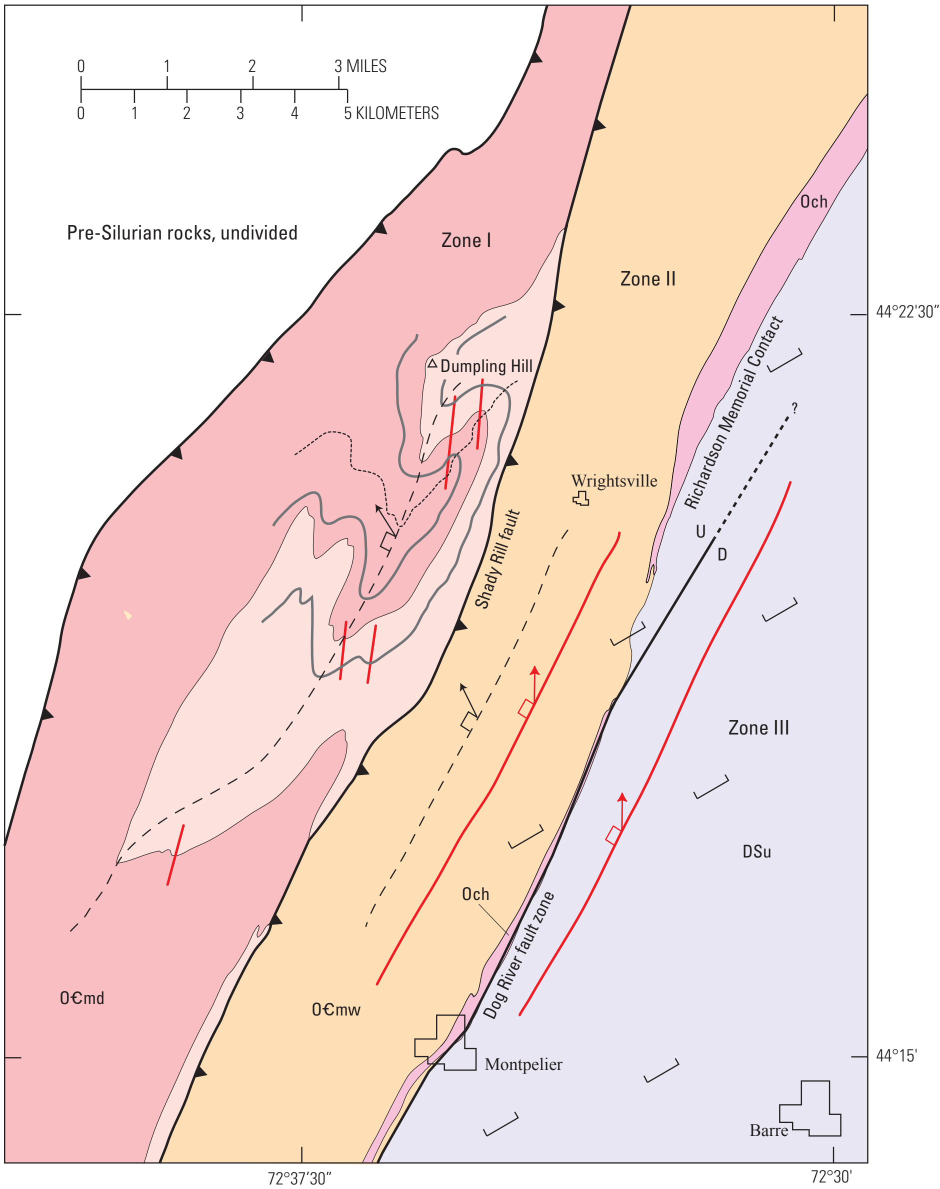


Figure 8. Schematic diagrams illustrating the distribution and style of the five ductile fabrics in the map area. *A*, Schematic down-plunge view of penetrative D_1 to D_3 foliations and folds. These three periods of deformation produced tight to isoclinal folds. D_4 and D_5 produced nonpenetrative open folds and (or) crenulation cleavages and are not shown in this diagram. *B*, Schematic cross section showing the distribution of fabrics. Bedding (S_0) is present in all zones but it is not the same age. In Zones I and II, bedding is difficult to see in most outcrops because it is parallel to and transposed by subsequent deformation. "F_1" shows the location of relict fold hinges. *C*, Schematic block diagrams showing the general style of folding (F_1–F_5) and the distribution of the folds across the map area.



EXPLANATION

DSu — Shaw Mountain, Northfield, and Waits River Formations, undivided (Devonian and Silurian)

—Richardson Memorial Contact (RMC)—

Och — Cram Hill Formation of the Wrightsville belt (Ordovician)

O€mw — Moretown Formation of the Wrightsville belt (Ordovician and Cambrian)

O€md — Moretown Formation of the Dumpling Hill belt (Ordovician and Cambrian)

U / D — Reverse fault of Acadian age, parallel to S_3 (Acadian S_1)—U, upthrown side; D, downthrown side

Thrust fault of Taconian age, parallel to S_2—Sawteeth on upper plate

Strike and dip of S_4 cleavage—Acadian S_2 in Silurian and Devonian rocks

Trace of S_3 showing dip of axial surface and trend of fold axis—Acadian S_1 in Silurian and Devonian rocks

Trace of S_2 showing dip of axial surface and trend of fold axis

S_1 in pre-Silurian rocks

S_0 in pre-Silurian rocks

Figure 9. Simplified geologic map showing the major structural zones in the area and the distribution and orientation of significant ductile deformational fabrics. In addition to the structural differences between the three zones, the Moretown Formation in the Dumpling Hill belt (Zone I) lacks interlayered greenstone and the Ordovician(?) and Silurian(?) metadiabase and greenstone dikes found in the Wrightsville belt (Zone II).

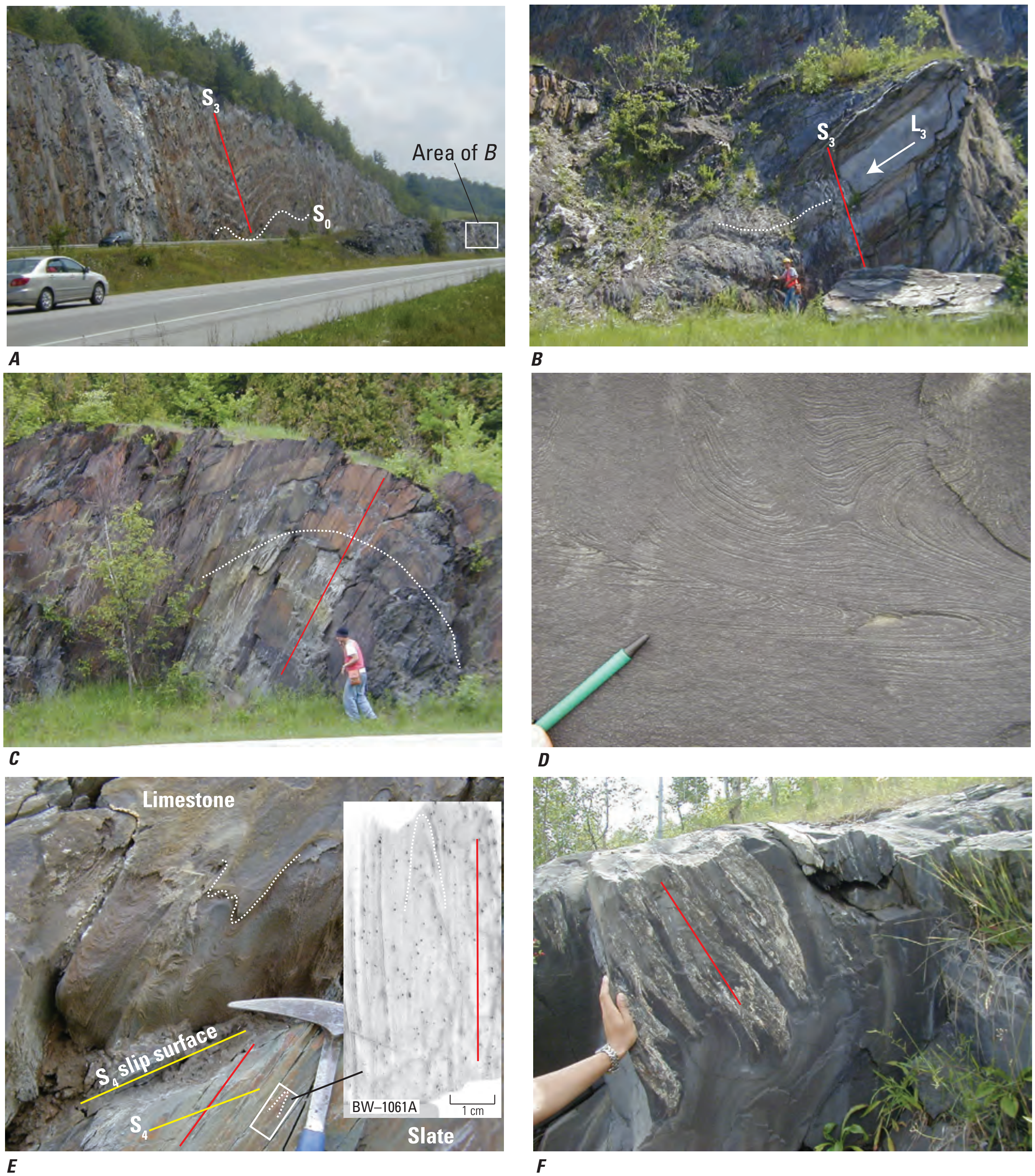


Figure 10. Photographs of F_3 (Acadian F_1) folds in the Waits River Formation. In all photographs, the white dotted line is bedding (S_0) and the red solid line is S_3. *A*, Oblique view looking east at large, tight F_3 folds along I–89, 1 km southeast of Interchange 8. Bedding is defined by concentrations of rusty-weathering sulfide (pyrite) horizons and alternating layers of slate and limestone. White rectangle shows area of photograph *B*. *B*, Down-plunge view looking northeast showing F_3 folds of bedding, steep S_3 cleavage, and north-plunging L_3 cleavage-bedding intersection lineation. *C*, Cross-sectional view showing tight F_3 folds of weakly visible bedding in slate and phyllite along State Route 63, 1 km east of I–89, Interchange 6. View is to the north, west is to the left. *D*, Isoclinally folded bedding laminations typical of folds in impure siliceous limestone or marble. *E*, Folded bedding laminations in limestone (top) are generally invisible in the slate at the outcrop but can be seen in thin section (inset; white rectangle shows location of sample). Here, the contact between limestone and slate also exhibits slip. Cross-sectional view from roadcut on State Route 63, 0.5 km east of I–89, Interchange 6. View is to the north, west is to the left. *F*, Isoclinal F_3 folds in thinly interbedded calcareous metapelite and limestone (gray and white, top) and massive siliceous limestone or marble (dark gray and brown, bottom). View is to the south, west is to the right. Cross-sectional view from roadcut on State Route 62, 1 km northwest of junction with U.S. Route 302.

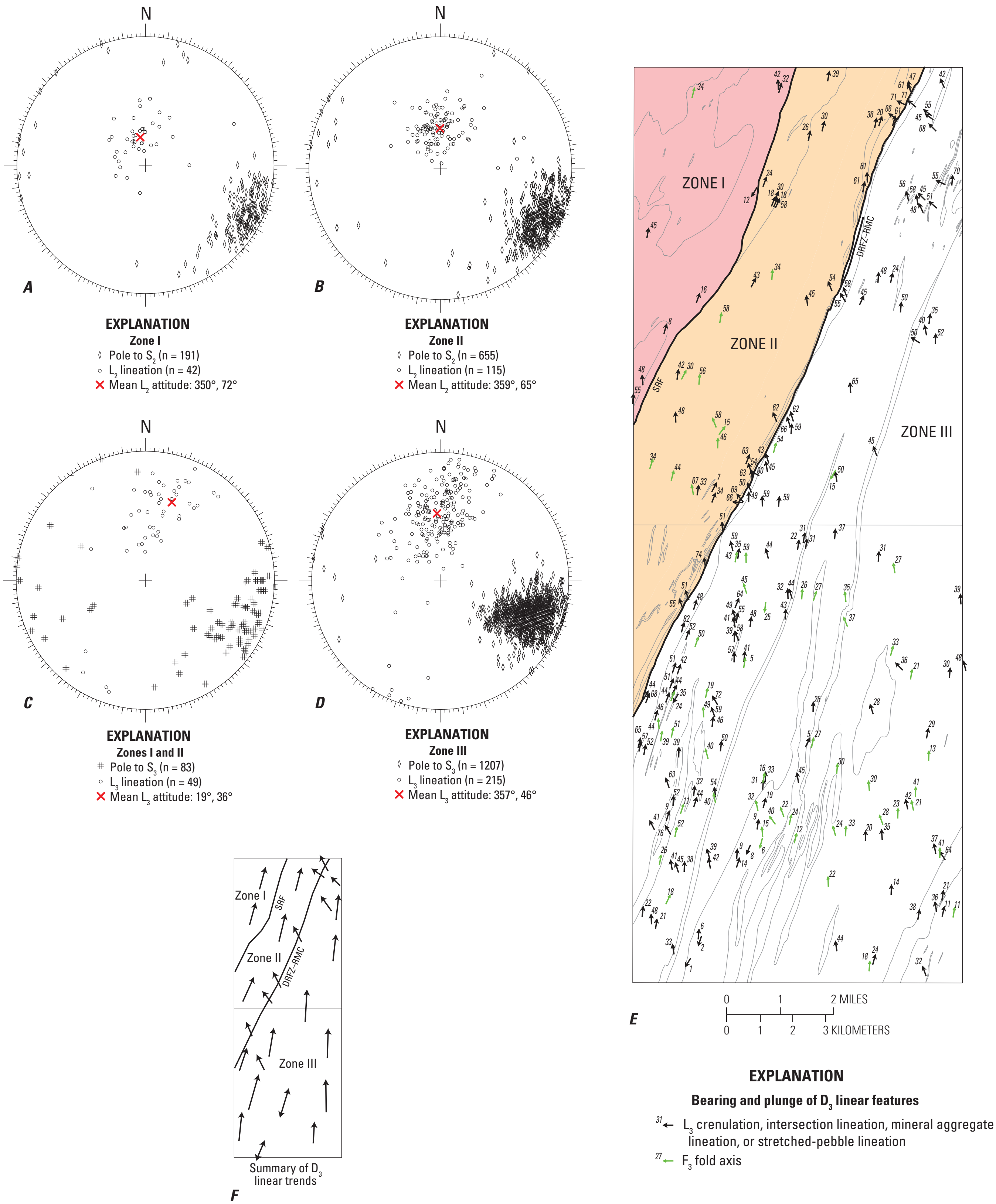


Figure 11. Lower hemisphere equal area projections (stereonets) of poles to penetrative foliation and their associated lineations (*A–D*) and maps showing D_3 linear features (*E,F*). *A* and *B*, Poles to foliation (S_2) and lineations (L_2) in Zone 1 (*A*) and Zone II (*B*). *C* and *D*, Poles to foliation (S_3) and lineations (L_3) in Zones I and II (*C*) and Zone III (*D*). Note the similarity in foliation orientation between S_2 and S_3. Also note, however, that L_2 lineations plunge more steeply to the north than do L_3 lineations. Thus the D_3 deformation is generally coplanar but not coaxial. Data are plotted using Structural Data Integrated System Analyser (DAISY 4.01) software by Salvini (2004). North is marked by "N," and the number of data points is indicated by "n." DRFZ, Dog River fault zone; RMC, Richardson Memorial Contact; SRF, Shady Rill fault.

Third-Generation Foliation—S_3 (Acadian S_1)

The third-generation foliation (S_3) is variably penetrative across the area and varies from a spaced cleavage in Zone I to a penetrative schistosity or cleavage in Zones II and III. The S_3 foliation is most penetrative in the vicinity of the Dog River fault zone (see discussion below). The S_3 foliation is the oldest and dominant deformational fabric in the CVGS and strikes northeast and dips steeply northwest (fig. 11*C,D*).

The S_3 foliation also is referred to as “Acadian S_1” because it is the first deformation in the CVGS. The S_3 foliation is associated with tight to isoclinal folds (F_3) of older S_1 and S_2 foliations in Zones I and II and large map-scale tight to isoclinal folds (F_3, or Acadian F_1) of bedding (S_0) in the CVGS. Lineations associated with S_3 include crenulations and intersection lineations in Zones I and II. These western L_3 lineations are parallel to F_3 fold axes. The most common L_3 lineation in Zone III is a cleavage-bedding intersection. Mineral aggregate lineations and stretched-pebble lineations occur near the Dog River fault zone, and here they show a north-northwest trend that is oblique to the overall north-northeast trend of intersection, crenulation, and fold axis lineations in other parts of the map area (fig. 11*E,F*). F_3 fold axes in the Dog River fault zone are subparallel to the aggregate lineations and stretched-pebble lineations.

Large map-scale F_3 folds in the pre-Silurian rocks are not apparent due to the difficulty in mapping marker horizons in these rocks. Third-generation (F_3) fold axes vary from gently to moderately north plunging in Zones I and II (fig. 11*E,F*). In Zone III, the fold axes also plunge moderately to gently to the north, but gentle plunges to the south occur especially in the central and southern part of the Barre West quadrangle (fig. 11*E,F*; see map). Because outcrop-scale F_3 fold hinges and L_3 cleavage-bedding intersection lineations in the central part of the Barre West quadrangle plunge gently both to the north and south, our map and cross sections *A–A′* and *B–B′* show doubly plunging F_3 anticlines and synclines. In the northern two-thirds of the map (in Zone III), F_3 folds and L_3 lineations consistently plunge to the north.

Large outcrop-scale F_3 (Acadian F_1) folds were observed at almost all large roadcuts in the CVGS (fig. 10). Small-scale F_3 folds are preferentially preserved in the limestones of the CVGS where bed-parallel laminations, defined by aligned muscovite, quartz, and calcite, show isoclinal folds (fig. 10*D–F*). Such folds are difficult to see at outcrop scale in the pelitic rocks of the CVGS but were seen locally in thin section (fig. 10*E*). Bain (1931) and Ern (1963) called these “flow” or “flowage” folds. Unlike bedding in the pre-Silurian rocks of Zones I and II, bedding in the CVGS (Zone III) is well preserved and readily visible at most large exposures, especially in the Waits River Formation. In the CVGS, the S_3 foliation is parallel to bedding in some outcrops, but in many outcrops it dips more gently to the west than the bedding. Despite the tight to isoclinal nature of the F_3 folds, the relation where bedding is steeper than cleavage and both dip steeply to the west is consistent with the generally overturned nature of the bedding on the western limb of the Townshend-Brownington syncline (fig. 2).

Moretown Formation “Pinstripe”

Hatch and Hartshorn (1968) first described a dominant lithology in the Moretown Formation in northwestern Massachusetts as “pinstripe” granulite. Hatch and Stanley (1988) characterized this “pinstriping” as 1- to 3-mm-thick quartz-plagioclase layers separated by thin partings of mica. Earlier, Cady (1945) recognized and described this fabric in central Vermont, and this “pinstripe” fabric is characteristic of a major map unit in the Moretown Formation. The “pinstriping” we observed, both mesoscopically and microscopically during this study, is a tectonic fabric characterized by alternating quartz-feldspar (QF) and mica (M) domains (fig. 12*D*). We observed three generations of “pinstripe” tectonic fabric in the Moretown Formation; the first two are presumed to be Taconian, whereas the third is Acadian. The first generation is the oldest metamorphic tectonic fabric in the field area (S_1) and consists of alternating quartz-feldspar and chlorite-muscovite layers that are associated with a mapped folding event that, enigmatically, was not seen at outcrop scale. The S_1 fabric is folded by steeply plunging isoclinal F_2 folds that have an axial planar “pinstripe” fabric (S_2) (fig. 12*A,B*). Locally, especially near the Dog River fault zone, F_3 folds are severely tightened to the point that a third generation of “pinstriping” develops axial planar to the F_3 folds where the foliation shears out the limbs.

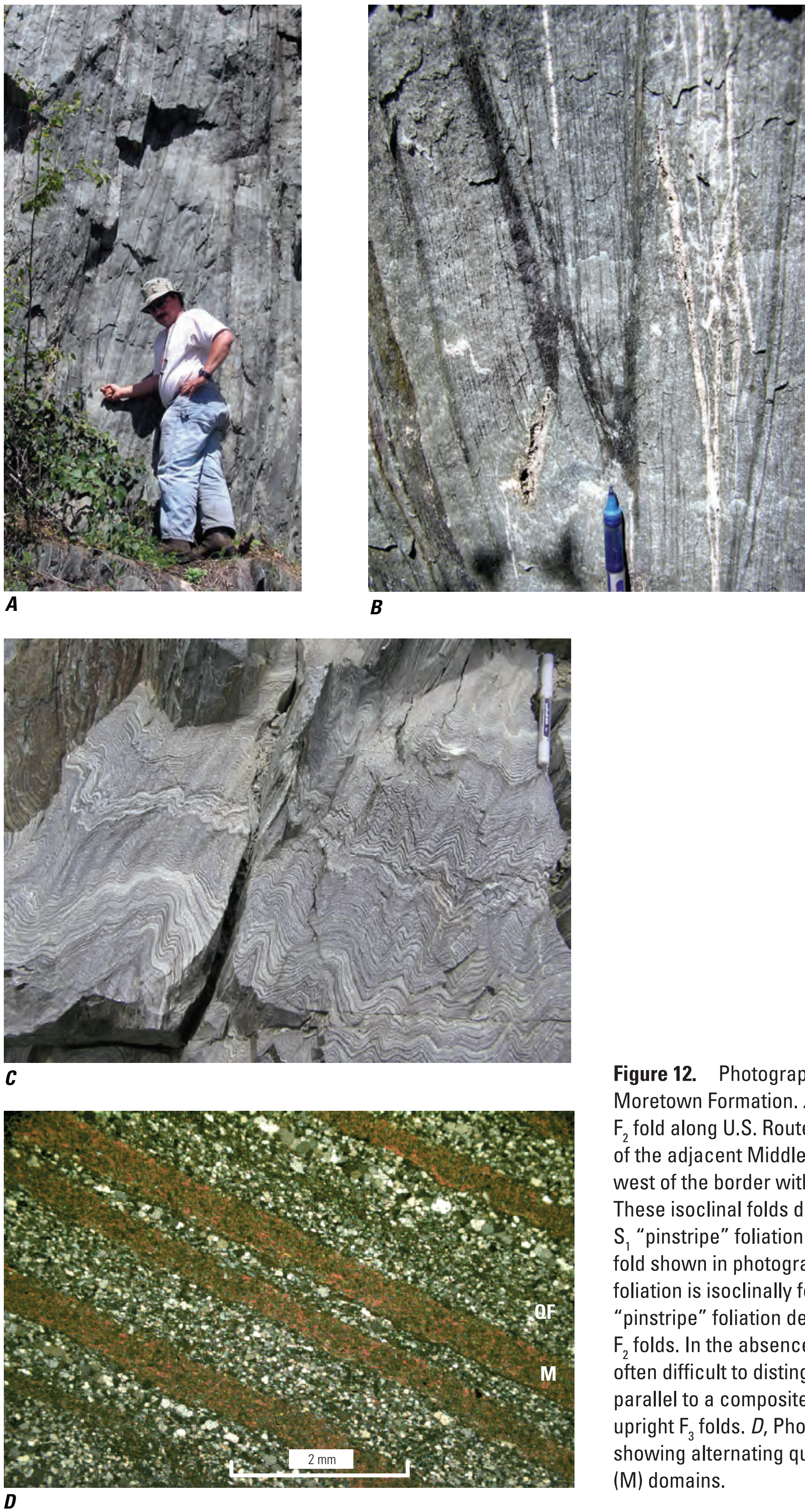


Figure 12. Photographs of “pinstripe” fabric in the Moretown Formation. *A*, Large-amplitude isoclinal F_2 fold along U.S. Route 2 in the easternmost part of the adjacent Middlesex quadrangle, 0.52 km west of the border with the Montpelier quadrangle. These isoclinal folds deform a previously developed S_1 “pinstripe” foliation. *B*, Close-up of nose of F_2 fold shown in photograph *A*. Earlier S_1 “pinstripe” foliation is isoclinally folded and a second “pinstripe” foliation developed axial planar to the F_2 folds. In the absence of such fold closures, it is often difficult to distinguish S_1 from S_2. *C*, “Pinstripe” parallel to a composite S_1–S_2 foliation deformed by upright F_3 folds. *D*, Photomicrograph of “pinstripe” showing alternating quartz-feldspar (QF) and mica (M) domains. Figure 12

Fourth-Generation Foliation—S_4 (Acadian S_2)

The fourth-generation foliation (S_4) is a spaced cleavage with associated crenulation lineations (L_4) and open folds (F_4). S_4 is widespread in Zone III but decreases towards the west, where it is sporadically identified in Zone II and rarely identified in Zone I. The S_4 foliation is the second-generation fabric in the CVGS; thus it is also referred to as "Acadian S_2." The S_4 foliation is associated with outcrop-scale open folds (F_4) of older foliations that mostly strike northeast and dip moderately northwest but also strike northwest and dip northeast consistent with a kink, or box-fold, geometry seen at some outcrops (fig. 13). Fourth-generation fold axes (F_4) and crenulation lineations (L_4) are gently to moderately north plunging (fig. 13*A*). In the southeastern part of the Barre West quadrangle, the S_4 fabric strikes northwest and dips moderately northeast, and there it deforms the S_3 foliation and map unit contacts into a map-scale kink fold. At most outcrops in Zone III, the L_4 crenulation fabric is readily visible in the finer grained metapelitic rocks of the CVGS, but it is poorly developed or absent in the massive impure limestones. Aligned biotite flakes are locally found parallel to the L_4 lineation, especially in the Gile Mountain Formation (fig. 13*D*), as are pressure shadows around garnet (see section on Metamorphism). Regionally, S_4 is the foliation that forms the "cleavage arch" of White and Jahns (1950).

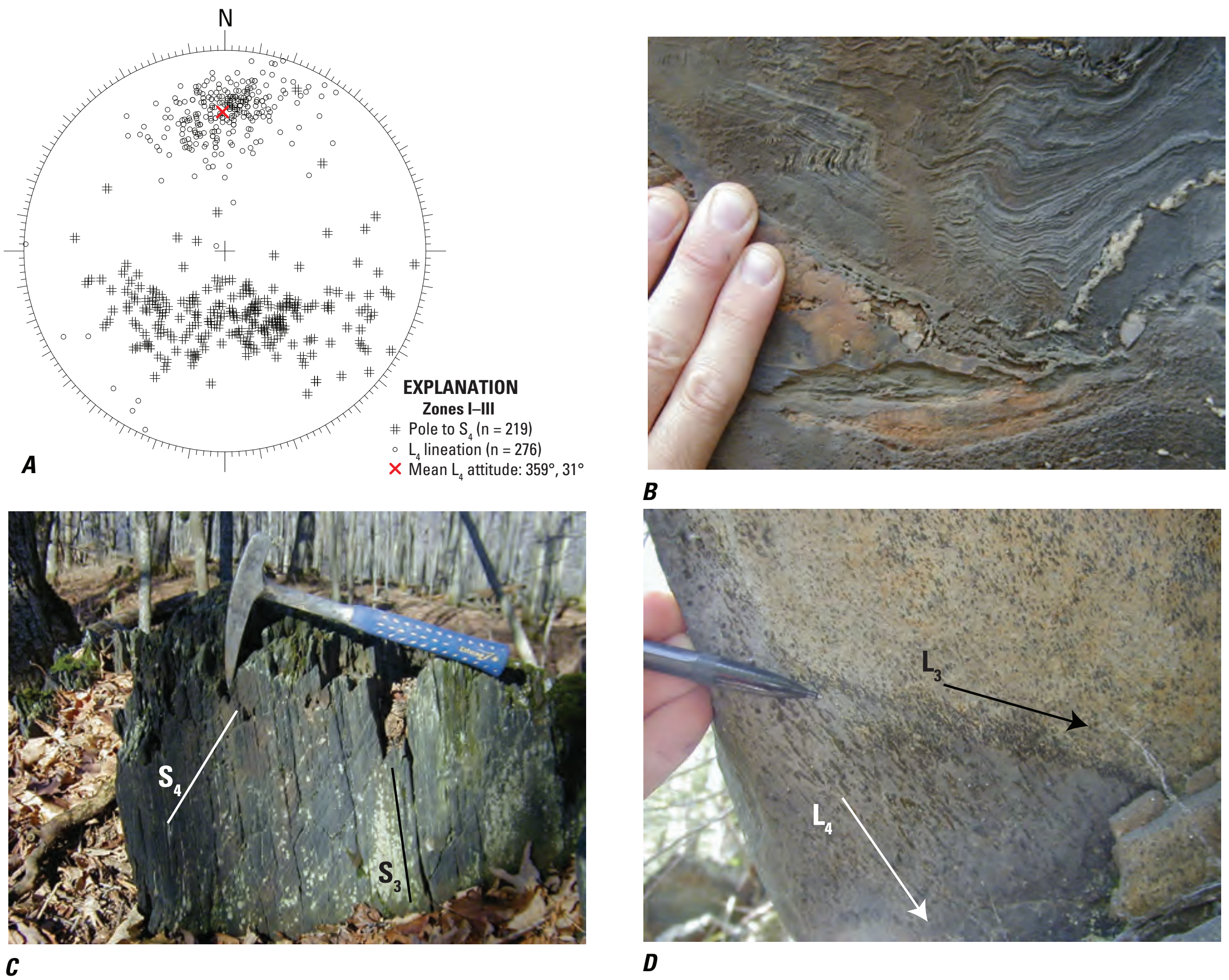


Figure 13. Stereonet and photographs of S_4 and L_4 fabric. *A*, Stereonet of poles to S_4 and L_4 lineations, mostly from Zone III. Note the concentration of poles to S_4 shows preferred northwestern and northeastern strikes with northeastern and northwestern dips, respectively. Data are plotted using Structural Data Integrated System Analyser (DAISY 4.01) software by Salvini (2004). North is marked by "N," and the number of data points is indicated by "n." *B*, Photograph showing cross-sectional view of conjugate box-type F_4 folds in impure limestone of the Waits River Formation; view is to the north, west is to the left. *C*, Photograph showing cross-sectional view of typical northeast-striking and northwest-dipping S_4 cleavage and steeply dipping S_3 cleavage in the Waits River Formation; view is to the north, west is to the left. *D*, Photograph of cross-sectional view onto the plane of S_3 showing L_3 and L_4 lineations; view is to the west, south is to the left. The L_3 lineation shows the intersection of bedding and S_3 foliation in the Gile Mountain Formation. The light-colored horizon on top is psammitic, and the gray horizon is pelitic. The L_4 lineation is defined by crenulations and aligned biotite flakes.

Fifth-Generation Foliation—S_5

The fifth-generation foliation (S_5) is weakly developed cleavage or kink bands with associated crenulation lineations (L_5) and rarely developed outcrop-scale folds. S_5 occurs sporadically in Zone III and rarely occurs in the western zones. The S_5 foliation is the third-generation fabric in the CVGS; thus it is also referred to as "Acadian S_3." The S_5 cleavage is recognized in areas where a clear L_4 crenulation lineation was overprinted by the S_5 cleavage or an L_5 crenulation lineation (fig. 14) or in places where F_4 axial surfaces are broadly warped into upright folds. In many places, only the L_5 crenulation lineation was visible at the outcrop, and it was difficult to clearly identify the orientation of the plane of S_5. The S_5/L_5 fabric is only readily visible in the finer grained metapelitic rocks of the CVGS, and it is not developed in the massive impure limestones. Limited structural data show variable orientations for S_5 and gently plunging northeast-southwest L_5 lineations (fig. 14). Regionally, S_5 is the dome-stage foliation (Woodland, 1977; Fisher and Karabinos, 1980; Offield and others, 1993; Walsh, 1998; Ratcliffe, 2000a,b).

Shady Rill Fault

Two significant ductile faults occur in the map area: the Shady Rill fault and the Dog River fault zone. The Shady Rill fault (SRF) is mapped as an overturned conjectural thrust fault that separates the Dumpling Hill belt from the Wrightsville belt. The presence of the SRF is inferred by four lines of evidence: (1) The northwest-trending early folds and fabric (D_1) and quartzite-rich unit (OꞒmdh) found in the Dumpling Hill belt could not be mapped to the east across the SRF; (2) mafic rocks found in the Wrightsville belt are absent in the Dumpling Hill belt; (3) the interlayered green and dark-gray phyllite unit of the Moretown Formation (OꞒmw) terminates to the south as if truncated; and (4) the mapped contact is parallel to a zone of penetrative foliation with consistent northwest-trending lineations. Although similar metasedimentary rocks occur on both sides of the SRF, they differ in the absence of mafic rocks and the greater abundance of quartzites to the west. The absence of mafic rocks in the Dumpling Hill belt does not alone provide evidence for the fault, but may suggest that the two zones of the Moretown Formation (OꞒmdh and OꞒm) were not originally continuous during both deposition of the volcanic and volcaniclastic rocks and intrusion of the dikes. More significantly, the mapped trace of the SRF is parallel to the dominant foliation in the rocks and appears to be related to the S_2 (Taconian) foliation. The metadiabase and greenstone dikes found in the Wrightsville belt postdate the S_2 foliation and predate the S_3 foliation, and, if the absence of the dikes to the west is related to transport, then the SRF might have experienced some movement during D_3 time. The dominant fabric is penetrative near the SRF; however, it is not as readily apparent as the D_3 deformation in the Dog River fault zone. We hypothesize that the SRF was initially a Taconian, D_2 or earlier, east-dipping thrust fault that juxtaposed the Wrightsville belt over the Dumpling Hill belt. We cannot rule out the possibility that juxtaposition, or possible reactivation of the SRF, occurred during Acadian D_3 deformation. The contact was subsequently rotated through the vertical to its current westward dip during later Acadian deformation.

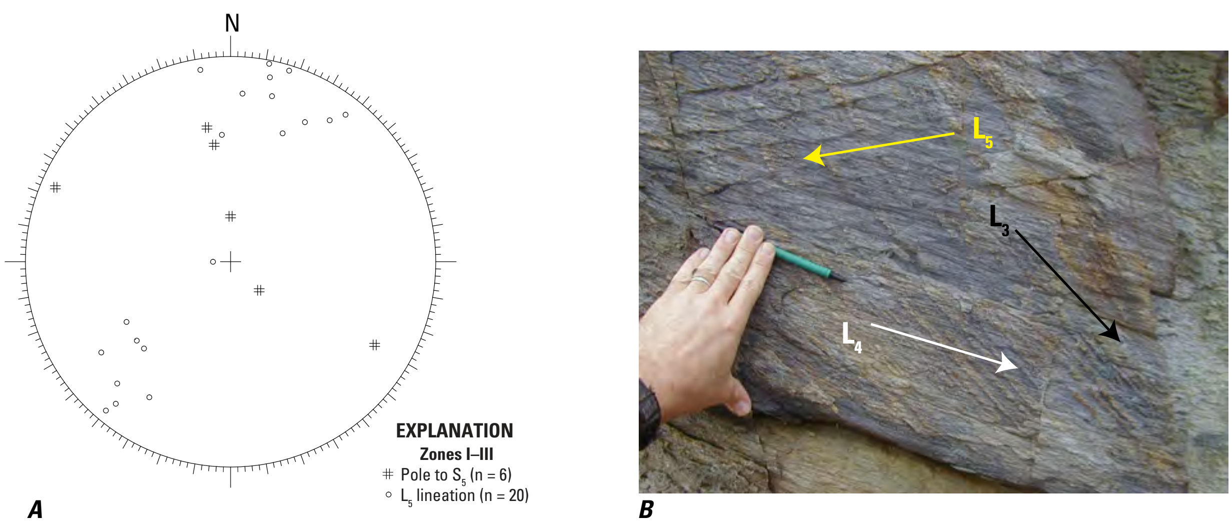


Figure 14. Stereonet and photograph of S_5 and L_5 fabric. *A*, Stereonet of poles to S_5 and L_5 lineations. Data are plotted using Structural Data Integrated System Analyser (DAISY 4.01) software by Salvini (2004). North is marked by "N," and the number of data points is indicated by "n." *B*, Photograph of cross-sectional view onto the plane of S_3 showing three lineations (L_3, L_4, and L_5) in the Waits River Formation; view is to the west, south is to the left. The L_3 lineation shows the intersection of bedding and S_3 foliation, and L_4 and L_5 are crenulations.

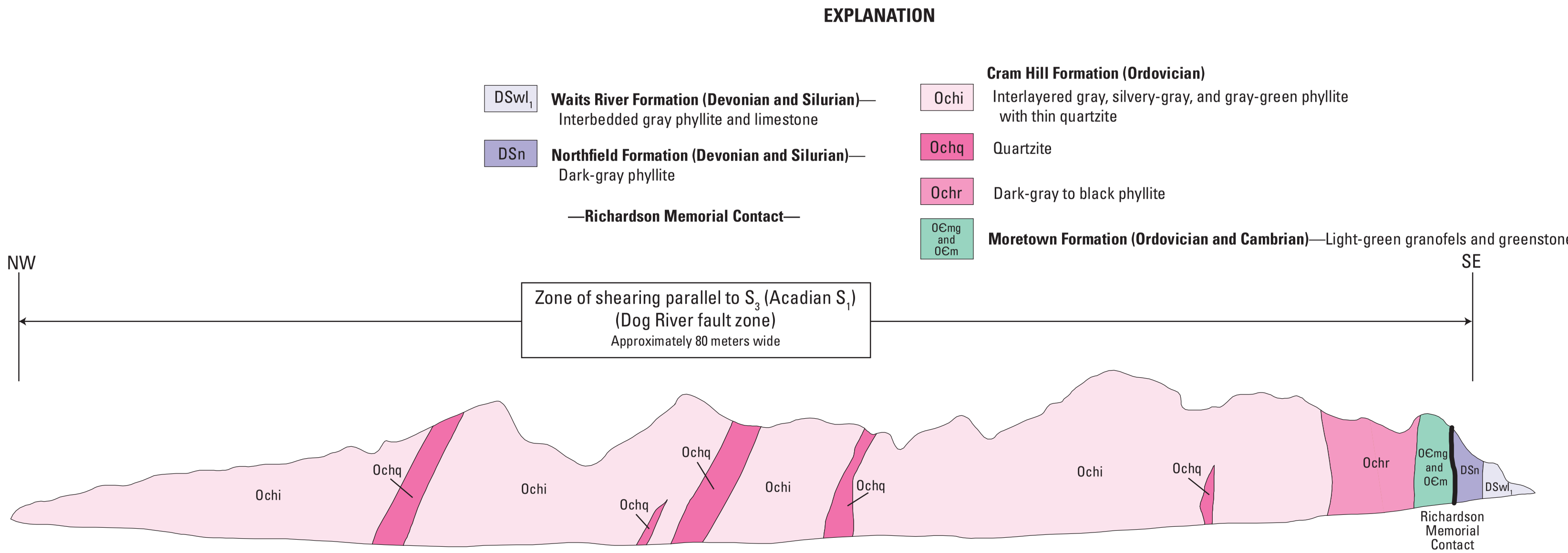
Richardson Memorial Contact-Dog River Fault Zone

In central Vermont, the Richardson Memorial Contact (RMC) is a boundary of controversial origin (tectonic versus stratigraphic) that separates pre-Silurian rocks to the west (Cram Hill and Moretown Formations) from Silurian and Devonian rocks to the east (Shaw Mountain, Northfield, and Waits River Formations). Richardson (1919) thought that the quartz-pebble conglomerates of the Shaw Mountain Formation sat unconformably on the Moretown and Cram Hill Formations, and later work supported this interpretation (Currier and Jahns, 1941; White and Jahns, 1950; Doll and others, 1961). On the basis of mapping along the RMC in the Northfield-Montpelier area, Westerman (1987) suggested that the RMC corresponds to the "Dog River fault zone" along which pre-Silurian and Silurian rocks were juxtaposed. In central and southern Vermont, the RMC has been mapped as an unconformity, with only localized offset along syntectonic Acadian faults (Currier and Jahns, 1941; White and Jahns, 1950; Armstrong, 1994; Martin, 1994; Walsh and others, 1994; Walsh and Ratcliffe, 1994a,b; Walsh and others, 1996a,b; Ratcliffe, 1996, 2000a,b; Ratcliffe and Armstrong, 1999, 2001). In Massachusetts, Hatch and Stanley (1988) interpreted the RMC equivalent as a décollement called the "surface of Acadian structural disharmony" (SASD). This interpretation was based primarily on the disparity in size and amplitude of first-generation Acadian isoclinal folds found in Silurian rocks (large high-amplitude) versus those found in the underlying pre-Silurian rocks (small low-amplitude). In addition, the SASD was rarely deformed by any of these isoclinal folds. Cross sections by Hatch and Hartshorn (1968) and Hatch and Stanley (1988) portray the isoclinally folded Silurian and Devonian rocks as a crumpled rug above a décollement at the top of the pre-Silurian section. Kim (1996) noted a thin (~5 cm), highly fissile, papery schist zone in the garnet schist of the Devonian Goshen Formation and lithologic truncations along the SASD in northwestern Massachusetts.

On this map, the best exposure of the RMC and Dog River fault zone occurs at a roadcut at Interchange 8 on I–89 (fig. 15). The RMC is located near the southeastern end of the cut (fig. 15). The RMC separates light-green muscovite-quartz-calcite-chlorite-plagioclase granofels with minor greenstone, which we map as Moretown Formation, from dark-gray carbonaceous phyllite of the Northfield Formation. The contact between the two formations is sharp and parallel to the S_3 foliation (fig. 15*C*). The roadcut shows a strongly developed penetrative S_3 fabric as the dominant foliation in all the rocks. Across the outcrop, however, the S_3 fabric shows varying degrees of transposition of bedding and older fabrics. A zone of high strain and intense transposition associated with S_3 extends from about 10 m east of the RMC to approximately 80 m west of the RMC, and this is the Dog River fault zone as we map it (fig. 15). In the Northfield and Waits River Formations more than 10 m east of the RMC, bedding is deformed into isoclinal F_3 folds, but it is not transposed. As the RMC is approached from the east, bedding is progressively transposed in the Northfield Formation. From the western edge of the Northfield Formation to a point approximately 80 m west of the RMC, bedding and at least one, perhaps two, older schistosities in the Cram Hill and Moretown Formations are transposed, and quartzite layers are preserved only as tectonic slivers. Thus, the RMC at this roadcut is a faulted surface within an approximately 90-m-wide fault zone, and the original unconformable relation is not preserved here. In the vicinity of the Dog River fault zone, L_3 lineations consisting of quartz rods, stretched pebbles, and F_3 fold axes are subparallel, indicating high strain and showing moderate plunges to the northwest (fig. 11). Away from the Dog River fault zone, the L_3 lineations and F_3 fold axes show greater variability and locally much shallower plunges to the north-northwest and south (fig. 11).

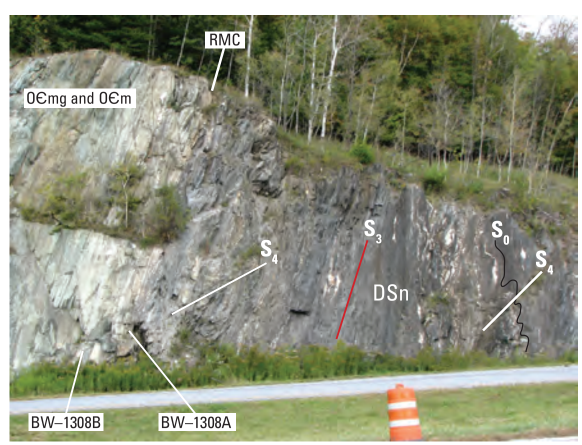
Kinematic analysis of three oriented thin sections from the Interchange 8 roadcut shows west-side-up reverse relative motion. Type II S-C mylonitic fabrics (Lister and Snoke, 1984) in all three samples show S-surfaces that correspond to the S_3 fabric and microscopic C-surfaces that were not recognized in the field. Two samples (BW–1308A and BW–1308B, fig. 15) collected from a muscovite-carbonate-plagioclase-chlorite-quartz granofels at the RMC and a muscovite-quartz-calcite-chlorite-plagioclase granofels 2 m west of the RMC, display Type II S-C fabrics, mica fish, and slightly asymmetric porphyroclasts with consistent west-side-up relative motion. The asymmetric fabrics are overprinted by late, post-tectonic carbonate and lesser muscovite porphyroblasts. The third sample, a micaceous quartzite from a tectonic sliver about 8 m west of the RMC, shows similar microstructures with the same relative displacement but also contains many symmetrical fabrics indicative of flattening. Combined with the consistent northwest-trending lineations, the overall sense of displacement in the Dog River fault zone is reverse, left-lateral transpression, in agreement with the findings of Westerman (1987). Because the RMC currently dips steeply to the west, these kinematics either support west-side-up reverse motion or initial east-side-down normal motion along an east-dipping normal fault followed by rotation of the fault plane through the vertical by subsequent D_4 or D_5 deformation.

Although the RMC is a pronounced tectonic boundary in most parts of the study area, it does not continuously follow the same lithologic contacts from north to south. We define the RMC in the study area sensu stricto as the base (western side) of the Shaw Mountain Formation where present or the contact between the Moretown or Cram Hill Formation and the Northfield Formation where the Shaw Mountain Formation is absent. Using this boundary as a reference, we found places where this surface does not exhibit strong tectonic overprinting like that found at Interchange 8. For example, at an outcrop of Shaw Mountain Formation cited by Cady (1956) on the eastern flank of Hersey Hill in the town of Calais, a metamorphosed coarse quartz-pebble conglomerate with isolated metamorphic rock fragments shows virtually no downdip stretching or flattening of pebbles that would indicate high-strain in a fault zone. We have seen the intensely sheared



A

B



C

Figure 15. *A* and *B*, Cross-sectional sketch (*A*) and composite panoramic photograph (*B*) of the roadcut across the Richardson Memorial Contact (RMC) and Dog River fault zone at Interchange 8 on I–89. *C*, Photograph showing the RMC in detail and the orientation of the S_3 and S_4 foliations. See text for discussion.

quartz-pebble conglomerates of the Shaw Mountain Formation that mark the Dog River fault zone south of Montpelier (Westerman, 1987), and the level of strain observed on Hersey Hill is not comparable. Although the exact position of the fault zone is not known at Hersey Hill, the lack of tectonic overprint in the conglomerate suggests that the fault zone was either deflected to the east into the Silurian and Devonian rocks or that it has ended. On our map we terminate the Dog River fault zone just north of Horn of the Moon Pond in East Montpelier because we were unable to clearly map the strong tectonic overprint any farther north. Admittedly identifying fault zone fabrics in the relatively monotonous CVGS rocks is difficult. We think it is reasonable to assume that the relatively undeformed metaconglomerates of the Shaw Mountain Formation were unconformably deposited on the underlying Cram Hill Formation. Thus, the RMC as an unconformity and the Dog River fault zone are not always coincident. Currier and Jahns (1941) mapped the RMC in Northfield and found that the unconformity was both folded and faulted. This observation was also reported by White and Jahns (1950) and later confirmed by N.M. Ratcliffe (written commun., 2008).

The RMC in central Vermont is either an unconformity or an Acadian fault zone, and, in some places, it is both. In order to understand the tectonic history of this contact, it is critical to examine the geologic context of correlative Silurian lithologies from southern Québec where the deformation and metamorphic overprint of the Acadian orogeny are much less severe. In southern Québec, the contact between the Silurian units and the underlying pre-Silurian lithologies of the Dunnage and Internal Humber tectonic zones is predominantly a Late Silurian unconformity marked by basal quartz-pebble conglomerate (Lavoie and Asselin, 2004). The majority of these Late Silurian units grades upward from basal quartz-pebble conglomerate to sandstone and siltstone to fossiliferous limestone (Lavoie and Asselin, 2004) making them nearly identical to the members of the Shaw Mountain Formation (for example, Currier and Jahns, 1941; Cady, 1956; Konig and Dennis, 1964). One of the most striking aspects of the configuration of the authochthonous Late Silurian units in southern Québec is that the St. Luc, Cranbourne, and Lac Aylmer Formations and Glenbrooke Group occur as outliers unconformably overlying pre-Silurian rocks west of the Devonian La Guadeloupe fault. This fault separates pre-Silurian rocks to the west from Silurian and Devonian metasedimentary rocks of the CVGS to the east (Cousineau and Tremblay, 1993; Tremblay and others, 2000; Lavoie and Asselin, 2004) and is a possible along-strike correlative to the Dog River fault zone because it occurs at the same stratigraphic boundary, the RMC. Whereas the basal contacts of the St. Luc and Cranbourne Formations and the Glenbrooke Group with the underlying pre-Silurian rocks are unconformable, the Lac Aylmer Formation contacts have a dual nature. The northwestern side of the Lac Aylmer Formation unconformably overlies Dunnage Zone lithologies; however, the southeastern side is coincident with the La Guadeloupe fault (for example, Cousineau and Tremblay, 1993; Tremblay and others, 2000). The Dog River fault zone and the La Guadeloupe fault both show a northwest-southeast transport direction, but, unlike the Dog River fault zone, the La Guadeloupe fault dips to the southeast and shows high-angle east-over-west, northwest-directed relative motion (Tremblay and others, 1989; Tremblay and St.-Julien, 1990; Labbé and St.-Julien, 1989). Although the Acadian motion along the La Guadeloupe fault is reverse northwest directed, earlier motion along this fault may have been normal (Tremblay and Castonguay, 2002). According to Alain Tremblay (Université du Québec à Montréal, oral commun., 2006), the fault zone in the lower plate west of the La Guadaloupe fault is much wider because strain was preferentially partitioned into the Ascot Complex rocks. We see a similar relation in central Vermont where the fault zone is wider in the pre-Silurian rocks but the higher strain is recorded in the upper plate.

Brittle Structures

The planar brittle structures, or fractures, identified in this study are separated on the basis of whether or not they are related to an older fabric in the metamorphic rocks. Fractures that are parallel and related to older sedimentary or metamorphic fabrics due to structural inheritance occur along bedding, axial surfaces of folds, cleavage, compositional layering, schistosity, and veins. Fractures that cross the sedimentary or metamorphic fabric of the rocks include brittle faults, joints, and joint sets. The orientation of joints measured in this study includes those with trace lengths greater than 20 cm (Barton and others, 1993). Joints were measured subjectively using methods described in Spencer and Kozak (1976) and Walsh and Clark (2000), and the dataset includes the most conspicuous joints observed in a given outcrop. Fracture data (fig. 16) are plotted on stereonets (lower hemisphere equal area projections) and rose diagrams (azimuth-frequency) using the Structural Data Integrated System Analyser (DAISY 4.01) software by Salvini (2004). Rose diagrams generated with the DAISY software use a Gaussian curve-fitting routine for determining peaks in directional data (Salvini and others, 1999) that was first described by Wise and others (1985). The rose diagrams include strike data for steeply dipping fractures (dips ≥60°, after Mabee and others, 1994).

Five minor outcrop-scale faults were observed in the area and are shown by strike and dip symbols on the map. Faults were identified by slickensided surfaces. Many other fractures are identified in the accompanying database and are not plotted on the map with individual strike and dip symbols. Joints and joint sets measured in this study include fractures with no displacement that are not clearly associated with parting along a preexisting structure in the rock, such as foliation, axial surfaces, cleavage, and so forth. Spacing of joint sets ranges from approximately 10 cm to 1 m with an average of 35 cm. Most joints are unmineralized, but a few contain trace patches of sulfide minerals, quartz, calcite, dolomite, or gypsum.

In the pre-Silurian rocks west of the RMC, the steeply dipping joints are dominated by throughgoing fractures that

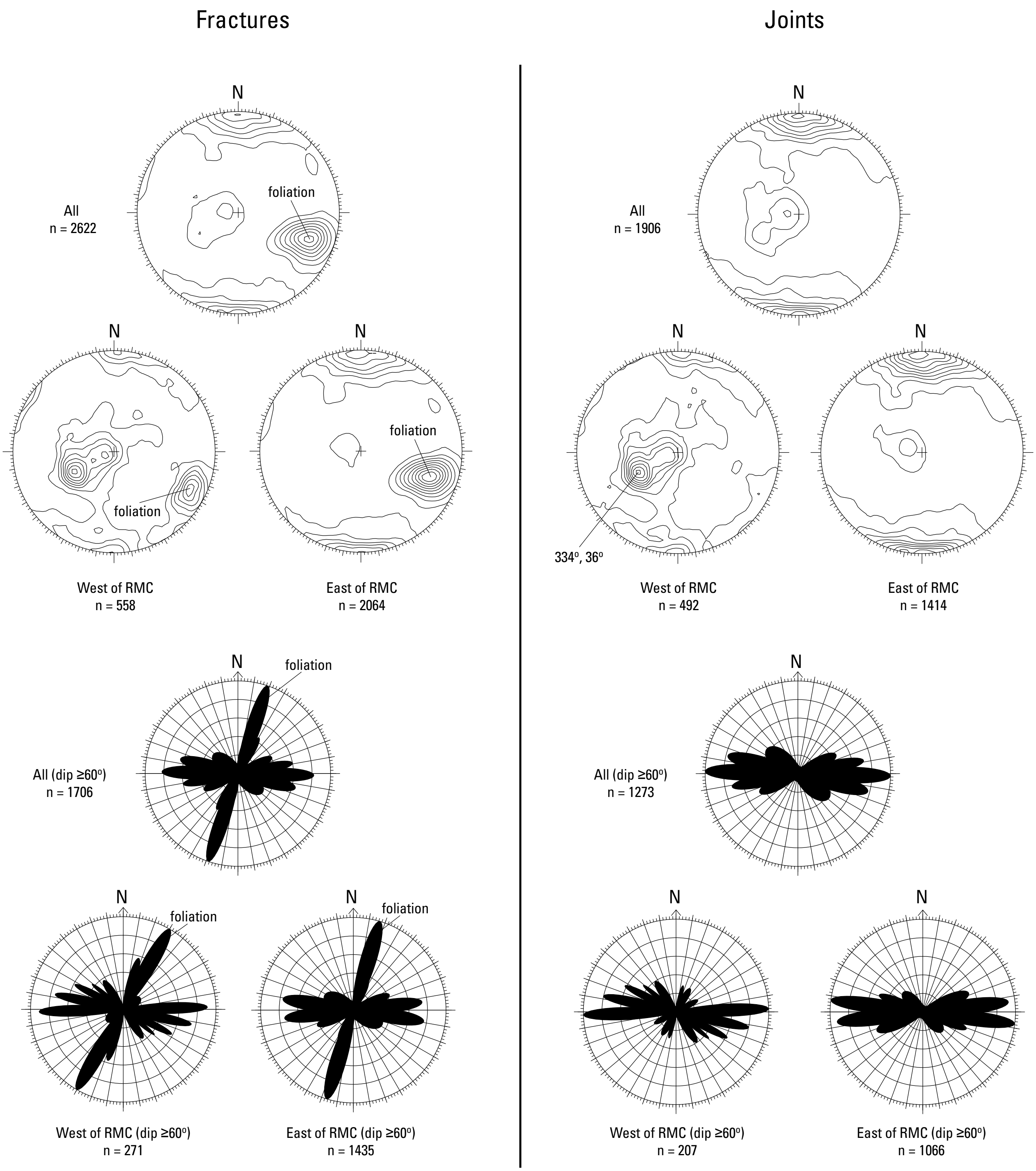
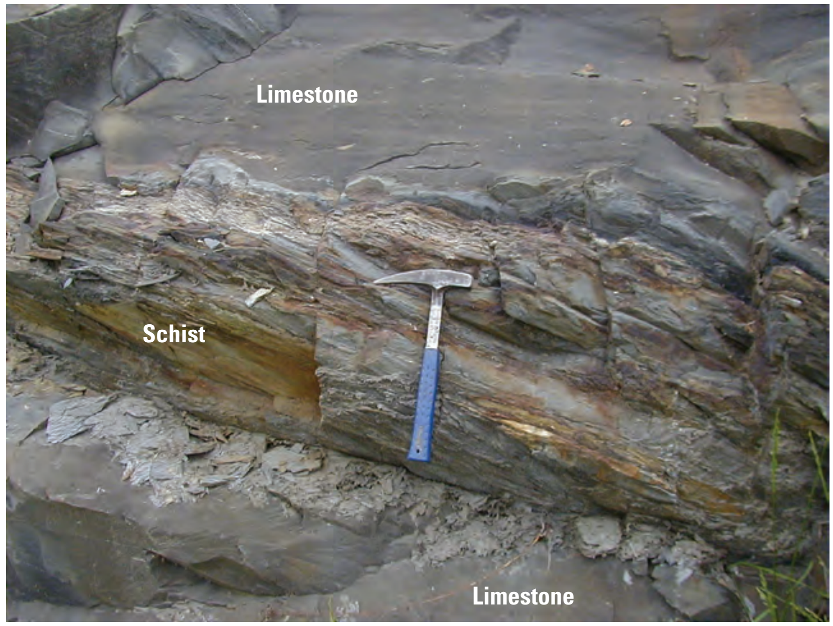


Figure 16. Stereonets (top) and rose diagrams (bottom) of fractures in the Barre West and Montpelier quadrangles. Stereonets show poles to all fractures and joints, contoured at 1 percent intervals. Rose diagrams only show strike of steeply dipping (dip ≥60°) fractures and joints. Data in the left column labeled "Fractures" include partings along bedding, axial surfaces of folds, cleavage, compositional layering, schistosity, veins, brittle faults, joints, and joint sets. Major trends labeled "foliation" include partings along axial surfaces of folds, cleavage, compositional layering, and schistosity. Data in the right column labeled "Joints" is a subset of the data on the left and include only brittle faults, joints, and joint sets. The number of data points in each diagram is indicated by "n." RMC, Richardson Memorial Contact.

cross entire outcrops with trace lengths on the order of meters and tend to cross the foliation at a high angle (fig. 17*B*); these joints are called "crossing" fractures (Barton and others, 1993). In the Silurian and Devonian rocks east of the RMC, crossing fractures are less abundant than to the west, and many of the fractures abut the bedding (fig. 17*A*), or abut the foliation; these joints are called "abutting" fractures (Barton and others, 1993). The difference in relative abundance of crossing and abutting fractures is probably a function of rock homogeneity. West of the RMC, the rocks are macroscopically more homogeneous and contain less distinct layering and thus less contrast in mechanical properties. East of the RMC, the rocks are dominated by the mechanically heterogeneous Waits River Formation with its well-foliated interbedded slate and phyllite horizons alternating with more massive impure limestone beds.

Fracture data for the area (fig. 16) show that fractures are dominated by three trends: (1) steeply west-dipping, north-northeast-striking parting along the foliation, (2) steeply dipping, west-northwest-striking joints, and (3) gently to moderately northeast-dipping and northwest-striking sheeting joints. For the analysis, the data were separated into locations east and west of the RMC according to the distribution of crossing and abutting joints and into fractures and joints for the purpose of illustrating the strong fracture trends found in the rocks due to parting along the metamorphic foliation. Despite the recognized difference in the distribution of crossing and abutting joints across the RMC, the overall fracture and joint trends are similar across this boundary (fig. 16). The principal difference in fracture trends across the RMC is the abundance of moderately northeast-dipping and northwest-striking joints in the rocks of the Moretown and Cram Hill Formations. This trend is similar to the strike and dip of the S_4 cleavage (compare with fig. 13*A*), and it is possible that the joints measured in this orientation west of the RMC may represent a structural weakness in the rocks that was not distinctly recognized in the field as the S_4 cleavage.



A

B

Figure 17. Photographs of joint types. *A*, Abutting joints in the Waits River Formation. Joints present in the schist terminate at the contact with the limestone on State Route 63 in Barre (station BW–1137). *B*, Northwest-striking and northeast-dipping joints (white arrows) and north-northwest-striking, steeply dipping crossing joints (yellow arrows) in the Moretown Formation at Interchange 8 on I–89 (station 62402–2). Fractures parallel to the foliation are apparent in both photographs.

A summary diagram for steeply dipping fractures in the area (fig. 18) shows the Montpelier and Barre West quadrangles on a shaded relief map of central Vermont. Fracture analysis shows that the principal fracture trends are dominated by foliation-parallel parting both east and west of the RMC, and this north-northeast topographic grain is clearly visible on the shaded relief map. West of the RMC, kilometer-scale west-northwest-trending drainage patterns and valleys are probably associated with the principal trends of crossing joints measured in our study. East of the RMC, however, the west-northwest trends are not as prominent, and we speculate that the more subdued topographic expression is the result of the abutting nature of the joints. Thus the distinct layering in the Silurian and Devonian rocks, and especially the well-layered Waits River Formation, inhibits the formation of kilometer-scale crossing joints and joint sets.

Metamorphism

The rocks in the Montpelier and Barre West quadrangles were metamorphosed to greenschist facies conditions. Rocks in the CVGS experienced peak metamorphic conditions in the garnet zone, and the pre-Silurian rocks experienced peak metamorphic conditions in the biotite zone. Laird and others (1984) presented petrologic data that showed that both Ordovician (Taconian) and Devonian (Acadian) metamorphic events were preserved in the pre-Silurian rocks west of the RMC, whereas only Devonian metamorphism affected the Silurian and Devonian rocks east of this discontinuity. With the exception of the Belvidere Mountain, Tillotson, and Worcester mafic complexes (for example, Laird and others, 1984, 1993, 2007; Gale, 1986; Kim and others, 2001), the pre-Silurian lithotectonic belts of northern Vermont underwent biotite-garnet-grade Taconian metamorphism followed by muscovite-chlorite-grade Acadian retrogression. Devonian metamorphism in the CVGS is mostly biotite to garnet grade but locally reached sillimanite grade (Doll and others, 1961; Laird and others, 1993). On the basis of $^{40}Ar/^{39}Ar$ ages, the Taconian metamorphism in central and northern Vermont occurred around 471 to 460 Ma (excluding the Belvidere Mountain Complex), and the Acadian metamorphism occurred around 397 to 350 Ma (Sutter and others, 1985; Spear and Harrison, 1989; Laird and others, 1993).

Laird and others (1984, 1993, 2007) used the geochemical composition of amphiboles (Na M4 and Tschermakite substitutions) in mafic rocks from central and northern Vermont to delineate high (~12–14 kilobars (kb)), medium-high (~9–11 kb), medium (~5–7 kb), and low (~3–4 kb) pressure facies series. The vast majority of the mafic rocks analyzed were from the pre-Silurian section. It is important to note that all amphiboles (actinolite) analyzed from metadiabases of the Wrightsville belt in the Montpelier and Barre West quadrangles fell in the low pressure facies series. Amphiboles from mafic rocks in the central part of the CVGS south of the field area also plot in the low-pressure facies series. Amphiboles analyzed by Laird and others (1984, 1993) from lithotectonic belts to the west of the Moretown Formation in north-central Vermont fit in the medium- and medium-high-pressure facies series.

The greenschist facies metamorphism that affected rocks of the Montpelier and Barre West quadrangles during the Taconian and Acadian orogenies were directly associated with discrete deformational events. Five deformational events affected the pre-Silurian section (D_1–D_5), whereas three deformational events affected the Silurian and Devonian section (D_3–D_5).

The greenschist facies rocks of the pre-Silurian Wrightsville and Dumpling Hill belts are dominantly chlorite-muscovite grade with biotite present locally. Although no almandine garnet was found in either the Wrightsville or Dumpling Hill belts in the map area (spessartine is probable in coticules), Gale and others (2006) found isolated garnet-bearing layers in parts of the Moretown Formation to the west. The first two deformation events (D_1 and D_2) in the pre-Silurian section produced isoclinal folds with penetrative axial planar foliations defined by alternating domains of quartz-feldspar (QF) and chlorite-muscovite±biotite (M). These two deformational events and the associated greenschist facies metamorphism are assumed to be Ordovician or, at least, pre-Devonian.

The third deformational event (D_3) to affect the pre-Silurian rocks was the first event in the Silurian and Devonian rocks east of the RMC and is Devonian in age. The locally penetrative axial planar S_3 foliation is composed both of reoriented S_1/S_2 micas and newly formed micas. S_3 is more penetrative in the vicinity of the Dog River fault zone and is the dominant fabric in Silurian and Devonian rocks.

In the Montpelier and Barre West quadrangles, the Acadian garnet isograd divides the CVGS into two north-northeast-trending belts. The garnet isograd is mapped on the distribution of the garnetiferous phyllite in the Waits River Formation (DSwg); west of this limit the rocks experienced subgarnet grade metamorphism during the Acadian (east of the RMC) or during both the Acadian and Taconian orogenies (west of the RMC). In the garnet zone, inclusion patterns in garnet and biotite porphyroblasts indicate that both minerals grew after the development of the S_3 foliation but prior to or during the early stages of S_4 cleavage development (fig. 19*A,B*). Microscopic study shows that the S_4 foliation wraps around garnet porphyroblasts in most samples, indicating that cleavage development or modification continued after porphyroblast growth. One sample shows deformed S_3 inclusion trails in garnet indicating that porphyroblast growth began after the onset of D_4 deformation (fig. 19*A*). During D_4, quartz pressure shadows formed around biotite and garnet, and the pressure shadows are aligned with the L_4 crenulation lineation. These findings indicate that peak metamorphic conditions occurred after D_3 but prior to the completion of D_4 deformation. Subsequent to D_4, some garnet porphyroblasts exhibit static retrogression to chlorite (fig. 19*C,D*). In these places,

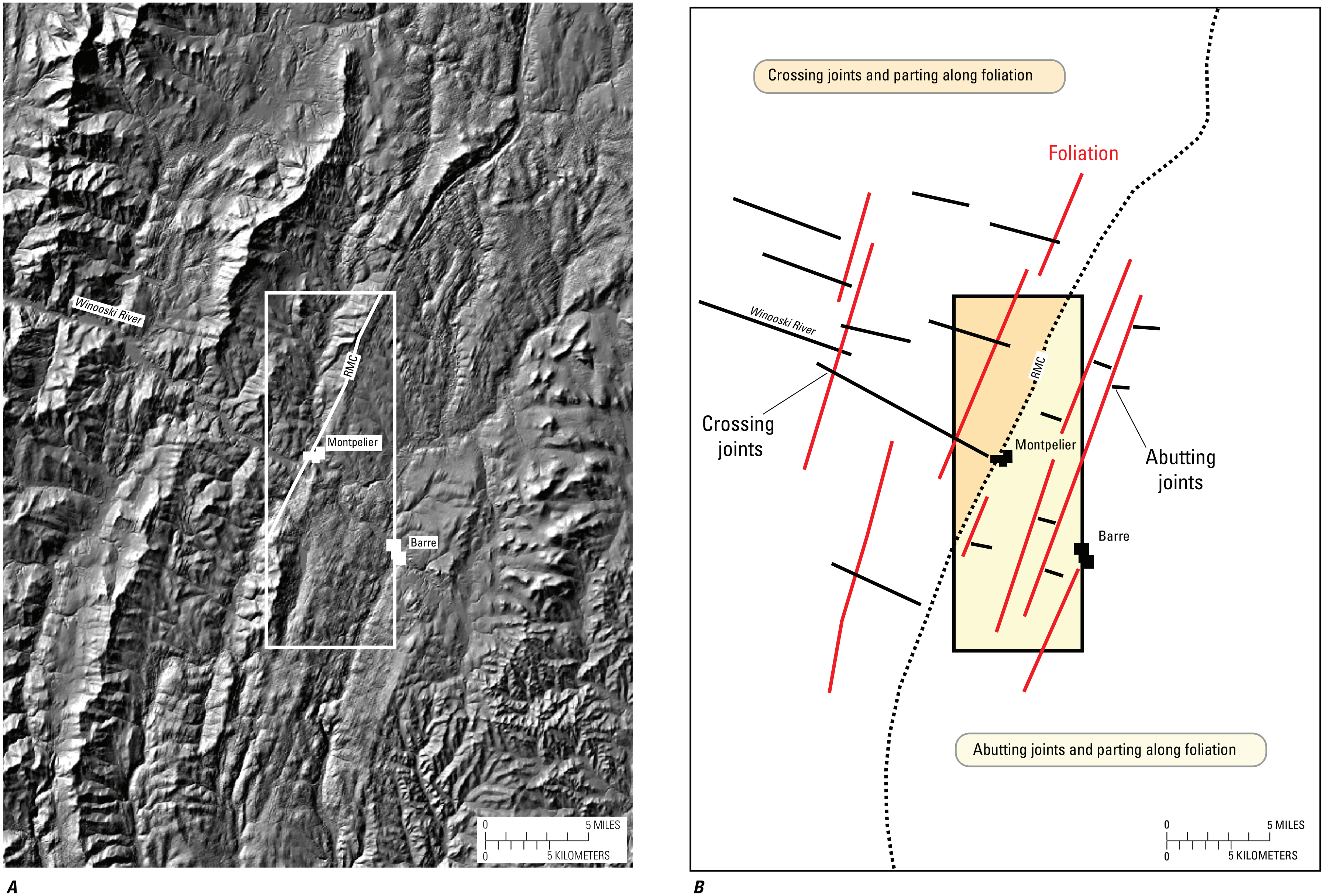


Figure 18. Shaded-relief map (*A*) and interpretive summary diagram (*B*) of fracture types and principal fracture trends in the area of the Montpelier and Barre West quadrangles. Shaded-relief map from the Vermont Center for Geographic Information (http://www.vcgi.org) hillshade dataset generated from the USGS National Elevation Dataset (NED). RMC, Richardson Memorial Contact.

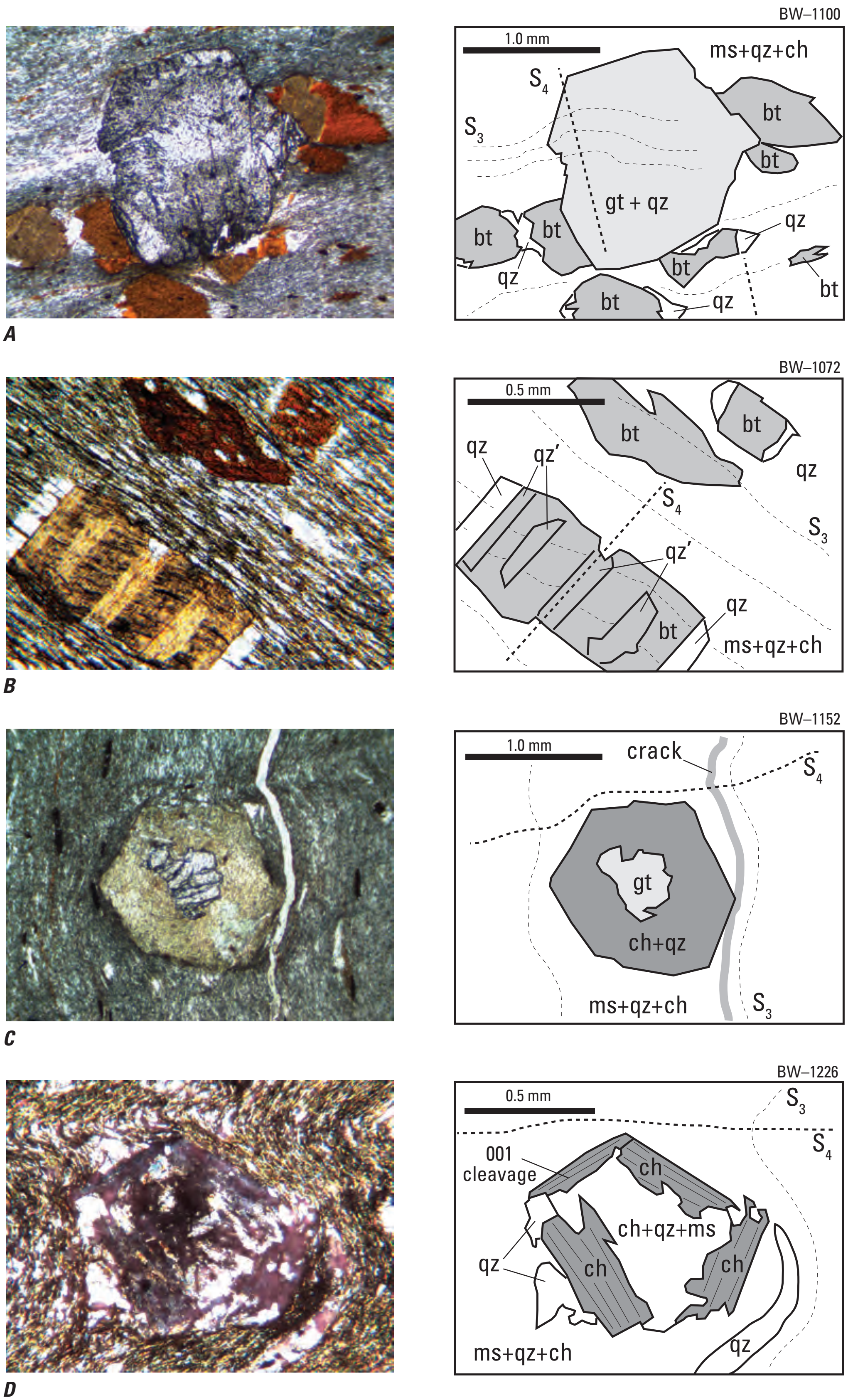


Figure 19. Photomicrographs (left) and sketches (right) of porphyroblasts in the Acadian garnet zone. *A*, Garnet (gt) and biotite (bt) are post-S_3 and syn-S_4. Garnet contains deformed S_3 inclusion trails, and biotite contains quartz (qz) pressure shadows. Sample BW–1100, plane light, 2.5X. *B*, Biotite is post-S_3 and syn-S_4. Biotite overgrew quartz pressure shadows (qz') indicating incremental growth during D_4. Sample BW–1072, plane light, 6.3X. *C*, Euhedral chlorite (ch) pseudomorph indicting static replacement of garnet. Note how S_4 is deflected around the pseudomorph indicating cleavage developed after garnet. Sample BW–1152, plane light, 2.5X. *D*, Similar to *C*, but garnet is completely replaced and basal 001 cleavage in chlorite is aligned with relict crystal faces of garnet indicating chlorite growth took place after D_4. Sample BW–1226, polarized light, 6.3X. ms, muscovite.

chlorite formed euhedral, undeformed pseudomorphs after garnet and, locally, some chlorite grew in sheets with the basal 001 cleavage subparallel to the shape of the original garnet crystal faces (fig. 19*C,D*). Because the chlorite in the garnet pseudomorphs is undeformed, this period of retrogression occurred after D_4 and may have occurred after D_5, although no fabrics associated with D_5 were observed microscopically.

Regionally, other workers have reported similar results to our findings, with the exception that peak Acadian metamorphism in eastern Vermont, toward the core of the Acadian high, locally outlasted what we consider D_4 deformation. In the area of Acadian doming in the Strafford-Willoughby arch in eastern Vermont, Menard and Spear (1994) found that staurolite and kyanite grew after D_4 at temperatures of approximately 550 to 600 °C. In the Royalton area, Woodland (1977) found that biotite growth postdated D_3 but predated D_4 and D_5, garnet growth predated D_5 and in part predated D_4, and staurolite and kyanite predated D_5. In the Hartland area, Walsh (1998) reported that garnet porphyroblasts grew syn-D_4 to post-D_4. In the Chester dome, Ratcliffe (2000a, p. 17) reports that peak Acadian metamorphic assemblages grew syn-tectonically with respect to his ". . .northeast- and northwest-trending cleavages," which probably correspond to either our D_4 or D_5 structures.

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