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Preliminary bedrock geologic map of parts of the Lower Waterford, Concord, Littleton, and Miles Pond 7 1/2-minute quadrangles, Vermont and New Hampshire

by

Douglas W. Rankin
U.S. Geological Survey
National Center, Stop 926
Reston, Virginia 22092

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INTRODUCTION

The map area, in east-central Vermont and adjacent New Hampshire, consists of parts of the Lower Waterford, Concord, Littleton and Miles Pond 7 1/2-minute quadrangles (Fig. 1) that together constitute the Littleton 15-minute quadrangle. The mapping is part of the effort to produce a new bedrock geologic map of Vermont through the collection of field data at a scale of 1:24,000. The focus of my part of the project is to map and interpret the "New Hampshire sequence" rocks (White and Jahns, 1950) that crop out in Vermont and their relationship to those of the "Vermont sequence", or the Connecticut Valley trough, west of the Monroe line, here a fault (Hatch, 1988a). The work is a continuation of mapping just initiated by N.L. Hatch, Jr., prior to his death in 1991. This particular map area was chosen as the place to initiate this study because it includes one of the largest areas of the New Hampshire sequence in Vermont, because it is adjacent to and on strike with the Littleton-Moosilauke area in New Hampshire that includes the type area of most of the units of the New Hampshire sequence (Billings, 1935, 1937), and because the Connecticut River here runs roughly east to west across the regional strike and might provide a good stratigraphic section across the rocks under study. The mapping showed that no bedrock is exposed along either bank of the Connecticut River across most of the area, but there are excellent exposures in the spillways of two large dams, Moore Dam on the east and Comerford Dam on the west (about 100 m west of the Lower Waterford quadrangle), along Interstate Highway 93 (I-93), and adequate exposures in the hills above the river. My mapping was mostly in the Vermont parts of the Littleton 15-minute quadrangle but included some work in the Barnett 7 1/2 x 15-minute quadrangle to the west and a zone along the New Hampshire side of the Connecticut River that included Albee Hill, Partridge Lake, Highland Croft farm, the former Fitch farm, and the outskirts of Littleton. The Vermont mapping is thus tied to the classic Littleton-Moosilauke area of Billings (1937) and the fossiliferous Fitch and Littleton Formations in their type areas.

The geologic framework in which modern mapping has taken place was established by the publication of geologic maps of the Moosilauke and New Hampshire part of the Littleton 15-minute quadrangles by Billings (1935, 1937). The Vermont part of the Littleton 15-minute quadrangle, which includes the Vermont part of Sheets 1 and 2, was mapped by Eric (1942) and Eric and Dennis (1958). Hall (1959) mapped the St. Johnsbury 15-minute quadrangle adjacent to the west. Hatch (1990) published an Open-File reconnaissance map of the rocks northwest of the Monroe fault in the Concord 7 1/2-minute quadrangle. Recent smaller scale maps that present reinterpretations of some of the larger scale maps include Moench and others (1987), Moench, (1989; 1990; 1993), and Lyons and others (in press). I am grateful to R.H. Moench for providing me with a copy of his unpublished bedrock

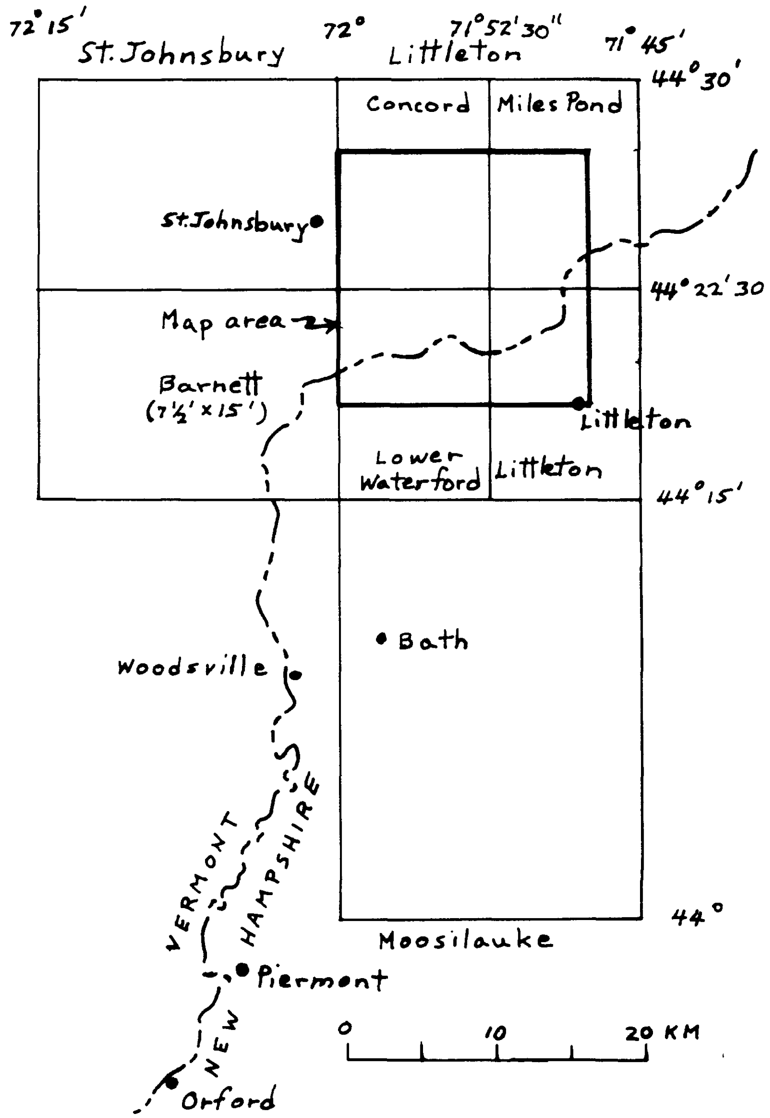

Figure 1. Index map

maps of the Littleton-Moosilauke-Piermont area and, in June 1994, of the Lower Waterford-Groveton area at a scale of 1:48,000, and for introducing me to the rocks in the field. Moench's 1:48,000 scale maps, which are based upon local detailed mapping, reconnaissance, and compilation of older mapping, include the area of this report, which straddles the overlap between Moench's two maps. I am also grateful to J.B. Lyons and Douglas Rumble, III for two days in August 1992 spent guiding me through the geology of the Orford-Piermont area.

STRATIGRAPHY

The stratigraphy of the New Hampshire sequence, established by Billings (1935, 1937) in the Littleton-Moosilauke area, and extended by him and others over much of central New England, is shown below. Some of the age information post-dates the 1937 work.

Littleton Formation - Lower Devonian
Fitch Formation - Lower Devonian and Upper Silurian
Clough Conglomerate (now Quartzite) - Lower Silurian
Partridge Formation - Upper Ordovician
Ammonoosuc Volcanics - Upper and Middle Ordovician
Albee Formation - Ordovician or older

Billings recognized an unconformity between the Clough and Partridge.

Billings defined the Gardner Mountain anticline, cored by the Albee Formation, which projects into the Vermont part of the Littleton 15-minute quadrangle where it was mapped by Eric and Dennis (1958), as the major structure southeast of the Monroe fault. The Silurian and Devonian units of the New Hampshire sequence have been interpreted as being deposited along a topographic high, the crest of which is the Bronson Hill anticlinorium, a few km east of the Gardner Mountain anticline (Hatch and others, 1983). The Albee Formation is not present beneath the Ammonoosuc Volcanics on the crest of the Bronson Hill anticlinorium (Billings, 1937; 1955). The Silurian section thickens from about 350 m near Littleton (Moench and others, 1987) westward into the Connecticut Valley trough and thickens tremendously across a tectonic hinge zone into the Central Maine trough to the east, where the section is as much as 4600 m thick (Hatch and others, 1983).

Moench, beginning with work near Piermont, New Hampshire, about 50 km south-southwest of Littleton, became convinced that the Albee Formation was actually a composite unit made up of Silurian rocks similar to those he had mapped along and east of the tectonic hinge zone in western Maine (Moench and others, 1987; Moench, 1989; 1990). He not only recognized similar rocks, but placed them in units in the same stratigraphic order, and assigned them the stratigraphic names of the units in western

Maine. The succession of units particularly applicable to the area of Sheet 1 into which Moench and others (1987) and Moench (1989; 1990) divided the "Albee terrane" include from youngest to oldest going down:

Madrid Formation
Smalls Falls Formation
Perry Mountain Formation
Rangeley Formation

The names and stratigraphic order are taken from the Silurian section near Rangeley, Maine, about 115 km northeast of Littleton. The Madrid is roughly correlative with the Fitch Formation and the Rangeley with the Clough of the Bronson Hill anticlinorium. In their type areas near Rangeley, the Rangeley and Smalls Falls Formations are dated by fossils. No fossils have been recovered from the Albee terrane of western New Hampshire and adjacent Vermont.

The Albee terrane constitutes the Piermont allochthon of Moench and others (1987) and Moench (1989; 1990), thought to have been transported westward on the premetamorphic, but Acadian Foster Hill thrust fault. The Foster Hill fault takes its name from Foster Hill in New Hampshire in the south-central part of Sheet 1. The fault places Silurian rocks (of Moench's model) on Ordovician rocks including the Ammonoosuc Volcanics (Moench and others, 1987; Moench, 1990). The Piermont allochthon was thought to have been emplaced prior to or during the intrusion of the 410±5 Ma-old Fairlee pluton (near Orford, Fig. 1) (Moench, 1990). The Piermont allochthon was interpreted to have been truncated on the west by the Monroe fault.

More recently it has been shown in northern New Hampshire where the Monroe fault is less clearly defined, that Silurian rocks of the "Piermont sequence" (Moench, 1993) are laterally gradational westward into Silurian rocks (Frontenac Formation) of the Connecticut Valley trough (Marvinney and others, 1994). To accommodate these new observations Moench (1993) included the Silurian rocks of the Connecticut Valley trough along with the largely Silurian Piermont sequence in a newly defined Piermont-Frontenac allochthon. Moench (1993) notes that these relationships present an enigma of an eastern source for rocks of the allochthon, based on stratigraphic sequential similarity, but a western root. His hypotheses for emplacement of the allochthon include 1) large-scale strike-slip movement from either the northeast or southwest, or 2) west-directed gravity sliding in which the Piermont sequence moved farther than the Frontenac Formation. The now folded but originally more or less flat Foster Hill fault would still floor the allochthon as it is preserved.

The above synopsis is very much simplified and is intended only as a framework in which to present this report. The time spent in the field to date includes three weeks in August 1992, 11 weeks in the summer of 1993, and 5 weeks in the summer of 1994. This is a progress report. My approach to the problem was to begin mapping the area of Sheet 1 at a scale of 1:24,000. The early work was in the Vermont part of the Lower Waterford quadrangle. I had many false starts. I could not reproduce the map pattern portrayed by Moench on the unpublished 1:48,000-scale maps covering the area of Sheet 1, nor could I find any evidence of faulting in the well exposed chlorite-grade rocks on Foster Hill. Some of our differences in map pattern is because I found that many of the fine-grained mafic igneous bodies in the Spvb unit of Moench and others (1987, Figure 1 and p. 251) northwest of Albee Hill were tabular bodies with chilled margins on both sides. I interpreted them to be dikes (my unit Scs, see below) rather than lava flows. I also do not recognize Moench's Smalls Falls and Madrid Formations as units distinct from the rocks he mapped as Rangeley and Perry Mountain respectively.

In the area of Sheet 1, I have divided the Albee terrane of Billings (1937) and Eric and Dennis (1958) or the Piermont allochthon of Moench and others (1987) into two units. Unit 1 (here mapped as the Orfordville Formation, Oo) consists of interbedded dark-gray phyllite, light- to medium-gray metasiltstone and very fine-grained metasandstone, and minor light-gray metamorphosed impure dolostone. The phyllite and metasiltstone/sandstone are commonly sulfidic and rusty weathering. Beds are typically of thin to medium thickness and many are graded. Channelling is common and in places soft sediment deformation is clearly demonstrable. Excellent samples of channelling are found in a pavement outcrop from which the vegetation has been stripped at an elevation of about 800 ft northeast of the bridge of I-93 over VT-18 beside a secondary road shown on the map (now abandoned), and a road cut at an elevation of about 1240 ft 1.9 km N5°E of the Vermont end of the VT-18 bridge over the Connecticut River, Lower Waterford quadrangle (Sheet 1). Excellent examples of soft sediment deformation are found in a pavement outcrop on the west side of an abandoned lodge at an elevation of about 1780 ft north of the summit of Hurlburt Hill, and on top of the highest part of a road cut along northbound I-93 at an elevation of 1100 ft west of the Bill Little fault, Lower Waterford quadrangle.

Unit 2 (here mapped as the Albee Formation, Oal) consists of interbedded light- to medium-gray, or bluish-gray, or greenish-gray metasiltstone, phyllite, quartzite, and minor metamorphosed impure dolostone. The metasiltstone is typically white weathering and may be tuffaceous. Some felsic metatuff is recognized and a felsic metavolcanic member is recognized on the north slope of Fuller Hill (north-central part of Sheet 1). Some metasiltstone is calcareous; some phyllite and metasiltstone is highly sulfidic. Bedding thickness varies, and some beds are graded, but most bedding contacts are sharp. Quartzite beds are as thick as 3 m.

In summary, unit 2 is distinguished from unit 1 by the absence of extensive dark-gray pelite, the abundance of white-weathering metasiltstone, and the presence of thicker quartzites. Overall, unit 2 is siltier and sandier than the more pelitic unit 1. Unit 2 includes most of the rocks Moench mapped as the Perry Mountain Formation and to a lesser extent the Madrid Formation in the Piermont allochthon in the area of Sheet 1. Unit 1 includes most of the rocks that Moench mapped as the Rangeley and Smalls Falls Formations.

Because Unit 2 appears on both sides of the Albee terrane and is adjacent to the Ammonoosuc Volcanics, it is thought to be the younger of the two. Graded beds are relatively common in unit 1 and to a lesser extent unit 2, but generally are not observed close to the contact between the two units. In a few places graded beds close to the contact, particularly near the summit of Hurlburt Hill and on the southwest ridge of Hurlburt Hill, are consistent with the proposed stratigraphic order. Moench and others (1987) and Moench (1990, 1993, and unpublished data) likewise reported graded beds across the contact indicating that unit 2 (his Perry Mountain Formation) is younger than unit 1 (his Rangeley Formation). For the purposes of this report, unit 1 is considered to be stratigraphically beneath unit 2, which, in turn is here considered to be stratigraphically beneath the Ammonoosuc Volcanics.

Billings (1935) established the type area of the Albee Formation as that part of Gardner Mountain that lies between Hunt Mountain (south of Sheet 1 in the Barnett quadrangle) and Albee Hill (south of the Connecticut River in the Lower Waterford quadrangle). The type area thus spans 10 km and includes outcrops of both units 1 and 2. In a more formal publication the Albee Formation (Oal) will be redefined to be interbedded light colored metasiltstone, phyllite, quartzite, and minor metamorphosed impure dolostone as exposed on the summit and northwestern slope (down to the lowest outcrops) on Albee Hill. The redefined Albee Formation (Oal) is, thus, unit 2 of the above discussion.

Unit 1 is here correlated with and called the Orfordville Formation (Oo), a unit defined by Hadley (1942) near Orford, New Hampshire (Fig. 1) and interpreted by him to be stratigraphically beneath the Albee Formation in the Piermont anticline. Hadley describes the Orfordville in the type area as black to dark-gray mica schist, quartz-mica schist and feldspathic quartzite. The type Orfordville is southwest of the Mesozoic Ammonoosuc fault and at staurolite or kyanite grade. Hadley notes that the rocks are typically carbonaceous and the pelites commonly sulfidic. Beds are readily visible in many outcrops and are a fraction of an inch to several inches thick; micaceous quartzite beds may be a foot or more thick. The Orfordville includes a thick and extensive mafic volcanic unit, the Post Pond Volcanic Member, at its base and the thin Sunday Mountain (mafic) Volcanic Member at its top.

Rumble (1969) remapped much of the area Hadley had mapped, interpreted the type Orfordville to be Partridge, the volcanic members to be Ammonoosuc, and the stratigraphic section in the Piermont "anticline" to be inverted. Moench (1990) accepted Rumble's interpretation that the type Orfordville in the Piermont "anticline" (=Orfordville antiform) is Partridge and that the structurally overlying Sunday Mountain Volcanic Member is Ammonoosuc. He, however, placed the rocks above the Sunday Mountain (Albee in the mapping of Hadley and Rumble) in the Perry Mountain Formation of the Piermont allochthon. The contact between the Sunday Mountain Volcanic Member and the overlying Albee Formation in the Piermont anticline (to use Hadley's 1942 terminology) is in the Moench interpretation the premetamorphic sole fault, the Foster Hill fault, of the Piermont-Frontenac allochthon.

Hadley's Orfordville Formation, once mapped as an extensive unit in the Connecticut River valley (Billings, 1955) has been reinterpreted, much probably correctly, to be variously the Littleton Formation, Clough Quartzite, Partridge Formation and Ammonoosuc Volcanics. The Orfordville Formation is at present discredited; the name is not used on the new bedrock geologic map of New Hampshire (Lyons and others, in press).

I cannot resolve these conflicting interpretations, but can make some observations. In the chlorite grade rocks of Sheet 1, unit 1, for which I am resurrecting the name Orfordville, is clearly distinguishable from the more pelitic, more sulfidic, and less well bedded Partridge Formation in its type area (also chlorite grade). Staurolite-grade Partridge Formation mapped by Billings in the Moosilauke 15-minute quadrangle (about 4 km east of Bath, Fig. 1) southeast of the Ammonoosuc fault is easily correlated with Partridge of the type area. Although of considerably higher metamorphic grade, it is still a very fine-grained sulfidic phyllite in which bedding is difficult to discern. The Orfordville of Hadley (1942) in stream exposures along Jacobs Brook at the northeast edge of Orford, New Hampshire is to me indistinguishable from the Orfordville of Sheet 1 except for the higher metamorphic grade. I had the same impression of several other outcrops of the Hadley's Orfordville in the vicinity of Orford including a new road cut at an elevation of about 1050 ft on the gravel road southwest of Indian Pond about 6 km 170° south of Piermont (Piermont 7 1/2-minute quadrangle). None of these outcrops looks like the staurolite grade Partridge Formation that Billings mapped in the Moosilauke quadrangle. They do resemble somewhat sandier outcrops included by Moench (1990) in the Rangeley Formation of the Piermont allochthon at an elevation of about 640′ on Bean Brook 2.4 km 170° south of Piermont. Rocks immediately above the Foster Hill fault on Cottonstone Mountain 4.8 km 205° south of Piermont, interpreted by Moench to be Perry Mountain Formation and by Hadley and Rumble to be Albee, closely resemble the Albee of Albee Hill except for the higher metamorphic grade and the fact that they contain boudenaged amphibolite layers up to 2 m thick. If my working hypothesis for Sheet 1 is correct, the Cottonstone Mountain sequence is as interpreted by Hadley, an upright stratigraphic sequence from the Orfordville up through its Sunday Mountain Volcanic Member into the Albee.

Eric and Dennis (1958, p. 27) report sills and dikes of metadiabase in the Albee Formation just southeast of the Monroe fault as mapped by them, "where they constitute 80 percent of the exposures in an area approximately 2 miles wide." The concept of sheeted dikes had not been developed at that time, but surely these intrusives represent that kind of an extensional environment. The dikes (Scs) plus a composite intrusive in which no screens of country rock have been observed (Scm) and an associated pegmatitic metagabbro (Scg) here are named informally the Comerford intrusive suite.

The pegmatitic metagabbro and some of the Scm unit were mapped by Eric and Dennis (1958) as the Moulton Diorite, a widely developed unit defined by Billings (1937 in New Hampshire, that intrudes rocks as young as the Littleton Formation. Eric and Dennis (1958), therefore assigned a Devonian age to the Moulton in Vermont and placed the Monroe fault along the eastern side of the Moulton separating that body from the dike swarm. Hall (1959) concurred with this interpretation and mapped a small body of the Moulton Diorite that he interpreted to be intrusive into the Meetinghouse Slate Member (west of the Monroe fault) in the St. Johnsbury 15-minute quadrangle about 1.7 km west of the map area just north of the Connecticut River. The pegmatitic metagabbro (Scg) is here interpreted to be related to the sheeted dikes because what appear to be cognate xenoliths of Scg occur in some dikes. The body of the Mounton Diorite in the Meetinghouse Slate west of the map area is here interpreted to be a fault slice of combined Scm and Scg because of the strongly sheared contacts against the Meetinghouse Slate. No other bodies or dikes of the Comerford intrusive suite have been observed in the present work northwest of the Monroe fault. Rocks of the Comerford intrusive suite are locally strongly sheared adjacent to the fault. The Comerford intrusive suite is, therefore, only bracketed as being younger than the Ammonoosuc Volcanics (unit Oam) and older than the regional Acadian metamorphism. It is interpreted as of Silurian age, perhaps related to the dike swarm of the Second Lake rift (Moench and others, 1992), and to the opening of the Connecticut Valley trough.

Most of the dikes are steeply dipping, nearly conformable with bedding in the country rock except on the 1522 ft hill and in the adjacent Pike Industries quarry at the south edge of the Concord quadrangle (see Sheets 2 and 3). Although the dikes contain the same fabric as the country rocks they do locally cross cut more gently dipping strata. Metadiabase dikes in unit Scm are also near vertical. It is hard to imagine an environment in which such a volume of igneous material including the near-vertical dikes in Scm could have been intruded as thin subhorizontal sills over such a large area. Furthermore, the eastern dike swarm appears to be younger than F_1 folding. The favored interpretation is that the tabular bodies are dikes, which implies that the enclosing strata must have been rotated to near vertical (folded) prior to dike intrusion.

Billings (1935; 1937) shows a small body of Moulton Diorite along the Fitch-Littleton contact at the northeastern end of Walker Mountain (Sheet 1). Billings (1937, p. 503) gives a mode of a rock from this body as consisting of 73% albite, 18% chlorite, 4% illminite, sphene, and 5% carbonate. He stated that the rock has an ophitic texture. My traverse across the northeast end of Walker Mountain was northeast of the diorite body mapped by Billings. On this traverse I crossed two outcrop belts of a dark, high specific gravity igneous rock that is tentatively identified as pyroxenite in which poikilitic pyroxene crystals as much as 3 cm across. No thin section is yet available. The easiest explanation for the presence here of ultramafic rock is that it is part of the Moulton Diorite, whether present in very large xenoliths of either mantle cognate cumulates.

A group of granitoid dikes (Mf) and a sheet of hypabyssal biotite granite (Mg) have been identified in the Gile Mountain Formation northwest of the Monroe line that so far as I know have not been reported before. The dikes are biotite-rich, medium-gray, fine-grained and non-foliated. Quartz and feldspar are commonly poikilitic and may be in graphic intergrowths. The dikes are unusual in that they are characterized by scattered spherical or ellipsoidal bodies a few mm to several cm long of polycrystalline quartz with or without feldspar, biotite, or calcite. The borders of the bodies are sharply gradational into the granitoid. In some dikes the bodies are in zones parallel to, but not at the dike contacts. The elliptical bodies are interpreted to be amygdules. In places, the dikes contain xenoliths of deformed and metamorphosed Gile Mountain Formation, more mafic rocks, and less biotite-rich granitoid. The last two types are probably cognate. Some dikes are composite with more mafic parts similar in appearance to the more mafic xenoliths. Pavement outcrops about 0.16 km southeast of Cushman Cemetery in the central northern part of Sheet 3 show the contact from the granitoid into the Meetinghouse Member of the Gile Mountain Formation through zones of partically digested Meetinghouse xenoliths. One xenolith-rich dike intruding the Meetinghouse was interpreted by Eric and Dennis (1958, Plate 7) to be a volcanic agglomerate.

The granophyric textures and the presence of amygdules indicates that the dikes are relatively shallow intrusives. They intrude deformed and metamorphosed sedimentary rocks of probable Devonian age and are themselves nonfoliated. My preferred interpretation is that they are of Mesozoic age, possibly related to the Early Jurassic White Mountain province of McHone and Butler (1984). It is puzzling that none of these dikes has been found southeast of the Monroe fault.

The hypalyssal biotite granite (Mg) forms a steeply southeast-dipping sheet 20 to 40 m thick and at least a km long in the Meetinghouse Member, central-north part of Sheet 1 (and 2). It is very light-gray, porphyritic with a very fine-grained groundmass, and non-foliated. Phenocrysts include euhedral quartz a few mm across, Carlsbad twinned alkali feldspar is large as 10 mm, and euhedral biotite a couple of mm across. No thin section of this rock is yet available. This granite is also interpreted to be of Mesozoic age and may be related to the White Mountain province.

STRUCTURE

Two generations of Paleozoic deformation have been identified east of the Monroe fault. Many of the metasedimentary rocks are pinstriped, the result of tectonic transposition of bedding. The pinstriping is folded by the dominant fold set implying that the fold set is a second generation one. No closures on a mesoscopic scale related to the earlier set have been identified. The dominant fold set (F_2) is tight to isoclinal, and most axes and bedding-S_2 intersections plunge moderately southwest although several plunge rather gently to the northeast. In a few outcrops the axes porpoise (change direction of plunge across the outcrop). Regional foliation is steep, mostly southeast dipping, and is axial planar to F_2. Most of the F_2 folds, whether northeast or southwest plunging indicate a sense of movement of east-side-up. This observation is consistent with that of Eric and Dennis (1958). A significant number of F_2 folds, however, have the sense of movement of west-side-up. Some of these folds are in places where such a sense of rotation would be consistent with their being minor folds on the limbs of macroscopic F_1 folds. They have not, however, been mapped separately. It is clear from the map pattern in the Hurlburt Hill-Fuller Hill area, that F_2 folds do not control the gross distribution of map units but are second generation folds deforming an older generation of tight folds (F_1) that does control the distribution of map units. Billings (1937) and Moench (1992) noted that southwest plunging folds are common at the southwestern ends of both the Walker Mountain syncline and the Salmon Hole Brook syncline both of which carry the Littleton

Formation in their troughs. Perhaps these southwest plunging folds are also of the F_2 generation, and do not, therefore, correctly predict stratigraphic tops.

It is possible that the structure southeast of the Monroe fault is even more complex than the present interpretation. Foliation-bedding relationships in about five outcrops where facing direction of the beds is known from sedimentary features and only one foliation is observed, indicate the presence of downward-facing folds. The most readily accessible of these is the quarry in the Littleton Formation at Slate Ledge, Littleton quadrangle, where upright bedding dips steeply southeast and the foliation (here a cleavage) dips southeast at a more gentle angle (Sheet 1). Another area of apparently downward facing folds is in the Albee Formation at the southwest end of the southwest ridge of Hurlburt Hill. At present it is not known whether these anomalous folds are local or are indicative of widespread structural inversion prior to F_2 folding. These observations have not been incorporated into a structural model. This problem obviously needs more work.

No F_1 folds have been recognized northwest of the Monroe fault. Foliation is generally parallel or nearly parallel to bedding. A few F_2 folds have been recorded. F_2 axes mostly plunge southwest like those southeast of the Monroe fault, most of the folds have a sense of rotation of east over west. Excellent examples of F_2 folds may be seen in the Gile Mountain Formation in outcrops along the exit ramp of west-bound I-93 at VT-18 (Sheet 1), but no axial plunge or sense of rotation could be determined for the F_2 folds in this outcrop. The Gile Mountain Formation has been deformed by a third fold set, F_3. F_3 folds over most of the mapped area northwest of the Monroe fault are more open than F_2; some are chevron folds. Axes mostly plunge moderately northeast and the sense of movement is west-side-up. A spaced or crenulation cleavage is axial planar to F_3 and generally dips moderately southeast, but becomes more steeply dipping toward the southwest. F_3 folds are also well developed in the same outcrop just mentioned on the I-93 exit ramp. In some outcrops, particularly those in which the crenulation cleavage is more steeply dipping, and northwest beyond the mapped area, bedding is transposed into the more closely spaced crenulation cleavage which becomes indistinguishable from the earlier S_2 foliation. These relationships were also described by Eric and Dennis (1958) and similar relationships were described by Hall (1959) and White and Jahns (1950) for areas to the west and south. White and Jahns (1950) noted a symmetry of late-stage folds across the Connecticut Valley trough. The sense of rotation of the late stage folds (F_3? of this report) on opposite sides of the trough (the folds are generally north plunging on both sides of the trough) is such that the center of trough moved up to form a broad arch 16 to 32 km across.

The Monroe fault is a fundamental break in the geology of the map area. The style of folding is different on opposite sides; F_3 folds have been observed only northwest of the fault. The Comerford intrusive suite is truncated by the fault. Biotite-rich granitoid dikes (Mf) are found only northwest of the fault. In the map area the Monroe fault is interpreted to be a steeply southeast dipping and northwest directed late Acadian thrust fault as it also was by Hatch (1988a; 1990). Hatch also noted evidence, such as kink bands and brittle fractures, for Mesozoic reactivation of the Monroe fault. Evidence for Mesozoic reactivation is strong farther south as documented by Hatch (1988a). In the map area, however, brittle structures and kink bands are quite widespread and not more pronounced along the Monroe fault. Some of these brittle faults are shown on the maps and cross sections. The major Mesozoic fault is the Bill Little fault which was mapped to the south and extended into the map area by Moench.

METAMORPHISM

The metamorphic grade within the map area ranges from chlorite in the southeast to garnet in the northwest. Assemblages of index minerals that coexist with quartz and muscovite in metasedimentary rocks are shown on Sheet 2 as well as the approximate position of the crude biotite isograd based upon those assemblages. The garnet isograd is projected into the Concord quadrangle from the position shown by Hall (1959) in the St. Johnsbury quadrangle to the west. Control is not adequate at this point to continue the garnet isograd further into the Concord quadrangle, but if the isograd continues a northeast trend through the Gile Mountain Formation, it could have several km of dextral offset on the Monroe fault. The assemblages are prograde and the metamorphic peak post-dates deformation. Garnet porphyroblasts are not retrograded; biotite porphyroblasts grow across foliation. The metamorphism is probably Late Acadian.

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DESCRIPTION OF MAP UNITS

Ml Mafic dikes (Mesozoic: Early Cretaceous?)
Shown only on sheets 2 and 3. Dusky yellowish brown (10 YR 2/2) (Goddard and others, 1970) lamprophyre and deuterically altered rhomb porphyry. The lamprophyre contains phenocrysts of pseudoleucite(?) and abundant reddish brown biotite. Dikes and irregular masses a few cm to seven m wide. Most dikes trend north-northwest with near-vertical dips. Columnar jointing is common. Some dikes are enechelon (see southeast end of cross section CC[1] and Sheet 2). Scattered exposures both northwest and southeast of the Monroe fault. May be part of the Early Cretaceous New England-Quebec dike swarm of McHone and Butler (1984) which include the Monteregian Hills (Foland and others, 1986)

Mf Biotite-rich granitoid (Mesozoic: Early Jurassic?)
Shown only on sheet 2. Medium light-gray (N6) to medium dark-gray (N4), fine-grained, nonfoliated. Typically 20 percent biotite, commonly with abundant chlorite (probably after biotite). Quartz and feldspar commonly poikilitic and may be in graphic intergrowths. Characterized by scattered spherical or ellipsoidal bodies a few mm to several cm long of polycrystalline quartz with or without feldspar, biotite, or calcite. Borders of the bodies are sharply gradational into the granitoid. In some dikes the bodies are in zones parallel to, but not at the dike contacts. The bodies are interpreted to be amygdules. Xenoliths of deformed and metamorphosed Gile Mountain Formation. Other xenoliths of more mafic rock and less biotite-rich granitoid, both probably cognate. Some dikes are composite with more mafic parts similar in appearance to the more mafic xenoliths. Found only northwest of the Monroe fault. Interpreted to be of Mesozoic age, possibly related to the Early Jurassic White Mountain province of McHone and Butler (1984)

Mg Hypabyssal biotite granite
Very light-gray (N8) porphyritic biotite granite with very fine-grained groundmass. Phenocrysts of euhedral quartz a few mm across, Carlsbad-twinned alkali feldspar as large as 10 mm, and euhedral biotite about 2 mm across. Nonfoliated. Interpreted to be of Mesozoic age, possibly related to the Early Jurassic White Mountain province of McHone and Butler (1984).

Dp Two-mica tonalite (Devonian)
Medium-grained very light-gray (N8) to light-gray (N7) nonfoliated biotite-muscovite tonalite. Present in a small body at Stiles Pond in the Concord quadrangle.

Mapped as Kirby Quartz Monzonite by Eric and Dennis (1958), and correlated with the Barre Granite at the quarries in Graniteville, Vermont to the southwest by Hatch (1990)

Dd Two-mica granitoid dikes (Devonian)

Shown only on sheet 2. Fine-grained light-gray biotite-muscovite granitoid dikes. Mostly northeast trending and steeply dipping. Probably related to the same igneous event as Dp

Dm Moulton Diorite

"Medium-grained, dark-gray diorite, composed mainly of secondary minerals such as oligioclase, hornblende, epidote, chlorite, and carbonate" (Billings, 1937). Northeasternmost outcrops on Walker Mountain consist of pyroxenite in which poikilitic pyroxene crystals are as much as 2 cm across.

Di Intermediate dikes (Early Devonian; premetamorphic)

Shown only on sheet 2. Dikes are foliated, some are gently folded, are various shades of gray, and are of intermediate silica content based upon mineralogy. Some contain prominent replaced phenocrysts now acicular pale amphibole, probably after hornblende, and(or) biotite (in some rocks now pseudomorphed by chlorite). The dikes may not be all the same age; some cut the Gile Mountain Formation, some cut the mafic dikes of the Comerford intrusive suite in the Chamberlin formation (in the adjacent Barnett quadrangle), and one cuts the Chamberlin formation

Littleton Formation (Lower Devonian)

Dl Main body

Dark-gray to grayish-black slate and gray to dark-gray very fine- to fine-grained argillaceous metasandstone, volcanic conglomerate, and crystal tuff. Mostly thin graded beds, but sandstone beds are as thick as 20 cm. Locally abundant pyrite cubes as large as 5 mm. Volcanic conglomerate contains rounded clasts of felsite rarely as large as 26 x 12 cm. Exposures examined only in the vicinity of Slate Ledge and at the northeastern end of Walker Mountain, Littleton quadrangle

Dlf Crystal tuff

Gray, massive rock composed of blocky, white-weathering feldspar as large as 5 mm, abundant quartz, biotite and probably other minerals. No interlocking grain-structure observed. Nonfoliated but with a prominent jointing that is parallel to one observation of grain-size layering. No thin section yet available. It is possible that this is a granite.

Dgm

Gile Mountain Formation (Lower Devonian)

Meetinghouse Slate Member

Medium dark-gray (N4) to grayish-black (N2) slate to phyllite with minor interbeds of gray metasandstone. Metapelites typically contain small porphyroblasts of crossed biotite and, north of the garnet isograd, euhedral, nonretrograded garnet. Thin graded beds are typical. Identical to rocks in the main body of the Gile Mountain Formation, but is dominantly metapelite. Contact with the main body is placed where metasandstone or siltstone is more than 50 percent of the unit. In an outcrop on the west side of south-bound I-93 (Sheet 1) a continuous section of graded beds across the contact indicates that the Meetinghouse is stratigraphically above the main body of the Gile Mountain, a conclusion also reached by Hatch from evidence elsewhere (1988b)

Dg

Main body

Gray to tan, fine- to very fine-grained metasandstone with interlaminations and beds of dark-gray metapelite and dark-gray (dark-brownish-gray weathering) calcareous metasiltstone. Graded bedding is conspicuous. Bedding thickness overall is irregular, but locally regular sets of graded beds are common. Beds in some regular sets are as much as 2 to 3 m thick.

DSf

Fitch Formation (Lower Devonian and Upper Silurian)

Metamorphosed limestone, calcareous sandstone, siltstone and pelite. Does not crop out in line of Section CC[1]

Sc

Clough Quartzite (Lower Silurian)

White weathering quartzite and calcareous quartzite.

Comerford intrusive suite (informal name) (Silurian(?))

A composite intrusive suite of metamorphosed diabase, gabbro, pegmatitic gabbro, diorite, tonalite, and aplite. Abundant mafic dikes of the suite are well exposed in the spillway of Comerford Dam on the Connecticut River about 100 to 200 m west of the west edge of the Lower Waterford quadrangle. The suite is bounded on the west by the Monroe fault against which the rocks of the suite are strongly sheared. Away from the fault massive parts of the suite are not foliated, whereas many of the dikes possess the same foliation as the rocks that they intrude. Mafic dikes interpreted to be part of the suite intrude western belts of the Orfordville and Albee Formations and the Ammonoosuc Volcanics. The western boundary of unit Scs is placed at the westernmost screen of country rock, which in the area mapped is of the Albee Formation

Scm

A composite intrusive of metamorphosed diabase, gabbro, pegmatitic gabbro, diorite, tonalite and aplite. The composite intrusive is well exposed in a large abandoned quarry 50 m west of the west edge of the Lower Waterford quadrangle at lat 44°20.4'N. In the least altered rocks the primary mafic mineral in both the gabbro and tonalite is hornblende with or without biotite. Apatite, titanite, and magnetite are common accessory minerals. Tonalite contains as much as 25 percent quartz. Secondary minerals include pale amphibole, chlorite, epidote-clinozoisite, leucoxene and calcite. The petrography of the metadiabase is as described in unit Scs. No systematic age relationship is apparent among the components of the suite although aplitic veins appear to be the youngest. Some contacts between the components are sharp, others are gradational

Scg

Metamorphosed pegmatitic gabbro.
Mapped where dominant rock type. Composed mostly of plagioclase and hornblende with prominent apatite and some biotite. Hornblende may contain cores of clinopyroxene. Grain size is generally measured in cm. Local concentrations or hornblende contain crystals as long as 15 cm. Near the 1040+ ft summit 2.5 km S 80° W of West Waterford, Lower Waterford quadrangle, the pegmatitic metagabbro contains as much as 15 percent magnetite. Plagioclase-rich pegmatites (as much as 85 percent plagioclase) 15 to 30 cm thick cut the pegmatitic metagabbro. In one of these hornblende crystals as long as 8 cm extend from the pegmatite walls toward the center of the vein

Sheet 2 Scs

Sheet 3 Scs

Mafic sheeted dikes. Mapped where dikes constitute 50 percent of outcrops. The eastern boundary of this unit is gradational and clearly approximate. It is shown on Sheet 1 as "scratch boundary" (on a full color map, the color or pattern representing the unit would end without showing a line contact). The position of this boundary is not stratigraphically controlled. The percentage of dikes decreases rapidly east of the boundary and in general beyond one km, dikes correlated with the Comerford intrusive suite constitute less than 5 percent of the outcrops. In addition to the Comerford Dam spillway, the dikes are well exposed in the Waterford Sand and Gravel, Pike Industries quarry west of Chandler Brook at the southern border of the Concord quadrangle and in road cuts along I-93 north of the saddle between Hurlburt Hill and Badger Mountain, southern Concord quadrangle. Dikes constitute about 20 percent of the long road cut on the east side of north bound I-93 through this saddle (not mapped as Scs) but constitute more than 90 percent of the road cut 200 to 300 m to the north. Dikes may be aphyric or porphyritic. In some, plagioclase laths up to 5 mm long constitute 10 to 15 percent of the rock. In others, stubby plagioclase phenocrysts 3 or more mm thick constitute 20 percent, and some dikes contain both plagioclase and pyribole phenocrysts. Many dikes have relict diabasic texture but if they originally contained pyroxene, it has been replaced by various combinations of pale amphibole, biotite, chlorite, epidote-clinozoisite and calcite. Some dikes resemble weathered carbonates, are punky weathering with a brown weathering rind, and contain secondary white mica and as much as 25 percent calcite. Dikes range in thickness from a few cm to about 10 m. Chilled margins are common on one or both sides. No preferred side of chilling has been observed. Some dikes contain angular xenoliths of pegmatitic gabbro thought to be Scg

Sheet 2

Scd

Metadiabase. Shown on Sheets 2 and 3 to indicate recorded location and attitude of individual dikes within the Comerford intrusive suite

Sheet 3

Scd

Op

Partridge Formation (Upper or Middle Ordovician)

Dark-gray to black, rusty-weathering sulfidic and graphitic slate exposed along I-93 and NH-18, Littleton quadrangle

Ohh

Highlandcroft Plutonic Suite

Highlandcroft pluton (Late Ordovician)

Highlandcroft Granodiorite of Billings (1937). Heavily sheared green granite with microcline, quartz, sericitized plagioclase, chloritized biotite, calcite and opaques (Lyons and others, 1986). 450±5 Ma U-Pb zircon age by Lyons and others (1986).

Ohj

Hypabyssal metatonalite of the Joslin Turn pluton (Middle Ordovician)

Medium-grained, greenish-gray to light-brownish gray, much shattered and annealed metatonalite. Consists of quartz, plagioclase, chloritized biotite, opaques (both magnetite and pyrite), and apatite. Secondary minerals include chlorite, epidote, calcite, and sericite. Granophyric intergrowths of quartz and plagioclase suggest hypabyssal intrusion. 469±1.5 Ma U-Pb zircon age by Aleinikoff and Moench (1992). Interpreted by Aleinikoff and Moench (1992) to be intrusive into and comagmatic with the lower part of the Ammonoosuc Volcanics (Oaf), and here interpreted to be an intrusive along and near the contact between Oal and Oaf. Exposed along Halls Brook upstream from Joslin Turn and under power line southwest of that, Littleton quadrangle

Oar Metamorphosed rhyolite dikes (Ordovician)
Shown on Sheet 2. Only one dike observed, which intrudes the Joslin Turn pluton

Oai Metamorphosed mafic to intermediate dikes (Ordovician)
Shown on Sheets 2 and 3. Unit on Sheet 2 indicates area where dikes constitute 5 to 50 percent of the outcrops. Symbols record observations of attitudes of individual dikes within the swarm. Shown on Sheet 3 to record location and dips of individual dikes within the swarm. Chilled margins common; some dikes bifurcate and crosscut bedding at a low angle. Dikes intrude the eastern belt of the felsic Ammonoosuc Volcanics (Oaf) adjacent to the Joslin Turn pluton. Well exposed in road cuts at the intersection of I-93 and NH-18, east edge of Lower Waterford quadrangle

Ammonoosuc Volcanics (Upper and Middle Ordovician)
Thick sequence of metamorphosed tuffaceous rhyolitic and andesitic volcanic and volcaniclastic rocks. In the map area, rhyolite is probably younger than andesite. Clear intrusive relationship between the Ammonoosuc and either the Joslin Turn pluton or Highlandcroft pluton is not established in the map area; the Ammonoosuc may be in part coeval with the plutons. Felsic tuff (Oaf) exposed in the spillway of Moore Dam contains rare clasts of sheared tonalite that could be of the Joslin Turn pluton

Oaf Metamorphosed rhyolitic tuff, lapilli tuff and tuff breccia.
Includes crystal-lithic and lithic-crystal layered tuff and some welded tuff. Strongly foliated with waxy sheen on foliation surfaces of finer grained rocks. Most rocks dark-greenish-gray (5G 4/1), greenish-gray (5G 6/1), light-bluish-gray or medium-bluish-gray (5B 7/1). Crystals (commonly broken) in the tuff include plagioclase and(or) quartz, some of which is embayed. Pyrite cubes as large as a few mm are common in some outcrops. Secondary knots of epidote. No confirmed lava flows, but a foliated but otherwise homogeneous metarhyolite containing 3 percent phenocrysts of plagioclase (some cumulophyric) beside the power house of Moore Dam, Lower Waterford quadrangle, is a

candidate. Excellent exposures may be found along I-93 along Moore Reservoir in New Hampshire and in the spillway of Moore Dam. In the south-central part of Sheet 1 (Lower Waterford quadrangle) between Reynolds Pond and the Albee Formation on Foster Hill gray phyllite and laminated siltstone are interlayered with felsic crystal tuff. Some interlayered phyllite, particularly near the Albee contact, is very dark gray and sulfidic, closely resembling the Partridge Formation. One dolostone bed occurs close to the contact

Oaa

Metamorphosed dark-greenish gray (5G 4/1) or medium-bluish-gray (5B 5/1) andesitic tuff, crystal tuff and tuff breccia. Strongly foliated but foliation surfaces not as waxy as the metarhyolites. Some bedded tuff and crystal tuff. Some hornblende andesite tuff breccia: has rounded clasts of hornblende andesite up to 20 cm across containing 15 percent hornblende phenocrysts in matrix of hornblende andesite. Some clasts are deformed against one another, suggesting that they were not totally solidified when emplaced. The source for these cannot have been far away. Much of the tuff is exceedingly fine grained or aphanitic and the mineralogy includes chlorite, sericite, epidote, calcite, some biotite. No lava flows have been identified. The first outcrop along east bound I-93 east of Moore Reservoir superficially resembles a pillow lava because of weathering pits. Close inspection shows that the rock is a tuff breccia in which the breccia fragments contain amygdules, and that the weathering pits are rims around epidosite seggregations many cm across. Excellent exposures along I-93 east of Moore Reservoir, Littleton quadrangle

Oam

Interlayered metamorphosed rhyolitic and andesitic volcanic and volcaniclastic rocks. The volcanic rocks are similar to those described above, but layered irregularly on outcrop-scale

Albee Formation (Ordovician or older)

The unit is redefined to include sharply interbedded light-colored metasiltstone, phyllite, quartzite, and minor metamorphosed impure dolostone exposed on the summit and northwestern slope (down to the lowest outcrops) of Albee Hill. A volcanic member is exposed on the northern slope of Fuller Hill

Oal

Main body

Sharply interbedded light- to medium-gray or bluish-gray or greenish-gray metasiltstone, phyllite, quartzite, minor metamorphosed impure dolostone and

olive-gray (5Y4/1) felsic metatuff. Metasiltstone is dominant, typically white-weathering, and may be tuffaceous. Some metasiltstone is calcareous with as much as 25 percent dolomite. Some phyllite and metasiltstone is highly sulfidic with pyrite cubes and clusters as large as 5 x 2.5 cm. Locally quartzite beds are as much as 3 m thick and are locally abundant. Eric and Dennis (1958) mapped a zone of abundant quartzite across Hurlburt and Fuller Hills. Such a zone is not confirmed by the present mapping. Locally quartzite is prominent near the contact with the underlying Orfordville Formation on the southwest ridge of Hurlburt Hill and on the steep southeast slope ridge about 2 km WNW of Joslin Turn. Tourmaline is an accessory mineral in some quartzite. Bedding thickness is quite variable; most bedding contacts are sharp but graded beds ("fast" grades, i.e. grading over a short thickness) are locally common. In addition to the Albee Hill exposure, excellent exposures are found on the east slope of Hurlburt Hill near section BB', Lower Waterford quadrangle under an east-west trending power line (not on topographic base) that crosses VT 18 at an elevation of about 1000 ft near the eastern border of the Concord quadrangle, under the power line between Whites Corner and Shadow Lake, and on Foster Hill, Lower Waterford quadrangle in New Hampshire.
Felsic lapilli tuff crops out in one of the screens within the sheeted dike complex (Scs) in the spillway of Comerford Dam

Oalf

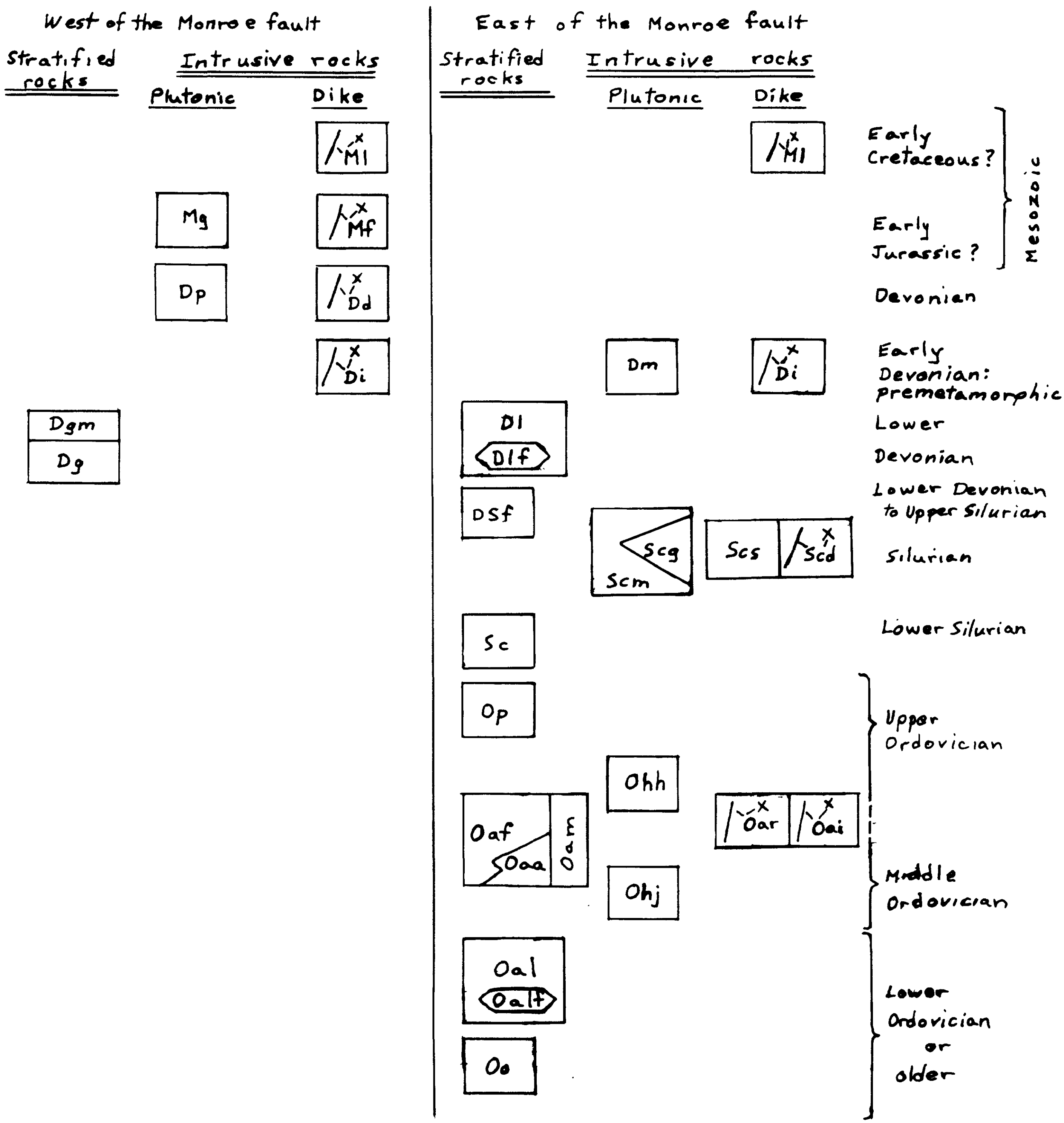
Felsic volcanic rocks
Light blue-gray felsite, some quartz and(or) feldspar phyric, some aphyric. Lapilli tuff and tuff breccia indicates that at least some of the volcanic activity was explosive. Metamorphic biotite visible in many rocks. Scattered pyrite cubes as large as 1 cm. Locally, felsite is associated with dark purple slaty siltstone. Forms a mappable unit along the northwest slope of the Fuller Hill

Oo

Orfordville Formation (Ordovician or older)
Dark-gray phyllite, light- to medium-gray metasiltstone and very-fine grained metasandstone and minor light-gray, punky brown-weathering metamorphosed impure dolostone. Phyllite and metasiltstone/sandstone are typically sulfidic (either pyrite or pyrrhotite) and rusty weathering. White mica is a prominent mineral in the metamorphosed dolostone. The pelite-arenite units are thin- to medium-bedded and many are graded. Channelling is common and in places soft sediment deformation is clearly demonstrable. Well exposed on the 1360+ ft hill north-northwest of Lower Waterford and in a pavement outcrop at an elevation of about 800

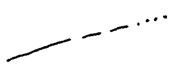
ft northeast of the bridge of I-93 over VT-18 beside a secondary road shown on the map (now abandoned)

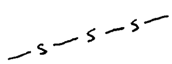
CORRELATION OF MAP UNITS



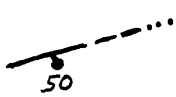
EXPLANATION OF MAP SYMBOLS

Where two or more symbols for planar or linear features are combined, their intersection marks the point of observation. Where a planar feature and linear feature are combined, the center of the planar feature marks the point of observation. For linear symbols alone the base of the arrow marks the point of observation.


Contact, dashed where approximately located, dotted where covered by water

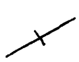

Scratch contact. On a colored map the line would mark the end of one color or overprinted pattern with no contact shown, here used to show eastern limit of abundant dikes in the Albee Formation

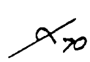

Ductile fault, broken where approximately located; Teeth on upper Plate 2



Brittle fault, ball or downthrown side, if known. Angle of dip given if known. Dashed where approximately located, dotted where covered by water

Strike and dip of inclined bedding, ball indicates younging direction of beds known from sedimentary features


Strike of vertical bedding

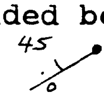


Strike and dip of overturned bedding

Generalized bedding

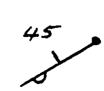
Symbols used for sedimentary features by which the younging direction was determined

Graded bedding

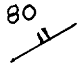


Cross bedding

Channelling



Symbols used for dikes (shown only on Sheet 2): unless otherwise labelled, all dikes are interpreted to be of the Comerford intrusive suite (Scd)

 Strike and dip of inclined dike

 Strike of vertical dike

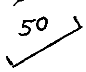
 Trend of dike, dip not known

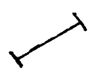
 Location of dike, no measurement

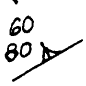
 Strike and dip of S_2 foliation. Axial planar to F_2

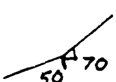
 Strike of vertical S_2 foliation

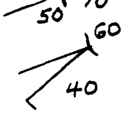
 Generalized strike and dip of inclined S_2 foliation

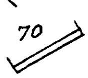
 Strike and dip of inclined S_3 crenulation cleavage. Axial planar to F_3, folds (Acadian)

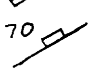
 Strike and dip of vertical S_3 crenulation cleavage

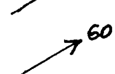
 Strike and dip of parallel bedding and S_2 foliation where bedding and foliation have same strike but different dips. Dip of bedding is indicated by number at head of bedding symbol. Similar combinations are used with respect for bedding and S_3 crenulation cleavage

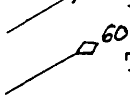
 Strike and dip of intersecting bedding and S_2 foliation

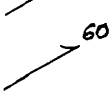
 Strike and dip of intersecting bedding and S_3 crenulation cleavage

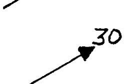
 Strike and dip of spaced cleavage southeast of Monroe fault

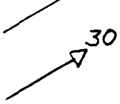
 Strike and dip of prominent joint set

 Trend and plunge of mineral lineation

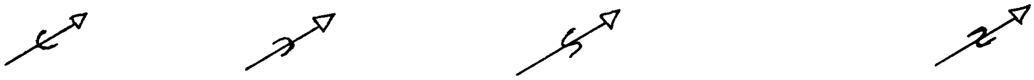
 Trend and plunge of slickensides

 Trend and plunge of intersection of bedding and S_2 foliation

 Trend and plunge of F_3 fold axis (Acadian)

 Trend and plunge of F_2 fold axis (probably Acadian) May include some F_1 fold axes

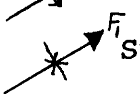
Other information about folds; can be used for either generation



syncline   anticline   S-fold, looking down plunge   Z-fold, looking down plunge

Macroscopic F_1 folds

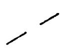

Anticline


Syncline

 On Sheet 3 (cross-sections), facing direction of strata where known from sedimentary features

On Sheet 3 (cross-sections), apparent dip of planar features shown as light lines under ground surface

 Bedding

 Crenulation cleavage

 Form lines of bedding

▲ On Sheet 2, sample location of metasedimentary rock in which the named minerals coexist with quartz and muscovite

Chl, chlorite

Bi, biotite

gar, garnet