BEDROCK GEOLOGY OF THE CAMELS HUMP-BOLTON MOUNTAIN AREA, NORTH-CENTRAL VERMONT

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Cover Photograph: View of Camels Hump (Elevation 4083 feet) from the west.

ABSTRACT

Late Proterozoic to Cambrian age rocks exposed in the core of the Green Mountains in the Camels Hump-Bolton Mountain area consist of the Camels Hump Group (Pinnacle, Underhill, Hazens Notch, Mount Abraham and Pinney Hollow Formations), the Ottauquechee Formation, and possibly Sweetsburg Formation. Although age relations among the units of the Camels Hump Group remain uncertain, pace-and-compass mapping at a scale of 1:24,000, with selected areas mapped at 1:9,000 and 1:3,000, confirms that Christman and Secor's (1961) map units are viable. The Underhill type locality described by Christman and Secor is inadequate. The summit (The Chin) on Mount Mansfield is more precisely located, and is typical of the unit described by Christman and Secor. The Underhill Formation is typically a silver-green, magnetite-bearing schist. Schists of the Hazens Notch have abundant graphite and rusty weathering. A transitional unit characterized by non-rusty weathering, tourmaline, and lack of magnetite can be mapped in some areas. Greenstones are rare in the Underhill in the Camels Hump-Bolton Mountain area, whereas they are common in some of the Hazens Notch. Slices of non-greenstone-bearing graphitic schists which contain carbonates are intercalated with the Underhill at the deepest structural levels, and may correlate with a more proximally deposited unit (Sweetsburg?) than the Hazens Notch.

Greenstone geochemistry suggests tectonic settings for the Underhill and the Hazens Notch Formations, but must be used with care due to the possible emplacement of greenstones along faults, and to the small number of samples analyzed. Greenstones in both formations are transitional between continental and mid-ocean ridge basalt compositions, with the Underhill more proximal than the Hazens Notch. Based on Ti/P ratios, the Hazens Notch in the Camels Hump-Bolton Mountain area appears more proximal than Hazens Notch reported from other areas.

At least three periods of deformation occurred. Evidence for early west-directed (D1) isoclinal folds and thrust faults is poorly preserved. Greenstone-bearing Hazens Notch rocks were thrust westward along the Bolton thrust zone during D1. Some of the Taconic slices may have been derived from this zone. The major F2 structure of the Camels Hump-Bolton Mountain area is a large overturned, east-facing syncline. East-directed (D2) backfolds, shear zones, and reactivated D1 faults are associated with pervasive foliation (S2) parallel to the axial planes of isoclinal F2 minor folds. Post-peak metamorphism faults, including the Honey Hollow fault, cut F2 folds and S2 foliation. The Green Mountain anticlinorium (D3) deforms all pre-existing structures. F3 minor folds are open, with axial planes dipping steeply to the east, and crenulation or spaced cleavage parallel to F3 axial planes in the finer grained rocks.

Peak metamorphism is associated with D2, but exact timing of peak and retrograde metamorphism with deformation has not been determined. Greenstones contain greenschist and epidote-amphibolite facies assemblages. Garnet occurs in pelitic rocks in the core of the anticlinorium.

INTRODUCTION

LOCATION AND PHYSIOGRAPHY

In north-central Vermont the Winooski River cuts across the Green Mountain anticlinorium, exposing late Proterozoic to Cambrian age rocks assigned to the Camels Hump Group. The study area of this report lies within four U.S. Geological Survey 7.5- minute quadrangles: Huntington, Waterbury, Richmond and Bolton Mountain. The area extends from the village of Jonesville at the west edge to Waterbury in the east, and from Bolton Mountain at the north edge, south along the axis of the Green Mountains to include Camels Hump (see Plate 1).

Camels Hump (elevation 4083 feet) is one of the highest mountains in the state, while the Winooski River, located about 3.5 miles north of the summit is at an elevation of only 400 feet. The Winooski River valley bisects the study area from east to west while several smaller valleys, notably Duck Brook, Pinneo Brook, Joiner Brook, Preston Brook, Gleason Brook, and Ridley Brook, trend mostly north and south.

Road access in the area is limited to the major valleys. The Long Trail follows roughly along the crest of the Green Mountains from Bolton Mountain to Camels Hump, crossing the Winooski River at Jonesville. There are numerous side trails in the Camels Hump area. Bolton Valley Ski Area ski trails provide access to the western slopes of Ricker and Bone Mountains and the upper parts of Joiner Brook valley. Abandoned sections of the Long Trail can be followed on the ridge east of Duck Brook and on Robbins Mountain.

PREVIOUS WORK AND REGIONAL GEOLOGIC SETTING

Reconnaissance studies by E. Hitchcock (1861), C.H. Hitchcock (1884) and Jacobs (1938) covered parts of the Camels Hump-Bolton Mountain area. The first geologic map of the Camels Hump 15-minute quadrangle, by Christman and Secor (1961), was based on field work done during the summers of 1958 and 1959. Doll, et al. (1961) incorporated Christman and Secor's work in the Centennial Geologic Map of Vermont. During the 1970's several students from the University of Vermont conducted detailed studies of parts of the Camels Hump quadrangle, including Thresher (1970; 1972), Eiben (1976), and Aubrey (1977).

The late Proterozoic Camels Hump Group is exposed in the center of the Green Mountain anticlinorium, and covers a twenty-mile-wide area at the latitude of the Winooski River (Doll, et al., 1961). The crest of the anticlinorium lies approximately halfway between Jonesville and Waterbury, close to the summits of Camels Hump and Bolton Mountain (Plate 1). The axial trace forms an en echelon pattern, offset eastward to the north. Along the crest there is a mile-wide zone of fairly flat-lying rocks. The Camels Hump Group consists of highly deformed and metamorphosed volcanics, graywackes, pelitic schists and quartzites.

The apparent lack of symmetry in rock units across the anticlinorium was explained by Christman and Secor (1961) as facies interfingering between Underhill and Hazens Notch Formations. Eiben (1976) concluded that earlier phases of folding unrelated to the anticlinorium were important in controlling the map pattern. He mapped out greenstones and several types of schist around Stimson Mountain as different members of the Underhill Formation (Plate 1, E11-14 to H11-14). Aubrey (1977) followed a similar interpretation, but suggested that some of the rocks might belong to other formations of the Camels Hump Group (Plate 1, F15-19 to I 16-20).

Stanley and Ratcliffe (1985) proposed that early faults, as well as facies changes and folds, must be considered in the interpretation of map patterns within the Group. The Camels Hump Group is continuous to the south with rocks along the east side of the Green Mountain anticlinorium, which may contain the root zone for the Taconic allochthons (Stanley and Ratcliffe, 1985). Geochemical analysis of greenstones within the Camels Hump Group (Coish, 1987; 1989) suggests that they were deposited over a range of continental and transitional rift environments. Greenstones to the east have basaltic compositions progressively more oceanic in character.

The rocks of the Camels Hump-Bolton Mountain area thus were situated along the western margin of the Iapetus Ocean before the basin closed during Ordovician time. Because of the extent to which imbricate thrust faults and folds developed during the closure (Taconian orogeny), it is difficult to reconstruct the relative stratigraphic positions of the units. The corresponding zone of structural complexity along strike to the north in Quebec is described by St-Julien, et al. (1983) as the "Internal Domain".

METHODS

Field mapping was done on U.S. Geological Survey 1:24,000 topographic maps. Mapping included pace-and-compass traverses, with an altimeter used to determine elevations. The Long Trail and most side trails on Camels Hump were mapped. Detailed mapping was done in three areas at a scale of approximately 1:9,000, and in one area at 1:3,000. We have incorporated Eiben's (1976) and Aubrey's (1977) work, with modifications in assignment of units (Table 1) and in structural interpretation. Eiben's and Aubrey's field areas are delineated on Plates 2 and 3. They both mapped at a scale of 1:12,000, following north-south traverses spaced at 50 feet, so that they visited nearly every outcrop. (Eiben's outcrop locations are shown on Plate 1. Outcrop locations were not available for Aubrey's area.)

We found field magnets to be indispensable in differentiating some of the formations. Locally the outcrops contain so much magnetite that compass readings are unreliable.

TABLE 1

ASSIGNMENT OF EIBEN'S (1976) AND AUBREY'S (1977) UNITS TO FORMATIONS USED IN THIS REPORT

SOURCE: SYMBOL	LITHIC DESCRIPTION	FORMATION ASSIGNED (SYMBOL)
Eiben: Ꞓumg	Magnetite schist	Underhill (ꞒZu)
Ꞓug	Albite granulite	Mostly Underhill (ꞒZu); some ꞒZp and ꞒZhn
Ꞓurs	Rusty albite schist with granulite and marble lenses	Hazens Notch (ꞒZhn and (ꞒZhnn)
Ꞓursg	Granulite (mislabelled on Eiben's map as Ꞓurs)	Pinnacle (ꞒZp)
Ꞓugs	Heterogeneous rusty graphitic schist with black quartzites, tan carbonates, siliceous granulites.	Hazens Notch (ꞒZhn) or (?Ꞓs, see discussion)
Ꞓugr	Greenstone and amphibolite	Hazens Notch (g)
Aubrey: Ꞓuag	Albite gneiss	Hazens Notch (ꞒZhn)
Ꞓursl	Lower rusty schist	Hazens Notch (ꞒZhn (or ?Ꞓs, see discussion)
Ꞓursu	Upper rusty schist	Hazens Notch (ꞒZhn)
Ꞓugs	Gray quartzitic schist and gray-green magnetite schist	Underhill (ꞒZu)

Thin sections were made of eleven pelitic rocks and of ten greenstones. Modes were estimated for the greenstones by Cornell College student, Donald Callen. Thirteen greenstone samples were sent to R. A. Coish at Middlebury College where P.A. Pugin did major and trace element geochemical analyses, which are presented later in this report. Jo Laird, University of New Hampshire, used the electron microprobe to study amphiboles in three greenstone samples, and her observations are discussed in the section on metamorphism.

STRATIGRAPHY

INTRODUCTION

Christman and Secor (1961) defined the basic map units in the Camels Hump quadrangle. We have found their formation descriptions valuable and workable. However, detailed mapping shows that the map pattern is more complicated than Christman and Secor's interpretation. Christman and Secor mapped most of the central part of the quadrangle as Underhill Formation partly because most of the prominent ridges and ledges do indeed consist of the more resistant Underhill. We have separated out areas that should have been mapped as Hazens Notch Formation. For example, Christman and Secor mapped three patches of Hazens Notch west of Camels Hump. Identical rocks can be followed from one of these patches (on Bald Hill, Plate 1: D25) northward to connect with graphitic schists mapped by Eiben northwest of Stimson Mountain (Plate 1: F10) and on to the north edge of the study area. Careful mapping of greenstones has also helped to define the map pattern. The greenstones, however, should not be considered a marker horizon, as there is no evidence in the field area that the greenstones were once a single layer. Age relations among the units in the Camels Hump Group remain uncertain and the order of rock descriptions below may not reflect their relative ages. Mafic dikes, probably of Jurassic age (McHone, 1978), mostly follow prominent east-west joints.

PINNACLE FORMATION (€Zp)

Christman and Secor (1961, p. 14) described the Pinnacle Formation as containing "principally thick sections of [meta]graywacke with some interlayered [phyllite and schist]". Thresher (1972) assigned graywackes which contain biotite and stilpnomelane to the Pinnacle (his Huckleberry Hill Member), and assigned graywackes containing chloritoid instead of biotite to the Underhill Formation (his Duck Brook Member). We have mapped Pinnacle graywackes along the western edge of the study area (Plate 1: A13 to D4), where they contain biotite and blue quartz pebbles. Graywacke lenses, usually lacking in biotite, are common within the Underhill Formation, especially west of the Honey Hollow fault (Plate 1: A29 to F4). The criteria for distinguishing these formations will need to be refined as detailed mapping progresses west toward Richmond. The relationship between these formations in the Gilson Mountain and Jeffersonville quadrangles seems to be that the Underhill is in part a distal facies of the Pinnacle, and in part younger than the Pinnacle (Doolan, et al., 1987, p. 172; Mock, 1989).

Several bodies of quartz-feldspar-biotite gneiss east of the Honey Hollow fault are assigned to the Pinnacle Formation (Plate 1: B24, F23, E14, G12, and H7) on the basis of their mineralogy and massive layering, despite the fact that most of these bodies are surrounded by Hazens Notch Formation. The most accessible of these outcrops (location E14) is 1.7 miles east of Jonesville along Route 2. The Hazens Notch Formation also contains other gneisses which look less like metagraywackes, such as those mapped separately as albitic gneiss by Aubrey (1977). Aubrey's albitic gneisses are not shown separately on our Plate 1.

UNDERHILL FORMATION, sensu stricto (ЄZu)

We have mapped rocks as Underhill Formation using stricter criteria than Christman and Secor (1961), Doll, et al., (1961), Eiben (1976) and Aubrey (1977). This approach results partly from field experience near Bakersfield, Vermont (Thompson, 1975), and also from the conviction that Cady, et al. (1962), Cady, et al. (1963), and Christman and Secor (1961) defined the formations quite strictly, although mapping at a scale of 1:62,500 did not allow detailed separation of the units. Christman (pers. comm., 1987) found that "each unit contained local layers similar to all the other units". The distinction was perhaps less important for earlier workers who viewed the interlayering of rock types as due mainly to facies relationships without additional structural interlayering along faults or shear zones.

The Underhill consists mainly of silver-green, magnetite-bearing chlorite-muscovite-quartz (-albite) schist and gneiss. Some layers are very rich in albite whereas other layers lack feldspar entirely. Biotite and garnet are rarely present. Rocks of the Underhill are relatively resistant to weathering and form many of the cliffs on both sides of the Winooski River in Bolton, as well as the summits of Camels Hump and Bone Mountain.

The type locality for the Underhill Formation is vague: "Underhill township in the northern part of the Camels Hump quadrangle and in the southern part of the Mount Mansfield quadrangle" (Christman and Secor, 1961, p. 18). The Underhill Formation caps The Chin on Mount Mansfield, which we propose as a more precise type locality. The rocks on The Chin fit Christman and Secor's lithic description and are within the town of Underhill. The Chin is the highest point on Mount Mansfield and can be reached by a one-mile hike north from the top of the Toll Road. The Underhill Formation is well exposed from the gondola terminus to the summit. Christman (1959, p. 33) includes petrographic data for several samples from this area. Excellent exposures in our field area can be seen where the road to Bolton Valley Ski Area crosses Joiner Brook (Plate 1: I8, elev. 1300').

The Underhill contains local layers and lenses of quartz-feldspar granulite and white quartzite, usually less than a meter thick and discontinuous along strike. The quartzites weather light gray to pinkish tan, and contain 5-10% muscovite and accessory pyrite. Among the more prominent quartzites are the following on Plate 1: A28 (elev. 1260'), J23 (elev. 1900'), L14 (elev. 1240'), and within the body of Underhill north of Stimson Mountain (G9 to H6).

Magnetite is present in nearly all outcrops of the Underhill, either as conspicuous porphyroblasts or as finely disseminated grains. Modes for Underhill Formation samples estimated by Christman and Secor (1961, p. 19) generally indicate one to two percent magnetite. Pyrite may be present, but it is rarely abundant enough to impart rusty weathering to the rocks (in contrast to the Hazens Notch Formation where rusty weathering and pyrite occurrences are common). Rocks within the Underhill which are similar to a pyrite-bearing schist of the Pinney Hollow Formation (Plate 1: W20) were observed at one location (Plate 1: J8, elev. 1720'). Local dark silver-blue horizons may contain minor graphite, but graphite is generally not abundant in the Underhill. Magnetite and non-rusty weathering are thus the chief field criteria used in distinguishing the Underhill from the Hazens Notch.

West of the mapped area, the Underhill Formation is a finer grained, somewhat rusty weathering phyllite, which lacks albite and contains many greenstone horizons such as those near Huntington and Gillett Pond (Christman and Secor, 1961; Coish, et al., 1985). On strike to the south, the greenstone-bearing Underhill (for example, the undifferentiated Underhill of Tauvers (1982) east of the "Underhill thrust") lies east of the garnet isograd and is therefore coarser grained and more similar to Underhill in the area we have mapped except for the presence of greenstones (mafic schists). We have mapped very few greenstones (€Zug) entirely within the Underhill (see Plate 1, G7, M11, and L16). Excellent exposures of magnetite-bearing greenstone along the power lines west of Pinneo Brook (L16) grade upward into Underhill albitic gneiss and schist. Because of the gradational contact we have included them with the Underhill. (See discussion of greenstone chemistry under Hazens Notch Formation.)

MOUNT ABRAHAM FORMATION (€Za)

The Mount Abraham Formation is a fine grained, chlorite-paragonite(?)-quartz (-muscovite-kyanite-garnet-chloritoid-magnetite) schist typically lacking visible albite. Foliation surfaces have a distinctive silvery appearance, often somewhat rusty, and often speckled by tiny chloritoid porphyroblasts. Garnet is common in the Mount Abraham schists around Wind Gap (Plate 1: H28).

Mappable layers of Mount Abraham schist are found only in the southernmost part of the field area, where they are in association with both Underhill and Hazens Notch Formations (Plate 1: B27 to 29, C25 to 26, F27, G28, and H27.) Elsewhere, notably on the eastern and northern slopes of Camels Hump and on Robbins Mountain (Plate 1: H25 elev. 3320', K19 elev. 2000', and B19 elev. 1320') Mount Abraham-like schists are interlayered within the Underhill Formation at thicknesses ranging from a few centimeters to several meters, occasionally to tens of meters. Thus, in most areas Mount Abraham-like rocks cannot be separated from Underhill Formation at a scale of 1:24,000. The stratigraphic relationship between the Mount Abraham and Hazens Notch is not well demonstrated in our area because most contacts are faults.

HAZENS NOTCH FORMATION (€Zhn, €Zhnn, g)

The Hazens Notch Formation is the most heterogeneous unit mapped. The Hazens Notch Formation was defined by Cady, et al. (1963) as graphitic schist and phyllite and dark quartzite; the ledges north of Route 58 in Hazens Notch were designated as type locality. Christman and Secor (1961) mapped a contact between Underhill and Hazens Notch Formations east of, and parallel to, the anticlinorial hinge. Their contact corresponds very roughly with the eastern limit of the major part of the Underhill Formation on our Plate 1 (M1 to M29). However, we have also mapped numerous lenses of Hazens Notch Formation west of this contact. There is good field evidence that some of these lenses are in fault contact with the Underhill (see later discussion of structures), and we interpret most of these lenses as tectonically emplaced (Plate 4).

Rocks of the Hazens Notch Formation consist of rusty-weathering, sulfidic, chlorite-muscovite-biotite-quartz-pyrite (-albite-garnet) schists and gneisses, interlayered, on a scale ranging from about a centimeter to several meters, with strongly graphitic, black schists with similar mineralogy. Magnetite is absent. Albite ranges from white to black depending on the abundance of graphite inclusions. The color variation has no systematic geographic distribution. There are local horizons of dark gray quartzite, and lenses of tan-weathering carbonate. Numerous layers of greenstone and amphibolite occur within the Hazens Notch.

Eiben (1976) mapped a detailed stratigraphy on Stimson Mountain which we interpret as an imbrication of rocks from the Underhill, Hazens Notch, and possibly Pinnacle Formations. Although Aubrey (1977) also assigned all the rocks in his area to the Underhill, he suggested that the graphitic rocks might be Hazens Notch or Ottauquechee. Table 1 shows how we have reassigned Eiben's and Aubrey's units. Those of Eiben's rocks belonging to the Hazens Notch are: rusty albite schist with local lenses of granulite and marble; rusty graphitic schist with 1-5 cm. black quartzites and local tan carbonates; deep red, rusty micaceous schist; light gray garnet schist with quartz laminae; and greenstone.

Non-graphitic rusty schists which are extensive enough to map have been shown separately on Plate 1 as €Zhnn, notably from Stimson Mountain (G12) north to the ridge at I5 and I6, southwest of Bone Mountain (J11), near the summit of Bolton Mountain (M1) and as fault slivers northwest of Bolton Falls Dam (N14-16) The non-graphitic rusty schists commonly contain conspicuous tourmaline, lack magnetite, and are somewhat less chlorite-rich than the Underhill. They are grouped with the Hazens Notch Formation because they most resemble the non-graphitic schist which is interlayered on a small scale with graphitic schist in typical Hazens Notch. They may represent a transitional facies between the Hazens Notch and the Underhill.

Tan-weathering dense gray dolomitic carbonate pods are locally abundant in the Hazens Notch Formation (shown by "c" on Plate 1; for example, an excellent exposure in Joiner Brook at H11). They occur mainly in deeper levels in the core of the anticlinorium. The presence of carbonates is the chief reason for the tentative assignment of some parts of the Hazens Notch to Sweetsburg(?) Formation on Plate 4 (see discussion below).

Discontinuous layers of somewhat micaceous quartzite, ranging in color from white to bluish black, depending on graphite content, are present in some areas. Quartzites occur in the Sweetsburg(?) rocks, and are also common in the eastern part of the Hazens Notch (Plate 1: U10, T18, V19, and R27). The thin layers of Hazens Notch west of the Honey Hollow fault also contain black quartzites, especially in Duck Brook (Plate 1: D10), and south of Robbins Mountain (A20). These layers may also be Sweetsburg(?), although no carbonates were found. Distinctive thin white quartzites and quartz conglomerates of unknown affinities are interlayered with schists and greenstones in a complex area north of Route I-89 (Plate 1: O13-O17).

A very curious dolomitic breccia occurs as an isolated outcrop on the east bank of Ridley Brook (Plate 1: N19, elev. 510'). A dolomitic matrix surrounds rounded quartz granules and angular dark gray to white carbonate clasts. The rock is possibly a boulder, but its very large size (15 m. x 20 m.) and angular shape suggest an outcrop. It may be a block brought in along a fault.

Except for a meter-thick layer of possible talc schist associated with tan weathering marble on Route I-89 east of Bolton Falls (Plate 1: R17), we have not found any ultramafic rocks in the Hazens Notch Formation in the mapped area. We could not relocate the talc body reported by Christman and Secor (1961) near a branch of Crossett Brook (Q26). Some very fine-grained chlorite-rich rocks were at first thought to contain talc (Thompson and Thompson, 1987), but they do not. Examples of these fine-grained rocks are those collected at stations N204, N614, and N719, found on Plate 1 at locations P17, O15, and O14, respectively.

Greenstones

Discontinuous greenstone layers, locally up to 50 meters thick but usually much thinner, are common within the Hazens Notch Formation in the Camels Hump-Bolton Mountain area. Their mineralogy is highly variable, including chlorite-albite-carbonate-epidote greenstone, chlorite-albite-quartz schist, and Ca-amphibole-albite-epidote-chlorite amphibolite (see Table 2). In the field the greenstones can often be recognized by pitted, irregular weathering and extensive moss growth. White albite porphyroblasts in the green matrix are usually conspicuous and the more amphibole-rich rocks are commonly coarse-grained, with large, felty clumps of dark green hornblende.

Eiben (1976) mapped out greenstone layers west of Stimson Mountain, noting that amphibolite is more common where layers are thickest, especially in fold hinges, whereas mafic schists are found on fold limbs. We have found that the margins of many greenstone bodies are more schistose, perhaps due to shear strain concentrated along contacts with the enclosing rocks. Thin section studies of extremely fine-grained chloritic phyllite from along fault zones north of Bolton Falls (Table 2, sample N719) indicate such rocks are strongly sheared amphibolites. Hornblende is rarely observed in the thinnest bodies. The distribution of the various greenstone types does not present a coherent pattern; the mineralogy commonly changes over short distances along strike. It was impossible to map the different types of greenstones at a scale of 1:24,000.

Despite highly variable mineralogy, the geochemistry of the eleven samples shown in Table 3 is surprisingly similar: all have trace element ratios most like those of modern intraplate basalts (Figure 1A). Average Ti content is intermediate between that of mafic volcanics erupted in continental rift environments (for example, Pinnacle and Underhill greenstones) and that of greenstones derived from mid-ocean rift basalts (for example in the Stowe) (Figure 1B). This intermediate relationship is seen even more clearly on plots of titanium versus phosphorus and scandium (Figures 1C and 1D), although Coish (pers. comm., 1991) has found a much wider range of variation in Ti/Sc ratios for the Underhill (14 samples) than Walsh and Kimball (1989). Ti/Sc ratios for many of our samples plot near the overlap of Coish's Zone 2 (Pinnacle and Underhill) and Zone 3 (Hazens Notch and Pinney Hollow). Most of the samples from the present study have somewhat higher Ti/P ratios than those previously reported for the Hazens Notch (Coish, 1987). Regional implications of the geochemistry are discussed in later sections.

TABLE 2

GREENSTONES FROM CAMELS HUMP-BOLTON MOUNTAIN AREA
MINERALOGY: VOLUME % (MODE)

SAMPLE NO.	N719	N204	N473	N198 +*	N191 +	N496	N496A *	N344A	N344B	N331
PLATE 1 LOC.	O14	P17	O10	O17	M7	L16	L16	N15	N15	O14
ROCK TYPE	CP	GS	GS	GS	GS	A	A	A	A	A
MINERALS:										
chlorite	48	33	40	19	10	---	---	---	---	8
carbonates	---	40	41	5	6	6	---	---	---	---
biotite	X	---	1	5	X	---	28	24	8	X
plagioclase	---	20	X	24	40	57	42	33	39	49
epidote	---	---	---	10	14	12	11	24	5	5
actinolite	45	---	---	---	---	---	---	13	---	---
hornblende	---	---	---	29	25	4	11	---	38	35
opaques	Tr	2	2	1	2	19	8	X	2	1
sphene	7	---	---	7	3	2	---	6	10	X
apatite	---	X	---	---	X	X	X	X	X	X
quartz	---	5	15	---	---	---	---	---	X	1

Explanation:

* = sample also analyzed by Coish and Pugin (See Table 3 and text).
+ = sample also studied by Laird (zoned with actinolite: see text under Metamorphism).

CP = Chlorite phyllite; **GS** = Greenschist; **A** = Amphibolite

X = < 1%; **Tr** = Trace; **---** = not present

Modes estimated by D. Callen, 1988.

TABLE 3

GREENSTONES FROM CAMELS HUMP-BOLTON MOUNTAIN AREA
GEOCHEMISTRY: MAJOR AND TRACE ELEMENT ANALYSES

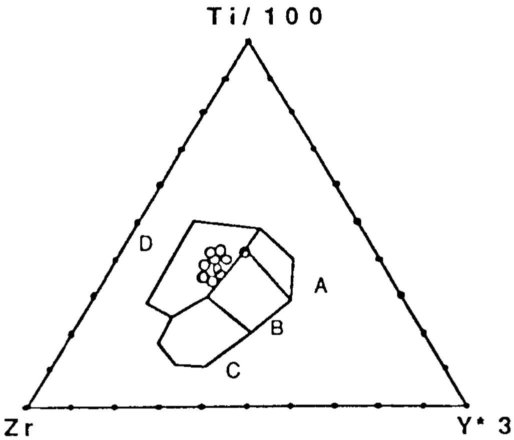
SAMPLE NO.	N614	N126	N198-2	N496	N496-c	S182	N344	N652	N878	PS313	S377
PLATE 1 LOC.	O15	R13	O17	L16	L16	D28	N15	O15	G5	C27	E18
ROCK TYPE	CP	GS	GS	GS €Zug	GS €Zug	GS	A	A	A	A	A
OXIDES (%):											
SiO2	44.13	49.09	54.10	48.78	49.00	49.50	50.35	49.63	50.35	48.93	48.13
TiO2	2.56	1.88	2.94	3.38	3.43	2.52	2.44	2.70	2.10	2.35	3.50
Al2O3	16.91	14.85	13.28	13.04	13.04	17.89	17.51	16.03	16.50	14.66	16.52
Fe2O3	11.33	12.71	13.39	15.51	14.58	10.85	9.67	11.18	10.48	13.21	15.76
MnO	0.12	0.22	0.16	0.26	0.25	0.20	0.17	0.18	0.16	0.22	0.18
MgO	9.05	7.13	3.98	6.00	5.47	5.91	3.85	6.13	9.52	7.55	6.03
CaO	5.92	12.51	5.52	6.28	5.63	5.20	8.29	8.58	7.60	8.28	5.25
Na2O	3.39	2.58	5.17	4.12	4.38	5.40	4.36	4.70	4.10	4.46	2.70
K2O	4.07	0.71	0.64	1.60	1.37	0.65	2.22	0.29	0.60	0.13	0.78
P2O5	0.14	0.08	0.08	0.16	0.16	0.15	0.26	0.16	0.12	0.08	0.26
TOTAL	97.61	101.76	99.27	99.12	97.30	98.26	99.12	99.58	101.53	99.86	99.31
TRACES (ppm):											
Sc	29	36	34	36	36	35	22	31	28	57	41
Y	34	30	31	45	44	29	27	27	24	33	50
Zr	157	126	146	242	248	142	152	144	126	100	222

Explanation:
CP = Chlorite phyllite; **GS** = Greenschist; **A** = Amphibolite

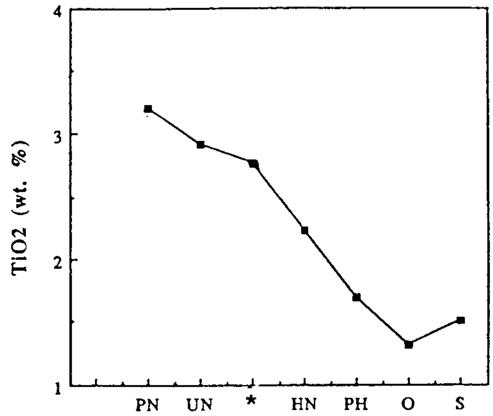
All samples are more closely associated with Hazens Notch rocks than Underhill rocks, except samples indicated €Zug under Rock Type.

Analyses by P.A.Pugin and R.A. Coish, 1989.

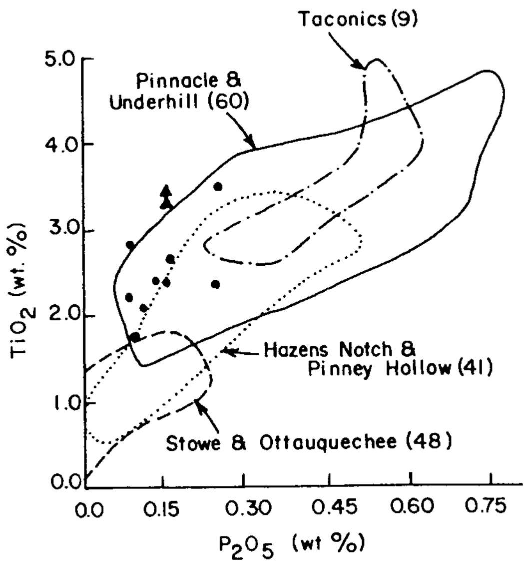
Fig. 1 GREENSTONE GEOCHEMISTRY



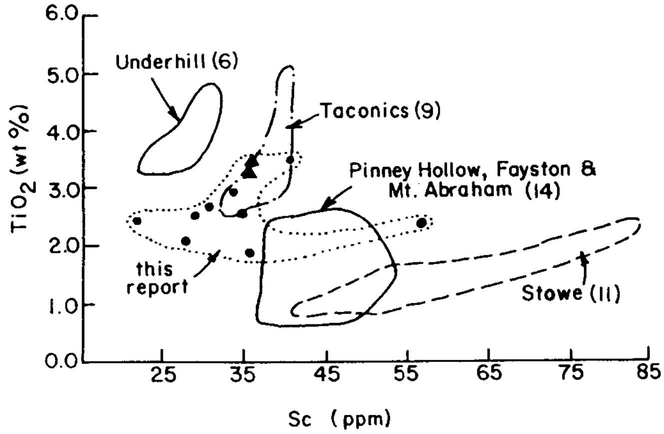
A. Tectonic environments: Ti-Zr-Y ternary plot for samples from this study (data from Coish, pers. comm., 1990) compared to fields after Pearce & Cann (1973): A, Island arc tholeiite (IAT); B, Mid-ocean ridge basalt and IAT; C, calc-alkaline basalt; D, Within-plate basalt.



B. Regional trend in Vermont greenstones: average concentration of TiO_2 compared to data from Coish, 1989: PN, Pinnacle, UN, Underhill; * this report; HN, Hazens Notch; PH, Pinney Hollow; O, Ottauquechee; S, Stowe.



C. Variation of TiO_2 vs. P_2O_5 compared to other greenstones: • €Zhng, ▲ €Zug, this report; Taconics data (9 analyses) from Ratcliffe, 1987; other formations from Coish, 1987.



D. Variation of TiO_2 vs. scandium compared to other greenstones: • €Zhng, ▲ €Zug, this report; Taconics data from Ratcliffe, 1987; other formations from Walsh and Kimball, 1989.

Two greenstone samples from along a gradational contact with albitic Underhill schist (Plate 1, L16) have relatively high Ti contents (Table 3, N496), adding further justification for assigning them to the Underhill Formation rather than the Hazens Notch. However, a third sample with high Ti (S377) is from a greenstone surrounded by Hazens Notch (Plate 1, E18). Note that data for the three samples with high Ti are included in Figure 1 diagrams.

PINNEY HOLLOW FORMATION (€Zph)

Light green to gray chlorite-quartz-muscovite schist is exposed along Route I-89 and south of the Winooski River west of Waterbury (Plate 1: W19 to U25). We have assigned these rocks to the Pinney Hollow rather than Underhill mainly because of their geographic location, which is on strike with Pinney Hollow near North Fayston (Stanley, et al., 1987b; Walsh, 1989). Some layers contain magnetite, whereas others have conspicuous pyrite cubes up to 1 cm. across (Plate 1, W20). The proportion of albite is variable, and it is both white and black. The Pinney Hollow occurs in a mixed zone between the Hazens Notch and the Ottauquechee. In most places the silver-green schists are interlayered with graphitic schists and quartzites. A layer of fine-grained, pale green chlorite schist within a shear zone along the Interstate may be a metavolcanic rock.

OTTAUQUECHEE FORMATION (€o)

Typical graphitic quartzose schists and dark gray quartzites of the Ottauquechee Formation are exposed in the roadcuts at the Waterbury-Stowe interchange on Route I-89, and along Crossett Brook in Duxbury. The schists are similar to graphitic schists of the Hazens Notch, except that they are finer grained, lack albite, and contain distinctive quartzose laminae. Large pyrite cubes are common. The roadcuts along the Interstate contain sheared lenses of black quartzite, talcose schist, and carbonate pods. Rocks assigned to the Ottauquechee are much more quartz-rich than either the Hazens Notch or the Sweetsburg(?) Formations.

DISCUSSION OF STRATIGRAPHY

The Underhill and Hazens Notch Formations have been the subject of some controversy in the recent geological literature. First, there are misunderstandings about the lithic definitions. Second, not all agree on the original depositional settings of these formations.

In the Camels Hump-Bolton Mountain area we have found that Christman and Secor's formations are viable, mappable units if one adheres to strict lithic criteria, omitting all strongly graphitic rocks from the Underhill, and omitting all magnetite-bearing chlorite-muscovite-quartz schists from the Hazens Notch. Albite may occur in either formation, and is of no help in distinguishing them from each other. Both Eiben (1976) and Aubrey (1977) pointed out that the proportion of albite in both formations commonly increases near contacts.

One source of controversy is that the map pattern for these two units on the state map (Doll, et al., 1961) is only a first approximation to the actual distribution of units. As we have shown in the Camels Hump quadrangle, rocks identical to the Underhill were included in the Hazens Notch and vice versa. This problem is so serious in some parts of the state that it has been suggested that the names "be abandoned or redefined" (Stanley, et al., 1987a, p. 274). We considered calling our Hazens Notch rocks "Granville Formation" (Thompson and Thompson, 1989) based on descriptions of graphitic rocks mapped farther to the south (Osberg, 1952). Recent mapping in Osberg's area indicates that the lack of greenstones in the Granville is significant and precludes equivalence with our greenstone-bearing graphitic rocks (Stanley, pers. comm., 1989).

The tectonic setting of the Hazens Notch Formation is the second unresolved question. We suspect that the rock types which now make up the rusty and graphitic unit mapped as Hazens Notch Formation were originally deposited over a wide range of space and time. The geochemistry of Hazens Notch greenstones may provide important clues to the formation's depositional setting relative to other map units (Figure 1) unless the greenstones were tectonically emplaced. To the west, the Pinnacle Formation and Tibbit Hill volcanics certainly were deposited as the pre-Iapetan continent was rifting (Doolan, et al., 1987; Coish, 1987). To the east, the greenstones in the Ottauquechee and Stowe Formations appear to have formed at an ocean ridge (Coish, 1987). Mafic schists in the western Underhill are similar to those in the Pinnacle, whereas those in the Pinney Hollow and Hazens Notch Formations have intermediate compositions (Coish, 1987; this report), suggesting a transitional tectonic setting.

Stanley, et al. (1987a, p. 290) present a model in which the carbonaceous (graphitic) units originally lay on top of the non-graphitic units. From west to east, Underhill, Mount Abraham, Pinney Hollow, and Stowe are lithic correlatives and once formed a continuous sheet, with Hazens Notch and Ottauquechee covering them. Doolan, et al. (1987) also consider the Ottauquechee and its correlative Sweetsburg Formation as cover rocks, but they prefer a model whereby the Hazens Notch Formation is a mélange derived from subduction of the Ottauquechee Formation and incorporation of slivers of other rock types, including ophiolites and Camels Hump Group units. According to this model, the graphitic matrix for the mélange would have been deposited oceanward from the Ottauquechee. Geochemical results for the Camels Hump-Bolton Mountain area greenstones are more consistent with Stanley's model in which the Hazens Notch was more proximal than the Ottauquechee. It could be argued that the mélange incorporated volcanics from various environments. Clearly detailed mapping and greenstone geochemistry are both critical to resolving these questions.

On Plate 4 we have attempted to differentiate between two types of graphitic rocks in the core and flanks of the Green Mountain anticlinorium. It appears that most of the graphitic rocks which contain carbonates occur nearer the core of the anticlinorium, whereas graphitic rocks lacking carbonates, but containing numerous greenstones, are found in zones on the east and west flanks of the structure. On Plate 4 the graphitic rocks with carbonates have tentatively been assigned to Sweetsburg Formation using criteria noted by Armstrong (1989) and Doolan, et al. (1987). Lack of carbonates in the greenstone-bearing graphitic rocks, suggests that they were originally deposited in a more distal location. The greenstone geochemistry discussed earlier is consistent with this interpretation. Such evidence should, however, be regarded as very tentative due to the small number of samples analyzed.

STRUCTURE

INTRODUCTION

In the Camels Hump-Bolton Mountain area there is evidence for at least three phases of deformation, and for both pre- or syn- and post-peak metamorphism faults. Only the most obvious faults are shown on Plate 1. Early fold and lineation data are presented on Plate 2, and later folds and lineations on Plate 3. Representative folds are illustrated in Figure 2, and structural data for selected areas are shown in Figure 3. Although fold phases have been distinguished on the basis of what surfaces are deformed and what, if any, surfaces define the axial planes, one should not assume that all folds assigned to a phase formed synchronously throughout the area.

The lack of symmetry across the Green Mountain anticlinorium is one of the intriguing puzzles of the area. Older folds and faults are responsible, but the relationships are not entirely clear. One possible interpretation is proposed in the map and cross sections of Plate 4.

PHASE ONE STRUCTURES

Phase one structures are not well exposed in the Camels Hump-Bolton Mountain area. A deformation older than phase two is indicated by the fact that phase two folds deform a weakly developed foliation. More direct evidence for early (F1) folds consists of scarce isoclinal E-W fold hinges (Figure 2), and abundant quartz rods and fine quartz lineations on bedding and foliation surfaces (Plate 2). Some of the quartz rods appear to be quartz veins which were folded and then dismembered. The quartz lineations have an average WNW-ESE orientation, and were probably rotated to their present positions during F2 deformation (Figure 3).

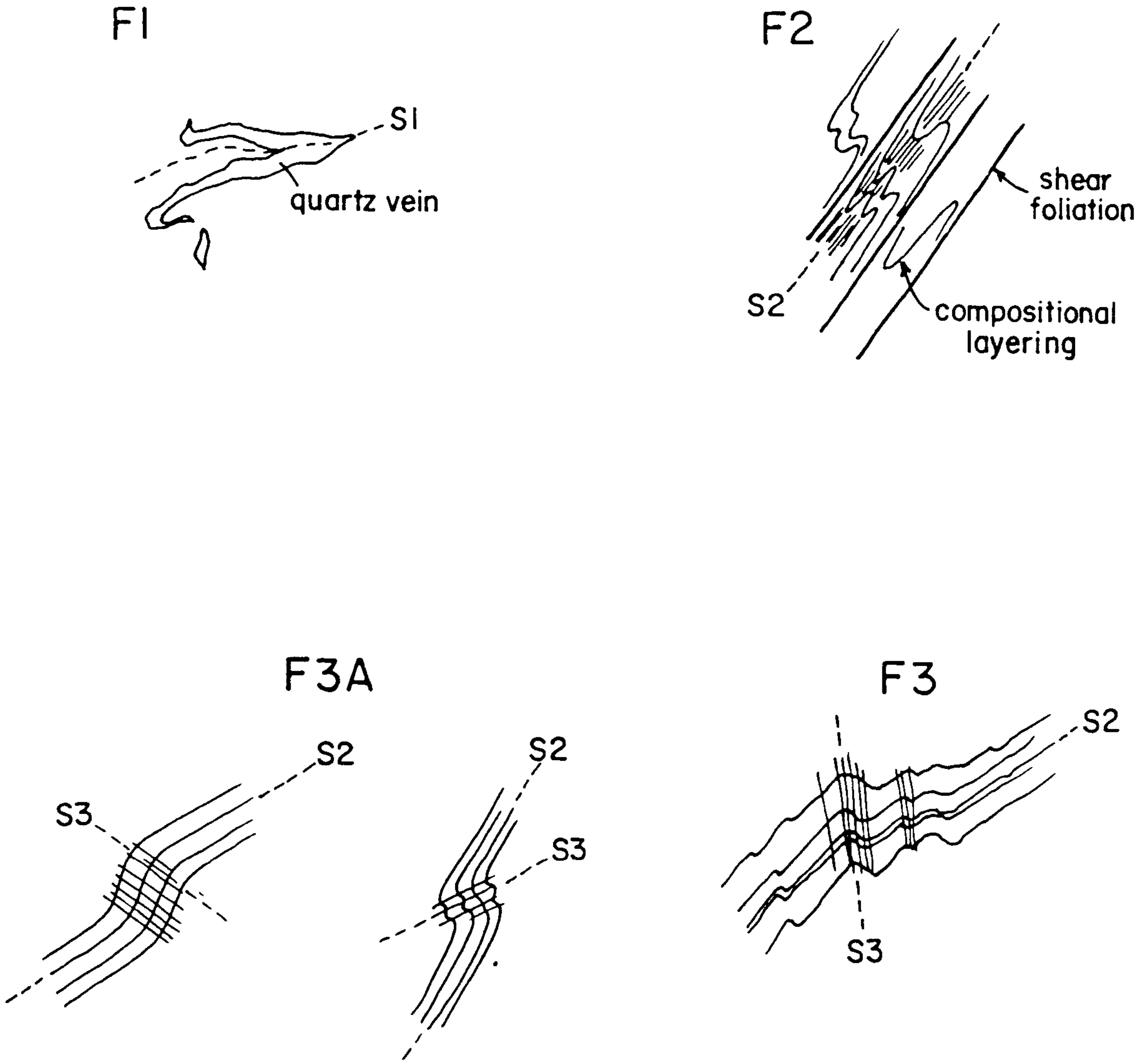
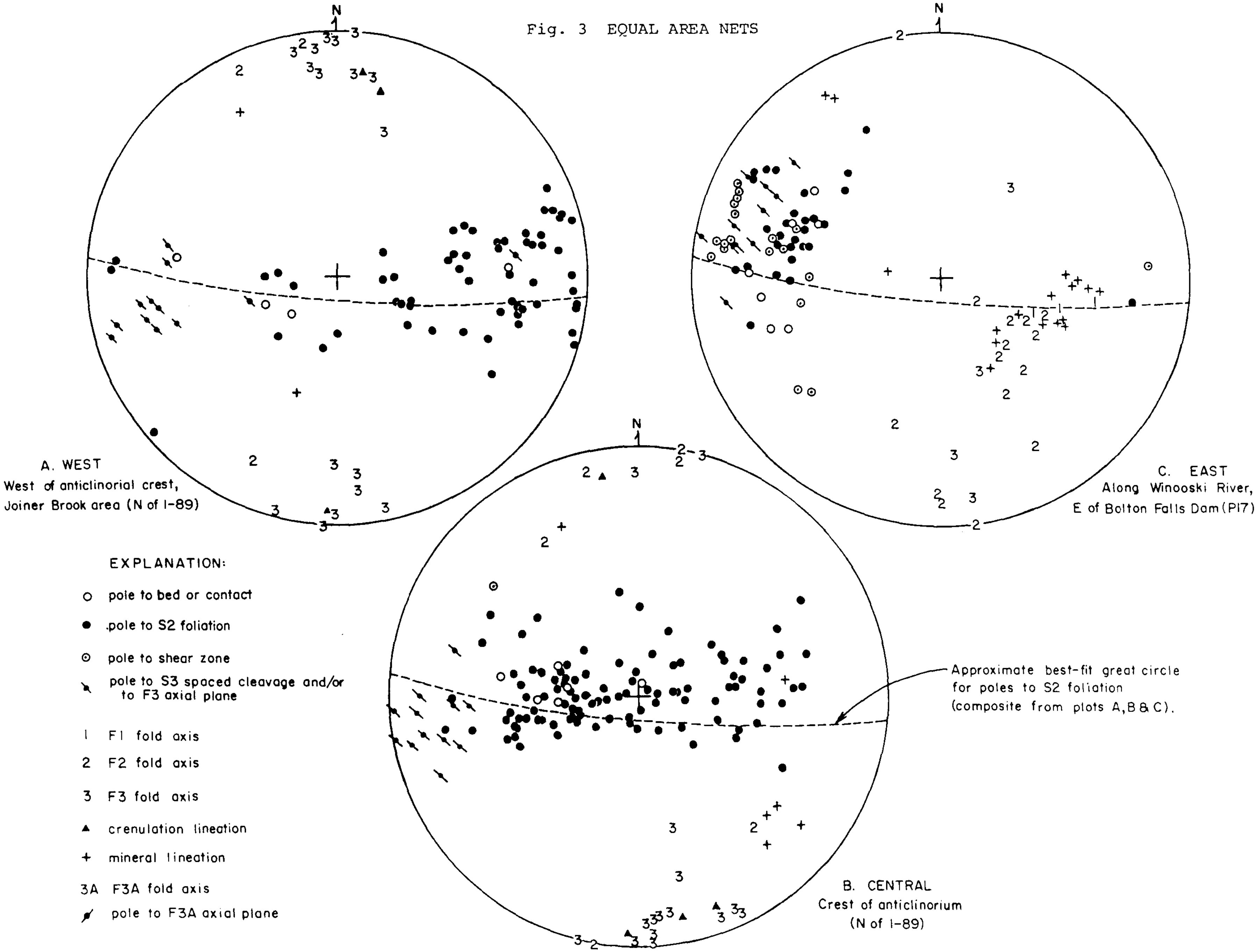
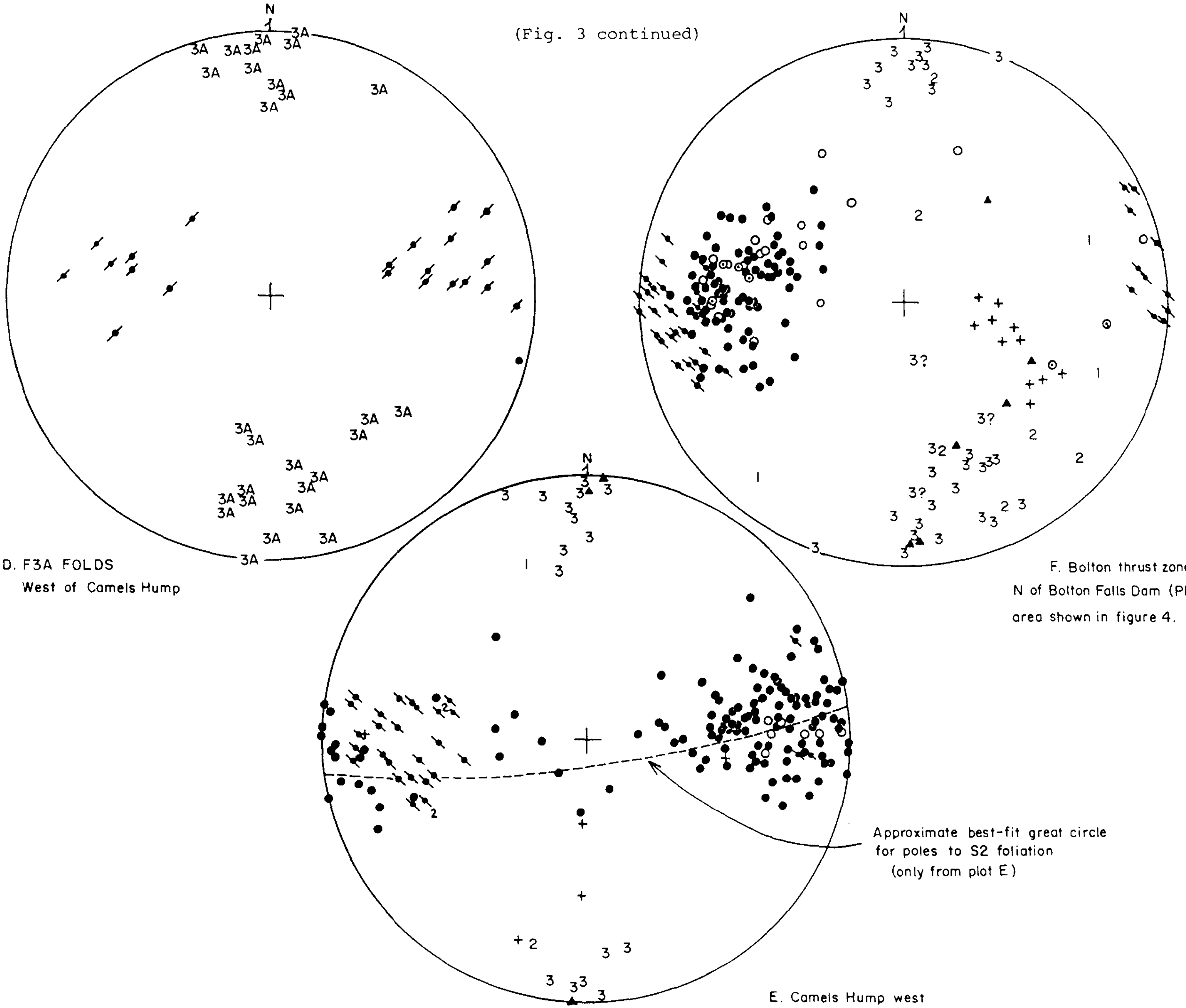


Fig. 2 Schematic profile views, looking north, of minor folds on the west limb of the Green Mountain anticlinorium, west of Camels Hump.

Fig. 3 EQUAL AREA NETS



(Fig. 3 continued)



D. F3A FOLDS
West of Camels Hump

F. Bolton thrust zone
N of Bolton Falls Dam (P17);
area shown in figure 4.

E. Camels Hump west
to Honey Hollow fault

PHASE TWO STRUCTURES

Phase two (F2) folds are identified as having a pervasive foliation (S2) parallel to their axial planes. F2 folds are generally isoclinal and very commonly show evidence of shearing along limbs (Figure 2). Many S2 foliation surfaces have fine mica or chlorite lineations (chlorite or amphibole lineations in the mafic rocks). In a few places a weak linear fabric was observed on S2 surfaces due to intersection with older planes, but this older fabric is obscured in most cases by intersections with S3 (see below). As seen on Plate 2, F2 folds are more numerous than F1 folds, although some F1 folds may have been misidentified as F2. F2 fold axes have a wide spread in orientation, and many are approximately parallel to F3 fold axes (Figure 3).

Close attention to the rotation senses of F2 folds in map pattern and in outcrops near contacts aids in understanding the history of deformation. Many F2 folds were difficult to measure exactly, but rotation sense was noted if possible, and these data are presented on Plate 4 using "W", "E" and "N" for west, east and neutral senses of rotation. (Although some of Eiben's (1976) rotation data are included on Plate 4, there were difficulties in interpreting his map symbols.) South of Bone Mountain layers of Underhill and Hazens Notch Formations are repeated, the Underhill forming cliffs and steep slopes and the Hazens Notch forming gentler slopes. If the alternating layers were only due to F2 isoclinal folds, the rotation sense of related minor folds should change back and forth. However, mostly west-over-east F2 minor folds have been found. Faults have apparently sheared out the east-over-west F2 folds, perhaps on the east limb of a much larger overturned syncline. The degree to which F1 structures may have influenced the map pattern is difficult to assess.

West of Joiner Brook and Bolton, most of the F2 minor folds have east-over-west sense, apparently on the west limb of a large F2 overturned, east-facing syncline. Eiben (1976) concluded that the greenstones west of Stimson Mountain were a single folded layer, in part by using F2 rotation reversals. (See map in Thompson and Thompson, 1987, p. 495). The same rock type is not consistently west of the greenstone, however, and the greenstone cannot be followed continuously north of Eiben's area. An interpretation involving faults as well as folds, such as on Plate 4, is probably more correct. Still farther west, west of Honey Hollow fault, S2 foliation becomes nearly vertical and F2 folds are more or less upright.

Map-scale F2 folds can be seen on Plates 1 and 4 at G16, G18, G25, I24, L13, L16 and M2. The fold at M2 is very well exposed in a cliff along the Long Trail at elevation 3360', where giant isoclinal west-over-east folds, with nearly horizontal axial planes, fold three units: Underhill, greenstones along the contact and non-graphitic Hazens Notch.

PHASE THREE STRUCTURES

The Green Mountain anticlinorium dominates the structure of the Camels Hump-Bolton Mountain area. Along its crest bedding and foliation are nearly horizontal (Plate 3 and Figure 3-B). Most outcrops contain fairly open minor folds (F3) which deform the pervasive foliation and older structures (Figure 2). The folds plunge gently south or north, with axial planes dipping steeply east (Figure 3). In the more schistose rocks a crenulation cleavage or spaced cleavage (S3) parallels the axial planes. S3 commonly forms a linear fabric where it intersects older planes such as S2 foliation and bedding. These intersection lineations may be found on either S2 or S3 surfaces. East of the anticlinorium S3 becomes parallel to S2, and F3 minor folds are less common; stress was taken up by movement along S2 surfaces.

Because the anticlinorium is asymmetrical, the hinge lies somewhat west of the crest (the trace of the crest is shown on all Plates). Minor F3 folds east of the hinge have east-over-west sense and in the broad hinge area they are more or less symmetrical (neutral). West of the hinge there are two styles of F3 folds: one set with east-over-west sense, which are shown as F3A on Plate 3, and the other set, with the expected west-over-east sense, climbing toward the hinge. Both sets have associated spaced cleavage, but in the few outcrops which contain both sets, the relative ages are not conclusive. We hypothesize that the F3A folds developed earlier, and then were passively rotated to their present positions. They can be differentiated from F2 folds because they are more open and they deform the pervasive S2 foliation (Figure 2).

FAULTS

Evidence for faults is of three kinds: (1) map contacts truncated by other contacts, (2) discontinuous slices, and (3) other field evidence, such as truncated beds and foliation, mylonitic fabrics, and papery-weathering phyllites. Either direct field evidence or truncations of lithic units in the map pattern support all the faults on Plate 1. Plate 4 shows several additional faults based mainly on lithostratigraphic arguments. The amount and direction of displacement is unknown for all faults.

Pre- or syn-peak metamorphism faults are difficult to recognize in the field. Several instances of mylonitic zones folded by F2 were observed, but not in places critical to explaining the map pattern. Some early faults shown on Plate 4 are drawn along contacts between stratigraphically dissimilar units, for example Pinnacle and Hazens Notch rock types (Plate 1: E13-16, F22-23, H7). Other faults are shown where contacts lack late fault fabric but where the geometry seems to demand a fault, for example, between Underhill and carbonate-bearing Hazens Notch (Sweetsburg(?) Formation) south and east of Stimson Mountain (Plate 1: F14-G11). Many of the early faults may have been reactivated with different slip directions after peak metamorphism.

Post-peak metamorphism faults cut S2 folds or the dominant foliation associated with them. The two best exposures are at the base of a 200 foot cliff south of Bone Mountain (L12, elev. 2200'), and in the gap south of Montclair Glen Shelter on the Long Trail (H28, elev. 2900'). These faults are marked by strongly weathered zones up to one meter thick of papery schist and disconnected quartz rods. A more accessible post-S2 fault lies approximately 250 m. west of Honey Hollow fault (D13, elev. 560'). Here a meter-thick sliver of sheared graphitic rocks is faulted between layers of Underhill, and is folded by an F3 fold. Because the other faults in this western part of the map also involve thin slivers of Hazens Notch and are parallel to the Honey Hollow fault, they are probably of the same age as the fault at D13. Thus, they are likely deformed by the F3 anticlinorium.

On the east limb of the anticlinorium (Plate 1, N9 to N18), there is a zone of mixed lithologies marking the eastern edge of the main mass of Underhill Formation. A comparable mixed fault zone on the west flank of the anticlinorium also involves many thin greenstones (Plate 1, D14 to H4). Because the fault zones on both sides of the anticlinorium are well exposed in the township of Bolton, we propose calling them the "Bolton thrust zone". The high density of greenstones immediately north of the Winooski River is a function of the scale of mapping; the zones are equally complex to the north and south, but have not been mapped in the same detail. We suspect that the fault zones were connected prior to being eroded from the crest of the anticlinorium; further mapping to the north will be needed to test this hypothesis.

In the eastern Bolton thrust zone, thin layers of greenstone and rock types from both Underhill and Hazens Notch, and possibly Pinnacle and Mount Abraham, can be followed along strike for up to hundreds of meters. Although the units were probably juxtaposed early in the sequence of deformation (D1), the zone was further deformed during and after D2. Mapping at 1:9,000 reveals a few isoclinal F2 folds. More importantly, many contacts terminate against faults (Figure 4). The faults are subparallel to axial planes of west-over-east F2 folds, and in some cases faults cut the F2 folds. Mylonitic fabrics range from incipient to pervasive. Some faults are marked by papery phyllites from a few centimeters to a meter thick.

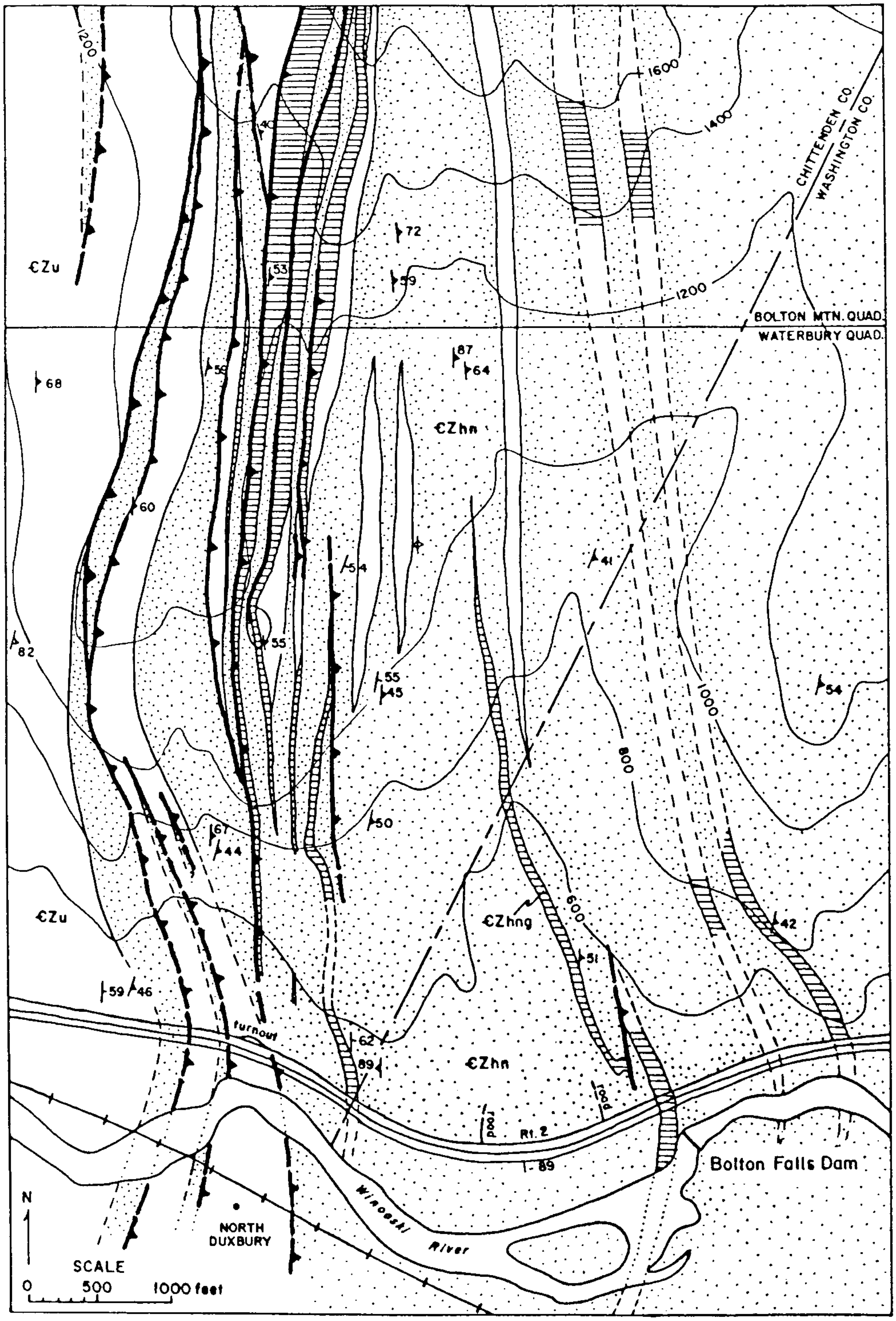


Fig. 4. Detailed map of the Bolton thrust zone east of the Green Mountain anticlinorial hinge, north of Bòlton Falls Dam, showing intercalation of the Underhill Formation (CZu), Hazens Notch Formation (stippled, CZhn), and greenstones (lined, CZhng). Heavy lines are shear zones and faults; bedding, or compositional layering in greenstone; S2 foliation; S3 spaced cleavage.

SUMMARY OF STRUCTURAL HISTORY (Figure 5)

In the Winooski River valley, the deepest structural level exposed consists of interlayered Underhill Formation and carbonate-bearing Hazens Notch Formation (Sweetsburg(?), dotted pattern on Plate 4). Some of the contacts are faults, but others are gradational and presumably depositional, for example, the inverted Underhill-greenstone-Sweetsburg(?) sequence. The initial stacking of these layers took place by early isoclinal folding (F1?), perhaps analogous to folds mapped in the Gilson Mountain quadrangle (Doolan, et al., 1987), and by early thrust faulting (D1). At a higher level, Underhill and non-graphitic Hazens Notch were thrust over the Sweetsburg(?) (from the east?), and at a still higher level, greenstone-bearing Hazens Notch was emplaced along the Bolton thrust zone, presumably also from the east. As the west-directed transport met resistance from the North American craton, east-directed backfolds developed (D2). Eventually shear zones and discrete faults, including the Honey Hollow fault, cut across the backfolds. These F2 folds and faults further thickened the stack. Older faults, for example in the Bolton thrust zone, were locally reactivated, this time with motion eastward. On Plate 4 only the initial transport direction is shown for the Bolton fault zone and Honey Hollow fault. Finally, all the older structures were arched by the anticlinorium (D3).

REGIONAL CONTEXT OF STRUCTURES

Doolan (1989) pointed out that the trend of the Appalachian orogen from south to north in Vermont changes from north-northwesterly to north-northeasterly approximately at the Winooski River. A reentrant or arcuate bay in the Cambrian North American coastline at this latitude may have had a strong effect on the structural styles during Taconian deformation. For example, the involvement of basement slices becomes gradually less important from the Berkshires north to Quebec (Stanley and Ratcliffe, 1985). The D3 foliation arch in the Camels Hump Group is well defined from our area toward the north, but loses definition toward the south. It has been suggested that a basement slice analogous to the Lincoln massif (but as yet unexposed) moved westward and upward along a thrust fault ramp to cause the anticlinorial arch at this latitude (Doolan, et al., 1987; Walsh, 1989). An unpublished seismic reflection transect in the western Winooski River valley unfortunately stops near Stimson Mountain, just short of the anticlinorium. Reflections on the seismic profile from the eastward projection of the Champlain thrust are at least 8700 m. deep near Stimson Mountain (Stanley, pers. comm., 1986).

The strongly sheared Bolton thrust zone at the base of the greenstone-bearing Hazens Notch Formation does seem to be a major pre-F2 fault zone, contrary to our earlier conclusions (Thompson

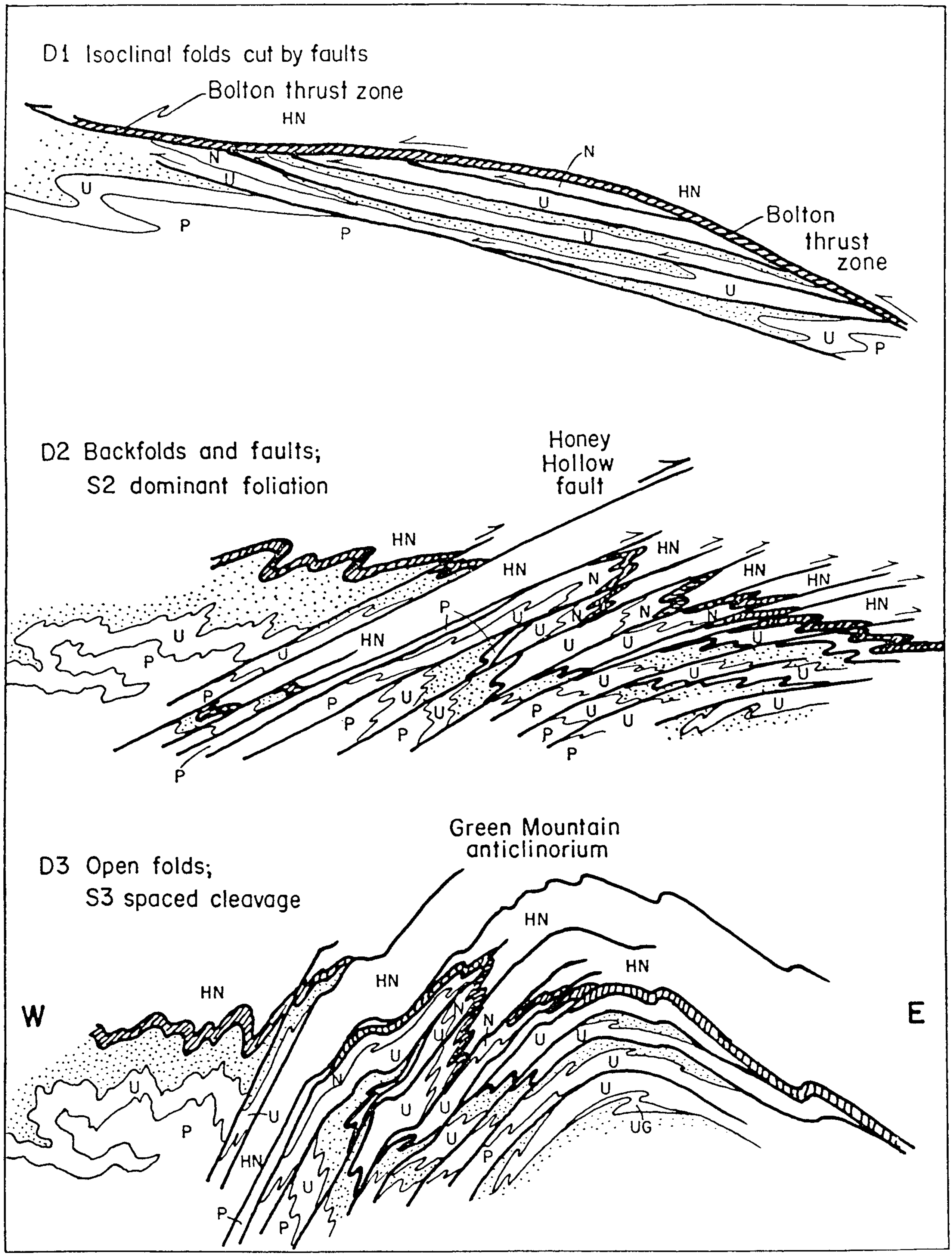


Fig. 5 Schematic cross sections to show structural evolution. Symbols as follows: lined pattern--Bolton thrust zone, stippled pattern--Sweetsburg(?) Formation, HN--greenstone-bearing Hazens Notch Formation, N--non-graphitic Hazens Notch, U--Underhill Formation, UG--Underhill greenstone, P--Pinnacle Formation.

and Thompson, 1989), and corresponds roughly with Stanley and Ratcliffe's (1985) "Hazens Notch thrust". We now believe that the graphitic Sweetsburg(?) rocks at deeper levels in the anticlinorium (Plate 1, F15 to M15) are a more proximal facies than those above the fault zone, and that the greenstones below the fault zone (Plate 1, L16) were erupted closer to the continent than those above.

If we assume that a systematic decrease in titanium occurred as volcanics were erupted through gradually more typical oceanic crust, we can speculate on the original location of various greenstones relative to the continent. The fact that the average Ti content of greenstones in the Hazens Notch above the Bolton fault zone is somewhat higher than that previously reported from the Hazens Notch (Coish, 1987) could indicate a more proximal facies of the Hazens Notch in our study area, although still farther from the continent than the Underhill (Figure 1B). Most of the Hazens Notch greenstones are less rich in Ti than metabasalts from the Taconic allochthons (Ratcliffe, 1987). Based on the titanium/scandium ratios shown in Figure 1D, the original position of the Taconic allochthons and our Hazens Notch greenstones can be placed between the Underhill and the Pinney Hollow. The root zone for some of the Taconic slices may correspond to the Bolton thrust zone.

Greenstone-bearing Hazens Notch Formation does not appear west of the Honey Hollow fault, presumably because this unit moved upward west of the fault and has been eroded away. The Honey Hollow fault is a major through-going structure, which juxtaposes less intensely deformed, lower-grade Underhill and Pinnacle Formations against rocks to the east. We hypothesize that it continues northeast toward Jeffersonville, so that the Hazens Notch Formation and greenstones near Stimson Mountain occupy a similar structural position as the Hazens Notch and Peaked Mountain Greenstone near Bakersfield (Dennis, 1964; Thompson, 1975). East-directed structures have been described to the north along the Green Mountain-Sutton Mountain anticlinorium (Osberg, 1965; Thompson, 1975; Doolan, et al., 1987; Colpron, 1989; Marquis, 1989). Following the Honey Hollow fault south toward Mt. Ellen will be an important first step in correlating our work with that of Walsh (1989) and O'Loughlin and Stanley (1986), where east-directed faults and folds have not been recognized.

METAMORPHISM

We have not made a comprehensive study of the metamorphism. More detailed studies are needed to work out the timing of peak and retrograde metamorphism relative to deformation.

Garnet occurs in some of the pelitic units in a broad central swath between the Honey Hollow fault and the east side of the anticlinorium near Bolton Falls. We have not attempted to refine

Christman and Secor's (1961) garnet isograd locations, but disagree with their conclusion that "rocks in the Hazens Notch formation are not conducive to the formation of garnet" (p. 38). Rusty schists in the central area are, in fact, more apt to contain garnet than Underhill schists in the same locale. Garnet in the Underhill becomes more common in the southern part of the area, especially in the very aluminous Mt. Abraham-like horizons, which also contain chloritoid. Verifiable kyanite was not found in these aluminous rocks, although there are tiny rusty weathered micaceous blades much like those described as kyanite pseudomorphs by O'Loughlin and Stanley (1986).

Garnets observed in thin section have ragged outlines and are partly replaced by post-S2 chlorite, whereas biotite and chloritoid have sharp outlines cutting across the dominant S2 foliation. Albites contain S-shaped inclusion trains and in some thin sections are rimmed by clear albite. These relationships are consistent with peak garnet-grade metamorphism roughly synchronous with the S2 dominant foliation, followed by retrograde metamorphism to biotite grade. The peak metamorphism was reached during the Taconian orogeny; the overprint could be late Taconian or Acadian. (See discussion in Laird, 1987.) Anderson (1987) studied the complicated relationship between mineral assemblages and textures in schists and veins along Route 2 east of the anticlinorial axis. Anderson reported compositional zoning in minerals from Underhill schist (in the vicinity of N196, Plate 1: N17) which shows one stage of prograde growth for garnet and two stages for plagioclase. The plagioclase cores consist of cloudy albite surrounded by cloudy oligoclase, synchronous with S2. The cores are rimmed by clear albite and oligoclase, synchronous with S3.

Greenstones in the Camels Hump-Bolton Mountain area have greenschist and epidote-amphibolite facies assemblages (Table 2). Laird (pers. comm., 1988) studied amphiboles with the electron microprobe from five greenstone samples: one from N198 (Plate 1: O17) has hornblende cores and actinolite rims, one from N191 (Plate 1: M7) has actinolite cores and hornblende rims, and the other three are less clearly zoned. Comparisons to metamorphic trajectories elsewhere in Vermont (Laird, 1987) are thus inconclusive.

ACKNOWLEDGEMENTS

This study was undertaken with the support of the Vermont Geological Survey, under the direction of Charles A. Ratté. Rolfe Stanley made the initial suggestion that mapping a transect along the Winooski River between Richmond and Waterbury would help fill the gap between work being done to the north and south. Funding was provided by the Vermont Geological Survey, and Cornell College, Mount Vernon, Iowa.

The authors wish to thank those who assisted with various aspects of the project. Rolfe Stanley, Barry Doolan, Dave Elbert and Ray Coish reviewed this text, making many helpful suggestions. Ray Coish and Phil Pugin contributed geochemical analyses of greenstones; Jo Laird studied some of the amphibolites; Don Callen did petrographic work on greenstones. Many people went in the field with us and discussed our work in progress, among them Chuck Ratté, Rolfe Stanley, Barry Doolan, Tim Mock, Maurice Colpron, Sharon O'Loughlin, Eric Lapp, Tom Armstrong, Greg Walsh, Norm Hatch, and Dave Eiben. Will Aubrey and Robert Christman, although unable to join us in the field, also provided insights on their previous work in the area.

REFERENCES

Albee, A.L., 1957, Bedrock geology of the Hyde Park quadrangle, Vermont: U.S. Geological Survey Geologic Quadrangle Map GQ 102, scale 1:62,500.

Anderson, J.R., 1987, Metamorphic veins in the Paleozoic rocks of central and northern Vermont: in Westerman, D.S., ed., Annual Meeting, New England Intercollegiate Geological Conference, 79th, Montpelier, Vermont, Norwich University, Guidebook for field trips in Vermont, Volume 2: p. 133-151.

Armstrong, T.R., 1989, The Vermont pre-Silurian cover sequence: regional tectonostratigraphic relationships based on detailed structural and lithological analysis: in Colpron, M. and B.L. Doolan, eds., Proceedings, Quebec-Vermont Appalachian Workshop, Burlington, Vermont: p. 63-66.

Aubrey, W.M., 1977, The structure and stratigraphy of the northern ridges of Camels Hump Mountain, Camels Hump quadrangle, north-central Vermont [M.S. thesis]: Burlington, Vermont, University of Vermont, 57 p.

Cady, W.M., A.L. Albee, and J.F. Murphy, 1962, Bedrock geology of the Lincoln Mountain quadrangle, Vermont: U.S. Geological Survey Geologic Quadrangle Map GQ 164, scale 1:62,500.

Cady, W.M., A.L. Albee, and A.H. Chidester, 1963, Bedrock geology and asbestos deposits of the upper Missisquoi valley and vicinity, Vermont: U.S. Geologic Survey Bulletin 1122-B.

Christman, R.A., 1959, Bedrock geology of the Mt. Mansfield quadrangle, Vermont: Vermont Geological Survey Bulletin No. 12, 75 p.

Christman, R.A., and D.T. Secor, Jr., 1961, Geology of the Camels Hump quadrangle, Vermont: Vermont Geological Survey Bulletin, No. 15, 70 p.

Coish, R.A., 1987, Regional geochemical variations in greenstones from the central Vermont Appalachians: in Westerman, D.S., ed., Annual Meeting, New England Intercollegiate Geological Conference, 79th, Montpelier, Vermont, Norwich University, Guidebook for field trips in Vermont, Volume 2: p. 345-350.

Coish, R.A., 1989, The significance of geochemical trends in Vermont greenstones: Vermont Geology, v. 6, p. 78-80.

Coish, R.A., F.S. Fleming, M. Larsen, R. Poyner, and J. Seibert, 1985, Early rift history of the Proto-Atlantic Ocean: geochemical evidence from metavolcanic rocks in Vermont: American Journal of Science, v. 285, p. 351-378.

Colpron, M.,1989, Taconian structures from the hinterland of the Eastern Townships of Quebec: The result of continental (A-type) subduction?: Vermont Geology, v. t, p. 32-35.

Dennis, J.G., 1964, The geology of the Enosburg area, Vermont: Vermont Geological Survey Bulletin No. 23, 56 p.

Doll, C.G., W.M. Cady, J.B. Thompson, Jr., and M.P. Billings, 1961, Centennial geologic map of Vermont: Vermont Geological Survey, scale 1:250,000.

Doolan, B.L., 1989, Hinterland tectonics of the Vermont-Quebec Appalachian orogen: in Colpron, M. and B.L. Doolan, eds., Proceedings, Quebec-Vermont Appalachian Workshop, Burlington, Vermont: p. 46-49.

Doolan, B.L., T. Mock, and A. McBean, 1987, Stratigraphy and structure of the Camels Hump Group along the Lamoille River transect, northern Vermont, in Westerman, D.S., ed., Annual Meeting, New England Intercollegiate Geological Conference, 79th, Montpelier, Vermont, Norwich University, Guidebook for field trips in Vermont, Volume 2: p. 152-191.

Eiben, D.B., 1976, Stratigraphy and structure of the Stimson Mountain area, Camels Hump quadrangle, north and central Vermont [M.S. thesis]: Burlington, Vermont, University of Vermont, 112 p.

Hitchcock, C.H., 1884, Geological sections across New Hampshire and Vermont: American Museum of Natural History Bulletin, v.1, No. 5.

Hitchcock, E., 1861, Report on the geology of Vermont: v. 2, 988 p.

Jacobs, E.C., 1938, The geology of the Green Mountains of northern Vermont: Vermont State Geologist, 21st Biennial Report, p. 1-73.

Laird, J., 1987, Metamorphism of pre-Silurian rocks, central Vermont: in Westerman, D.S., ed., Annual Meeting, New England Intercollegiate Geological Conference, 79th, Montpelier, Vermont, Norwich University, Guidebook for field trips in Vermont, Volume 2: p. 339-344.

Marquis, R., 1989, Taconian structures from the hinterland of the Eastern Townships of Quebec: the result of continental (A-type) subduction?: in Colpron, M. and B.L. Doolan, eds., Proceedings, Quebec-Vermont Appalachian Workshop, Burlington, Vermont: p. 37-45.

McHone, J.G., 1978, Distribution, orientation, and ages of mafic dikes in central New England: Geological Society of America Bulletin, v. 89, p. 1645-1655.

Mock, T.D., 1989, Bedrock geology of the East Fletcher-Bakersfield area, northern Vermont: Vermont Geological Survey Special Bulletin No. 10, 28 p.

O'Loughlin, S.B., and R.S. Stanley, 1986, Geology of the Mt. Abraham-Lincoln Gap area: Vermont Geological Survey Special Bulletin No. 6, 29 p.

Osberg, P.H., 1952, The Green Mountain anticlinorium in the vicinity of Rochester and East Middlebury, Vermont: Vermont Geological Survey Bulletin No. 5, 127 p.

Osberg, P.H., 1965, Structural geology of the Knowlton-Richmond area, Quebec: Geological Society of America Bulletin, v. 76, p. 223-250.

Pearce, J.A., and J.R. Cann, 1973, Tectonic setting of basic volcanic rocks determined using trace element analyses: Earth and Planetary Science Letters, v. 19, p. 290-300.

Ratcliffe, N.M., 1987, Basaltic rocks in the Rensselaer Plateau and Chatham slices of the Taconic allochthon: chemistry and tectonic setting: Geological Society of America Bulletin, v. 99, p. 511-528.

Rose, H., M. Colpron, and B.L. Doolan, 1990, Stratigraphic and structural correlation across the internal domain of the southern Quebec Taconide zone: Geological Society of America, Abstracts with Programs, v. 22, no. 2, p. 66-67.

Slivitzky, A., and P. St-Julien, 1987, Compilation geologique de la region de l'Estrie-Beauce: Direction generale de l'Exploration geologique et minerale MM 85-04, 40 p.

St-Julien, P., A. Slivitsky, and T. Feininger, 1983, A deep structural profile across the Appalachians of southern Quebec, in Hatcher, R.D., Jr., H. Williams, and I. Zietz, eds., Contributions to the tectonics and geophysics of mountain chains: Geological Society of America Memoir 158, p. 103-112.

Stanley, R.S., and N.M. Ratcliffe, 1985, Tectonic synthesis of the Taconian orogeny in western New England: Geological Society of America Bulletin, v. 96, p. 1227-1250.

Stanley, R.S., V. DelloRusso, S. O'Loughlin, E. Lapp, T. Armstrong, J. Prewitt, J. Kraus, and G. Walsh, 1987a, A transect through the pre-Silurian rocks of central Vermont: in Westerman, D.S., ed., Annual Meeting, New England Intercollegiate Geological Conference, 79th, Montpelier, Vermont, Norwich University, Guidebook for field trips in Vermont, Volume 2: p. 272-313.

Stanley, R.S., T. Armstrong, J. Kraus, G. Walsh, J. Prewitt, C. Kimball, and A. Cua, 1987b, The pre-Silurian hinterland along the valleys of the White and Mad Rivers, central Vermont: in Westerman, D.S., ed., Annual Meeting, New England Intercollegiate Geological Conference, 79th, Montpelier, Vermont, Norwich University, Guidebook for field trips in Vermont, Volume 2: p. 314-338.

Tauvers, P.R., 1982, Bedrock geology of the Lincoln area, Vermont: Vermont Geological Survey Special Bulletin No. 2, 8 p.

Thompson, P.J., 1975, Stratigraphy and structure of Shattuck Ridge, Bakersfield and Waterville, Vermont [M.S. thesis]: Burlington, Vermont, University of Vermont, 68 p.

Thompson, P.J., and T.B. Thompson, 1987, Winooski River transect: refolded folds and thrust faults in the core of the Green Mountain anticlinorium: in Westerman, D.S., ed., Annual Meeting, New England Intercollegiate Geological Conference, 79th, Montpelier, Vermont, Norwich University, Guidebook for field trips in Vermont, Volume 2: p. 492-504.

Thompson, P.J., and T.B. Thompson, 1989, Geology of the Winooski River transect, north central Vermont: in Colpron, M., and Doolan, B., eds., Proceedings of the Quebec-Vermont Appalachian workshop, Burlington, Vermont, University of Vermont: p. 70-73.

Thresher, J.E., 1970, Stratigraphy, structure, and metamorphism in the Richmond area, Vermont [M.S. thesis]: Burlington, Vermont, University of Vermont, 88 p.

Thresher, J.E., 1972, Polymetamorphism in the Richmond area, Vermont: in Doolan, B.D. and R.S. Stanley, eds., Annual Meeting, New England Intercollegiate Geological Conference, 64th, Burlington, Vermont, University of Vermont, Guidebook for field trips in Vermont: p. 269, and field trip handout not bound in NEIGC volume, 21 p.

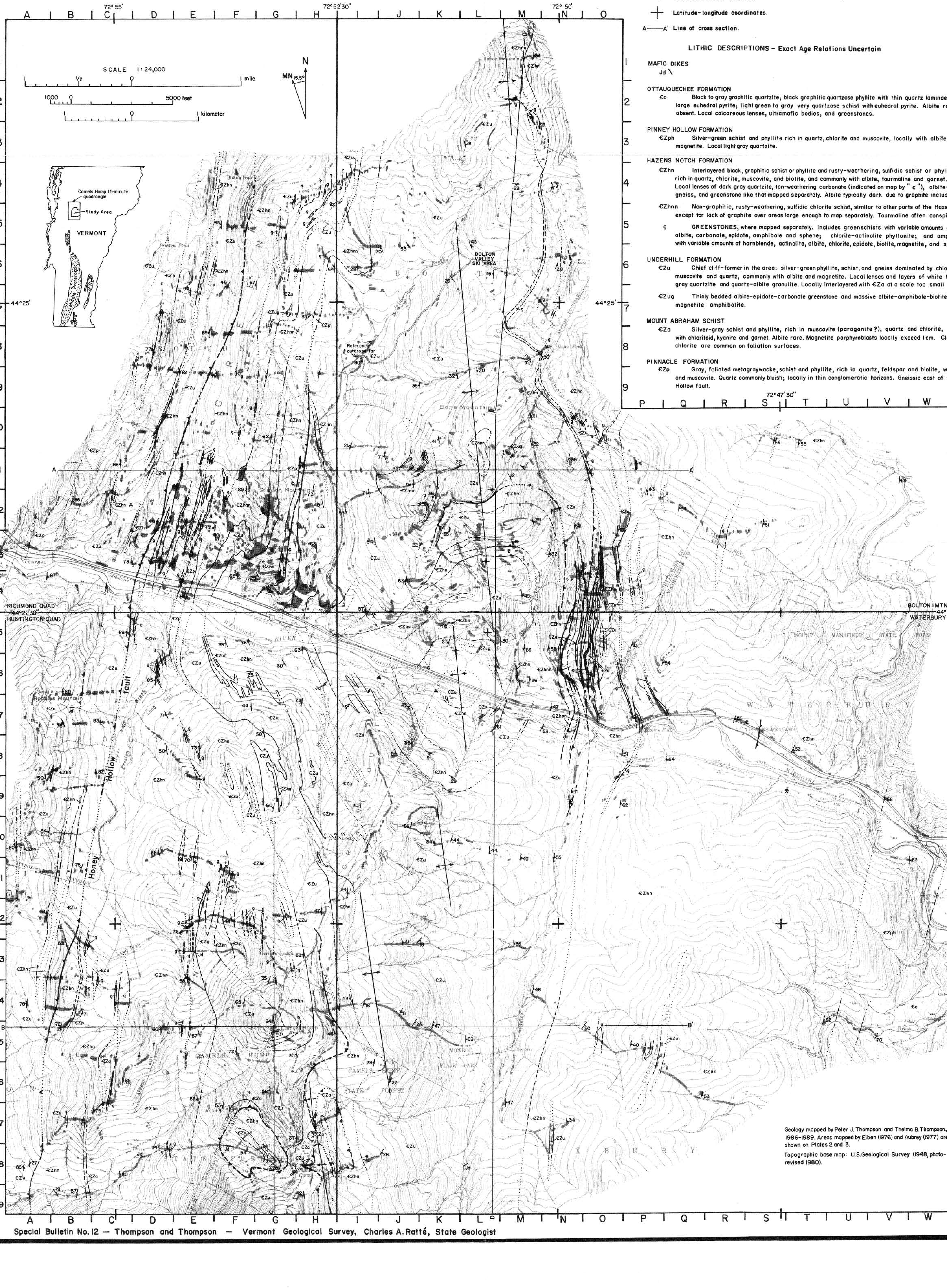
Walsh, G.J., 1989, The tectonic geology of the Fayston-Waitsfield area, central Vermont [M.S. thesis]: Burlington, Vermont, University of Vermont, 224 p.

Walsh, G.J., and C.V. Kimball, 1989, Geochemistry of the metabasic rocks from the pre-Silurian rift-clastic sequence of central Vermont: in Colpron, M., and Doolan, B., eds., Proceedings of the Quebec-Vermont Appalachian workshop, Burlington, Vermont, University of Vermont: p. 74-76.

PLATE I

Bedrock Geology of the Camels Hump-Bolton Mountain Area, North-Central Vermont

Peter J. Thompson and Thelma B. Thompson



EXPLANATION

CONTACTS

Lithic contact. Dashed where approximate, dotted where inferred.

Post-peak-metamorphism fault (pre-F3). Dashed where approximate, dotted where inferred.

OTHER SYMBOLS

Observed bedrock outcrops.

Latitude-longitude coordinates.

A——A' Line of cross section.

STRUCTURAL FEATURES

Dominant foliation (S2). Represe tive symbols selected from Pl

Vertical S2.

Horizontal S2.

Trace of Green Mountain anticli crest.

LITHIC DESCRIPTIONS - Exact Age Relations Uncertain

MAFIC DIKES

Jd

OTTAUQUECHEE FORMATION

€o Black to gray graphitic quartzite; black graphitic quartzose phyllite with thin quartz laminae large euhedral pyrite; light green to gray very quartzose schist with euhedral pyrite. Albite r absent. Local calcareous lenses, ultramafic bodies, and greenstones.

PINNEY HOLLOW FORMATION

€Zph Silver-green schist and phyllite rich in quartz, chlorite and muscovite, locally with albite magnetite. Local light gray quartzite.

HAZENS NOTCH FORMATION

€Zhn Interlayered black, graphitic schist or phyllite and rusty-weathering, sulfidic schist or phyll rich in quartz, chlorite, muscovite, and biotite, and commonly with albite, tourmaline and garnet. Local lenses of dark gray quartzite, tan-weathering carbonate (indicated on map by " c "), albite- gneiss, and greenstone like that mapped separately. Albite typically dark due to graphite inclus

€Zhnn Non-graphitic, rusty-weathering, sulfidic chlorite schist, similar to other parts of the Haze except for lack of graphite over areas large enough to map separately. Tourmaline often conspi

g GREENSTONES, where mapped separately. Includes greenschists with variable amounts albite, carbonate, epidote, amphibole and sphene; chlorite-actinolite phyllonite; and am with variable amounts of hornblende, actinolite, albite, chlorite, epidote, biotite, magnetite, and s

UNDERHILL FORMATION

€Zu Chief cliff-former in the area: silver-green phyllite, schist, and gneiss dominated by chlo muscovite and quartz, commonly with albite and magnetite. Local lenses and layers of white gray quartzite and quartz-albite granulite. Locally interlayered with €Za at a scale too small

€Zug Thinly bedded albite-epidote-carbonate greenstone and massive albite-amphibole-biotite magnetite amphibolite.

MOUNT ABRAHAM SCHIST

€Za Silver-gray schist and phyllite, rich in muscovite (paragonite ?), quartz and chlorite, with chloritoid, kyanite and garnet. Albite rare. Magnetite porphyroblasts locally exceed 1cm. Cl chlorite are common on foliation surfaces.

PINNACLE FORMATION

€Zp Gray, foliated metagraywacke, schist and phyllite, rich in quartz, feldspar and biotite, w and muscovite. Quartz commonly bluish; locally in thin conglomeratic horizons. Gneissic east of Hollow fault.

Geology mapped by Peter J. Thompson and Thelma B. Thompson, 1986-1989. Areas mapped by Eiben (1976) and Aubrey (1977) are shown on Plates 2 and 3.

Topographic base map: U.S.Geological Survey (1948, photo- revised 1980).

PLATE 2

Earlier Structures in the Camels Hump–Bolton Mountain Area

Peter J. Thompson and Thelma B. Thompson

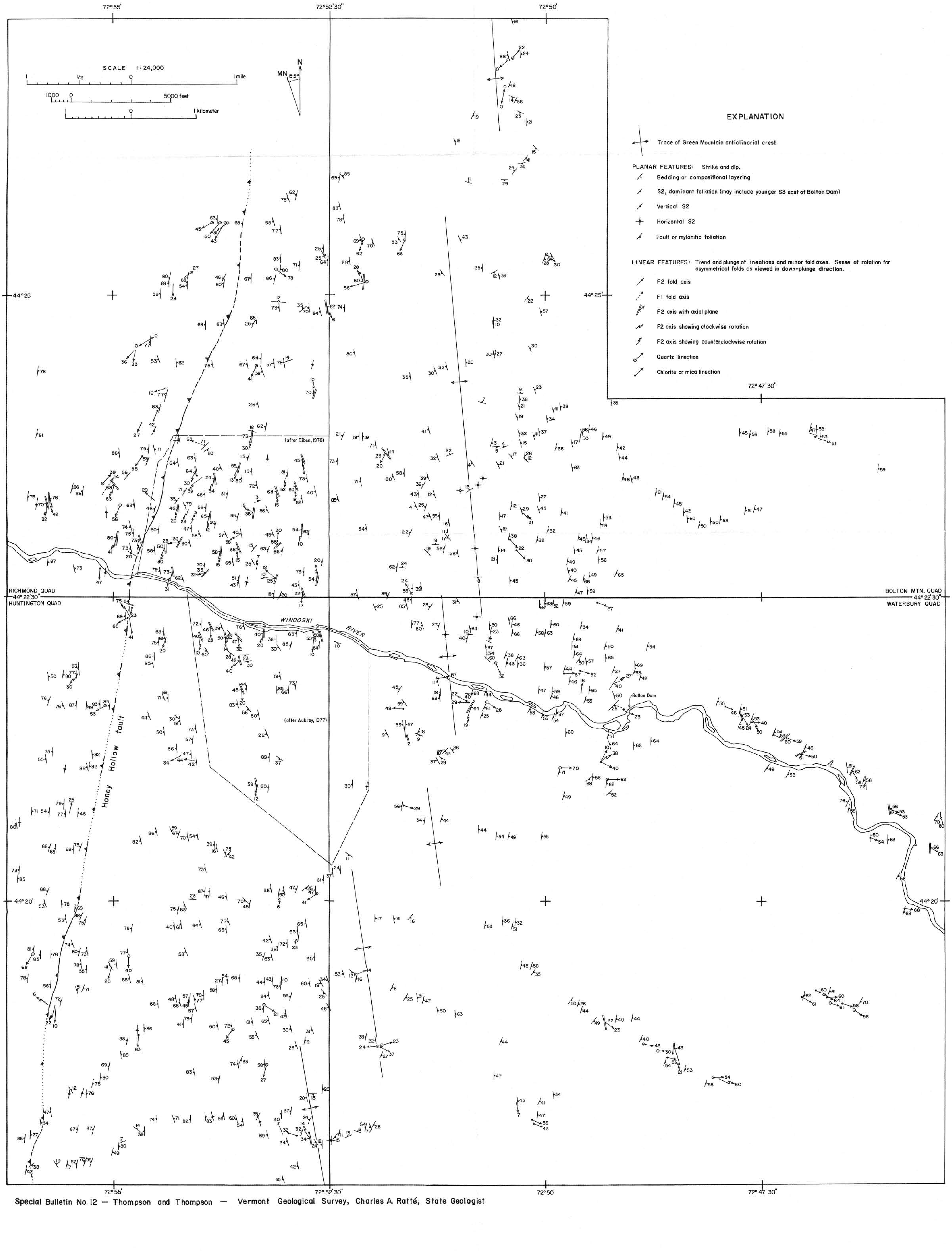


PLATE 3

Later Structures in the Camels Hump-Bolton Mountain Area

Peter J. Thompson and Thelma B. Thompson

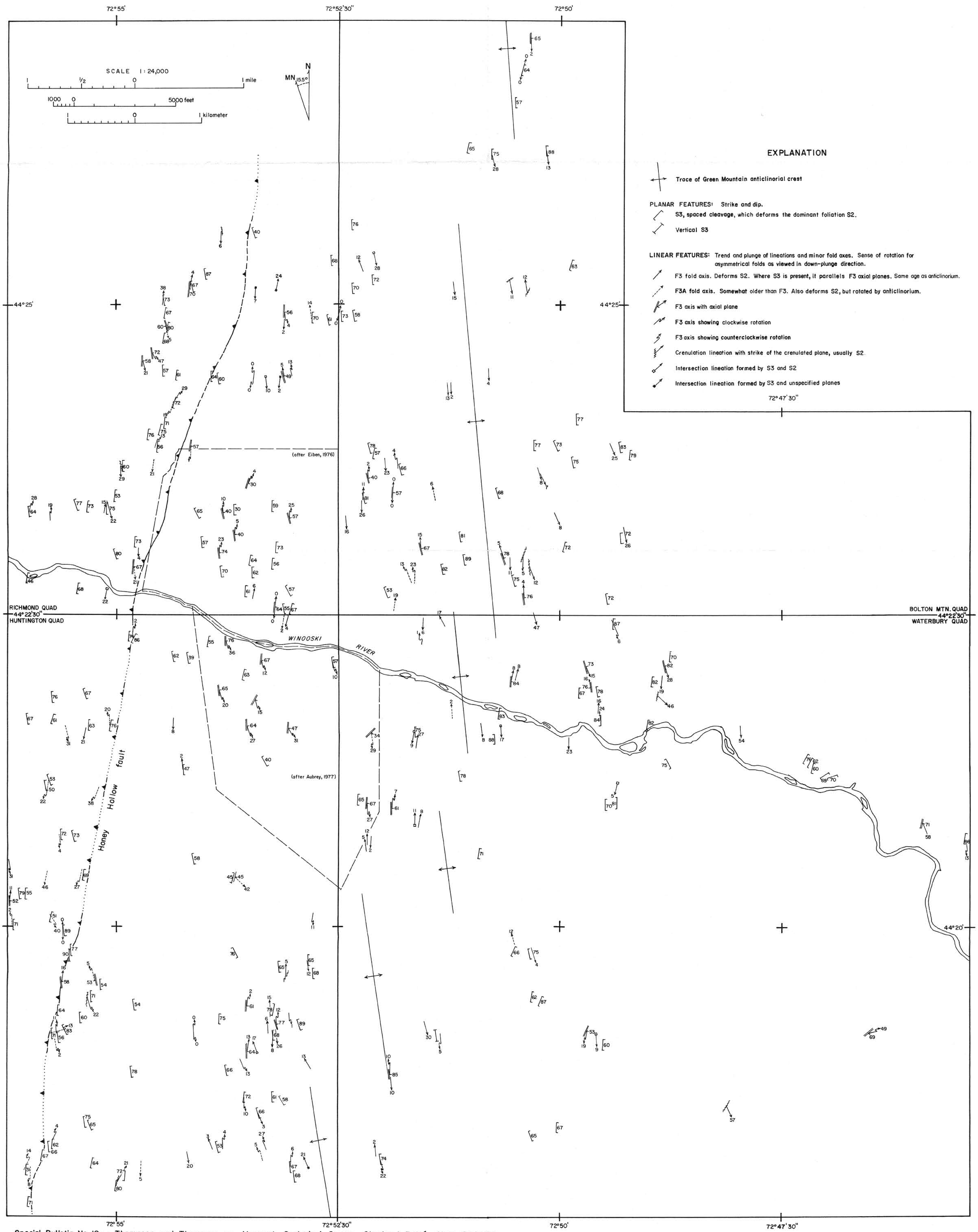


PLATE 4

Interpretive Geologic Map and Cross Sections

Thompson and Thompson

EXPLANATION

CONTACTS

- Pre- or syn-S2 fault
- Post-S2 fault
- Lithic contact. Units as on Plate 1, except as noted below:
- Greenstones in Hazens Notch Formation
- ? Sweetsburg Formation

ROTATION SENSE OF F2 FOLDS

Map	Cross Section	
W		West-over-east, clockwise looking N
E		East-over-west, counterclockwise
N		Neutral

OTHER SYMBOLS

- Trace of Green Mountain anticlinorial crest
- Axial trace of fold