WINOOSKI RIVER TRANSECT: REFOLDED FOLDS AND THRUST FAULTS IN THE CORE OF THE GREEN MOUNTAIN ANTICLINORIUM

Peter J. Thompson and Thelma Barton Thompson
Geology Department, Cornell College
Mount Vernon, Iowa 52314

INTRODUCTION

A transect across the Camels Hump Group parallel to the Winooski River is being mapped from Jonesville to Waterbury, Vermont, in the Camels Hump 15' quadrangle as part of the Vermont Bedrock Geology Mapping Project. This report is based on field work in the summer of 1986 and in June, 1987, and is presented as a progress report rather than final conclusions. The report incorporates detailed mapping by Eiben (1976) and Aubrey (1977), on Stimson Mountain and the northern ridges of Camels Hump, respectively. The Winooski River cuts a deep WNW valley transverse to the dominantly N-S trending structures, thus providing a deeper view of structures which, on the Green Mountain ridges, appear as parallel belts of rock due to low-plunging late folds.

GEOLOGIC SETTING

The late Proterozoic Camels Hump Group occupies the center of the Green Mountain anticlinorium, covering a twenty-mile-wide area at the latitude of the Winooski River (Doll *et al*., 1961). The hinge of the anticlinorium lies approximately halfway between Jonesville and Waterbury, passing close to the summits of Camels Hump and Bolton Mountain (Christman and Secor, 1961). The hinge shifts en echelon eastwards from south to north, and along the crest there is a mile-wide zone of fairly flat-lying rocks. 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 (fig. 1). 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 (fig.2). Aubrey (1977) followed a similar interpretation, but suggested that some of the rocks might belong to other formations of the Camels Hump Group. Stanley and Ratcliffe (1985) concluded 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

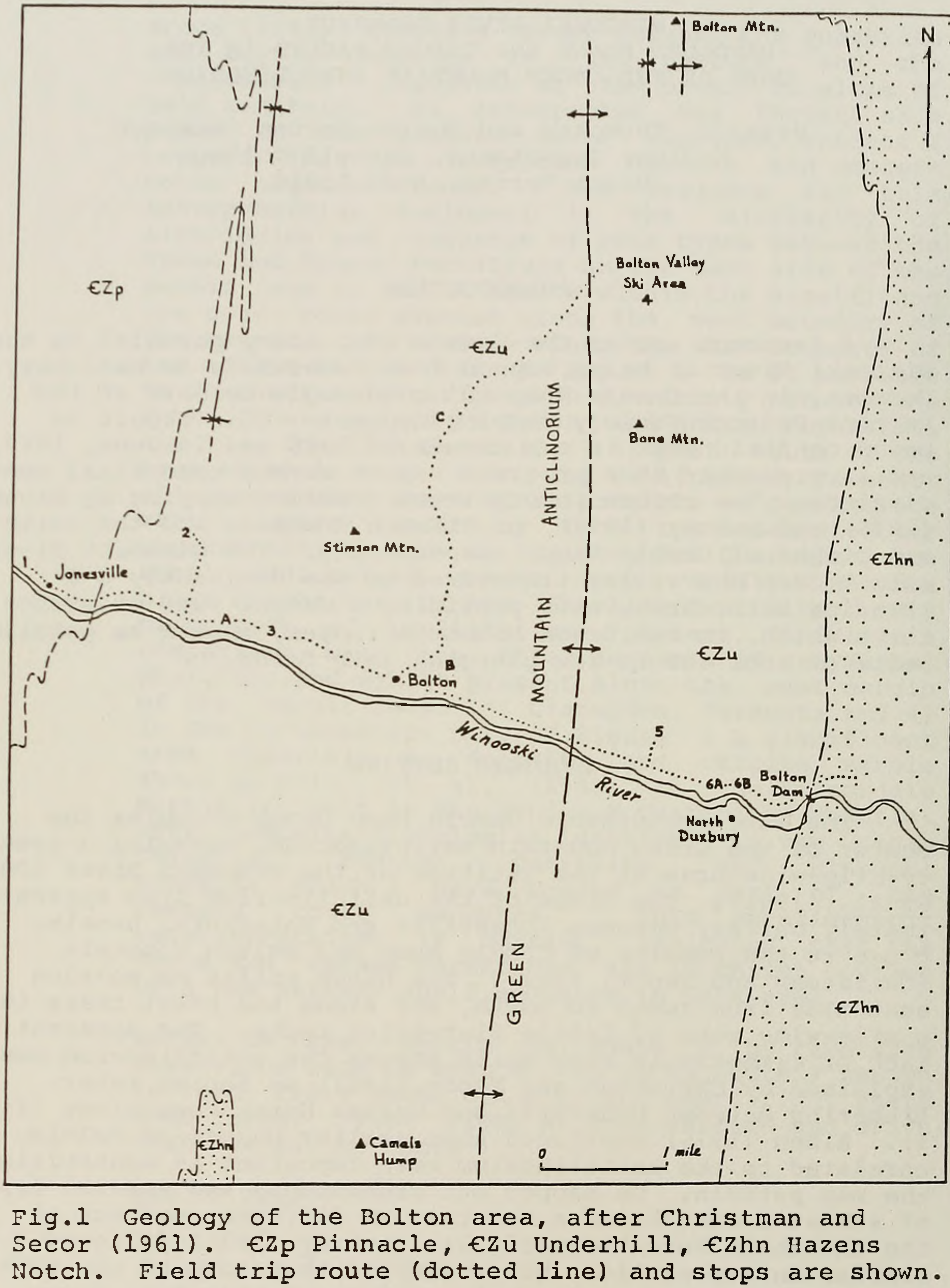

Fig.1 Geology of the Bolton area, after Christman and Secor (1961). €Zp Pinnacle, €Zu Underhill, €Zhn Hazens Notch. Field trip route (dotted line) and stops are shown.

along the east side of the Green Mountain anticlinorium, which according to Stanley and Ratcliffe (1985) contain the root zone for the Taconic allochthons.

STRATIGRAPHY

The Camels Hump Group (Doll *et al*., 1961) includes rocks deposited in three different, though adjacent, tectonic settings: clastic and volcanic rift facies deposited on North American continental basement (Pinnacle Formation and Tibbet Hill Volcanics), transitional continental slope and rise graywackes and shales (Underhill and Pinney Hollow Formations), and ocean floor eugeoclinal carbonaceous pelitic rocks and volcanics (Hazens Notch Formation). These rocks were juxtaposed and imbricated during the development of an accretionary wedge along the eastern margin of the continent (Stanley and Ratcliffe, 1985). Only the Hazens Notch contains local slices of metamorphosed ultramafics; its western contact thus corresponds to Cameron's Line.

Pinnacle Formation

The Pinnacle Formation is characterized by pin-striped metagraywackes and greenish-gray phyllite and schist. Blue quartz grains and local quartz conglomerate beds have been reported (Christman and Secor, 1961; Thresher, 1972). Thresher's work showed that typical Pinnacle graywackes (his Huckleberry Hill Member) contain biotite and stilpnomelane, whereas others contain chloritoid but lack biotite (the latter he assigned to the Underhill Formation). The Pinnacle Formation crops out mainly west of the area we have mapped, but there *are* metagraywackes or granulites in the area which might belong to the Pinnacle.

Underhill Formation, *sensu stricto*

We have mapped rocks as Underhill Formation using much stricter criteria than Christman and Secor (1961), Doll *et al*. (1961), Eiben (1976) and Aubrey (1977). The Underhill consists mainly of silver-green magnetite-bearing chlorite-muscovite-quartz(-albite) schist and gneiss. Biotite and garnet are rarely present. There are local lenses of quartz-feldspar granulite. Magnetite is present in nearly all outcrops of the Underhill, either as conspicuous porphyroblasts or as finely disseminated grains. Pyrite may be present, but is rarely abundant enough to impart rusty weathering to the rocks, in contrast to the Hazens Notch Formation. Graphite may be locally present, giving the rock a dark blue-black color. Magnetite and non-rusty weathering are thus the chief field criteria used in mapping the Underhill. Rocks of the Underhill are relatively resistant and form many of the cliffs north of the river in Bolton, as well as

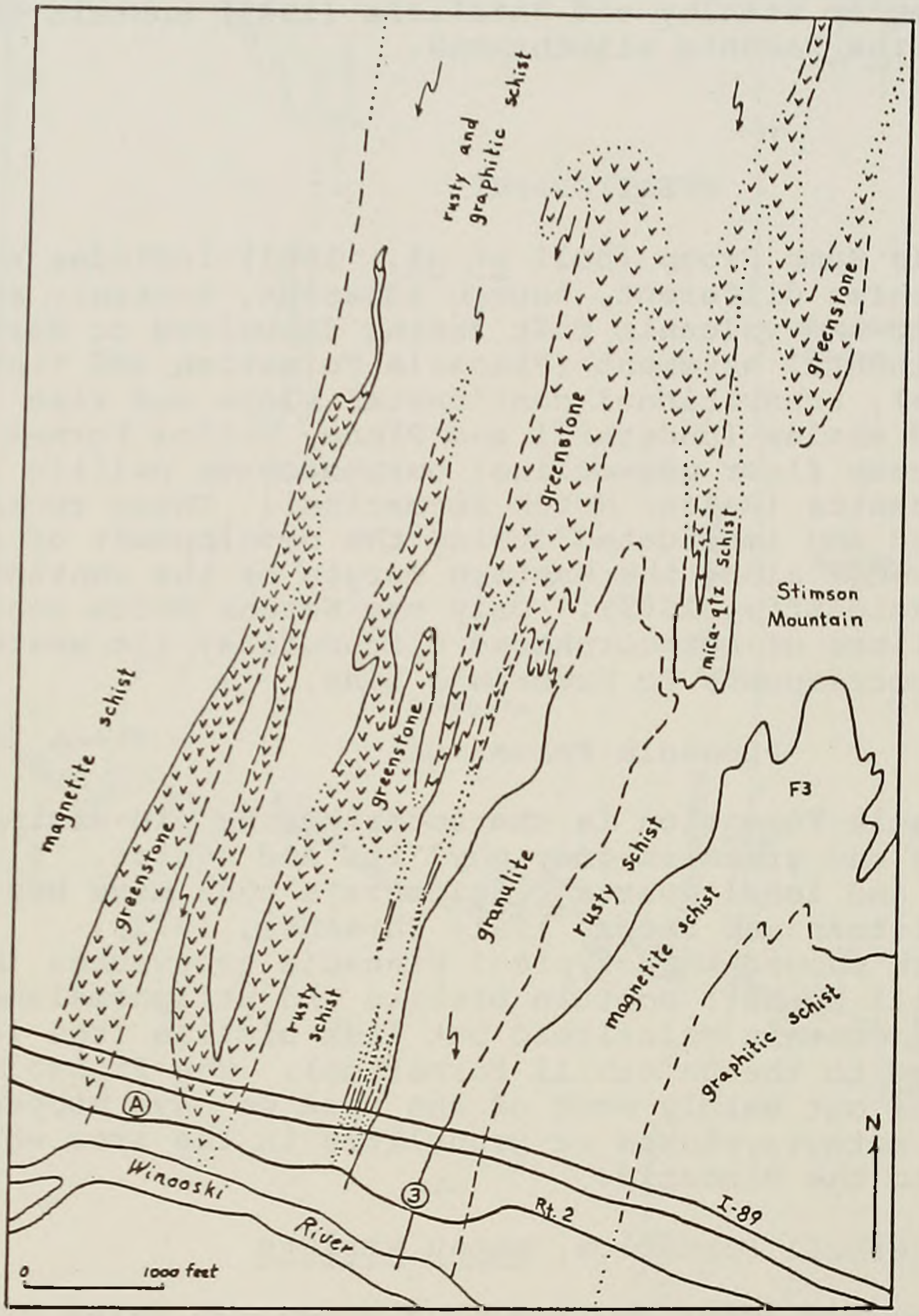

Fig.2 Geology of area west of Stimson Mountain, after Eiben (1976). Arrows indicate F2 fold rotation sense.

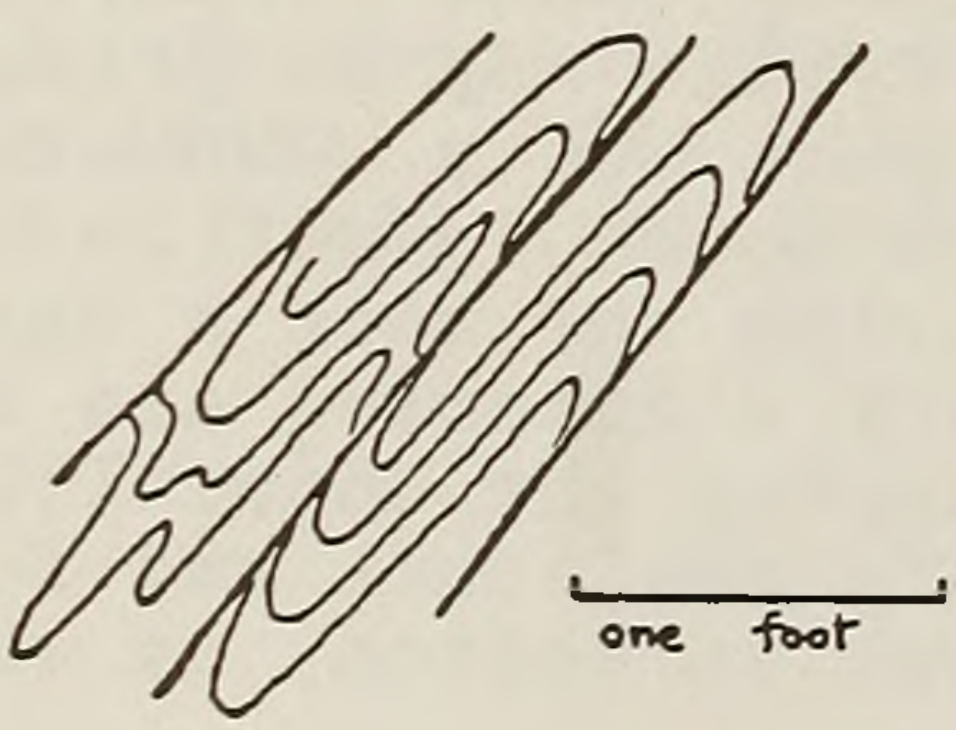

Fig.3 Sketch from outcrop of typical sheared F2 fold hinges.

the summits of Camels Hump, Bone Mountain and Mount Mansfield. We have not yet encountered greenstones within the Underhill in Bolton, but they are present elsewhere in the Underhill in the quadrangle (Christman and Secor, 1961).

Hazens Notch Formation

The Hazens Notch Formation is the most heterogeneous unit mapped. Christman and Secor (1961) mapped a contact between Underhill and Hazens Notch Formations east of, and parallel to, the anticlinorial hinge (fig.1). Rocks of the Hazens Notch Formation consist of rusty-weathering, sulfidic, chlorite-muscovite-biotite-quartz(-albite-garnet) schists interlayered with strongly graphitic, black schists with similar mineralogy. There are local horizons of tan-weathering carbonate. Several layers of greenstone and amphibolite occur within the rusty and graphitic rocks.

Rock types similar to those of the Hazens Notch are exposed in many places west of the anticlinorium, within what Christman and Secor (1961) mapped as Underhill Formation. They recognized this problem, and found that "each unit contained local layers similar to all the other units" (Christman, pers. comm., 1987). 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. Those 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 greenstones. Eiben (1976) reported a variety of metavolcanics and concluded that amphibolites were more commonly preserved in fold hinges whereas greenschists resulted from higher shear strain and retrograde metamorphism on fold limbs.

The metavolcanics in the Hazens Notch east of the anticlinorial hinge are also variable, including chlorite-albite-carbonate-epidote greenstone, chlorite-albite-quartz schist, and amphibole-albite-epidote-chlorite amphibolite. One occurrence of talc-carbonate rock was found within the Hazens Notch Formation in a roadcut along Route 2 near Bolton Dam.

We have attempted to map the Hazens Notch-like rocks separately from the Underhill, and the resulting pattern is shown in figure 4. Greenstone marks the main contact along the east edge of the Underhill east of Bone Mountain, but in many other places there is no greenstone between them. It is doubtful that the Underhill-Hazens Notch contact is <u>anywhere</u> a depositional contact. In some places the contact is clearly a fault, as discussed below. Elsewhere, rela-

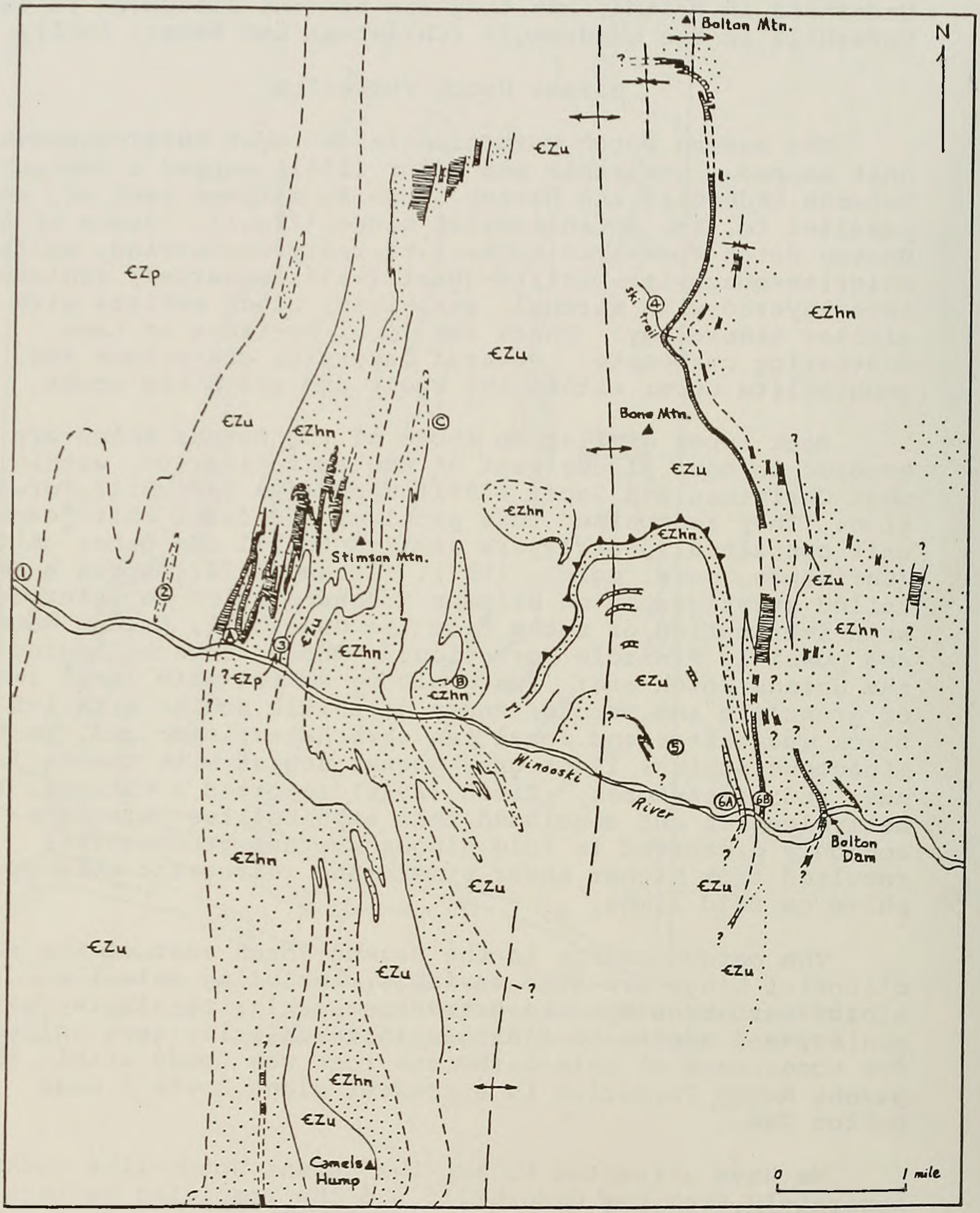

Fig.4 Geology of the Bolton area according to this study. Symbols as in figure 1. Greenstone is horizontally ruled.

tionships are uncertain, especially where both units become richer in albite near the contact (Eiben, 1976 and Aubrey, 1977), a phenomenon also noted in the Bakersfield-Waterville area to the north (Thompson, 1975). The albite porphyroblasts cut across the foliation and are interpreted as Acadian in age. Late metamorphism may thus obscure the original nature of the contact, making it appear transitional.

STRUCTURE

Phase Three Structures

The Acadian Green Mountain anticlinorium dominates the structure of the Bolton area. Along its hinge bedding and foliation are nearly horizontal. Most outcrops contain minor folds related to the anticlinorium. The folds plunge gently south or north, with axial planes dipping steeply to vertical. West of the hinge the folds have an asymmetrical shape and west-over-east rotation sense, and east of the hinge, the folds are east-over-west. Folds with both senses of rotation, or folds with symmetrical (neutral) shape, are found in the hinge area. In the more schistose rocks a crenulation cleavage or spaced cleavage parallels the axial planes. The Acadian structures have been called "phase three" because there is evidence for two older phases of deformation (Eiben, 1976).

Phase Two Structures

The phase three folds (F3) discussed above deform both bedding and a pervasive foliation (S2) which is parallel to the axial planes of phase two folds (F2). F2 folds are generally isoclinal and very commonly show evidence of shearing along limbs (fig.3). F2 fold axes have a wide spread in orientation, but many are approximately parallel to the Acadian F3 fold axes. F2 folds are believed to be Taconian in age.

F2 folds are unfortunately much less common than F3 folds. Close attention to the rotation senses in map pattern and in outcrops near contacts aids in understanding the history of deformation. 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 (fig.4). If the alternating layers were due to F2 isoclinal folds, the rotation sense of related minor folds should change back and forth. However, only west-over-east F2 minor folds have been found. Faults have apparently "sheared out" the east-over-west F2 folds. Eiben (1976) based his fold interpretation of the greenstones west of Stimson Mountain (fig.2) in part on F2 rotation reversals. The same rock type is not consistently west of the greenstone, however, and the greenstone cannot be followed continuously north of Eiben's area (fig.4). An interpretation involving faults as well as folds is probably more correct.

Faults

Evidence for faults is of three kinds: (1) contacts truncated by other contacts, (2) discontinuous slices, and (3) field evidence. Along the eastern contact of the main mass of Underhill Formation north of Bone Mountain there is consistently a greenstone, dipping east under the Hazens Notch Formation. To the south this contact appears to truncate layers of Hazens Notch within the Underhill. East of the contact is an exceedingly complex zone about a half-mile wide in which slices of greenstone, Underhill magnetite schist, and white quartzite occur within rocks typical of the Hazens Notch Formation. As of this writing detailed mapping of this zone is underway. We suspect it may represent a pre-metamorphic fault zone. One confusing aspect of the zone is that although the layers are discontinuous, the sequence of rock types across strike maintains some semblance of order for hundreds of feet along strike.

Direct field evidence of faults is best observed along the Underhill-Hazens Notch contacts south of Bone Mountain. F2 folds and pervasive foliation are locally truncated. Extremely sheared sulfidic schists with papery texture and brecciated quartz veins occur mainly within the Hazens Notch. F3 folds deform these features, indicating a late Taconian, pre-Acadian age for the faults.

Phase One Structures

Strongly developed E-W mineral lineations and quartz rods and scarce isoclinal E-W fold hinges (F1) suggest a phase of deformation older than F2. F1 folds may have been rotated to their E-W orientations during F2 deformation, and this orientation may indicate the sense of movement during F2.

METAMORPHISM

Platy minerals commonly are parallel to the pervasive foliation (Taconian metamorphism?), but locally biotite and muscovite grains (Acadian?) lie across the foliation. Christman and Secor (1961) showed the Bolton area mostly within a four- to five-mile wide garnet zone which coincides with the Green Mountain anticlinorium. However, the garnet isograd along the west side corresponds roughly with the western limit of patches of Hazens Notch Formation, and thus may reflect the presence or absence of rocks of appropriate composition rather than P-T conditions. (The Underhill Formation rarely contains garnet or biotite.)

The present authors have done no thin-section work to date. Samples of amphibolite have been collected for study by Jo Laird to determine whether the amphiboles show evidence for a high-pressure Taconian metamorphism preceding the Acadian greenschist metamorphism.

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ITINERARY

Assembly point is Quinn's Store and Post Office, Jonesville, Vermont, on Route 2 between Richmond and Waterbury, at 8:30 A.M. Topographic Maps: Richmond, Bolton Mountain, and Waterbury 7.5' quadrangles. People approaching Jonesville from Waterbury have excellent views of Bone Mountain cliffs as they leave Waterbury. Optional stops are intended to replace Stop 4 in case of inclement weather.

Mileage

0.0 STOP 1: North side of Route 2 opposite Post Office. This is mainly a stop to inspect the Pinnacle Formation: chlorite schist and pin-striped metagraywacke granulite with blue quartz. Blue quartz is more abundant in massive granulite (Stop 8, Thresher, 1972) 0.1 mile east. At Stop 1 early folds are deformed by upright Acadian folds with associated spaced cleavage, and still younger (late Acadian?) kink bands.

Consolidate transportation and purchase lunch materials if necessary. Proceed east on Route 2.

0.3 Long Trail crosses Winooski River and Route 2. Underhill Formation in roadcut on left.

1.4 Turn left (north) on Bolton Notch Road under Route I-89.

1.5 Small roadcut: Underhill Formation magnetite schist.

1.9 Where road becomes paved turn left onto road to gravel pit.

2.0 STOP 2: Park in gravel pit. Walk through woods along south edge of pit and follow former Long Trail 900 feet west along narrow glacial ridge (esker?) toward Duck Brook. First outcrops along trail are silver-green magnetite schist of Underhill Formation. F3 folds have a west-over-east sense of rotation, whereas F2 folds are east-over-west. Leave trail and go directly down to Duck Brook. Next large outcrops to west are Hazens Notch Formation: rusty and graphitic schist. These rocks are the westernmost exposures of Hazens Notch Formation we have found to date, and are believed to be a fault slice. Follow Hazens Notch outcrops west along south side of brook. Dark gray quartzite at 130 feet. Western contact with the Underhill (115 feet farther west) is marked by quartz veins which cut a tan-weathering "phyllonite". The actual contact is poorly exposed. Duck Brook descends over ledges of Underhill to the west. Return to vehicles and return to Route 2.

2.7 Turn left (east) on Route 2. View of Stimson Mountain to NE mapped by Eiben (1976).

3.1 Optional STOP A: Roadcuts both sides of road. Hazens Notch Formation: rusty-weathering, locally graphitic schist with black albite and pyrite.

3.3 Turnout: Rusty schist on north side of road. Projection from greenstone outcrops north of Route I-89 suggests that greenstone crosses Route 2 between this outcrop and Stop A to the west (see fig.2).

3.4 Turnout. View of north ridges of Camels Hump to SE mapped by Aubrey (1977).
STOP 3: Roadcuts on north side of Route 2.
West end of cut: quartz-feldspar-biotite granulite, massive with local (?) primary layering. This rock type is not typical of Hazens Notch Formation. Could it be a slice of Pinnacle Formation? It extends about a mile north from Stop 3.
East end of cut: granulite interlayered with rusty Hazens Notch-like schist. The proportion of schist generally increases towards east end of cut. Quartz-calcite veins locally abundant. Joint surfaces coated with iron oxides. Foliation dips fairly steeply west. Proceed east on Route 2.

3.6 View north toward cut on Route I-89: Underhill magnetite schist. A layer of Underhill sandwiched within Hazens Notch forms most of the cliffs visible on the south slope of Stimson Mountain (fig.2).

4.7 Turn left (north) on road to Bolton Valley Ski Area (under Route I-89).

4.9 Optional STOP B: Devil's Washbowl, Joiner Brook. No hammers. Hazens Notch Formation: black albite schist with rusty horizons. Falls formed when glacier lowered base level in Winooski River valley.

7.0 Optional STOP C: Large, slanted outcrops north of road--smooth and slippery--use care!
Underhill Formation: albitic layers define east-over-west dismembered F2 folds, some of which are deformed by F3.

7.5 Road crosses Joiner Brook. Underhill Formation. Foliation still dips west.

8.8 Small road cuts south of road. Underhill Formation. Foliation nearly horizontal.

9.0 Bolton Valley Ski Area. Bolton Mountain is highest peak to north. Park in public parking area below road.
STOP 4: Hike up ski trail east of lift #3 (behind real estate office and swimming pool). Abundant outcrops of Underhill Formation from elevation 2240 to 2420', at top of lift #3, where we will go slightly down to the east to another ski trail which continues up to the south.

Elevation 2440': View to north of Bolton Mountain. Conspicuous cliffs on Bolton (alternate Stop 4) are Underhill Formation with flat-lying foliation which is axial planar to large F2 folds. Farther east along the cliffs recumbent F2 folds deform greenstone found at the Underhill-Hazens Notch contact. The Long Trail follows the base of these cliffs and then goes to Bolton Mountain summit, which is rusty garnet schist of the Hazens Notch Formation.

Elevation 2600': Ski trail reaches greenstone overlying Underhill Formation (contact is poorly exposed here). This contact trends northerly across the upper ski slopes to the Bolton Mountain location described above.
Elevation 2630': Greenstone overlain by Hazens Notch Formation. Rusty schist is interlayered (or folded?) with greenstone at the contact.
Elevation 2630 to 2780': Excellent exposures of typical Hazens Notch Formation (rusty biotite schist, locally very graphitic).
Return to vehicles and return to Route 2.

12.3 View of Camels Hump ahead to south: 3740 feet of relief.

13.3 Turn left (east) on Route 2. Bamforth Ridge to SE, across river: Underhill Formation.

13.5 Roadcuts to left (north): Underhill and Hazens Notch interlayered. Foliation dips west.

13.9 Cliffs to north behind trailer park are Underhill; the small valley between them and "Bolton Ledges" is Hazens Notch.

14.2 "Bolton Ledges": Tall cliff of Underhill.

14.6 Crossing anticlinorial hinge. Distant glimpse to north of cliff on Bone Mountain (elevation 2200');