

**BEDROCK GEOLOGY**  
**OF THE**  
**MT. GRANT - SOUTH LINCOLN AREA**  
**CENTRAL VERMONT**

by

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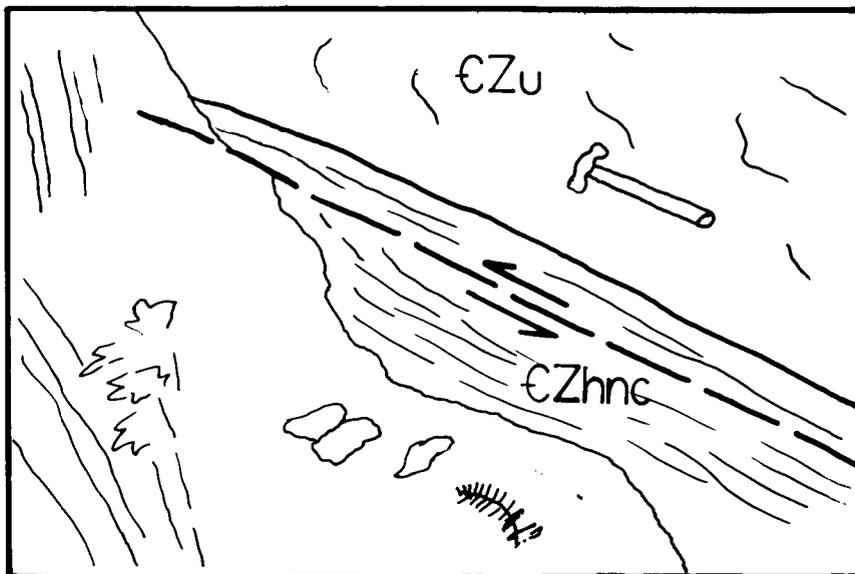
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**NOTES:** Other figures are shown on plates 1 through 3 and are referenced following the plate on which they appear. For example, "Pl. 1, Fig. 1" refers to Figure 1 of Plate 1, whereas "Fig. 1" alone refers to Figure 1 of the text.

All letter-number pairs (e.g. G-2) mentioned in the text refer to grid locations on the geologic map (Pl. 1, Fig. 3).



**Cover photograph and sketch (above):** Nettle Brook Fault Zone (Locality D-8) looking northeast. Note the prominent east-dipping, post-peak metamorphic fault surface (dashed line below hammer). Heavy solid line above fault is interpreted to be an earlier fault contact between the Underhill Formation (EZu) and black carbonaceous schist of the Hazens Notch Formation (EZhnc).

Development of the dominant schistosity (S<sub>1</sub>) occurred during garnet to kyanite grade (medium- to medium-high-pressure) metamorphism. Pervasive minor folds (F<sub>1</sub>) which fold S<sub>1</sub> are coaxially refolded (by F<sub>2</sub>) only in the western part of the field area (E<sub>2</sub> and E<sub>2</sub>g). Deformation after the peak of metamorphism locally sheared and lineated S<sub>1</sub> and was accompanied by retrograde metamorphism in all units. Late (F<sub>2</sub>) cross-biotite and muscovite found only in the E<sub>2</sub> and E<sub>2</sub>g may have grown below older, higher and hotter thrust slices (E<sub>2</sub>a + E<sub>2</sub>h<sub>1</sub> + E<sub>2</sub>h<sub>2</sub>). Based on published information, the age of the dominant schistosity and the peak of metamorphism are believed to be Taconian.

Several previously unmapped bodies of mafic schist (E<sub>2</sub>h<sub>1</sub>s and E<sub>2</sub>h<sub>2</sub>s) in the E<sub>2</sub>g and E<sub>2</sub>u were recognized in this study. Based on outcrop evidence and preliminary major and trace element geochemistry by Coish and students (pers. com.), the mafic schists are interpreted to be metamorphosed Late Proterozoic rift volcanics associated with the early development of the proto-Atlantic ocean.

The black carbonaceous schist (E<sub>2</sub>h<sub>1</sub>c) at Lincoln Gap, is a critical unit that is found to the south as discontinuous bodies (with sharp, commonly sheared contacts) in both the Hazens Notch Formation (E<sub>2</sub>h<sub>1</sub>) and the Mt. Abraham Schist (E<sub>2</sub>a). These bodies of E<sub>2</sub>h<sub>1</sub>c are interpreted as the remnants of a thrust slice or slices (subsequently folded and metamorphosed) that structurally overlies the E<sub>2</sub>h<sub>1</sub>, E<sub>2</sub>a and the Underhill Formation (E<sub>2</sub>u). Contacts between the Hoosac Formation (E<sub>2</sub>h<sub>1</sub>g) and E<sub>2</sub>u, E<sub>2</sub>a, and E<sub>2</sub>h<sub>1</sub> and E<sub>2</sub>h<sub>1</sub>c represent relict depositional sequences. Isolated bodies of E<sub>2</sub>u in E<sub>2</sub>a, E<sub>2</sub>h<sub>1</sub> in E<sub>2</sub>u, and E<sub>2</sub>a in E<sub>2</sub>u are interpreted as folded fault slivers.

Detailed (1:12,000) mapping and petrography of the 25 square kilometers Mt. Grant - South Lincoln area in central Vermont, has shown that the Late Proterozoic Hoosac, Underhill, Mt. Abraham and Hazens Notch Formations are a highly deformed and metamorphosed group of rocks, consisting of 11 mappable units. Rock types include metamorphosed rift volcanic and clastic rocks, albitic, carbonaceous and aluminous schists and minor quartzite. The complex distribution of mapped units and their structures indicates that the original stratigraphy was severely overprinted by folds and faults.

## ABSTRACT

## INTRODUCTION

### Location and Physiography

The study area is located in north-central Vermont, east of the village of South Lincoln and corresponds approximately to the central rectangle of the Lincoln, VT 7.5' quadrangle (Pl. 1, Fig. 1 and Fig. 1). The area covers 25 square kilometers of National Forest land, along the topographic axis and east flank of the Green Mountains. The relief from Mt. Grant in the southeastern part of the field area, to South Lincoln in the western part, is 2,300 feet (720 m).

The eastern boundary of the study area follows the Long Trail from Lincoln Gap southward to Mt. Grant and Cooley Glen. The southern boundary is Cooley Glen, a small east-west valley drained by a tributary of the New Haven River. The New Haven River flows north-south to form the western boundary of the study area. The east-west trending Lincoln Gap road is the northern boundary. The topography is shown in half tone on the geologic map (Pl. 1, Fig. 3).

Access to the area is limited to hiking trails, logging trails and a few secondary and unimproved roads. A relatively recent fire access road referred to in this report as the "Fire Road" greatly improved access to the northeastern part of the field area, including several critical exposures which will be discussed later. Outcrop quantity and distribution is variable, generally best along prominent ridges and stream drainage areas.

### Regional Geology

The study area is located in pre-Silurian schists just east of the Lincoln massif, which is the northernmost exposure of Middle Proterozoic basement in Vermont (Pl. 1, Fig. 1 and Fig. 1). A report by Gordon (1927) described the general geologic relations of the Lincoln Gap area, but the most comprehensive previous study of bedrock geology in the area was done by Cady and others (1962) for the Lincoln Mtn. 15 minute quadrangle. These data formed the basis for the Centennial Geologic Map of Vermont (Doll and others, 1961).

Under the direction of Dr. Rolfe Stanley at the University of Vermont, numerous graduate students have recently studied in detail the geology of areas adjacent to this study area (Pl. 1, Fig. 1). Closely related to this study are the work of O'Loughlin (1986) to the north, DelloRusso (1986) to the west and Prewitt and Haydock (in progress) to the east. More detailed information on the area is presented in theses by Lapp (1986), O'Loughlin (1986) and DelloRusso (1986), at the University of Vermont.

### Purpose and Significance of Study

The purpose of this study was to re-evaluate the stratigraphy, structure and metamorphism of the area using detailed mapping and petrography, and to integrate these observations with more recent thought on the geologic history of the region. The study was done as part of a larger project to provide a detailed basic geologic framework for a more comprehensive understanding of

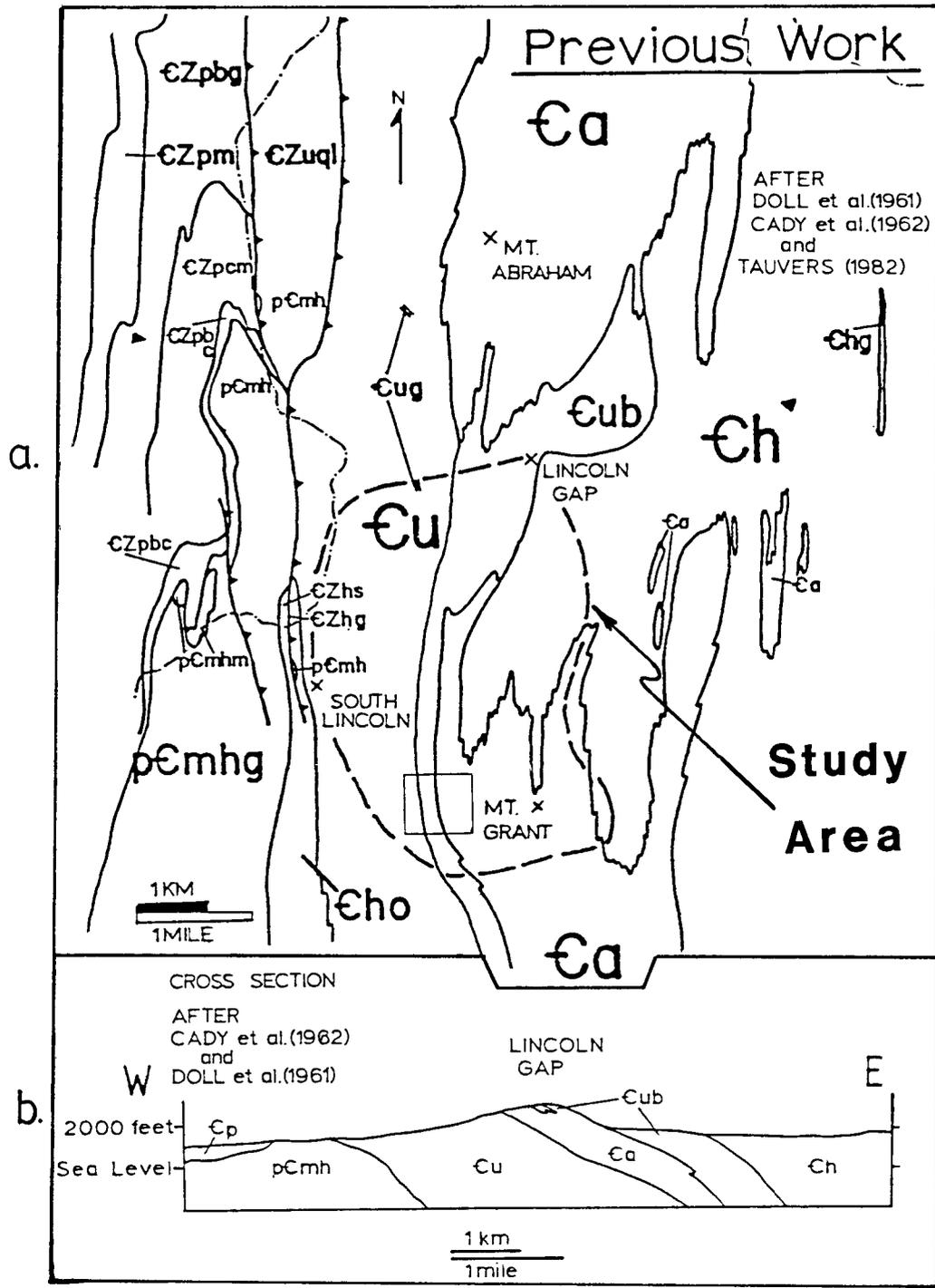


Figure 1. a. Location of study area (thick dashed line) on detailed geologic compilation map. Refer to Plate 1 for lithic designators. Box west of Mt. Grant is study area of Albee (1965); triangular ticks mark line of cross section shown in b.

the tectonics, metamorphic petrology, geochronology and geochemistry of central Vermont.

Geologically, the study area is located along the axis of the Green Mountain anticlinorium, where the westernmost kyanite-grade rocks in central Vermont are in close proximity to the northernmost Middle Proterozoic basement massif (the Lincoln massif) in western New England (Pl. 1, Fig. 1 and Fig. 1). Rock types include highly deformed and metamorphosed rift-volcanic and clastic rocks, semipelitic, aluminous and carbonaceous schists and minor quartzites.

The principal working hypothesis at the beginning of the study was that the rocks of the Mt. Grant-South Lincoln area are not a simple east-dipping homoclinal sequence, with all contacts depositional, but that the area is structurally complex, with significant deformation, involving map scale folds and faults of Taconian age within and between mappable rock units. It was further postulated that the Mt. Abraham Schist and the mafic schists might represent tectonically emplaced slices of higher metamorphic grade. Stanley and Ratcliffe (1985) proposed that the formation boundaries in the Mt. Grant-South Lincoln area are Taconian thrust faults and that this area is the northern root zone for the eroded part of the Taconic slices.

#### Methods and Techniques

The field mapping was accomplished using pace and compass (and altimeter) techniques, during the summer and fall of 1984. Topographic basemaps at a scale of 1:12,000 were constructed by 100% enlargement of standard 1:24,000 U.S.G.S. quadrangle maps. A copy of the basemap with observed outcrops appears in half tone on Plate 1. The outcrops shown represent 60-70% of the total outcrop available. A letter/number grid borders the map and is used in the text for general locations (e.g., Locality C-4). Exact locations and more detailed information are found in Lapp (1986), available at the University of Vermont, Burlington, VT.

Traverses proceeded in a grid-like fashion from the Long Trail south and west, from the Fire Road east and west, along all streams and ridges, and between streams, parallel to the slope. Contacts were "walked out" whenever possible. Approximately 400 hand specimens were collected including oriented samples from fault zones and additional samples from mafic schist for future radiometric and geochemical analyses. One hundred and fifty thin sections were prepared and studied using a standard petrographic microscope and a microfiche reader for textural studies. Several samples were stained for identification of plagioclase and potassium feldspar. Contoured lower hemisphere equal area projections of structural data were generated by a microcomputer.

## LITHIC UNITS

### Previous Work and Introduction

The following discussion of previous work is augmented by Figure 1 (text) and Figures 1 and 2 on Plate 1. Figure 1 is a compilation of previous mapping in the immediate vicinity of the field area prior to the start of this study. Plate 1 (Fig. 1) shows a more regional compilation map and a correlation chart (Pl. 1, Fig. 2) which compares formation names, symbols and brief rock descriptions. Our correlations are based on similarity of rock types. The stratigraphic order assumed by earlier workers is not considered valid in this study since many of these contacts which were previously assumed depositional, are now mapped as faults.

An early account of the geology of the Lincoln Gap area by Gordon (1927) did not define formation names, but noted the presence of magnetite-bearing, carbonaceous, and garnetiferous schists and greenstones. Osberg (1952), who mapped the Rochester-East Middlebury area, along strike to the south, named and described the rocks in much greater detail (Pl. 1, Fig. 2).

Cady and others (1962) recognized the Underhill Formation, the Mt. Abraham Schist and the Hazens Notch Formation in the field area of this report (Fig. 1). Rocks west of the Underhill Formation but east of the Precambrian were called the Pinnacle Formation. Cady's compilation of the geology of the Lincoln Mountain Quadrangle for the state map (Doll and others, 1961) showed all units as part of the Camels Hump Group. He included the Mount Abraham Schist as a member of the Underhill Formation, showed a "Battell" (carbonaceous) Member of the Underhill Formation as the most easterly Underhill unit, and showed the part of the Pinnacle Formation which lies directly east of the Precambrian as the "Hoosac" Formation.

The intricate map pattern in the areas north and south of Lincoln Gap was attributed by Cady and others (1962) to complex stratigraphic facies changes. Structurally, their interpretation was a simple eastward-dipping and upward-younging homoclinal sequence (Fig. 1b). Cady retained much of Osberg's map pattern in compiling the Rochester-East Middlebury area for the state map but renamed most of the units as shown on Figures 1 and 2 of Plate 1.

The Lincoln and Starksboro areas, northwest of the study area, were recently mapped in detail (1:24,000) by Tauvers (1982) and DiPietro (1983), who documented the nature of "Pinnacle/Hoosac" rocks and the western part of the Underhill Formation. Detailed (1:12,000) mapping was done in the central part of Camels Hump 15' quadrangle by Eiben (1976) and Aubrey (1978). These two workers considered their units to be members of the Underhill Formation as defined by Doll and others (1961), but comparison of rock descriptions and their location, which is exactly along strike with the rocks of this study, suggests that Eiben and Aubrey's Underhill units correlate with rocks in the Underhill, Mt. Abraham and Hazens Notch Formations, as mapped in the present study (Pl. 1, Fig. 2).

The following discussion describes in detail the rocks of the Mt. Grant-South Lincoln area, generally from west to east in a structural order from

lowest to highest, and relates them to previous work. Petrographic details are listed in Tables 1.1, 1.2, 2.1, and 2.2.

## Hoosac Formation

**Metawacke and schist (EZhq):** The western-most lithic unit in the field area is a rusty tan to gray metawacke. The best exposures of this unit occur along a small ridge which parallels the west side of Gerry Road, northeast of the center of South Lincoln (Pl. 1, Fig. 3, Locs. G-1 and B-2). Other outcrops of the unit are found in the New Haven River valley and the low ridges to the west in the area mapped by DelloRusso (1986) (Pl. 1, Figs 1 and 3). Thin layers (2-7 m thick) of this unit are also found interlayered with mafic schists at the Cota Brook sequence (D-4), described below.

The rock type is typically a massive to schistose, fine- to medium-grained metawacke or semipelite, with rare well-segregated laminae defined by alternating 2-3 mm thick quartzo-feldspathic and micaceous layers. Quartz, plagioclase (some detrital), white mica, chlorite, minor biotite and garnet are the dominant minerals (Table 1.1). Rarely, biotite and white-mica crosscut the dominant foliation of the rock.

Small lenses (up to a few tens of meters in length) of more aluminous rocks, similar to the sericite schist (EZus) and the garnetiferous schist (EZugs) of the Underhill Formation to the east, also occur in the mapped belt of Hoosac Formation. The eastern contact of this unit with the schists of the Underhill Formation is not exposed in the field area and rocks on either side of the drawn contact show a gradational (mineralogically) relationship, thus the Hoosac-Underhill contact is interpreted as a relict depositional sequence in the study area.

### Mafic Schist (EZhms)

1. Gerry Road locality (H-2): Two groups of previously unmapped exposures of medium- to coarse-grained, amphibole-rich mafic schist were discovered in the Hoosac Formation. The first group is located 0.6 km northeast of the village of South Lincoln on the east side of Gerry Road (Loc. H-2). The contacts between the mafic schist and the metawacke are not exposed and the three outcrops of mafic schist vary in texture and mineralogy. The most amphibole-rich samples of mafic schist here show coarse, poorly-oriented porphyroblasts of green amphibole up to 2 cm in length in a lighter green, plagioclase-rich matrix. Quartz, chlorite, biotite, epidote and opaques are also present (Table 1.2). Other samples contain chlorite pseudomorphs after amphibole, a greater percentage of plagioclase and quartz, and a significant amount of carbonate.

2. Cota Brook locality (D-4): The second group of mafic schist outcrops assigned to the Hoosac Formation is found well-exposed and interlayered with metawackes along Cota Brook (D-4) and is here referred to as the "Cota Brook sequence". It is the thickest exposure of mafic schist in the Mt. Grant-South Lincoln area. The contacts between the interlayered massive quartzo-feldspathic metawackes and the mafic schist are sharp but generally devoid of fault zone fabrics, inferring a relict depositional sequence. The

Table 1.1. Average estimated modes (volume %) for pelitic and semipelitic schists of the Camels Hump Group, Mt. Grant-South Lincoln area, central Vermont

<u>Mineral</u>	LITHOLOGIC UNIT						
	WEST	LITHOLOGIC UNIT				EAST	
	Hoosac Fm.	Underhill Fm.	Mt. Abraham Sch.	Hazens Notch Fm.			
	EZhg	EZu	EZugs	EZa	EZap	EZhnc	EZhn
Quartz	35	31	33	30	33	50	30
W. Mica	27	44	45	42	43	17	40
Chlorite	5	8	15	9	10	4	12
Chloritoid	-	tr	7	13	2	-	-
Albite	28	7	tr	tr	8	12	23
Garnet	tr-1	1	2	tr	tr	tr	tr
Biotite	2	1-2	-	-	-	-	1-2
Kyanite	-	-	-	tr-2	tr	-	-
Graphite	tr	1	-	-	-	15	1
Opaques	tr-1	1	1	1	1	tr-1	1
Number of Estimated Modes:	7	23	5	25	9	15	15

Table 1.2. Average estimated modes (volume %) for mafic schists of the Camels Hump Group, Mt. Grant-South Lincoln area, central Vermont

<u>Mineral</u>	Hoosac Fm. (EZhms)	Underhill Fm. (EZums)
Quartz	23	3
Plagioclase	14	36
Epidote	3	9
Garnet	tr	tr
Amphibole	30	15
Chlorite	15	13
Biotite	1	5
Carbonate	10	12
Opaques	2	2
Number of Estimated Modes:	11	17

eastern contact of the Cota Brook sequence with the Underhill Formation, however, is a highly-sheared, 10 m thick zone of schists. Although poorly exposed, the western contact of the Cota Brook sequence with the Underhill metawacke (Ezufg) includes well-lined quartzo-feldspathic rocks. These observations suggest that the Cota Brook sequence is a fault sliver of Hoosac Formation (mafic schist and metawacke) within the Underhill Formation.

The massive metawackes within the Cota Brook sequence commonly display wedge-shaped, detrital plagioclase grains and elongate quartz, whereas schistose parts show elongate quartz and bent white micas.

The mafic schist texture is dominantly massive with coarse clots of amphibole needles in a lighter plagioclase-rich matrix. In thin section these amphibole clusters commonly display an anastomosing shear fabric with blue-green grains showing rare, patchy, fine exsolution lamellae. Less amphibolitic samples contain more chlorite, biotite and carbonate.

DelloRusso (1986) recently mapped a group of mafic and semipelitic rocks similar to the Cota Brook sequence, along strike to the south. These localities, in addition to those described above, are regionally important and were not previously reported. The stratigraphic/structural position and geochemistry of the mafic schist (discussed later) suggest their correlation with the Tibbit Hill Volcanic Member of the Pinnacle Formation in northern Vermont (Doll and others, 1961). In terms of original protolith, Hoosac mafic schist probably represents metamorphosed volcanic rocks related to Late Proterozoic rifting of North America.

## Underhill Formation

**Foliated metawacke (Ezufg):** Outcrops of this unit occur in the northwestern part of the field area and along strike to the north in the area mapped by O'Loughlin (1986). Exposures discussed in this report are limited to the vicinity of the Cota Brook sequence (Loc. D-4). The reader may also refer to O'Loughlin and Stanley (1986) for further description and discussion.

The Underhill foliated metawacke has mineralogical and textural characteristics of both the schistose parts of the Hoosac metawacke (Ezhg) and the massive parts of the Underhill undifferentiated schist (Ezu) (see corresponding descriptions). This unit's eastern and western contacts are not well exposed in the study area. The unit is extremely well-foliated for several meters east of (structurally above) its contact with the Cota Brook sequence (Loc. D-4).

**Undifferentiated muscovite schists (Ezu):** This north-south trending belt of rock forms the hills and slope between the New Haven River valley and the break in slope below the steep ridge to the east (crest of the Green Mountains). This unit contains several belts of aluminous schists and several bodies of mafic schist described here for the first time. Significantly, several discontinuous lenses (interpreted as fault slivers) of more easterly, structurally higher rock units including the Mt. Abraham Schist (Eza) and Hazens Notch Formation (Ezhn and Ezhnc) were also found in this unit. The undifferentiated schist also occurs as fault slivers to the east. The

northeastern part of the undifferentiated schist (EZu) is cut by complex fault zones, involving both the Mt. Abraham Schist (EZa) and the Hazens Notch Formation (EZhnc), whereas the southern part (in the vicinity of Albee's 1965 study) appears to be in more simple (interpreted as relict depositional) contact with the Mt. Abraham Schist (EZa) (Pl. 1).

The undifferentiated schist (EZu) is typically a locally rusty-weathering quartz-mica schist, containing chlorite, plagioclase, biotite, garnet (commonly rimmed with chlorite), quartz veins and minor magnetite porphyroblasts (Table 1.1). Both coarse biotite (porphyroblasts up to 2 cm in thickness) and white mica commonly have grown at random angles to the dominant foliation, appearing as needles on the foliation surface. Coarse (1 cm) gray plagioclase (albite to oligoclase) porphyroblasts with macroscopic Carlsbad twins and graphite inclusions are common. Folded, light- to dark-gray quartzite layers from 2 to 20 cm in thickness also occur in this unit.

The undifferentiated schist is quite rusty where it is in contact with the carbonaceous schist (EZhnc) and although scattered patches of graphite are found within the unit, the carbonaceous schist of the Battell Member (Doll and others, 1961) was not found between it and the Mt. Abraham Schist (EZa) in the southeastern part of the study area (compare Fig. 1a and Pl. 1, Fig. 3).

**Sericite schist (EZus):** This unit occurs predominantly along the eastern boundary of the undifferentiated schist (EZu) and is closely related to both EZu and the garnetiferous schist (EZugs) described in the following section. This rock type is a fine-grained schist with chlorite, white mica, biotite and small amounts of garnet. Along the southwestern side of Mt. Grant (Loc. Q-7) this unit and the garnetiferous schist are transitional rock types between the undifferentiated schist (EZu) and the Mt. Abraham Schist (EZa).

**Garnetiferous schist (EZugs):** Gordon (1927), Osberg (1952), Cady and others (1962), Albee (1965), Eiben (1976) and Aubrey (1978) all recognized garnet schist in the Underhill Formation in central Vermont. In the Mt. Grant-South Lincoln area this rock type occurs as folded, elongate north-trending belts in the undifferentiated schist (EZu), along the western margin of the Mt. Abraham Schist (EZa) and as lenses within EZa. The type locality for this unit is the Prospect Rock area in the northwestern part of the field area (Loc. G-4).

The rock type is a distinctive, slightly rusty-weathering, lustrous, white-mica schist containing coarse red garnets up to 2 cm in diameter. Significantly, this unit contains chloritoid (7% average, Table 1.1) and trace amounts of albite, suggesting it may be related to more chloritoid-rich rocks of the Mt. Abraham Schist (EZa and EZap) to the east. This unit is also lithically similar to the Mt. Abraham magnetite-garnet schist (EZamg) in the area mapped by O'Loughlin (1986) to the north (Pl. 3), although EZugs south of the Gap road contains little magnetite.

**Mafic schist (EZums)** Numerous bodies of fine- to medium-grained mafic schist are found in the northeastern part of the Underhill Formation (Pl. 1, Fig. 3). These outcrops show a variety of contact relationships with the surrounding rocks, some of which suggest they were originally flows or

intrusives, some of which were later sheared and carried along on faults.

Contacts between the mafic and pelitic schists are commonly sharp and the degree of alteration, layering, mineral segregation and textures is quite variable. Where the undifferentiated schist (EZu) surrounds the mafic bodies, the schist commonly becomes increasingly albitic toward the contact with the mafic rocks.

The mineralogy of the most amphibolitic samples of Underhill mafic schist (EZums) includes amphibole, plagioclase, chlorite, quartz, epidote, carbonate, opaques, biotite and minor but conspicuous garnet (Table 1.2). Amphibole-poorer samples contain more plagioclase, chlorite, carbonate, biotite and epidote.

**1. Locality C-6:** Small outcrops of albite-carbonate-chlorite schist occur both north and south of the Lincoln Gap Road, just west of BM 1567 (Loc. C-6). These outcrops are shown as a greenstone on the map by Cady and others (1962). Samples of this rock are albitic, calcareous, weakly-foliated, rusty-weathering, gray-green schist. The northern end of this body is located between outcrops of Hazens Notch albitic schist (EZhn) to the east, and Underhill garnetiferous schist (EZugs) to the west, although the exact contacts are not well-exposed (Loc. C-6). The southern end of the body is exposed in the stream bed of Cota Brook, infolded with the Underhill garnetiferous schist (EZugs). The mineralogy of the greenstone is plagioclase, carbonate, chlorite and epidote, with minor amounts of opaques and white-mica.

**2. Locality D-6 ("Dike 1750\*"):** A single exposure of a thin body (1-2 m thick x 8 m long) of massive black, fine-grained mafic schist was found at Locality D-6, entirely within the undifferentiated schist (EZu). The contacts of this body with the schist are sharp, deeply-weathered and carbonate-bearing, over a 0.3 m wide zone. Two 10 cm long oval inclusions and a folded, irregularly-shaped, 1 m long body of the coarsely albitic schist (EZu), appear to be completely isolated within the mafic schist at this locality. The nature of the contact zone and inclusions are suggestive of original igneous features such as weathered chilled margins and xenoliths, respectively.

The mafic schist at Locality D-6 has an equigranular texture with small (< 1 mm) garnet porphyroblasts, barely visible in hand specimen. The mineralogy is plagioclase, amphibole (with exsolution lamellae), chlorite, quartz, garnet, opaques and trace biotite.

**3. Locality E-7 ("Castle Hill"):** A series of exposures of well-layered and tightly folded, green to black mafic schist occur along a hill at Locality E-7. Both the eastern contact with the garnetiferous schist (EZugs) and the western contact with the undifferentiated schist (EZu) are well-exposed, chlorite-rich and well-foliated, suggesting that the body is a reactivated fault sliver.

The largest exposure of this rock type (on the north side of the hill at Loc. E-7) shows well-segregated layers (1 cm to 1 m thick) enriched in one or

more of the following minerals: plagioclase, amphibole, epidote, carbonate, chlorite, biotite, quartz, magnetite and minor iron sulfides.

Microprobe analyses by Laird (1986, pers. com.) and Kimball (1986, pers. comm.) indicate that the amphiboles from this locality are ferrohornblende which grew under medium pressure (>5 kbar) in the garnet zone of metamorphism.

4. Locality I-6 ("Camp Stanley" greenstones): Approximately 0.8 km south of Locality E-7 are three groups of mafic schist outcrops which define an east-west trending line, but may not simply be different parts of the same body, as they are separated by different rock types. The mineralogy and texture of the western and central bodies closely resemble the black fine-grained mafic schist at Locality D-6, whereas the eastern body closely resembles the greenstones at localities M-6 and C-6. The central body is in tectonic contact with a sliver of Hazens Notch Formation (EZhn), a structurally higher and more easterly unit which may have been emplaced at the same time.

5. Locality M-6: Two outcrops of greenstone similar to the eastern body of Locality I-6 and the greenstone at Locality C-6, occur in the coarsely-albitic schist (EZu) at Locality M-6. Access to the outcrops can be gained by following a rough jeep trail shown on the topographic base map (Pl. 1, Fig. 3). This body does not appear to be a fault sliver, but unlike the body at Locality D-6, which has a similar setting, it lacks amphibole and contains more plagioclase, chlorite and carbonate.

**Geochemistry of mafic schist:** Kolar (1975) used whole-rock geochemistry to postulate that the Hazens Notch greenstone east of Lincoln Gap was originally ocean tholeiite or alkali basalt. Coish and others (1985) used major and trace element geochemistry to conclude that the Hancock greenstone, southeast of the study area (Pl. 1, Fig. 1) was an oceanic basalt, and that high  $TiO_2$  greenstones in the Pinnacle and Underhill Formations in northern Vermont were rift volcanics.

Preliminary major and trace element geochemistry of all mafic schist samples from the Hoosac and Underhill Formations in the South Lincoln area (Gavigan, 1986) show a well-defined, high- $TiO_2$ , transitional alkalic to tholeiitic, within-plate signature, which suggests a strong correlation with the Libbit Hill rift volcanics in the Pinnacle and Underhill Formations to the north (Fig. 2). This plot includes data for a mafic schist body from the study area of O'Loughlin (1986), referred to as the "Battell greenstone". The latter greenstone has mineralogical and textural characteristics of the mafic schists at localities D-6 and E-7 (Pl. 1, Fig. 3) and is located 4 km to the north (labelled EZums at the northern edge of the geologic map on Plate 3).

We suggest that mafic schist in the Hoosac and Underhill Formations are metamorphosed rift-volcanics related to the opening of the proto-Atlantic ocean, based on the preliminary geochemistry data and close association with metawackes.

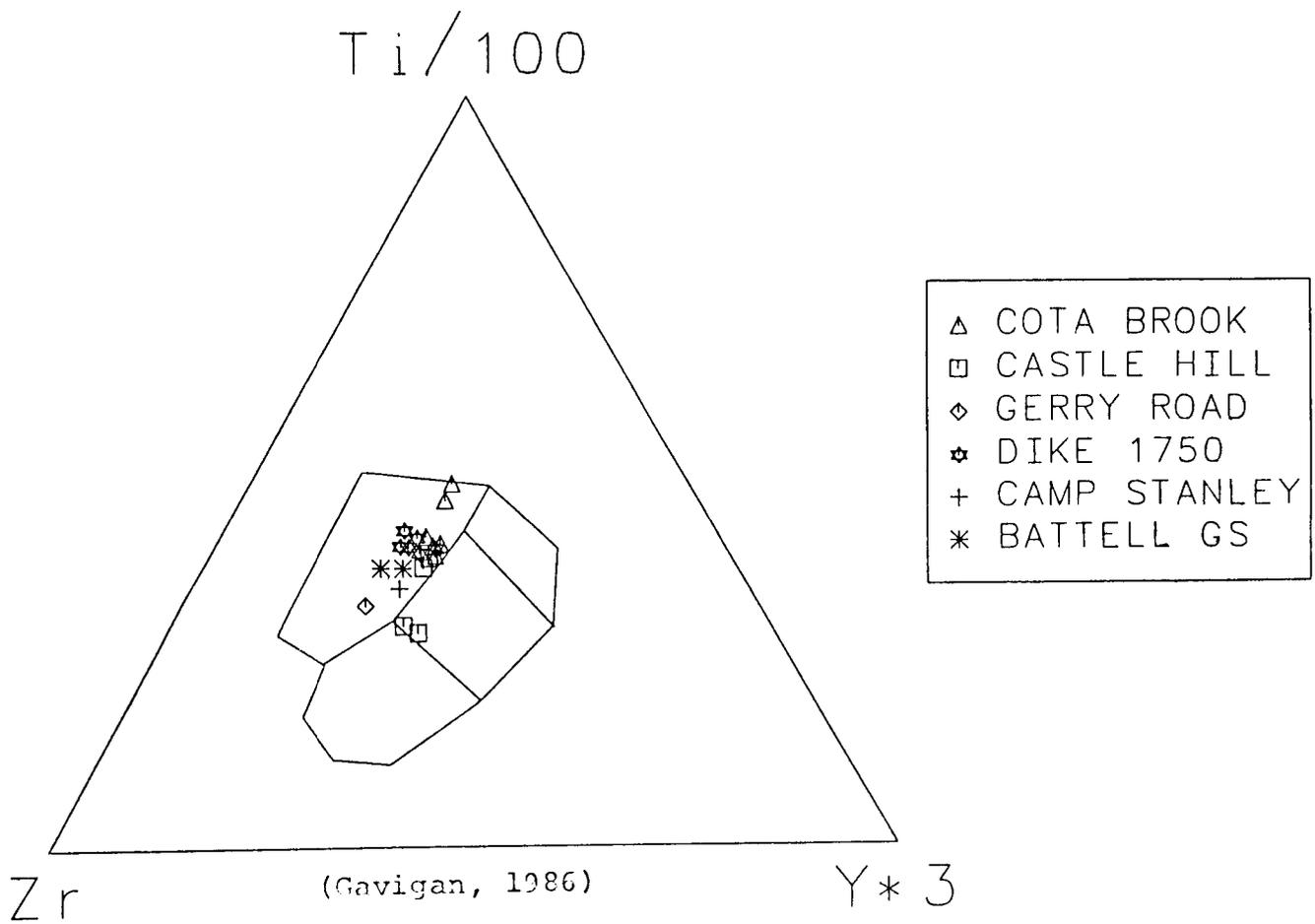


Figure 2. Geochemistry of mafic schist from the South Lincoln area (Hoosac and Underhill Formations) showing well-defined, high  $TiO_2$ , within-plate signature, suggesting correlation with the Tibbit Hill Volcanics in northern Vermont.

Table 2.2. Recrystallization history/structural age of minerals in mafic schist from the Mt. Grant-South Lincoln area (Hoosac and Underhill formations combined).

MAFIC SCHIST				
Mineral	Structural Age			
	Sn-1/pre-Sn	syn-Sn	post-Sn/syn-Fn+1	post-Sn+1/syn-Fn+2
QUARTZ				
PLAGIOCLASE				
EPIDOTE				
GARNET				
AMPHIBOLE				
CHLORITE				
BIOTITE				
CARBONATE				
OPAQUES				

## Mt. Abraham Schist

Chloritoid-white mica schist (E<sub>Za</sub>): The roughly U-shaped belt of the Mt. Abraham Schist (E<sub>Za</sub>) is located in the central and southeastern parts of the field area, and surrounds the highest part of the topographic ridge. This unit contains numerous bodies of carbonaceous schist (E<sub>Zhnc</sub>) and smaller bodies of other units not reported in earlier publications, which are here interpreted as fault slivers (Pl. 1, Fig. 3). Small bodies of this unit also occur in the noncarbonaceous schist (E<sub>Zhn</sub>) and as slivers in the carbonaceous schist (E<sub>Zhnc</sub>) of the Hazens Notch Formation. Contacts between E<sub>Za</sub> and E<sub>Zhn</sub> are commonly gradational by a gradual change in composition involving an intermediate schist (E<sub>Zap</sub>), discussed below.

The Mt. Abraham Schist (E<sub>Za</sub>) is a distinctive, silvery blue-gray schist, commonly with abundant quartz veinlets, magnetite porphyroblasts and white-mica (paragonite according to Albee's 1965 analysis). The rock commonly displays chlorite streaks on the dominant foliation surface. Closer examination reveals these streaks to be pressure shadows developed around chloritoid and garnet. Zones and veins locally abundant in chloritoid, kyanite, chlorite, ilmenite (possibly hematite) and magnetite, in various combinations, are also common. One vein of 80% chloritoid, 0.5 to 1 m thick, occurs at Locality L-7, similar to a vein reported by Albee (1965) to the south.

Syntectonic garnet, kyanite and chloritoid porphyroblasts in samples of this unit commonly show evidence for post-peak metamorphic deformation and metamorphism. These features include pressure shadows, kinked blades (kyanite) and inclusion-free rims (chloritoid). Pseudomorphs of white-mica after kyanite are common, and are poorly-oriented within or at a low angle to the plane of the dominant schistosity. The pseudomorphs are visible as small (1 cm ave.) rusty needles (Pl. 2, Fig. 3d). Thin sections show the pseudomorphs to be lath-like patches or clusters of optically-continuous, fine white-mica (Pl. 2, Fig. 3d).

Albite-chloritoid-white mica schist (E<sub>Zap</sub>): This unit is closely related to the Mt. Abraham Schist (E<sub>Za</sub>) and generally outcrops as folded linear bodies in or near the noncarbonaceous schist (E<sub>Zhn</sub>) and in the carbonaceous schist (E<sub>Zhnc</sub>) of the Hazens Notch Formation. One small, isolated body of E<sub>Zap</sub> unit (which contains kyanite pseudomorphs) occurs to the west in the Underhill Formation (Loc. E-6) and is interpreted to be a fault sliver.

The mineralogy and texture of this unit (E<sub>Zap</sub>) is much like the chloritoid-white mica schist (E<sub>Za</sub>), but it contains quartzite layers, less chloritoid, significant amounts of plagioclase (ave. 8%, Table 1.1), and is commonly in close proximity to the noncarbonaceous schist of the Hazens Notch Formation (E<sub>Zhn</sub>). These relations suggest the unit was originally a transitional sediment (intermediate in composition and location) between E<sub>Za</sub> and E<sub>Zhn</sub>.

## Hazens Notch Formation

**Noncarbonaceous schist and quartzite (EZhn):** This unit is found on the high ridge in the northeastern part of the field area and as bodies in the Mt. Abraham Schist and the Underhill Formation (Pl. 1, Fig. 3). Complex fault zones, involving carbonaceous schist and small amounts of other units occur in this unit.

The rock type is light-gray to light-green, micaceous, albitic schist, commonly containing albite porphyroblasts, quartzo-feldspathic and quartzite layers from a few cm to 2 m in thickness. The quartzites are massive, with equant, recrystallized quartz grains seen in thin section. Rare layers of the schist are rich in zoned plagioclase porphyroblasts, some of which show macroscopic Carlsbad twins and a gray color due to inclusions of graphite. This unit contains garnet and small but significant amounts of biotite, not found in the Mt. Abraham schists (Table 1.1). The matrix of the unit is slightly graphitic and commonly quite rusty-weathering where it is in contact with the carbonaceous schist (EZhnc).

**Dolomitic marble (EZhnm):** Small lenses (1-5 m) of brown-weathering, blue-gray dolomitic marble that contain white-mica and quartz are found in a shear zone at Locality K-11. This is the only occurrence of this rock type in the field area and may represent a fault sliver of "exotic" material or original sedimentary layers that were later sheared.

**Carbonaceous schist and quartzite (EZhnc):** This unit occurs as large irregular bodies, interpreted as fault slices, in the eastern half of the field area and as small slivers along faults in the Underhill Formation to the west. Small slivers of rocks from both the Mt. Abraham Schist and Underhill Formation occur within the carbonaceous schist.

The rock type is a distinctive dark-gray to black, quartz mica schist, commonly containing zoned (rarely Carlsbad twinned), fine- to coarse-grained, black plagioclase (due to graphite inclusions), dark-gray quartzite layers (1 cm to 0.5 m thick), minor pyrite, and trace carbonate (Table 1.1). Outcrops are commonly well-lined and foliated. This unit has significantly less white-mica and more quartz and graphite than all other units (Table 1.1). The plagioclase content is similar to the Hazens Notch Formation noncarbonaceous schist (CZhn).

## STRUCTURE

### Previous Work and Introduction

The 1925-1926 report of the State Geologist (Gordon, 1927, p. 297-307) noted that the rocks of the South Lincoln-Lincoln Gap area were highly deformed, with "severely sheared" carbonaceous schist, "contorted bands of white quartz" and no apparent remains of bedding. Osberg (1952), who worked in the Rochester-East Middlebury area to the south, was the first to recognize that complex folds control the map pattern in central Vermont. He noted numerous examples of superposed minor folds which he related to the major structure (the Green Mountain anticlinorium). He also recognized complex

fabrics in thin section.

Cady and others (1962) interpreted much of the complex map pattern to be the result of lateral and vertical sedimentary facies changes, rather than a complex structural history. These authors claimed to recognize bedding, stated that observed contacts were gradational and that the gross structure was an east-dipping homocline of upward (and eastward) younging units (Fig. 1b). Although Cady and others (1962) documented numerous schistositys, minor folds and lineations, they believed the map pattern was only affected by late folds. Significantly, no faults were shown on Cady and others' 1962 map.

The exact trace of the Green Mountain anticlinorium in the study area is not shown on the state map (Doll and others, 1961). This may be due to the absence of east-facing folds and the lack of west-dipping schistositys. Cady and others (1962) inferred the existence of the Green Mountain anticlinorium in this area in part from the metamorphic high recognized along the topographic crest.

Doulan and others (1973) and Kolar (1975) noted two generations of sub-parallel, north-trending, east-dipping schistositys in a small area east of Lincoln Gap (Pl. 1, Fig. 1). Eiben (1976) and Aubrey (1978) documented isoclinal folds and multiple schistositys in the central part of the Camels Hump 15' Quadrangle to the north and attributed the Green Mountain anticlinorium to "F3" folding. Osberg (1952), Cady and others (1962), Eiben (1976) and Aubrey (1978) all present evidence of relatively shallow east- or west-dipping dominant schistositys along strike with the rocks of this study.

Northwest of the study area, Tauvers (1982) and DiPietro (1983) documented multiple generations of folds, major thrust zones and truncated stratigraphy (Pl. 1, Fig. 1, and Fig. 1a). Based on detailed thin section and fabric analysis, Strehle (1985) and Strehle and Stanley (1986) showed that the Underhill and Jerusalem thrusts developed under upper greenschist facies conditions.

Concurrent with this study, DelloRusso (1986) and DelloRusso and Stanley (1986) have documented extensive Paleozoic fault zones in the Lincoln massif and eastern cover sequence in the area to the west, while Lapp (1986), Lapp and O'Loughlin (1986), O'Loughlin (1986) and O'Loughlin and Stanley (1986) presented a complex, folded, fault-controlled pattern for the Lincoln Gap area. Stanley and others (1986) have noted extensive faulting in the Waitsfield-Granville Gulf area to the east.

The structural history of the Mt. Grant-South Lincoln area is very complex, involving shortening during the development of multiple generations of faults, folds and schistositys. The following sections describe the fabrics, orientation, distribution and significance of the observed structures.

The explanation on Plate 1, Figure 3 describes the structural nomenclature used during the mapping and analyses. This includes the designation of the dominant schistosity at the outcrop as the "n" generation ( $S_n$ ). Folds which fold the dominant ( $S_n$ ) schistosity are thus " $F_{n+1}$ ", and

folds which fold  $F_{n+1}$  are " $F_{n+2}$ ". Field occurrences of pre- $F_{n+1}$  folds and pre- $S_n$  and post- $S_n$  schistosity were too sparse to analyze statistically.

During the structural analyses it became evident that two distinct structural domains could be delineated by the orientation of  $S_n$  schistosity and  $F_{n+1}$  axial surfaces. These two domains correspond approximately to the eastern and western halves of the study area and are also referred to as the "South Lincoln" and "Mt. Grant" domains, respectively (Pl. 2, Fig. 2 and Pl. 3).

### Dominant ( $S_n$ ) Schistosity

The single most prominent structural feature observed in the study area is the dominant schistosity ( $S_n$ ). This structure is a metamorphic layering (commonly folded) defined by the sub-parallel arrangement of recrystallized phyllosilicates and other non-equidimensional minerals. In semi-pelitic rocks  $S_n$  is commonly defined by quartzo-feldspathic domains interspersed with mica domains. In pelitic rocks  $S_n$  is generally defined by micas, with quartz segregated into small intrafolial folds.

The peak metamorphic ( $M_p$ ) mineral assemblages in most rocks are generally syntectonic with  $S_n$ . Locally, and in the carbonaceous schist ( $E_{Zhc}$ ) in particular, the dominant schistosity is extremely well-developed, displaying prominent down-dip lineations formed by recrystallized quartz and less commonly by chlorite.

Plate 2, Figure 2 (a) shows a synoptic diagram derived from statistical analyses of contoured, lower hemisphere, equal area projections of poles to  $S_n$  for eastern and western domains (outlined on the adjacent map). From the evidence presented in this figure,  $S_n$  is documented as north-trending and east-dipping, with a more shallow dip in the eastern domain of the field area. An abrupt steepening of  $S_n$  occurs from east to west across a 0.5 km-wide zone which corresponds to the domain boundary. This steepening of  $S_n$  is interpreted to be the result of a "buttressing" effect from the Lincoln massif to the west. Statistically, it is important to note that nearly four times as much data and approximately twice the amount of outcrop occur in the eastern domain as compared to the western domain.

### Pre- and Post- $S_n$ Schistosity

Primary depositional features, such as bedding, are not present in the pelitic and semipelitic rocks of the study area due to the high degree of deformation and metamorphism. The closest resemblance to relict bedding is the crude layering of quartzo-feldspathic and mica domains in the massive metawackes of the Hoosac and Underhill Formations. In the more pelitic rocks a schistosity that predates  $S_n$  is preserved as relict fold hinges in microlithons and as orthogonal (at a high angle to  $S_n$ ) or spiral inclusion trails in porphyroblasts.

An  $S_{n+1}$  schistosity locally deforms  $S_n$  and is seen as a spaced (1 mm to 1 cm) slip or crenulation cleavage oriented at low to moderate angles to the dominant schistosity ( $S_n$ ). These  $S_{n+1}$  surfaces are nearly parallel to  $S_n$

because  $F_{n+1}$  folds are commonly tight or isoclinal in profile and are commonly sheared-out along later fault zones which are subparallel to the dominant ( $S_n$ ) schistosity.

### Minor Folds ( $F_{n+1}$ )

Pervasive minor folds and crenulations that fold the dominant schistosity are designated  $F_{n+1}$ . Fold styles vary from symmetric to asymmetric, and open to tight-isoclinal. Refolded fold patterns are common. Plate 3 (included in both this report and O'Loughlin and Stanley (1986)) shows axial surface and fold axes measurements for  $F_{n+1}$  folds in the combined study areas of Lapp (1986) and O'Loughlin (1986) plotted at a scale of 1:24,000. Synoptic diagrams derived from statistical analyses of the contoured lower hemisphere equal area projections are presented for each of the domains.

Minor ( $F_{n+1}$ ) fold data are more evenly distributed between eastern and western domains than  $S_n$  data. Fold styles are similar in both domains but crenulations in pelitic rocks and open folds in massive metawackes are more common in the western domain. Isoclinal folds with axial surfaces that are parallel to  $S_n$  are common in the eastern domain. Most asymmetric  $F_{n+1}$  folds give an east-over-west sense of rotation (Pl. 3), consistent with their location east of a major fold structure (the Lincoln anticline).

$F_{n+1}$  axial surfaces and fold axes: From Plate 3 and Plate 2, Figures 2a and 2b, it is obvious that  $F_{n+1}$  axial surfaces in the eastern and western domains show different patterns. Poles to  $F_{n+1}$  axial surfaces in the west show a girdled distribution with weak maxima defined by northeast- and southeast-trending surfaces that dip moderately to the south. The eastern domain shows no girdle but has a well-defined north-trending, east-dipping maximum essentially parallel to the dominant schistosity (compare eastern domain  $S_n$  of Figure 2a with eastern axial surface in 2b on Pl. 2). One explanation for the girdle in the western domain is that  $F_{n+1}$  folds were coaxially refolded (about an axis sub-parallel to  $F_{n+1}$ ) in an east-over-west sense.

Data for  $F_{n+1}$  fold axes are less convincing (Plate 3 and b. of Pl. 2, Fig. 2). They generally show a gentle plunge to the south-southeast in both eastern and western domains. A few north-plunging folds were observed in the northern part of the Mt. Grant domain (Pl. 3). Field evidence for shallow doubly-plunging folds was observed as canoe-shaped refolded fold patterns along this topographic ridge (Pl. 1, Fig. 3; Pl. 3).

### Pre- and Post- $F_{n+1}$ Folds

Pre- $F_{n+1}$  folds are less-commonly observed and are highly refolded. Many appear to be sub-parallel to  $F_{n+1}$  and are seen as intrafolial fold hinges in pelitic rocks, or in microlithons and inclusions in thin section.

Post- $F_{n+1}$  folds were rarely observed in the field and are restricted to the western domain where they are seen as broad warps of  $F_{n+1}$  axial surfaces. This deformation is evident from careful study of the structural data map on Plate 3. Also note that the statistical  $F_{n+2}$  fold axis is nearly parallel to

that of  $F_{n+1}$  (b of Pl. 2, Fig. 2). Because the  $F_{n+2}$  folds are not seen in the eastern domain, we contend that west-dipping  $F_{n+1}$  axial surfaces in the western domain resulted from rotation as the area moved over a structure at depth, such as a thrust ramp in the Middle Proterozoic rocks below. In this scenario,  $F_{n+1}$  folds in the eastern domain tightened and flattened without much rotation.

## **Sn Faults and Fault Zones**

Faults that are parallel to the dominant schistosity in the outcrop are designated as Sn faults. These faults are generally zones of distributed shear which display sharp, highly-foliated and lineated (down dip) surfaces that are not folded (Pl. 2, Fig. 3b and 3e).

Plate 2, Figure 2c, is a synoptic diagram of fault surfaces and mineral lineations derived from contoured lower hemisphere equal area projections. Most of the Sn fault data is from the eastern (Mt. Grant) domain, probably because outcrop is more abundant and the mechanically-weak carbonaceous schist (EZhnc) is present. Asymmetric fabrics associated with the lineations give an east-over-west sense of displacement. The following two sections discuss the evidence for repeated deformation and metamorphism at key field localities.

**Nettle Brook fault zone:** At Locality D-8 a large, undercut exposure of rusty-weathering Underhill schist (EZu) structurally overlies highly-sheared graphitic schist and quartzite (cover photograph and sketch on pg. ii). The contact between the units is extremely sharp and is parallel to the dominant schistosity, which is folded by  $F_{n+1}$  folds with steep axial surfaces. The intensely-sheared zone in the carbonaceous schist at the base of the outcrop is a quartz-lineated, east-dipping fault zone that truncates  $F_{n+1}$  folds. A thin quartz vein from the extremely sharp, annealed, Sn contact between the two units shows deformation lamellae and deformation bands which possibly developed during folding, before the latest faults developed in the carbonaceous schist below. Chlorite pressure shadows around garnets in the Underhill schist (EZu) of the upper plate developed during post- $F_{n+1}$  deformation.

The Sn contact is a pre-peak metamorphic fault, based on map truncation. The sequence of events at this outcrop therefore was: Sn faulting, folding of the Sn fault, followed by truncation of the  $F_{n+1}$  folds during post-peak metamorphic faulting.

**The Fire Road fault zone:** Several outcrops that display a variety of contact relationships and fault fabrics of different ages and in different rock types are well-exposed and easily accessible from a fire access road 2 km southwest of Lincoln Gap (Pl. 1, Fig. 3 and Pl. 2, Fig. 3). The first of these outcrops, at Locality F-8, is marked by a very conspicuous (20 m x 1-2 m) milky-white quartz vein (Pl. 2). Carbonaceous schist (EZhnc) occurs along the lower (western) part of this outcrop, while rusty-weathering, garnetiferous Mt. Abraham Schist (EZA) occurs above (Pl. 2, Fig. 3). Outcrops of the latter unit to the east and north are less rusty and contain kyanite pseudomorphs.

Contacts between the two schists are extremely sharp and highly "interfingered" (Pl. 2, Figs. 3b and 3e). One exposure shows  $F_n$  folds in the rusty schist truncated by the carbonaceous schist along an  $S_n$  (pre- to syn- $M_p$ ) fault (Pl. 2, Fig. 3b). The schist contact was later folded by  $F_{n+1}$  folds and intruded by the large quartz vein. Post- $F_{n+1}$  faults displaced the schists to the west, over the quartz vein, along a corrugated surface (Pl. 2, Fig. 3e). The east-west trend of the hinge line of the corrugations is parallel to quartz lineations on the carbonaceous schist ( $E_{zhnc}$ ), which is also found as lineated slivers within the quartz vein (Pl. 2, Fig. 3c).

Additional evidence for post-peak metamorphic (post- $M_p$ ) deformation is shown on Plate 2, Figure 3a. Garnet in the Mt. Abraham Schist was sheared parallel to the dominant schistosity and chloritized during the post- $M_p$  faulting. Quartz and mica domains from the same rock show planar arrangement of white-mica and highly-recrystallized and elongate quartz in thin section.

The above observations suggest a history of repeated deformation and metamorphism at this fault zone. Early  $S_{n-1}$  faulting of the carbonaceous and rusty schists was followed by  $F_n$  folding, and truncation along  $S_n$  faults during kyanite-grade metamorphism.  $F_{n+1}$  folds of the  $S_n$  fault contacts were intruded by the quartz vein, which was displaced over the schists, and itself cut by post- $F_{n+1}$  faults.

Reactivated fault zones similar to the Nettle Brook and Fire Road fault zones also occur between the carbonaceous and noncarbonaceous schists of the Hazens Notch Formation. One such locality (F-9, G-10) is also conveniently located along the Fire Road approximately 0.25 km southeast of locality F-8. These fault zones show pre- $M_p$  faults that are folded by  $F_{n+1}$  and reactivated during post- $M_p$  faulting.

### Post- $F_{n+2}$ Faults

A third locality along the Fire Road (G-10, G-11) displays a late fault zone that truncates the regional fabric. Here the massive quartzo-feldspathic Hazens Notch Formation ( $E_{zhn}$ ) is cut by wide-spaced (1-2 meters) south-dipping, east-west trending slip surfaces that display "chatter marks" which have a right-lateral sense of motion. This fault zone and two other such localities (L-7 and C-5) with similarly oriented structures do not appear to involve great displacements as they do not affect the map pattern.

## METAMORPHISM

### Previous Work and Introduction

Gordon (1927) noted "profound alteration" and pre-tectonic magnetite in the rocks of the Mt. Grant-South Lincoln area. Osberg (1952) gave detailed mineral descriptions, located isograds and discussed protoliths for the rocks along strike to the south. Cady and others (1962) presented mineral assemblages and included all the rocks in the Mt. Grant-South Lincoln area within the garnet zone. The distribution of kyanite was reportedly too scattered to draw an isograd with confidence.

Albee (1965) discussed in detail the petrology of a small area west of Mt. Grant, along the boundary between the Mt. Abraham Schist and the Underhill Formation (Fig. 1a). The principal assemblages were believed by Albee (1965) to have equilibrated at a single temperature, pressure and activity of water. These workers used microprobe, X-ray, and oxygen-isotope analyses of coexisting minerals. Albee (1965) attributed both the complete equilibration and reported monomineralic zones to the movement of large volumes of fluid through the rocks parallel to the dominant schistosity.

A kyanite-chloritoid isograd was shown for the Mt. Grant area on the metamorphic map of Doll and others (1961). This was published again by Albee (1968) where he also reported staurolite. A kyanite isograd is not shown on the Lincoln Mtn. map (Cady and others, 1962) or on the small map in Albee's 1965 report. Albee (1968) claimed that the high grade rocks of north-central Vermont correspond to the crests of the Green Mountains and to areas with aluminous rocks but admitted that equally high metamorphic conditions may have existed over a wider area where bulk compositions were not appropriate for kyanite.

Interestingly, Albee (1968), then in the minority, believed most deformational and metamorphic features along the Green Mountain anticlinorium were Taconian. Laird and others (1981a and b, 1984) suggest that Taconian (471 m.y.) medium to medium-high pressure (500-550 C, 4-5 kbar) metamorphism in the Mt. Grant area was followed by medium pressure Acadian (385 m.y.) metamorphism. Sutter and others (1985) claim Acadian metamorphism did not affect rocks of the Mt. Grant area and that the younger ages are cooling ages from earlier, hi-pressure Taconian metamorphism. Detailed metamorphic petrology of mafic schist and geochronologic analyses of mafic and pelitic schist from the Mt. Grant-South Lincoln area is currently addressing this problem (Laird and Sutter, pers. com.).

### Peak (Mp) and Post-Mp Metamorphism

Data on the metamorphic petrography of pelitic and mafic schist for this study are presented on Tables 1.1, 1.2, 2.1, 2.2 (pg. 12), and Plate 2, Figure 2. Detailed petrographic analyses of the Mt. Grant-South Lincoln area has found little in conflict with the observed assemblages of Cady and others (1962) or Albee (1965). The development of peak metamorphic assemblages was generally synchronous with the development of the dominant schistosity (Sn). Tables 2.1 and 2.2 list critical textural observations and the relation of minerals to structural events for all pelitic and mafic units. These data are summarized on Plate 2, Figure 2.

Evidence for widespread post-peak metamorphic (post-Mp) deformation and metamorphism, not previously emphasized, is documented in this study. Chloritization of garnet in the Underhill and Hoosac Formations, and the shearing, chloritization and nature of exsolution lamellae in mafic schist are evidence for post-Mp events in the western domain. The chloritization of garnet and chloritoid, and replacement of kyanite by fine-grained white-mica are common in the western domain. The carbonaceous schist shows pervasive post-Mp deformation. Samples from the Mt. Abraham Schist (EZap) that contain



both plagioclase porphyroblasts and kyanite pseudomorphs and the conspicuous plagioclase zonation in the Hazens Notch Formation also represent post-peak metamorphism in the eastern domain.

Veins of chlorite, chloritoid and quartz in the Mt. Abraham Schist and quartz and plagioclase in the carbonaceous schist are late metamorphic events (Table 2.1). The growth of cross-biotites and muscovite in the Underhill Formation was the last metamorphic event observed, and is interpreted to have occurred below hot thrust slices of the eastern domain.

In addition to the work in progress cited above, suggestions for future research on the metamorphism of the area include microprobe study and thermobarometry of mineral assemblages to better quantify the pressure, temperature, time path for rocks in the study area.

### SYNTHESIS AND CONCLUSIONS

The following is a brief discussion of the critical observations made and the interpretations and conclusions drawn from this study. Review of the summary diagrams of Figures 1 and 3, and Plate 2, Figures 1 and 2, clarifies the arguments.

Comparison of the detailed mapping of this study with that of Cady and others (1962), shows significantly greater detail in rock types and their distribution and structural relations in the Mt. Grant-South Lincoln area. A summary lithic correlation diagram which incorporates the work of O'Loughlin (1986) is presented as Figure 3. Horizontal correlation with the units of Doll and others (1961) and Cady and others (1962) is based only on lithic similarities. The vertical arrangement is a simplification of the relations described in the text and figures of this report.

The most important stratigraphic observations from the western part of the field area (Hoosac and Underhill Formations) include the presence of: metamorphosed rift volcanic and clastic rocks, bodies of rocks from units in the eastern part of the area (interpreted as fault slivers), and the lack of the black carbonaceous schist in the Underhill Formation (Pl. 1, Fig. 3).

More detailed mapping of the eastern units reveals the presence of the black carbonaceous schist (EZhnc) as fault slivers in all units (interpreted as structurally on top), and the presence of rocks from the western belt (tectonic windows). The largest body of carbonaceous schist in the Lincoln Gap area (EZhnc in the central part of the map on Plate 3) appears to be the youngest tectonic slice, because it truncates previously folded sequences in the Mt. Abraham, Hazens Notch and Underhill Formations. The intermediate rock types between the eastern and western belts (EZugs and EZus), and within the domains (E Zufg and EZap) are interpreted as remnants of highly shortened depositional sequences.

Most importantly the "stratigraphy" of the area is tectonically controlled. The complexity of the map pattern, which involves mapped truncations of contacts which predate the dominant folding, suggests an early history of pre-metamorphic faulting. Fabrics of these faults were masked by

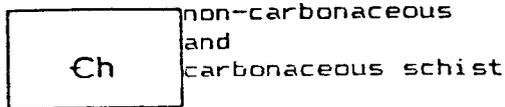
# SUMMARY LITHIC CORRELATIONS

## FOR THE MT. GRANT - SOUTH LINCOLN AREA

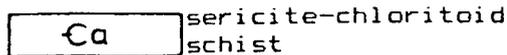
A. Doll (1961) and  
Cady et al. (1962)

B. This Report &  
Lapp and O'Loughlin (1986)

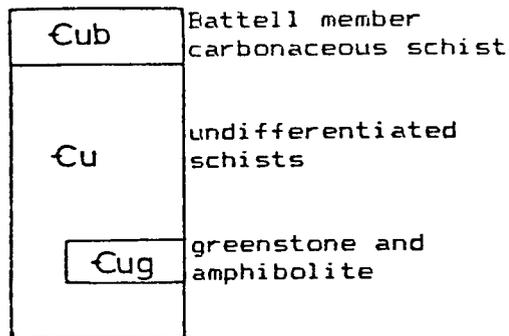
### HAZENS NOTCH FORMATION



### MT. ABRAHAM SCHIST



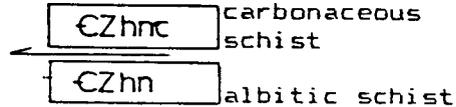
### UNDERHILL FORMATION



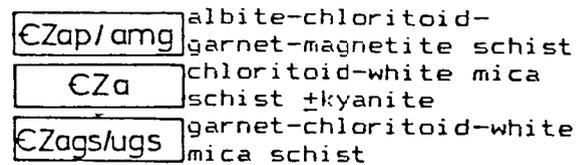
### HOOSAC FORMATION



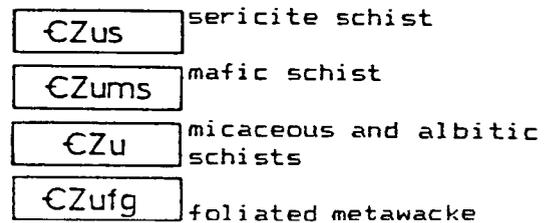
### HAZENS NOTCH FORMATION



### MT. ABRAHAM SCHIST



### UNDERHILL FORMATION



### HOOSAC FORMATION



Figure 3. Summary lithic correlations for the Mt. Grant-South Lincoln area. Note the greater detail and structurally controlled sequence in B. compared with A. In particular, note the absence of carbonaceous schist in the Underhill Formation of B.

the dominant metamorphic event, and are shown on the map and cross section with open teeth symbols. Numerous faults which post-date the peak of metamorphism are found within units and along the old fault zones. These are shown with closed teeth symbols and dashed lines and display the most obvious fault zone fabrics in the field. These later faults, however, probably involve less displacement and in large part do not affect the map pattern.

The metamorphism of the area records a dominant, garnet to kyanite grade event (Mp) that was followed by cooling during continued deformation (Pl. 2, Fig. 2). Extensive evidence for post-peak metamorphism was found throughout the study area.

The dominant schistosity developed during peak metamorphism, was pervasively folded and commonly reactivated along post-Fn+1 faults. The Green Mountain anticlinorium in the vicinity of the field area is defined by the shallowing of the dominant schistosity and the refolding of N+1 folds (east-over-west). These late folds and the development of cross-biotite and muscovite are restricted to the western domain. Post-N+2 faults are sharply discordant to the dominant regional grain but do not offset the map units at a scale of 1:12,000.

#### ACKNOWLEDGEMENTS

Funding for this study was provided by the following sources: the U. S. Forest Service (U. S. Department of Agriculture contract 524526, awarded to Rolfe Stanley); the National Science Foundation (grant EAR 8516879, to Rolfe Stanley); and the U. S. Department of Energy (grant DE-FG02-81WM46642, awarded to the Vermont Geological Survey). Any opinions, findings, conclusions or recommendations expressed herein, are those of the authors and do not necessarily reflect the views of the Department of Energy. Dr. Charles A. Ratte, Vermont State Geologist, provided a very helpful review of the manuscript.

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# PLATE 1

## Bedrock Geology of the Mt. Grant-South Lincoln Area, Central Vermont

Eric T. Lapp and Rolfe S. Stanley

Figure 1. Compilation of Previous Work

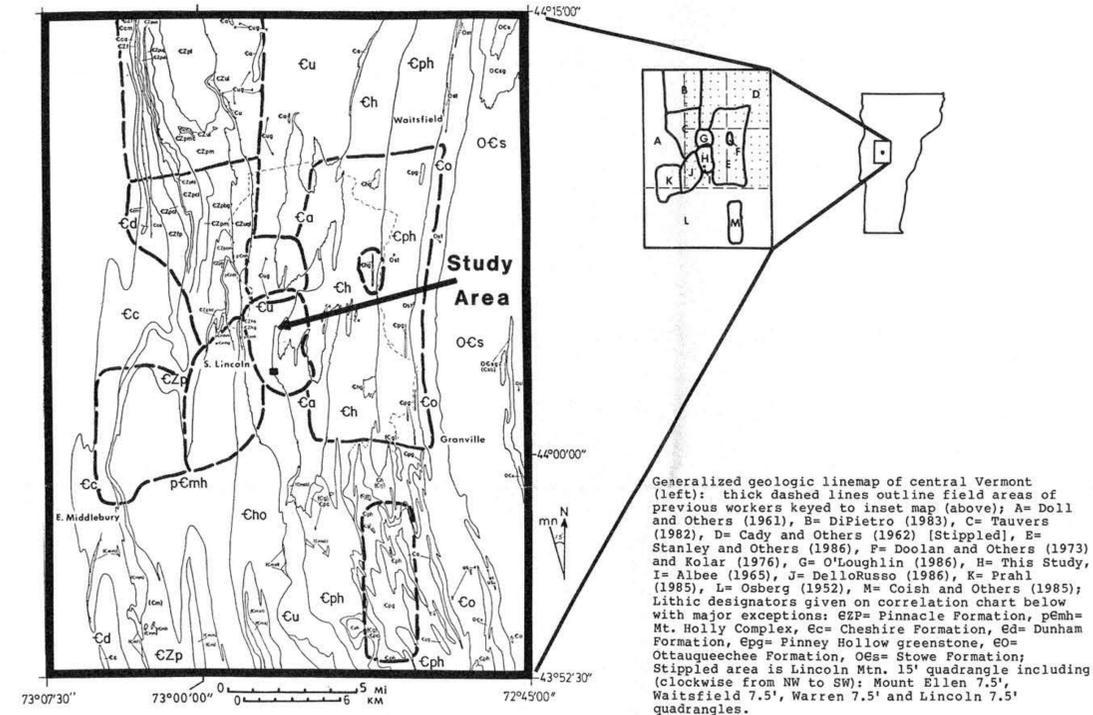


Figure 2. Lithic Correlations in the Camels Hump Group, Central Vermont

NORTH			SOUTH		
EISEN (1976) and AUBREY (1978) (modified) CENTRAL CAMELS HUMP 15' QUADRANGLE 1:12,000			OSBERG (1952), ROCHESTER AND EAST MIDDLEBURY AREA 1:62,500		
TAUVERS (1982) and DIPIETRO (1983) (modified) LINCOLN-STARKESBORO AREA 1:24,000			CADDY ET AL (1962) LINCOLN MOUNTAIN 15' QUADRANGLE, 1:62,500 (East of the Lincoln Massif)		
THIS REPORT (1986) MT. GRANT-SOUTH LINCOLN AREA 1:12,000			DOLL ET AL (1961), CENTENNIAL GEOLOGIC MAP OF VERMONT, 1:250,000 (East of the Lincoln Massif)		
<b>UNDERHILL FORMATION</b>	<b>HAZENS NOTCH FORMATION</b>	<b>HAZENS NOTCH FORMATION</b>	<b>HAZENS NOTCH FORMATION</b>	<b>FINNEY HOLLOW FORMATION</b>	<b>FINNEY HOLLOW FORMATION</b>
Cug: Albite granulite Cugs: Siliceous granulite lens Cugr: Graphitic schist	CZhn: Non-carbonaceous schist & quartzite CZnc: Carbonaceous schist & quartzite CZa: Albite-Chloritoid-white mica schist	Ch: Carbonaceous & Non-carbonaceous schist & quartzite Ca: Sericite-Chloritoid-schist Cg: Magnetite schist	Cu: Carbonaceous & Non-carbonaceous schist & quartzite Cph: Sericite-Albite-Chlorite schist Cpc: Carbonaceous schist & phyllite	Cu: Carbonaceous & Non-carbonaceous schist & quartzite Cg: Graphitic Quartz-Muscovite schist	Cph: Albite-Quartz-Chlorite-Muscovite schist Cg: Granville Formation Cms: Muscovite schist
Cumg: Magnetite schist Cugs: Graphitic schist	CZap: Albite-Chloritoid-white mica schist CZa: Chloritoid-white mica schist	Ca: Sericite-Chloritoid-schist Cg: Magnetite schist	Cu: Carbonaceous & Non-carbonaceous schist & quartzite Cph: Sericite-Albite-Chlorite schist Cpc: Carbonaceous schist & phyllite	Cu: Carbonaceous & Non-carbonaceous schist & quartzite Cg: Graphitic Quartz-Muscovite schist	Cms: Muscovite schist Cmsb: Battell Member: carbonaceous schist & quartzite Cmsc: Battell Member: carbonaceous schist & quartzite
Cug9: Garnet schist lens Cugs: Graphitic schist lens Curs: Greenstone Cugr: Rusty Albite schist Curs9: Granulite lens	CZugs: Garnetiferous schist CZus: Sericite schist CZums: Mafic schist CZur: Undifferentiated Muscovite schist CZul: Quartz-laminated schist CZuq: Foliated metawacke CZug: Greenstone	Cu: Non-carbonaceous schist & local carbonaceous schist Cg: Greenstone & amphibolite	Cu: Carbonaceous & Non-carbonaceous schist & quartzite Cph: Sericite-Albite-Chlorite schist Cpc: Carbonaceous schist & phyllite	Cu: Carbonaceous & Non-carbonaceous schist & quartzite Cg: Graphitic Quartz-Muscovite schist	Cms: Battell Member: carbonaceous schist & quartzite Cmsb: Battell Member: carbonaceous schist & quartzite Cmsc: Battell Member: carbonaceous schist & quartzite
<b>HOOSAC FORMATION</b>	<b>"HOOSAC FORMATION"</b>	<b>FINNEY HOLLOW FORMATION</b>	<b>HOOSAC FORMATION</b>	<b>HOOSAC FORMATION</b>	<b>HOOSAC FORMATION</b>
CZh: Schistose Biotite greywacke and Biotite schist CZns: Metagreywacke and Biotite schist	CZh: Schistose Biotite greywacke and Biotite schist CZns: Metagreywacke and Biotite schist	Cp: Schistose & schistose quartzite	Cu: Greenstone Cg: Graphitic Quartz-Muscovite schist	Cu: Carbonaceous & Non-carbonaceous schist & quartzite Cg: Graphitic Quartz-Muscovite schist	Cu: Carbonaceous & Non-carbonaceous schist & quartzite Cg: Graphitic Quartz-Muscovite schist

NOTE: Relative age of units is not implied by vertical arrangement

Figure 3.

### Lithic Descriptions

#### Hazens Notch Formation

**Non-carbonaceous schist and quartzite**  
Light-green to white, medium-grained, chlorite-plagioclase-quartz-muscovite-schist, with minor graphite, biotite, garnet and opaques; locally, 2 cm to 2 m thick layers of massive, light-gray quartzite; commonly the schist contains 1 mm to 1 cm albite porphyroblasts

**Carbonaceous schist and quartzite**  
Rusty or shiny, dark-gray to black, graphite-chlorite-muscovite-plagioclase-quartz schist and schistose quartzite; distinctively well-laminated; locally, the schist contains pyrite

#### Mt. Abraham Schist

**Albite-chloritoid-white mica schist**  
Same as E2a, but includes minor amounts of albite porphyroblasts

**Chloritoid-white mica schist**  
Silvery-gray, medium-grained, chlorite-chloritoid-quartz-white mica schist, locally with minor garnet, magnetite porphyroblasts and kyanite; distinctive chlorite streaks and 1 cm rusty needles (altered kyanite) common

#### Underhill Formation

**Garnetiferous schist**  
Silvery to rusty, medium- to coarse-grained, garnetiferous chloritoid-chlorite-quartz-white mica schist; distinctive 1-2 cm garnet porphyroblasts

**Sericite schist**  
Silvery to rusty, fine-grained, chlorite-quartz-sericite schist, with minor garnet, biotite and chloritoid

**Mafic schist**  
Dark-green to black, fine-grained, chlorite-quartz-plagioclase amphibolite, with minor biotite and garnet; green to dark-green, medium-grained, chlorite-biotite-epidote-plagioclase-amphibole schist; green, medium-grained, epidote-biotite-chlorite-carbonate-plagioclase schist, with minor quartz and amphibole

**Undifferentiated muscovite schists**  
Rusty or silvery, medium-grained, plagioclase-chlorite-quartz-muscovite schist, with minor biotite, garnet and graphite; locally, 2-20 cm layers of gray quartzite; locally, the schist contains medium-grained cross-biotite and/or cross-muscovite

**Foliated metawacke**  
Light-gray to rusty, massive to schistose, fine- to medium-grained, metawacke similar to E2hg; but more foliated, with well-oriented micas in 1 cm layers

#### Hoosac Formation

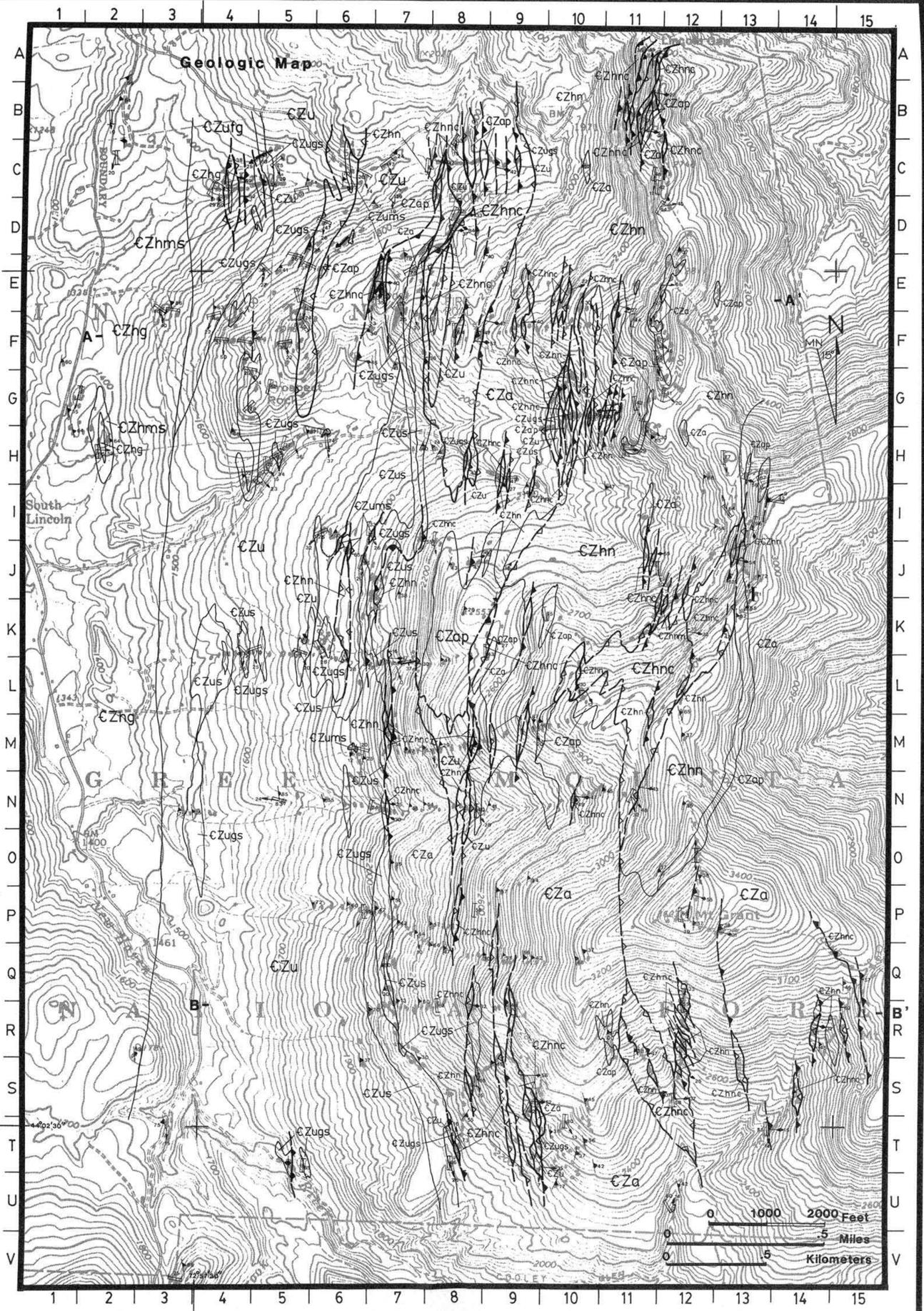
**Metawacke and schist**  
Light-gray to rusty, massive to schistose, fine- to medium-grained, chlorite-sericite-plagioclase-quartz schist/metawacke, with minor biotite, garnet, epidote and opaques

**Mafic schist**  
Green to dark-green, fine to medium-grained, chlorite-carbonate-quartz-plagioclase-amphibole schist and massive amphibolite, with minor biotite, epidote, garnet and opaques; greenish-gray, fine to medium-grained, carbonate-chlorite-quartz-plagioclase schist

NOTE: Relative age of units is not implied by vertical arrangement

### Explanation

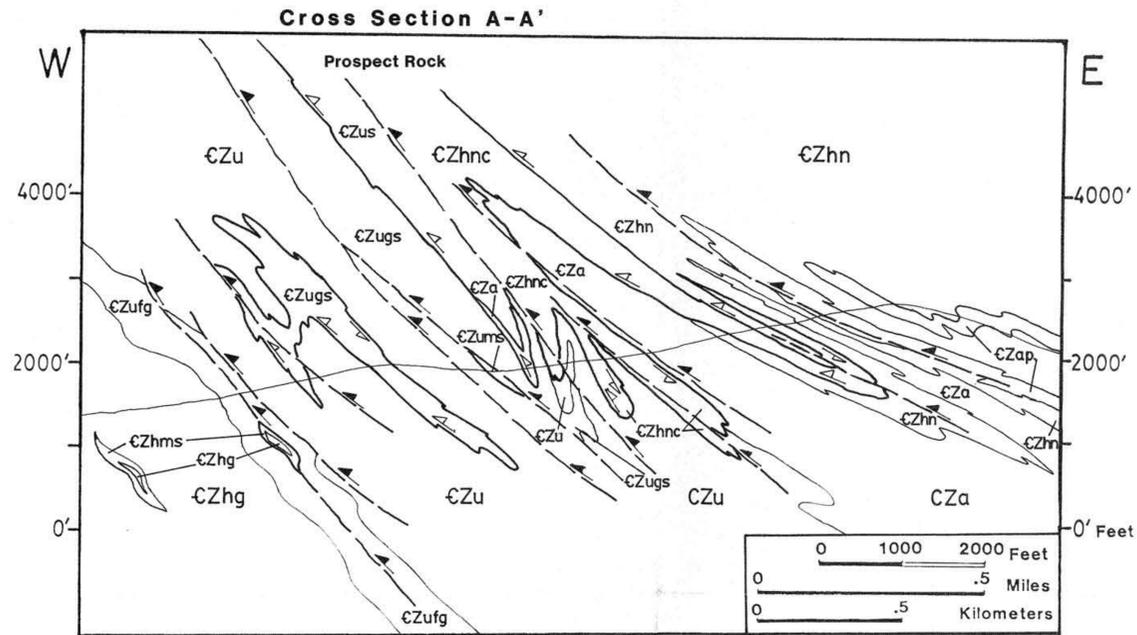
- CONTACTS**
- lithic contacts: everywhere solid, accuracy of location determined by outcrop density (in half tone on topographic base)
  - pre- to syn-peak metamorphic fault contact: teeth on inferred upper plate, tick shows true dip of contact where folded, commonly subparallel to the dominant schistosity
- PLANAR FEATURES**
- post-peak metamorphic fault: teeth on upper plate, dashed where inferred, dip of fault given by tick next to tooth, commonly subparallel to the dominant schistosity
  - post-Fn-2 fault: rare, discontinuous, crosscuts regional structural grain, shown only with associated mineral lineation (given as arrow)
  - strike and dip of dominant schistosity (Sn) vertical
  - strike and dip of Fn-1 axial surface vertical
  - strike and dip of Fn-2 schistosity: rare
- LINEAR FEATURES**
- trend and plunge of mineral lineation associated with post-peak metamorphic fault
  - trend and plunge of mineral lineation associated with post-Fn-2 fault
  - trend and plunge of Fn-1 fold axis: no rotation sense counterclockwise rotation sense clockwise rotation sense
  - trend and plunge of Fn-2 fold axis
- MISCELLANEOUS**
- lines of cross-section
  - register marks (intersection of latitude and longitude lines)
  - V3 grid location coordinates, referred to in text



# PLATE 2

Eric T. Lapp and Rolfe S. Stanley

Figure 1. CROSS SECTIONS



**Explanation:**

Geologic cross sections for the Mt. Grant-South Lincoln area; thin solid line = ground surface, medium solid line = lithic contacts (lithic designators given on plate 1), solid thick lines with open teeth indicate pre- to syn- peak metamorphic faults, dashed thick lines with solid teeth indicate post-peak metamorphic faults.

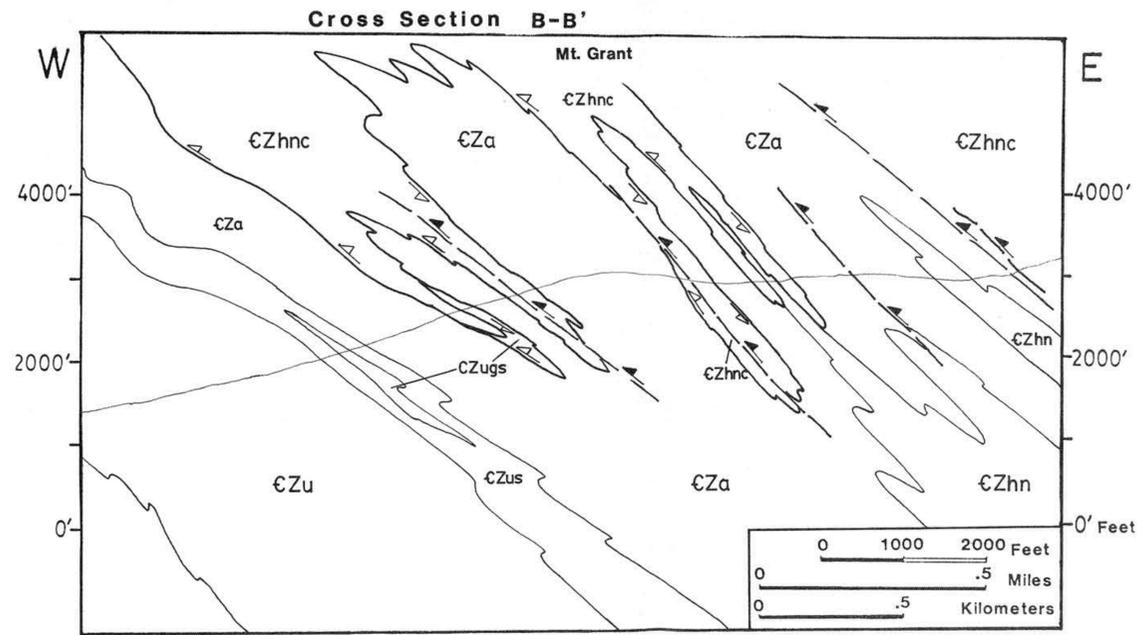


Figure 2.

Summary Structural and Metamorphic Relations; Domain map (right) outlining eastern and western domains for structural analyses (divided by thick dashed line) superposed on generalized line map (lithic designators given on plate 1). Synoptic Structural Data (center right); lower hemisphere equal area projections, by domain, for: a. planes corresponding to statistical point maxima for dominant schistosity (Sn); b. solid line = statistical F<sub>n+1</sub> axial surface for eastern domain, dashed line = girdle of poles to F<sub>n+1</sub> axial surfaces for western domain, larger dot is statistical F<sub>n+2</sub> fold axis defined by pole to F<sub>n+1</sub> girdle, smaller dots are statistical F<sub>n+1</sub> fold axes for eastern and western domains; c. statistical syn- to post-peak metamorphic fault surface and mineral lineation (both domains). Structural and Metamorphic Relations (far right): Approximate metamorphic grade and timing of key structural and metamorphic events.

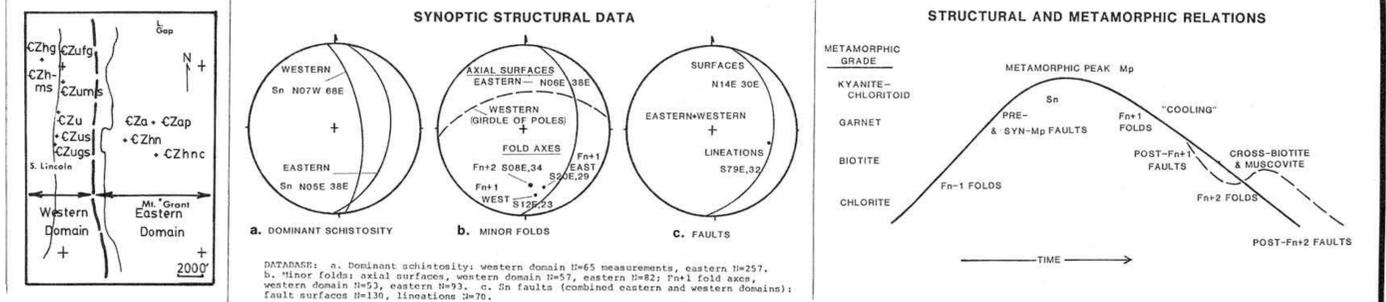
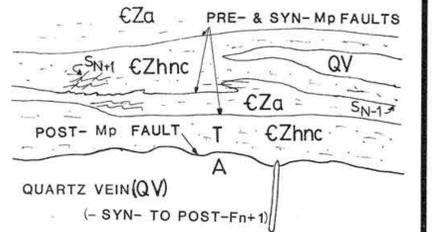
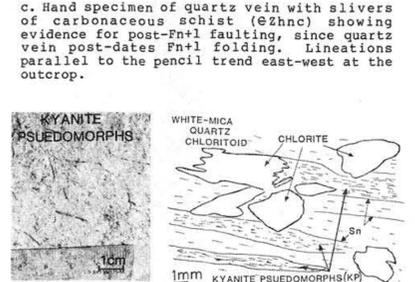
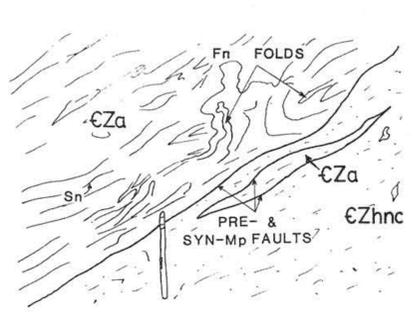
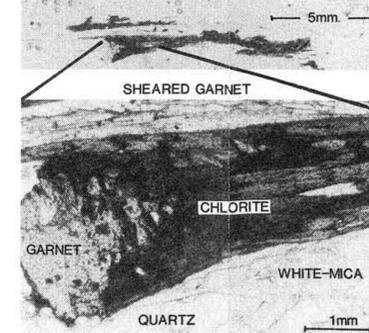
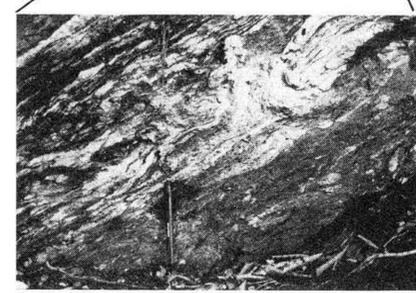
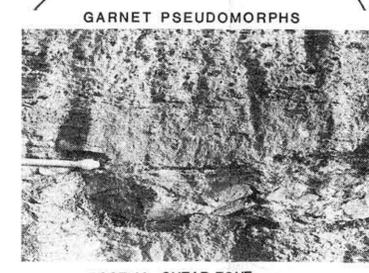
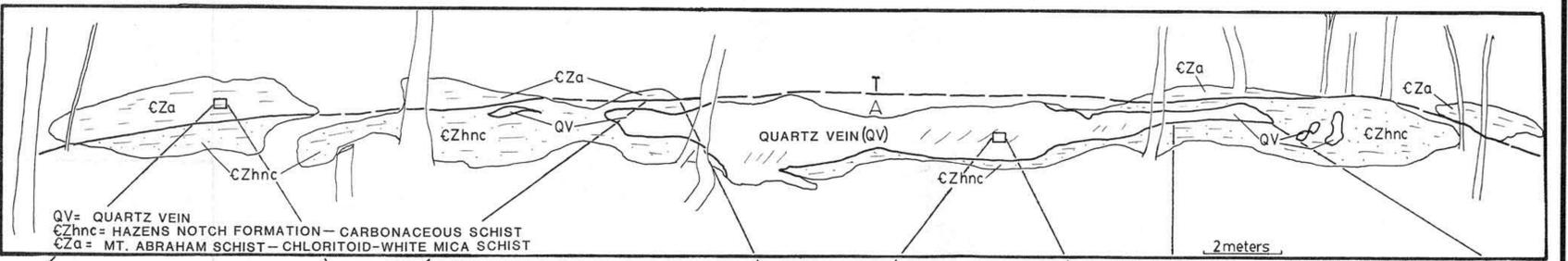


Figure 3. Fire Road Fault Zone



Photomosaic and sketch of critical outcrop along the Fire Road (station 36, locality F-8); view is east, thin line outlines observed outcrop, thick line is post-peak metamorphic fault (dashed where inferred), T= movement toward the observer, A= movement away.



a. Outcrop and thin section evidence for post-metamorphic peak (Mp) deformation: top photo shows increase in ellipticity of pits (sheared and retrograded garnets) toward post-Mp shear zone; bottom photos show sheared garnet with long chlorite pressure shadow (sample 33).

b. Photo and sketch of sharp, folded, annealed Sn fault contact (lower left to upper right) between rusty quartz-veined Mt. Abraham Schist ( $\epsilon$ Za) and black carbonaceous schist ( $\epsilon$ Zhnc).

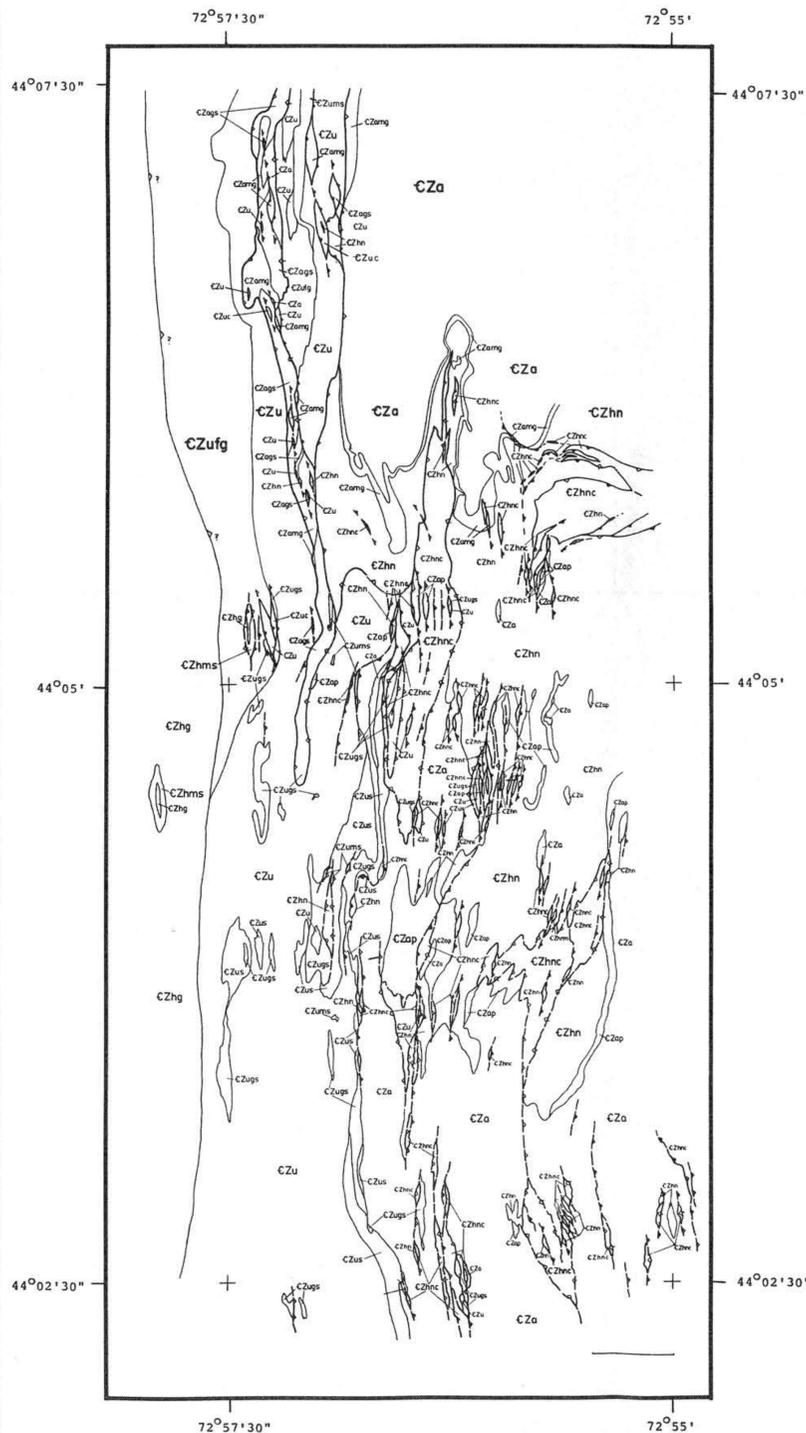
e. Photo and sketch of reactivated fault zone: pre- and syn-peak metamorphic faults between rusty Mt. Abraham Schist ( $\epsilon$ Za) and black carbonaceous schist ( $\epsilon$ Zhnc) were post-dated by emplacement of the quartz vein, which was overthrust after F<sub>n+1</sub> folding by the corrugated surface (long axis of corrugations trends S20E 46E).

# PLATE 3

Sharon B. O'Loughlin, Eric T. Lapp, and Rolfe S. Stanley

## Crenulate and Mesoscopic Fold Data from the Mt. Abraham - Mt. Grant Area, Central Vermont

### Combined Geologic Map



### Explanation

#### COMBINED GEOLOGIC MAP

For symbols, abbreviations, and explanation, refer to Plate 1.  
Lithic units which are not explained on Plate 1 are from either Lapp (1986) or O'Loughlin (1986) and include:

- CZhm Marble associated with the Hazens Notch Formation.
- CZap Similar units of the Mt. Abraham Schist.
- CZags Coarse garnet schist attributed to the Mt. Abraham Schist and the Underhill Formation, respectively.
- CZus Sericite schist of the Underhill Formation.
- CZhg Metawacke of the Hoosac Formation.

#### STRUCTURAL DATA MAP

##### Planar Features

- 51 Strike and dip of axial surface (Sn+1) to crenulate or mesoscopic Fn+1 folds which deform the dominant schistosity (Sn).
- Vertical axial surface (Sn+1) to crenulate or mesoscopic Fn+1 folds which deform the dominant schistosity (Sn).
- 89 Strike and dip of axial surface (Sn+2) to crenulate or mesoscopic Fn+2 folds which deform Fn+1 axial surfaces.

##### Linear Features

- 15 Trend and plunge of Fn+1 fold axis.
- 21 Trend and plunge of Fn+1 fold axis with known clockwise sense of rotation.
- 19 Trend and plunge of Fn+1 fold axis with known counter-clockwise sense of rotation.
- 12 Trend and plunge of Fn+2 fold axis.
- Geologic contact and domain boundary. Most geologic contacts are not represented.
- Lincoln Gap Road and domain boundary.

##### Other

- + Register mark.

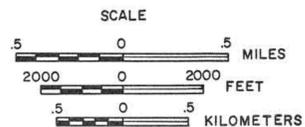
#### NETS

Lower hemisphere, equal area projections of summary relationships determined from plots of Fn+1 axial surfaces (Sn+1 schistosity). Five domains are represented. These are:

- Mt. Abraham Domain - the area including Mt. Abraham, west to the contact and south to the Lincoln Gap Road.
- Prospect Rock Belt Domain - the area which comprises the Prospect Rock Belt, south to the Lincoln Gap Road.
- Battell Trails Domain - the area west of the Mt. Abraham Domain and north of the Lincoln Gap Road, excluding the Prospect Rock Belt.
- Mt. Grant Domain - the area including Mt. Grant, west to the contact and north to the Lincoln Gap Road.
- South Lincoln Domain - the area to the east of South Lincoln, east to the contact and north to the Lincoln Gap Road.

On the plots, N denotes the orientation of north and a cross marks the center of the projection. The plane of the projection is horizontal. The number of measurements (poles) represented in each domain is n. A solid half circle represents the statistical plane derived by contouring the poles to Sn+1. The orientation of this plane is labelled. A dashed half circle, where present, corresponds to the orientation of the pi girdle through poles to Sn+1. The pole to the girdle represents the fold axis (solid dot) of Fn+2 deformation in the domain.

Geologic mapping and structural data north of Lincoln Gap Road from O'Loughlin (1986); south of Lincoln Gap Road from Lapp (1986).



### Fn + 1 and Fn + 2 Structural Data Map and Nets

