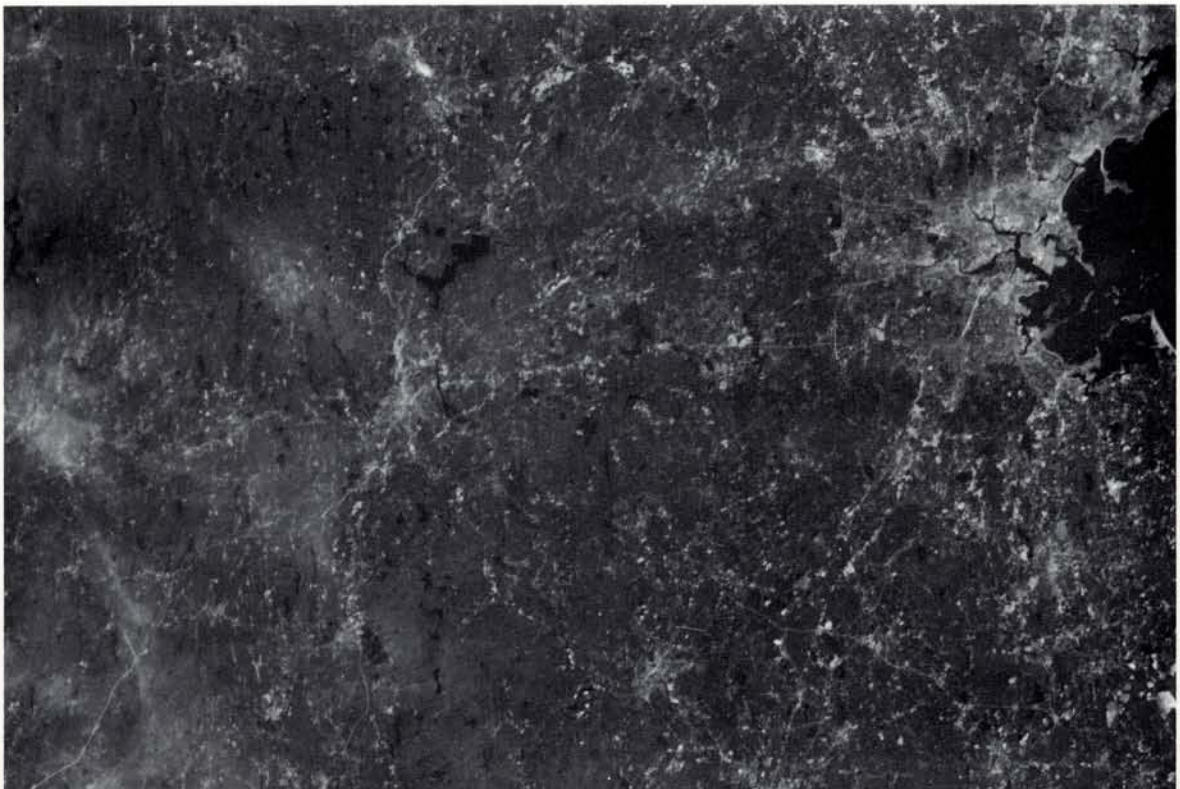
28th International Geological Congress

Tectonostratigraphic Terranes in the Northern Appalachians

Field Trip Guidebook T 359

Leader: E-an Zen

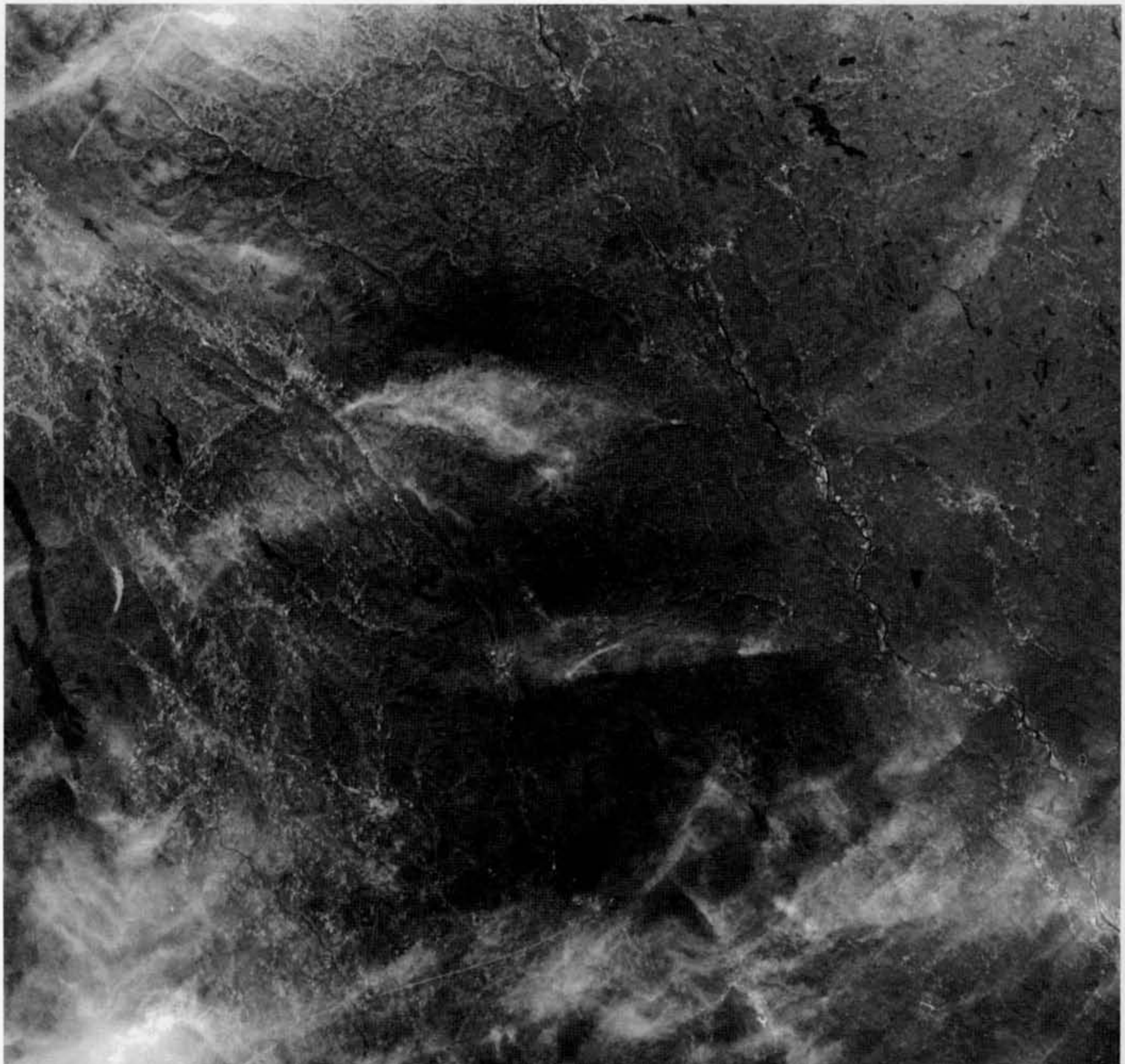


Albany, New York to Providence, Rhode Island

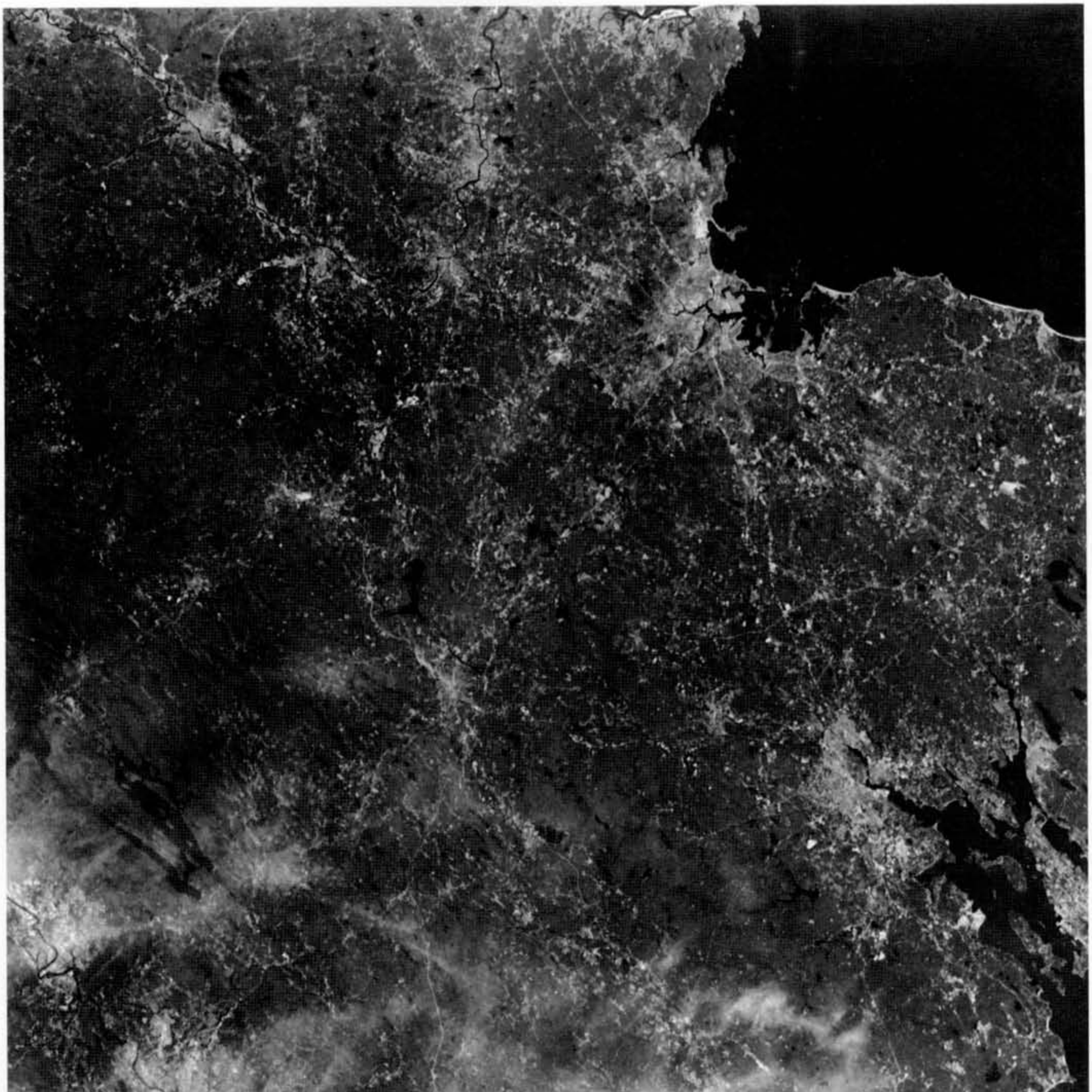
July 19–26, 1989

Tectonostratigraphic Terranes in the Northern Appalachians:

Their Distribution, Origin, and Age; Evidence for Their Existence



FRONTISPIECE Photograph of the excursion area from space. This large-format camera photograph was taken on a U.S. Space Shuttle flight and is a reduced-scale print of the actual photograph (No. 4107-0664, Data Pass 37.0). Scale of print, 1:884,500; original scale of photograph, 1:778,000. Altitude of Shuttle, 237.1 km. Original negative measures 9 inches by 18 inches (23 cm by 46



cm). Albany, New York, is just visible from under the clouds along the lower edge of the left frame of the picture; Lake George is near the left margin of the same frame. Boston, Massachusetts is near the center of the right frame of the picture; Narragansett Bay and Providence, Rhode Island is near the lower center of that frame. North is toward the upper left.

COVER Large format camera photograph of part of the excursion area. North is at the top. Scale is 1:778,000. The area shown includes most of the excursion stops for Day V and Day VI (Central Maine, Massabesic-Merrimack, Nashoba, and Atlantica terranes). Boston is the large metropolis to the upper right, Providence is the large metropolis near lower center, Worcester is just to the left of center, and Fitchburg is to the left of center along the top edge. See Frontispiece for location and additional information.

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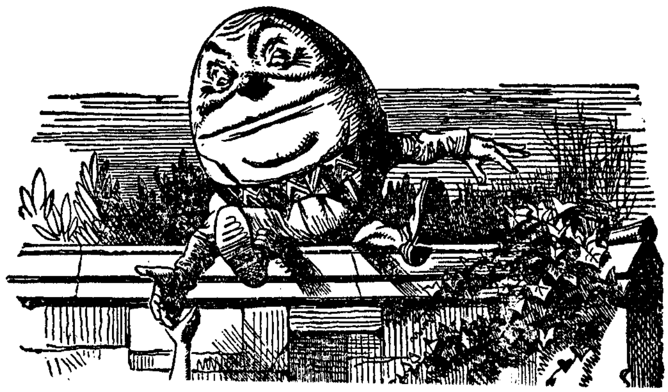


Humpty Dumpty sat on a wall
     Humpty Dumpty had a great fall.
All the King's horses and all the King's men
     Could not put Humpty Dumpty in his place again.

-- From "Through the Looking Glass", by Lewis Carroll

INTRODUCTION

Evolution of the Appalachian orogen spanned the Paleozoic and Mesozoic Eras. Within the confines of the northern Appalachians of the United States (the New England States - Maine, New Hampshire, Vermont, Massachusetts, Connecticut and Rhode Island - and New York), the sequence of known major Appalachian tectonic events is late Proterozoic rifting of the proto-North American craton; Ordovician subduction accompanied by destruction of the Iapetus Ocean and by obduction of tectonostratigraphic sequences; Devonian deformation, accretion, plutonism, and metamorphism, of uncertain plate tectonic context but likely related to a continent-continent collision; formation of late Carboniferous transtensive (oblique strike-slip) basins in which coal formed; and late Carboniferous to Permian thermal, plutonic, and metamorphic events. During the Mesozoic, the New England Appalachians underwent crustal extension associated with both alkalic and tholeiitic magmatism. These extensional processes (II-7, V-1)[1/] reflect the opening of the North Atlantic Ocean and the creation of a passive margin, which remains today.

Concepts of the tectonic evolution of the northern Applachians have changed over the years. An early attempt at plate tectonic synthesis was made by Bird and Dewey (1970). Rodgers (1970) provided an encyclopaedic summary of the field relations of the orogen. Other plate tectonically oriented regional and trans-Atlantic studies include those by Osberg (1978), Robinson and Hall (1980), Williams and Hatcher (1983), Williams (1978), Williams and Max (1980), Poole and others (1983), Stanley and Ratcliffe (1985), St-Julien and Hubert (1975), Keppie (1985), Neuman (1984), Skehan (1983), and Rast and Skehan (1983). Zen (1983) interpreted the field evidence from the New England and adjacent Canadian Appalachians in terms of sequential accretion of terranes. The possibility that the Appalachian orogen consists of microplates accreted during its long history is the focus of much current debate. This field trip is designed to show the arguments, both pro and con, for this model along a particular traverse from unchallenged North American craton to the last vestige of possible accreted terranes exposed in New England; all the major candidate terranes that we know of in the northern Appalachians but one (the Meguma of Nova Scotia; see Keppie, 1985) will be seen and are briefly described below (FIGURES 1-5).

TABLE 1 (Zen, 1988a) lists criteria useful for the delineation of tectonostratigraphic terranes. These criteria will be used as bases for much of the ensuing discussion.

The stratigraphic nomenclature and age designations used in this guidebook are those of various authors. These names have not been reviewed for conformance to the North American Stratigraphic Code, nor do they necessarily follow the usage of the U. S. Geological Survey or various State agencies.

THE NORTH AMERICAN CRATON

The North American Craton (NAC) has a Grenville-province crystalline basement consisting of complex sequences of paragneiss and orthogneiss, charnockite, anorthosite, metavolcanic rocks, and mafic intrusive rocks having Middle Proterozoic (about 1 Ga) metamorphic age ("Grenvillian") (I-3, I-4). In late Proterozoic time (ca. 600 Ma), this continent was rifted, and the rift valleys were filled with immature quartzofeldspathic sediments and associated tholeiitic lava (Stanley and Ratcliffe, 1985). These sediments graded upward at the start of the Cambrian into a cover sequence of shallow-water, shelf-facies sedimentary rocks that are now orthoquartzites, dolostones, and limestones that show features and faunae indicating warm-water tidal sedimentation (I-5, I-6, I-7, I-8, II-8, III-2). This simple pattern of sedimentation was terminated in Middle Ordovician time by subduction offshore, so that the former shelf area became one of deposition of turbiditic shales (I-1, 1-2, I-7) and greywackes that presaged the destruction of the Iapetus Ocean and the collision of the NAC against an island arc (J.B. Thompson, 1988, oral communication) or against another sialic landmass ("Craton X" of Zen (1983); possibly the Central Maine terrane).

The Taconic allochthon (II-1 through II-7) (Zen, 1967, 1972a, b; Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985) is composed of sediments whose deposition site was transitional between shelf edge and

---

1/ Roman and arabic numbers between parentheses indicate Day and Stop of the road log.

FIGURE 1

A, map showing geographical location of the geologic map (FIGURE 2) and locations of FIGURES 1B through 1F (daily routes and stops).

B, Day I (solid line) and Day II (dashed line).

C, Day III.

D, Day IV (solid line) and Day V (dashed line).

E, Day VI.

F, Day VII.

Individual stops are given by heavy dots; example: VI-4 denotes Day VI, Stop 4.

Lodging cities are underlined.

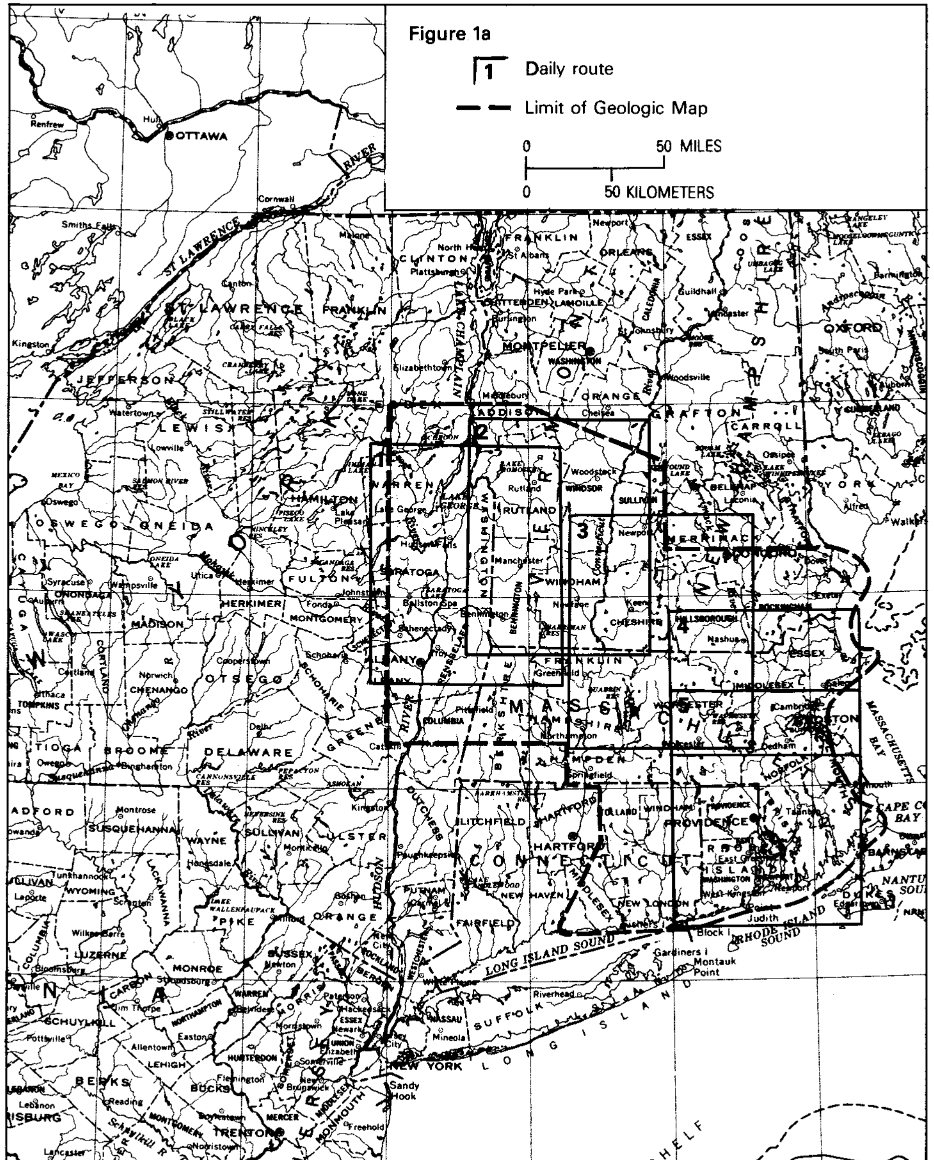


Figure 1a

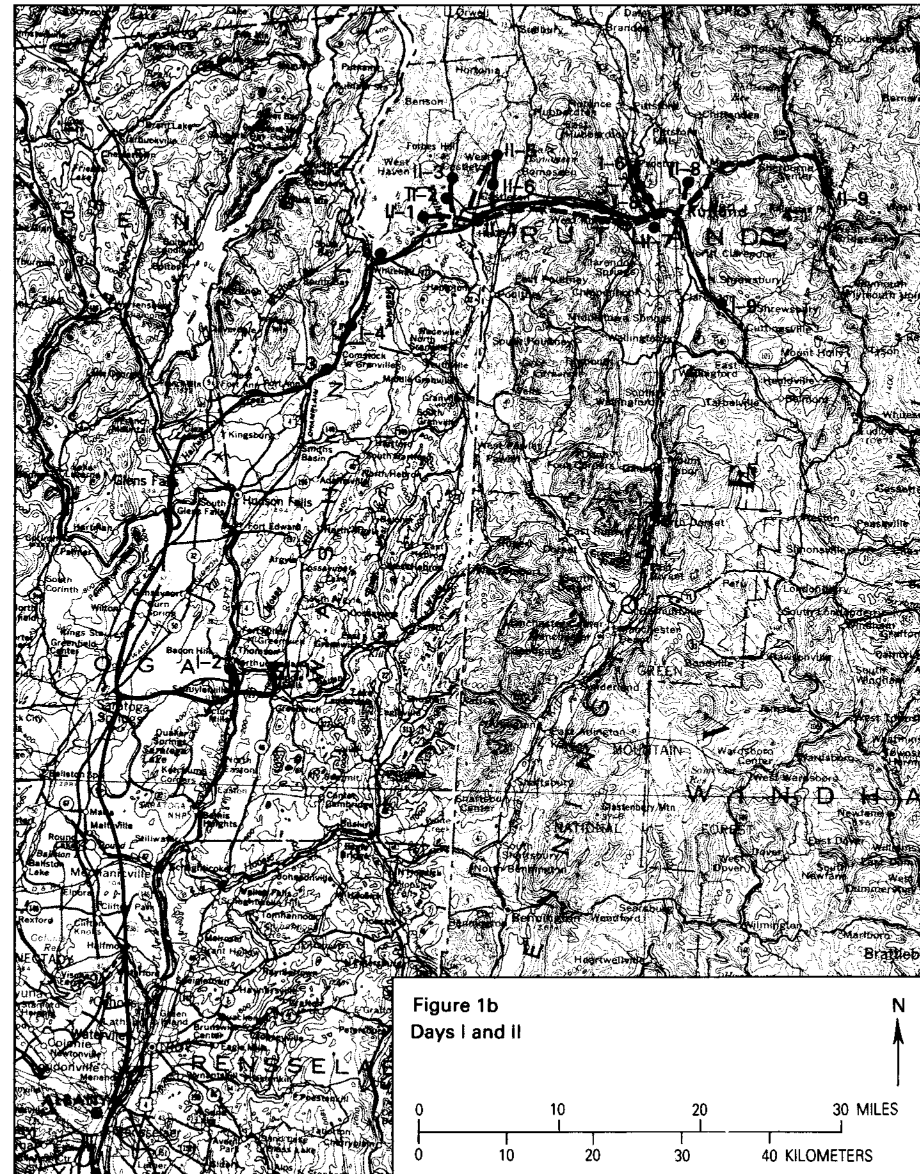


Figure 1b
Days I and II

Figure 1c
Day III

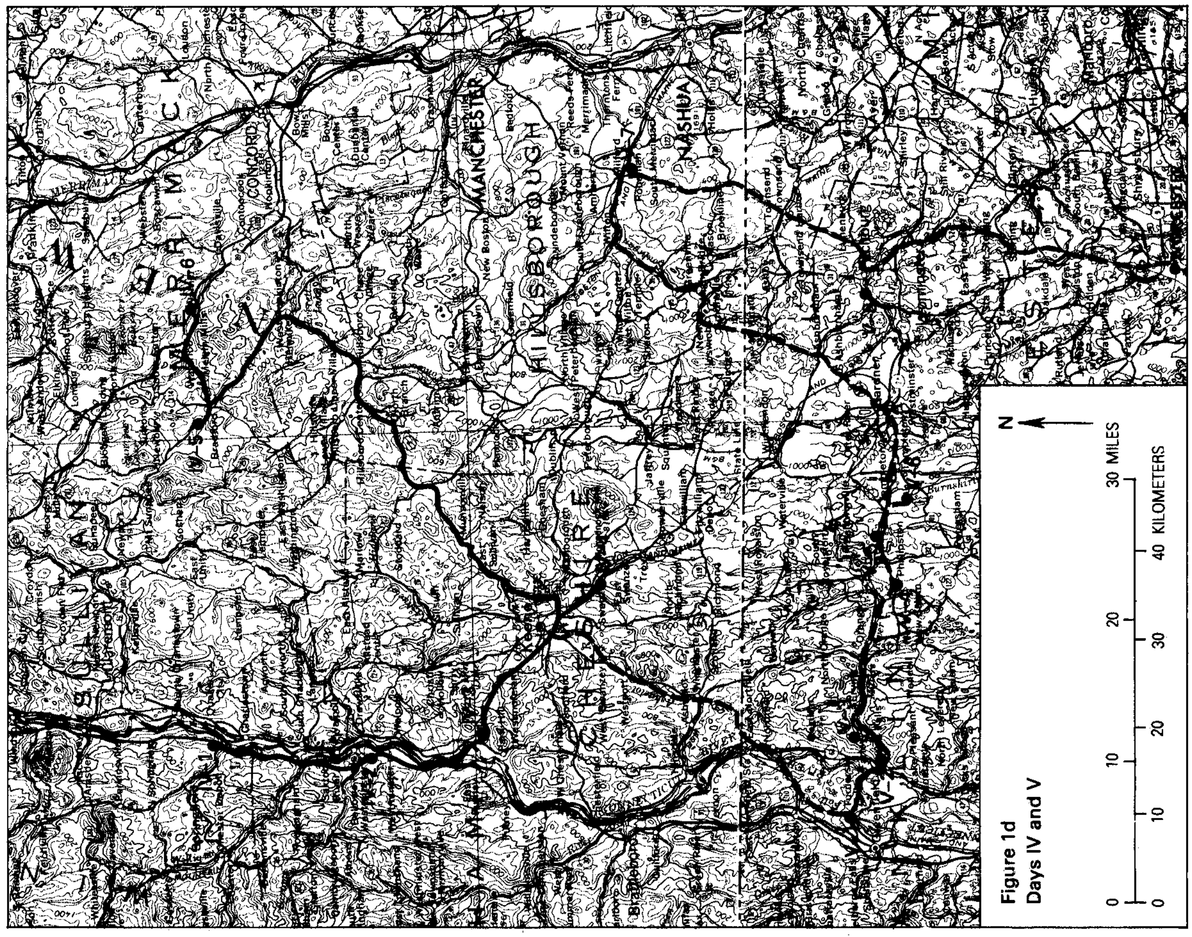


Figure 1d
Days IV and V

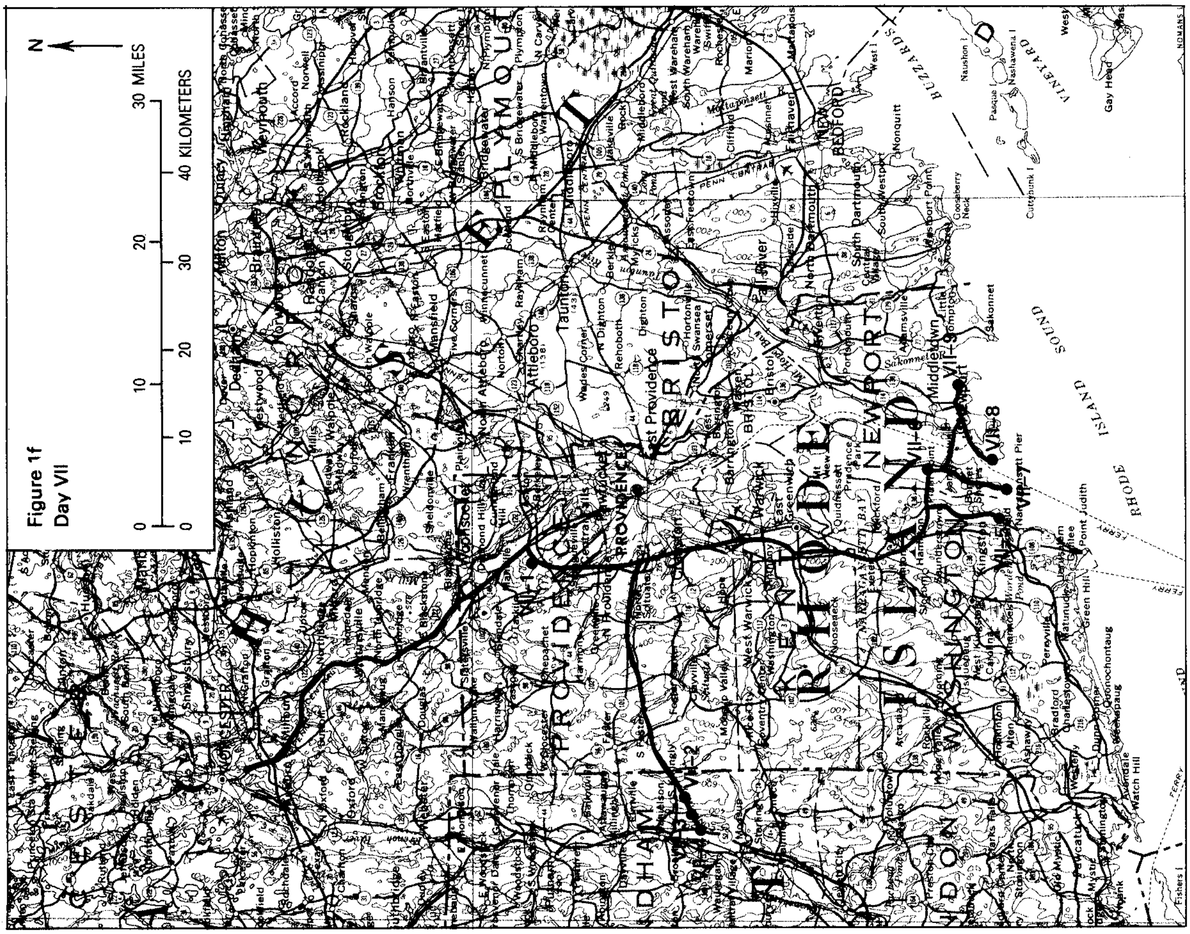


Figure 1f
Day VII

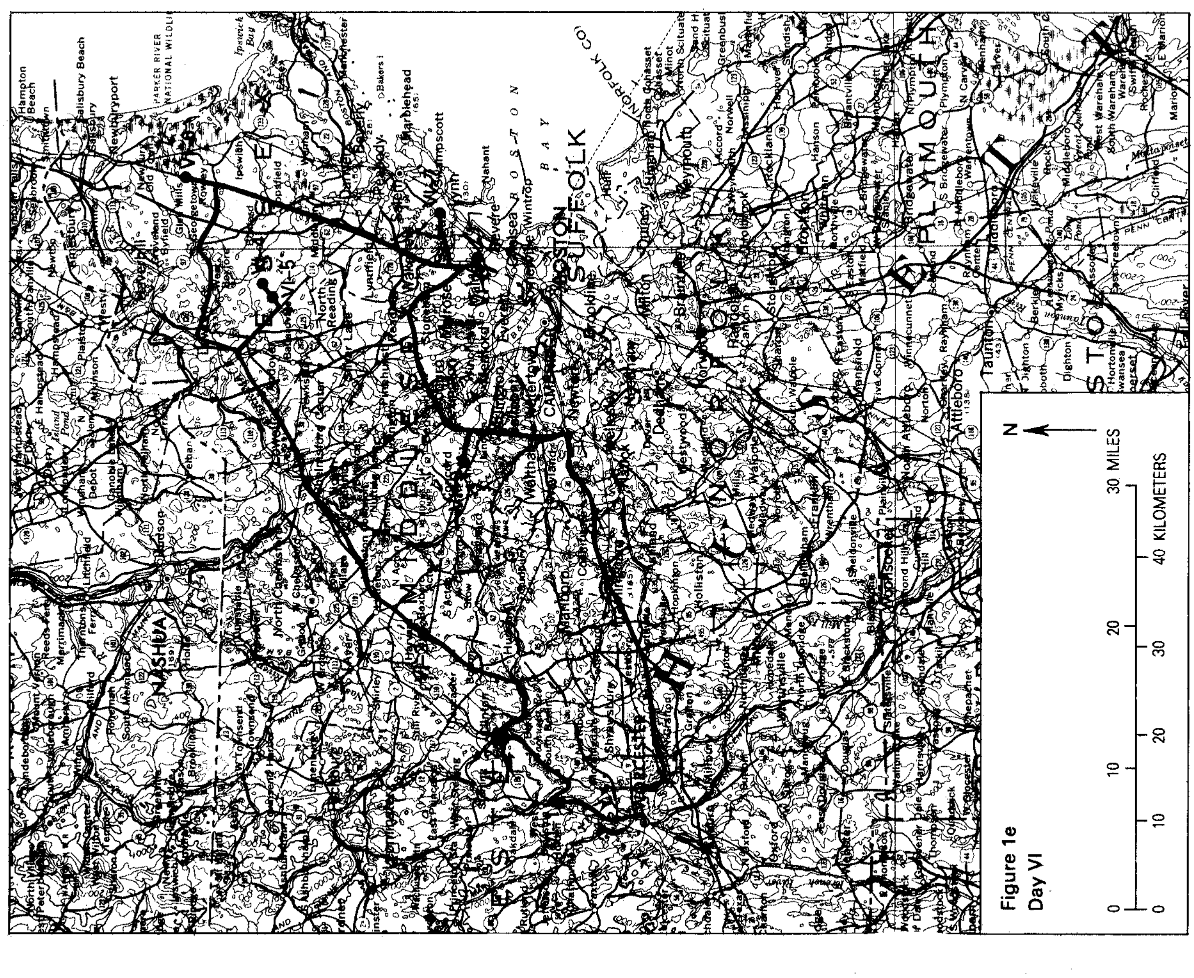


Figure 1e
Day VI

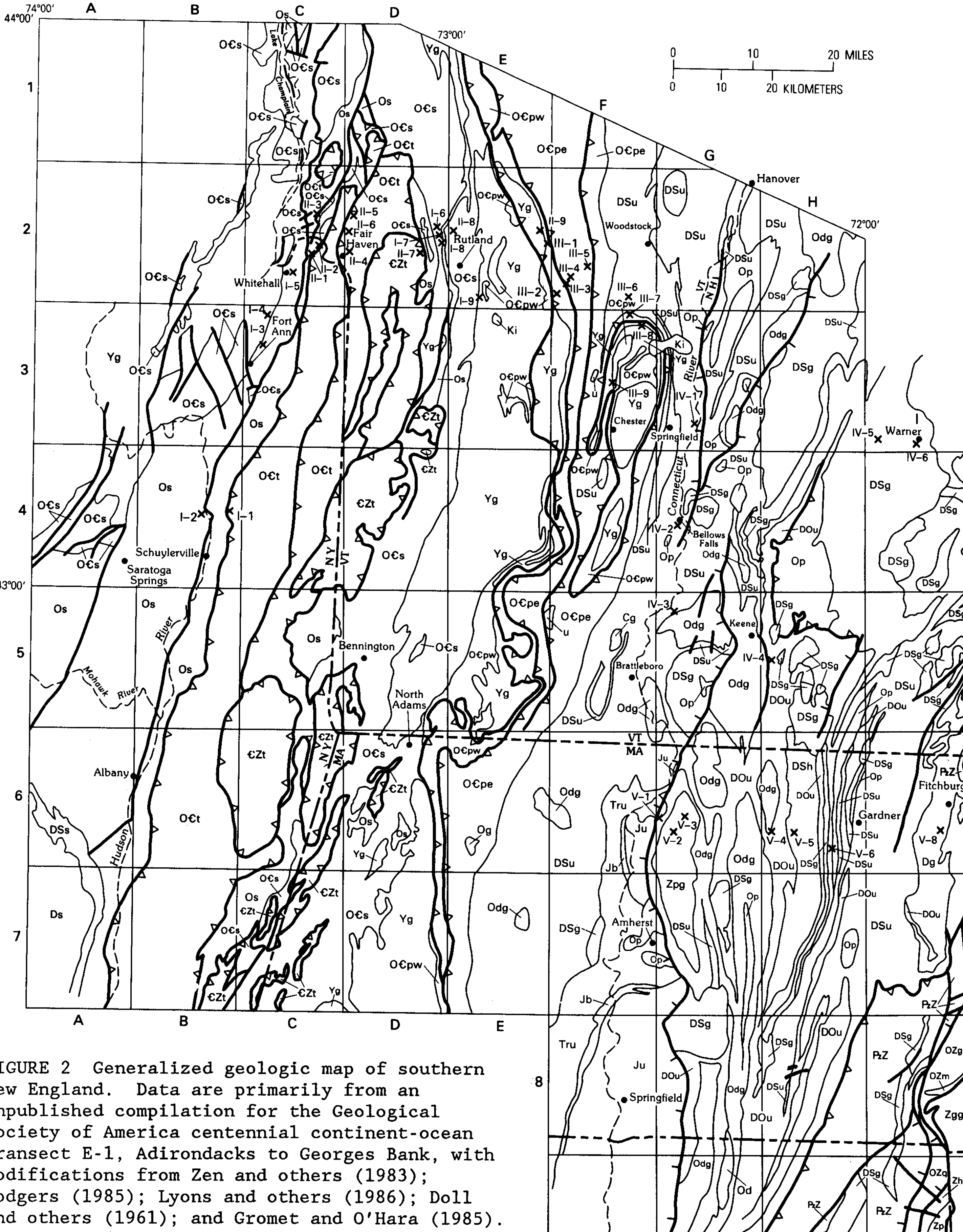
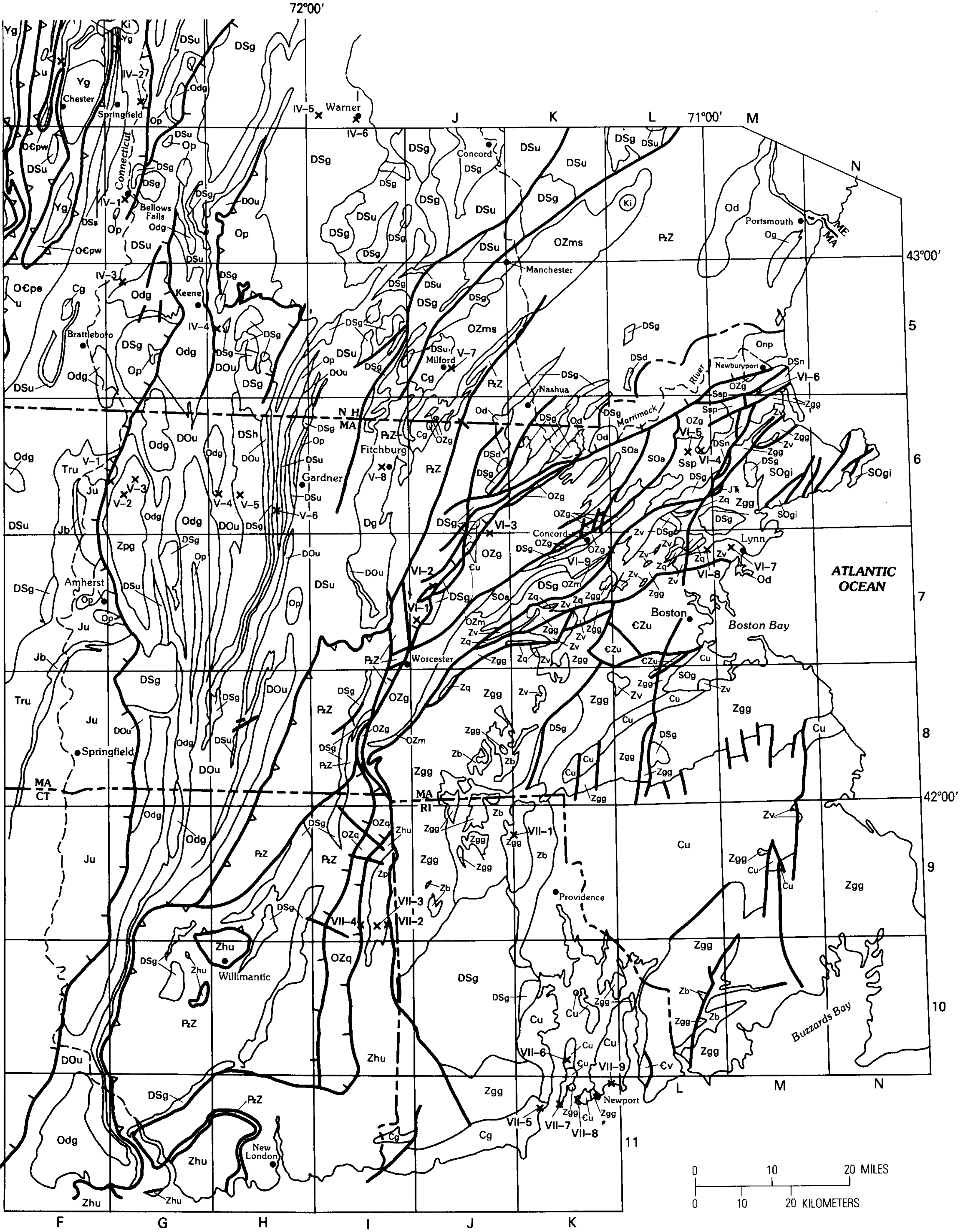


FIGURE 2 Generalized geologic map of southern New England. Data are primarily from an unpublished compilation for the Geological Society of America centennial continent-ocean transect E-1, Adirondacks to Georges Bank, with modifications from Zen and others (1983); Rodgers (1985); Lyons and others (1986); Doll and others (1961); and Gromet and O'Hara (1985). Locations of excursion stops are shown. Grid system is added for convenience.


72°00′
71°00′
43°00′
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Springfield
Warner
Concord
Bellows Falls
Connecticut
Portsmouth
ME
MA
Manchester
Keene
Brattleboro
Milford
Nashua
Newburyport
Merrimack
River
N H
MA
Fitchburg
Gardner
Concord
Lynn
ATLANTIC OCEAN
Amherst
Boston
Boston Bay
Worcester
Springfield
MA
CT
MA
RI
Providence
Willimantic
Buzzards Bay
Newport
New London
IV-1
IV-2
IV-3
IV-4
IV-5
IV-6
V-1
V-2
V-3
V-4
V-5
V-6
V-7
V-8
VI-1
VI-2
VI-3
VI-4
VI-5
VI-6
VI-7
VI-8
VI-9
VII-1
VII-2
VII-3
VII-4
VII-5
VII-6
VII-7
VII-8
VII-9
0 10 20 MILES
0 10 20 KILOMETERS

Rock units on FIGURE 2, Geological Map, to accompany IGC trip T359

E-an Zen Compiler

POST-ACCRETION ROCKS

Post-Alleghanian orogeny

Intrusive rocks:

- Ki Cretaceous plutons of the White Mountain Plutonic-Volcanic Suite (NAC, BCT, MMT)
- Cg Carboniferous granitic plutons (MMT, NCM, AT)
- Dg Fitchburg Complex (Lower Devonian) (CMT, MMT)

Layered rocks:

- Ju Jurassic sedimentary rocks (CMT)
- Jb Jurassic basalt (CMT)
- Tru Triassic sedimentary rocks (CMT)
- JTr Triassic and Jurassic sedimentary rocks (AT)

Post-Acadian orogeny

Intrusive rocks:

- Cg Carboniferous granitic plutons (BCT)
- DSg Silurian and Devonian granitic plutons (CMT, MMT, NCM, AT)

Layered rocks:

- Cu Carboniferous sedimentary and minor volcanic rocks (NCM, AT)

Post-Taconian orogeny

Layered rocks:

- Ds Devonian clastic cover rocks on NAC
- DSs Silurian and Devonian calcareous cover rocks on NAC
- DSu Silurian to Devonian metasedimentary rocks; overlap sequence to Taconian orogeny (BCT, CMT; may include some Upper Ordovician strata in BCT. The trace of a marker unit, the Standing Pond Volcanics, is locally shown)

TECTONOSTRATIGRAPHIC TERRANES

North American Craton (NAC)

- Os Middle Ordovician syntectonic flysch
- OЄt Cambrian to Middle Ordivician sedimentary rocks of the Taconic allochthon (lower, younger structural slices)
- ЄZt Late Proterozoic and Cambrian sedimentary rocks of the Taconic allochthon (higher, older structural slices)
- OЄs Lower Paleozoic carbonate rocks of the shelf sequence
- OЄpw Lower Paleozoic pelitic rocks
- Yg Grenvillian gneiss, granulite, charnockite, and metasedimentary rocks of the Adirondack, the Green Mountain, and the Berkshire massifs

Brompton-Cameron Terrane (BCT)

Intrusive rocks:

- DSg Silurian and Devonian granitic plutons
- Odg Core gneiss of domes, including some meta-volcanic rocks
- u Ultramafic bodies, only largest bodies shown

Layered rocks:

- DSu Silurian and Devonian metasedimentary rocks
- OЄpe Cambrian and Ordovician pelitic rocks
- Yg Core gneiss of domes

Central Maine Terrane (CMT)

Intrusive rocks:

DSh Silurian and Devonian Hardwick Tonalite
DSg Silurian and Devonian granitic plutons
Odg Oliverian Plutonic Suite and some metavolcanic rocks in cores of Oliverian gneiss domes

Layered rocks:

DOu Ordovician to Devonian metasedimentary rocks
Op Partridge Formation
Zpg Gneiss and schist of Pelham dome

Massabesic-Merrimack Terrane (MMT)

Intrusive rocks:

DSd Silurian and Devonian mafic plutons
DSg Silurian and Devonian granitic plutons
Od Ordovician mafic pluton
Onp Ordovician Newburyport Complex
Og Ordovician plutons

Layered rocks:

PzZ Upper Proterozoic and Lower Paleozoic formations
OZms Ortho- and paragneisses of Massabesic Gneiss Complex

Nashoba-Casco-Miramichi Terrane (NCM)

Intrusive rocks:

DSg Silurian and Devonian granitic plutons
Ssp Silurian Sharpners Pond Diorite
SOa Ordovician and Silurian Andover Granite

Layered rocks:

OZq Quinebaug Formation
OZg Felsic gneiss and metamorphic rocks of Nashoba terrane
Zp Plainfield Formation
Zhu Hope Valley Alaskite Gneiss
OZm Marlboro Formation

Atlantica Terrane (AT)

Atlantica I

Intrusive rocks:

DSg Silurian and Devonian granitic plutons
SOgi Ordovician and Silurian alkalic plutons of Cape Ann
SOg Ordovician and Silurian granitic plutons
Od Ordovician mafic intrusions
Zgg Upper Proterozoic granite and orthogneiss

Layered rocks:

Єu Cambrian sedimentary rocks; includes some related uppermost Proterozoic rocks
ЄZu Upper Proterozoic and Cambrian sedimentary rocks
Zv Upper Proterozoic volcanic rocks
Zq Westboro Formation, mainly quartzite
Zb Metamorphosed Upper Proterozoic sedimentary and volcanic rocks

Atlantica II

DSn Newbury Volcanic Complex and related sedimentary rocks
Єv Cambrian(?) metamorphosed volcanics rocks south of Tiverton, RI

SYMBOLS FOR FAULTS

—▵—▵— Thrust faults, teeth on upper plate

—⊥—⊥— Normal faults and possible detachment faults, bars on upper plate

——— Undifferentiated faults, including thrust faults, high angle reverse and normal faults

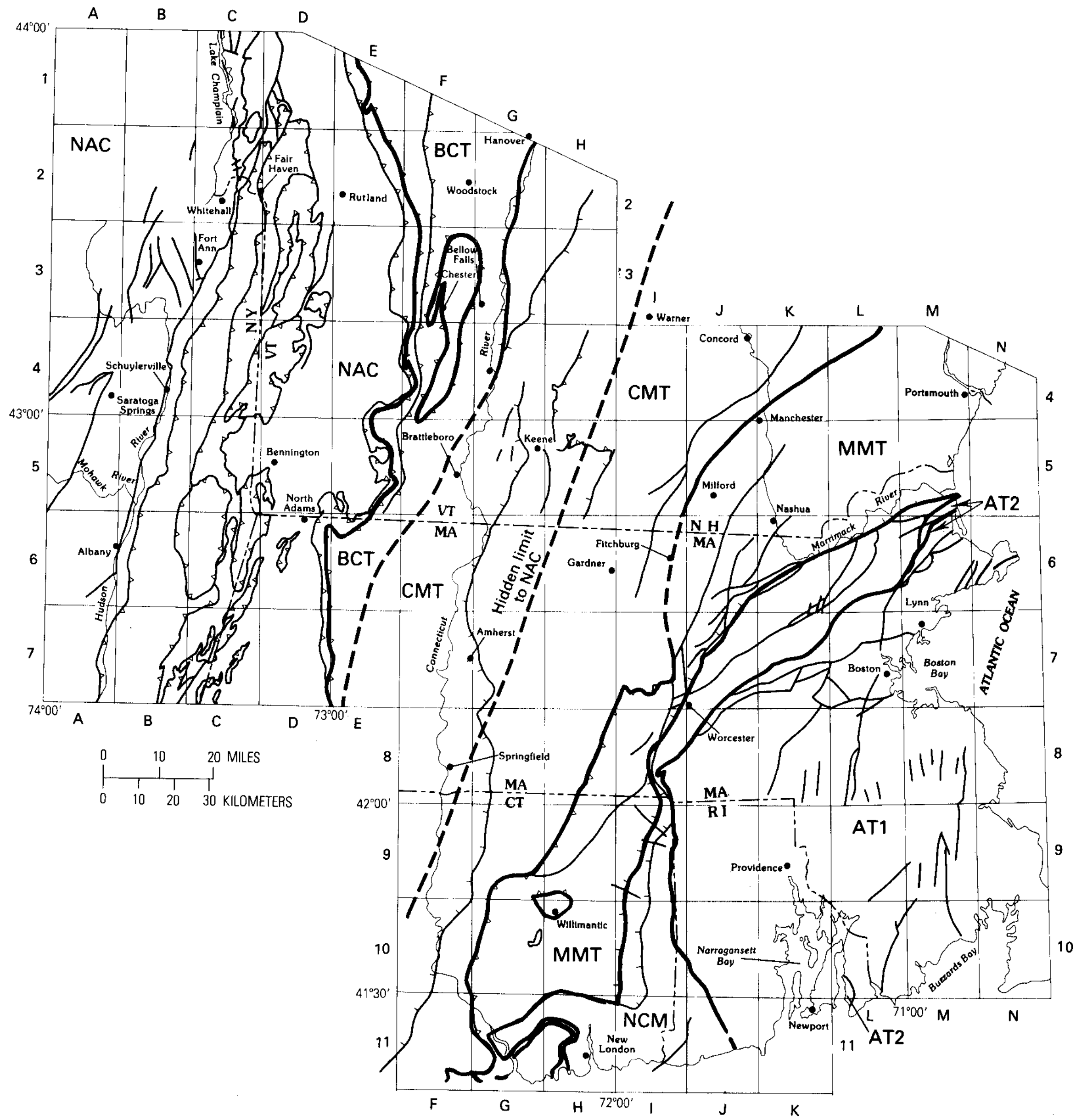


FIGURE 3 Map showing possible tectonostratigraphic terranes within the area of Figure 2. NAC, North American craton; BCT, Brompton-Cameron terrane; CMT, Central Maine terrane; MMT, Massabesic-Merrimack terrane; NCM, Nashoba-Casco-Miramichi terrane; AT1, Atlantica I; AT2, Atlantica II. Terrane boundaries are dashed where hidden or cut out by plutons. Grid system is same as for Figure 2.

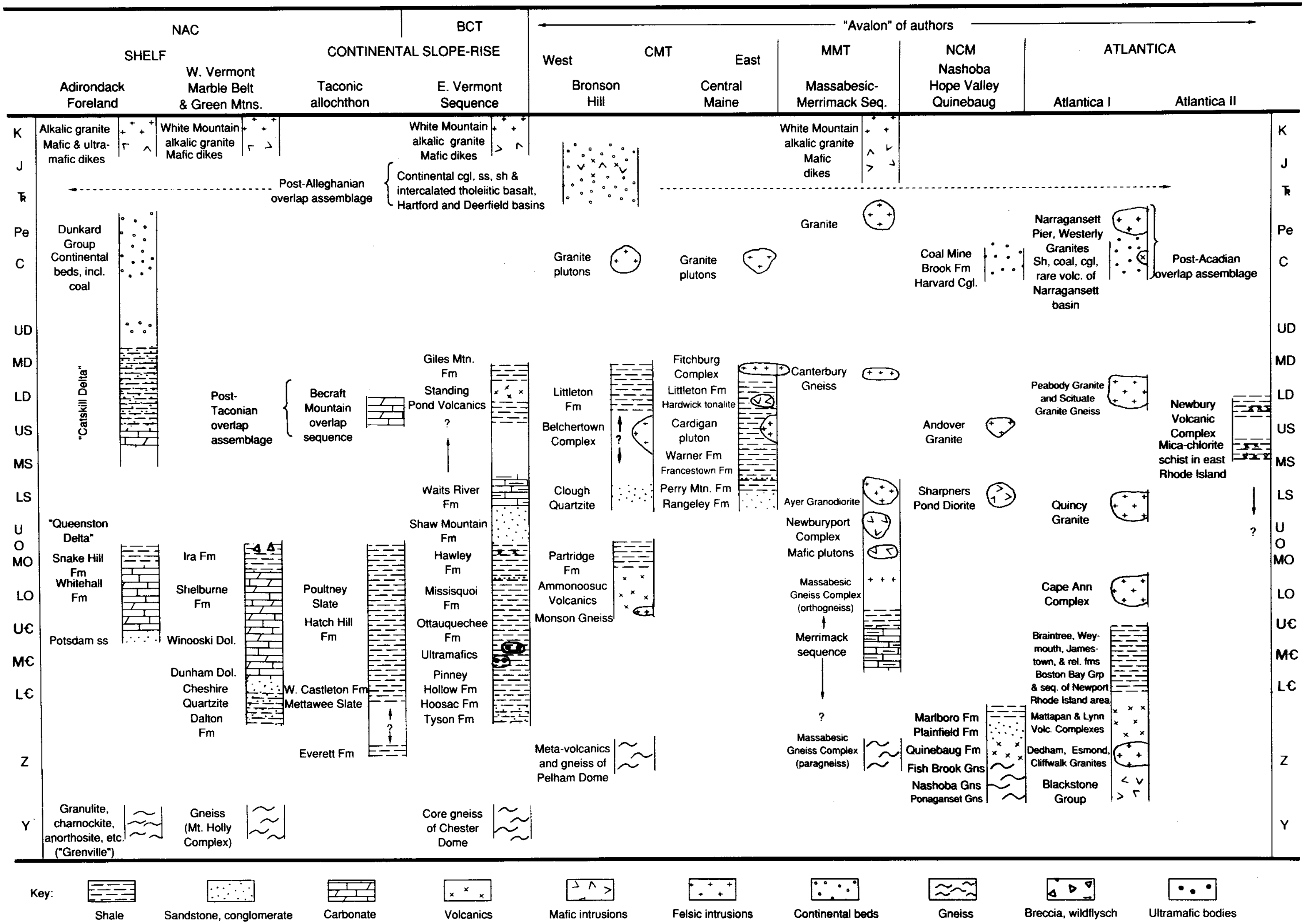


FIGURE 4 Restored stratigraphic columns for terranes encountered on the excursion, showing stratigraphic names, ages, and major rock types.

Northwest	NAC	BCT	CMT	NCM+MMT	AT I	AT II	AT Meguma	Southeast
Carboniferous	← CONTINENTAL SEDIMENTATION →			Sparse plutons		Sparse plutons		Carboniferous
Late Devonian	Catskill Delta - Old Red Sandstone Overlap Sparse plutons, low 207/204		Abundant plutons, mod 207/204		Abundant plutons high 207/204			Late Devonian
Middle Devonian Late Ordovician	METAMORPHISM SHALE OVERLAP METAMORPHISM		North Atlantic faunae			Within plate volcanics + sediments Atlantic shell faunae	Shallow marine sediments + bimodal volcanics	Middle Devonian Late Ordovician
Middle Ordovician	Black shale with ophiolite detritus mixed + cosmop. warm + cool North Atlantic faunae	Rare plutons arc sediments + volcanics	Rare plutons Celtic transition faunae arc volcanics + sediments ?	Plutons Metamorphism				Middle Ordovician
Early Ordovician Cambrian	Shelf sediments North American warm water faunae	Slope-rise + melange sediments Ophiolite Ocean Crust	Slope-rise sediments + arc volcanics ? Pacific + North Atlantic faunae Ophiolite on NW side	Slope-rise sediments + arc volcanics	Alkalic plutons Atlantic faunae Slope-rise sediments <u>Paradoxides</u>	Metamorphism Bimodal volcanics + sediments	Turbidite	Early Ordovician Cambrian
Late Proterozoic	RIFT	?	Metavolcanics + gneiss ?	Gneiss	0.6 Ma ptn Ediacaran faunae	?	?	Late Proterozoic
Middle Proterozoic	1.1 Ga gneiss	?	>1.5 Ga protolith ?	>1.5 Ga protolith	Metamorphic (0.8 Ga) gneiss		>1 Ga gneiss	Middle Proterozoic

FIGURE 5 Tectonostratigraphic chart summarizing geologic history of individual terranes and composite terranes and showing environments of sedimentation, nature of faunal affinity where known, igneous and metamorphic events, nature and age of basement, presence of ocean-floor ophiolite, and age of overlap assemblages.

continental slope marginal to the NAC and is a major byproduct of this collision event. The thrust sheets were transported onto the craton in a geometrically complex fashion and include subseafloor thrusting (I-1, I-2, II-1, II-3). In northern Maine, the present-day location of the edge of the NAC strikes northeast (Zen, 1983) and dips to the southeast (Spencer and others, 1987). Within the area of our traverse, the location of this edge must be at least as far east as the Connecticut River valley, as the basement-cover relationships around the Green Mountain massif (I-9, II-9, III-1) and in the Chester Dome area (III-8, III-9) indicate former continuity with the NAC. Most likely, this edge is hidden by transported rocks of the Brompton-Cameron terrane and Central Maine terrane at higher structural levels.

The Acadian orogeny was recorded on the NAC in part by the influx of coarse clastic sediments, commonly referred to as the "Catskill Delta." For a recent survey of these rocks and their tectonic implications, see Woodrow and Sevon (1985).

THE BROMPTON-CAMERON TERRANE

The Brompton-Cameron terrane (BCT) refers to a sequence of penetratively deformed and metamorphosed lower Paleozoic sedimentary and volcanic rocks. Along this traverse, the sequence is seen in eastern Vermont (III-1 through III-5). The BCT is separated from the NAC by a diffuse tectonic boundary whose base (western limit) is called "Cameron's line" in Connecticut (Rodgers, 1985), the "Whitcomb Summit thrust" in Massachusetts just south of this traverse (Zen and others, 1983), or the mainland portion of the "Baie Verte-Brompton Line" (Williams and St-Julien, 1982) in Quebec, Canada, and in northern Vermont. The diffuse boundary is in fact a zone of extensive ductile deformation and tectonic transport. This zone contains scattered ultramafic bodies that in Quebec include the Thetford ophiolite, generally conceded to be ocean floor material. In southeastern Vermont (III-7) and adjacent Massachusetts, the ultramafic bodies are serpentinites or talc-magnesite bodies; their origin is less obvious, but they can be interpreted as being of oceanic provenance (Zen, 1983). Within these areas, these ultramafic rocks first appear within the upper part of the Pinney Hollow Formation but occur in most of the overlying pre-Taconian Paleozoic rocks as well (Doll and others, 1961). The line on the map should be regarded as the "floor" of this movement zone.

Even though these ultramafic rocks could be interpreted as marking a terrane boundary, rocks of the BCT are stratigraphically similar to the transitional but North American (Neuman and others, 1988) rocks of the Taconic allochthon. Rocks of the BCT were presumably laid down on the North American side of the Iapetus Ocean; if so, these ultramafic rocks do not represent the primary subduction suture but rather a relatively minor piece of obducted ocean floor, perhaps formed near the rifted edge of the NAC. This inference is consistent with the observation that the ophiolite of Thetford is isotopically contaminated by continental material (Shaw and Wasserburg, 1984). The depositional site(s) of the slices of the Taconic allochthon must be covered by the BCT now (FIGURE 6) (Stanley and Ratcliffe, 1985).

The core gneiss of the Chester and related domes (III-8) is part of the NAC. If the Brompton-Cameron line is truly a tectonic boundary, then the core gneiss and its autochthonous cover rocks (III-9) would be in a tectonic window through the BCT, as was also suggested by Stanley and Ratcliffe (1985).

THE CENTRAL MAINE TERRANE

The name Central Maine terrane (CMT) refers to a sequence of Paleozoic rocks, at least the pre-Silurian part of which is distinct from those of the BCT and the NAC. Ordovician rocks are widespread; important among these are Middle Ordovician tholeiitic volcanic rocks as well as granitic, granodioritic, and trondhjemitic plutonic rocks (TABLE 2) (Leo, 1985, Leo and others, 1984; Thompson and others, 1968; Naylor, 1969). These volcanic and plutonic rocks occur primarily on the northern and western sides of the terrane, near its junction with the BCT. This fact, together with the alignment and compositions of the plutonic bodies and their garlands of coeval and related volcanic and volcaniclastic rocks (IV-4, V-4), suggests that these rocks were roots of island-arc volcanoes that once fringed a craton (Craton X of Zen, 1983) which then became the upper plate of the subduction system. Pre-Silurian fossils from this terrane, outside of our traverse area, have been characterized (Neuman and others,

TABLE 1 Criteria for Recognizing Terranes (Zen, 1988a)

I. Primary evidence useful in establishing discrete terranes

Coeval but incompatible fossils and faunal affinity

Inconsistent paleomagnetic latitude

Contrasting apposed sedimentary facies and truncated sedimentary dispersal system

Intercalated oceanic ophiolite, spreading center deposits, or melange

II. Evidence useful in corroborating or suspecting the existence of terranes

a. Indicators of arc-trench and plate-margin environment

Arc volcanism and magmatism
Trench melange
Blueschist and related rocks, especially associated with melange

b. Indicators of different basements underlying suspect terranes

Different aeromagnetic patterns
Different gravity patterns
Different deep seismic reflection patterns and crustal velocity structures
Different geochemistry of plutons, including isotope ratios
Different isotopic geochemistry of sedimentary rocks
Different ages of basement rocks

c. Indicators of transport of rocks

Large transcurrent faults
Large thrust faults
Different metamorphic and tectonic histories

TABLE 2 Chemical Analysis and CIPW Norms of Selected Volcanic Rocks

	STARKS KNOB Pillow Lava 1/	BRONSON HILL ZONE 2/ Ammonoosuc Volcanics	Trondhjemite
SiO_2	47.55	48.6	74.8
TiO_2	0.87	2.0	0.22
Al_2O_3	16.65	15.5	12.9
Fe_2O_3	4.94	3.4	1.2
FeO	5.12	8.2	1.4
MnO	0.46	0.25	0.01
MgO	5.63	7.2	0.45
CaO	4.96	11.4	2.4
Na_2O	4.20	2.0	4.6
K_2O	2.52	0.53	0.68
P_2O_5	0.27	0.36	0.05
H_2O+	5.57	0.48	0.53
H_2O-	0.24	0	0.02
Cl	0.10	nd	nd
F	0.06	nd	nd
S	0.01	nd	nd
C	0.80	nd	nd
CO_2	0.15	0.01	0.01
Total	100.10	99.9	99.3
ASI 3/	0.94	0.64	1.02
		Rock norms	
q	0	1.4	39.2
c	0	0	0.4
or	14.9	3.1	4.0
ab	33.5	16.9	38.9
an	19.1	31.8	11.5
ne	1.1	0	0
di	2.2	18.2	0
hy	0	18.5	2.4
ol	12.7	0	0
mt	7.2	4.9	1.7
il	1.7	3.8	0.4
ap	0.6	0.8	0.1
Total	93.0	99.4	98.7

1/ "Selected rock from the center of one of the large lava balls, as free as possible from calcite. E.W. Morley, analyst" (Cushing and Ruedemann, 1914).

2/ Leo (1985), no. 30 (Ammonoosuc volcanics); no. 17 (trondhjemite).

3/ Aluminum saturation index, defined as molar ratio of alumina to the sum of potash, soda, and lime corrected for lime in apatite.

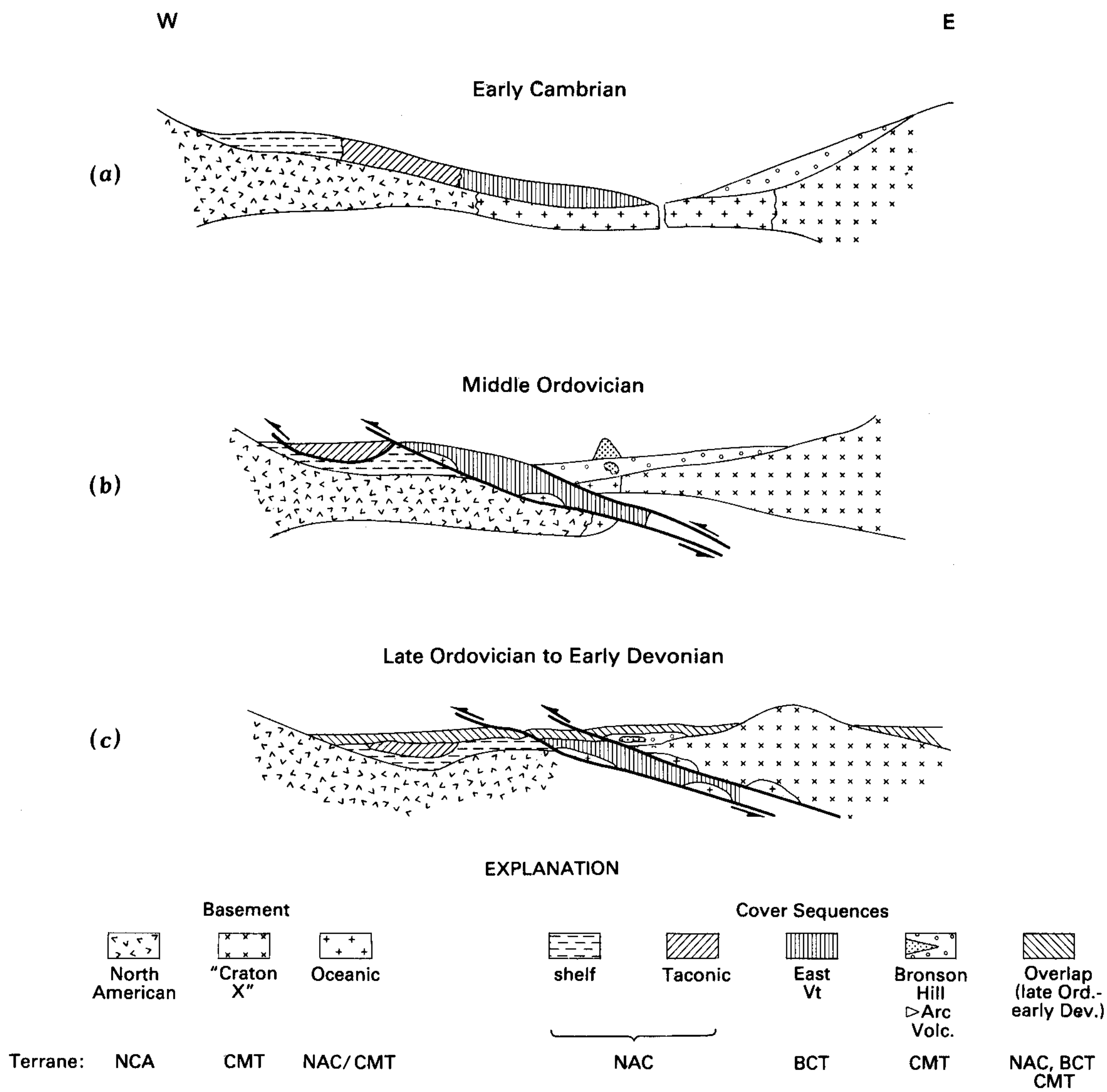


FIGURE 6 Schematic cross section interpreting evolution of tectonic elements of North American Craton (NAC), Brompton-Cameron terrane (BCT) and Central Maine terrane (CMT) to the start of the Acadian orogeny. A, Shortly after the opening of the Iapetus Ocean. B, During Taconian southeastward subduction of the North American craton under Craton X (= CMT?) and concomitant obduction of rocks deposited on ocean floor that became BCT. C, Between the Taconian and Acadian orogenies during deposition of overlap assemblage. The overlap assemblages of eastern Vermont and of the cover rocks for the domes of the Bronson Hill zone are shown as having easterly and westerly sources, respectively, as discussed in the text. The source area is shown as covered by later tectonic transport. For the effect of the Acadian deformation (nappes, backfolding, diapiric gneiss dome uprising) in the Bronson Hill anticlinorium (western part of known CMT), see Figure 7.

1988) as mixed Pacific and North Atlantic fauna for the Cambrian and as transitional Celtic fauna for the Middle Ordovician, distinct from the North American faunae that occur in the NAC.

The known basement rocks of the CMT are latest Proterozoic, variably metamorphosed sedimentary rocks both in the Pelham Dome (V-2, V-3) (Robinson and others, 1979; Zen and others, 1983) and on strike in central Maine (Neuman, 1967; Hall, 1970). Recent seismic and other geophysical studies in Maine (Unger and others, 1987; Spencer and others, 1987; Luetgert and others, 1987) show that the deep crust is sialic. The same inference can be drawn from the abundant highly evolved peraluminous granitic plutons throughout the terrane; for instance, Sm/Nd and U/Pb isotopic studies (Barreiro and Aleinikoff, 1985) of the Devonian Kinsman Quartz Monzonite (IV-5, IV-6) indicate a sialic source for the magma (see also Lux and others, 1986). Studies in Maine (Ayuso, 1986) and in New Brunswick (Bevier, 1987) show that the feldspars of granitic rocks from this terrane have distinctly different lead isotope ratios, indicating that the basement is different from the NAC basement.

The contact between the BCT and the CMT is marked by discontinuous areas of ultramafic and mafic intrusive-extrusive rocks and associated sediments, including melanges, and has been interpreted (e.g., Boudette, 1982; Boudette and Boone, 1976; Zen, 1983) as the principal suture zone between the obducted North American rocks of the BCT and the opposite side of Iapetus Ocean represented by the CMT. (This zone is known in western Newfoundland as the Baie Verte ultramafic belt. However, the Baie Verte line does not continue on the mainland as the Brompton line, as suggested by Williams and St-Julien (1982)). This zone includes (Zen, 1983) the Ordovician Elmtree ophiolite (Rast, 1980), the Caucomgomoc Lake Complex of Pollock (1982), and the Boil Mountain Complex and the Jim Pond Formation, together with the associated melange rocks (see Boudette, 1970, 1982; Boudette and Boone, 1976) in Maine. The Chain Lakes massif of northwestern Maine, on the northern side of this suture, has been interpreted to be an allochthonous CMT mass (Zen, 1983; Unger, 1988). The massif contains 1.5 Ga detrital zircon and also evidence of a 770 Ma metamorphism (Cheatham, 1985a, b).

The BCT and the CMT share similar Middle Paleozoic sedimentary rocks. Two overlap assemblages may be recognized: a far-transported but originally "eastern" assemblage (present-day cardinal orientation) and a somewhat more indigenous but similar "western" assemblage. The eastern assemblage is defined in northwestern Maine and has been followed continuously through New Hampshire into central Massachusetts (Robinson, 1981). The assemblage is locally fossiliferous (IV-1) and begins with Upper Silurian quartz-rich conglomerate and sandstone, intercalated with calcareous siltstone. These rocks are followed upsection by Lower Devonian silty shales (IV-2) some of which were true flysch sediments. Source direction, at least for the Silurian, is from the northwest in Maine (Moench, 1970), and presumably the same is true as far as Massachusetts (Robinson, 1981), though here a source area has not been identified. The western overlap assemblage in eastern Vermont (III-6) has been assigned in the past to the Silurian and Devonian but may include rocks as old as Late Ordovician (Bothner and Finney, 1986). Both overlap assemblages are depicted in FIGURE 6 only in their depositional configurations.

Assignment of the cover sequence of the Oliverian gneiss domes of the CMT (IV-3, IV-4) is uncertain; Thompson (1985) distinguished the cover rocks of Keene Dome from the eastern assemblage, but J.B. Thompson (1988, oral communication) mapped a stratigraphic difference between the cover rocks on the west (IV-3) and east (IV-4) sides of this dome. In any event, these rocks are all different from the western overlap assemblage of Vermont, and the source area for the eastern, largely allochthonous sequence must now be buried by their later westward tectonic transport during the Acadian deformation.

Rocks of the CMT, together with the overlap rocks, were strongly deformed and metamorphosed during the Acadian orogeny (Thompson and others, 1968; Robinson and others, 1979). After nappe formation, the rocks were backfolded and arched by doming of the underlying gneisses of the Ordovician Plutonic Suite (FIGURE 7; IV-4, V-4). Metamorphism took place at high pressure and temperature in central Massachusetts and New Hampshire (Robinson and others, 1986; Chamberlain and England, 1985; Spear and Chamberlain, 1986, and references) (V-6), accompanied by high-pressure plutonism (IV-5, IV-6, V-5) and crustal anatexis (IV-5, V-6).

Uppermost Silurian and Devonian rocks also cover the NAC, including the Taconic allochthon (FIGURE 8). Although the original continuity of all the Silurian and Devonian rocks has not been shown, it is probably safe to assume that, by Early Devonian time, the NAC, BCT, and CMT were firmly welded together.

THE MASSABESIC-MERRIMACK TERRANE

The units of the Massabesic-Merrimack terrane (MMT) include (FIGURE 2) much of the metamorphic rocks of eastern Connecticut, marked off from the CMT to the west by a complex zone of faults, including the Bonemill Brook fault described by Pease (1982) and its southern continuation, the Cremation Hill fault zone of London (1988) (see also Rodgers, 1985). North of the northern mapped limit of the Bonemill Brook fault, the western boundary of the MMT is another fault that coincides (Rodgers, 1985) with the boundary between sulfide-rich black pelite, which has been mapped as part of the Ordovician rocks of the CMT, and an extensive area of calcareous pelite. In Massachusetts, the MMT consists of the continuation of this calcareous pelite (VI-1, VI-2) east of the Fitchburg plutonic complex (V-8). In southern New Hampshire, the western boundary of the MMT is the western margin of the Massabesic Gneiss Complex (V-7), and the calcareous pelite and other clastic sedimentary units occur east of the Massabesic, as its cover rocks, as a separate terrane, or as its metamorphic equivalent (Bothner and others, 1984). The pelitic rocks are collectively referred to by authors (e.g., Lyons and others, 1982; Hepburn and others, 1987) as the Merrimack sequence. The rocks are cut by Ordovician and Silurian intrusive bodies (VI-2), so they must be no younger than early Paleozoic, but could be as old as late Proterozoic.

The Fitchburg plutonic complex (V-8) is Devonian (390±15 Ma, Zartman and Marvin, in press). Evidence permits the interpretation that it is a welding pluton between the MMT and the CMT. The Canterbury Gneiss in eastern Connecticut is its age- and petrographic correlative (392-395 Ma; Zartman and Naylor, 1984), but occurs entirely within the MMT.

Even though rocks of the MMT are here interpreted to be distinct from rocks of the CMT, they have been correlated with the much-deformed cover rocks in the Bronson Hill volcanic arc region (see Robinson and Tucker, 1982), although the recent age determinations on plutons cutting the MMT, mentioned above, would seem to make this interpretation untenable. Rodgers (1981, 1982) suggested that the MMT represents a Paleozoic accreting prism, and that the Taconian plate-margin processes off North America might have jumped from the primary subduction zone (the boundary of the NAC and rocks here called the BCT according to Rodgers, but the boundary of the BCT and the CMT in this guidebook) to a more oceanward locus when the buoyant sialic material of the NAC and the CMT butted against each other; he suggested a back-and-forth migration of the island arc (including the volcanic arc of Bronson Hill). Whether this process, or any other, can accommodate all the known data on stratigraphic and geochronological age, structure, or sedimentary pattern remains to be determined.

THE NASHOBA-CASCO-MIRAMICHI COMPOSITE TERRANE

The fault-bounded Nashoba-Casco-Miramichi composite terrane fringes the MMT on the south and east. In Connecticut and Rhode Island, with the exception of an enigmatic tract of volcanic rocks (the Quinebaug Formation; VII-4), the NCM is bounded on the western side by the Lake Chargoggagoggmanchauggagoggchaubunagungamaugg (Lake Char for short)-Honey Hill fault system. This fault system has been thought to die out at its southwestern end because synclines containing rocks thought to be shared by both footwall and hanging wall sequences continue on the ground in the Chester and Hunts Brook synclines (Lundgren, 1968; Rodgers, 1985). Zen here reinterprets the relations as a folded fault such that rocks in the cores of the synclines are above the fault, and intense Alleghanian deformation and amphibolite-grade metamorphism are considered to have obliterated the blastomylonite that elsewhere characterizes the fault zone. Goldstein (1982, 1984) pointed out that these faults have some attributes of detachment faults and show west-down movement sense; decoupling rocks of the Hunts Brook syncline from its substrate, as suggested above, would make such an interpretation at least geometrically viable. The fault system delimiting the MMT from the NCM continues northeastward to merge into the Clinton-Newbury fault, which also dips westward (Skehan, 1968; Hepburn and others, 1987). Rocks of the MMT, thus, might be displaced cover rocks of the NCM,

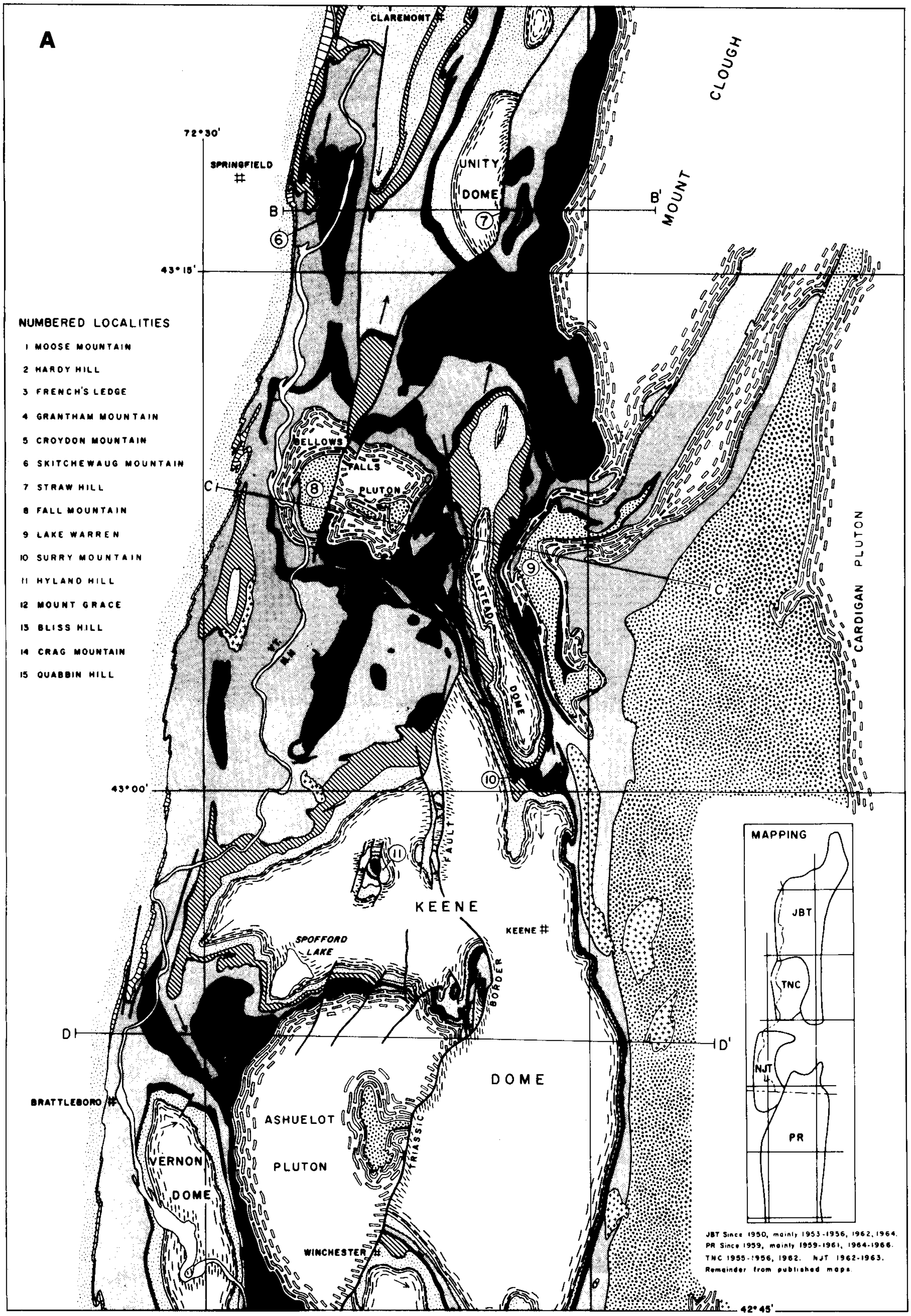
FIGURE 7 Acadian structure of the Bronson Hill anticlinorium across southern New Hampshire and Vermont, and in central Massachusetts, illustrating the effect of nappes, backfolding, and diapiric gneiss dome uprise on the configuration of the rocks. From Thompson and others, 1968; reproduced by permission of Wiley-Interscience.

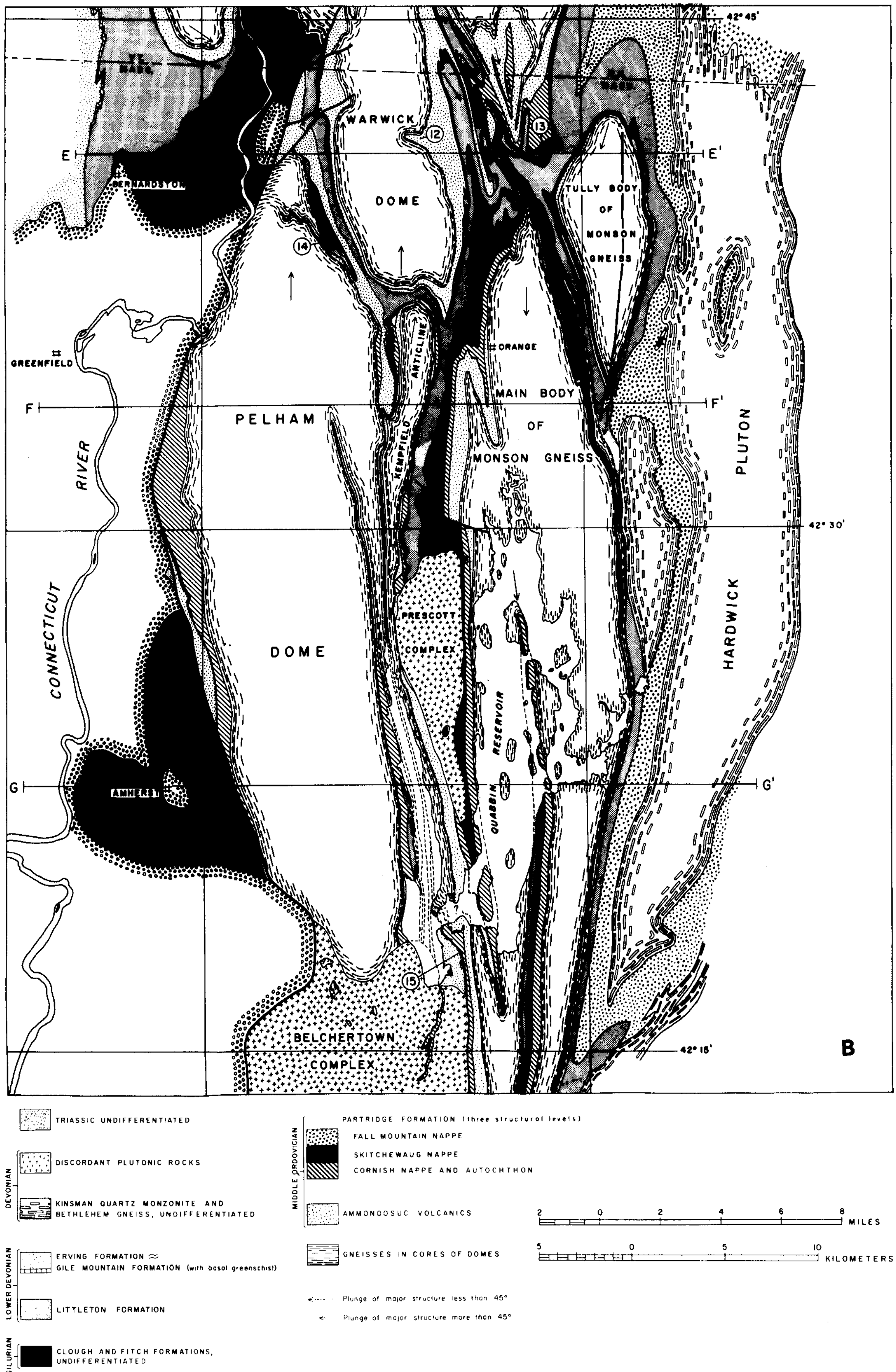
A, map view for parts of Vermont and New Hampshire.

B, Map view for parts of Massachusetts.

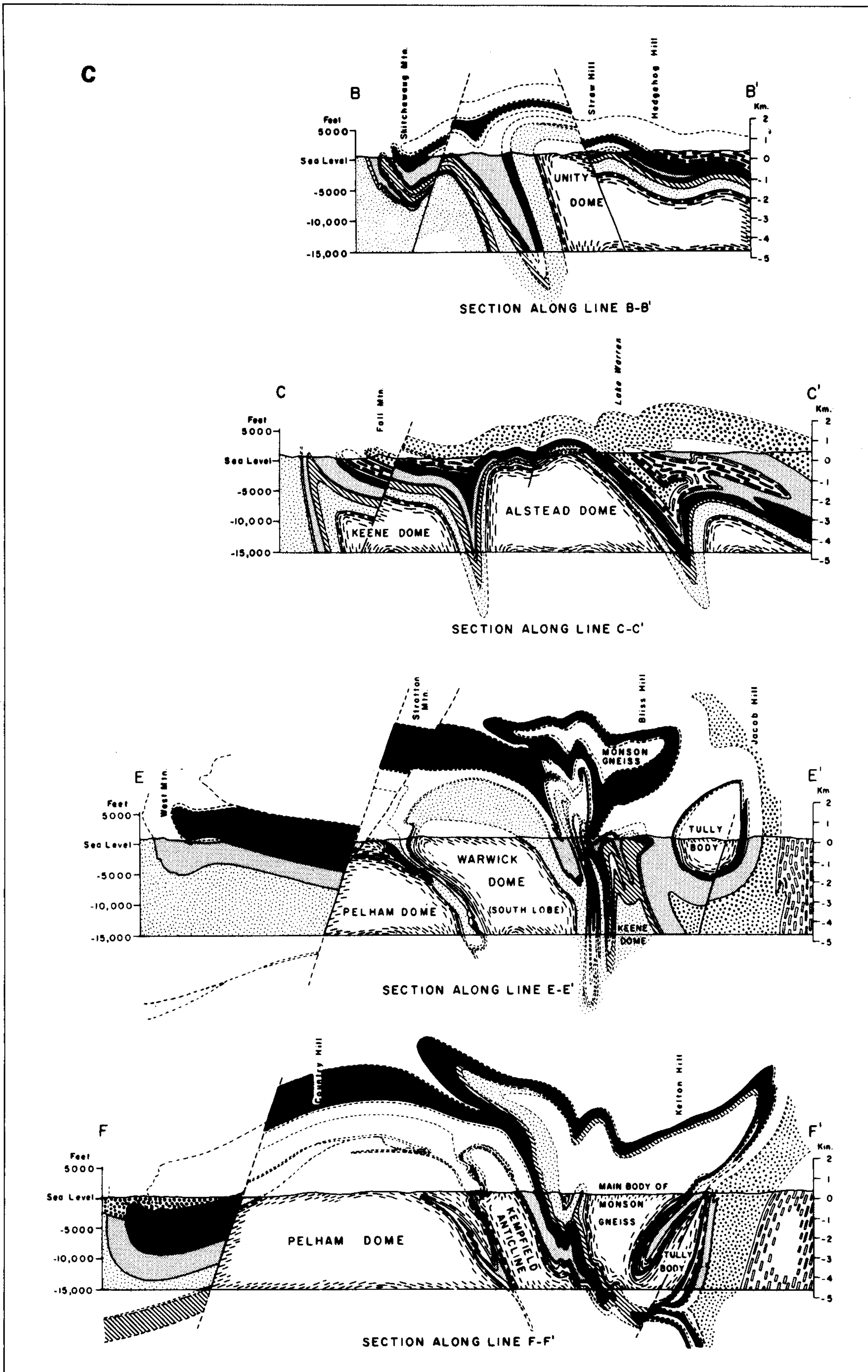
C, Cross sections.

(This black-and-white photographic reproduction of Thompson and others' maps and cross-sections could not distinguish between the Clough-Fitch Formations and the Partridge Formation of the Skitchewaug Nappe. For information regarding the distribution of these units, see Thompson and others, 1968)

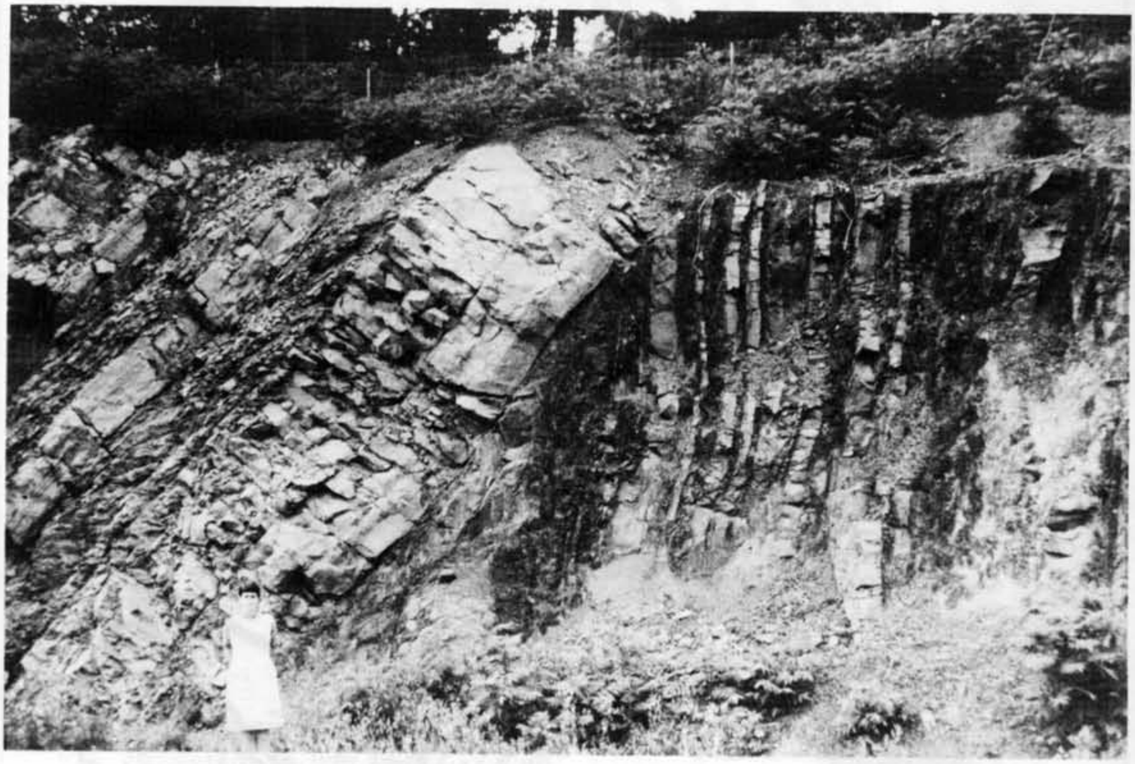

A
CLAREMONT
CLOUGH
MOUNT
72°30'
SPRINGFIELD
UNITY
DOME
B
B'
43°15'
NUMBERED LOCALITIES
1 MOOSE MOUNTAIN
2 HARDY HILL
3 FRENCH'S LEDGE
4 GRANTHAM MOUNTAIN
5 CROYDON MOUNTAIN
6 SKITCHEWAUG MOUNTAIN
7 STRAW HILL
8 FALL MOUNTAIN
9 LAKE WARREN
10 SURRY MOUNTAIN
11 HYLAND HILL
12 MOUNT GRACE
13 BLISS HILL
14 CRAG MOUNTAIN
15 QUABBIN HILL
BELLOWS
FALLS
PLUTON
C
C'
ALSTEAD
DOME
CARDIGAN PLUTON
43°00'
FAULT
KEENE
KEENE
SPOFFORD
LAKE
BORDER
D
D'
DOME
BRATTLEBORO
ASHUELOT
PLUTON
TRIASSIC
VERNON
DOME
WINCHESTER
MAPPING
JBT
TNC
NJT
PR
JBT Since 1950, mainly 1953-1956, 1962, 1964.
PR Since 1959, mainly 1959-1961, 1964-1966.
TNC 1955-1956, 1962. NJT 1962-1963.
Remainder from published maps.
42°45'



42° 45'
VT.
MASS.
N.H.
MASS.
WARWICK
12
13
E
E'
BERNARDSTON
DOME
TULLY BODY
OF
MONSON
GNEISS
14
GREENFIELD
ANTICLINE
ORANGE
MAIN BODY
OF
MONSON GNEISS
F
F'
PELHAM
KEMPFIELD
PLUTON
RIVER
42° 30'
CONNECTICUT
PRESCOTT
COMPLEX
DOME
HARDWICK
RESERVOIR
QUABBIN
G
G'
AMHERST
15
BELCHERTOWN
COMPLEX
42° 15'
B
TRIASSIC UNDIFFERENTIATED
DEVONIAN
DISCORDANT PLUTONIC ROCKS
KINSMAN QUARTZ MONZONITE AND BETHLEHEM GNEISS, UNDIFFERENTIATED
LOWER DEVONIAN
ERVING FORMATION ≈ GILE MOUNTAIN FORMATION (with basal greenschist)
LITTLETON FORMATION
SILURIAN
CLOUGH AND FITCH FORMATIONS, UNDIFFERENTIATED
MIDDLE ORDOVICIAN
PARTRIDGE FORMATION (three structural levels)
FALL MOUNTAIN NAPPE
SKITCHEWAUG NAPPE
CORNISH NAPPE AND AUTOCHTHON
AMMONOOSUC VOLCANICS
GNEISSES IN CORES OF DOMES
2 0 2 4 6 8 MILES
5 0 5 10 KILOMETERS
Plunge of major structure less than 45°
Plunge of major structure more than 45°


C
B
B'
Straw Hill
Hedgehog Hill
Feet
5000
Sea Level
-5000
-10,000
-15,000
Km.
UNITY
DOME
SECTION ALONG LINE B-B'
C
C'
Fall Mtn.
Lake Warren
ALSTEAD DOME
KEENE DOME
SECTION ALONG LINE C-C'
E
E'
West Mtn.
Stratton Mtn.
Bliss Hill
Jacob Hill
MONSON GNEISS
TULLY BODY
WARWICK DOME (SOUTH LOBE)
PELHAM DOME
KEENE DOME
SECTION ALONG LINE E-E'
F
F'
Kelton Hill
MAIN BODY OF MONSON GNEISS
PELHAM DOME
KEMPFIELD ANTICLINE
TULLY BODY
SECTION ALONG LINE F-F'

A



B

FIGURE 8 Taconian unconformities not visited on this excursion, showing Uppermost Silurian overlap assemblage on pre-Taconian Middle Ordovician strata. A, On the Taconic allochthon, Mt. Ida, NY, described by Craddock (1957). B, On autochthonous rocks of the Middle Ordovician Queenston Delta. New York Thruway interchange 21 with State Route 23 north of Catskill.

not having moved far.

Within the area of the excursion, the NCM rocks include the "Hope Valley terrane" of O'Hara and Gromet (1985) in western Rhode Island and eastern Connecticut (VII-3), the Quinebaug Formation (VII-4), and the highly deformed and metamorphosed Proterozoic and early Paleozoic rocks of the Nashoba terrane (VI-3, VI-4, VI-5). The Willimantic dome (see Wintsch, 1979) in Connecticut is a window exposing these NCM rocks; the Massabesic Gneiss Complex of the MMT, in fact, could also be in a tectonic window.

Northeast of the area of the excursion, the NCM is a major component of the Appalachian orogen. The rocks include the Casco Bay areas in southwestern coastal Maine (Hussey, 1987; Osberg and others, 1985), the Passagassawakeag Gneiss (Stewart and Wones, 1974; Zen, 1983), and the large tract of Miramichi sequence in New Brunswick and adjacent eastern Maine (Fyffe and Fricker, 1987; Zen and others, 1986). The units of the NCM seem to share these properties: Sialic basement; protolith containing zircon older than 1.5 Ga; a major 700-800 Ma thermal, igneous, and metamorphic imprint (VI-3, VI-4; Olszweski, 1980); Late Proterozoic to early Paleozoic mafic volcanism (Hepburn and others, 1987); Ordovician metamorphism and plutonism (VI-5; Hepburn and Munn, 1984) of uncertain plate tectonic context but possibly indicating an ocean-closing event unrelated to Iapetus; and major Devonian peraluminous granite. The composite nature of the NCM and its probably diachronous history of accretion must be stressed; mutual relations of its subunits are far from understood. As far as we know these subunits are all fault bounded today, and no sedimentary rocks in them are of known Silurian and Devonian ages -- the missing section is precisely the age span of the overlap sequence of the CMT and the BCT --, with the important exception of the Miramichi, which contains an Upper Silurian to Devonian section yielding Pridolian North American shelly faunae (Fyffe and Fricker, 1987).

Parts of the NCM could be basement to the CMT. Rocks resembling the Proterozoic(?) metasedimentary units of the Hope Valley terrane appear as part of the basement rocks of the Pelham Dome of the CMT (VII-3, VII-4; cf. V-2, V-3) (Robinson and others, 1979; Robinson, 1988). However, because blocks of the NCM are now fault-bounded and do not otherwise preserve Paleozoic stratigraphic continuity with the CMT, the correlation is tenuous; at the present level of exposure, all units of the NCM are distinct from the CMT whether they shared an ancestry or not.

THE ATLANTICA COMPOSITE TERRANE

The name, Atlantica Composite terrane (AT), was introduced by Zen and others (1986) for rocks previously included in the Avalon, the Meguma, and other related (and possibly unrelated) rocks and terranes. Three types of fragmentary terranes are recognized: Atlantica I, Atlantica II, and Meguma. These fragments are mutually bounded by faults. We will see Atlantica I and II.

Atlantica I (FIGURE 9) consists of platformal Middle and Upper Cambrian marine shales and rarer platformal carbonates that rest on a crystalline basement. Detrital zircons contained in these rocks show a >1.5 Ga source and a thermal and metamorphic event around 800 Ma (Olszewski and Gaudette, 1981). The basement is cut by approximately 580 to 620 Ma calc-alkalic plutons and associated volcanics (VI-7, VI-8, VI-9, VII-1) (Kovach and others, 1977; Hermes and Zartman, 1985; Zartman and Naylor, 1984; Hepburn and others, 1987). Except where they are affected by the late Paleozoic Alleghanian deformation, these Late Proterozoic rocks show only greenschist facies metamorphism, and so little deformation that even the ignimbrite textures of felsic volcanics are preserved (VI-7; Smith and Hon, 1984; Thompson, 1984, 1986). Sedimentary rocks in the Boston area have yielded latest Proterozoic to earliest Cambrian microfossils (Lenk and others, 1982). The relation of these rocks to the trilobite-bearing Cambrian strata just south of Boston is obscured by faulting and intrusion; however, they could be part of a continuous succession (FIGURES 4, 9). In the Narragansett Bay area, Lower Cambrian microfossils occur in rocks (VII-8) that apparently pass upward into Middle Cambrian rocks (VII-7; Murray and Skehan, 1979). No Ediacaran fossils have been found in the area of the traverse; however, the well-known Ediacaran macrofauna-bearing beds on the Avalon peninsula of southeastern Newfoundland (King and others, 1974) are part of Atlantica I. The Cambrian macrofossils of Atlantica I are of the Atlantic fauna (Neuman and others, 1988), distinct from that of coeval North American rocks. In Atlantica I of Massachusetts, the Ordovician and possibly

Silurian are marked by anorogenic peralkaline plutons (Zen and others, 1983).

In the northern Appalachians of the United States (Zen and others, 1983; Osberg and others, 1985; Skehan and others, 1986) and in maritime Canada (Belt, 1968), Atlantica I is overlapped by Carboniferous continental sedimentary rocks that include economically significant coal beds. These rocks are pan-Appalachian overlap assemblages that document the docking of Atlantica to North America. In Massachusetts and Rhode Island, only Westphalian and Stephanian beds are known in the large transtensive Narragansett Basin (P.C. Lyons, 1979). The pre-Carboniferous rocks south of the basin contain units unknown north of the basin (Zen and others, 1983) and might include discrete terranes. Rocks in the southwestern end of the Narragansett basin have been intensely deformed, metamorphosed (VII-6, VII-9), and intruded by Permian peraluminous granite such as the Narragansett Pier Granite (VII-5).

Atlantica II is best preserved along the coast of eastern Maine and consists mainly of pre-Silurian bimodal volcanics metamorphosed to the upper greenschist facies (the Ellsworth Group, Stewart, 1974). The terrane is interpreted as tectonically intercalated with Atlantica I. The Ellsworth is not known for certain southwest of Maine, but an isolated large exposure of mica-chlorite schist near Sakonett on the eastern shore of Narragansett Bay in Rhode Island (Quinn, 1971) may be a fragment of the same terrane (FIGURE 3). In Maine, the Ellsworth is overlain by within-plate bimodal volcanic rocks and associated shallow water sediments that carry a typical Atlantic-province shelly fauna of Late Silurian and Early Devonian age (Gates and Moench, 1981; Gates, 1987). As implied by them and as interpreted by Zen and others (1986), the virtually undeformed and unmetamorphosed Newbury Volcanic Complex in northeastern Massachusetts (VI-6), which carries comparable faunae, is also part of Atlantica II (Shride, 1976a, b). The fact that these faunae are distinct from the North American Pridolian fauna of the Miramichi subunit of the NCM suggests that Atlantica II was still separate from the enlarged North America at that time, though it was definitely accreted in the Carboniferous or possibly even in late Devonian time.

The thermal histories of Atlantica I and II, which show little metamorphism since the latest Proterozoic (Atlantica I) or since Late Silurian (Atlantica II) and by and large register only brittle deformation, contrast with the record for rocks within the NCM, MMT, CMT, and BCT, which recorded major Devonian thermal and ductile deformational events. This contrast supports the exotic relations between these two groups of terranes.

The third subunit assigned by Zen and others (1986) to Atlantica is the Meguma terrane. To date, Meguma terrane is recognized in onshore North America only in Nova Scotia, Canada, but it is known in adjoining parts of the Gulf of Maine (Keppie, 1985). The Meguma consists of a thick (~6-10 km) section of lower Paleozoic quartzofeldspathic and turbiditic sandstone and shale, and is succeeded upsection by Silurian and Devonian shallow marine sediments and bimodal volcanic rocks (Keppie, 1985). These rocks are intruded by Late Devonian crustally derived peraluminous granitic batholiths (the South Mountain batholith; McKenzie and Clarke, 1975), followed by lower Carboniferous sedimentary rocks that are part of the pan-Appalachian overlap sequence.

Major faults are abundant within the MMT, NCM, and AT. Some are terrane-bounding faults. Examples are the Nonesuch River-Campbell Hill fault system on the western side of the MMT, interpreted to be welded by the 390-Ma Fitchburg plutonic complex; the Clinton-Newbury fault on the northwestern side of the Nashoba block of the NCM (Skehan, 1968); the Lake Char fault and the Honey Hill thrust (VII-4; Rodgers, 1985) in eastern Connecticut; the Bloody Bluff fault (VI-9; Nelson, 1987); the Hope Valley ductile shear zone in Rhode Island (VII-2; O'Hara and Gromet, 1985) which deforms the 370-Ma Scituate Granite Gneiss; the Turtle Head fault in Maine (Stewart and Wones, 1974) intruded by the 380-Ma Lucerne Granite (Wones, 1980); and the Portage Lakes-Serpentine River fault and the Bellisle fault of New Brunswick (Fyffe and Fricker, 1987). Diachronous accretion of individual blocks is suggested by the ages. The faults dip variably, though mainly to the northwest. Lack of full understanding of the geometry, major movement sense, and age of these faults impedes full description of the nature and process of accretion of the terranes or, as an opposite, of some intra-terrane crustal evolution. FIGURE 10 summarizes and contrasts the major depositional, tectonic, metamorphic, and igneous events of units in the MMT, NCM and AT.

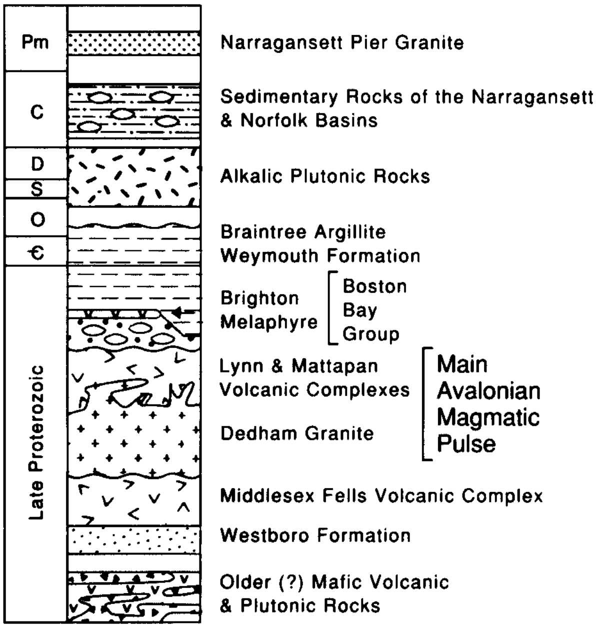


FIGURE 9 Simplified lithostratigraphic section of Atlantica I in eastern Massachusetts according to Hepburn and others (1987, figure 3).

The Narragansett Pier Granite of Rhode Island is projected into the section.

TERRANE (of this study)	AT I	NCM	MMT
AGE	BOSTON-AVALON ZONE	NASHOBA BLOCK	MERRIMACK TROUGH
Permian 286	K-Ar Mineral Ages PERALUMINOUS GRANITE METAMORPHISM & DEFORMATION	K-Ar Mineral Ages Ductile Shearing (?)	K-Ar Mineral Ages GRANITIC PLUTONISM METAMORPHISM
Carboniferous 360	(Gs - Amph. Facies; Ky- Sill.) Sedimentation K-Ar Mineral Ages	Metamorphism (?) Rb-Sr, Sm-Nd, and Ar-Ar Mineral Ages	(Greenşchist Facies, Worcester, Mass.) GRANITIC PLUTONISM
Devonian 408	↑ ALKALIC PLUTONISM ↓	Newbury Volcanic Complex (UNMETA.) DIORITE & GRANITE	Acadian Meta. Effects (?) GRANITIC PLUTONISM
Silurian 438	(Contact Metamorphism)	PERALUMINOUS GRANITE DEFORMATION & METAMORPHISM (Amph. Facies, And.-Sill.) (Polymeta.)	GRANITIC PLUTONISM
Ordovician 505	ALKALIC PLUTONISM	DIORITE GRANITE ? ↑ ↓ ?	METAMORPHISM (Greenschist-Amphibolite Facies) (Polymetamorphism, And.-Sill.)
Cambrian 570	Sedimentation (Contact Metamorphism)	Sedimentation MAFIC VOLCANICS	↑ Sedimentation (?) ?
Late Protero-zoic	CALC.-ALKALINE PLUTONISM - VOLC. Metamophism (?) ? ↑ DEFORMATION MAFIC-BIMODAL VOLC. - PLUTONISM Sedimentation	↓ ? METAMORPHISM (?) DEFORMATION SILICIC MAGMATISM (Fishbrook Gn.)	GRANITIC PLUTONISM (Massabesic Orthogneiss) ↓ METAMORPHISM (?) (Amph. Facies) DEFORMATION (?) Sedimentation

FIGURE 10 Comparison of geologic events in MMT ("Merrimack trough"), NCM ("Nashoba block"), and Atlantica I ("Boston-Avalon zone") in eastern Massachusetts and adjacent areas, slightly modified from Hepburn and others (1987, figure 5).

Carboniferous and Permian thermal and plutonic events are becoming increasingly evident within the various terranes (Osberg and others, 1985; Zen and others, 1983; Rodgers, 1985; Aleinikoff and others, 1979; Hayward and others, 1988; Zartman and others, 1970), but the significance of the plutonic and thermal events remains unclear. The Upper Triassic and the Jurassic are preserved in the continental beds of the Newark Supergroup that occur in Massachusetts and Connecticut in the Deerfield and Hartford basins as well as in a few small isolated areas (Zen and others, 1983; Rodgers, 1985). Intercalated in these sediments is continental tholeiitic basalt, perhaps the best known of which is the Palisades sill near New York City. The basins are partially fault bounded, in Massachusetts and Connecticut on the eastern side (V-1); whether there are pre-Triassic beds in these basins is uncertain. The Mesozoic basins clearly are precursors to the opening of the modern North Atlantic Ocean; their development is synchronous with that of a remarkable group of Jurassic mafic dikes that trend northeast, extend from Connecticut to northeastern Maine, and mark a gravity gradient in central Maine (Unger and others, 1987). Late Cretaceous events include the intrusion of the peralkaline anorogenic White Mountain Plutonic-Volcanic Suite and of west-northwest-trending lamprophyre dikes; one such dated dike (II-7) has reverse polarity and has been normal faulted east side down, the fault orientation being consistent with the opening of the North Atlantic Ocean (Zen, 1972a).

Ayuso (1986) showed that the lead isotope ratios of feldspar from Acadian granites of Maine follow a distinct pattern that supports the division of the major terranes suggested by Zen (1983). Because anatectic magmatic events as recorded by isotopic ages tend to lag behind the triggering tectonic events by several tens of millions of years (Zen, 1988b), these Acadian granites probably reflect anatexis due to the Taconian subduction.

Acknowledgments

I thank my coleaders for instructive discussions of the geological relations during the preparation of this guidebook. I also thank Wally Bothner, Dick Goldsmith, Art Goldstein, Norm Hatch, Don Hermes, Rudi Hon, Ed Landing, John Lyons, Nick Ratcliffe, and Phil Whitney for discussions and for providing helpful data. I thank Doug Rankin and Bob Speed for making available to me geologic compilations that provided the basis for FIGURE 2. I thank the State Geologists -- Gene Boudette of New Hampshire, Allan Cain of Rhode Island, Bob Fakundiny of New York, Chuck Ratté of Vermont, Joe Sinnott of Massachusetts, and Hugo Thomas and Sid Quarrier of Connecticut -- for help in numerous ways. I thank property owners and managers and many local people for their permission to visit rock outcrops on their land and for many other kindnesses. The manuscript was reviewed by Peter Gromet, Mary Lou Hill, Peter Lyttle, Rob Robinson, and John Rodgers. The assistance of Karen Gray in all phases of the guidebook preparation is gratefully acknowledged. I acknowledge the graphics work by Shirley Brown and Cynthia Crampsey. Finally, I express my appreciation to all those whose efforts have made this trip logistically workable.

CALENDAR

Day 0, Wednesday July 19. Albany, NY from Washington DC. Evening in Albany NY.
Day 1, Thursday July 20. Evening in Rutland, VT.
Day 2, Friday July 21. Evening in Rutland.
Day 3, Saturday July 22. Evening in Keene, NH.
Day 4, Sunday July 23. Evening in Keene. Afternoon free.
Day 5, Monday July 24. Evening in Worcester, MA.
Day 6, Tuesday July 25. Evening in Worcester.
Day 7, Wednesday July 26. Evening in Providence, RI.
Day 8, Thursday July 27. Dispersal at several airports.

PLEASE SEE FIGURE 1 FOR TRIP ROUTE AND FIGURE 11 FOR EXACT STOP LOCATIONS.

We respectfully request that you avoid hammering the outcrops. Most of the features to be examined can be seen, and seen better, on a weathered surface; if a hammer is necessary on a given outcrop, the trip leaders will provide it.

Colleagues who use this guidebook after the official trip are requested to exercise the same restraint and also to avoid drilling these outcrops for paleomagnetic samples. They are further urged to contact property owners for permission before going onto private land.

We appreciate your cooperation.

STOP DESCRIPTIONS

A stop preceded by the symbol * means it is optional. Statements between brackets [] that appear in quoted material are Zen's comments.

DAY I: ALBANY, NY TO RUTLAND, VT
Zen and Thompson, leaders

Stop descriptions prepared by E-an Zen

MAINLY THE NORTH AMERICAN CRATON

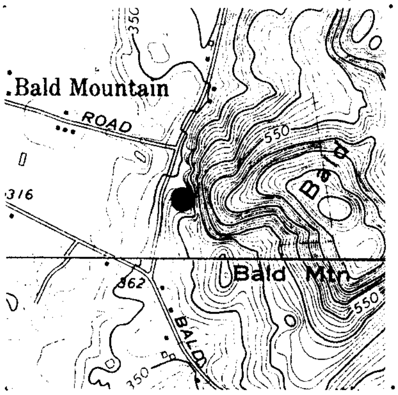
*** Day I, Stop 1. Base of Taconic allochthon, Bald Mountain quarry.**

Bald Mountain quarry is a classic site in the annals of North American geology, and the complex relations exposed here have been much debated. The rocks have been described by Rodgers (Billings and others, 1952): "On both sides of road and in woods to right [east] is Beekmantown dolomite (Lower Ordovician **). Just in front of main quarries is a screen of black slate (Ordovician?), farther part of which contains pebbles and larger irregular fragments as much as several feet across of limestone of several kinds, also dolomite and other rocks. Quarries are in large masses of pure limestone, badly shattered and brecciated, with some seams of black slate; much at least of this limestone seems to be Middle Ordovician, as are some of the fragments in the screen of black slate. Upper margin of quarry limestone is very irregular, marked by more black slate with limestone fragments; above this, at upper lip of quarry, lies Cambrian slate and grit. Lower Cambrian fossils have been found in shaly limestone in the slate, higher on the hill."

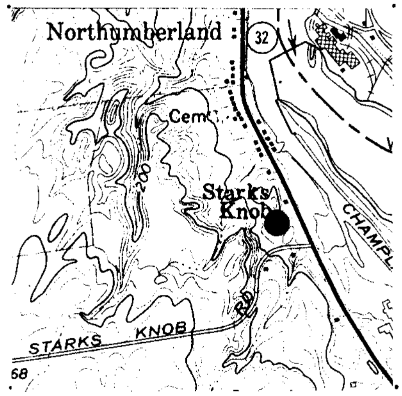
The Taconic allochthon was thrust onto Middle Ordovician marine flysch black shales that rest on older Ordovician carbonate of the shelf sequence on the North American craton. Relations seen in the quarry, therefore: (1) Locate the western margin of the Taconic allochthon

FIGURE 11 Detailed locations and topographic maps of excursion stops for individual days. See box below for details; the longitude (west) and latitude (north) of each stop is given to the nearest 3 seconds. All topographic sheets are reproduced at true scales.

```
*****************************************************************
*                                                               *
*                KEY TO TOPOGRAPHIC MAP CUTOUTS                 *
*                                                               *
*   Day I Stop 2 ... Date and stop number (see FIGURE 1a)       *
*                                                               *
*   Monadnock Mtn NH ... Name of topographic quadrangle map;    *
*        name of State (location straddles quadrangle boundary  *
*        if names of two maps are given)                        *
*                                                               *
*   1:24,000 (1972/82) ... Scale of map, edition and date of    *
*        revision.  Year refers to both sheets if the location  *
*        straddles two sheets but only one year given.          *
*                                                               *
*   73°13'45"/42°52'25" ... Longitude (west) and latitude       *
*        (north) of stop location shown on cutouts (±03")       *
*                                                               *
*****************************************************************
```

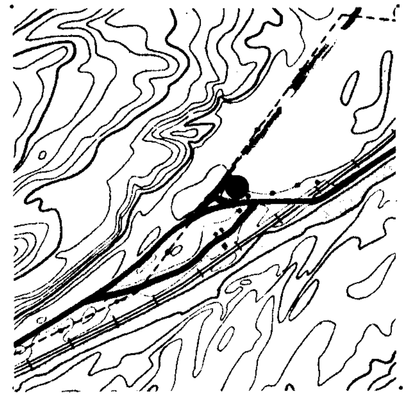


Day I Stop 1
Fort Miller NY
Schuylerville NY
1:24,000 (1967)
73°31'52"/43°07'34"



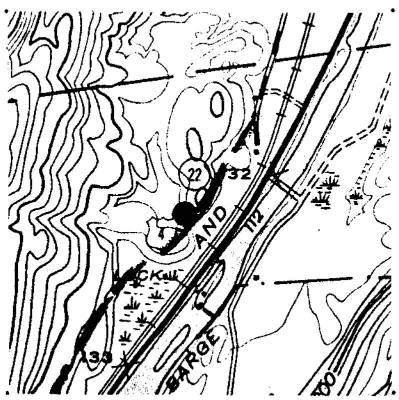
Day I Stop 2

Schuylerville NY
1:24,000 (1967)
73°35'17"/43°07'06"

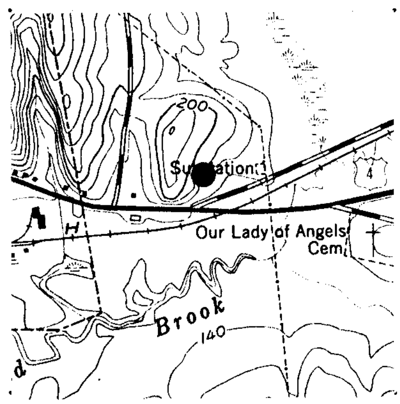


Day I Stop 3

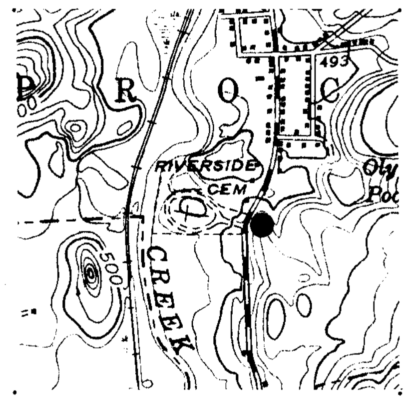
Fort Ann NY
1:24,000 (1944)
73°27'50"/43°25'53"



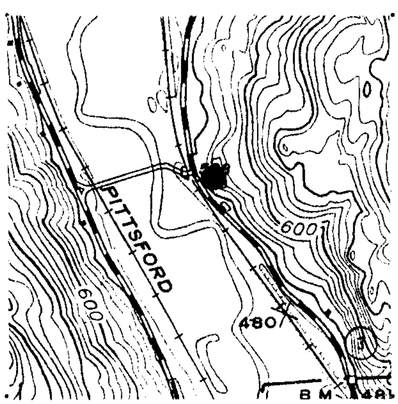
Day I Stop 4
Fort Ann NY
1:24,000 (1944)
73°26'05"/43°28'15"



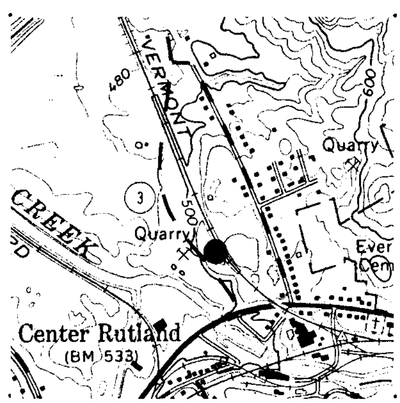
Day I Stop 5
Whitehall NY-VT
1:24,000 (1950)
73°22'58"/43°32'58"



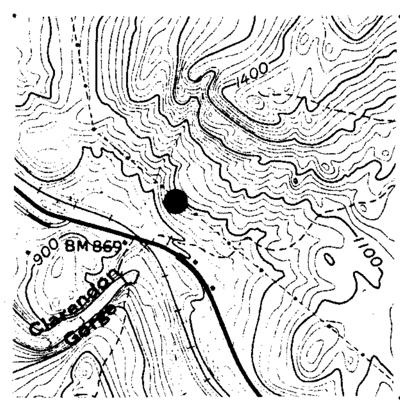
Day I Stop 6
Proctor VT
1:24,000 (1944)
73°01'59"/43°39'04"



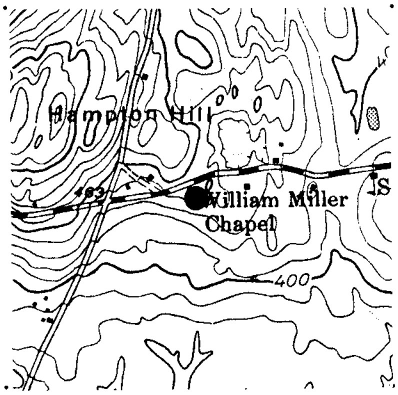
Day I Stop 7
Proctor VT
1:24,000 (1944)
73°02'07"/43°37'56"

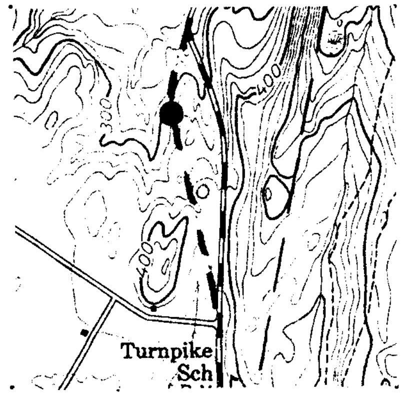


Day I Stop 8
West Rutland VT
1:24,000 (1964/72)
73°00'56"/43°36'21"



Day I Stop 9
Rutland VT
1:24,000 (1961)
72°55'20"/43°31'16"

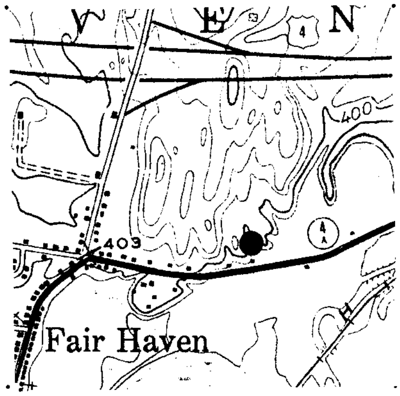


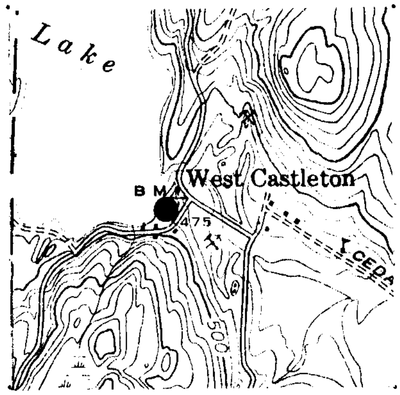


Day II Stop 1
Thorn Hill NY-VT
1:24,000 (1946/72)
73°18'44"/43°35'42"

Day II Stop 2
Thorn Hill NY-VT
1:24,000 (1946/72)
73°17'41"/43°36'21"

Day II Stop 3
Benson VT-NY
1:24,000 (1946)
73°17'57"/43°38'33"

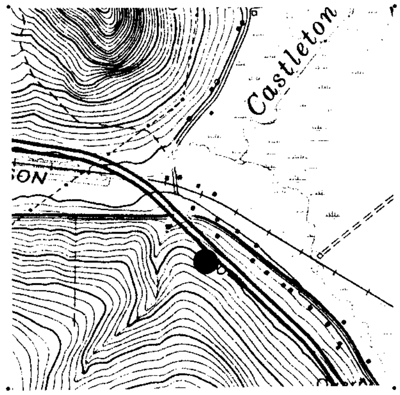


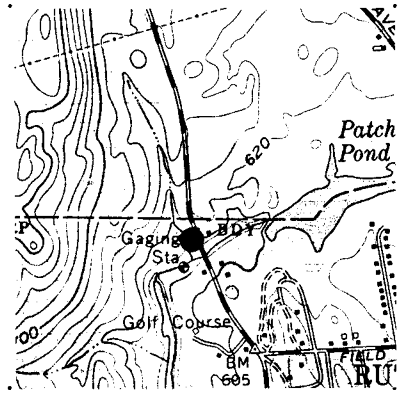


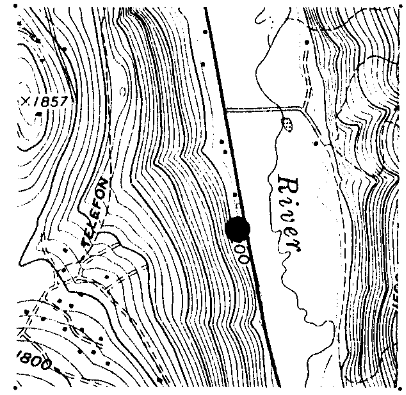
Day II Stop 4
Thorn Hill NY-VT
1:24,000 (1944/72)
73°15'20"/43°35'59"

Day II Stop 5
Bomoseen VT
1:24,000 (1944/72)
73°13'57"/43°39'29"

Day II Stop 6
Bomoseen VT
1:24,000 (1944/72)
73°13'59"/43°37'53"



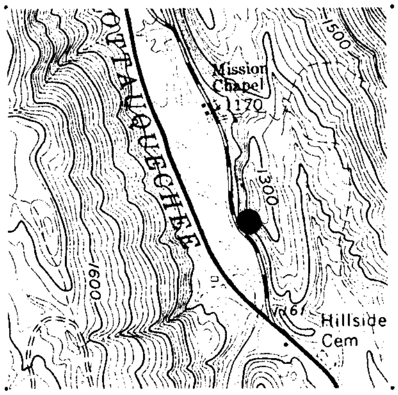




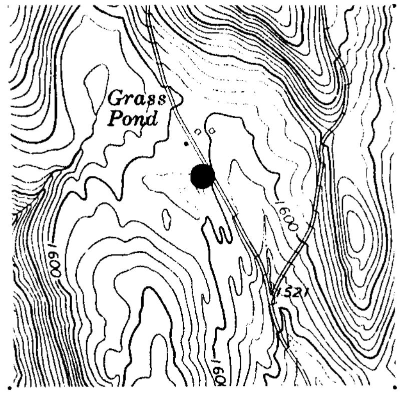
Day II Stop 7
West Rutland VT
1:24,000 (1964/72)
73°03'50"/43°36'11"

Day II Stop 8
Chittenden VT
1:24,000 (1961)
72°59'21"/43°37'48"

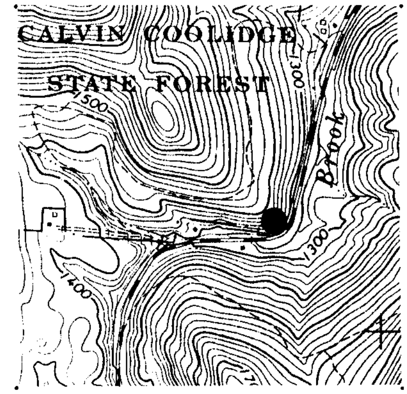
Day II Stop 9
Pico Peak VT
1:24,000 (1961/80)
72°46'13"/43°38'50"



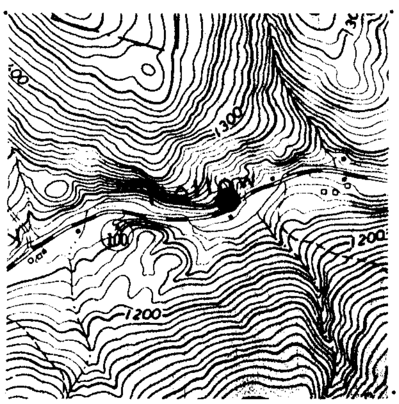
Day III Stop 1
Killington Peak VT
1:24,000 (1961)
72°45'21"/43°36'59"



Day III Stop 2
Plymouth VT
1:24,000 (1966)
72°44'00"/43°32'40"



Day III Stop 3
Plymouth VT
1:24,000 (1966)
72°42'44"/43°32'40"



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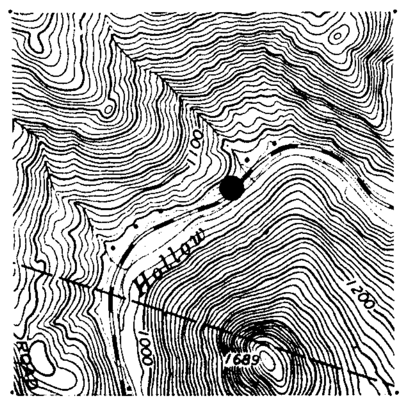
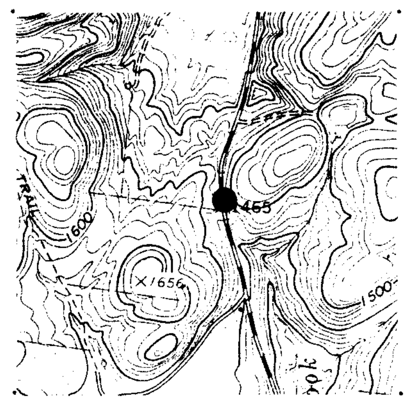
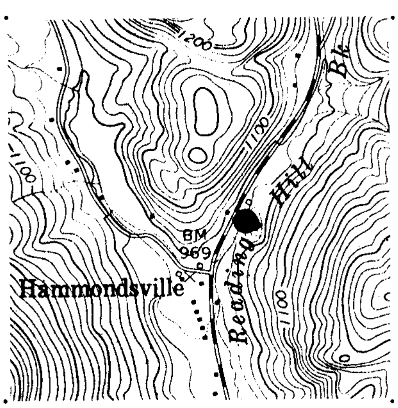
Plymouth VT
1:24,000 (1966)
72°41'34"/43°33'47"



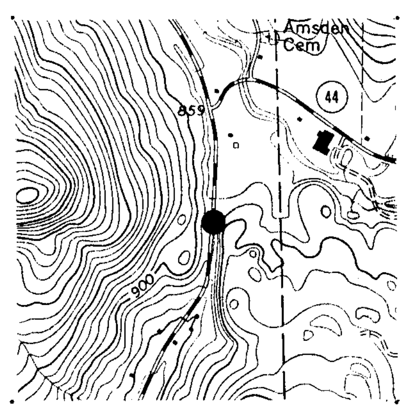
Day III Stop 5
Plymouth VT
1:24,000 (1966)
72°40'36"/43°34'18"



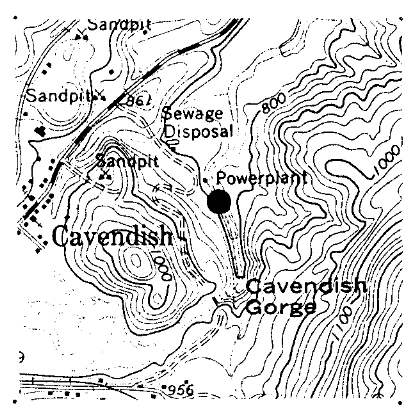
Day III Stop 6
Woodstock South VT
1:24,000 (1966)
72°33'23"/43°31'52"



Day III Stop 7
Cavendish VT
1:24,000 (1972)
72°33'10"/43°29'30"



Day III Stop 8
Cavendish VT
1:24,000 (1972)
72°32'02"/42°27'54"



Day III Stop 9
Cavendish Vt
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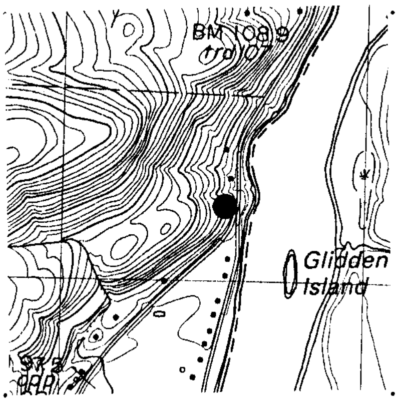
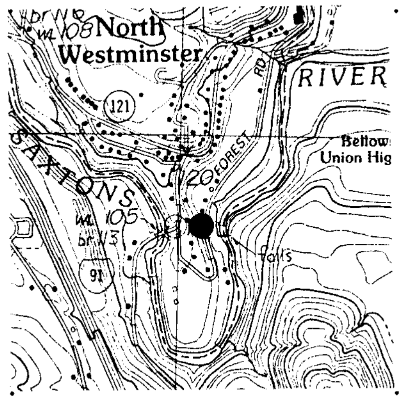
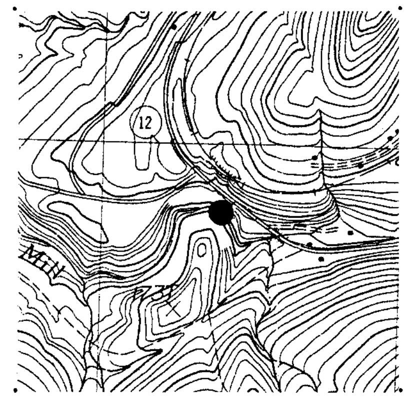
72°35'55"/43°23'02"



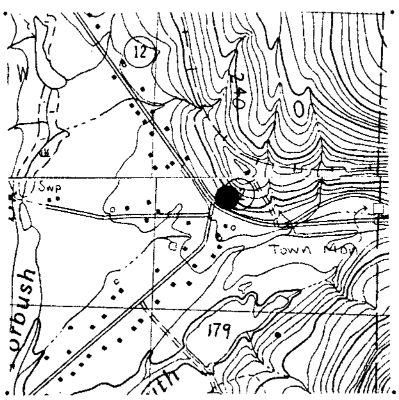
Day IV Stop 1
Springfield VT-NH
1:25,000 (1984)
72°24'16"/43°18'02"



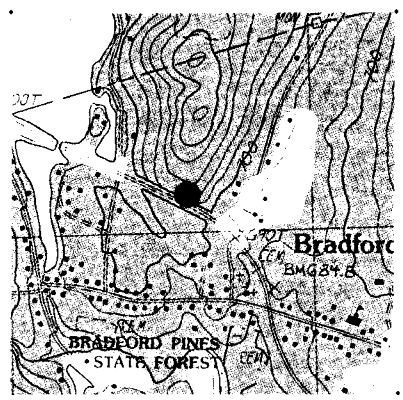
Day IV Stop 2
Walpole NH-VT
1:25,000 (1985)
72°27'14"/43°07'00"



Day IV Stop 3
Keene NH-VT
1:25,000 (1984)
72°25'53"/42°59'26"

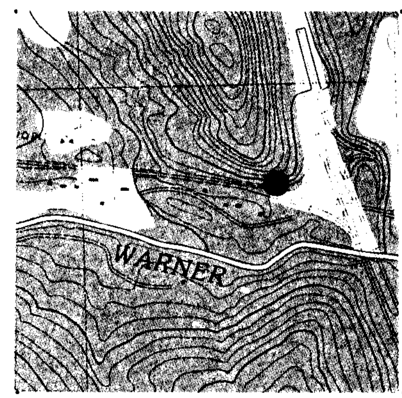


Day IV Stop 4
Monadnock Mtn NH
Marlborough NH
1:25,000 (1984)
73°13'50"/42°52'28"



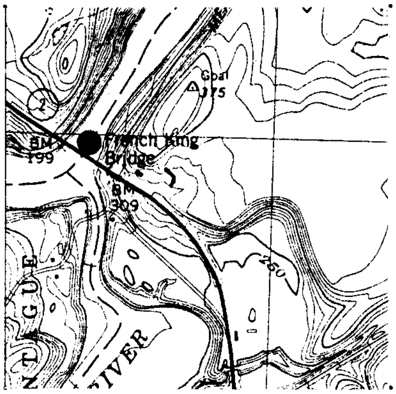
Day IV Stop 5

Bradford NH
1:24,000 (1987 provisional)
71°57'45"/43°16'20"

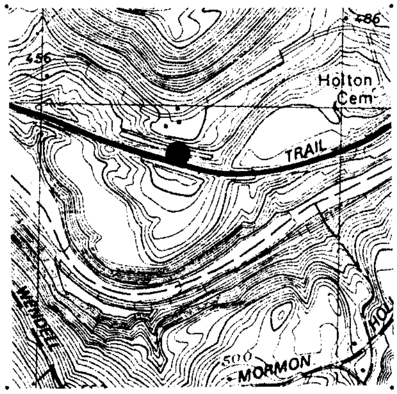


Day IV Stop 6

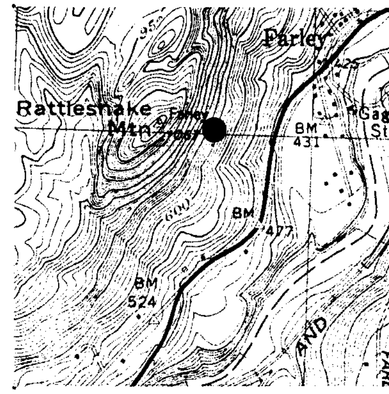
Warner NH
1:24,000 (1987 provisional)
71°50'25"/43°17'22"



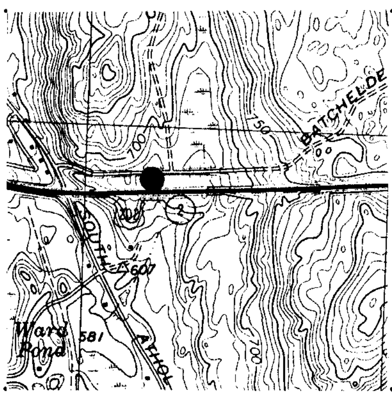
Day V Stop 1
Millers Falls MA
1:25,000 (1977)
72°29'45"/42°35'49"



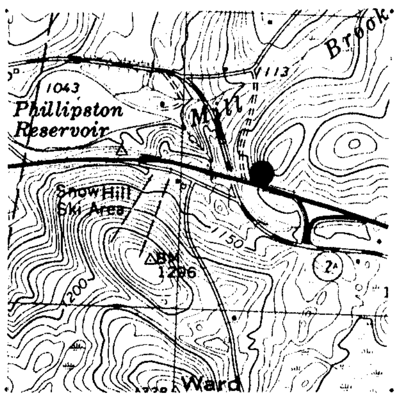
Day V Stop 2
Millers Falls MA
1:25,000 (1977)
72°28'20"/42°34'40"



Day V Stop 3
Millers Falls MA
1:25,000 (1977)
72°26'39"/42°35'49"



Day V Stop 4
Athol MA
1:25,000 (1970)
72°14'42"/42°33'49"



Day V Stop 5
Athol MA
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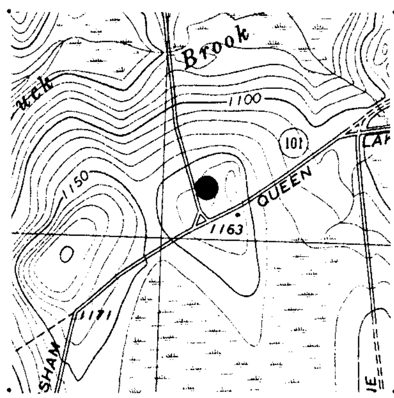

Day V Stop 6
Athol MA
1:25,000 (1970)
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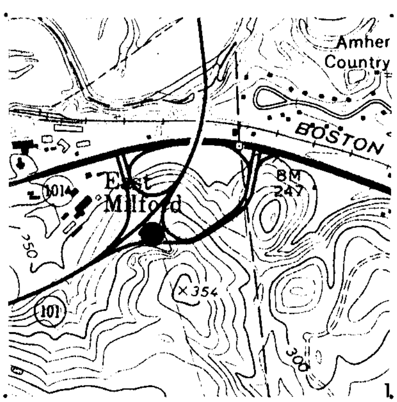
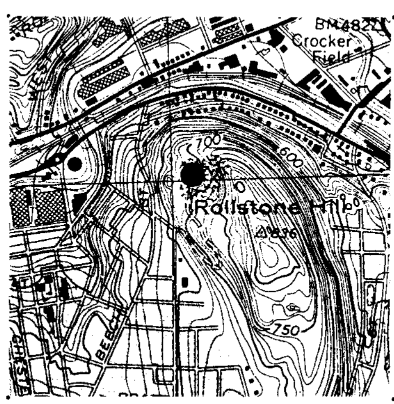
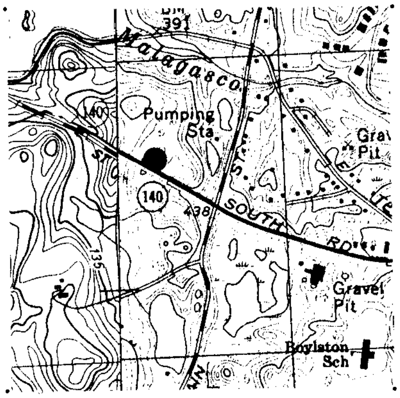


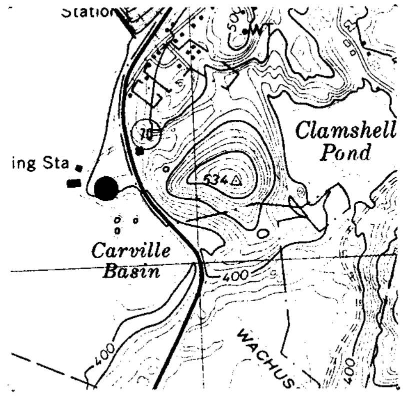
Day V Stop 7
South Merrimack NH
1:24,000 (1968/85)
71°37'11"/42°49'20"



Day V Stop 8
Fitchburg MA
1:25,000 (1969/79)
71°48'50"/42°34'53"

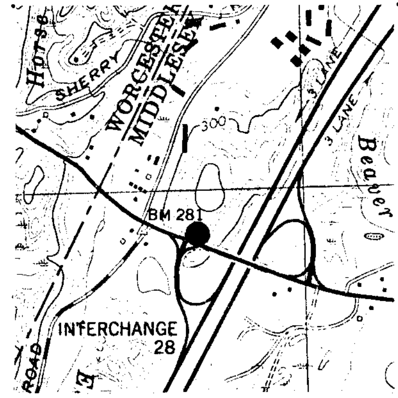


Day VI Stop 1
Worcester North MA
Shrewsbury MA
1:25,000 (1983/79)
71°44'56"/42°20'14"



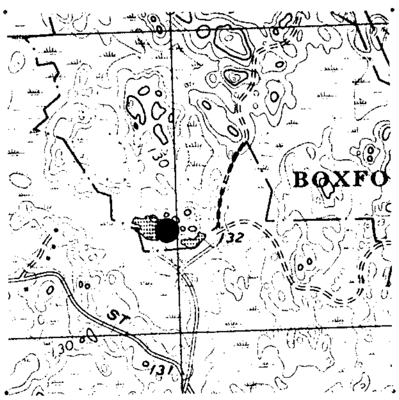
Day VI Stop 2

Clinton MA
1:25,000 (1965/79)
71°41'23"/42°23'54"



Day VI Stop 3

Hudson MA
1:25,000 (1966/79)
71°32'51"/42°29'15"



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South Groveland MA
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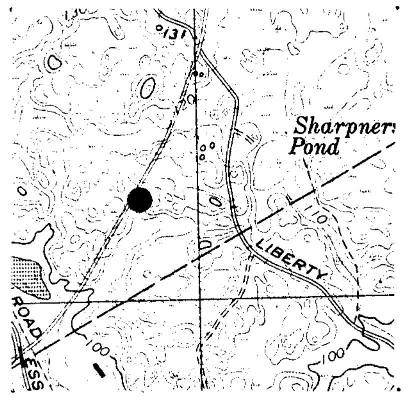

Day VI Stop 5
South Groveland MA
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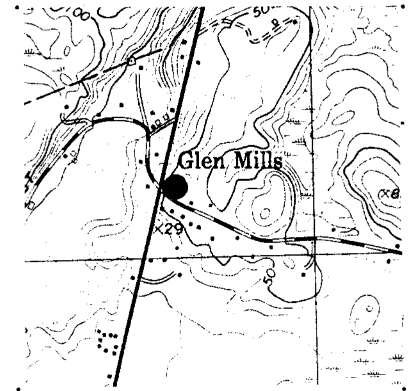
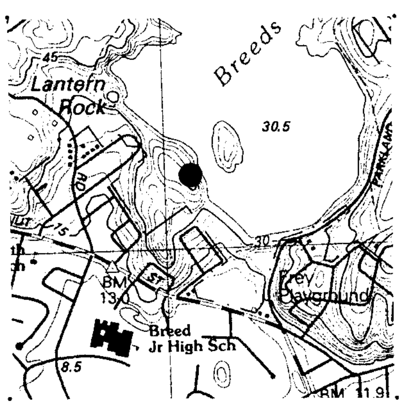
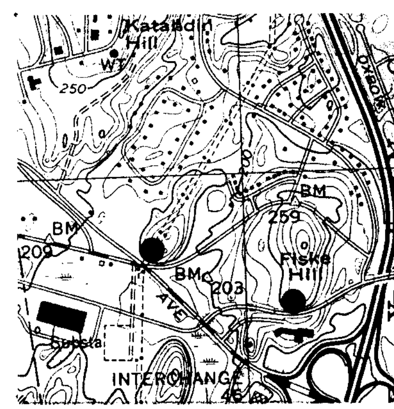


Day VI Stop 6
Georgetown MA
1:25,000 (1966/79)
70°53'58"/42°44'16"

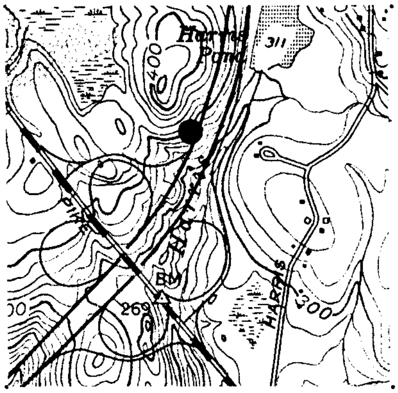


Day VI Stop 7
Lynn MA
1:25,000 (1985)
70°58'54"/42°28'32"

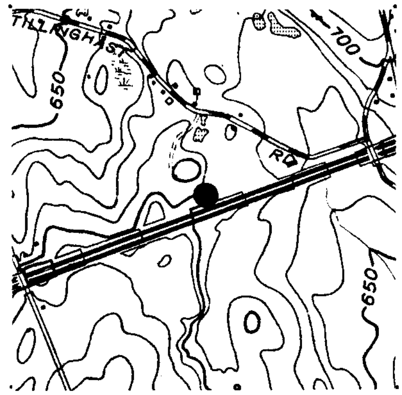
Day VI Stop 8
Boston North MA
1:25,000 (1985)
71°01'43"/42°27'48"



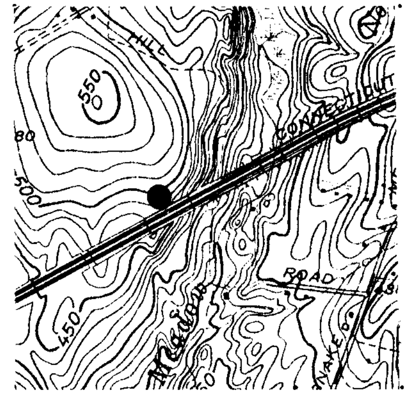
Day VI Stop 9
Concord MA
1:25,000 (1970/79)
71°15'34"/42°26'45"



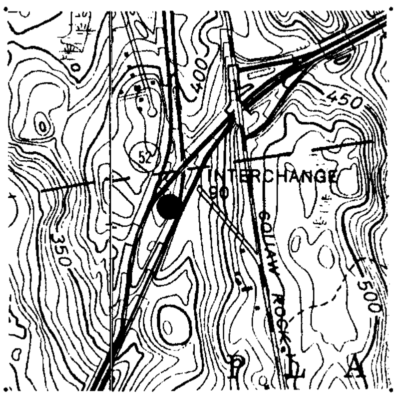
Day VII Stop 1
Georgiaville RI
1:24,000 (1954/75)
71°30'33"/41°54'45"



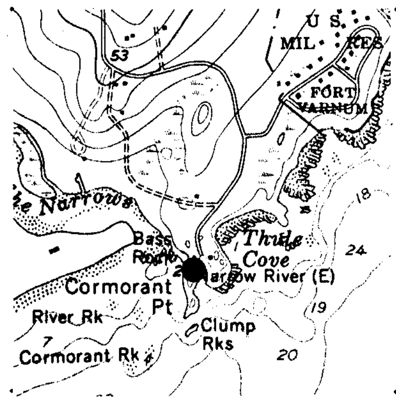
Day VII Stop 2
East Killingly CT-RI
1:24,000 (1955/74)
71°49'07"/41°47'06"



Day VII Stop 3
East Killingly CT-RI
1:24,000 (1955/74)
71°51'07"/41°46'28"

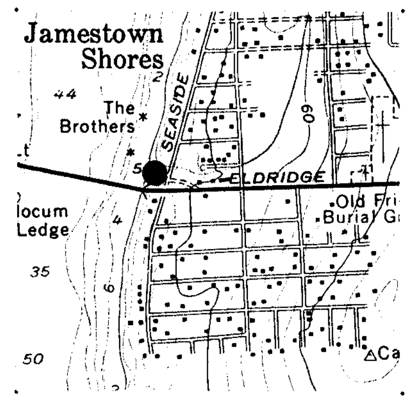


Day VII Stop 4
East Killingly CT-RI
Danielson CT
1:24,000 (1955/74)
71°52'21"/41°45'48"



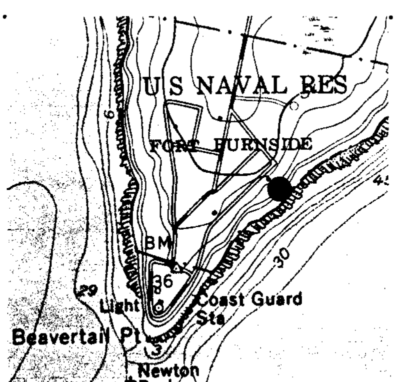
Day VII Stop 5

Narragansett Pier RI
1:24,000 (1957/75)
71°26'21"/41°26'26"

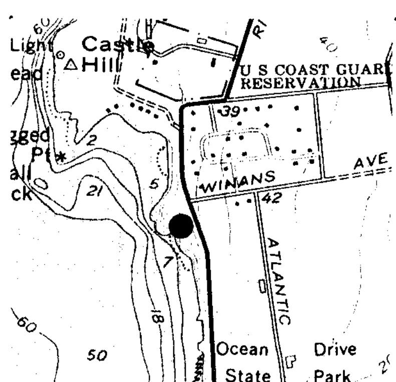


Day VII Stop 6

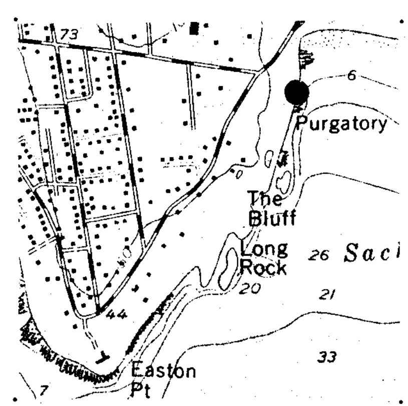
Wickford RI
1:24,000 (1957/75)
71°23'30"/41°31'36"



Day VII Stop 7
Narragansett Pier RI
1:24,000 (1957/75)
71°23'42"/41°27'08"



Day VII Stop 8
Newport RI
1:24,000 (1957/75)
71°21'33"/41°27'25"



Day VII Stop 9
Newport RI
1:24,000 (1957/75)
71°16'06"/41°29'12"

(because fossils found within the allochthon are of North American affinity, the allochthon does not define an exotic terrane). (2) Show that the age of this thrusting is Middle Ordovician (graptolite Zone 13 of Berry, 1963) or younger; if blocks of Taconic rocks within the black shale matrix are correctly identified as olistoliths (Zen, 1967), then the age of thrusting is precisely fixed. (3) demonstrate that the Taconic allochthon was emplaced from a deep-water slope-rise position to the shelf surrounding a craton. This emplacement, however, occurred after the shelf itself had begun to sink and to receive deep-water flysch from an oceanward source.

The rocks exposed in the quarry, between the Cambrian rocks of the Taconic allochthon and the Ordovician shelf carbonate, have been variously called a mylonite, karst, sedimentary melange, fault slivers, or a fault duplex (for discussions and summaries, see Zen, 1967; Rowley and Kidd, 1981; Bosworth and Chisick, 1987). Note that the large limestone blocks are not oriented the same way; the irregular shapes thus do not simply reflect the irregular outlines of an erosion surface. Note the fossils in many blocks. As Rodgers (1969) pointed out, the lithofacies of the carbonate is more eastern (i.e. open ocean) than the shallow shelf facies of the autochthonous coeval carbonate of this area and thus suggests considerable tectonic transport. The detailed relations shown within the quarry probably encompass all the proposed processes: deposition of sedimentary melange, brecciation of carbonate and matrix shale alike (which may be part of a later tectonic event), and tectonic slivering of the shelf carbonate.

For the regional significance of the relations at the Bald Mountain quarry and their bearing on the early development of North American geology, the interested reader should see the summary by Rodgers (1969).

Day I, Stop 2. Olistolith of pillow lava underneath the Taconic allochthon, Starks Knob

Starks Knob, also known as the Northumberland plug, is underlain by an olistolith of basaltic pillow lava (see TABLE 2, chemical analysis of the center of a pillow, Cushing and Ruedemann, 1914) in an area of Middle Ordovician wildflysch-bearing dark shale. Phacoidal black shale is readily seen; the matrix shale contains bits of other exotic material resembling that at Bald Mountain (Day I, Stop 1).

Woodworth (1903) and Cushing (Cushing and Ruedemann, 1914) described the geology. Zen (1974) published brief descriptions of selected samples. The rock was originally an olivine-phyric (and, more rarely, augite-phyric) basalt, having fine microlitic groundmass plagioclase in a hyalopilitic texture. The interpillow palagonite remains unaltered, but the abundant olivine phenocrysts have been extensively replaced, apparently in stages, first by magnesian chlorite, which in turn is replaced by calcite. The rock has not been much deformed (amygdules remain nearly round) or metamorphosed, consistent with its present tectonic location. Note the abundant interpillow carbonate, whereas chert has never been noted. Landing (in press) reported Early to Middle Ordovician macluritid snail and segments of trilobite from some of the interpillow limestone, showing that some of the limestone is marine sedimentary rather than secondary. The sparse fossil data are consistent with a shallow-water environment for the pillow lava.

Cushing (Cushing and Ruedemann, 1914) considered whether the basalt was in place or was exotic, and concluded that "in weighing the evidence for or against the lava being in place, ** we must confess our inability to come to any definite conclusions in the matter. The overthrusting [of the lava into black shale] seems a priori so unlikely that our sympathies are entirely with the other view. But we cannot relieve ourselves of the suspicion that it may, after all, be an overthrust mass, a fragment of a surface flow which came up through and was poured out upon a surface of limestone, thus acquiring its inclusions, and later on thrust westward coming to rest with rocks with which it had originally little to do." Given the modern interpretation of the Taconic allochthon as near-surface thrust sheets, including the development of an apron of submarine melange, Cushing's intuition is well supported. The phacoid structures of the black shale, already noted by Cushing, further support this interpretation.

Starks Knob is named after General John Stark of the Continental Army during the American Revolution, whose gun battery mounted on this knoll during the final phase of the Battle of Saratoga (now Schuylerville) in the late autumn of 1777 contributed to British General John Burgoyne's decision to surrender. The British defeat in turn led to diplomatic recognition of the new American nation by the French Government and so was pivotal to the American cause (see Furneaux (1971) for details of the campaign). Time and weather permitting, walk along the footpath to the top (please do not climb up the quarry face!) to view the surroundings and to observe the carbonate block in the pillow lava showing baked contact. Note also the plaque, here quoted in full:

"On this volcanic knoll October 13 1777 General John Stark mounted his battery and effectively obstructed the effort of Burgoyn[e] t[o] withdraw his defeate[d] army northward through the narrow valley of the Hudson. [O]pposite this knob on the east side of the Hudson were Fellows' batteries while in the woods to the left were Morgan's sharp shooters.

"Starks Knob is a dead volcano and the only one in the State[.] The igneous plug or rock core alone remains projecting above the sedimentary strata[.]

"New York State Conservation Dept."

NO HAMMER AT THIS OUTCROP, PLEASE.

Day I, Stop 3. Middle Proterozoic-Cambrian unconformity, abandoned roadcut near U.S. 4 and Flat Rock Road.

Grey biotite-plagioclase gneiss, part of the 1 Ga Grenvillian basement of the early Paleozoic North American craton. On the east side of the roadcut, this gneiss is overlain by the Upper Cambrian Potsdam Sandstone, less than 1 m of which is preserved here. This cross-stratified arkosic sandstone contains grains of well-sorted and rounded to subrounded quartz and feldspar as much as 2 mm across, indicating a coarsely crystalline source. The contact here shows fresh basement rocks against the overlying sandstone. Elsewhere in eastern New York, this same contact is gradational, the gneiss being increasingly disintegrated and having more of a clayey matrix towards the Potsdam, ending in the sandstone. Both kinds of relations are interpreted as an unconformity and demonstrate that the Potsdam and its overlying stratigraphic sequence are part of the original cover rocks of the North American craton.

The brown bands in the gneiss at the northern end of the cut contain the low-grade assemblage dolomite+quartz and are apparently a Paleozoic, possibly Taconian, feature (Whitney and Davin, 1987; see also Whitney, 1985).

NO HAMMER AT THIS OUTCROP, PLEASE.

Day I, Stop 4. Middle Proterozoic (Grenvillian) gneiss and marble, roadcut along U.S. 4 south of Whitehall.

Another look at Grenvillian basement rocks. From north to south the outcrops show (Whitney, 1985): (1) paragneiss and interlayered marble containing exotic amphibolite blocks; (2) garnet-bearing quartzofeldspathic gneiss; (3) charnockitic gneiss; (4) thin marble containing exotic blocks; (5) monzodioritic gneiss; (6) pink calc-silicate rock; and (7) interlayered sillimanite-garnet gneiss, charnockite, marble, and calc-silicate containing boudins of amphibolite. The mineral assemblage of the 3-m-thick calc-silicate gneiss in unit (1) is diopside (as much as 10 cm across), plagioclase, K-feldspar, scapolite, phlogopite, and quartz; near its contact with the granulite, the marble is darker, and the clinopyroxene has been altered to serpentine (Whitney and Davin, 1987, loc. C). Mineral associations for unit (6) include (Whitney, 1985) wollastonite-grossular-diopside-calcite-K-feldspar-quartz-sphene. The blocks of amphibolite in units (1) and (4) show diverse orientations of the foliation; they are distinct from the lamprophyre dikes that cut the outcrop at both the south and north ends. The dikes are undeformed and unmetamorphosed but are of uncertain age.

Lunch, village of Whitehall on the Champlain Canal. Champlain Canal connects the Hudson River with Lake Champlain and from thence with the St. Lawrence River. Built in 1823, it was a barge canal of some commercial interest in the 19th century. Whitehall claims to be the birthplace of the U.S. Navy. In the summer of 1775, early during the American Revolution, a schooner belonging to a Tory (British loyalist), Mr. Skene (Whitehall was then known as Skenesborough), was captured by the Americans and renamed the Liberty; it became their first naval vessel on Lake Champlain. Under the command of Benedict Arnold, the nascent Navy gave the Americans control of the lake for a while, paving the way for them to capture Montreal and to lay siege to Quebec City that winter. The revolutionaries also built additional small vessels, known as gundalows and galleys, here in Skenesborough to augment their naval strength (see Fowler, 1976).

Day I, Stop 5. Cambrian and Lower Ordovician shelf sediments, quarry east of Skene Mountain, Whitehall village.

Two types of rocks are exposed: dolomitic quartzite below and massive grey dolostone above. These rocks were described (Rodgers, in Billings and others, 1952, p. 35) as "dark gray crystalline and sandy dolomite; cryptozoön layers above and thin sandstone at the top" and as "light generally cherty dolomite, upper part commonly replaced laterally by limestone **; cryptozoön layers" respectively (see also Rodgers (1969, p. 6-10), where both units were assigned to the Whitehall Formation). The rocks are latest Cambrian to earliest Ordovician and are in stratigraphic sequence above the Potsdam, i.e. they are part of the shelf-facies cover sequence of the North American craton. Dolostone rather than limestone is the dominant carbonate of the inner shelf, possibly laid down in a quasi-evaporative environment.

*** Day I, Stop 6. Cambrian shelf sediments, roadcut on Vermont Route 3 south of Proctor.**

Since the last stop, we have crossed the entire width of the Taconic allochthon, which will be studied on Day II. We now look at the more easterly, and thus originally more oceanward, facies of the carbonate shelf. This stop is in the Middle Cambrian Winooski Dolomite, characteristically a yellow-ochre weathering silty dolostone showing green micaceous (originally clayey?) partings at about 0.5-1 m intervals. Some of these partings are arkosic. The rocks are now metamorphosed in the biotite zone, or low greenschist facies.

* 1.9 km (1.2 miles) south, massive Upper Cambrian dolostone; approximately coeval with the dolomitic quartzite of Day I, Stop 5.

Day I, Stop 7. Cambrian and Lower Ordovician shelf sediments and Middle Ordovician dark shale, roadcut on Vermont Route 3

Grey dolostone and white marble are exposed in the small abandoned quarry. These rocks are Lower Ordovician, part of the Shelburne Formation. Stops 6 and 7 together span the age of Stop 5 and illustrate the facies change across the carbonate shelf of the North American craton. The marble is part of the strata that supports the marble industry of Vermont. All commercial-quality marbles are from the Ordovician part of the stratigraphy and only on the eastern side of the carbonate shelf, for reasons of facies transgression already mentioned.

* 2.1 km (1.3 miles) south, roadcut in dark grey phyllite, the equivalent of the Middle Ordovician black shale seen at Stops 1 and 2, here possibly slightly older (Graptolite Zone 12/13 of Berry, 1963). This unit, called the Ira Formation, is part of the flysch deposit that unconformably overlies the carbonate, reflecting the change of sedimentary source (from westerly cratonal carbonate and clastics to easterly basinward clastics) caused by the early phase of the Taconian orogeny and the resulting bathymetric reversal (Zen, 1967, 1968).

*** Day I, Stop 8. Massive vitreous Lower Cambrian Cheshire Quartzite, roadcut on Vermont Route 3**

The Cheshire is here juxtaposed against the Ira Formation across a fault. The Cheshire is the basal Paleozoic sandstone of the North American craton, in facies equivalent of the Potsdam Sandstone, but it is Lower Cambrian. The relations allow the simple interpretation that the shelf sequence transgressed onto the craton from a generally easterly direction; therefore, at any time during deposition, the more easterly sediments were of more distal facies, and the base of the sequence was also progressively older eastward. The Cheshire is extremely resistant and forms cliffs; carried by the Wisconsinan ice sheet over great distances, its boulders are typically round and are known to local farmers as "gumrock." Try to bounce your hammer off the rock, and note its elastic properties!

Day I, Stop 9. Middle Proterozoic-early Paleozoic unconformity at the western side of the Green Mountain massif, Appalachian

Trail (or Long Trail) off Vermont Route 103, town of Clarendon.

The Middle Proterozoic crystalline rocks of the Green Mountain massif are known as the Mount Holly Complex; like the Grenvillian basement rocks seen at Day I, Stops 3 and 4, they were metamorphosed in the granulite facies and give a ~1.1 Ga isotopic age. The Mount Holly has been retrograded by Paleozoic metamorphism, mainly hydration and carbonation, but the former mineral assemblages or ages have not been completely obliterated. The rock immediately above the unconformity is the Dalton Formation, a discontinuous but locally thick unit below the Cheshire Quartzite, of latest Proterozoic to earliest Cambrian age.

This outcrop has been described by Thompson (Theokritoff and Thompson, 1969, Stop 1), and the following is in part paraphrased from that reference. Follow the Appalachian Trail markers (white rectangular blazes) north to the powerline, then follow the powerline westward (left). The first outcrops are gneisses containing ptygmatically folded, boudinaged, and sheared pegmatite. Mica is rare. Notice the pale green saussuritized plagioclase and the blue iridescent quartz. The blue colour of quartz in this unit is produced by inclusions of rutile a few hundred angstroms across, in size just right for diffraction. Presumably the TiO_2 was dissolved in quartz during high grade metamorphism, and partially exsolved by a lower-grade event. Migmatite and amphibolite are minor rock types found along the traverse. The presence of pegmatite has been used to distinguish the Proterozoic rocks from the Paleozoic rocks because the latter have not been metamorphosed above the biotite grade (Karabinos, 1987).

The Paleozoic Dalton Formation can be seen at the highest crest of the powerline just before the ground falls off to the west. A 2-m-wide zone of laminated, probably sheared rock intervenes. Is this zone a part of the overlying sequence, a cataclastic zone (note the remnants of deformed pegmatite), a recrystallized regolith, or some combination of these alternatives? The Dalton is a coarse sandstone to fine conglomerate. The conglomerate beds contain abundant detrital grains of blue quartz and feldspar, and rare grains of gneiss; these features are best seen on a large southwest-facing ledge. The abundant magnetite and white mica suggest a paleosol.

NO HAMMER, PLEASE!

The Appalachian Trail follows the backbone of the Appalachian Mountains from Springer Mountain in northern Georgia to Mount Katahdin in central Maine, for a total distance of about 3400 km. It is maintained by volunteer workers and is a popular hiking trail. Many people have walked its entire length. In Vermont, a separate trail system, known as the Long Trail, traverses the length of the State and follows the backbone of the Green Mountains; the two trail systems locally coincide, as they do here.

DAY II: RUTLAND VT
Zen, Kidd, and Thompson, <u>leaders</u>

Stop descriptions prepared by E-an Zen

NORTH AMERICAN CRATON, <u>INCLUDING</u>
THE TACONIC ALLOCHTHON

*** Day II, Stop 1. Base of the Taconic allochthon, William Miller Chapel.**

Exposure of the basal thrust of the Taconic allochthon, here the lowest, Giddings Brook slice (Zen, 1967). Behind the chapel, a brown-grey silty greywacke, part of the Lower Cambrian rocks of the Taconic allochthon (Bomoseen Graywacke, Zen, 1961), is exposed. Though a steeply east-dipping fracture cleavage is prominent, the beds are nearly flat lying. About 20 m southeast in the open is a large exposure of karstic blue-grey micritic limestone that contains boudinaged beds of a buff fine dolostone showing characteristic fracture patterns ("thread-scored beeswax" of mid-19th century local geologic reports). No fossil has been recovered here, but the carbonate is identical to upper Lower Ordovician carbonate of the shelf sequence of this area. The contact between this rock and the Bomoseen, then, marks the basal Taconic thrust of Middle Ordovician age (though it is not known for certain whether the carbonate is in place or represents a tectonic sliver comparable to the relations exposed at Bald Mountain). The actual contact is exposed about 30 m to the east in the woods, below a barn.

NO HAMMER, PLEASE

William Miller Chapel is the first Seventh Day Adventist place of worship in the United States.

Day II, Stop 2. Lower Ordovician stratigraphy of the Taconic allochthon. Poultney River.

From the secondary road beyond the farmhouse, cross the barbed wire fence carefully, and walk through the swampy tract to the northeastern corner of the field. Beware of the electric fence! Touch it only with the wooden handle of your hammer to avoid a shocking experience. Trip leaders will assist you in crossing. Go down a steep incline to the Poultney River.

Thin-bedded fine siltstone and mudstone showing centimeter-scale lamination, intercalated with well-sorted calcareous sandstone showing cross bedding, channel cutting into underlying shales, as well as massive calcareous sandstone containing angular carbonate chips in "edgewise conglomerate." This sequence is part of the Poultney Slate (Zen, 1967). Different parts of this unit, at different places, have yielded (Berry, 1963, 1968) Ordovician graptolites ranging from Zone 1 (Dictyonema flabelliforme and Staurograptus dichotomous) through Zone 11 (Nemagraptus gracilis), thus the unit spans the entire Lower and part of the Middle Ordovician, and its age overlaps the carbonate rocks of Skene Mountain (Day I, Stop 5), near West Rutland (Day I, Stop 7), and at the last stop, but how vastly different their sedimentary facies! Benthonic fossils, mainly from the Lower Cambrian part of the Taconic allochthon (chiefly trilobites of the Elliptocephala asaphoides fauna), however, show that rocks of the allochthon are of North American affinity and do not constitute an exotic terrane.

Walk south (upstream) along the river bank for about 500 m to a large outcrop of hard black shale that contains layers of phosphate nodules and thin silty carbonate layers, many containing fine cross beds. The tops evidence seen here had helped to work out the physical stratigraphic succession, confirmed by Berry's graptolite studies mentioned above, and provided one of the keys to solving the internal structural geometry of the Taconic allochthon (Zen, 1961).

NO HAMMER, PLEASE

Note the splendid exposure of lodgment till (late Wisconsinan) on the eastern (Vermont) bank of the river at the last stop.

Day II, Stop 3. Imbricated Middle Ordovician carbonates, shales, and melange just below the Taconic allochthon.

This outcrop has been discussed by Bosworth and Kidd (1985), from which FIGURE 12 is taken (see also Baldwin and Raiford, 1987):

"The part of this roadcut to be examined ** consists of the outcrop opposite the parking area and its continuation to the north. A thrust-repeated section of medial Ordovician strata is discernable [sic] from medium-bedded limestone (fossiliferous calcarenites to calcisiltites) without shale - Orwell Limestone, passing up abruptly into thin-bedded limestones (micrites) interbedded with dark shale - Glens Falls Limestone, overlain by dark shale, in part melange - here referred to as Hortonville shale ** It is important to recognize that the dark shale ** is a stratigraphic member of this succession **. That some of it has been structurally damaged by the imbrication and duplication of the sequence is a secondary effect, reflected in the lenticular (phacoidal) cleavage visible especially in the shale closest to the base of the succeeding limestone. Two of the eight sections lack the basal Orwell Limestone, probably because of local ramping of the active thrust, or original irregularities in the depositional arrangement. It is not valid, in our view, to regard this exposure as 'all melange' with blocks of limestone floating in shale. Rather, it is a thrust-imbricated repeated lithic sequence, probably forming a thrust 'duplex' above more extensive shaly melange, not containing limestone clasts, that is exposed on the slope to the west **. The duplex is below the Frontal Thrust of the Taconic Allochthon which comes to the surface about 50 m east of this road cut; wackes of the Bomoseen formation of the Allochthon form the prominent topographic feature of 'the Great Ledge' visible to the east **. Noteworthy in the narrow (less than 1 m) zones of shaly melange beneath each slice of limestone in the cut are a few blocks and cobbles of green micaceous arenite identical to the Bomoseen Formation of the Allochthon. The largest of these (approx. 1 m across) occurs at the very

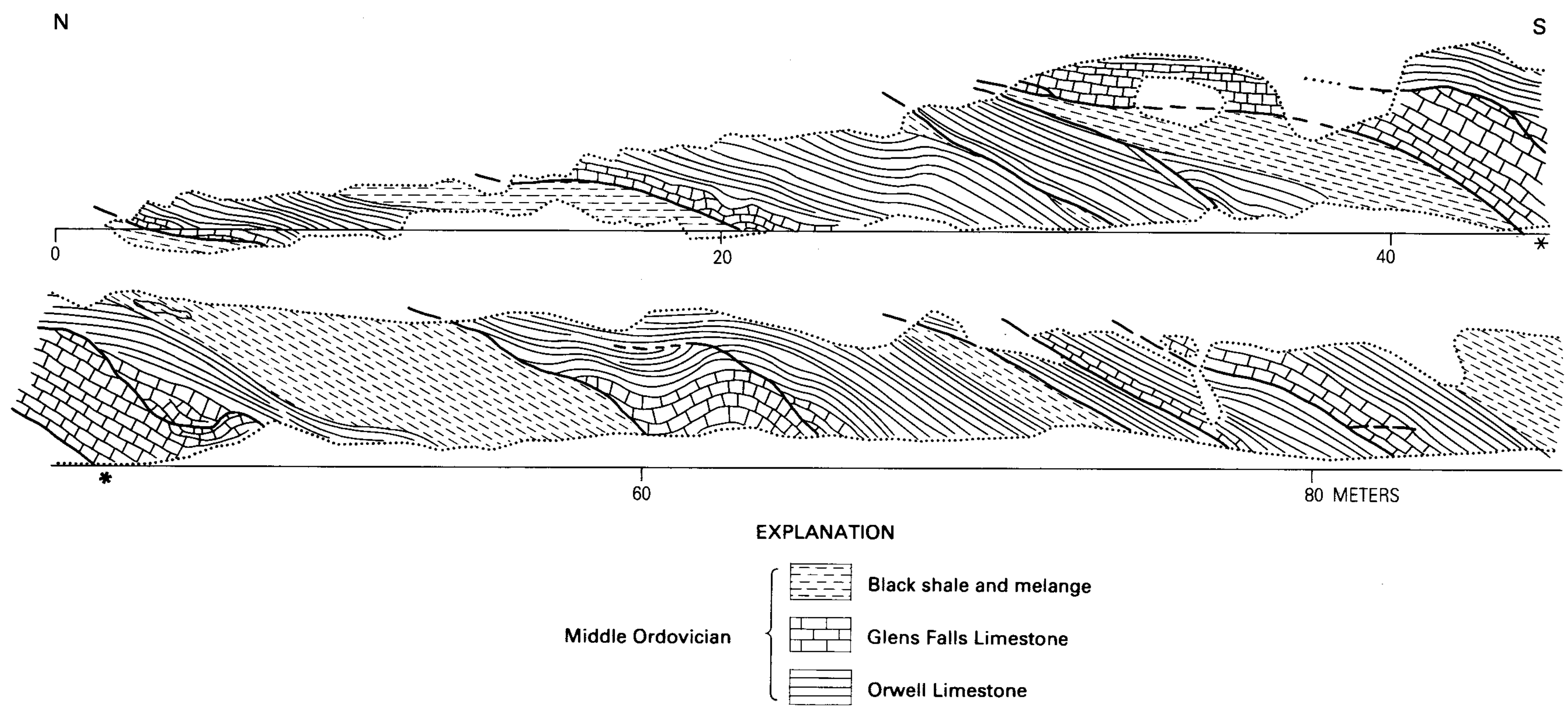


FIGURE 12 Details of roadcut on Day II, Stop 3, from Bosworth and Kidd (1985). View is to the east. The two profiles overlap at the point indicated by an asterisk. Major thrust faults are shown in thick lines. The dips shown are the apparent dips in the plane of the section. Distance in meters. No vertical exaggeration.

northern end of the outcrop, but other smaller ones occur within the outcrop **. These we do interpret as olistolithic clasts shed from the front of the Taconic thrust sheet during its motion, and they require that the active thrust outcropped on the sea-floor, at a deep-sea trench-type feature. A similar, but larger (several m across) olistolith of Bomoseen wacke occurs in the outcrop of melange to the north. It is our observation, however, that there is a limit of a few meters to the size of these blocks that are clearly identifiable as olistoliths. Truncated bedding, slickensides and other features characteristic of ramp-flat thrust geometry can be seen in this outcrop. The present attitude inferred for the Taconic Frontal Thrust (about 10^o east dip) and the steep east dip of these limestone-shale imbricate slices are consistent with their identification as duplex structures. Their attitude is not consistent with a model of tabular olistolithic slabs lying in the bedding orientation."

*** Day II, Stop 4. Carbonate conglomerate in Lower Cambrian Mettawee Slate NE of Fair Haven.**

The abandoned quarry is in a carbonate conglomerate; however, some of the micritic limestone may consist of boudinaged thin beds. The matrix material is pelitic (now slate), readily seen on the western rim of the quarry. Time permitting, ascend the quarry rim, go northwest across a small valley, and walk up the next slope in the open to see dark grey limestone beds which are part of the stratigraphically overlying West Castleton Formation (Lower Cambrian). Evidently, the sedimentary basin of the Taconic sequence in early Cambrian time was accessible to sources of carbonate, presumably from the direction of the carbonate shelf; we thus infer that the site of deposition of the sequence is immediately seaward of the shelf. See Rodgers (1968) and Zen (1972b) for further discussions.

*** Day II, Stop 5. Fold of Upper Cambrian strata, settlement of West Castleton on Glen Lake.**

A low roadcut immediately west of this site contains dark grey limestone within soft black shale that has produced Lower Cambrian fossils; this place is the type locality of the Lower Cambrian West Castleton Formation (Zen, 1961). The rock in the fold could be the uppermost Cambrian Hatch Hill Formation, which underlies the Poultney Slate, but Bosworth and Kidd (1985) considered this outcrop to be of the Poultney Slate.

NO HAMMER, PLEASE

Day II, Stop 6. Lower Cambrian purple and green Mettawee Slate. West shore of Lake Bomoseen.

Rocks are exposed both along the road (beware of traffic!) and in the abandoned quarry just west of the road. This slate was exploited commercially by the roofing industry; only token activity remains by comparison with a century ago. Note the presence of thin green chloritic quartzite layers; note that the colour of the slate around the calcareous layers is green, never purple (purple is the result of combining the green of chlorite and the red of hematite). Note "reduction spots" along the slaty cleavage; not all are elliptical, and few, if any, can be proven to have been spherical initially, an assumption vital to their use for the measurement of strain.

*** Day II, Stop 7. Normal-faulted Cretaceous lamprophyre dike in roadcut on U.S. Route 4 near West Rutland.**

The host rock is a chlorite-muscovite-albite-quartz phyllite of the Taconic allochthon that contains two foliations; the second is visible in outcrop, but the first is seen in thin section only as folia folded by the second as its "axial" surface (Zen, 1972a). The dike is unmetamorphosed; its hornblende yielded a conventional K-Ar age of 107$\pm$4 Ma (corrected for decay constants), or Albian Age. The dike has been broken by an east-side down normal fault (strike 350^o, dip 30^o NE); rocks in the movement zone have been granulated. A similar dike about 150 m farther east has yielded (McEnroe and others, 1987) a reversed and steeply inclined paleomagnetic pole orientation (D=180, I=-55).

Day II, Stop 8. Sedimentary(?) breccia in the Lower Cambrian dolostone of the shelf sequence, Grove Street, City of Rutland.

This sedimentary breccia is in a massive grey dolostone, the Dunham Dolomite, which is stratigraphically between the Cheshire Quartzite (Day I, Stop 8) and the Winooski Dolomite (Day I, Stop 6). This outcrop was discussed by Thompson (1972; Stop 1); bear it in mind on Day III, Stop 2. Cambrian hyolithids have been found in this unit about 200 meters east of this outcrop (Theokritoff and Thompson, 1969, p. 15).

Day II, Stop 9. Proterozoic-Paleozoic unconformity on the eastern side of the Green Mountain massif, roadcut on U.S. 4 south of Sherburne village.

This outcrop was described by Thompson (19/2, Stop 5). The relations are best seen by standing on top of the outcrop and looking down. Deformed but recognizable composition banding in the gneiss of the Mount Holly Complex (see Day I, Stop 9) is abruptly truncated by coarse and cross-bedded feldspathic sandstone of the basal Paleozoic Tyson Formation. Grain-size grading was visible when the outcrop was new. The contact is sedimentary, and so at least the lower strata of the Paleozoic rocks must be part of the cover rocks of the North American craton.

NO HAMMER, PLEASE

DAY III: RUTLAND VT TO KEENE NH
Thompson, <u>leader</u>

Stop descriptions prepared by E-an Zen, with contributions by J.B. Thompson, Jr.

NORTH AMERICAN CRATON AND BROMPTON-CAMERON TERRANE

Day III, Stop 1. "Terra rossa" in basal Paleozoic rocks on side road to U.S. 4, near West Bridgewater.

This outcrop is an improved version of another one just north of here, described by Thompson (1972, Stop 7). A tripartite stratigraphy is observed here: a basal dolostone, an intermediate iron-rich dolostone breccia having many magnetite grains decorating the blocks, and an upper albitic schist. The unit is the Tyson Formation; at Day II, Stop 9, we saw the base of this unit. The iron-rich breccia is interpreted to be a regolith. The tripartite stratigraphy is useful to trace out intricate structures as well as to demonstrate the original sedimentary continuity with rocks farther east (Day III, Stop 9).

Day III, Stop 2. Dolomite breccia, Plymouth.

This breccia is in the Plymouth Member of the Hoosac Formation, the next unit above the unconformity seen on Day II, Stop 9. "[The] rock closely resembles the dolomite breccia ** at [Day II, Stop 8]. Outcrops in woods west of pasture are of underlying quartzites resembling the Cheshire Quartzite at [Day I, Stop 8]" (Thompson, 1972, Stop 14). If the identification is correct, then the basal part of the Paleozoic sequence on the east flank of the Green Mountain massif is not only North American, as shown on Day II, Stop 9, but retains the feather edge of the shelf sequence! Because rocks of the Taconic allochthon were laid down more seaward than the shelf sequence, but presumably more cratonward than the units that directly overlie this breccia (and that we will see today), a geometric-tectonic problem could exist that will be analyzed in the next few stops. This problem was also discussed by Stanley and Ratcliffe (1985) and Karabinos (1987).

Day III, Stop 3. Pinney Hollow Formation in Pinney Hollow, the next unit above the Hoosac.

Virtually identical to a stop described by Thompson (1972, Stop 8), from which the following has been paraphrased. Green chloritoid-bearing phyllite, some faintly purple owing to hematite. Assemblage is quartz-muscovite-paragonite-chlorite-chloritoid ±hematite. Notice the abundant vein quartz, the interfolia folds, and the lack of clear evidence for bedding. This aluminous schist was interpreted by Thompson as part of an uninterrupted but strongly sheared stratigraphic sequence continuous with the Tyson Formation, but by Stanley and Ratcliffe (1985) as a tectonic unit at the boundary between the NAC and the BCT. Thompson considered boundary to be higher up, possibly seen on Day III, Stop 5. If this schist is a coherent sedimentary unit, it would be a more oceanward facies equivalent to the Mettawee Slate (Day II, Stop 6).

Day III, Stop 4. Roadcut of carbonaceous quartzite and carbonaceous and sulfide-rich schist of the next-higher Ottauquechee Formation. Pinney Hollow.

Carbonaceous quartzite as much as 3 m thick is intercalated with schist. Are these sedimentary layers or olistoliths? Again, this unit may be part of a coherent stratigraphic sequence that has undergone strong ductile deformation, or it may be part of an expanded "suture" zone (see Thompson, 1972, Stop 9).

*** Day III, Stop 5. Quartz-biotite-chlorite-garnet-muscovite schist of the upper part of the Ottauquechee Formation, Pinney Hollow.**

This "variegated" schist contains dark and light layers; the mineral assemblage is quartz-biotite-muscovite-chlorite-garnet; both types of layers are garnet rich but the dark layers are also sulfide rich and are more micaceous. This rock type is also found in the Rowe Schist, which is the on-strike continuation of the Pinney Hollow and Ottauquechee formations about 80 km to the south in Massachusetts, and which has been interpreted to be a tectonic unit (Stanley and Ratcliffe, 1985), representing the junction of the BCT and the NAC (see Thompson, 1972, Stop 10).

We will drive around the village green of Woodstock. These public parks are characteristic of New England villages. Originally part of the common grazing ground for cows, today they are recreation sites and, during summer evenings, frequently host community-based band concerts. Woodstock was a favourite summer resort during the early 19th century; the houses around its village green display the period architecture and the village boasts of four Paul Revere church bells. The village is preserved through the efforts of the Rockefeller family. A reconstructed (1974) covered bridge was built on a 1820 pattern; notice the exclusive use of wooden pegs.

Day III, Stop 6. Waits River Formation, roadcut on Vermout Route 106.

This unit has long been considered to be late Silurian to early Devonian in age. However, it may include Upper Ordovician rocks because of recently discovered graptolites farther to the north (Bothner and Finney, 1986). In any event, the Waits River is part of the post-Taconian overlap assemblage. Rocks here are interbedded mica schist and massive to thin-bedded silty limestone; notice the zoisite in the calcareous layers.

Day III, Stop 7. Ultramafic body, village of Hammondsville.

The open-pit area is mostly in massive talc and in talc-magnesite rocks. Veins of magnesite are abundant. On the west rim of the open pit, near the adit, there are exposures of a poorly developed black wall (massive biotite) associated with talc and with some chlorite- and actinolite-rich bodies. The rusty rocks above the adit are massive talc also. This body has been followed underground for considerable distance. Its country rock is the Ottauquechee Formation; the body could be an exotic ocean-floor rock related to a Taconian obduction event.

Day III, Stop 8. Core gneiss of Chester Dome, roadcut on Vermont Route 106.

Interlayered dark and light gneiss containing a conspicuous mineral foliation. The mineral assemblage in both kinds of layers is microcline-plagioclase-biotite-muscovite-epidote-quartz; biotite is rare in the light layers. Apatite and sphene are important accessories. Some amphibolite layers are present. Several sets of non-coaxial folds are visible near the north end of the cut. Rock has an old zircon lead-alpha age of 900 Ma (Faul and others, 1963); last known gasp of the North American Craton.

*** Day III, Stop 9. A tripartite sequence of albite schist, magnetite-bearing ferruginous dolostone, and massive dolostone in the Chester Dome, Cavendish Gorge.**

The rocks exposed at the parking area are the layered core gneiss seen at the last stop. In the gorge, a ductilely deformed and inverted sequence of dolostone and albite schist can be seen, just like the sequence on the east flank of the Green Mountains (Day II, Stop 9 and Day III, Stop 1), confirming that, however gingerly, we are still in the NAC. The Taconic sequence must have been deposited farther outboard than this site.

DAY IV: KEENE NH (HALF DAY ONLY)

Thompson and Zen, leaders

Stop descriptions prepared by E-an Zen, with contributions by J.B. Thompson, Jr.

CENTRAL MAINE TERRANE

Day IV, Stop 1. Fossiliferous Silurian Clough Quartzite (overlap assemblage), Skitchewaug Nappe, U.S. Route 5 roadcut along the western bank of the Connecticut River, which here separates the States of Vermont and New Hampshire.

Rusty-weathering calcareous bands in the Clough quartzite contain highly deformed fossils and fossil fragments. Recognizable remains are chiefly crinoid stems and corals, but brachiopods, a cephalopod, and a possible trilobite were found (Thompson, 1954; Boucot and Thompson, 1963). A metamorphosed mafic dike (now amphibolite) cutting the quartzite is exposed just to the south. The rocks are in the staurolite zone of Acadian metamorphism.

NO HAMMER, PLEASE.

Day IV, Stop 2. Devonian pelite (overlap assemblage) in the Skitchewaug Nappe, Saxtons River.

Devonian pelite, the Littleton Formation, the highest unit of a tripartite stratigraphy of Clough-Fitch-Littleton spanning Silurian and Devonian ages, forming the overlap sequence on rocks on the opposite side of the Iapetus Ocean (thence non-North American), here called the Central Maine terrane. The rocks are staurolite schist showing graded bedding. Rock belongs to the Skitchewaug Nappe, one of the major nappes developed during the Devonian Acadian orogeny and regional metamorphism; the rocks were laid down many kilometers to the east but have been carried westward by nappe transport. Structurally higher Silurian Fitch Formation is exposed a few hundred meters downstream to the east (See Thompson and Rosenfeld, in Robinson and others, 1979, Stop 1).

NO HAMMER, PLEASE.

Day IV, Stop 3. Autochthonous cover rocks, northwestern side of Keene Dome, gorge of Mill Brook.

The Ordovician Partridge Formation, a sulfide-rich carbonaceous black kyanite-staurolite schist, is exposed just below the culvert where Route 12 crosses Mill Brook. Descend carefully into the gorge and observe, on the south bank, the unconformable contact of the Partridge with the Silurian Clough Quartzite, which is part of the overlap-cum-cover sequence and which here contains baseball-sized pebbles, mostly of quartzite, now deformed into discoids. The next higher unit of the overlap sequence is the Devonian Littleton Formation (staurolite-biotite-garnet); it is exposed in the roadcut to the west. All the units dip gently west off the Keene Dome. Those who choose not to descend into the gorge can study the deformed conglomerate in a roadcut, but no contact relation is exposed along the road. The overlap sequence was originally laid down in a basin more westerly than the units seen on Day IV, Stops 1 and 2. Compare this outcrop with the next one.

Day IV, Stop 4. Autochthonous cover sequence, east flank of the Keene Dome. Roadcut on New Hampshire Route 12.

Keene Dome is one of a linear chain of gneiss domes within the "Bronson Hill zone" on the western side of the Central Maine terrane. The Bronson Hill zone, now a structural anticline, has been interpreted to be the locus of a paleo-island arc (Kay, 1951; Rodgers, 1970, p. 106), and the gneiss domes may correspond to the roots of volcanoes on the hanging-wall side of the Taconian subduction zone. As discussed in the Introduction, however, the stratigraphic contrast of the cover rocks on the east and west sides of the Keene Dome suggests major original sedimentary differences, so that this outcrop may represent the eastern overlap sequence. The original contrasts are accentuated by large-scale tectonic transport and ductile deformation (according to J.B. Thompson, 1988, oral communication, the east flank of Keene Dome could possibly include the root zones of one or more Acadian nappes, with the tectonic movement concentrated within the weak Partridge Formation). At this outcrop, the gneiss and its cover rocks have been metamorphosed to the sillimanite zone (for stratigraphic and structural relations, see Robinson and others (1979), Thompson and others (1968)).

"The lowest exposed part of the dome gneiss is fairly coarse-grained and compositionally massive. The uppermost 200 feet [60 m] is finer-grained and more layered. The exact contact with the Ammonoosuc Volcanics [island-arc tholeiite overlying the dome gneiss, of similar age (Naylor, 1969), and part of the same island-arc magmatic cycle] is open to debate and depends on the criteria chosen. Aside from the possibilities for later faulting, this contact and others like it have been interpreted as intrusive **, as a change of volcanic chemistry **, and as a possible unconformity **. The mafic lower unit of the Ammonoosuc Volcanics is about 60 feet [20 m] thick, and is well layered and highly varied in composition. A few layers contain pale brown or pale green anthophyllite, gedrite or cummingtonite (or chlorite secondary after these minerals) that are characteristic of the unit. The felsic upper unit of the Ammonoosuc is a brown-to-red-weathering slabby felsic gneiss. Here it is about 20 feet [6 m] thick but about 75% of the exposure is pegmatite. The overlying Partridge Formation of sillimanite-rich pyrrhotite-mica schist is about 60 feet [20 m] thick, and it is overlain by Clough Quartzite and muscovite-garnet schist, also filled with pegmatite. Although the contact of the overlying Littleton Formation is not perfectly exposed, the Clough appears to be about 80 feet [25 m] thick. The thinness of the total section at this exposure is probably the product of tectonic thinning" (Robinson and others, 1979, p. 124).

*** Day IV, Stop 5. Kinsman Quartz Monzonite of the Cardigan pluton (Lyons and Clark, 1971, Stop 4). New Hampshire Route 103 near Bradford.**

The Kinsman is a garnet-cordierite-sillimanite granodiorite containing large K-feldspar megacrysts. 413$\pm$5 Ma Sm/Nd whole rock and garnet isochron (Barreiro and Aleinikoff, 1985) and 411$\pm$19 Ma Rb/Sr isochron (initial Sr ratio 0.7107, according to J.B. Lyons, 1979). The garnet-biotite-K feldspar megacryst association is well displayed, but cordierite is not apparent and sillimanite is mainly fibrolite. Note the igneous foliation defined in part by the alignment of the K-feldspar, the xenoliths showing selvages of biotite, and the intrusion of the later, more hydrous 2-mica granite and associated pegmatite and aplite dikes. The apparently late muscovite and some of the hydration of the mafic minerals in the Kinsman might be related to this later event.

Variously interpreted as forcefully injected concordant sheets or as the product of K-metasomatism, the Kinsman could be simply the result of partial fusion of preexisting peraluminous volcanic rock, perhaps ignimbrite, within the stratigraphic section (Thompson and others, 1968). Indeed, almandine-garnet bearing peraluminous ignimbrites of this kind occur within the Devonian section along the trend of the structure in Maine. Thermal modelling (Zen, 1988b) indicates that this hypothesis is energetically feasible. If true, however, the tectonic event that caused crustal thickening and triggered the thermal processes was probably 30 to 50 m.y. older than the age of the pluton (i.e. Devonian (Acadian) pluton resulting from Ordovician (Taconian) tectonism). If the hypothesis of <u>in situ</u> remelting is correct, then the significance of the isotopic ages is ambiguous, as they could record the original extraction of the melt from the source area rather than the anatectic event. Gravity data (Lyons and Clark, 1971) indicate that the maximum thickness of the Cardigan pluton is less than 2.5 km; at this locality, it is less than 0.2 km.

*** Day IV, Stop 6. Cardigan pluton, roadcut on New Hampshire Route 103 at ramp to I-89 near Warner (Lyons and Clark, 1971, Stop 3).**

Garnet-rich and biotite-rich phases are shown. Cordierite and sillimanite (fibrolite) are present, and the K-feldspar megacrysts display myrmekitic rims. In this outcrop, the Kinsman is intruded by aplites and pegmatites of 2-mica granite, and some of the garnet has been retrograded to chlorite.

DAY V: KEENE NH TO WORCESTER MA
Robinson and Zen, <u>leaders</u>

Stop descriptions prepared by E-an Zen, with contributions by Peter Robinson.

CENTRAL MAINE TERRANE AND NASHOBA-CASCO-MIRAMICHI TERRANE

Day V, Stop 1. View of Mesozoic border fault, Massachusetts Route 2, French King Bridge over the Connecticut River.

View of Late Triassic-Early Jurassic border fault, an extensional feature that may have presaged the opening of the North Atlantic Ocean.

*** Day V, Stop 2. Poplar Mountain gneiss of the Pelham Dome (FIGURE 7). Roadcut on Massachusetts Route 2.**

This unit so far has not been dated isotopically. However, another member of the gneiss dome complex, the Dry Hill Gneiss, has a zircon Pb-Pb age of 560$\pm$30 Ma (Robinson and others, 1979). This outcrop is within the deepest structural level of the Pelham Dome. The rock could be a true basement to the Central Maine terrane.

Day V, Stop 3. Poplar Mountain gneiss at Rattlesnake Mountain, Farley. <u>This stop involves a short but stiff climb up to the base of cliffs about 100 m above road level</u>.

The rock was described by Ashenden (1973). The gneiss contains 10-cm sized K-feldspar megacrysts and is interlayered with meter-thick quartzite. The quartzite is grey to brown, thin to massive quartz-biotite-feldspar granulite containing either muscovite or actinolite concentrated in layers. Hastingsite-bearing felsites in 5-cm layers are readily visible. The sequence clearly consists of metamorphosed sedimentary (and possibly volcanogenic) rocks. Bear in mind the nature of the rock and compare it with outcrops to be seen on Day VII, Stop 3.

Day V, Stop 4. Ordovician Monson Gneiss (root of a volcano?), south end of Tully Dome (FIGURE 13). Roadcut on Massachusetts Route 2.

The Tully dome is one of the extremely convoluted domes of the Bronson Hill zone (see FIGURE 7). This roadcut shows the core gneiss, called the Monson Gneiss (440$\pm$10 Ma, Zartman and Marvin, in press), in a simple anticline overturned to the east, and contains late dome-stage asymmetrical folds on both limbs. The gneiss is cut on the west side by a normal fault, possibly of Mesozoic age, downdropping grey schists of the Littleton Formation. This outcrop of the Littleton is of the eastern facies seen on Day IV, Stop 2. This eastern facies can be traced into the State of Maine, there demonstrably having a westerly source area (the Rangeley through Warner Formations of Thompson (1985), and of FIGURE 4; equivalent to the Rangeley through Madrid Formations of northwestern Maine, Moench (1970)). The source area for these rocks has disappeared through later west-directed tectonic movement.

The eastern limb of the fold exposed in the cut includes a thin layer of rusty schist of the Partridge Formation and amphibolite of the associated Ammonoosuc Volcanics. Next to the east are gneisses that encircle the Tully Dome, interpreted to be in an early recumbent anticline formed contemporaneously with the Skitchewaug Nappe. The rocks are interpreted to be part of the basement sequence of the Pelham Dome. If this interpretation is correct, then the <u>basement and its cover rocks were coupled during the Devonian dome-forming episode (Robinson and others, 1979, Stop 6)</u>.

Day V, Stop 5. Hardwick Tonalite, roadcut on Massachusetts Route 2.

This hornblende-rich tonalite pluton has been studied by Shearer (1983). The aluminum content of its hornblende (1.78-2.14/23 oxygen) indicates a pressure of crystallization on the order of 6 kbar (Hammarstrom and Zen, 1986). The outcrop is within the belt of highest recorded pressure during the Acadian metamorphism. The pressure recorded by the amphibole verifies the pressure estimated by the chemistry of coexisting metamorphic minerals (Robinson and others, 1986).

The Hardwick has not yet been dated. However, from its involvement in Acadian deformation and intrusion into Silurian and Devonian rocks, it is considered a Devonian pluton. In southern New Hampshire, a pluton in the presumed related Spaulding suite of gabbro to granite has a Rb/Sr whole rock isochron age of 393$\pm$5 Ma (Lyons and others, 1982).

Day V, Stop 6. High-pressure metamorphism and anatexis in the Littleton Formation

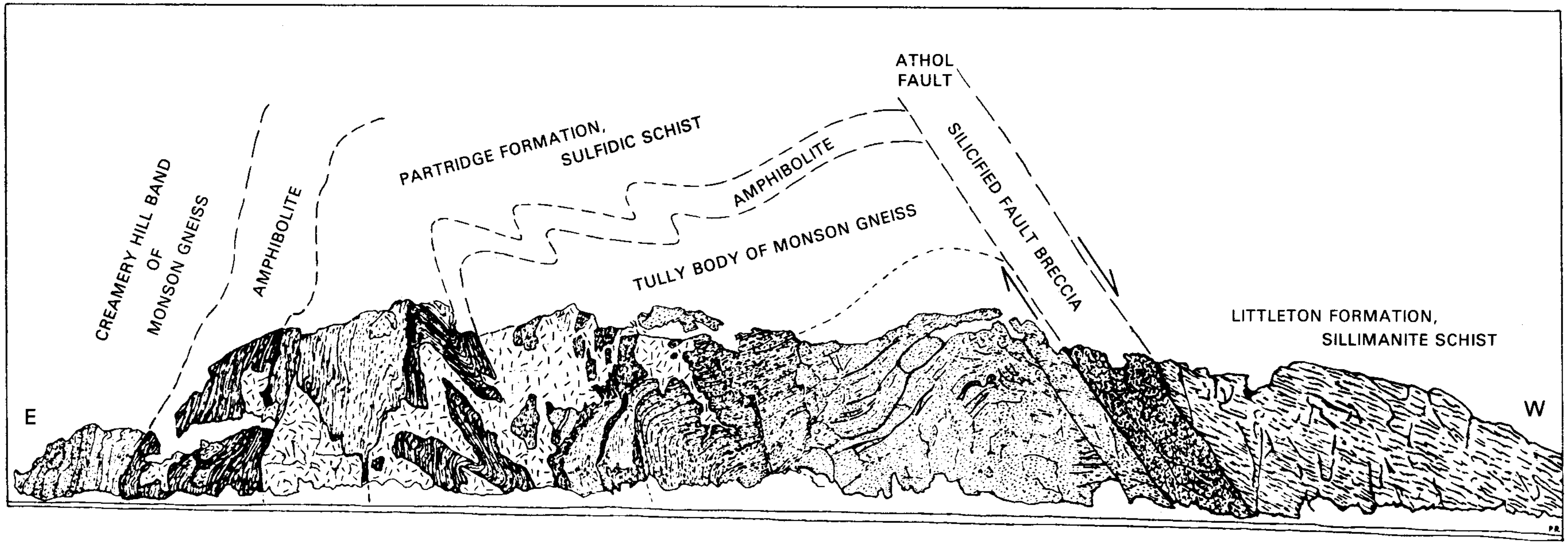


FIGURE 13 Southern wall of roadcut on Day V, Stop 4. Mesozoic Athol fault cuts crest of the Tully body of the Monson Gneiss. The Creamery Hill band of gneiss is interpreted as an extremely attenuated basement nappe separated from the Tully body by an isoclinal syncline of the Ordovician Partridge Formation. Outcrop is approximately 15 m high at the highest point; no vertical exaggeration. From Robinson and others (1979, figure 5-13).

(eastern facies). Roadcut near Phillipston, MA.

Sillimanite-orthoclase-garnet-cordierite rock, containing local pods of probable partial melts. "Two types of coarse garnet-cordierite-sillimanite gneiss can be seen here. In one, coarse garnets are set in patches rich in orthoclase and are believed to have grown to large size in the presence of felsic melt. In the other coarse garnets are in a matrix of cordierite plagioclase and quartz without orthoclase. The rock may be a residuum from partial melting. Mineral compositions from this zone suggest peak temperatures from 670 to 740^{o}C at pressures of 6.2-6.4 kbar. At this outcrop there is [also] abundant evidence of production of sillimanite and biotite by retrograde hydration" (Robinson and others, 1979, Stop 5A). The outcrop is about 100 m west of the Coys Hill pluton, a cordierite-sillimanite-biotite peraluminous granite that is an appendage of the Cardigan pluton (Day IV, Stops 5 and 6).

Day V, Stop 7. Massabesic Gneiss Complex and associated intrusive rocks near Milford, NH.

Between this stop and Stop 6, we have crossed a major tectonic boundary, the Nonesuch River-Campbell Hill fault system (Lyons and others, 1982). The Massabesic, southeast of the fault, thus constitutes a suspect terrane. The contact is not exposed.

Aleinikoff and Green (1987) assigned the rocks here to three units: a late Proterozoic paragneiss, an Ordovician orthogneiss, and a late Paleozoic (Permian) pegmatitic granite. We will visit the rocks in a small abandoned quarry in one of the rock "islands" within the access complex. According to Aleinikoff and Green (1987, p. 269), "The paragneiss is well-foliated biotite-quartz-plagioclase gneiss with minor amounts of pelitic schist, calc-silicate rock, amphibolite (as boudins [readily seen along the walk from the parking area to the quarry]), and sparse quartzite. The ** gneiss is interpreted as metamorphosed intermediate-to-felsic volcanic rocks [and] has been dated using the U-Pb zircon method at about 650 Ma (Aleinikoff and others, 1979).

"The orthogneiss is pink to white, coarse-grained granitic gneiss. ** [This rock] often contains biotite-rich schlieren **. U-Pb dating of zircon from the orthogneiss in these outcrops indicates that it is about 475 Ma. **

"The terranes from which the [paragneiss] were derived may be about 1500 Ma. This age was estimated by dating detrital zircons (Aleinikoff and others, 1979). **

"Crosscutting all foliated rocks (paragneiss and orthogneiss) in many locations in these outcrops are dikes of the Permian granite. This granite is gray and composed of quartz, K-feldspar, biotite, plagioclase, and minor primary muscovite. It is massive, with only rare flow foliation indicated by weak alignment of biotite. The granite has yielded a U-Pb zircon age of about 275 Ma (Aleinikoff and others, 1979), making it among the youngest calc-alkaline plutonic rocks in New England. It is the same age as some granites of southern New England. **

"The 475-Ma orthogneiss and the 275-Ma granite are sometimes difficult to distinguish in outcrop, particularly when both contain xenoliths of paragneiss. However, the orthogneiss is generally white, coarse-grained, and foliated, whereas the granite is gray, medium-grained, and massive. As a guide in these outcrops, the Permian granite can be seen along the entire length of the roadcuts in the curbstone at the edge of the road. **

"The island of rocks [i.e. the quarry] contains the three principal rock units ** [where] three-dimensional views of the structural relationships are afforded by walking over this outcrop from northwest to southeast. On the hill side, dikes of the Permian granite cut the Massabesic Gneiss Complex."

The true tectonic setting of the Massabesic Gneiss Complex remains controversial. The contact against the Central Maine terrane is probably a major terrane-bounding fault. To the south and east of these rocks, metamorphosed pelitic and calcareous pelitic units (the Merrimack sequence) occur, some of which have been intruded by Ordovician and Silurian plutons (Olszewski and Gaudette, 1988) (we will see one such relation on Day VI, Stop 2); so the pelites are no younger than Middle Silurian. These pelitic units were shown by Zen and others (1983) as correlative of the Silurian and Devonian rocks of the Central Maine terrane, but Zen here interprets them as part of a separate terrane. Whether the Massabesic is basement to the Merrimack sequence rocks, whether they are the same rocks at different metamorphic grade (Bothner and others, 1984; also see Aleinikoff and Green, 1987), or whether they are in tectonic contact, remains unsettled.

*** Day V, Stop 8. The Fitchburg Complex, Rollstone quarry, town of Fitchburg, Massachusetts.**

The Fitchburg Complex consists of plutons of granite and granodiorite, nearly all peraluminous, and occurs south of the Massabesic Gneiss Complex, between the Central Maine terrane to the west and other suspect terranes to the east dominated by pelitic rocks southeast of the Massabesic (Day V, Stop 7). Several intrusions of the Fitchburg have been dated. Rocks of the Rollstone quarry have a zircon Pb-U age of 390±15 Ma (Zartman and Marvin, in press; based on Zartman and Naylor, 1984). The rock may be a terrane-welding pluton.

The rock is a light grey medium-grained tourmaline-rich two-mica granite containing ovoid to euhedral K-feldspar megacrysts as much as 1 cm across. Alignment of the megacrysts and of the mica plates defines the weak igneous foliation. The large (~5 mm) muscovite not so aligned might not be of the same generation.

DAY VI: WORCESTER MA
Hepburn and Zen, leaders

Stop descriptions prepared by E-an Zen and Chris Hepburn

MASSABESIC-MERRIMACK TERRANE, NASHOBA-CASCO-MIRAMICHI TERRANE, AND ATLANTICA TERRANE

Day VI, Stop 1. The Oakdale Formation of the Massabesic-Merrimack terrane. Roadcut on Massachusetts Route 140.

This unit is part of the sedimentary Merrimack sequence. The sequence occurs east of the Massabesic Gneiss Complex and of the Fitchburg Complex. "Typical light gray to purplish-brown weathering calcareous meta-siltstone and interbedded gray to gray-green phyllite **. Siltstone beds range in thickness from 1 to 10 cm. and are separated by thin partings of micaceous phyllite or interlaminated with paper thin phyllite partings on a scale of a few millimeters. Ankerite causes the characteristic purplish-brown weathering spots in the siltstones" (Hepburn, 1976, Stop 4).

Day VI, Stop 2. Intrusion of a 433 Ma pluton into deformed rocks of the Oakdale Formation. Pumphouse for the Wachusett-Marlborough Tunnel, east shore of Wachusett Reservoir.

Near the parking area, the rocks exposed along the shoreline are biotite-grade phyllite assigned to the Oakdale Formation by Zen and others (1983). The contact with the coarse, porphyritic granodiorite is exposed. Is this contact intrusive, or is it a fault? The intrusive rock is the Clinton facies of the Ayer Granodiorite (Gore, 1976) that has a 433±5 Ma zircon age (Zartman and Naylor, 1984). Note the well-developed igneous foliation defined by alignment of mafic minerals and of the megacrysts of K-feldspar. The rock contains abundant inclusions of pelitic country rock, interpreted to be part of the host Oakdale Formation. Proceed about 100 m southeast to a cove opposite a small island; the Ayer in the cove contains xenoliths that exhibit metamorphic foliation diverging sharply from the igneous foliation, indicative of an earlier metamorphism and deformation. If the identification of the inclusions as Oakdale is correct, then the Oakdale would have to be pre-Silurian, contrary to the age assigned to the unit by Zen and others (1983). About 70 km along trend to the northeast in New Hampshire, unfortunately too far for the excursion to visit, rocks assigned to the Eliot and Kittery formations, also of the Merrimack sequence, are intruded by the Exeter Diorite having a Pb-U zircon age of 473±37 Ma (Gaudette and others, 1984; Olszewski and Gaudette, 1988). Both dates suggest that the Merrimack sequence has no counterpart in the CMT and constitutes a suspect terrane.

Notice the andalusite crystals in some of the phyllitic pebbles along the shore. These pebbles are from the Merrimack sequence exposed a few km to the north and were carried in by the ice sheet.

Day VI, Stop 3. Gneiss of the Nashoba Formation, Nashoba-Casco-Miramichi terrane. Access ramp of Massachusetts Route 111 to I-495.

We have crossed another major fault zone. The fault here is called the

Clinton-Newbury (Skehan, 1968; Hepburn and Munn, 1984). Rocks southeast of the fault are assigned to the Nashoba block by Zen and others (1983) and considered by Zen (1983) as a separate terrane. Zen and others (1986) assigned it to part of a composite terrane, the Nashoba-Casco-Miramichi, whose elements extend from Long Island Sound all the way to the Gulf of St. Lawrence. Within the Nashoba block of northeastern Massachusetts, there is a complex and as yet incompletely understood intrusive and (or) stratigraphic sequence having uncertain though doubtless late Proterozoic to early Paleozoic age (Hepburn and Munn, 1984). The abundant evidence of 1.5 Ga detrital zircon in these rocks suggests an even older source terrane; these detrital ages are also reminiscent of those in the Massabesic Gneiss Complex and in the Berwick Formation of the MMT. The Nashoba Formation could be the basement to this sequence.

Hepburn and Munn (1984) described this outcrop as follows: "Nashoba Formation; gneisses and migmatitic gneisses. The large outcrops along the north side of Route 111 contain an excellent example of the migmatitic Nashoba. Here biotite gneisses are interlayered with migmatitic gneisses and pegmatites. Sillimanite is commonly present with biotite in the selvages along the rim of the melted material. Muscovite is ** in large, retrograded? flakes. Two generations of pegmatites are present here, the earlier having been deformed. Several generations of folding are also visible. Note the late brittle faults with gouge cutting the outcrop. It is believed that most of the pegmatite and granite in this outcrop is more or less locally generated by anatexis of layers with the appropriate composition. Note how the percentage of melt changes with the composition of the original layer."

*** Day VI, Stop 4. Fish Brook Gneiss of the Nashoba Block. Near Boxford.**

This outcrop has yielded a 730$\pm$26 Ma zircon Pb-U upper-intercept age (Olszewski, 1980; Zartman and Marvin, in press) interpreted to be a crystallization age of the volcanic protolith. Grey, strongly deformed gneiss containing grey, even-textured medium-fine granitic gneiss and rarer mafic inclusions. The ages are distinct from anything that we have for the North American craton, for the core gneiss of the Pelham Dome, or for the Massabesic Gneiss Complex (see also Hill and others (1984), for further outcrop description).

*** Day VI, Stop 5. Sharpners Pond Diorite near Boxford.**

The rock is sphene and hornblende rich, and little deformed or altered. A concordant zircon Pb-U age of 430$\pm$5 Ma (Zartman and Marvin, in press) indicates that the rocks have not undergone pervasive deformation and metamorphism since Early Silurian time, in distinct contrast with the rocks farther to the west.

Day VI, Stop 6. Undeformed Silurian-Devonian Newbury Volcanic Complex. U.S. Route 1, Glen Mills.

We have crossed yet another major complex fault zone, the Bloody Bluff, which we will visit at the end of the day. We are now in rocks referred to Avalonia sensu stricto by Zen (1983) and to the Atlantica composite terrane by Zen and others (1986). The rock is an Upper Silurian volcanic and volcanoclastic sedimentary sequence, described by Shride (1976a, b). The rock has yielded latest Silurian to Early Devonian shelly fossils, mainly brachiopod and ostracode, in the sedimentary layers associated with the volcanic rocks (Shride, 1976a).

The outcrop here consists of "intercalated flows and water-laid ash-fall(?) tuffs of the porphyritic andesite **. The first reported fossils ('marine types' comprising 'one or more species of brachiopods, a species of gastropod, fragments of crinoids, and probably a pelecypod' (Emerson, 1917, p. 163)) from the Newbury were collected here, apparently at the road intersection in rocks now deeply buried. Similar thin fossil zones exist in the vicinity, and additional collections were made in the 1960's" (Shride, 1976b, p. 296). We will see the andesite; note the lack of alteration and the preservation of filled but undeformed amygdules as well as plagioclase laths in the groundmass. These rocks clearly have not been penetratively deformed or metamorphosed beyond lowest greenschist facies since their formation in pre-Acadian time.

The Newbury Volcanic Complex may be related to volcanic and volcanogenic sedimentary rocks of the same age and faunal affinity exposed along coastal Maine (Gates and Moench, 1981; Gates, 1987) and could be a separate piece within the Atlantica composite terrane, as rocks like these are not known in sequence with typical "Avalon" rocks, either in eastern Newfoundland (type Avalon) or here in the Boston basin. Zen and others (1986) distinguished the typical "Avalon" rocks of the Boston area as Atlantica I, and the Newbury as Atlantica II (FIGURE 3). Indeed, Gates and Moench (1981, FIGURE 1) implied that the Newbury Volcanic Complex was once continuous with Silurian-Devonian volcanic rocks of coastal eastern Maine. These rocks may be unrelated to the rocks of Atlantica I except through later accidents of tectonic juxtaposition.

Day VI, Stop 7. Breeds Pond Member of the Lynn Volcanic Complex (Atlantica I), abandoned quarry on Breeds Pond.

The exposure "displays a rapid change in a variety of rock types with irregular contacts and possible dome-like intrusions. There are four rock types here; welded tuffs, crystal tuffs, breccias, and intrusive dome facies. The volcanic rocks are typical of [the Breeds Pond] Member with phenocrysts composed of plagioclase and hornblende and with the plagioclase dominant. The matrix is glassy and exhibits flow textures. The inclusions in the breccia are composed of fragments of other members of the Lynn. The dome facies here intrudes the volcanics in many places with a very irregular contact between the two facies." (Smith and Hon, 1984).

Rocks having a glassy matrix are readily seen on the glaciated surface above the quarry. The original flow layering and contact between crystal tuffs and flow-banded rhyolite are well exposed on the small knob next to the spillway. Note the lack of penetrative deformation, the preservation of delicate ignimbrite and other volcanic textures, and the absence of significant mineralogical alteration. Fractures are filled with quartz-epidote-celadonite assemblage. Many samples show glassy shards that have undergone various degrees of welding; lithic fragments include welded tuff.

Rocks at Day VI, Stops 5, 6 and 7 show that Atlantica has undergone no significant thermal and dynamic event since the late Proterozoic Era, in sharp contrast with what we saw during the first five days and providing a strong argument that Atlantica is exotic relative to the Acadian limits of North America.

*** Day VI, Stop 8. Dedham Granite (latest Proterozoic), highwall behind Stop and Shop store on U.S. Route 1. Beware of loose rocks overhead!**

Dedham Granite, a major component of Atlantica I in eastern Massachusetts, here consisting of "a coarse grained rock containing hornblende, biotite, plagioclase, quartz, and kspar [and reddish-brown sphene]. The Dedham is a typical calc-alkaline granodiorite with normative diopside up to 8%" (Smith and Hon, 1984). The feldspar is largely saussuritized, the biotite altered to epidote+chlorite, but the hornblende is only marginally altered to actinolite.

Smith and Hon (1984) continues: " There are two rhyolite dikes that intrude through the Dedham. Notice the contorted contacts between the dikes and the Dedham. These 'soft' contacts imply that the Dedham was not wholly crystallized but partly plastic when the dikes intruded". Notice also the mafic dikes showing contorted contacts against the Dedham.

The Rb/Sr whole rock isochron age for the Dedham (Kovach and others, 1977) is 608 ± 17 Ma; the initial Sr ratio is 0.7065 ± 0.0011. In petrography and in age, the Dedham closely resembles the Holyrood Granite of the type Avalon region of eastern Newfoundland (McCartney and others, 1966), which has a Rb/Sr isochron age of 574 ± 11 Ma. See also Day VII, Stop 1.

Day VI, Stop 9. Bloody Bluff fault zone. Minute Man National Historical Park.

The Bloody Bluff is a major terrane-bounding system of faults that extends from the northeastern shore of Massachusetts to Rhode Island, though the precise continuation on the ground is not everywhere clear. We are at the type locality of the fault, separating rocks of the NCM (Zen and others, 1983) from rocks of the Atlantica terrane (Zen and others, 1986).

The exposure at the southern end of Fiske Hill (Nelson, 1987, spelled the name as "Fisk") is within the Bloody Bluff fault zone. It consists of cataclastic granite of Atlantica I (possibly the Dedham Granite of the last stop) containing deformed as well as undeformed mafic rocks. The granite has a well-developed mylonitic foliation that mostly strikes northeast and dips gently northwest. The foliation itself is folded and contains a few rootless isoclines.

We will stop briefly at the bluff called Bloody Bluff on the grounds of Minute Man National Historical Park. Here again, shattered Dedham-like granodiorite is exposed, though mylonite is rare (see Nelson, 1987; Barosh, 1976, 1984). Bloody Bluff and Fiske Hill are sites of a late skirmish during the Battle of Concord, which occurred early in the American Revolution. The success of the ragtag militia here to repel the regular British troops did much to bolster the Americans' confidence and contributed to their eventual success, as attested by the inscriptions on the stone monument at the bluff.

Time permitting, we will stop at the North Bridge Visitor Center of the Park. The reconstructed North Bridge is the site of the first serious shooting during the Battle of Concord (April 19, 1775). Near the Visitor Center is the Old Manse, where Ralph Waldo Emerson spent much of his life, and where Nathaniel Hawthorne also lived briefly. Concord was the center of a remarkable intellectual community during the middle and late 19th century; besides Emerson and Hawthorne, other figures included A. Bronson Alcott and his daughter Louisa May Alcott, and the naturalist-philosopher Henry David Thoreau. Thoreau's cabin on Walden Pond, where he experimented with wilderness living, is nearby.

NATIONAL PARK REGULATIONS PROHIBIT SAMPLE COLLECTION OR USE OF GEOLOGICAL HAMMERS. PLEASE STRICTLY OBSERVE THIS RULE. THANKS!

DAY VII: **WORCESTER MA TO PROVIDENCE RI**
Skehan and Zen, leaders

Stop descriptions prepared by E-an Zen and Jim Skehan

NASHOBA-CASCO-MIRAMICHI TERRANE AND ATLANTICA TERRANE

Day VII, Stop 1. Intrusion of little-deformed latest Proterozoic Esmond Granite into a greenstone member of the Proterozoic Blackstone Group. South-bound I-295 ramp to west-bound Route 7.

The Esmond is one member of a group of Late Proterozoic granites in Atlantica I; we have seen an example in the Dedham Granite north of Boston (Day VI, Stop 8). Hermes and Zartman (1985) gave a 621±8 Ma zircon Pb-U age for this body of the Esmond. It intrudes into the volcanic and volcanoclastic rocks of the Blackstone Group (Quinn, 1971) which is part of the basement of Atlantica I, though clearly still a supracrustal rock.

*** Day VII, Stop 2. Sheared Ponaganset Gneiss in the Hope Valley shear zone, roadcut on spur between U.S. Route 6 and I-395.**

The Ponaganset is a Late Proterozoic augen gneiss of Atlantica I, here severely sheared. The foliation dips gently west, though elsewhere along its length the shear zone has steep dips. The Hope Valley shear zone was described by O'Hara and Gromet (1985); part of a major system of faults that include the Bloody Bluff fault (Day VI, Stop 9), it forms the western bound of Atlantica I. Southeast of this stop, the 370±7 Ma (Hermes and Zartman, 1985) Scituate Granite Gneiss has been deformed by the shear zone.

The Ponaganset Gneiss intrudes into rocks assigned by Quinn (1971) to the Blackstone Group and was regarded by him as the earliest formed of the older granite plutons of northwestern Rhode Island. It varies from granite, the most common, to tonalite. Major minerals are feldspar, quartz, and biotite; minor and accessory minerals are amphibole, epidote, sphene, garnet, and secondary muscovite.

Goldstein and Owens (1985) described this outcrop as follows: "The lithology seen is typical of the western Ponaganset Gneiss. This is a medium gray, porphyritic granite gneiss. The lineation is seen in the N-S, sub-horizontal elongation and rotation of the 2-4 cm, pink phenocrysts (porphyroclasts). Note the absence of foliation to the extent that there is little or no preferential orientation of phenocrysts perpendicular to lineation."

Gromet and O'Hara (1985) commented that "the large feldspar augen (up to 40 mm) commonly have asymmetric deformation tails when viewed on surfaces parallel to the lineation. The augen are circular, ovoid or tabular on surfaces normal to the lineation. Most asymmetric augen indicate right-lateral shear sense, although some with a[n] opposite shear sense are apparent.

"In addition to quartz, alkali feldspar, plagioclase and biotite, minor minerals in the coarse augen gneiss include hornblende, epidote, sphene, and rarer secondary muscovite. In thin section the lineation is defined by elongate aggregates of quartz and feldspar, and by trains of biotite and hornblende. Tails on feldspar augen are composed of finer recrystallized grains. Myrmekite is commonly developed around the margins of the augen. The leucocratic gneiss contains locally abundant secondary muscovite.

"This locality is approximately 2 km from the surface trace of the [Hope Valley Shear Zone] and the rocks here are among the most highly deformed found along this segment of the boundary."

Day VII, Stop 3. Plainfield Formation of the Hope Valley terrane of O'Hara and Gromet (1985). Roadcut on spur between U.S. Route 6 and I-395.

The Hope Valley terrane lies between two major faults -- the Hope Valley Shear Zone to the east and the Lake Char (short for Lake Chargoggagoggmanchauggagoggchaubuna-gungamaugg) fault-Honey Hill thrust system, and is here assigned to the Nashoba-Casco-Miramichi terrane.

The Plainfield Formation has long been correlated with the Westboro Formation (Atlantica I terrane) north and west of Boston. This correlation is now called into question, because the Hope Valley terrane is separated from Atlantica I by the Hope Valley shear zone. There are also lithic differences between the Plainfield and the Westboro. In southern Connecticut, quartzite assigned to the Plainfield Formation occurs as xenoliths within a granite dated at 616±79 Ma (Hills and Dasch, 1972).

Goldstein and Owens (1985) identified in this outcrop of the Plainfield Formation a pelitic member composed of quartz-mica schist and interlayered amphibolite and calc-silicate granofels, which grades westward into a quartzite member composed of dark grey and black, massive to strongly foliated quartzite. They further described the outcrop as follows: "Foliation is well developed in the schists as a sinuous, undulatory surface defined by the preferred orientation of micas and the flattening of quartz and plagioclase, and is developed in the quartzite **. Lineation is well defined in the quartzites as a 'mullion' structure and is less well defined in the schists as a preferred orientation of acicular minerals or a tight crenulation of micas in foliation. Asymmetric 1-cm micro-folds in foliation with axes that parallel lineation are quite common. Quartz rods and boudins are common within the schists. All of these structures probably were initiated during the isoclinal folding phase of the deformation. An axial planar foliation may have served as a pre-existant [sic] slip plane for later shearing. Fold axis parallel crenulations, minor folds, quartz rods, and boudins may have been subsequently rotated into parallelism with the shear-related lineation. Both lineation orientations (N-S, NW) are present in this outcrop and the transition from N-S orientations at the eastern end of the cut to NW at the western end of the cut is apparently abrupt. We have not found the two lineations on the same surface but in the center of the roadcut adjacent foliation surfaces can have lineations with divergent orientations."

The rock types exposed here are similar to those in the core of the Pelham Dome (Day V, Stops 2 and 3), prompting suggestions of a correlation of these units. If that correlation is valid, then rocks of this terrane are closely related to the basement of the Central Maine terrane. Even so, however, the rocks still could now be in separate, transported slivers. The question was also discussed by Hepburn and Munn (1984) and by Robinson (1988).

*** Day VII, Stop 4. Lake Char fault. Roadcut on spur between U.S. Route 6 and I-395.**

Quartzite of the Plainfield Formation is exposed in the footwall and rocks of the Quinebaug Formation are exposed in the hanging wall (FIGURE 14). The Quinebaug Formation consists of metavolcanic and volcanoclastic rocks; the mineral assemblage in both the schistose and the coarsely porphyroblastic gneiss here is plagioclase-microcline-epidote-quartz-green biotite (defining SC fabric)-sphene±hornblende; all the rocks are blastomylonites. Rodgers (1985) and Wintsch (1987) show the Quinebaug to be in a separate fault sliver between the Hope Valley terrane below and rocks of the Merrimack sequence above (for an earlier summary see Dixon and Lundgren, 1968); the Quinebaug is here assigned to the NCM

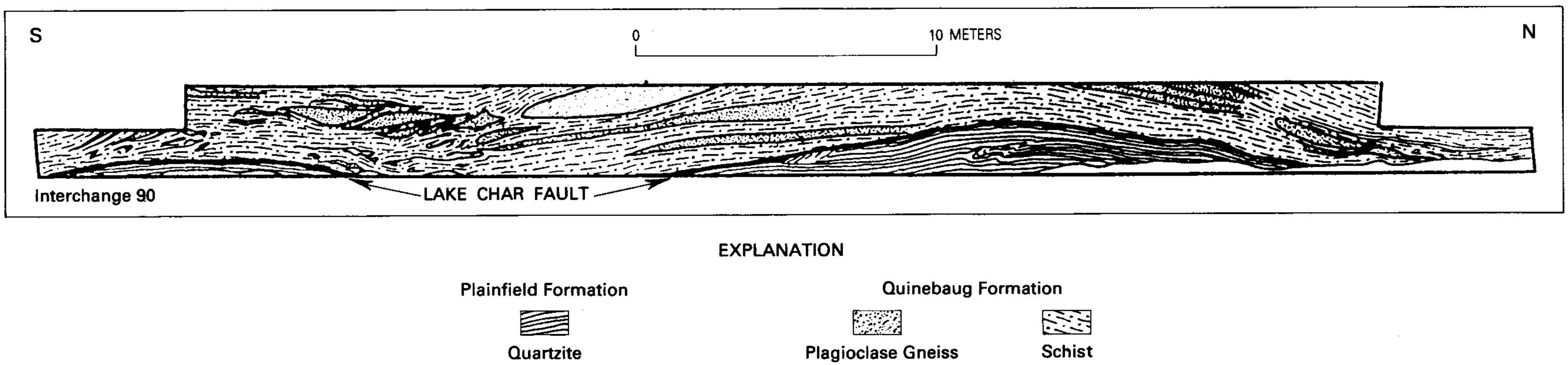


FIGURE 14 Details of roadcut on Day VII, Stop 4. The Plainfield Formation underlies the Quinebaug Formation across the Lake Chargoggagoggmanchauggagoggchaubunagungamaugg fault. View to the northwest. No vertical exaggeration. Adapted from Goldstein and Owens (1985).

composite terrane.

The Lake Char fault dips gently northwest (Rodgers, 1985). Goldstein (1982) described a primary west-side down movement sense on this fault along the Connecticut-Massachusetts border and suggested (Goldstein, 1984) that this could be a detachment fault rather than a thrust fault.

Day VII, Stop 5. Narragansett Pier Granite. Cormorant Point.

The Narragansett Pier Granite is extensively exposed along the southern shore of Rhode Island. Its well-determined age, combined with its relationship to deformation phases and to the regional metamorphism, provides important information on the Alleghanian orogeny (Skehan and Murray, 1979; Murray and Skehan, 1979).

The Narragansett Pier Granite can be divided into a pink facies and a white facies; we will only see the white facies. Murray and Skehan (1979) discussed the outcrop as follows. "The shoreline exposures consist of massive to gneissic medium- to coarse-grained garnet-biotite-muscovite-sodic oligoclase-microcline granite with subordinate layers and lenses of metasedimentary rocks. The host rock is the 'White Granite' of Kocis and others (1977, 1978) and is considered to be a border phase of the pink Narragansett Pier Granite.

"The metasedimentary rocks consist of carbonaceous garnet-biotite-muscovite-quartz-plagioclase-ilmenite schist, psammitic gneiss and stretched pebble conglomerate. Although there are no chill zones, the granite clearly truncates the fabric of the metasedimentary rocks and thus is considered to be intrusive into them.

"Metasedimentary layers are occasionally graphitic and rarely fossiliferous. In one such layer fossils are preserved as graphite carbonizations along bedding surfaces. Here the flora consist of many unidentifiable stems and foliage remains, and a surprisingly well preserved specimen of <u>Annularia</u> <u>stellata</u>. These fossils place a maximum age for the intrusion of the Narragansett Pier Granite at 295 m.y. (Brown and others, 1978) as it is [sic] confined to Westphalian D or younger rocks in the Narragansett Basin. The age is also consistent with an U-Pb age of 276 m.y. obtained from monazite from the white granite (Kocis and others, 1978)".

Murray (1987) further discussed this outcrop: "The white (i.e. leucocratic) facies of the Narragansett Pier Granite ** may be subdivided into five field units -- pegmatite, aplite, garnetiferous granite, massive granite, and quartz veins -- that define a crude igneous layering [notice, however, the apparently conjugate sets of pegmatite dikes in the outcrop south of the house]. ** The mineralogy of all varieties is similar, consisting of quartz, perthitic microcline, oligoclase, primary muscovite, biotite, and accessory garnet, apatite, zircon, monazite, and allanite. Variations in granite fabric and mineralogy found here reflect variations in activity of water, and to a lesser extent assimilation of the surrounding metasediments. ** The time of intrusion is well constrained by the following independent age determinations: (1) Stephanian A or younger (i.e. Late Pennsylvanian) plant fossils in one of the lenses (Brown and others, 1978); (2) U-Pb age of 275 Ma from igneous monazite (Hermes and others, 1981); and (3) Ar^{40}/Ar^{39} [sic] cooling age of 238 Ma (Dallmeyer, 1982)." Hermes (1988, oral communication) reported a zircon lower-intercept age of 276 Ma.

Tide permitting, we will see a xenolith of a stretched-pebble conglomerate, presumably of the Pennsylvanian Purgatory Conglomerate (Day VII, Stop 9). Notice sedimentary xenolith in a pegmatite just behind the house.

Day VII, Stop 6. Upper Carboniferous (Pennsylvanian; Westphalian D or younger) sedimentary rocks. East pier of Jamestown Bridge at Conanicut Island.

These sedimentary rocks are the youngest Paleozoic rocks exposed in southern New England and are part of the pan-Appalachian overlap assemblage. The rocks here have been metamorphosed to include garnet-staurolite-biotite schist, carbonaceous schist, metaconglomerate, and metasandstone. "The schists contain staurolite, garnet, and biotite porphyroblasts in a matrix of biotite, muscovite, quartz, opaques, and carbonaceous material. ** Megaflora of probable Westphalian D or younger age have been obtained from carbonaceous schist along the shore, 500 m to the south" (Murray and Skehan, 1979; see also Mosher and Wood, 1976).

Note the graded beds in upward-fining cycles ranging from conglomerate through sandstone to fine schist. Across the bridge to the west at Stook Hill, similar beds, presumably of the same age and likewise inverted, have yielded the kyanite-staurolite assemblage, suggesting temperature and pressure of metamorphism of as much as 590°C and 5 kbar (Grew and Day, 1972; see discussion by Murray and Skehan, 1979). As seen on Day VII, Stop 5, these rocks were intruded by the Narragansett Pier Granite. Latest Paleozoic plutons are increasingly being recognized in southern New England (cf. Day V, Stop 7), as are indications of a Permian (Alleghanian) thermal event (Zartman and others, 1970). Although there is no general agreement as to whether the thermal event records a delayed cooling or a distinct thermal pulse, the Alleghanian orogenic event might prove to be of larger scale and greater intensity than we have hitherto supposed (see Skehan and Murray, 1980).

Day VII, Stop 7. Deformed but weakly metamorphosed pelitic rocks carrying Middle Cambrian Acado-Baltic fauna trilobites. Beavertail Point.

Middle Cambrian trilobite-bearing faunae of the Atlantic coastal belt were reviewed by Neuman and others (1988). In Massachusetts, a number of other fossil localities are known, some less deformed than this one but none as readily studied or containing as good a stratigraphic sequence. The rocks are part of the "classic" Avalonian sequence of eastern Newfoundland and are assigned by Zen and others (1986) to Atlantica I. Though Avalonia has often been considered to be the opposite shore of Iapetus during its Taconian closing against the North American craton, lack of evidence of Acadian deformation and metamorphism refutes that assignment (cf. Day VI, Stops 5, 6, 7, 8; see also Zen (1983) and Zen and Palmer (1981)). Whatever the age and mode of accretion of Atlantica I to the Appalachian orogen, it was likely distinct from the main Taconian active margin subduction events that we studied early on this trip.

Rocks at Beavertail Point are assigned to three formations, named (from oldest to youngest) the Jamestown Formation, the Fort Burnside Formation, and the Dutch Island Harbor Formation by Skehan and others (1987); these formations appear to be part of a coherent sedimentary package representing related environments of deposition.

The Jamestown consists of fossiliferous green and grey phyllite and rhythmically layered buff to pink siltstone and black and grey phyllite. The Fort Burnside is sedimentologically similar in its finer grained components to those in the Jamestown. Lacking paleontological constraint, the Fort Burnside and the Dutch Island Harbor may range into Late Cambrian or Ordovician.

At least three different trilobites are represented by variously deformed fragments found within the Jamestown. The trilobites are: 1. A widespread species of medial Middle Cambrian Badulesia tenera (Hartt). "This species is known from New Brunswick and eastern Newfoundland, and from southern Germany, northern Spain, and eastern Turkey. Closely related species are also known from southern France. The best stratigraphic control is provided by Sduzy (1967) for northern Spain, where this species is shown to characterize a subzone within the Middle Cambrian Badulesia zone and to correlate approximately with the lower part of the Paradoxides paradoxissimus zone of northern Europe" (Murray and Skehan, 1979). 2. An indeterminate species of Paradoxides. 3. A third species represented by a deformed unidentifiable fragment having a strong granular ornamentation.

According to Murray and Skehan (1979), "The metasedimentary rocks in this part of the Basin have undergone two episodes of metamorphism. Mineral assemblages in the phyllites consist of porphyroblasts of ankerite and pyrite within a matrix of muscovite, chlorite and quartz. ** The rocks are presently classified as lower greenschist facies. Overgrowths rim both the ankerite and pyrite porphyroblasts and define two distinct mineral lineations. Two generations of mineral growth are recorded in the micas within the matrix and they apparently correlate with the two dominant cleavages seen in outcrop."

As Skehan and others (1987) directed, "Walk northeasterly along the shore for about 1,600 ft (500 m) to Lion Head Chasm **. Stay near the upper shoreline exposures and walk carefully around the head of the chasm, along the only path there, to the beginning of the traverse immediately north of the chasm.

"Along this traverse the entire inverted Middle Cambrian sequence of Jamestown may be seen, with the exception of one member. From the northeast to the southwest, examine the succession **. At the southwestern end of the traverse, the

Beavertail Point Member, in tectonic slide contact with the [younger] Dutch Island Harbor Formation, will be examined.

"The following features may be examined: (1) the [medial Cambrian] trilobite locality **, (2) structures associated with intraformational and interformational tectonic slides **, (3) folds and associated features **, (3) [=(4)] late brittle deformation features, such as faults and kink bands **. Many of these brittle faults contain slickensided vein quartz."

*** Day VII, Stop 8. Fossiliferous Lower Cambrian limestone, Brenton Point, Newport Neck.**

These rocks apparently stratigraphically underlie the Jamestown Formation seen at Beavertail Point. Both have been overthrust by older rocks of the Newport Neck Formation (Skehan and others, 1987). The late Proterozoic and Cambrian rocks of the Newport Neck area comprise several distinctive sequences: (1) a thick turbidite sequence of the Newport Neck Formation, (2) thinner bedded turbidites of the Price Neck formation, contact-metamorphosed by the 595$\pm$12 Ma Cliff Walk Granite (see Murray and Skehan, 1979, and references therein), (3) Lower Cambrian limestone of the Pirate Cave Formation (Skehan and others, 1987) at the base of and intercalated with maroon slates (seen at this stop in an overturned sequence), (4) green to grey phyllite, some rusty weathering siltstone (in the East Passage Formation, Skehan and others, 1987); and (5) dark-grey phyllite of the Dutch Island Harbor Formation.

The stop was described by Kay and Chapple (1976), and more fully by Skehan and others (1987) as follows: "From the northwestern entrance of Brenton Point State Park, walk north along Ocean Drive approximately 600 ft (200 m). Enter the stone gateway on the left and walk 250 ft (75 m) west to the cliff exposures on the shoreline. On this view point and northward are well-graded beds of the Castle Hill Member of the [Late Proterozoic] Newport Neck Formation developed in a large overturned syncline. An F_2-fold on the southern face of a small island (250 ft; 75 m long) can be viewed to the north across Pirate Cave.

"Southward along the coastline the Lower Cambrian limestones and phyllites are exposed. The unconformity, best observed at low tide, is exposed at the base of the nearby cliff that forms the south slope of this viewpoint, and is located south of Pirate Cave and north of Collins Beach **. The Precambrian rocks at this locality strike approximately 340° and dip variably northeast. The Lower Cambrian limestones in several places strike approximately 060° and dip at a shallow angle toward the northwest but are intensely and recumbently folded. Extensive exposures of the limestone beds are observable on the next point south, as is the unconformity with the coarse Precambrian turbidite sandstones. Although complexly folded by F_2-folds, two distinct limestone layers can be identified. Shell debris has been identified within both horizons, which on preliminary investigation appears to represent pretrilobite Lower Cambrian fossils (E. Landing, personal communication, 1986)."

These fossils are Eccentrotheca kanesia that could be of Tommotian Age but could be younger Early Cambrian (A.R. Palmer, written communication to Zen, 1987).

The Cambrian strata of the last two stops bear stunning lithologic similarity to coeval shales in the Taconic allochthon (Day II), yet the trilobite faunae of the two areas show that they must have been widely separated at the time of deposition.

Day VII, Stop 9. The Purgatory Conglomerate in the Carboniferous overlap assemblage. The Purgatory.

Boulders in this conglomerate outcrop are as much as 2 m long; they demonstrate the origin of this instance of a "stretched pebble conglomerate." This outcrop occurs on the east limb of an anticline and is part of a group of conglomerate layers interspersed with sandstone lenses and grading upward into the Rhode Island Formation seen on Day VII, Stop 6. The Purgatory Conglomerate consists of 95% quartzite pebbles (Perkins, 1920); pebbles of granite, schist and amphibolite are rare. On a surface south of the Chasm, there is exposed a small lens of matrix sandstone (foreset sand in the lee of gravel bars?) that contains mud chips. These chips probably represent penecontemporaneous disruption of mud layers laid down during waning flow.

This stop was described by Mosher and others (1987) as follows: "At this outcrop the approximately 440 ft thick (135 m), massive, clast-supported Purgatory

Conglomerate units are interbedded with thin sandstones and magnetite-rich sandstone lenses. The conglomerate represents a proximal to very proximal facies of a wet alluvial fan that formed off the southeastern block-faulted margin of the basin. Clasts are generally prolate triaxial ellipsoids and range from pebbles to boulders in size (majority are cobbles). Clasts are predominantly quartzite, with rare granite and schist cobbles. The outcrop forms part of one of several elongate, N-trending ridges that mark the positions of major F1 and F2 fold limbs. ** Metamorphism to chlorite grade was syn- to post-D2."

The mechanism of cobble deformation was detailed by Mosher (1976) and summarized by Mosher and others (1987): "Cobble deformation was achieved by pressure solution. Cobbles have tangential, almost planar, and deeply embayed contacts. Thin sections of cobble contacts show no evidence of quartz or mica deformation within cobbles nor any distortion of internal cobble bedding ** Large, fibrous, quartz pressure shadows can be seen at long axis terminations of most cobbles. Where cobbles are in close contact, matrix is 1 to 3 mm thick, depleted in quartz (<3%) and enriched in residual material remaining after pressure solution. Shear fractures offset margins of some cobbles. Substantial redistribution of cobble volume (Δ V) has been measured ** (23% hinges; 55% overturned limbs). Much of the apparent strain is caused by original cobble shapes; ** [r]eal strains are constrictional **.

"Purgatory Chasm is the result of weathering of closely spaced, quartz filled, 'joints' that may mark edges of large rectangular-shaped boudins. ** Exposed in the northern Chasm face is a N-trending fault."

Mosher and Wood (1976) commented on the regional sedimentary implications of the Purgatory Conglomerate:

"The overall Pennsylvanian stratigraphy, with red beds and subaerial volcanics ** in the north, passing southwards into coarse clastic sediments together with coals and shales ** and finally into a boulder conglomerate facies (Purgatory Conglomerate), would appear to indicate a southerly paleoslope in an environment of massive Pennsylvanian erosion and accompanying deposition. Swamps and constantly fluctuating streams existed in what may have been a subsiding and tilting basin or graben. The occurrence of the Purgatory Conglomerate in the south of the basin may indicate that the basin opened in that direction (Mutch, 1968) into a uniformly higher energy environment in which the coarse boulder units accumulated. One problem is the absence of marine fossils in any of the sandy and silty units associated with the Purgatory Conglomerate. Another problem is the source of the quartzite boulders. The boulders are, on the basis of Walcott's recognition of fossils, Upper Cambrian to Lower Ordovician in age (Walcott, 1898). Because some boulders contain several species of the brachiopod <u>Obolus</u> which is also found in the Lower Ordovician of Belle Island, Newfoundland, it has been suggested that the source of the Purgatory Conglomerate was a southward extension of the latter formation (Towe, 1959)".

The source of these boulders remains unknown. Conceivably, the source rocks were part of Atlantica I and have been eroded since Carboniferous time, but there is no sign that such rocks ever existed. Could these missing source rocks indicate postdepositional terrane translation? A similar source problem exists for the Carboniferous rocks of eastern Pennsylvania; there, too, terrane translation may be a way out of the problem (Zen, 1983).

END OF EXCURSION. GOOD LUCK AND HAVE A PLEASANT TRIP BACK HOME!

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