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# The Marlboro Formation in its type area and associated rocks just west of the Bloody Bluff Fault Zone, Marlborough area, Massachusetts

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# THE MARLBORO FORMATION IN ITS TYPE AREA AND ASSOCIATED ROCKS JUST WEST OF THE BLOODY BLUFF FAULT ZONE, MARLBOROUGH AREA, MASSACHUSETTS

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## Introduction

The Marlboro Formation underlies the eastern portion of the Nashoba Block, an exotic terrane (Zen, 1983a) in eastern Massachusetts bounded by the Clinton-Newbury and Bloody Bluff Fault Zones (Figure 1). Movement on these faults was likely large, although their displacement cannot yet be established since no definite correlation of Nashoba Block rocks can be made with rocks elsewhere. The Nashoba Block has been metamorphosed to the upper amphibolite facies in contrast to the Boston Platform and the eastern Merrimack Trough (Lyons, et al., 1982) which have generally undergone only low grades of metamorphism. The Nashoba Block is underlain by a thick series of metabasaltic rocks on the east (Marlboro Formation) and metamorphosed sediments and volcanogenic sedments on the west (Nashoba Formation). These stratified rocks have been intruded by a distinctive sequence of Ordovician to Silurian calc-alkaline intermediate plutons (Sharpners Pond, Assabet and Straw Hollow Diorites) and peraluminous granites (Andover) (Zen, 1983b; Zartman and Naylor, 1984). The structure in the Nashoba Block is complex. The terrane is cut by numerous faults and ductile shear zones (Barosh, et al., 1977; Bell and Alvord, 1976) and many exposures exhibit multiple fold generations.

Emerson and Perry (1907) first used the name Marlboro Formation for mafic rocks in the upper part of the Blackstone Series of Rhode Island. Later, Emerson (1917) redefined the Marlboro to include black biotite schists and hornblendic schists of eastern Massachusetts, and described a type locality along the north side of Main Street in the City of Marlborough, Massachusetts. However, Emerson described a Brimfield-type Schist just north of the Marlboro Formation and included the type Marlboro section in the Brimfield-type Schist on the 1917 state geologic map. Emerson (1917) included, in the Marlboro, rocks from the Boston Platform in both eastern Massachusetts and Rhode Island, but noted that these rocks might be more appropriately divided into distinct units. The Marlboro rocks in Rhode Island were eventually separated as the Huntinghill Greenstone of the Blackstone Series by Quinn, et al. (1949). Bell and Alvord (1976) redefined the Marlboro in eastern Massachusetts to include all the mafic rocks in the stratigraphic interval between the Bloody Bluff Fault and the base of the Shawsheen Gneiss to the northwest. Marlboro-type rocks east of the Bloody Bluff Fault were included into the Middlesex Fells Volcanic Complex and the Greenleaf Formations (Bell and Alvord, 1976). Bell and Alvord further subdivided the Marlboro into a lower unnamed member at the base, overlain by the Sandy Pond Amphibolite Member. Three informal members of the Marlboro Formation above the Sandy Pond Amphibolite Member have been mapped in the Marlborough quadrangle (DiNitto, 1983). These three members appear

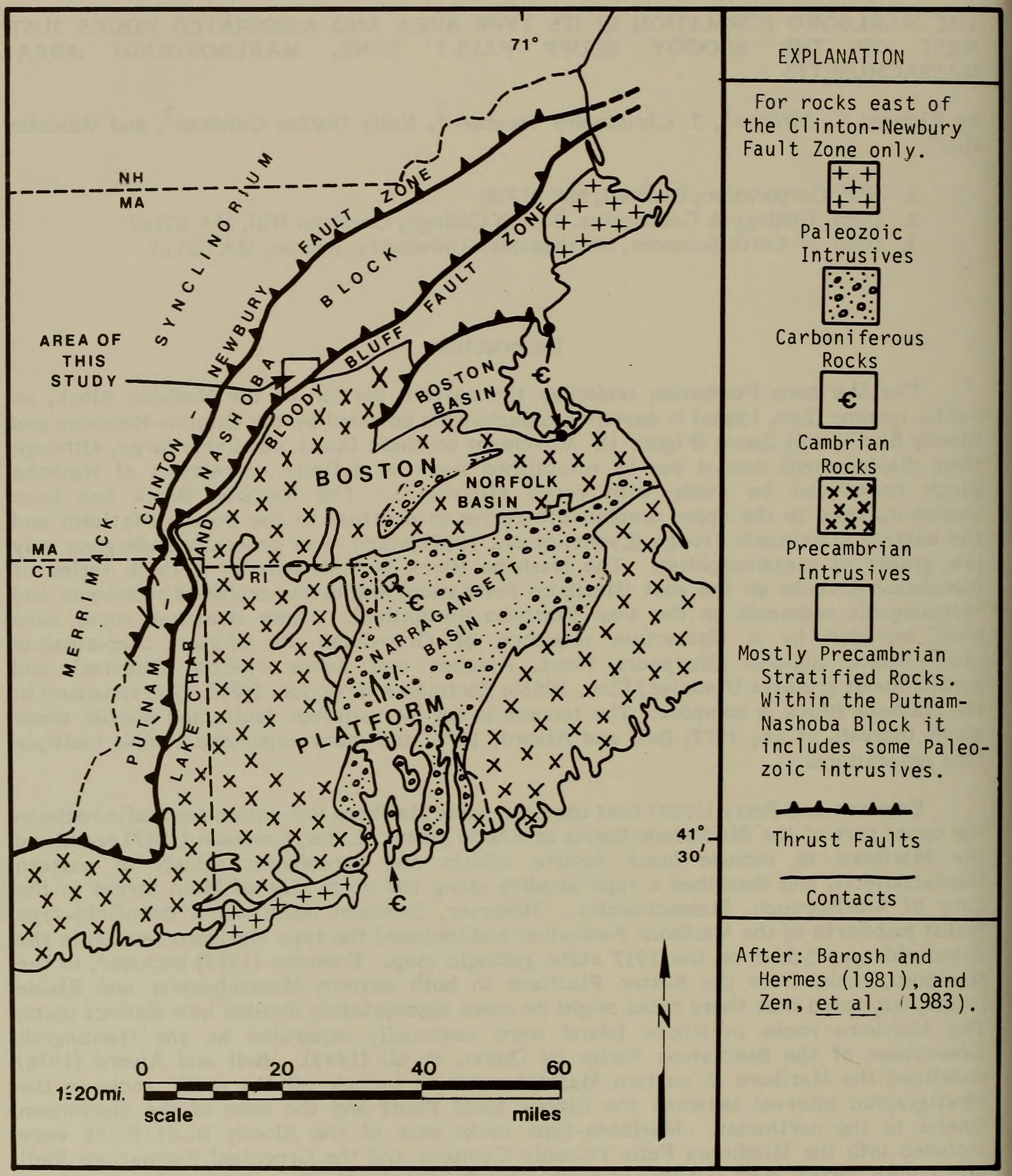



FIGURE 1 : Simplified Geologic Map of Southeastern New England.

to be at the same stratigraphic level as the Shawsheen Gneiss mapped by Bell and Alvord (1976) to the northeast (Figure 2). Lithologically, however, the three members in Marlborough do not appear to be similar to the Shawsheen Gneiss, making Bell and Alvord's (1976) definition difficult to apply in the Marlborough area.

Other work on the Marlboro in this region included mapping by Hansen (1956) in the Maynard and Hudson quadrangles, Nelson (1975a) in the Framingham quadrangle, Hepburn and DiNitto (1978) and Barosh (1978) in the Marlborough quadrangle. Skehan (1968), and Skehan and Abu-moustafa (1976) studied parts of the Marlboro in the Marlborough and Shrewsbury quadrangles during their mapping of the Wachusett-Marlborough Tunnel. Zen (1983b) on the recent state map of Massachusetts has summarized the previous mapping to date.

Our studies were taken to re-map and reevaluate Emerson's (1917) type locality for the Marlboro Formation and to determine whether any of the previously suggested correlations of the Marlboro rocks throughout eastern Massachusetts might still hold. As these studies progressed, other studies of the geochemistry of the Marlboro amphibolites were initiated to investigate the possible environment of emplacement and age for the Marlboro Formation.

## Stratigraphy

Two formations have been mapped within the Marlborough area: the Marlboro Formation to the east and the Nashoba Formation to the west (Figures 2, 3). The Marlboro Formation is fault bounded near its presumed base by the Bloody Bluff Fault and is separated from the Nashoba by the Assabet River Fault. Both formations strike northeast and have steep to moderate northwest dips. Repetition of strata is not observed, but some units or portions thereof are cut out by faulting. Bell and Alvord (1976) indicate that the rocks in the Nashoba Block likely form a homoclinal sequence topping toward the northwest. While the structure of the Nashoba Block is complex and topping directions within this sequence are as yet unknown, we will describe the units below in a general southeast to northwest direction away from the Bloody Bluff Fault Zone, consistant with Bell and Alvord's interpretation.

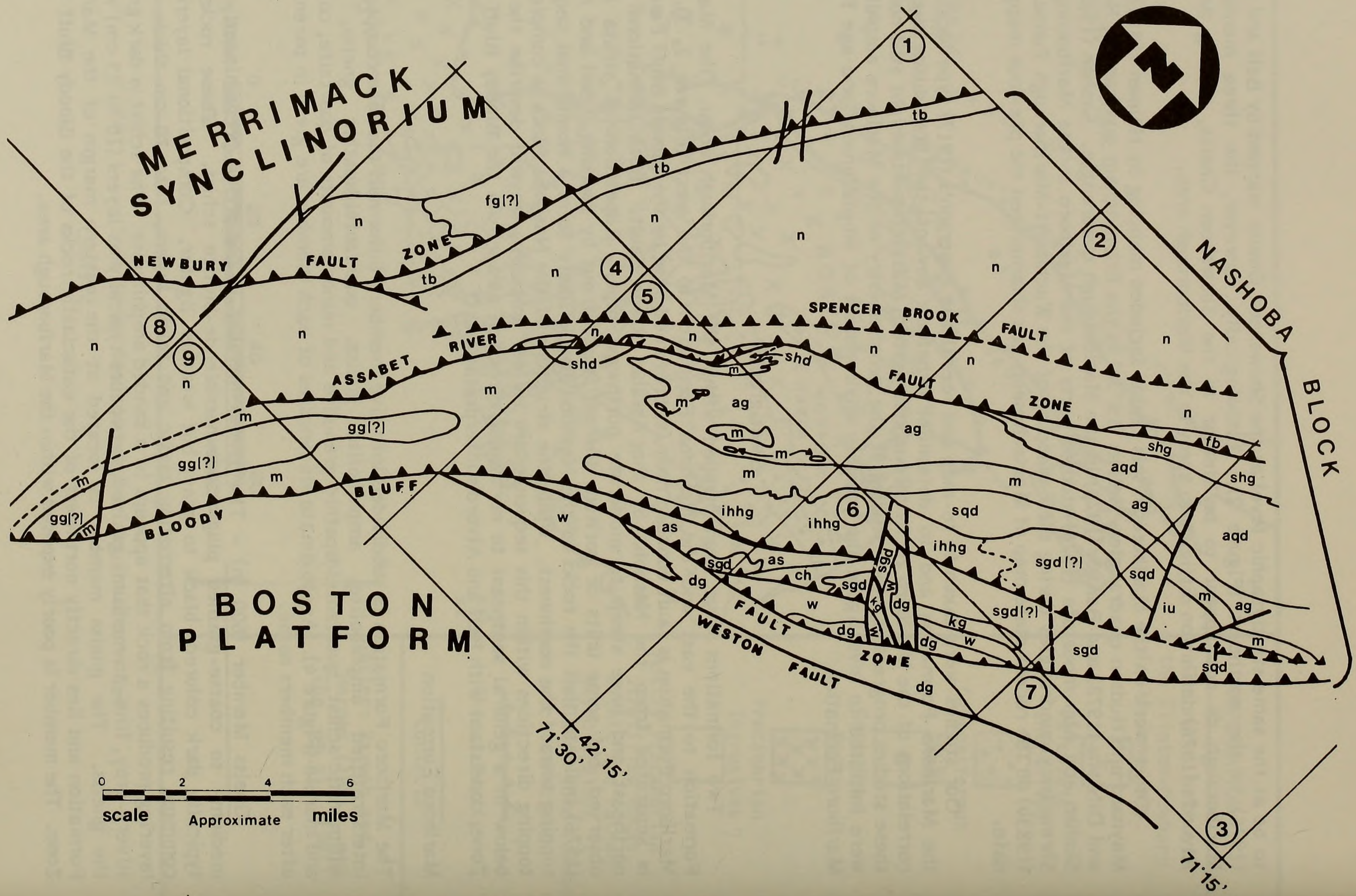
### Marlboro Formation

The Marlboro Formation is subdivided into five members (informal) that are composed of interstratified amphibolite, amphibolite gneiss, quartzofeldspathic gneiss, rusty sillimanitic schist, quartzofeldspathic granulite and minor amounts of quartzite, coticule and marble (Figure 4). Approximate thicknesses of each member are given in parenthesis after each members name.

Gneiss Member (600 m) - The gneiss member is comprised predominantly of a medium- to coarse-grained plagioclase-hornblende-biotite schist. These rocks are typically dark colored, black to gray, but weather lighter. Compositional layering is common, resulting from alternating mafic and felsic layers, 1 to 70 cm thick. The layering produces a rock that appears to a banded amphibolite. The schist is dark gray to silvery-gray, fine- to medium- grained and occurs typically as layers (10 to 25 cm) within the gneiss. The gneiss member is located at the eastern margin of the Marlboro Formation and lies directly northwest of the cataclastic rocks of the Bloody Bluff Fault Zone. The member is poorly exposed within the Marlborough area.

# FIGURE 2:

# REGIONAL GEOLOGIC MAP OF THE NASHOBA BLOCK, MA.



# KEY FOR FIGURE 2

## INTUSIVE ROCKS

LATE ORDOVICIAN TO EARLY DEVONIAN

- fg? — FITCHBURG GRANITE OF HEPBURN (1978), MUSCOVITE GRANITE OF SKEHAN & ABU-MOUSTAFA (1976).
- ihhg — INDIAN HEAD HILL GRANITE
- shd / aqd / sqd — STRAW HOLLOW DIORITE, shd; ASSABET QUARTZ DIORITE, aqd; SHARPNERS POND DIORITE, sqd
- sgd — SALEM GABBRO-DIORITE
- ag — ANDOVER GRANITE

AGE ?

- gg? — GRAFTON GRANITE (?)

PRECAMBRIAN

- dg — DEDHAM GRANODIORITE

AGE ?

- iu — INTRUSIVES, UNDIVIDED

## STRATIFIED ROCKS

PRECAMBRIAN TO ORDOVICIAN

- as — ALTERED AND SHEARED ROCKS
- ch — CLAYPIT HILL FORMATION
- kg — KENDALL GREEN FORMATION
- tb — TADMUCK BROOK SCHIST
- n — NASHOBA FORMATION
- fbg — FISH BROOK GNEISS
- shg — SHAWSHEEN GNEISS
- m — MARLBORO FORMATION
- w — WESTBORO FORMATION

CONTACTS, dashed where inferred

FAULTS, dashed where inferred

THRUST FAULTS, dashed where inferred

## QUADRANGLES

1. HUDSON, MA
2. MAYNARD, MA
3. CONCORD, MA
4. SHREWSBURY, MA
5. MARLBOROUGH, MA
6. FRAMINGHAM, MA
7. NATICK, MA
8. GRAFTON, MA

## SOURCES OF DATA

CONCORD QUADRANGLE : BELL & ALVORD (1976), BATTIN (1977).

FRAMINGHAM QUADRANGLE: NELSON (1975a), BELL & ALVORD (1976). DINITTO (RECONNAISANCE, 1977 & 1978).

HUDSON QUADRANGLE : HANSEN (1956), BELL & ALVORD (1976). DINITTO (RECONNAISANCE, 1977 & 1978).

MARLBOROUGH QUAD. : BELL & AVORD (1976), BAROSH (1978), HEPBURN & DINITTO (1978), DINITTO (1983).

MAYNARD QUADRANGLE : HANSEN (1956), BELL & ALVORD (1976), DINITTO (RECONNAISANCE, 1977 & 1978).

NATICK QUADRANGLE : NELSON (1975b).

SHREWSBURY QUAD. : BELL & ALVORD (1976), HEPBURN (1978), DINITTO (RECONNAISANCE, 1977).

ALL QUADRANGLES : BAROSH, et al. (1977), Zen (1983a).

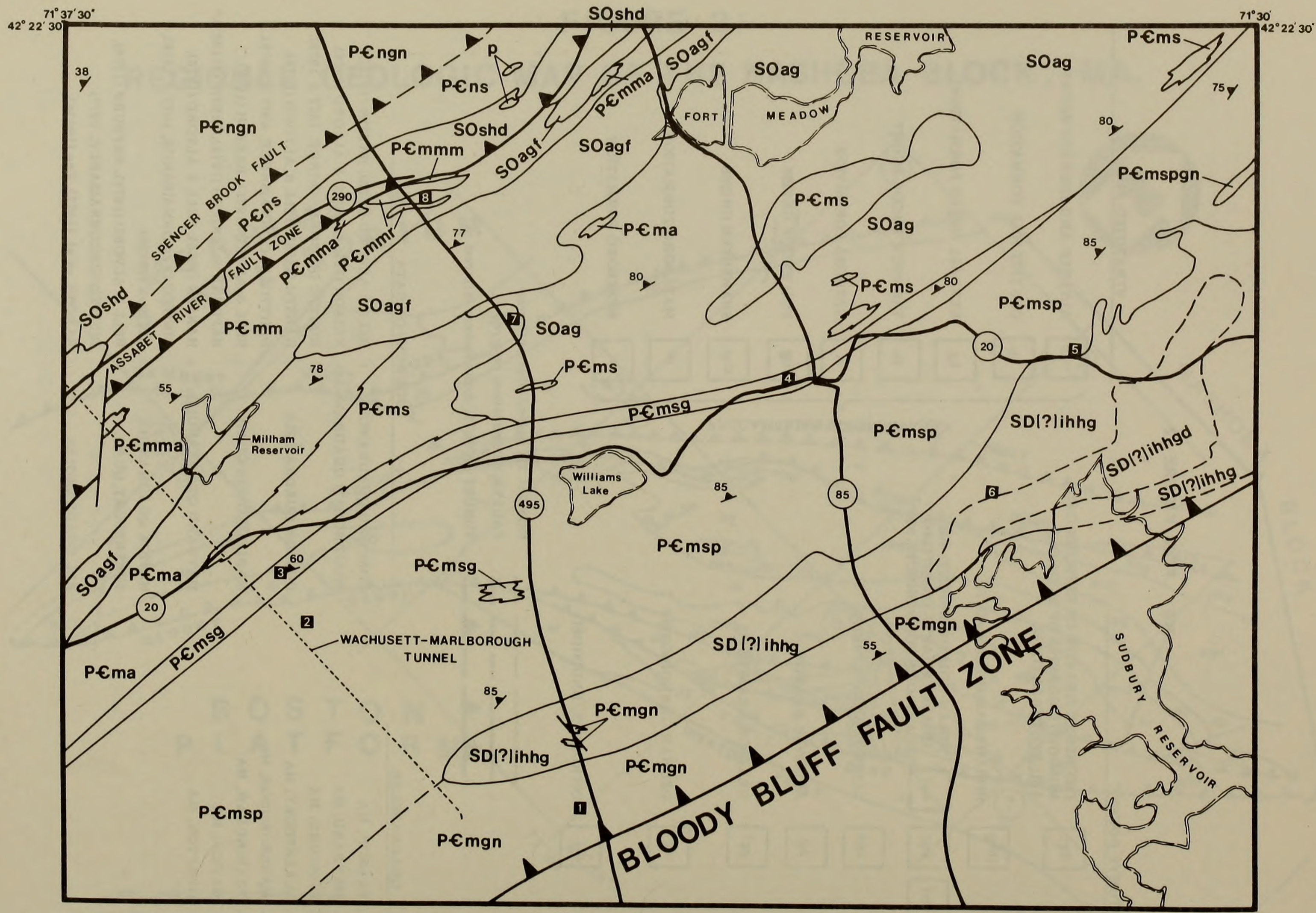
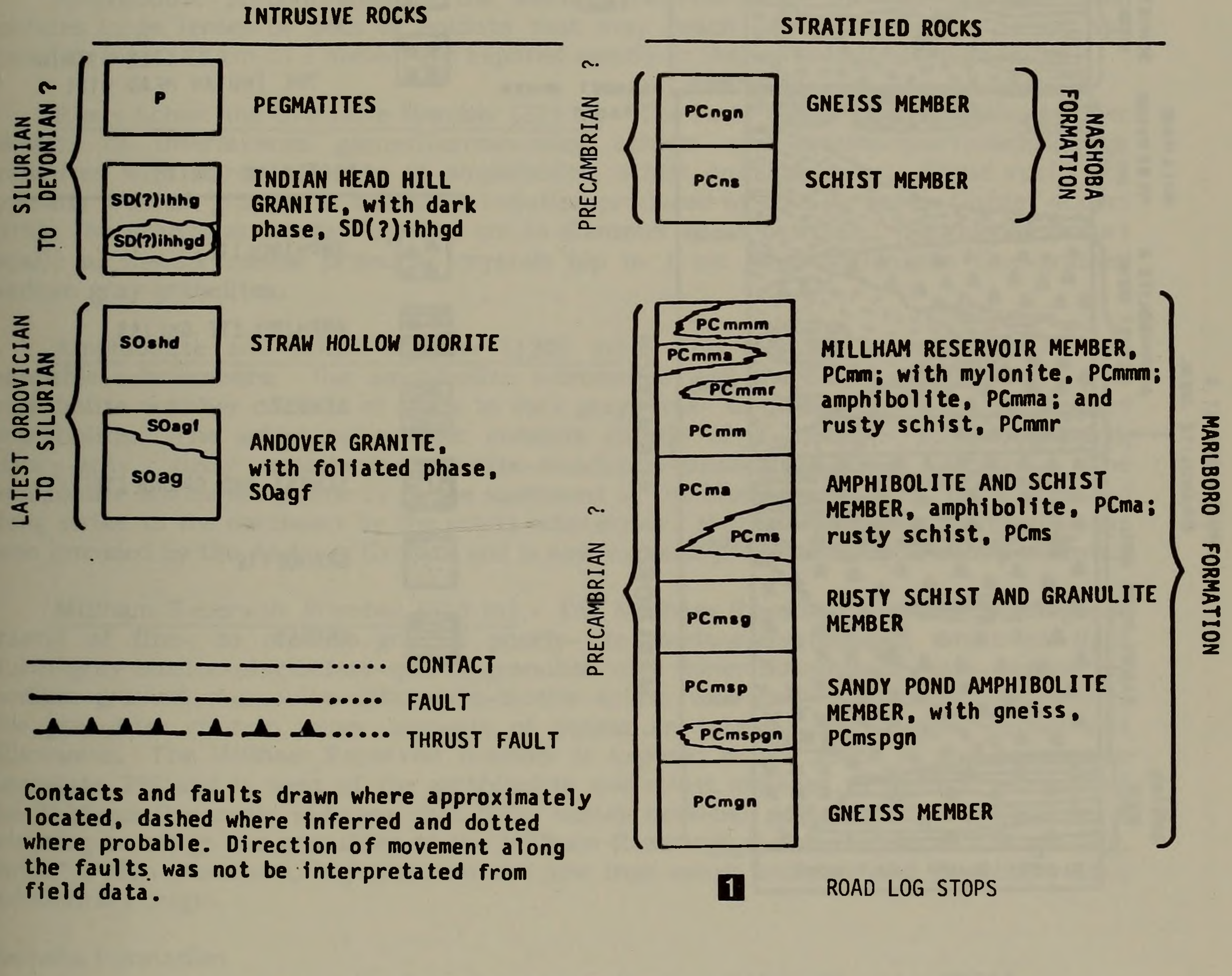



FIGURE 3: GEOLOGIC MAP OF THE NORTHERN HALF OF THE MARLBOROUGH QUADRANGLE, MA

## KEY FOR FIGURE 3



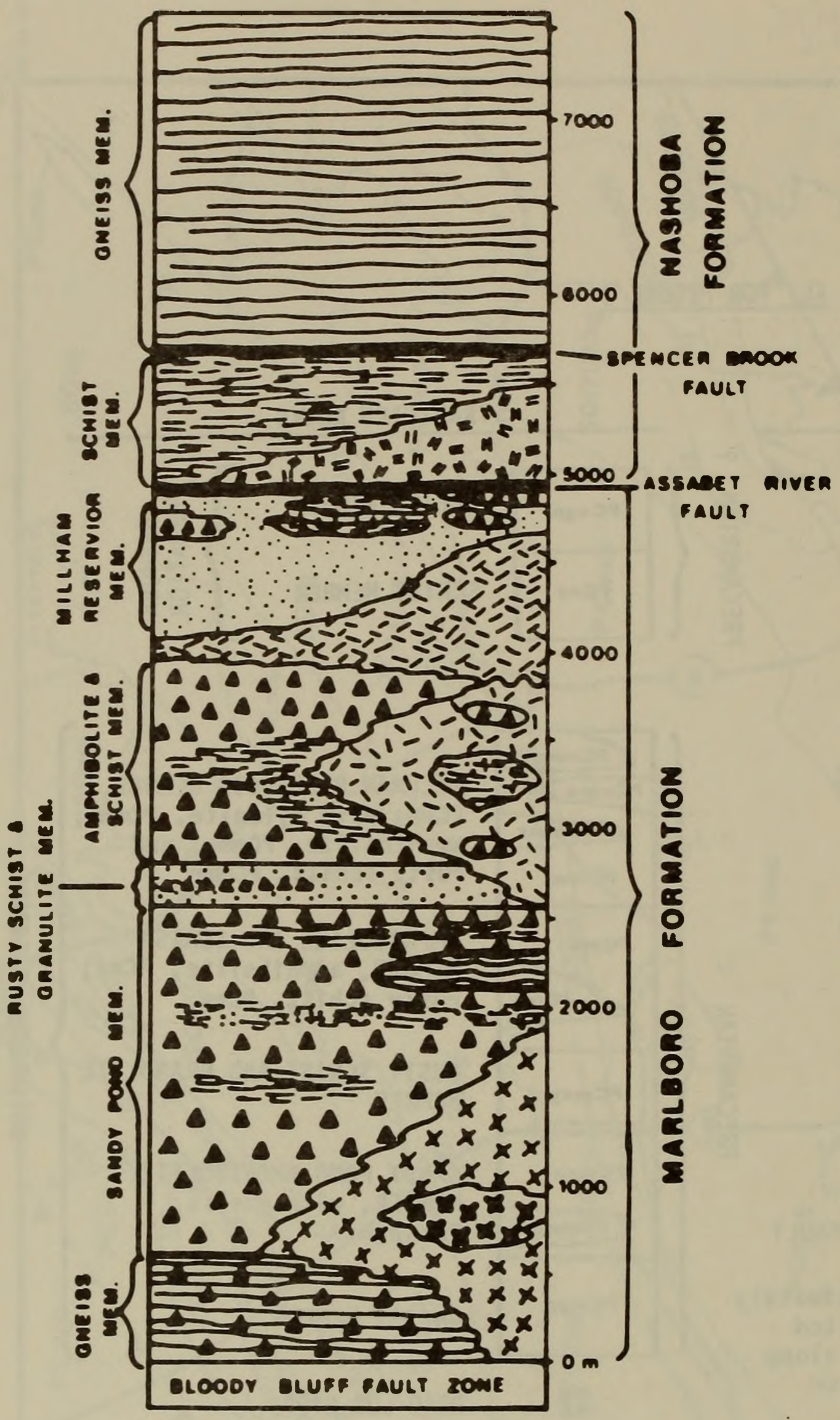



FIGURE 4 : Generalized stratigraphic column for the northwestern portion of the Marlborough quadrangle.

Sandy Pond Amphibolite Member (2000 m) - The Sandy Pond Amphibolite Member (Bell and Alvord 1976) consists predominantly of black, silvery-black, to dark gray, well-foliated, medium- to coarse-grained, massive to thinly layered amphibolites. Locally the amphibolites are interstratified with light gray to dark gray, garnet-sillimanite bearing biotite-quartz-plagioclase granulite and beige to light gray, moderately foliated, medium-grained biotite-sillimanite-plagioclase-quartz gneiss. Some of the foliation observed, results from the interlayering of thin, light gray granulite layers with the darker colored amphibolites and schists.

Amphibolite predominates in the western two-thirds of the member and often contains large lenses or pods of epidote that may reach 60 cm in legth. Schist and granulite layers (1 cm to 1 meter) are exposed mostly in the lower half of the member.

Rusty Schist and Granulite Member (225 m) - The rusty schist and granulite member consists of interlayered garnetiferrous-mica schists and biotite-quartzofeldspathic granulites with minor amounts of amphibolite, schist and quartzite. These rocks are typically medium gray, with a distinct foliation produced by fine laminae. Garnet occurs within the schists as crystals up to 5 cm in diameter or as coticule. Hornblende occurs locally as slender coarse prismatic crystals (up to 1 cm long) within the fine-grained medium gray granulites.

Amphibolite and Schist Member (1200 m) - This member is composed of two mappable submembers: the amphibolite submember and the schist submember. The amphibolite member consists of black to dark gray, fine- to coarse-grained, thick bedded amphibolite. The schist submember consists chiefly of a medium- to fine-grained, silvery-gray, rusty weathering biotite-muscovite-sillimanite-garnet schist. The amphibolite is exposed primarily to the southwest of the Marlborough area, being replaced along strike to the northeast by the schist submember. Much of the schist submember has been intruded by the Andover Granite and is now exposed predominantly as roof pendants.

Millham Reservoir Member (915 m) - The Millham Reservoir member is composed chiefly of fine- to medium-grained poorly- to moderately-foliated, white to light bluish-gray biotite-plagioclase-quartz granulite with minor amounts of rusty-weathering medium-grained muscovite-sillimanite-biotite-schist and coarse-grained, amphibolite. The granulites contain minor amounts of potassium feldspar, hornblende, garnet and sillimanite. The Millham Reservoir member is exposed to the south of and parallel to Interstate 290 and is west of the amphibolite and schist member. Chemical analysis of the Millham Reservoir indicate that $SiO_2$ varies between 66% and 69%. While it is tempting to assign the granulites of the Millham Reservoir member a volcanic origin (e.g. dacite?), high aluminum, high calcium and low iron values indicate the possibility of a sedimentary origin.

Nashoba Formation

The Nashoba Formation, in the Marlborough quadrangle is separated from the Marlboro Formation by the Assabet River Fault. The Nashoba Formation can be divided into two informal units that consist of rusty-weathering sillimanite-garnet schist and quartzo-feldspathic gneiss. Recent mapping by Bell and Alvord (1976) has distinguished 10 members of the Nashoba Formation primarily in areas to the northeast of Marlborough. The extent of these members in the Marlborough area and to the southwest is not well documented.

Schist Member (760 m) - The schist member consists of a silvery-medium to dark gray, rusty-weathering, medium-grained, garnet-sillimanite schist. Many garnets are megacrystic. Rocks of this member are poorly exposed and highly weathered. The eastern contact of this unit is considered to be the Assabet River Fault, but is not exposed in the field.

Gneiss Member - The gneiss member consists of silvery-dark gray, medium- to coarse-grained, strongly foliated, muscovite-biotite-sillimanite-plagioclase-quartz gneiss. Interlayered, locally are thin (5 to 30 cm) beds of sillimanite-muscovite-biotite schists. The strong foliation within the gneiss is developed by segregational layering that is common to the Nashoba gneisses. The western contact of this member is not located within this study area. Previous workers (Bell and Alvord, 1976; Barosh, 1978) have mapped a fault, the Spencer Brook Fault, at a postition that coincides with the contact between the schist and gneiss members. While field evidence of this fault is lacking in the Marlborough area, aeromagnetic data indicates a possible lineament near the contact that may be the result of a fault (Castle, et al., 1976).

## Plutonic Rocks

Three distinct igneous units are differentiated within the Marlborough area. These are the Indian Head Hill Granite, the Straw Hollow Diorite, and the Andover Granite.

### Indian Head Hill Granite

The Indian Head Hill Granite includes both a granitic phase and an older dioritic phase (see Hill, et al., this volume). The rocks that form the main pluton are medium gray, fine- to medium-grained, non-foliated, equigranular, biotite granites. The dioritic phase includes a biotite-potassium feldspar-hornblende-plagioclase diorite and a quartz-diorite. Both diorites are medium gray to black, locally foliated, and medium- to coarse-grained. Locally, the diorite is seen as xenoliths (up to 0.5 m in length) within the granite.

The Indian Head Hill Granite intrudes the eastern two members of the Marlboro Formation and is named after exposures at Indian Head Hill in Marlborough. Emerson first included these rocks within the Dedham Granodiorite, but had noted the differences of the exposures at Indian Head Hill.

### Andover granite

The Andover Granite, originally described by Clapp (1910) for exposures in Essex County, Massachusetts is the largest pluton within the Nashoba Block (Zen, 1983b). Within the Marlborough area, the Andover can be divided into two phases: a massive and a foliated phase. The massive phase consists of white to beige, coarse-grained, garnet-muscovite granite to granodiorite. The foliated phase consists of light to medium gray, medium- to coarse-grained, strongly foliated, garnet-muscovite-biotite granite that is mildly to strongly cataclastic in texture. The amphibolite and schist member and the Millham Reservoir member are both intruded by the Andover Granite.

### Straw Hollow Diorite

The Straw Hollow Diorite, also referred to as the Assabet Quartz Diorite by Barosh (1978) and Bell and Alvord (1976), was first identified by Emerson (1917) and later mapped by Hansen (1956) within the town of Hudson. The Straw Hollow Diorite consists of a fairly uniform, equigranular, medium-grained, dark bluish-gray, weakly-foliated, biotite-quartz-plagioclase-hornblende diorite. The Straw Hollow Diorite intrudes both the Nashoba and Marlboro Formations along the Assabet River Fault.

## Geochemistry of the Marlboro Formation Amphibolites

Despite the fact that the Marlboro amphibolites are metamorphic rocks,the geochemical data as a whole are quite coherent and retain igneous information. The alkali and alkaline-earth elements (K, Rb, Cs, Sr, Ba) have to some extent mobilized during metamorphism, causing the scatter seen on Figure 6, for these elements. The major element compositions (see representative data in Table 1) indicate the basalts were mildly alkaline to high alumina basalts ($TiO_2$ = 0.8-2.3%, $Al_2O_3$ = 15.5-18.5%, Mg numbers = 0.57-0.66). They are slightly Light Rare Earth Element (LREE) enriched (Figure 5); that is consistent with the higher concentrations of the incompatible elements compared to the more to compatible (left to right) elements on the "spidergram" (Figure 6). Also note on Figure 6 the distinctly lower Ta and Nb contents, relative to Th and Ce, for most samples for which data is available. This pattern is characteristic of basalts erupted at convergent plate boundaries or in marginal basins (Baker, 1984; Hole, et al., 1984; Marriner and Millward, 1984).

TABLE 1

| WT. % | K1 | K2 | K3 | K7 | K9 |
|---|---|---|---|---|---|
| $SiO_2$ | 47.57 | 45.99 | 48.43 | 47.06 | 49.18 |
| $TiO_2$ | 2.22 | 1.64 | 2.04 | 1.33 | 1.75 |
| $Al_2O_3$ | 15.30 | 16.72 | 16.15 | 18.37 | 13.30 |
| *$Fe_2O_3$ | 12.65 | 11.29 | 11.30 | 9.09 | 11.17 |
| MnO | 0.40 | 0.34 | 0.35 | 0.20 | 0.25 |
| MgO | 8.12 | 10.21 | 6.66 | 7.71 | 10.12 |
| CaO | 9.97 | 9.80 | 11.02 | 12.28 | 11.27 |
| $Na_2O$ | 2.95 | 2.74 | 3.79 | 3.34 | 2.35 |
| $K_2O$ | 0.24 | 0.60 | 0.18 | 0.28 | 0.19 |
| $P_2O_5$ | 0.24 | 0.18 | 0.18 | 0.28 | 0.14 |
| Total | 99.66 | 99.51 | 100.11 | 99.95 | 99.71 |

* Total Iron as $Fe_2O_3$

Neodymium isotope studies of 10 whole rocks (Hill, et al., 1984) did not yield an isochron, indicating either heterogeneity of the mantle source or, more likely, variable contamination with LREE-enriched crustal rocks. The Nd evolution diagram (Figure 7) shows clearly that the basaltic protoliths for the amphibolites formed by melting of a long-term LREE-depleted mantle source, quite similar to the source of most Mid-Ocean Ridge Basalts (MORB) and arc basalts today. Also shown on Figure 7 is the documented range in 143/144Nd with time for a MORB-source mantle, taken from Hart and Brooks

FIGURE 5

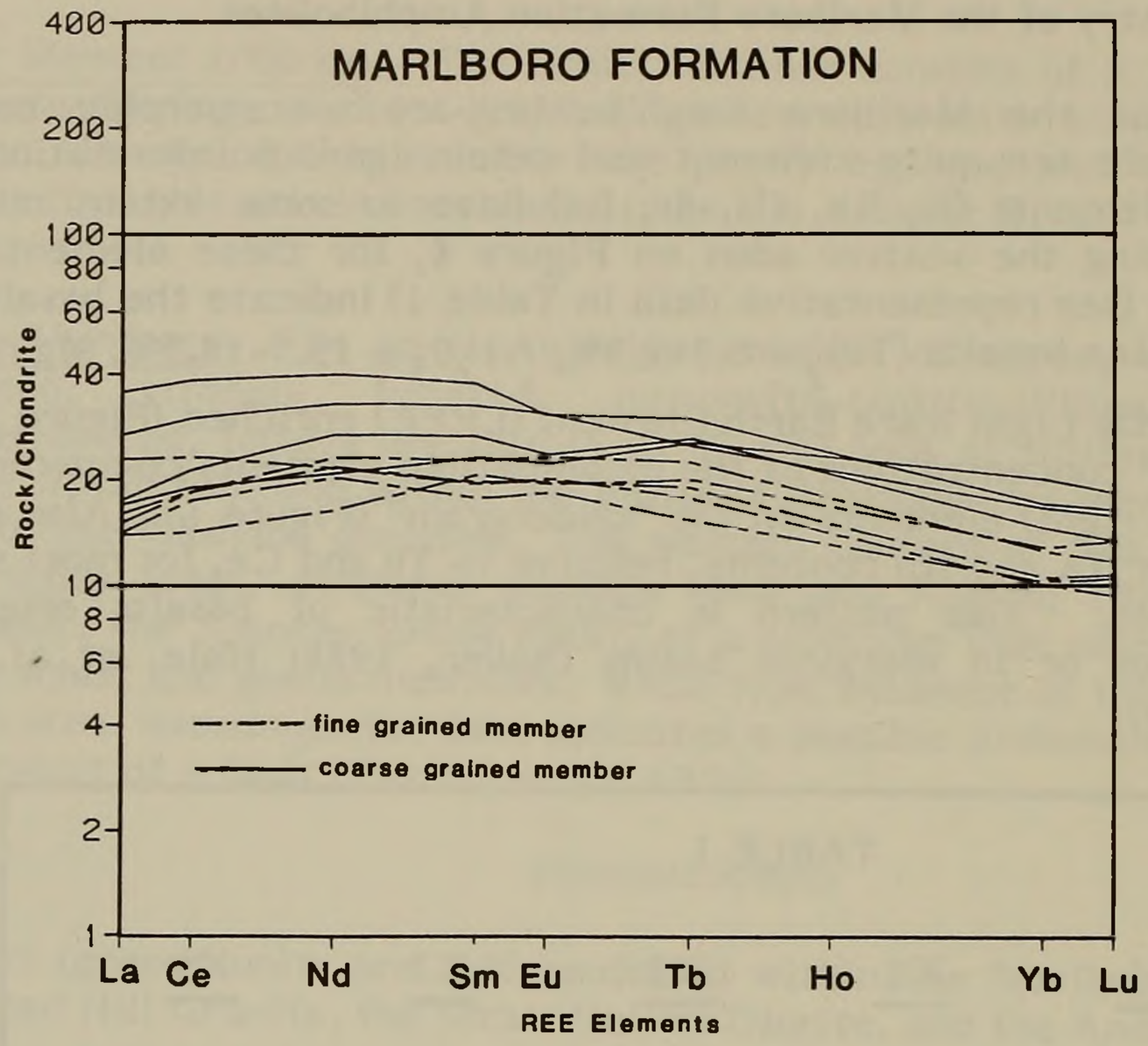
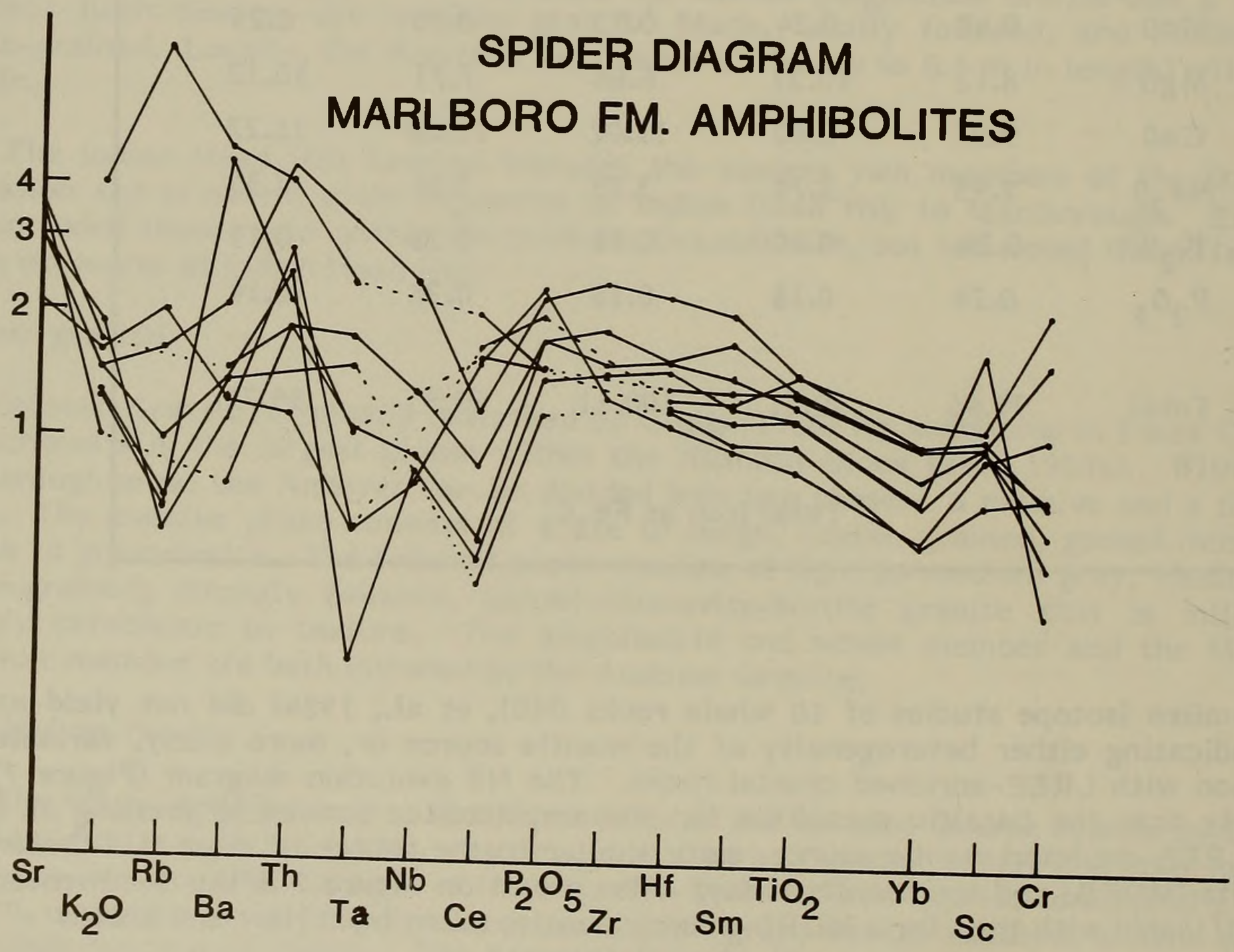
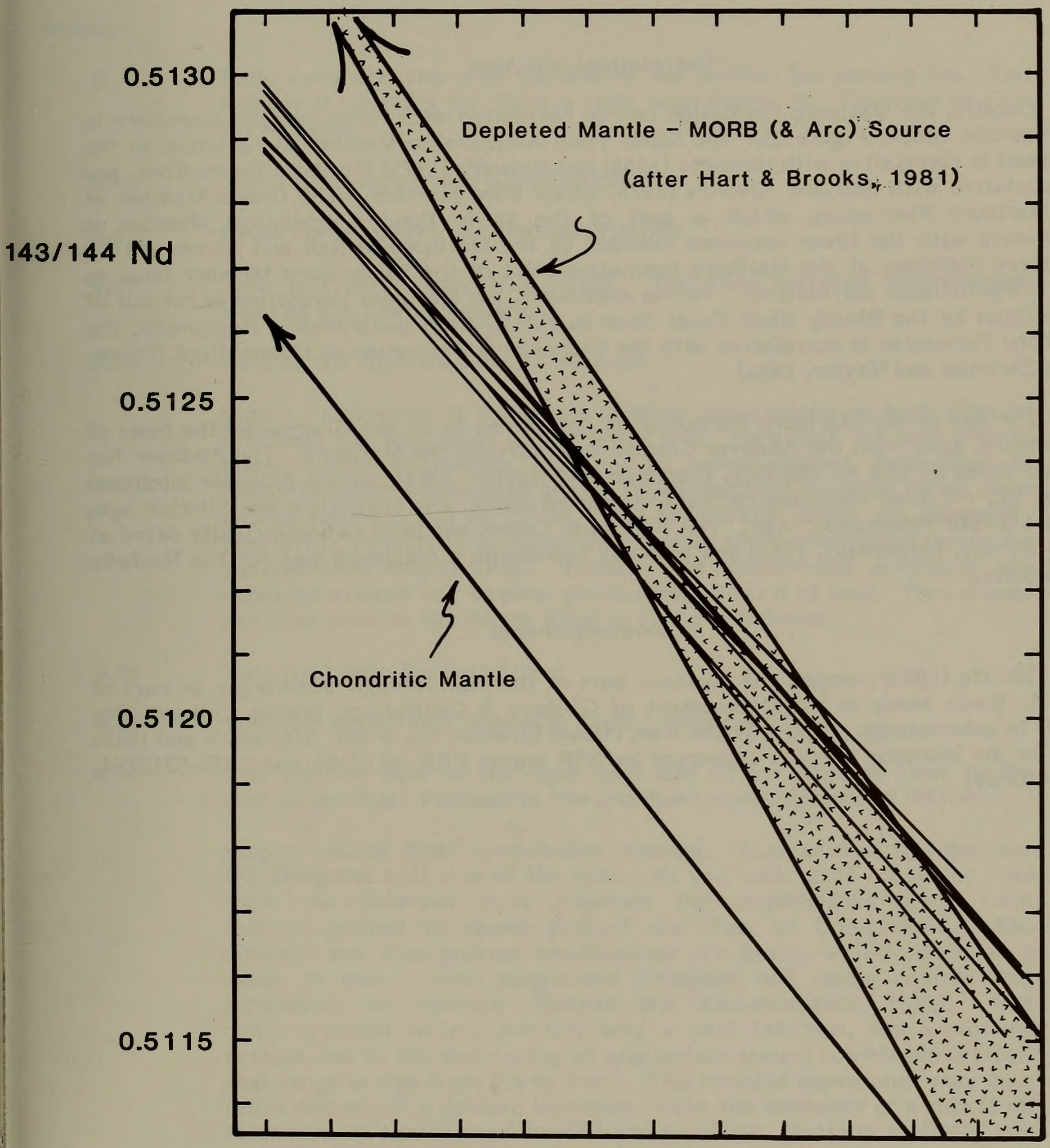



FIGURE 6



# FIGURE 7:
# ND EVOLUTION DIAGRAM
# MARLBORO FM. AMPHIBOLITES



(1981); this source should also apply to a sub-arc mantle. Model ages (the times of intersection of the rock 143/144Nd growth curves with this depleted mantle range) confirm a pre-450 m.y. age for the Marlboro. The most likely age lies in the range 450 to 550 m.y. because older intercepts are more likely to reflect contamination with LREE enriched crust. However, Late Proterozoic ages cannot be ruled out based on the present data.

## Correlations and Ages

Locally, the Marlboro Formation can be correlated with rocks mapped elsewhere in the Nashoba Block (Figure 2). The Sandy Pond Amphibolite Member along strike to the northeast is correlative with Hansen's (1956) and Nelson's (1975) Marlboro Formations, and is correlative with Bell and Alvord's (1976) Sandy Pond Member. The Gneiss Member of the Marlboro Formation, which is east of the Sandy Pond Amphibolite Member is correlative with the lower unnamed member of the Marlboro of Bell and Alvord (1976). The three members of the Marlboro Formation west of the Sandy Pond Member have no clearly identifiable correlatives. To the southwest, the Marlboro Formation is cut out of the section by the Bloddy Bluff Fault Zone in the Grafton quadrangle. Regionally, the Marlboro Formation is correlative with the Quinnebaug Formation of Connecticut (Dixon, 1968; Zartman and Naylor, 1984).

The age of the Marlboro Formation is considered to be pre-Silurian on the basis of radiometric ages from the Andover Granite that intrudes the Marlboro. The Andover has yielded dates of 408 to 450 m.y. (Zartman and Naylor, 1984), with a probable minimum age of 430 $\pm$ 5 m.y. Geochemical data, discussed above, also suggests a pre-Silurian age, but not a late Proterozoic Age. The Fishbrook Gneiss has been radiometrically dated at 730 $\pm$ 26 m.y. (Olszewski, 1980) and probably represents a maximum age for the Nashoba Block units.

## Acknowledgements

DiNitto (1983) mapped the northern part of the Marlborough Quadrangle as part of an M.S. thesis study in the Department of Geology & Geophysics, Boston College. He wishes to acknowledge support by the Rev. Daniel Linehan, S.J. Fund. Hepburn's and Hill's work on the Nashoba Block is supported by NSF grants EAR-8212760 and EAR-8212761, respectively.

# Road Log

Meet at the Holiday Inn parking lot, Marlborough, Massachusetts promptly at 9:00 a.m. It is located at the intersection of U.S. Route 20 and Interstate 495. To reach the Holiday Inn from Danvers, Massachusetts, take Interstate 95 (State Route 128) south to the Massachusetts Turnpike. Travel west on the turnpike, exiting at I-495 north. Proceed north on I-495 until you reach the Marlborough, Route 20 exit. Take the Route 20, east exit ramp. The Holiday Inn is directly across Route 20 from where you exit I-495.

| Mileage | |
|---|---|
| 0 | Field excursion starts at the side of the Holiday Inn parking lot. Exit Holiday Inn parking lot. Take a right onto Route 20. Continue to first set of lights. |
| 0.40 | Turn left at lights onto Glenn Street. |
| 0.95 | Cross Forest Street and continue straight. |
| 2.05 | Take left onto Cedar Hill Street. This road becomes Northborough Road at the Town boundary. |
| 2.70 | Park on the right shoulder of the road. |

Stop 1. Exposures of the gneiss member are exposed on both sides of the road; the best being on the south side. Seen here are dark gray to black, lighter weathering, medium- to coarse-grained, moderately to highly-foliated amphibolite gneiss. Segregational layering varies from approximately 5 mm to 15 cm. The leucocratic layers are commonly pegmatitic to dioritic in composition, while the darker mafic layers are well-foliated amphibolites. Locally, the amphibolite dominates the exposure without any obvious gneissosity. Return to cars. Turn around and head west on Northboro Road to Cedar Hill Street

| | |
|---|---|
| 4.30 | Turn right onto Bartlett Street |
| 4.45 | Turn left onto Hayes Memorial Drive. Head north. |
| 4.90 | Pull vehicles over to the right hand side of the road, as close to the curb as possible. Proceed to the sourthern most exposure at this stop. |

Stop 2. Sandy Pond Amphibolite Member. Exposures of this member are along the east side of the road. As you walk north along the road from the southern most exposure the amphibolites grade from medium-grained to coarse-grained and then to fine-grained. The medium and fine-grained amphibolites are black, well-foliated as a result of thin (1 mm) plagioclase stringers, and rarely contain thin interlayers of "epicule" (Skehan and Abu-moustafa, 1976). The coarse-grained variety exhibits only a mild foliation, and a mottled texture due to the weathering of plagioclase around hornblende crystals that range in size from 0.5 to 2 cm). This mottled appearance may be a relict texture of a gabbric intrusion. Note the existance of a thin (1 m) fault zone in the coarser amphibolite exposure. A flinty mylonite can be seen in the fault. The amphibolites at this exposure trend approximately N75E and dip 55 NW. Return to cars. Continue north on Hayes Memorial Drive.

5.20 Pull vehicles over to the right hand side of the road.

Stop 3. The rusty schist and granulite member exposed here consists of thinly interlayered, medium-gray, lighter gray weathering, fine- to medium-grained granulite; medium gray, rusty-weathering, fine- to medium-grained schist; and black, poorly foliated, fine- to medium-grained amphibolite. The dominant foliation seen here results from the interlayering and differential weathering of the three rock types. Also, note the conspicuous garnet crystals within the schist. Prior to the covering of portions of this outcrop garnet megacrysts up to 5 cm in size could be observed. Return to cars. Continue north on Hayes Memorial Drive.

5.30 Exposure on both sides of the road are amphibolites of the amphibolite and schist member of the Marlboro Formation.

5.35 Turn right onto Route 20, eastbound.

6.85 Cross over I-495 and continue straight.

8.35 Entering Marlborough Center. Exposure on the left hand side of Route 20, behind the storefront buildings, is Emerson's (1917) type locality for the Marlboro Formation.

8.65 Turn left into parking lot located just past City Hall, which is on the right hand side.

Stop 4. Along the north side of Main Street is the type locality of the Marlboro Formation defined by Emerson (1917). Please view only those rocks exposed at the edge of the parking lot, as local store owners have not given permission to walk behind the buildings. Additionally, the town has asked that no hammers be used because of landscaping activities the town has performed recently. Exposed here are interlayered rusty-weathering fine- to medium-grained, muscovite-biotite schist; medium gray, fine-grained, moderately-foliated granulite; and medium-grained, black to bluish-dark gray amphibolite. The rocks here trend nearly east-west (N8OE) with a steep dip (80°N). The exposure also contains numerous small open folds whose axial planes trend nearly east-west and have shallow dips to the north. One thin layer (10 cm) of granulite contains conspicuous porphyroblasts of hornblende that reach 2 cm in length. Return to cars. Take a left when exiting the parking lot and continue east along Route 20.

8.85 Turn left following Route 20, east. Exposures on the left hand side are amphibolites of the Sandy Pond Amphibolite Member of the Marlboro Formation.

9.15 Turn right at the lights following Route 20, east.

9.55 Continue through the lights along Route 20, east.

10.35 Turn left into Fire Station driveway. Please park only along the left hand side of the driveway.

Stop 5. Exposures behind the Fire Station are medium gray to black, medium- to coarse-grained, well-foliated epicule-bearing amphibolites of the Sandy Pond Amphibolite Member. These rocks are typical of the Sandy Pond and contain large conspicuous lenses and pods (up to 60 cm in length) of light green epicule, parallel to the foliation. Return to cars. Exit left from the fire station driveway.

10.45 Lunch stop. Turn left into McDonald's. Exit left from the parking lot, and continue along Route 20, east.

10.90 Turn right onto Farm Road.

11.10 Pass Marlboro Airport on left.

12.05 Pull vehicles off of the right hand side of the road. BE CAREFUL, watch for cars coming around the corner.

Stop 6. Indian Head Hill Granite. The granite here is an equigranular, medium-grained, bluish-medium gray granite that weathers to a ligher gray or a rusty beige color. This exposure is very typical of the Indian Head Hill exposed in the Marlborough area. Return to cars. Continue straight on Farm Road.

12.75 Turn right onto Framingham Road.

13.30 Turn right onto Maple Street and continue north back towards Marlborough Center.

13.90 Turn left following Maple Street. Continue straight on Route 20, west.

15.90 Take first ramp onto I-495 northbound, from Route 20.

16.70 Park on right-hand side of highway on the grass. Make sure your vehicle is off the breakdown lane.

Stop 7. This large roadcut on both sides of the highway belongs to the schist submember of the amphibolite and schist member of the Marlboro Formation, and represents the type locality for the schist submember. Exposed are highly-weathered, rusty-sillimanitic schists that are interlayered with minor amounts of dark gray to black, poor- to moderately-foliated, medium-grained amphibolite, quartzite and light gray, fine-grained granulite. Andover Granite intrusions can be seen throughout the roadcut, but are primarily exposed at the extreme northern end. Return to cars and continue northward on Route I-495.

17.00 Take exit 25A from I-495 to I-290, eastbound.

17.30 Pull vehicles off the exit ramp to the left and park on the grass. Lock your vehicles. Walk back along the exit ramp towards I-495, just south of the exit ramp.

Stop 8. At the southern end of this exposure is the foliated phase of the Andover Granite. The rock here is a light gray to white weathered, porphyritic, medium- to coarse-grained biotite-muscovite-garnet granite. The foliation seen here is produced by the wrapping of fine-grained micas around augens of plagioclase. The texture is cataclastic in origin, and would be classified as a protomylonite.

Proceeding northward, approximately 60 feet along the right side of I-495, towards the exit ramp to I-290, are exposures of the Millham Reservoir member of the Marlboro Formation. The Millham here, consists of a medium bluish-gray, light gray weathering, medium-grained, poorly to moderately-foliated granite. Many stringers and porphyroclasts of quartz and plagioclase define the foliation. These rocks are also considered to be protomylonites on the basis of cataclastic testures.

Continuing northward along the east side of the exit ramp the rocks in the roadcut change to a rusty-weathering sillimanitic schist that is highly weathered in places. The schist forms two rather large lenses within the Millham granulites at this I-495 and I-290 roadcut (Figure 3). These schists are very simlar to those of the schists of the amphibolite and schist member of the Marlboro Formation. Proceeding northeasterly towards the merger of the exit ramp from I-495 with the eastbound lane of I-290 the rocks become very sheared and represent a mylonitic submember of the Millham Reservoir member. These rocks grade (southwest to northeast) from protomylonite to ultramylonite. The rocks vary in textures and colors from medium bluish-grays and porphyroclastic protomylonite to fine-grained darker mylonite to very fine-grained, medium to light whitish-gray ultramylonite. All of the rocks are highly foliated and represent the presumed trace of the Assabett River Fault Zone. Return to cars. Continue on exit ramp towards I-290, eastbound. Follow I-290 to the end.

18.40 Turn right onto Fitchburg Street.

20.10 Continue through the intersection at the lights, crossing Elm Street.

20.30 Turn right onto Lincoln Street.

20.75 Merge with Route 20, west.

21.40 Turn right into Holiday Inn parking lot. End of road log.

# References


Baker, P.E., 1984, Geochemical evolution of St. Kitts and Montserrat, Lesser Antilles: Jour. Geol. Soc. London, v. 141, p. 401-411.

Barosh, P. J., 1978, Reconnaissance Bedrock Geologic Map of the Marlborough Quadrangle, Massachusetts: U.S. Geol. Survey Open-File Report, OF 78-221, 1:24,000.

Barosh, P.J., Fahey, R. J., and Pease, M. J., 1977, Preliminary Compilation of the Bedrock Geology of the land area of the Boston 2° sheet, Massachusetts, Connecticut, Rhode Island and New Hampshire: U.S. Geo. Survey, Boston, Massachusetts, 138 p.

Battin, D. P., 1977, Bedrock Geology of the Southeastern Concord and the Northern Natick Quadrangles, Massachusetts (Masters thesis): Unpublished, Boston College, Chestnut Hill, MA, 64 p.

Bell, K. G., and Alvord, D. C., 1976, Pre-Silurian Stratigraphy of Northeastern Massachusetts, in Page, L. R., ed., Contributions to the Stratigraphy of New England: Geol. Soc. Amer. Memoir 148, p. 179-216.

Castle, R. O., Dixon, H. R., Grew, E. S., Griscom, A., and Zietz, I., 1976, Structural Dislocations in Eastern Massachusetts: U.S. Geol. Survey Bull. 1410, 39 p.

Clapp, C. H., 1910, Igneous rocks of Essex County, Massachusetts: abstract of thesis, M.I.T., 12 p.

DiNitto, R. G., 1983, Bedrock Geology of the Marlborough Area, Massachusetts (Masters thesis): Unpublished, Boston College, Chestnut Hill, MA, 218 p.

Dixon, H. R., 1968, Bedrock Geologic Map of the Danielson Quadrangle, Connecticut: U.S. Geol. Survey Quad. Map, No. GQ-696.

Emerson, B. K., 1917, Geology of Massachusetts and Rhode Island: U.S. Geol. Survey Bull. 597, 289 p.

Emerson, B. K., and Perry, J. H., 1907, the Green Schists and associated Granites and Porphyries of Rhode Island: U.S. Geol, Survey Bull. 311, 74 p.

Hansen, W. R., 1956, Geology and Mineral Resources of the Hudson and Maynard Quadrangles, Massachusetts: U.S. Geol. Survey Bull. 1038, 104 p.

Hart, S. R., and Brooks, C., 1981, Sources of Terrestrial basalts: an isotopic viewpoint, in Basaltic Volcanism Study Project: Pergamon Press, Inc., N.Y., p. 987-1014.

Hepburn, J. C., 1978, Preliminary Reconnaissance Bedrock Geologic Map of the Shrewsbury quadrangle, Worcester County, MA: U.S. Geol. Survey Open-File Report OF-78-951, 1:24,000.

Hepburn, J. C., and DiNitto, R. G., 1978, Preliminary Bedrock Geologic Map of the Marlborough quadrangle, Middlesex and Worcester Counties, MA: U.S. Geol. Survey Open-File Report OF 78-222, 1:24,000.

Hill, M. D., Hepburn, J. C., and Durfee, K., 1984, Isotope and trace element geochemistry of mafic volcanic and intermediate plutonic rocks from the Nashoba Terrane, eastern Massachusetts: Geol. Soc. Amer., Abstracts with Programs, v. 16, p. 24.

Hole, M. J., Saunders, A. D., Marriner, G. F., and Tarney, J., 1984, Subduction of pelagic sediments: implications for the origin of Ce-anomalous basalts from the Mariana Islands: Jour. Geol. Soc. London, v. 141, p. 453-472.

Lacroix, A. V., 1968, Structure and Contact Relationships of the Marlboro Formation, Marlboro, Massachusetts (M. S. Thesis): Chestnut Hill, MA, Boston College, 83 p.

Lyons, J. B., Boudette, E. L., and Aleinikoff, J. N., 1982, The Avalonian and Gander Zones in Central New England: in St-Julien, P. and Beland, J., eds., Major Structural Zones and Faults of the Northern Appalachians: Geol. Assoc. Canada, Spec. Paper 24, p. 43-66.

Marriner, G. F., and Millward, D., 1984, The petrology and geochemistry of Cretaceous to Recent volcanism in Columbia: the magmatic history of an accretionary plate margin: Jour. Geol. Soc. London, v. 141, p. 473-486.

Nelson, A. E., 1975a, Bedrock Geologic Map of the Framingham Quadrangle, Middlesex and Worcester Counties, Massachusetts: U.S. Geol. Survey Quad. Map GQ-1274, 1:24,000.

Nelson, A. E., 1975b, Bedrock Geologic Map of the Natick Quadrangle, Middlesex and Worcester Counties, Massachusetts: U.S. Geol, Survey Quad. Map GQ-1208, 1:24,000.

Olszewski, W. J. Jr, 1980, The Geochronology of some Stratified Metamorphic Rocks in Northeastern Massachusetts: Can. Jour. Earth Sci., v. 17, p. 1407-1416.

Quinn, A. W., Ray, R. G., and Seymour, W. L., 1949, Bedrock Geology, Pawtucket quadrangle, Rhode Island-Massachusetts: U.S. Geol. Survey Quad. Map, GQ- (1), 1:24,000.

Skehan, S. J. J. W., 1968, Fracture Tectonics of Southeastern New England as Illustrated by the Wachusett-Marlborough Tunnel, East-Central Massachusetts, in Zen, E-an and others, eds., Studies of Appalachian Geology-Northern and Maritime: New York, Interscience pubs., p. 281-290.

Skehan, S. J., J. W., and Abu-moustafa, A. A., 1976, Stratigraphic Analysis of Rocks Exposed in the Wachusett-Marlborough Tunnel, East-Central Massachusetts, in Page, L. R., ed., Contributions to the Stratigraphy of New England: Geol. Soc. Am. Mem, 148, p. 217-240.

Zartman, R. E., and Naylor, R. S., 1984, Structural Implications of some Radiometric Ages of Igneous Rocks in Southeastern New England: Geol. Soc. Amer. Bull, v. 95, p. 522-539.

Zen, E-an, 1983a, Exotic terranes in the New England Appalachians-limits, candidates and ages: a speculative essay: in Hatcher, R. D., Williams, H. and Zietz, I., eds.: Contributions to the Tectonics and Geophysics of Mountain Chains, Geol. Soc. Amer. Memoir 158, p. 55-81.

Zen, E-an, ed., Goldsmith, R., Ratcliffe, N. M., Robinson, P., and Stanely, R., compilers, 1983, Bedrock Geologic Map of Massachusetts: U.S. Geol. Survey, 1:250,000.