1-1-1976

Genral Geology of Southeastern New Hampshire; Outline of the Pleistocene Geology of the Boston Basin

New England Intercollegiate Geological Conference.

Naylor, Richard S.

Cameron, Barry

Kaye, Clifford A.

GEOLOGY OF SOUTHEASTERN NEW ENGLAND

NEW ENGLAND INTERCOLLEGIATE GEOLOGICAL CONFERENCE
1976

GENERALIZED BEDROCK GEOLOGIC MAP
EASTERN MASSACHUSSETS AND VICINITY

PENNSYLVANIAN

- Cw — WORCESTER FM
- Cn — Red beds of the NARRAGANSET, NORFOLK BELLINGHAM and SCITUATE BASINS
- pzh — HARVARD CONGLOMERATE

DEVONIAN

upper ?

- DCbb — BOSTON BASIN GROUP

- a — AYER GRANITE
- d — DRACUT DIORITE
- n — NEWBURYPORT PLUTON
- ag — ANDOVER GRANITE and QUARTZ DIORITE

SILURIAN

- cag — CAPE ANN GRANITE
- pg — PEABODY GRANITE
- qg — QUINCY GRANITE
- ss — SHARON SYENITE
- DSm — MERRIMACK GROUP
- sg — SALEM GABBRO
- pztb — TADMUCK BROOK SCHIST
- SDvbh — BLUE HILLS VOLCANICS
- SDvm — MATTAPAN VOLCANICS
- SDvl — LYNN VOLCANICS
- SDvn — NEWBURY VOLCANICS
- pzn — NASHOBA FM.
- pzf — FISH BROOK GNEISS
- pzs — SHAWSHEEN GNEISS

CAMBRIAN

middle

- €b — BRAINTREE ARGILLITE

lower

- €h — HOPPIN and WEYMOUTH FMS

R. S. NAYLOR MAY 1976

COMPILED FROM :

BILLINGS (1976)
BELL and ALVORD (1974)
EMERSON (1917)
NELSON (1975)
QUINN (1971)
SHAW (1966)
SKEHAN (1968 + 1976)
AND RECONNAISANCE BY THE AUTHOR AND STUDENTS

PRECAMBRIAN

late

- p€e — ESMOND GRANITE
- p€mi — MILFORD GRANITE
- p€d — DEDHAM GRANO-DIORITE
- ?p€sc — SCITUATE GRANITE GNEISS
- p€(?)ms, p€(?)m — MARLBORO FM. incl SANDY POND MEMB.
- p€v — VOLCANIC ROCKS, mostly mafic
- p€q — QUARTZITE

- p€a — ABSALONA GNEISS
- p€ni — NIPMUCK GNEISS
- p€no — NORTHBRIDGE GNEISS
- p€b — BLACK-STONE GROUP
- p€g — GNEISS

GEOLOGY OF SOUTHEASTERN NEW ENGLAND

A Guidebook for Field Trips

to the Boston Area and Vicinity

Edited by

Barry Cameron

Department of Geology
Boston University

68th Annual Meeting

NEW ENGLAND INTERCOLLEGIATE GEOLOGICAL CONFERENCE

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1976 NEIGC CONFERENCE ORGANIZATION

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Assistant to the Conference Organizer: China O. Ayer, Boston University

NEIGC Secretary: Dabney W. Caldwell, Boston University

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PREFACE

In 1966, John Rodgers of Yale University, then Secretary of NEIGC, stated in the Mt. Katahdin, Maine, Guidebook that the New England Intercollegiate Geological Conference, familiarly known as the "NEIGC", "... is perhaps the oldest continuous 'organization' on the continent whose sole aim is geological field trips. It began with an informal field trip in 1901, run by William Morris Davis in the Connecticut Valley of western Massachusetts, and gradually extended itself... over New England..." A few meetings have also been held outside of New England, in neighboring states and provinces, e. g., New York City, Montreal, Albany, and Fredericton, New Brunswick, (Fig. 1, Table 1). The continual success of NEIGC each year attests to the need for an informal field trip-oriented geological organization in the northeast. There is only one so-called member, the Secretary (presently "D" Caldwell, since 1967). One of his duties is to insure that there is a conference scheduled for each fall. Each year, then, a different group of hard-working local volunteers organizes a field conference and publishes a field trip Guidebook for the meeting. The purpose of NEIGC, therefore, is to arrange for field trips in areas where recent geological work has been done in order to bring together geologists interested in current problems in New England geology.

Field geologists generally shun urban areas. However, the Boston area and vicinity poses many perplexing geologic problems. Since the last Boston NEIGC meeting (1964), there has been much new work done in the area by geologists working for Universities, the U.S. Geological Survey, and other organizations. The purpose of the 1976 NEIGC is to provide field demonstrations of work recently completed or currently in progress in the Greater Boston Region. No single thematic approach was chosen for the conference because of the variety and complexity of the geology in this southeastern New England area. This Field Trip Guidebook has been printed not only for the benefit of the Conference participants who will have the personal guidance of the field trip leaders, but also for those geologists, teachers, students, and the interested public who, in the absence of personally guided tours by the field trip leaders, may wish to use the Guidebook to visit and study the geological features of the Greater Boston Area described herein.

During the late 1960's, "D" Caldwell and others suggested that Boston, with its varied and complex geology, would be an appropriate meeting place during the 1976 Bicentennial Year. In May, 1974, he gathered a small group of local geologists to form a steering committee to initiate plans for this conference. Smaller groups of geologists later worked on specific organizational tasks and, as the conference time approaches, more and more people have been "volunteering" to do all kinds of work!

It is with some anxiety that I write an acknowledgement to all of the people who helped with the NEIGC so far this year for fear that I will have forgotten someone deserving thanks. Without the extraordinary efforts of the 60 field trip leaders and guidebook authors listed herein this conference would not have been possible. My greatest personal gratitude and appreciation goes to Ms. China O. Ayer, who has helped me faithfully almost every day since

FIGURE I

NEW ENGLAND INTERCOLLEGIATE GEOLOGICAL CONFERENCE MEETING PLACES

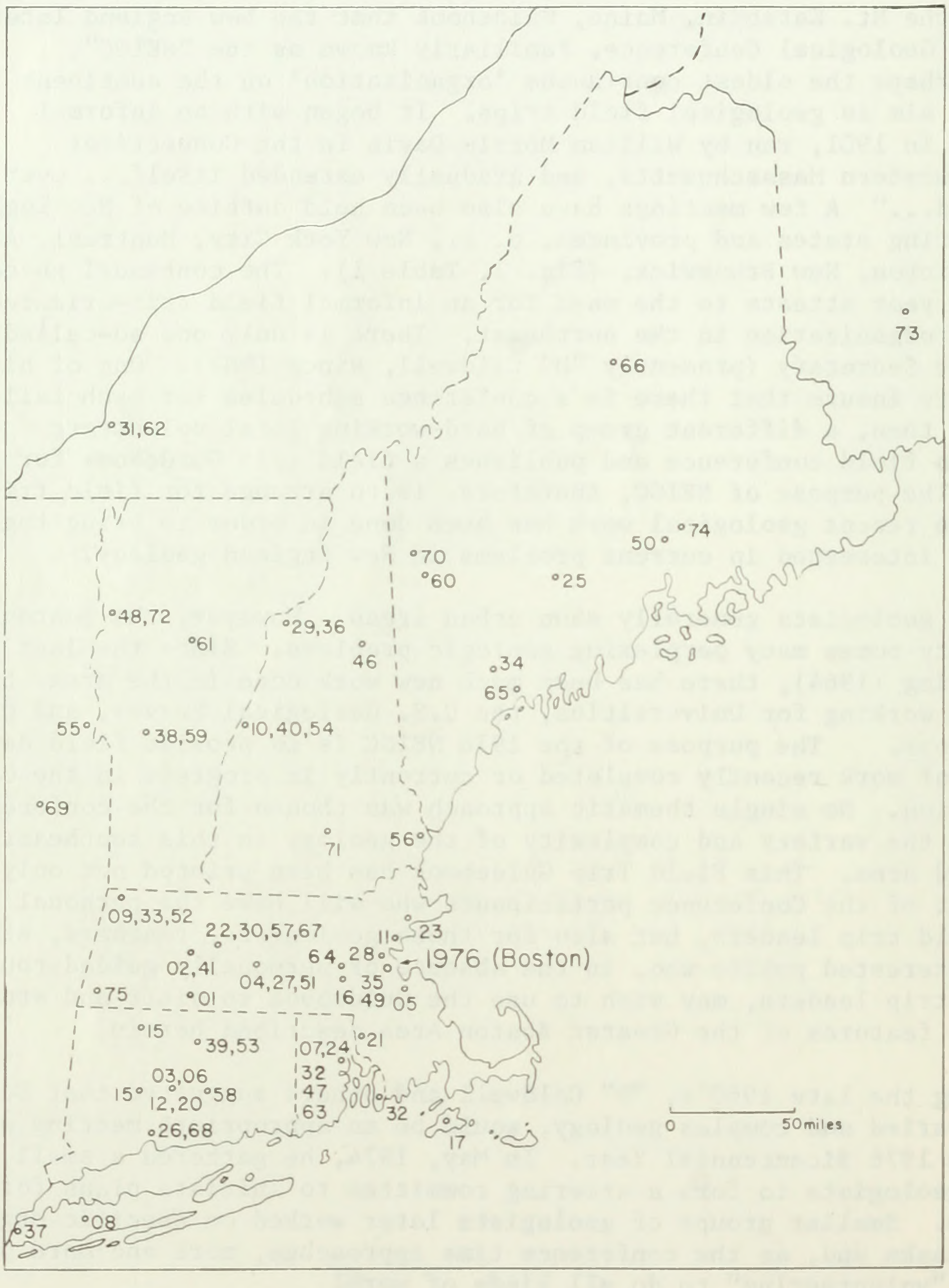

Table 1.

CHRONOLOGICAL SUCCESSION OF MEETINGS OF THE

NEW ENGLAND INTERCOLLEGIATE GEOLOGICAL CONFERENCE

Meeting	Year	Place	Organizers
1.	1901	Westfield River Terrace, Mass.	Davis
2.	1902	Mount Tom, Mass.	Emerson
3.	1903	West Peak, Meriden, Conn.	Rice
4.	1904	Worcester, Mass.	Emerson
5.	1905	Boston Harbour & Nantasket	Johnson, Crosby
6.	1906	Meriden to East Berlin, Conn.	Gregory
7.	1907	Providence, R. I.	Brown
8.	1908	Long Island, N. Y.	Barrell
9.	1909	North Berkshires, Mass.	Cleland
10.	1910	Hanover, N. H.	Goldthwait
11.	1911	Nahant & Medford, Mass.	Lane, Johnson
12.	1912	Higby-Lamentation Blocks	Rice
13.	1915	Waterbury to Winsted, Conn.	Barrell
14.	1916	Blue Hills, Mass.	Crosby, Warren
15.	1917	Gay Head & Martha's Vineyard	Woodworth, Wigglesworth
16.	1920	Lamentation & Hanging Hills	Rice, Foye
17.	1921	Attleboro, Mass.	Woodworth
18.	1922	Amherst, Mass.	Antevs
19.	1923	Beverly, Mass.	Lane
20.	1924	Providence, R. I.	Brown
21.	1925	Waterville, Me.	Perkins
22.	1926	New Haven, Conn.	Longwell
23.	1927	Worcester, Mass.	Perry, Little, Gordon
24.	1928	Cambridge, Mass.	Billings, Bryan, Mather
25.	1929	Littleton, N. H.	Crosby
26.	1930	Amherst, Mass.	Loomis, Gordon
27.	1931	Montreal, Que.	O'Neill, Graham, Clark, Gill, Osborne, McGerrigle
28.	1932	Providence, R. I.	Brown
29.	1933	Williamstown, Mass.	Cleland, Perry, Knopf
30.	1934	Lewiston, Me.	Fisher, Perkins
31.	1935	Boston, Mass.	Morris, Pearsall, Whitehead
32.	1936	Littleton, N. H.	Billings, Hadley, Cleaves, Williams
33.	1937	New York City & Duchess Co.	O'Connell, Kay, Fluhr, Balk, Hubbert
34.	1938	Rutland, Vt.	Bain
35.	1939	Hartford & Conn. Valley	Troxell, Flint, Longwell, Peoples, Wheeler
36.	1940	Hanover, N. H.	Goldthwait, Denny, Stoiber, Shaub, Hadley, Bannerman
37.	1941	Northampton, Mass.	Balk, Jahns, Lochman, Shaub, Willard
38.	1946	Mt. Washington, N. H.	Billings
39.	1947	Providence, R. I.	Quinn
40.	1948	Burlington, Vt.	Doll

Table 1. (cont.)

Meeting	Year	Place	Organizers
41.	1949	Boston, Mass.	Nichols, Billings, Schrock, Currier, Stearns
42.	1950	Bangor, Me.	Trefethen, Raisz
43.	1951	Worcester, Mass.	Lougee, Little
44.	1952	Williamstown, Mass.	Perry, Foote, McFadyen, Ramsdell
45.	1953	Hartford, Conn.	Flint, Gates, Peoples, Cushman, Rodgers, Aitken, Troxell
46.	1954	Hanover, N. H.	Elston, Washburn, Lyons, McNair, McKinstry, Stoiber, Thompson
47.	1955	Ticonderoga, N. Y.	Rodgers, Walton, MacClintock, Bartolome
48.	1956	Portsmouth, N. H.	Novotny, Billings, Chapman, Bradley, Stewart, Freedman
49.	1957	Amherst, Mass.	Bain, Johannson, Rice, Stobbe, Woodland, Brophy, Webb, Kierstead, Shaub, Nelson
50.	1958	Middletown, Conn.	Rosenfield, Eaton, Sanders, Porter, Lungren, Rodgers
51.	1959	Rutland, Vt.	Zen
52.	1960	Rumford, Me.	Griscom, Milton
53.	1961	Montpelier, Vt.	Doll
54.	1962	Montreal, Que.	Clark
55.	1963	Providence, R. I.	Quinn
56.	1964	Chestnut Hill, Mass.	Skehan
57.	1965	Brunswick, Me.	Hussey
58.	1966	Katahdin, Me.	Caldwell
59.	1967	Amherst, Mass.	Robinson, Drake, Foose
60.	1968	New Haven, Conn.	Orville
61.	1969	Albany, N. Y.	Bird
62.	1970	Rangeley Lakes, Me.	Boone
63.	1971	Concord, N. H.	Lyons, Stewart
64.	1972	Burlington, Vt.	Doolan, Stanley
65.	1973	Fredericton, N. B.	Greiner
66.	1974	Orono, Me.	Osberg
67.	1975	Great Barrington, Mass.	Ratcliffe
68.	1976	Boston, Mass.	Cameron

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the work of organizing this conference became a full-time job. The steering committee members listed on a previous page are thanked for their efforts, especially Dr. Richard S. Naylor, Dr. David C. Roy, Dr. Maurice H. Pease, and Dr. J. Christopher Hepburn for many extra duties and/or subcommittee work. Dr. Richard Naylor designed the Guidebook's cover. The facilities and staff of the Chairman's office of the Boston University Geology Department were made available by Dr. Arthur H. Brownlow. This included the dedicated efforts of our secretary and administrative assistant, Mrs. Lillian Paralikis, and our Curator, Mr. John Stewart. Mrs. Paralikis is also helping with the bus arrangements for the field trips. Mr. J. Richard Jones, Geography Department, Boston University, kindly drafted several figures, did many favors and is helping with the smoker and banquet arrangements. I would also like to thank the Program Resources office of Boston University for their help, especially Dr. William Folley and Ms. Valerie Chasen. I gratefully acknowledge Dean Warren Ilchman, College of Liberal Arts, Boston University, for his sponsorship. Others put in many hours of volunteer work: Molly Castellucci, Diane Grenda, Sally Sargent, John West, John Mahoney, Dr. Hardarshan Valia, Mohamed Bukhari, Dr. Hamed K. Mohamed, Jay Leonard, and Stephen Mangion. Dr. Nicholas Ratcliffe of the City College of New York, who organized the 1975 NEIGC meeting, gave helpful advice.

For maintaining the spirit and tradition of NEIGC during our nation's Bicentennial Year, I would like to dedicate this field trip guidebook to the many geologists who have shared freely their knowledge of the Boston area and to the many conference volunteers who put in countless hours of valuable but often unsung assistance to help make this conference possible.

Barry Cameron, Editor
June 20, 1976
Boston, Massachusetts

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*F = Friday field trips, A = Saturday field trips, & B = Sunday field trips

GENERAL GEOLOGY OF SOUTHEASTERN NEW ENGLAND

By

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-and-

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INTRODUCTION

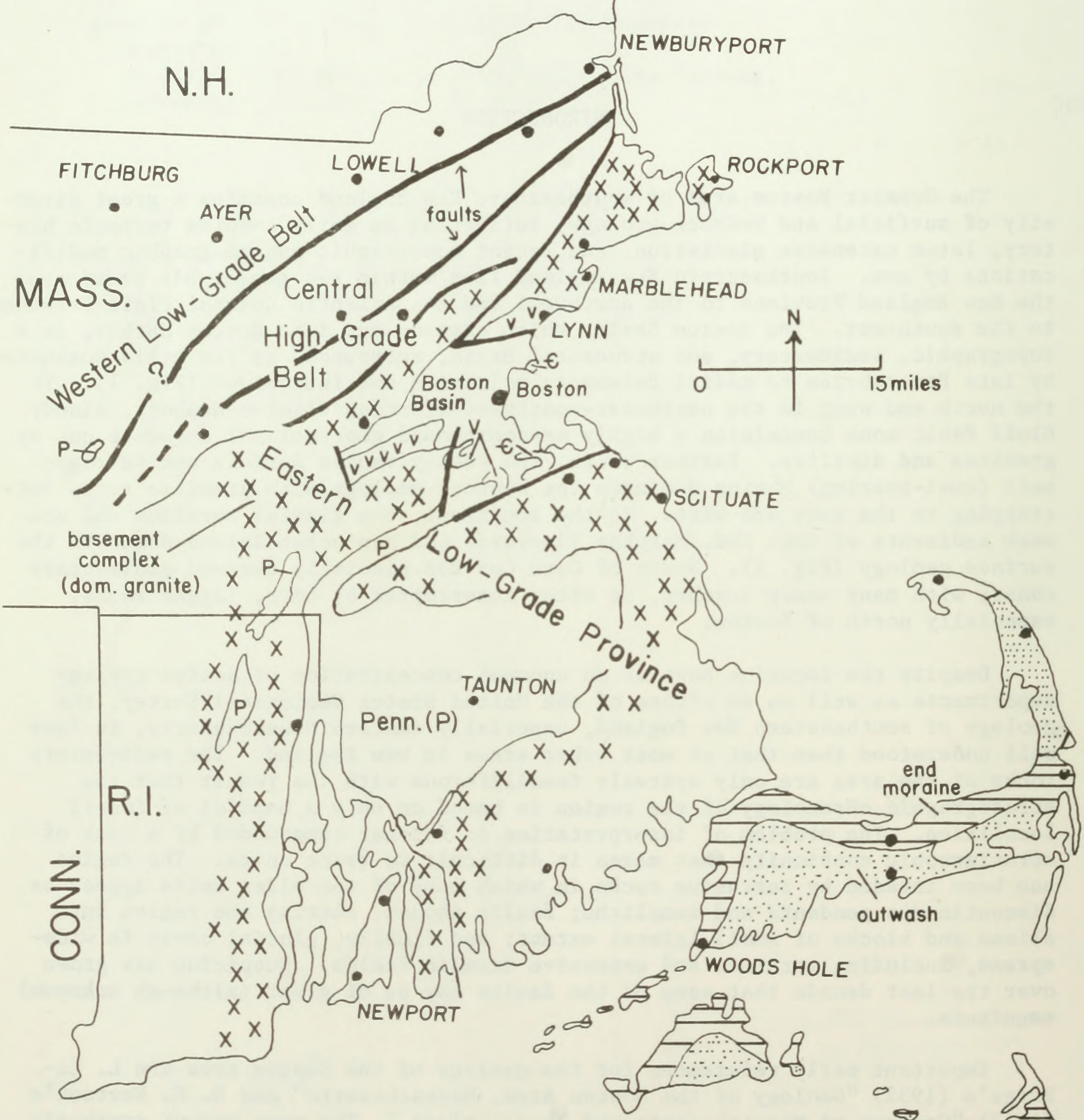
The Greater Boston area of southeastern New England contains a great diversity of surficial and bedrock geology, reflecting an early complex tectonic history, later extensive glaciation, and recent topographic and geographic modifications by man. Southeastern New England lies within two geomorphic provinces: the New England Province to the northwest and the Atlantic Coastal Plain Province to the southeast. The Boston Basin, which extends out into Boston Harbor, is a topographic, sedimentary, and structural basin, surrounded by low hills dominated by late Precambrian to medial Paleozoic volcanics and intrusives (Fig. 1). To the north and west is the northeast-southwest trending Clinton-Newbury, Bloody Bluff fault zone containing a highly metamorphosed geosynclinal sequence cut by granites and diorites. Farther south, the Pennsylvanian Norfolk and Narragansett (coal-bearing) basins dominate the bedrock geology with granitic rocks outcropping to the east and west. To the southeast, the glacial moraines and outwash sediments of Cape Cod, Marthas Vineyard, and Nantucket Island dominate the surface geology (Fig. 1). North of Cape Cod the glacially derived sedimentary coast, with many sandy beaches, is often interrupted by bare, jagged rocks, especially north of Boston.

Despite the location here of an unusual concentration of active geology departments as well as an office of the United States Geological Survey, the geology of southeastern New England, especially eastern Massachusetts, is less well understood than that of most other areas in New England. The sedimentary rocks of the area are only sparsely fossiliferous with the result that the stratigraphic chronology of the region is based on only a handful of fossil localities. The problem of interpretation is further compounded by a lack of stratigraphic continuity that makes it difficult to trace units. The region has been invaded by intrusive rocks in which many of the older units appear as discontinuous pendants and xenoliths; faults abound, cutting the region into slices and blocks of small lateral extent; and finally, glacial cover is widespread, including moraines and extensive drumlin fields. Suspicion has grown over the last decade that some of the faults may be of great (although unknown) magnitude.

Important early references for the geology of the Boston area are L. LaForge's (1932) "Geology of the Boston Area, Massachusetts" and B. K. Emerson's (1917) "Geology of Massachusetts and Rhode Island." The most recent synthesis

Figure 1

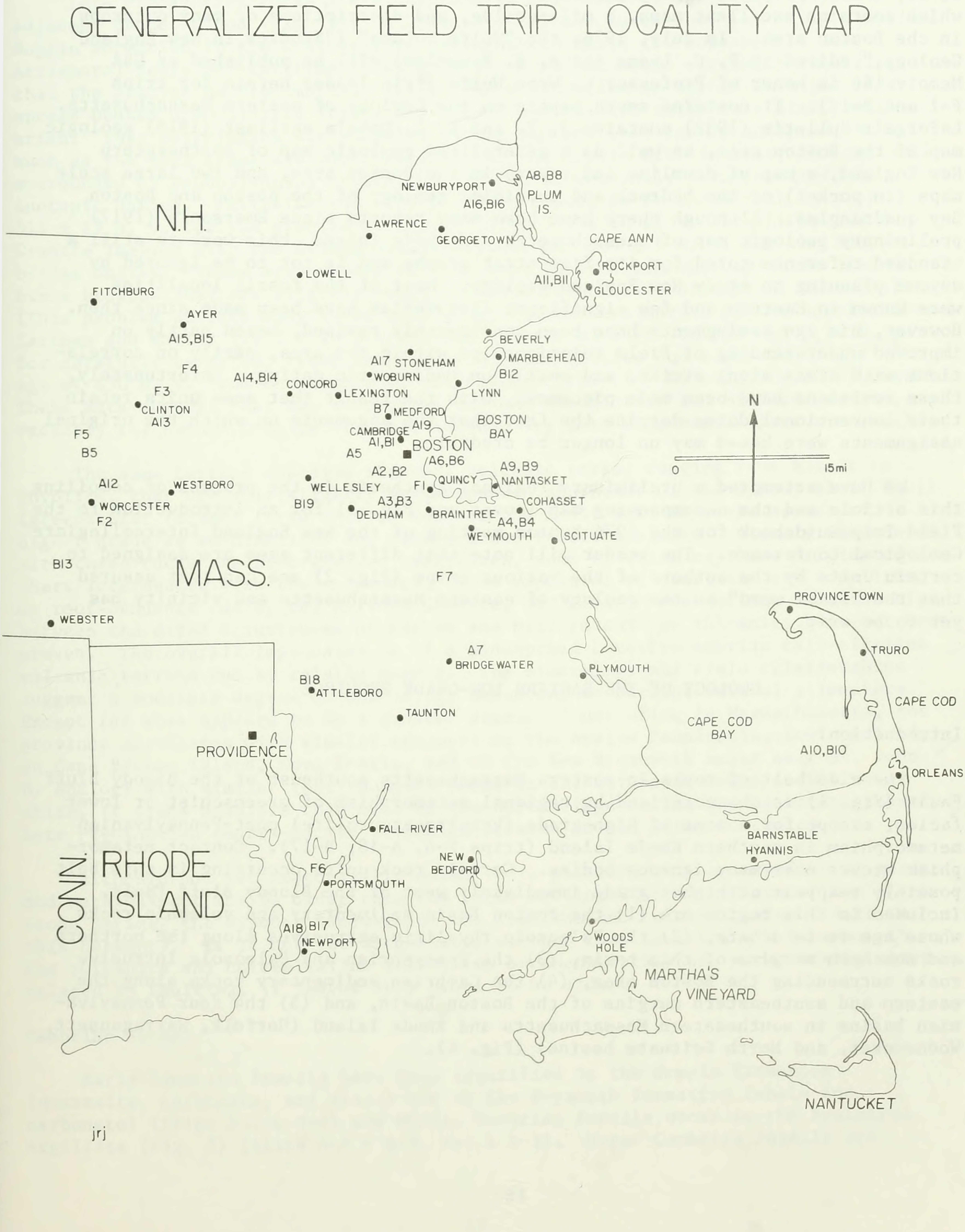
GENERALIZED GEOLOGIC MAP OF SOUTHEASTERN NEW ENGLAND



DOTS (●) REPRESENT CITIES ON FIGURE 2

jrj

Figure 2


GENERALIZED FIELD TRIP LOCALITY MAP
N.H.
MASS.
CONN.
RHODE ISLAND
NEWBURYPORT
A8,B8
PLUM IS.
A16,B16
LAWRENCE
GEORGETOWN
CAPE ANN
LOWELL
ROCKPORT
A11,B11
GLOUCESTER
FITCHBURG
AYER
A15,B15
BEVERLY
MARBLEHEAD
F4
A17 STONEHAM
A14,B14
CONCORD
WOBURN
B12
F3
LEXINGTON
LYNN
CLINTON
A13
B7
MEDFORD
A19
BOSTON BAY
N
F5
CAMBRIDGE
A1,B1
BOSTON
B5
A5
A6,B6
0
15mi
A2,B2
A9,B9
A12
WESTBORO
WELLESLEY
F1
QUINCY
NANTASKET
WORCESTER
B19
A3,B3
COHASSET
F2
DEDHAM
BRAINTREE
A4,B4
WEYMOUTH
SCITUATE
B13
F7
PROVINCETOWN
WEBSTER
TRURO
A7
BRIDGEWATER
PLYMOUTH
B18
ATTLEBORO
CAPE COD
TAUNTON
CAPE COD BAY
PROVIDENCE
A10,B10
ORLEANS
FALL RIVER
BARNSTABLE
HYANNIS
NEW BEDFORD
F6
PORTSMOUTH
A18
B17
NEWPORT
WOODS HOLE
MARTHA'S VINEYARD
NANTUCKET
jrj

of the bedrock and surficial geology of the Boston Basin are by Billings (1976 and this volume) and Kaye (this volume), respectively. Recently, J. W. Skehan, S. J., (1975) prepared a geologic field guide for historic trails of Boston which contains excellent maps, a mileage log, and descriptions of many outcrops in the Boston area. In July, 1976, the "Wolfe Volume" ("Studies in New England Geology," edited by P. C. Lyons and A. H. Brownlow) will be published as GSA Memoir 146 in honor of Professor C. Wroe Wolfe (trip leader herein for trips F-1 and B-12). It contains seven papers on the Geology of eastern Massachusetts. LaForge's Bulletin (1932) contains J. F. and S. L. Dana's earliest (1818) geologic map of the Boston area, as well as a generalized geologic map of southeastern New England, a map of drumlins and eskers in the Boston area, and two large scale maps (in pocket) of the bedrock and surficial geology of the Boston and Boston Bay quadrangles. Although there have been many reports since Emerson's (1917) preliminary geologic map of Massachusetts and Rhode Island, this work is still a standard reference noted for its fine stratigraphy and is not to be ignored by anyone planning to study New England geology. Most of the fossil localities were known to Emerson and few significant discoveries have been made since then. However, his age assingments have been considerably revised, based partly on improved understanding of field relationships within the area, partly on correlations with areas along strike, and partly on radiometric dating. Unfortunately, these revisions have been made piecemeal, with the result that some units retain their conventional dates despite the fact that the arguments on which the original assignments were based may no longer be credible.

We have attempted a preliminary regional synthesis in the process of compiling this article and the accompanying map (cover and Fig. 3) for an introduction to the Field Trip Guidebook for the 1976 Boston meeting of the New England Intercollegiate Geological Conference. The reader will note that different ages are assigned to certain units by the authors of the various trips (Fig. 2) and can rest assured that the "final word" on the geology of eastern Massachusetts and vicinity has yet to be writ.

GEOLOGY OF THE EASTERN LOW-GRADE PROVINCE

Introduction:

The wide belt of rocks in eastern Massachusetts southeast of the Bloody Bluff Fault (Fig. 1) is characterized by regional metamorphism of greenschist or lower facies, except for a zone of high-grade (kyanite-staurolite) post-Pennsylvanian metamorphism in southern Rhode Island (trips F-6, A-18, B-17). Contact metamorphism occurs near many igneous bodies. Certain rock units occurring in this belt possibly reappear at higher grade immediately west of the Bloody Bluff Fault. Included in this region are (1) the Boston Basin sedimentary and volcanic rocks whose age is in debate, (2) the Paleozoic rhyolitic extrusives along the northern and southern margins of this basin, (3) the Precambrian and Paleozoic intrusive rocks surrounding the Boston area, (4) the Cambrian sedimentary rocks along the eastern and southeastern margins of the Boston Basin, and (5) the four Pennsylvanian basins in southeastern Massachusetts and Rhode Island (Norfolk, Narragansett, Woonsocket, and North Scituate basins) (Fig. 4).

Precambrian Terrane:

Late Precambrian rocks are widespread in southeastern Massachusetts and adjacent Rhode Island (Fig. 3). Billings (1929) concluded that the Early Cambrian Hoppin Formation in the northwestern Narragansett Basin (at Hoppin Hill near Attleboro) rests non-conformably on granite, a relationship virtually requiring that the granite be Precambrian. From this observation he argued that the widespread Dedham Granodiorite (trips A-4 & B-4) and related units were also Precambrian. This correlation was somewhat daring and not universally accepted, inasmuch as the rock types are not identical and the Hoppin Hill locality is completely surrounded by Pennsylvanian strata, but it has subsequently been confirmed by isotopic dating. Fairbairn and others (1967) report Rb-Sr whole-rock ages of 514 ± 17 m. y. for the granite at Hoppin Hill, 591 ± 28 m. y. for the Westwood Granite (mapped with the Dedham Granodiorite), and 569 ± 4 m. y. for the Northbridge Gneiss. These ages appear to have been lowered somewhat by later disturbance because they are slightly young for Late Precambrian on current time-scales. (This problem affects many Rb-Sr ages along the eastern margin of the Appalachians.) Zartman and Naylor (1972 & in preparation) report an Rb-Sr age of 614 ± 24 m. y. for carefully selected, fresh samples of Milford Granite and a zircon $^{207}Pb/^{206}Pb$ age of 630 m. y. from one sample of Milford Granite. ($^{87}Rb = 1.39 \times 10^{-11}$ year^{-1}.) These data suggest that the widespread Dedham Granodiorite and Milford Granite, and probably the Esmond Granite of Rhode Island, are Late Precambrian intrusive rocks.

The same terrane contains abundant volcanic rocks, ranging from basalt to rhyolite, that are only slightly metamorphosed southeast of the Bloody Bluff Fault (greenschist facies) (trip A-17). West of the fault similar rocks appear at higher grade as amphibolites and fine-grained felsic gneisses. Closely associated with these rocks are fine-grained quartzites, some of which may have originated as chert interbedded with the volcanics. Some exposures of quartzite are xenoliths or roof-pendants cut by the Milford Granite, but clear cross-cutting relationships between the dated occurrences of Dedham and Milford and the volcanics have not been proven. The overall impression is of a widespread Late Precambrian calc-alkaline volcanic terrane cut by related magmas. The mineralogy and field relationships suggest a moderate degree of unroofing, amounting to perhaps several kilometers. Except for what appears to be a greater degree of unroofing in Massachusetts, the province correlates with similar terranes on the Avalon Penninsula, Newfoundland, on Cape Breton Island, Nova Scotia, and on the New Brusnwick coast near St. John. By analogy with similar (but younger) rocks in the Oliverian Domes on New Hampshire, it seems possible that much of the Northbridge Gneiss may be metamorphosed, Late Precambrian quartz-dacite volcanics related to the other volcanics.

Although not yet isotopically dated, it is possible that some bodies of gneiss and metasediment may be older than the rocks mentioned above. Parts of the Blackstone Series, the Nipmuck Gneiss, and the Absalona and related gneisses fall into this catagory. It is not yet established whether they constitute a basement to the volcanics and calc-alkaline intrusives or whether they are structurally intercalated by faulting, if indeed they prove to be older.

Cambrian Rocks:

Early Cambrian fossils have been identified in the Hoppin Formation (quartzite, carbonate, and slate) and in the Weymouth Formation (shale and carbonate) (trips A-4 & B-4) and Middle Cambrian fossils occur in the Braintree Argillite (Fig. 3) (trips A-4 & B-4, A-3 & B-3). Upper Cambrian fossils are

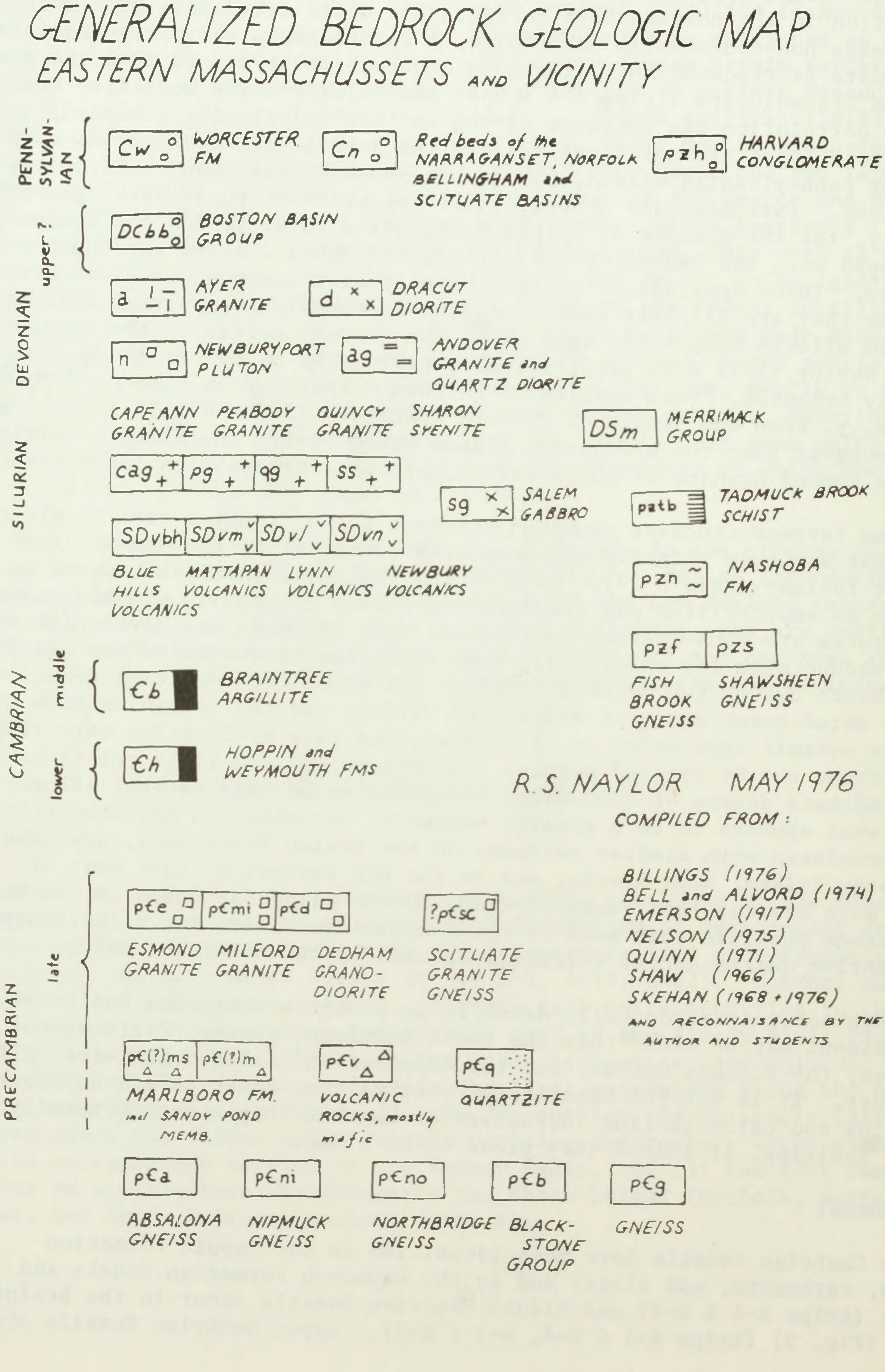
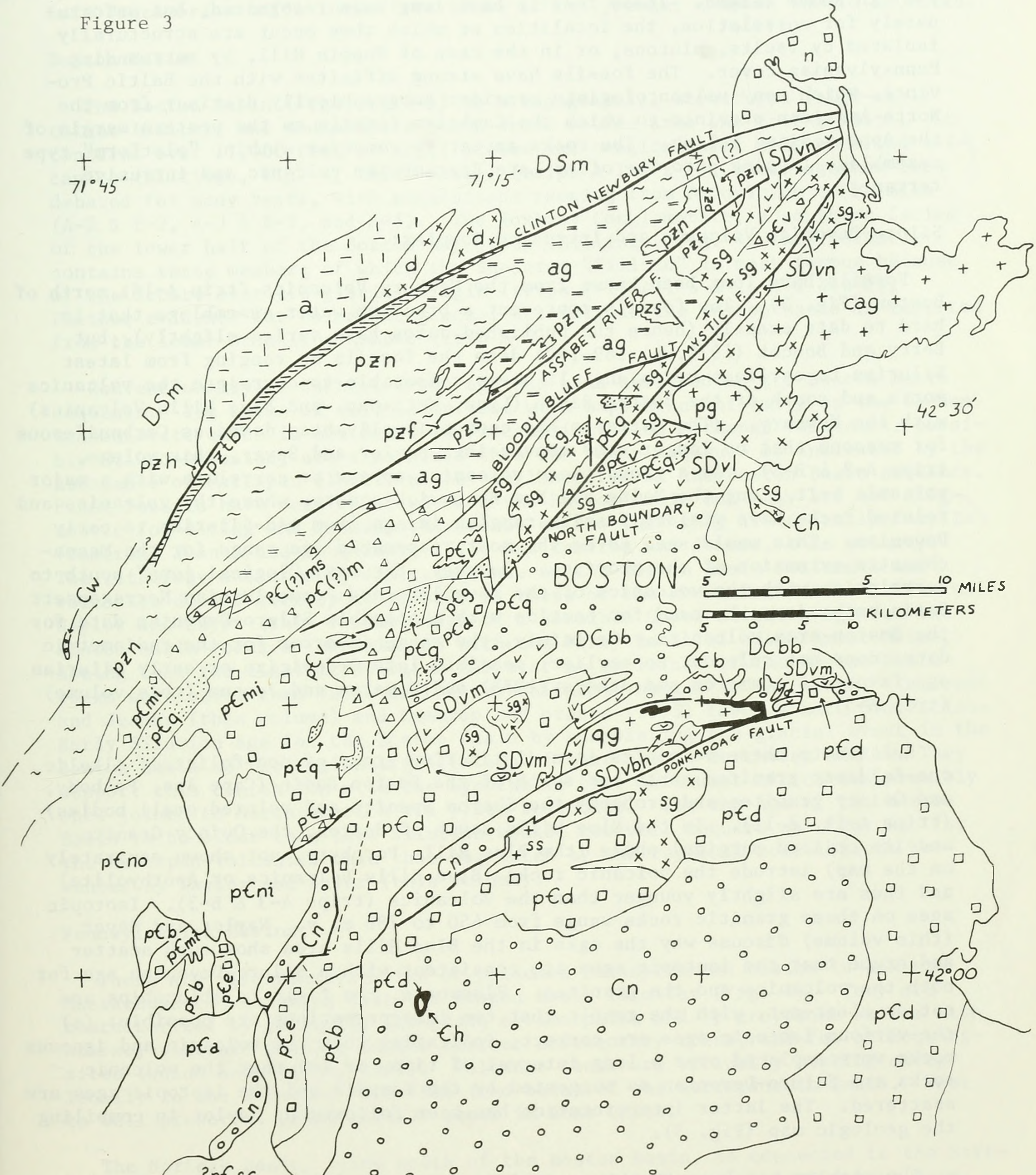

GENERALIZED BEDROCK GEOLOGIC MAP
EASTERN MASSACHUSSETS AND VICINITY
PENN-SYLVAN-IAN
Cw WORCESTER FM
Cn Red beds of the NARRAGANSET, NORFOLK BELLINGHAM and SCITUATE BASINS
pzh HARVARD CONGLOMERATE
DEVONIAN
upper ?
DCbb BOSTON BASIN GROUP
a AYER GRANITE
d DRACUT DIORITE
n NEWBURYPORT PLUTON
ag ANDOVER GRANITE and QUARTZ DIORITE
SILURIAN
CAPE ANN GRANITE
PEABODY GRANITE
QUINCY GRANITE
SHARON SYENITE
cag
pg
qg
ss
DSm MERRIMACK GROUP
sg SALEM GABBRO
pztb TADMUCK BROOK SCHIST
SDvbh
SDvm
SDvl
SDvn
BLUE HILLS VOLCANICS
MATTAPAN VOLCANICS
LYNN VOLCANICS
NEWBURY VOLCANICS
pzn NASHOBA FM.
pzf FISH BROOK GNEISS
pzs SHAWSHEEN GNEISS
CAMBRIAN
middle
Єb BRAINTREE ARGILLITE
lower
Єh HOPPIN and WEYMOUTH FMS
R. S. NAYLOR MAY 1976
COMPILED FROM:
BILLINGS (1976)
BELL and ALVORD (1974)
EMERSON (1917)
NELSON (1975)
QUINN (1971)
SHAW (1966)
SKEHAN (1968 + 1976)
AND RECONNAISANCE BY THE AUTHOR AND STUDENTS
PRECAMBRIAN
late
pЄe ESMOND GRANITE
pЄmi MILFORD GRANITE
pЄd DEDHAM GRANO-DIORITE
?pЄsc SCITUATE GRANITE GNEISS
pЄ(?)ms
pЄ(?)m
MARLBORO FM. incl SANDY POND MEMB.
pЄv VOLCANIC ROCKS, mostly mafic
pЄq QUARTZITE
pЄa ABSALONA GNEISS
pЄni NIPMUCK GNEISS
pЄno NORTHBRIDGE GNEISS
pЄb BLACK-STONE GROUP
pЄg GNEISS

Figure 3


71°45'
71°15'
42°30'
42°00
DSm
CLINTON NEWBURY FAULT
ASSABET RIVER F.
BLOODY BLUFF FAULT
MYSTIC F.
NORTH BOUNDARY FAULT
PONKAPOAG FAULT
BOSTON
MILES
KILOMETERS
5
0
5
10
pzn
pzf
pzs
pztb
pzh
pzn(?)
ag
cag
a
d
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SDvl
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sg
pg
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pЄq
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pЄd
pЄ(?)ms
pЄ(?)m
pЄmi
pЄno
pЄni
pЄb
pЄe
pЄa
?pЄsc
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Cn
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known only from clasts occurring in the Pennsylvanian Dighton Conglomerate (trip F-6) in Rhode Island. These fossils have long been recognized, but unfortunately for correlation, the localities at which they occur are structurally isolated by faults, plutons, or in the case of Hoppin Hill, by surrounding Pennsylvanian cover. The fossils have strong affinites with the Baltic Province, which many paleontologists consider geographically distinct from the North American province to which the Cambrian fossils on the western margin of the Appalachians belong. The rocks appear to comprise a thin, "platform"-type assemblage lapping onto the older Late Precambrian volcanic and intrusive terrane.

Siluro-Devonian Volcanic and Intrusive Complex:

Fossils have long been known from the Newbury Volcanics (trip A-16) north of Boston (Fig. 3). The fossils represent a brackish water assemblage that is hard to date exactly (hence the published dates have varied slightly), but Berry and Boucot (1970, p. 189-190) date the fossils as ranging from latest Silurian to earliest Devonian. It seems reasonable to correlate the volcanics north and south of the Boston Basin (Lynn, Mattapan, and Blue Hills Volcanics) with the Newbury. (The Mattapan has conventionally been dated as Carboniferous for reasons that no longer seem convincing; Naylor and Sayer, this volume, trips A-3 & B-3). As a group these volcanics appear to correlate with a major volcanic belt along the Maine and New Brunswick coasts, where the volcanics and related rocks have yielded fossils ranging in age from mid-Silurian to early Devonian. This would seem to be the most reasonable age range for the Massachusetts extension of the province. However, the next "logical jump" south to correlation with the volcanics of the fossiliferous Pennsylvanian Narragansett Basin emphasizes the need for caution with a possible Siluro-Devonian date for the Boston area volcanics. Certainly, the range in error for the radiometric dates does not rule out an earlier, possibly late Ordovician or early Silurian age favored by Cameron and others (1975) and Cameron and Jeanne (this volume) (trip A-5).

Related to these volcanics is a distinctive group of non-foliated, alkalic, one-feldspar granites north and south of the Boston Basin (Cape Ann, Peabody, and Quincy granites and probably the Sharon Syenite and related small bodies) (trips A-11, B-11). In the Blue Hills south of Boston, the Quincy Granite and its chilled marginal phase (the Blue Hills Porphyry, not shown separately on the map) intrude the volcanic rocks (Blue Hills Volcanics or Aporhyolite) and thus are slightly younger than the volcanics (trips A-3 & B-3). Isotopic ages on these granitic rocks range from 450 to 280 m. y. Naylor and Sayer (this volume) discuss why the ages in the Blue Hills area show such scatter and argue that the isotopic ages are consistent with a Siluro-Devonian age for both the volcanics and the granites. Elsewhere, the field relationships are not so clear-cut, with the result that two interpretations are possible: (a) the various isotopic ages are correct, indicating that the volcanic and igneous rocks were emplaced over a long interval of time, or (b) that the volcanic rocks are Siluro-Devonian as suggested by the fossils and the isotopic ages are scattered. The latter interpretation has been followed by Naylor in compiling the geologic map (Fig. 3).

The problem has been further complicated by recognition that large volumes of mafic intrusive rocks (mapped as Salem Gabbro) appear related to this same province (Bell and Dennen, 1972, and Dennen, 1972) (trips A-11 & B-11). In interpreting the age relationships, however, the difficulty of distinguishing Late Precambrian mafic rocks from those of the younger complex should be noted.

Boston Basin:

The Boston Basin (Figs. 1, 3-4) is a topographic, structural (high-angle thrust faults), and sedimentary basin whose source area was to the south. It contains over 17,000 feet of argillaceous and conglomeratic sediments and volcanics (Billings, Fig. 4, this volume) (trips A-1 & B-1), whose age has been debated for many years, with suggestions ranging from Ordovician to Permian (A-2 & B-2, A-3 & B-3, and A-5). The Roxbury Conglomerate, a southern facies of the lower half of the Boston Bay Group (Billings, Fig. 4, this volume), contains three members of which the Squantum "Tilloid" is most famous because of the debate over its glacial origin (trips F-1, A-1 & B-1, A-2 & B-2). Further evidence for Paleozoic glacial activity in the Boston Basin is reported from the lower Brookline Member (trip A-5).

Conventionally, a Carboniferous age has been assigned to the Boston Basin sequence. The rocks of this basin rest with mapped unconformity on the Dedham Granodiorite which is now dated as Precambrian. The Mattapan Volcanics, possibly Siluro-Devonian, are also older than the basin sequence as indicated by the abundance of Mattapan clasts in the conglomerates of the Boston Basin sequence. Plant fossils have been reported from the Boston Basin but they are not diagnostic for dating and considerable doubt exists that they are actually fossils (Cameron, Jeanne and Schneider, 1975, and Cameron and Jeanne, this volume). The lithology and stratigraphic sequence of the Boston Basin sediments and volcanics do not correspond closely to those of the known Carboniferous Basins. Naylor and Sayer (this volume) suggest a possible Upper Devonian age for the Boston Basin rocks by correlation with the Perry Basin of easternmost Maine, noting that the clast lithologies can best be explained if the Boston Basin rocks were older than those of the Carboniferous basins to the south. Cameron and Jeanne (this volume) and Cameron and others (1975) favor a Late Ordovician-Early Silurian age for the Boston Basin by correlating the glacial event in the Boston Basin to the regional glaciation of that age in northwest Africa. They support this contention with the hypothesis that northwest Africa was possibly once joined to North America via plate tectonics. For the age of the Boston Basin to be older than Late Silurian would, however, require an older age for the Mattapan Volcanics than that suggested by the regional correlations presented by Naylor and Sayer (this volume).

Pennsylvanian Basins:

There are five Pennsylvanian or presumed Pennsylvanian basins in eastern Massachusetts, assuming that the Boston Basin is older (Fig. 4). They are characterized by generally low-grade metamorphism and by graywacke suites with arkose, plutonic pebbles in the coarser sedimentary rocks, and few orthoquartzites (Quinn and Oliver, 1962). Volcanic rocks are virtually lacking except locally in the Wamsutta Formation (red beds) of the Narragansett Basin. Poor to well preserved plant fossils occur in some units.

The Norfolk Basin, lying south of the Boston Basin, is connected to the Narragansett Basin at its southwestern end (Fig. 4). These two basins have been assumed to be of similar Pennsylvanian age on the basis of their physical connection, similar lithologies and stratigraphy, and similar plant fossils. The Norfolk Basin contains two formations, a lower Pondville Conglomerate (trips

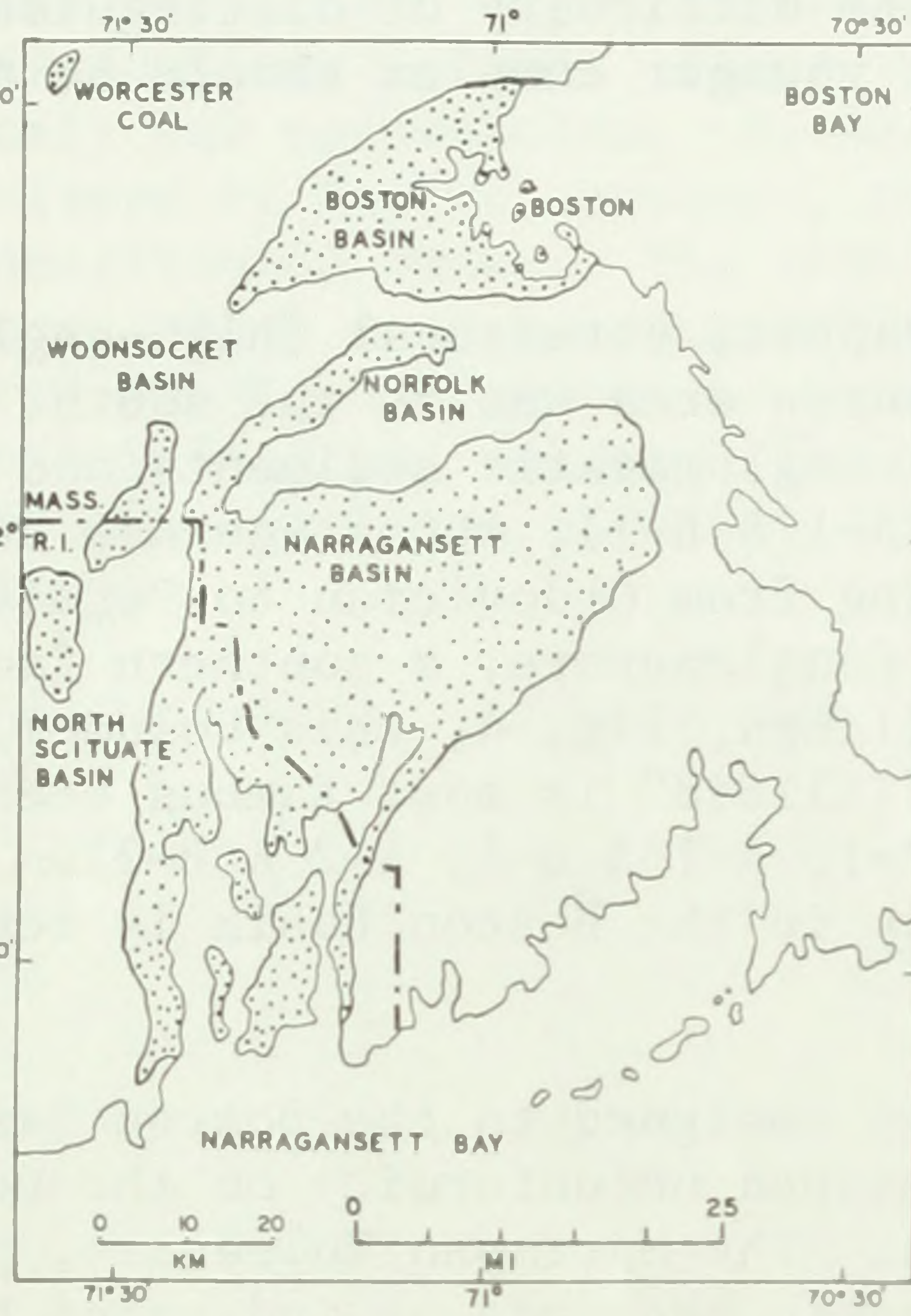

Figure 4. Paleozoic sedimentary basins of southeastern Massachusetts and Rhode Island. All but the Boston Basin are Pennsylvanian or presumedly Pennsylvanian in age (from Lyons, Tiffney and Cameron, 1976, Fig. 1).

A-3 & B-3) and an upper Wamsutta Formation. Lyons, Tiffney and Cameron (1976) described a new early Pennsylvanian plant fossil assemblage from the Pondville.

The Larger Narragansett Basin contains a rich Pennsylvanian flora, primarily associated with coal seams in the Rhode Island Formation along its northern and western margins (trip B-18). Some of the seams were mined during this and the last century (Lyons and Chase, this volume). This basin contains a Pondville Conglomerate - Wamsutta Formation sequence that is apparently younger than that in the Norfolk Basin (Lyons and others, 1976). To the north, this sequence is overlain by, as well as interfingered with, the Rhode Island Formation which is in turn overlain by the Dighton Conglomerate. The Purgatory Conglomerate to the south is equivalent to the Wamsutta (Mosher and Wood, Fig. 1, this volume). The degree of metamorphism in the basin increases from chlorite grade in the north to garnet and staurolite grade in the south (Quinn, 1971) (trips F-6, A-18, B-17).

The small Woonsocket and North Scituate basins are located about 10 km west of the Narragansett Basin (Fig. 4). They contain the Bellingham Conglomerate, which is believed to be time-equivalent with the Pondville Conglomerate of the Narragansett Basin, but no fossil evidence has yet been found.

Pennsylvanian fossils also occur west of Boston at Worcester in what is now interpreted to be a very small basin (trip A-12). It was dated as Early to Medial Pennsylvanian using plant fossils (mostly poorly preserved) in phyllite from the old Worcester coal mine (Grew and others, 1970). The better preserved fossils indicate a Medial Pennsylvanian age correlative with the Rhode Island Formation in the northern part of the Narragansett Basin (Lyons and others, 1976).

GEOLOGY OF THE CENTRAL HIGH-GRADE BELT

Between the Bloody Bluff Fault and the Clinton-Newbury Fault lies a belt of high-grade (sillimanite) metamorphic rocks (Figs. 1 & 3) (trips F-3, A-13, A-14 & B-14, A-15 & B-15). Rocks immediately west of the Bloody Bluff Fault are possibly related to those in the eastern, low-grade province, but apparently different sequences of rocks outcrop in the western part of the high-grade belt.

The major rock unit is the Nashoba Formation, a heterogeneous unit consisting mostly of felsic, biotite-gneiss, with lesser intercalated amphibolite, calc-silicate, and pelitic or quartzofeldspathic schists. Despite the heterogeneity of the unit, Bell and Alvord (1974) have shown that it can be subdivided into members showing considerable lateral extent (trips A-14 & B-14). East of the Nashoba these authors recognize a groups of dominantly felsic paragneisses, and to the west, a rusty-weathering schist designated the Tadmuck Brook Schist. Bell and Alvord (1974) interpreted all these rocks as a westward-dipping, westward-topping, homoclinal, geosynclinal sequence lying stratigraphically above the Late Precambrian province described above. Because the sequence is cut by numerous faults, some of which may be of very great magnitude, this interpretation should probably be treated with caution. Along strike in eastern Maine are several major structural provinces, including rocks of the Ellsworth, Penobscot, and Passagassawakeag "Groups." An alternate interpretation is that all, or some combination of this complex Maine terrane, may appear in Massachusetts as the Nashoba and related units. Ordovician fossils have been identified within this Maine sequence, but their structural position is uncertain and some of the rocks may be considerably older or younger than Ordovician. The rocks have been tentatively assigned to the Early Paleozoic in this compilation.

Rocks of this belt are cut by a heterogeneous group of granites and quartz diorites designated the Andover Granite. Zartman and Naylor (in preparation) report an Rb-Sr whole-rock isochron age of 415 ± 15 m. y. from aplites in the Andover Granite. This may be compared with an earlier Rb-Sr whole-rock age of 460 ± 23 m. y. (Hanford, 1965) based on samples including gneissic varieties of the Andover Granite.

GEOLOGY OF THE WESTERN LOW-GRADE BELT

Metamorphic grade drops abruptly across the Clinton-Newbury Fault, and for some distance to the west lies a belt characterized by low-grade regional metamorphism (Figs. 1 & 3) (trips F-2, F-4, A-15 & B-15, B-13). The major stratified rocks of this belt are assigned to the Merrimack Group and are tentatively considered to be of Silurian and Devonian age. The basis for this assignment is correlation along strike with fossiliferous Silurian rocks in the Waterville area, Maine. Many of these rocks were formerly considered Carboniferous on the basis of fossils in a locality at Worcester, but it is currently believed that the Carboniferous rocks are restricted to a very small basin in the immediate vicinity of the fossil locality. In considering the correlation with the Waterville sequence, however, it should be noted that several intervening plutons break the continuity of the beds along strike. The Merrimack Group is cut by the Ayer Granite, Dracut Diorite, and the Newburyport Complex.

The Harvard Conglomerate apparently rests unconformably on the Ayer Granite; its relationships to adjacent units are uncertain (trips F-4, A-15 & B-15).

METAMORPHISM

The patterns of metamorphism in eastern Massachusetts and vicinity are complex. Several metamorphic events are probably involved but the timing and extent of each is poorly understood.

The fact that Pennsylvanian rocks have been metamorphosed to high grade (kyanite-staurolite) in southern Rhode Island must be strongly emphasized (trips F-6, A-18, B-17). This metamorphism is related to the emplacement of the Narragansett Pier and Westerly granites but appears to be regional in extent, with garnet and chloritoid occurring in Pennsylvanian rocks as far north as northern Rhode Island. This metamorphism dies out northwards. The rocks of the northern part of the Narragansett Basin, the Norfolk Basin, and the Boston Basin are strongly indurated but uncleaved, and diagnostic metamorphic minerals have not been reported from these areas. The Pennsylvanian metamorphic belt continues to the west. Clasts in the Bellingham Conglomerate (Woonsocket Basin) are highly stretched and garnet occurs in the Pennsylvanian rocks at Worcester. The knowledge that Pennsylvanian metamorphism is locally intense and somewhat sporadically distributed has to be kept very much in mind when interpreting the metamorphism of the older rocks.

In the western low-grade belt the metamorphism is probably Acadian but the intensity is only biotite- to chlorite-grade, whereas Acadian metamorphism of of sillimanite-grade is widespread a short distance further west.

In the eastern low-grade belt fossiliferous Cambrian and Siluro-Devonian rocks show contact metamorphism near younger igneous bodies, but negligible regional metamorphism. This observation indicates that Acadian metamorphic effects have died out this far east. Most of the Precambrian rocks of this belt show slight metamorphism (low greenschist facies) with higher grades of contact metamorphism. This is consistent with the hypothesis that the Precambrian rocks were eroded to depths of several kilometers prior to deposition of the Cambrian strata. It remains to be determined whether certain rocks show higher grades of Precambrian metamorphism, and whether earlier episodes of Precambrian metamorphism can be identified.

PLEISTOCENE GLACIAL GEOLOGY

Glacial ice flowed southward during the Wisconsin Stage, forming three lobes in southeastern New England (the Buzzard Bay Lobe on the west, Cape Cod Bay Lobe in the middle, and the South Channel Lobe to the east). The ice had two major positions of standstill as evidenced by the two end moraines that occur in southeastern Massachusetts, one of which forms Nantucket Island and Martha's Vineyard while the other forms the Woods Hole area and the east-west part of Cape Cod (Fig. 1) (trips A-10 & B-10). Other end moraines are located near Plymouth (Ellisville Moraine) and the famous Beacon Hill in Boston is now also considered to be an end moraine by Kaye (this volume) (trips A-6 & B-6). Separate tills indicate several glacial ice advances and retreats in southeastern Massachusetts (Leonard and others, this volume), such as in the Boston area (trips A-6 & B-6). More than one till have been recognized elsewhere, such as in the Worcester area where outwash, drumlins, and glacial lake features can be studied (trips F-5 & B-5).

Ice contact features are in evidence in southeastern Massachusetts where proglacial lakes existed in the relatively low and flat area of the Narragansett Basin. Flowtill, derived entirely from superglacial debris, can be found in many ice-contact features, such as kames, kame terraces, and ice-channel fillings (Hartshorn, this volume) (trip A-7).

Glacially striated outcrops are common almost everywhere in New England (trips A-6 & B-6) and drumlins abound in eastern Massachusetts, as can be seen north of Boston (trips A-8 & B-8), in the metropolitan Boston area (trips A-6 & B-6), and south of Boston (trips A-9 & B-9).

COASTAL GEOLOGY

The shoreline of southeastern Massachusetts is dominated by Cape Cod, Cape Cod Bay, Martha's Vineyard and Nantucket Island which will be viewed from the air on part of trips A-10 and B-10. Northward, the coast is dominated by Massachusetts Bay with Boston Harbor centrally located. The northeastern region is marked by Cape Ann with the Plum Island-Castle Neck barrier island system in the Merrimack Embayment slightly to the northwest.

The coastal areas of eastern Massachusetts (trips A-8 & B-8, A-9 & B-9, A-10 & B-10) contain many glacial and non-glacial deposits or bare rock. Drumlins are common at Plum Island (trips A-8 & B-8), Boston Harbor (trips A-6 & B-6), and Nantasket Beach (trips A-9 & B-9). End moraines and outwash comprise most of Cape Cod and the associated islands (trips A-10 & B-10). Bedrock dominates some coastal regions, such as around Cape Ann (trips A-11 & B-11) and southward (trip B-12) to the Boston Harbor and in the Nantasket (trips A-9 & B-9) and Scituate areas south of the harbor. Salt marsh areas are ubiquitous along the entire coast (trips A-8 & B-8, A-9 & B-9, A-10 & B-10). Dunes are well developed on barrier islands and Cape Cod (trips A-8 & B-8, A-10 & B-10). Sand beaches are common up and down the coast. A "singing" sand pocket beach occurs at Manchester north of Boston. A few cobble beaches occur at Gloucester, pocket pebble beaches have developed around Cape Ann, and shingle beaches are present at Nantasket (trips A-9 & B-9).

Glacial deposits consitute the main sediment source for the sandy beaches, spits, bars, and barrier islands. The major storms that affect these coastal features come from the northeast and longshore drift is generally southward on north-south beaches.

ENVIRONMENTAL GEOLOGY

The relatively new concept of environmental geology is presented in several field trips. Associated with urbanization are a host of new or aggravated problems making demands on our natural environment and its resources. With regard to the Boston area, the effects of urbanization on surface water quality will be studied by trip B-19 on which the Charles River will be followed from its relatively clean rural area through to the increasingly polluted urbanized areas along its downstream course. The results of field testing during the trip will be discussed. Downstream, the Charles River, originally an estuary, is artificially impounded in the Charles River Basin between Boston and Cambridge. A new Charles River Dam is currently being built at Warren Avenue in Boston by the United States Army Corps of Engineers. It will provide flood control by maintaining the basin at a constant elevation above sea level in order to prevent damages such as those caused by the record flood of August, 1955. This new dam is a multi-purpose project with provisions for flood control, recreational and commercial navigation, and future highway transportation. Trip A-19 will consist of an inspection of the second stage cofferdam excavation, exposing the foundation conditions.

North of Boston, two trips will visit areas that are now protected from man's abuse. Prior to the Middlesex Fells (trip B-7) becoming a reservation in 1896, it had a long history of abuse. Its vegetational mosaic is now different in character from that of the time of colonial settlements because of lumbering, livestock grazing and both natural and man-induced fires. The effects of man's attempt to prevent shoreline erosion on the northern end of Plum Island in northeastern Massachusetts will be compared to the relatively disturbed natural system in the Parker River National Wildlife Refuge area of the middle and southern parts of Plum Island (trips A-8 & B-8).

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BEDROCK GEOLOGY OF THE BOSTON BASIN

by

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Introduction

The Boston Basin of eastern Massachusetts is a lowland, at or close to sea level, bounded on the north by the Fells Upland and on the south by the Blue Hills and Sharon Upland (La Forge, 1932, p. 8). To the west the Basin merges imperceptibly with the Needham Upland, but to the east is flooded by the waters of Boston Harbor and Boston Bay. The term Boston Basin also refers to the structurally complex synclinorium occupied by the Boston Bay Group. This paper is concerned primarily with the bedrock geology of the Boston Basin and Blue Hills.

The interpretation of the major features of the geology given in the paper does not differ greatly from that given by Billings (1929) and La Forge (1932). However, there are a few major differences.

(1) In the earlier papers it was assumed that the Cambridge Formation overlay the Roxbury Formation. But Billings and Tierney (1964) have shown that the Roxbury Formation is a southerly facies of the lower part of the Cambridge Formation.

(2) The concept of large tear-faults (transverse strike-slip faults) is now abandoned.

The importance of the study of the geology exposed in 32 miles of tunnels in the Boston Basin has been emphasized elsewhere (Billings, 1976). In that most recent paper the Dorchester Tunnel was not discussed. The writer prepared the original report when the tunnel was being planned (Billings, 1964), including a detailed analysis of the core borings. During construction the geology was mapped by Steven M. Richardson, to whom I am indebted for some data given in this paper.

Lithology

<u>General statement</u>. Figure 1 is a sketch map to show the distribution of the formations. Because of scale, it is not

intended to show details.

Five major units are shown in Figure 1: (1) Precambrian, (2) Cambrian, (3) Ordovician(?), (4) Mississippian(?), and (5) Pennsylvanian and Pennsylvanian(?). The Triassic diabases are not shown. The evidence for the dating will be discussed under the various units.

Precambrian. The dating of many of the rocks as Precambrian is based on exposures at Hoppin Hill, North Attleboro, 30 miles southwest of Figure 1, where fossiliferous Lower Cambrian rests unconformably on Dedham Granodiorite (Dowse, 1950). Thus the Dedham and its comagmatic rocks are Precambrian, as well as rocks into which they are intruded.

The Precambrian, which underlies large areas in Figure 1, consists of metamorphic and plutonic rocks. The metamorphic rocks are quartzite, amphibolite, and gneiss. The plutonic rocks are gabbro, diorite, quartz diorite, granodiorite, and granite. Detailed descriptions are given by La Forge (1932), Chute (1966, 1969), and Nelson (1975).

Cambrian. The Cambrian rocks are confined to two areas. They are extensively developed in the area extending from the Blue Hills to Weymouth, a distance of nine miles. Their distribution is shown very diagrammatically in Figure 1. They are also found at East Point in Nahant.

Traditionally the Cambrian rocks have been assigned to two formations. The Weymouth Formation, consisting of red shales, locally converted to hornfels, and a little limestone, is Lower Cambrian. The Braintree Formation is a dark-gray massive argillite of Middle Cambrian age. The very important paleontological studies by G. Stinson Lord and Benjamin Howell await publication.

Ordovician(?). In Figure 1 the alkalic igneous rocks of the Blue Hills complex have been assigned to three units: (1) volcanic complex, consisting of rhyolitic lavas and pyroclastic rocks; (2) Blue Hills Granite Porphyry; and (3) Quincy Granite, a riebeckite-aegirite granite. Zartman and Marvin (1971) utilizing the Pb/U method, concluded this group is late Ordovician.

Mattapan and Lynn Volcanic Complexes. The Mattapan Volcanic Complex occupies three large areas in Figure 1, two to the south of the center of the map, the other to the southwest. Smaller areas are also present. The Mattapan is composed of felsites and melaphyres (altered basalts and andesites), some of which are amygdaloidal. A detailed description of this rock in the Natick quadrangle (extreme western part of Figure 1) has been given by Nelson (1975), who has identified crystal tuff, lapilli tuff, breccia, and lahars. Much of the Mattapan un-

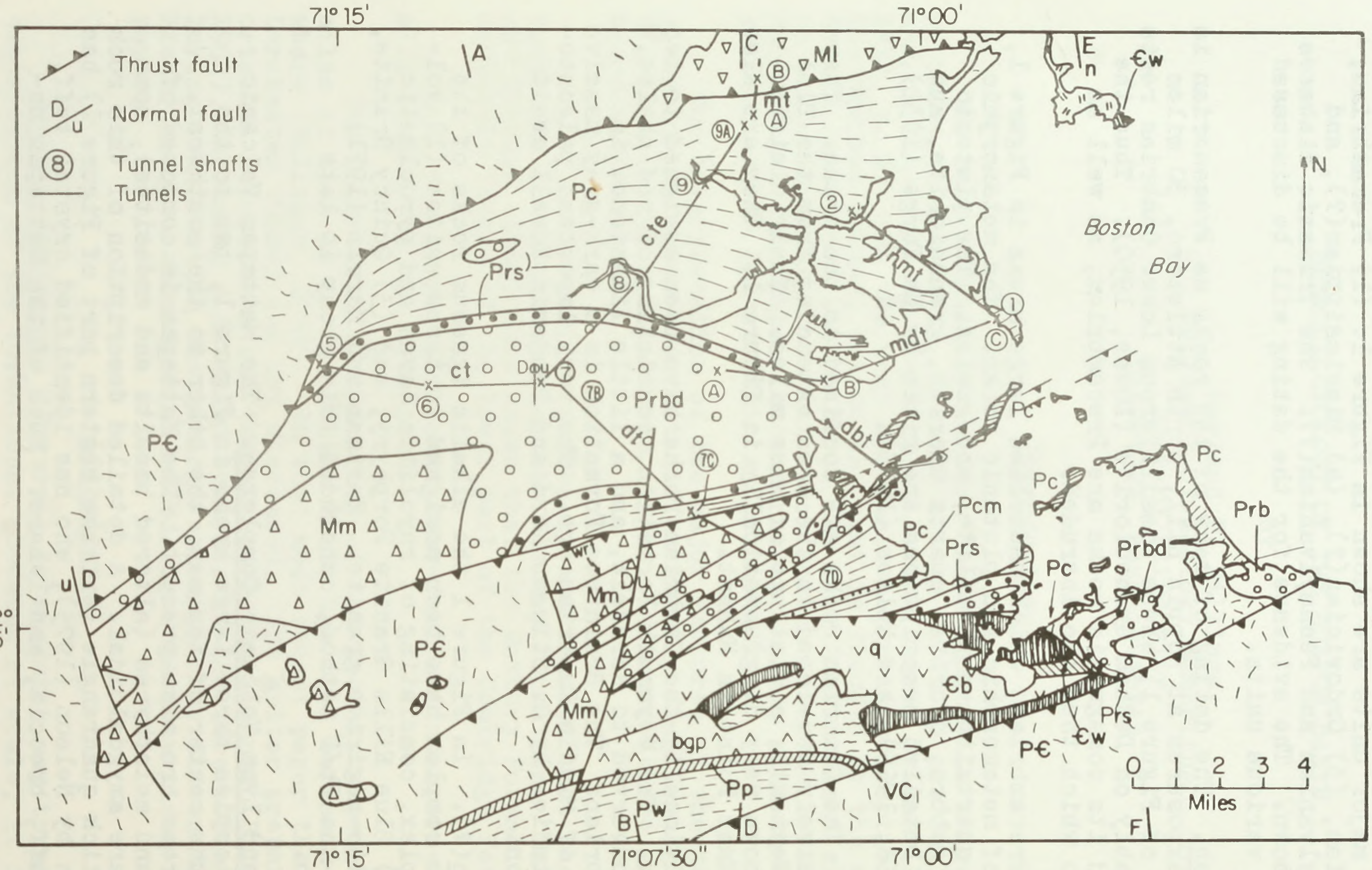
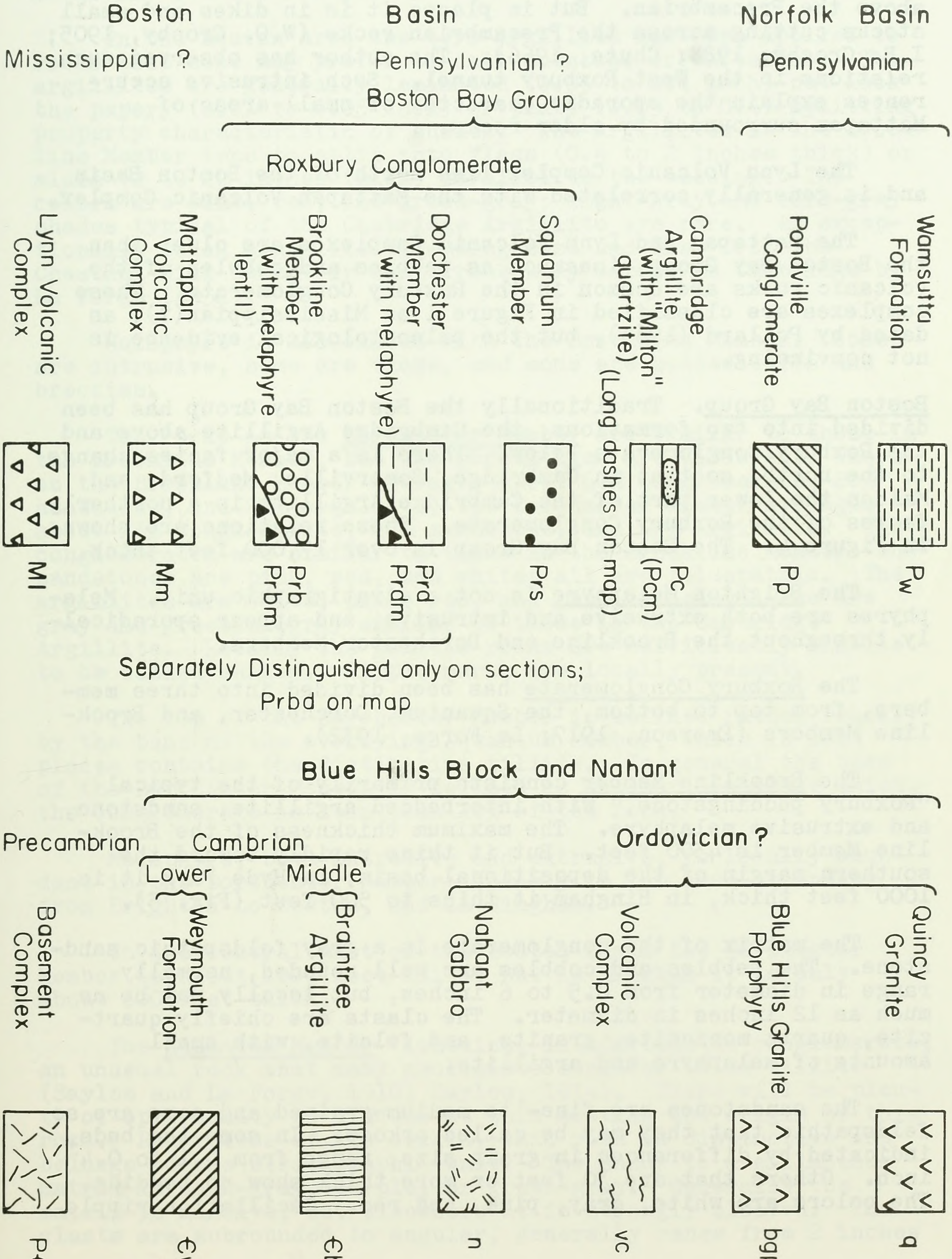


Fig. 1. Geological Sketch Map of Boston Basin and Blue Hills. See Fig. 2 for explanation of symbols for formations. In Fig. 1 Brookline and Dorchester Members are combined as Prbd. Tunnels labelled thus: mt, Malden Tunnel; cte, City Tunnel Extension; ct, City Tunnel; nmt, North Metropolitan Relief Tunnel; dbt, Dorchester Bay Tunnel; wrt, West Roxbury Tunnel; dt, Dorchester Tunnel.

Fig. 2. Explanation for Fig. 1.



doubtedly belongs to a depositional sheet laid unconformably above the Precambrian. But in places it is in dikes and small stocks cutting across the Precambrian rocks (W.O. Crosby, 1905; I.B. Crosby, 1928; Chute, 1966). The author has observed such relations in the West Roxbury tunnel. Such intrusive occurrences explain the sporadic character of small areas of Mattapan surrounded by older rocks.

The Lynn Volcanic Complex lies north of the Boston Basin and is generally correlated with the Mattapan Volcanic Complex.

The Mattapan and Lynn Volcanic Complexes are older than the Boston Bay Group, inasmuch as pebbles and cobbles of the volcanic rocks are common in the Roxbury Conglomerate. These complexes are classified in Figure 1 as Mississippian(?), as dated by Pollard (1965), but the paleontological evidence is not convincing.

Boston Bay Group. Traditionally the Boston Bay Group has been divided into two formations, the Cambridge Argillite above and the Roxbury Conglomerate below. There is a major facies change to the north, so that in Cambridge, Somerville, Medford, and Malden the lower part of the Cambridge Argillite is a northerly facies of the Roxbury Conglomerate. These relations are shown in Figure 4. The Boston Bay Group is over 17,000 feet thick.

The Brighton Melaphyre is not a stratigraphic unit. Melaphyres are both extrusive and intrusive, and appear sporadically throughout the Brookline and Dorchester Members.

The Roxbury Conglomerate has been divided into three members, from top to bottom, the Squantum, Dorchester, and Brookline Members (Emerson, 1917; La Forge, 1932).

The Brookline Member consists primarily of the typical "Roxbury puddingstone," with interbedded argillite, sandstone, and extrusive melaphyre. The maximum thickness of the Brookline Member is 4300 feet. But it thins rapidly toward the southern margin of the depositional basin; in Hyde Park it is 1000 feet thick, in Hingham it thins to 500 feet (Fig. 3).

The matrix of the conglomerate is a gray feldspathic sandstone. The pebbles and cobbles are well rounded, normally range in diameter from 0.5 to 6 inches, but locally may be as much as 12 inches in diameter. The clasts are chiefly quartzite, quartz monzonite, granite, and felsite, with small amounts of melaphyre and argillite.

The sandstones are fine- to medium-grained and some are so feldspathic that they may be called arkose. In some the beds, indicated by differences in grain size, range from 0.1 to 0.4 inch. Others that are 30 feet or more thick show no bedding. The colors are white, gray, pink, and red. Oscillation ripple marks are found locally.

In the Boston area the term argillite has been applied to rocks that some may prefer to call mudstone or siltstone. The argillites are generally laminated (0.05 to 0.4 inch) but lack the papery (0.01 to 0.05 inch) or platy (0.05 to 0.4) splitting property characteristic of shales. The argillites in the Brookline Member tend to split into flags (0.4 to 2 inches thick) or slabs (2 to 24 inches thick) parallel to the bedding. The colors are pink, red, and green-gray; light-gray and dark-gray shades typical of the Cambridge Argillite are rare. An exceptionally thick argillite extending east and west from the Chestnut Hill Reservoir was erroneously mapped as Cambridge by La Forge (1932).

Melaphyre is associated with the Brookline Member. Some are intrusive, some are flows, and some are bedded tuffs and breccias.

The rocks in the Dorchester Member are similar to those in the Brookline Member, but the percentages are different. Whereas the Brookline Member averages about 60% conglomerate, 20% sandstone, and 20% argillite, the Dorchester Member averages about 15% conglomerate, 25% sandstone, and 60% argillite. The conglomerates are similar to those in the Brookline Member. The sandstones are pink, red, and white; all are feldspathic. The argillites are white, pink, red, and purplish-gray; some are gray and greenish-gray similar to those in the Cambridge Argillite. Locally the pelitic rocks are sufficiently fissile to be called shales. Ripple marks are locally present.

The top of the Dorchester Member is defined rather readily by the base of the overlying Squantum Member, which in most places contains the distinctive tillite. In general the base of the Dorchester Member is defined as the horizon above which the conglomerate is less than 20% of the rock.

Melaphyre, both intrusive and extrusive, is locally abundant in the Dorchester Member; notably in the area extending from Brighton to Newton, and in Hingham.

In the central part of the Boston Basin the Dorchester Member is about 1000 feet thick, but in Hingham it is only about 600 feet thick.

The Squantum Member contains, in addition to conglomerate, an unusual rock that many geologists consider to be tillite (Sayles and La Forge, 1910; Sayles, 1914). There will be plenty of opportunity to discuss at this meeting the origin of this rock. Regardless of its origin, this rock is distinctive and belongs to one stratigraphic unit. The sandy to argillaceous matrix is dark-gray, purple, or green-gray. Generally the matrix is massive, but elsewhere it is strongly cleaved. The clasts are subrounded to angular, generally range from 2 inches to 3 feet in diameter and some are even larger; at Squantum Southeast (Sayles, 1914) one clast is 8 feet long. The clasts are granite, quartz monzonite, quartzite, felsite, and melaphyre.

The Squantum Member ranges in thickness from 70 to 400 feet. In general, the distinctive tillite constitutes much of the member. However, where crossed by the City Tunnel Extension in Brighton, it is conglomerate and contains no tillite. The band shown in Hingham (Fig. 1) contains no tillite, but has an exceptionally coarse conglomerate.

The Cambridge Argillite is composed almost exclusively of gray argillite, in which the beds range in thickness from 0.05 to 3 inches. The shades of gray differ in intensity; the grains in the light-gray rocks are silt or fine sand, whereas in the darker beds they are clay or fine silt. Much of the argillite shows a rhythmic layering due to alternation of lighter and darker beds 0.3 to 3 inches thick. Graded bedding is rare. The ubiquitous preservation of this thin bedding indicates that burrowing animals were not present. Some beds of argillite seem to be as much as 3 feet thick, but close examination shows that they consist of laminae 0.05 to 0.1 inch thick. The argillites are slightly calcareous. The fractures parallel to the bedding are 5 to 50 inches apart; because of two or more sets of joints transverse to the bedding the rocks break up into parallelopipeda. Occasional beds of sandstone 0.25 to 0.5 inch thick show minute cross-bedding.

The most prominent quartzite in the area was called the "Milton Quartzite" by Billings (1929). But "Milton" was preoccupied (Wilmarth, 1936) and should not have been used. But rather than propose a new name at this time, it seems best to retain the old name in quotes. This hard white sericitic quartzite, 400 to 500 feet thick, can be traced for about two miles in Quincy (Fig. 1). It was considered to be Upper Cambrian because quartzite pebbles with Upper Cambrian fossils are found in Pennsylvanian conglomerates in the Narragansett Basin (La Forge, 1932, p. 19).

La Forge (1932, p. 101) also says that Upper Cambrian fossils were found in quartzite and shale just west of the Blue Hills, but there is considerable doubt that the supposed fossils are organic. Moreover, the band of "Milton Quartzite" shown on Figure 1 appears to be a member of the Cambridge Argillite (Billings, 1976). On the other hand, southwest of where the "Milton" is truncated by the Blue Hill Fault, a quartzite is intruded by granite (Chute, 1969). If this is Quincy granite, this quartzite is pre-Ordovician(?)(Zartman and Marvin, 1971).

In earlier papers (Billings, 1929, p. 106; La Forge, 1932, p. 43) a green, red, and yellow quartzite at Tufts College that is 40 feet thick was believed to overlie the Cambridge and was called the Tufts Quartzite. Utilizing information from the City Tunnel Extension, it is now clear that this quartzite is a member of the Cambridge Argillite and is 7500 feet stratigraphically below the Squantum horizon.

Concerning the age of the Boston Bay Group, La Forge (1932, p. 41) says the following: "No fossils have been found in the Roxbury conglomerate except for a few short pieces of tree trunks that were collected near Forest Hills, probably in the Brookline conglomerate member. The pieces are casts of trunks from which the bark had fallen, and the genus to which they belong is uncertain but is probably either Cordaites or Lepidodendron. Their age, therefore, can not be determined more closely than that they are either Devonian or Carboniferous." A re-examination of one of these specimens by Elso Barghoorn suggested it could be Calixylon or Cordaites, and the rocks could not be dated better than Upper Devonian through Permian (Tierney, Billings, and Cassidy, 1968). Regional relations indicate that the most likely age is Pennsylvanian or Permian.

A detailed discussion of the geology of the Norfolk Basin is beyond the scope of this paper, but is mentioned because it has a bearing on the interpretation of the geology of the Blue Hills. The Pondville Conglomerate of Figure 1 is composed of two contrasting lithologic types. The lower part, a few hundred feet thick, is commonly referred to as the "giant conglomerate." Round boulders, 6 to 12 inches in diameter, are set in a matrix of feldspathic sandstone. The boulders are porphyritic alkaline granite, similar to, but not identical with some of the rocks in the Blue Hills. It may be incorrect to correlate this "giant conglomerate" with the type Pondville conglomerate. The upper part of the Pondville as shown in Figure 1 is a quartz conglomerate, the matrix of which is a light-yellow sericitic quartzite. The overlying Wamsutta Formation is red slate, red sandstone, and gray conglomerate. Plant fossils show that it is Pennsylvanian.

Mafic Dikes. La Forge (1932, p. 45-50) gives the best discussion of the mafic dikes. Most of them are diabase or altered diabase. Although many ages may be represented, some as old as Precambrian, others are younger than the late Paleozoic folding. These have traditionally been considered to be Triassic because of similarity to the Triassic diabases in the Connecticut Valley. The most famous in the Boston area is the Medford diabase dike, in places 500 feet thick.

Structural Geology

Introduction. The geological structure is shown by Figures 1, 3, and 4. The Boston Basin is bounded on the northwest by a thrust fault and on the south by a series of en echelon thrusts. The basin itself is characterized by folds plunging east-north-

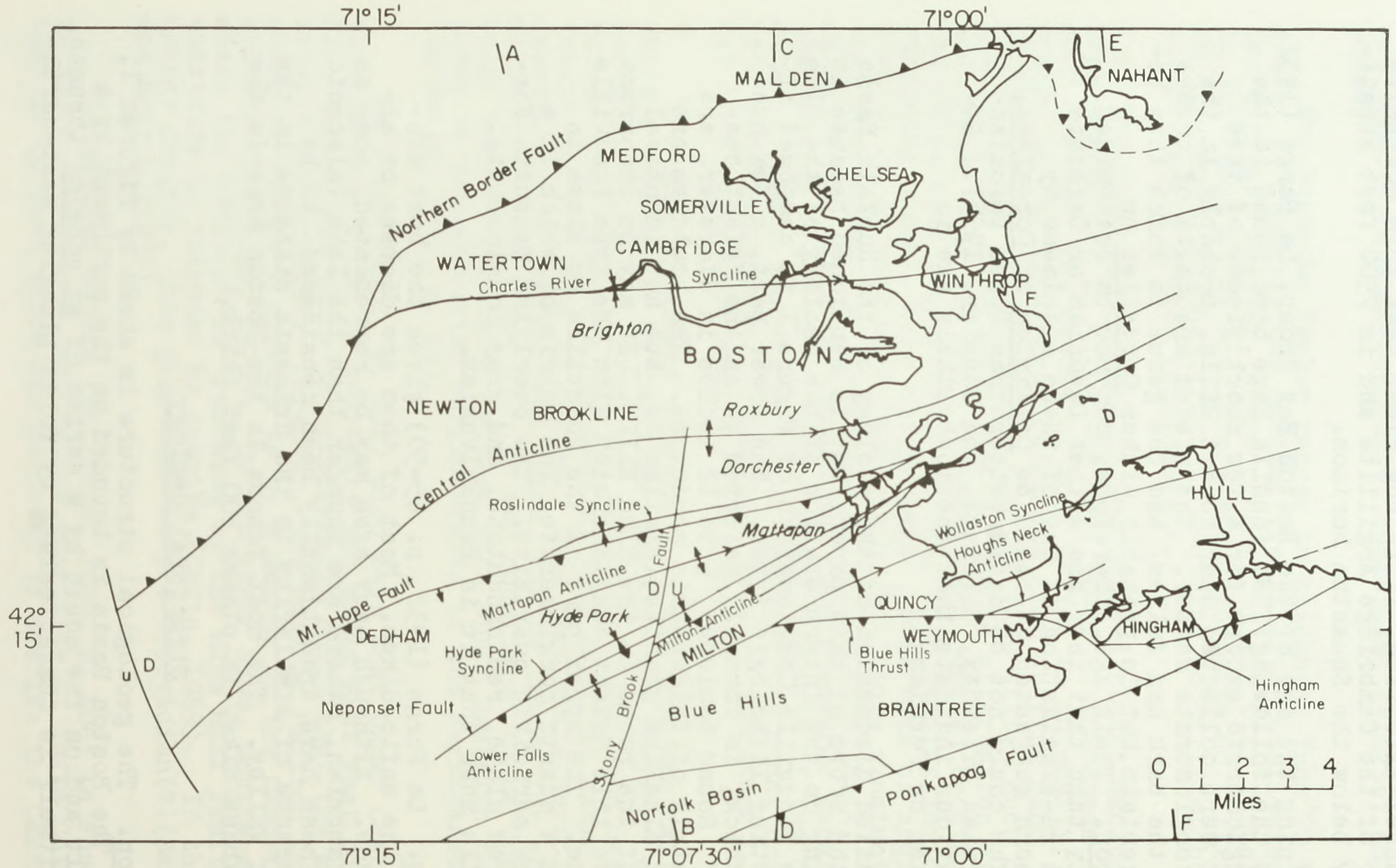


Fig. 3. Tectonic Map of Boston Basin and Blue Hills. Also shows cities and towns referred to in text, and location of structure sections.

east and several thrusts striking east-northeast.

Major Folds. The northern three quarters of the basin is dominated by two major folds - the Charles River Syncline and the Central (Shawmut) Anticline.

The morphology of the Charles River Syncline is well known, partially from outcrops but also because it is crossed by two tunnels - the City Tunnel Extension (Billings and Tierney, 1964) and the North Metropolitan Relief Tunnel (Billings, 1975). The distance between the two tunnels along the trace of the hinge of the Charles River Syncline is 6.5 miles. The average plunge of the hinge is 19° in a direction N 84° E. The dip of the north limb in most places ranges from horizontal to 60° SE, but a few anticlines and synclines with wave lengths of several hundred feet are present (Fig. 4, section CD; Billings and Tierney, 1964). In the north Metropolitan Relief Tunnel the northwest limb dips 30° to 60° SE. In the City Tunnel Extension the minor folds - those with a wave length of one to three feet - have an average plunge of 8° in a direction N 87° E. In the North Metropolitan Relief Tunnel the few minor folds that were observed plunge from 0° to 25° in a direction east-northeast (Billings, 1975, p. 130).

The south limb of the Charles River Syncline was well exposed in four tunnels - City Tunnel, City Tunnel Extension, Main Drainage Tunnel, and North Metropolitan Relief Tunnel. In most of these tunnels the dip is 15° to 30° N, but in the North Metropolitan Tunnel it ranges from 0° to 80° N, but averaging 60° N.

The hinge of the Central Anticline trends between N 60° E and N 80° E (Fig. 3). The map pattern (Fig. 1) and the attitude of the bedding indicates that the fold is broad and open and plunges 10° to 15° east. The north limb is the same as the south limb of the Charles River Syncline. The south limb dips 65° SSE. The axial surface dips about 75° N.

The Cambridge Argillite south of the Squantum Member on the south limb of the Central Anticline is 4500 feet wide, dips 75° SSE (Richardson, 1976), and tops to the south (Billings, 1929). This is the north limb of the Roslindale Syncline, which, however, has no south limb. Whether such one-limbed structures should be called a syncline is a matter of semantics. The Mt. Hope fault (Fig. 3) bounding this belt on the south is discussed below.

South of the Roslindale Syncline a long tongue of Mattapan Volcanics (Fig. 1), with bands of Roxbury Conglomerate on both sides, tapers to a point toward the northeast. This is the core of the northeasterly plunging Mattapan Anticline (Fig. 3). In the Dorchester Tunnel (Richardson, 1975) the base of the Roxbury Conglomerate dips 60° NW on the northwest limb. This contact, now considered to be an unconformity, was

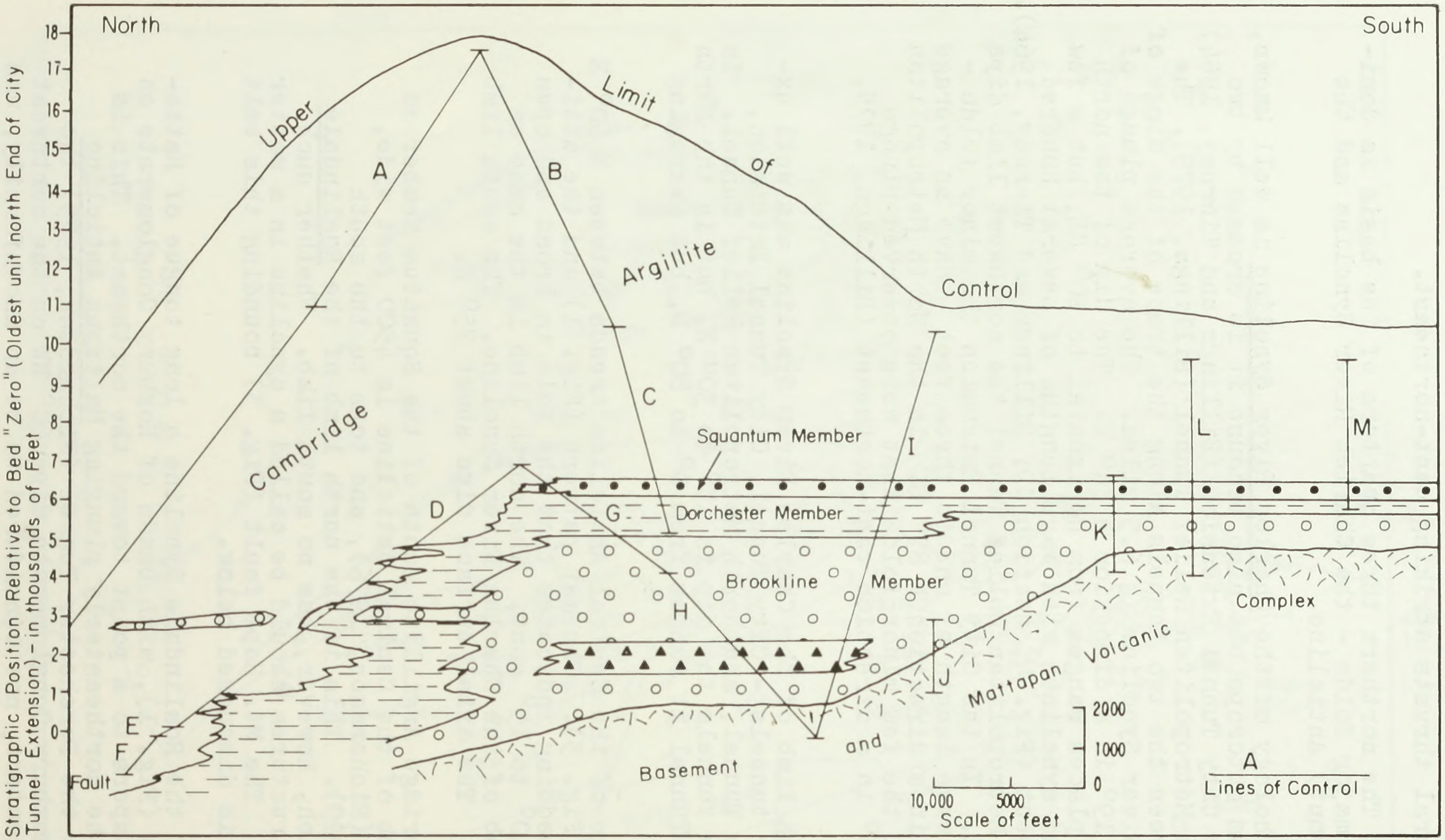


Fig. 4. Stratigraphy of the Boston Basin. Capital letters indicate nature of control. A. North part of North Metropolitan Relief Tunnel. B. South part of North Metropolitan Relief Tunnel. C. Main Drainage Tunnel. D. North part of City Tunnel Extension. E. Surface geology in Malden. F. Malden Tunnel. G. South part of City Tunnel Extension. H. Surface geology in Brookline. I. Surface geology Brookline to Dorchester. J. Surface geology north limb of Mattapan anticline. K. Surface geology south limb of Mattapan anticline in Hyde Park. L. Surface geology Dorchester Lower Mills. M. Furnace Brook at Adams Street, Quincy.

formerly (Billings, 1929) believed to be a fault called the Sally Rock thrust. The base of the Roxbury is vertical on the southeast limb of the Mattapan Anticline. The Roxbury Conglomerate both northwest and southeast of the Mattapan Volcanics is in synclines; the former is given no name in Figure 3, the latter is called the Hyde Park Syncline.

In Hyde Park the Squantum Member forms the core of the Hyde Park Syncline (section AB, Fig. 4). At Squantum, the Squantum Member and the basal beds of the Cambridge Argillite are present. Along section CD the Squantum is absent, as will be discussed below in the discussion of the Neponset Fault. The Hyde Park Syncline is another syncline without a southeast limb.

The Lower Falls Anticline, named after the Lower Falls of the Neponset River, is shown on Figure 1 by a tongue of Mattapan Volcanics that tapers to a point toward the northeast. Moreover, at Lower Falls an argillite near the base of the Roxbury Conglomerate is exposed along the MBTA tracks in an anticline plunging 18° in a direction N 67° E (Billings, 1976).

The Cambridge Argillite is poorly exposed in the Wollaston Syncline. But the presence of the Roxbury Conglomerate both northwest and southeast of the Cambridge demonstrates the reality of the syncline.

The north limb of the Houghs Neck Anticline is well exposed in the vicinity of Furnace Brook in Quincy. Vertical beds of the Dorchester Member, Squantum Member, and Cambridge Argillite strike southwest into the contact with the Quincy Granite (Fig. 1). Further east conglomerates, intruded by melaphyre, are found in the core of the anticline. The south limb is hypothetical, based largely on the presence of Cambridge to the east.

The Hingham Anticline, which plunges steeply west, has a core of the Dedham Granodiorite; it is based on excellent exposures (W.O. Crosby, 1894).

Faults. In the City Tunnel (Tierney et al., 1968), City Tunnel Extension (Billings and Tierney, 1964), and Main Drainage Tunnel (Rahm, 1962), 318 minor faults were recorded (Billings, 1976). Of those 278 faults in which the displacement could be determined, 186 were normal, 51 were reverse, and 41 were vertical. The most prominent strikes average N 20° E, N 10° W, and N 50° W; dips are 80° to 90°, although some dips are as low as 50° (Billings, 1976). The average vertical separation of these faults was three feet. But in 39 of the faults, the nature and amount of the displacement appeared to be greater than the diameter of the tunnel and could not be measured.

Six major faults are shown in Figures 1 and 3.

The North Border Fault has been known for a long time and

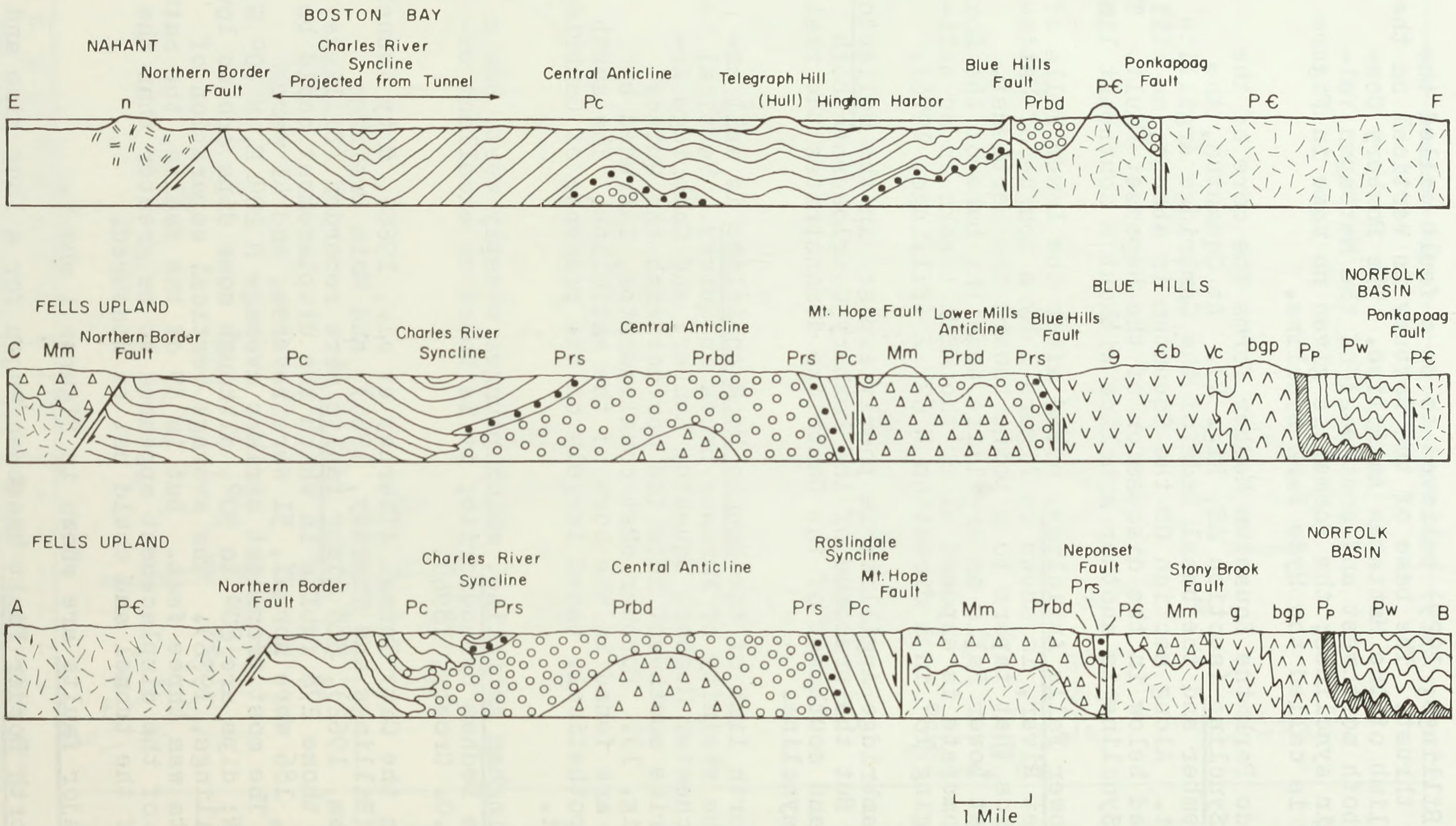


Fig. 5. Structure Sections of Boston Basin. Location of cross-sections is on Figs. 1 & 3. See Fig. 2 for legend. Dip of all faults, except Stony Brook Fault, is based on observation. Sections arranged to give down-plunge view of structure; that is, section AB is structurally lowest, EF is structurally highest.

has been considered to be a thrust (Billings, 1929, p. 107; La Forge, 1932, p. 63). The thrust was exposed in the Malden Tunnel (Billings and Rahm, 1966), where it is knife sharp, with no breccia or gouge, and dips 55° N. Lynn Volcanics are thrust over Cambridge Argillite that has been dragged into a vertical dip (Fig. 4, section CD). Further west various Precambrian units comprise the hanging wall. The stratigraphic throw is not necessarily great, but the length of the fault suggests it is large.

The northeasterly striking faults in the southern half of the Boston Basin are called thrusts despite the fact that they are now essentially vertical. It is significant that the synclines to the northwest lack southeastern limbs and the anticlines to the southeast lack northwestern limbs. The faults must have formed prior to any important folding (Billings, 1972, Fig. 10-1,A), dipped less than 45° SE, and then during the folding were rotated to their present vertical dip.

The Mt. Hope thrust trends east-northeast. Near the west end of the belt of Cambridge Argillite in the Roslindale Syncline (Fig. 1) the structural relations are clear near the Roxbury Latin School. Northwest of Center Street argillites of the Cambridge Formation, 2500 feet above the Squantum Member dip 60° S and ripple marks show they are right-side-up. Five hundred feet to the south the Precambrian Dedham Granodiorite crops out. A large fault, with a stratigraphic throw of at least 6000 feet is indicated.

Three and one-half miles to the east, near the line of the Dorchester Tunnel, both surface geology and observations in the tunnel indicate a large fault. In an abandoned quarry at the corner of Wildwood and Dumas Streets in Dorchester argillites of the Cambridge Formation, 4000 feet above the Squantum Member, dip 70° S; ripple marks show the beds are right-side-up (Billings, 1929, p. 117). A band of Roxbury Conglomerate lies a few hundred feet to the south. The actual contact, formerly exposed on Middleton Street, is a shear zone dipping 85° N (Billings, 1929, p. 117). The Dorchester Tunnel crossed this fault (Richardson, 1975). The Cambridge Argillite northwest of the fault, for a distance of 4300 feet dips rather uniformly 70° to 75° ESE. But for 200 feet northwest of the fault the beds dip 20° ESE. The fault plane strikes N 52° E and dips 85° NW. Southeast of the fault are felsites of the Mattapan Volcanics. The stratigraphic throw is 10,000 feet. Two and one-quarter miles to the northeast, northwest of Squantum, the Dorchester Member is apparently faulted against the Cambridge Formation under Dorchester Bay (Clarke, 1888; Billings, 1976).

The Neponset Fault is based in part on evidence in Hyde Park (Figs. 1 and 3). On the south limb of the Mattapan Anticline the Brookline, Dorchester, and Squantum Members appear in proper order dipping southeast. But directly south of the Squantum the Mattapan Volcanics crop out (Chute, 1966). The stratigraphic throw is at least 2000 feet. Two miles to the northeast minor thrusts accompany the fault (Billings, 1929, p. 121).

Still further east, to the west and north of Lower Mills, the folds plunge southwest, unlike most of those in the Boston Basin. The end of the Squantum Member, as shown in Figure 1, is due to this southwesterly plunge of a syncline. North of Lower Mills surface data indicate a syncline plunging 15° SW. The data in the Dorchester Tunnel are very clear on this point (Richardson, 1975). A major syncline between the Mattapan and Lower Mills Anticlines plunges 14° SW (Fig. 5, section CD). The Neponset Fault has ended somewhere to the southwest. But a similar fault is present in the Squantum area, where the Squantum Member is thrust against basal Cambridge.

The Blue Hills thrust bounds the Quincy Granite on the north (Figs. 1, 3, and 4). The evidence is clearest in Quincy, where successive northeasterly striking units of the Boston Bay Group - from east to west the Dorchester, Squantum, and Cambridge, including the "Milton" - are truncated at the east-west contact with the Quincy. Along Randolph Avenue near Milton Center this contact is an east-west trench 50 feet wide and 20 feet deep. Loughlin (1911) observed this fault during road construction and states that it dips 80° S. This fault continues to the coast at Nantasket (Hull). Here the best evidence is in Hingham where, on the north limb of the Hingham Anticline, the basement and all the members of the Roxbury Conglomerate are truncated against the Cambridge Argillite in Boston Harbor.

In Weymouth a fault is shown in Figure 1 branching off from the Blue Hill thrust, but exposures here are poor. Formerly (Billings, 1929) this was considered to be a tear-fault.

The Ponkapoag Fault is of special interest as it slices across the east end of the Norfolk Basin, the Blue Hills, and the Hingham Anticline. It is over 18 miles long. In East Weymouth, four miles east of where the Pondville Conglomerate ends, the Ponkapoag fault is exposed in a railroad cut. It dips 80° NW, with Precambrian Dedham Granodiorite to the south and Middle Cambrian Braintree Formation to the north. Downthrow is to the north, but sufficient data are not available to calculate the stratigraphic throw here. In Hingham (Billings et al., 1938, p. 1882) the Dedham south of the fault is in contact with basal Cambridge. The stratigraphic throw is at least 1340 feet.

By analogy with the faults to the north, it is assumed that the Ponkapoag fault originally dipped south and has been rotated into its present position. It is possible that this fault formed with its present attitude as an upthrust.

One and four-tenths miles N 60° E of Watertown Square, east of School Street, a coarse conglomerate was formerly exposed in an abandoned quarry. Sayles (Billings, 1929) considered this to be the Squantum Member. Be that as it may, Sayles, Billings, and La Forge (1932) agreed that it was at the top of the Roxbury Conglomerate. La Forge believed it was in the core of an anticline, whereas Billings (1929, 1976) assumed it was bounded on the north by a thrust.

But the structure observed in the City Tunnel Extension (Billings and Tierney, 1964) indicates that this is a tongue of conglomerate, 4500 feet below the Squantum, extending northwest into the Cambridge Argillite (Fig. 4).

The Stony Brook fault is a large cross-fault striking N 10° E. Billings (1929) formerly considered this to be a strike-slip fault. It is now considered to be a vertical fault, with the west side down-thrown 2100 feet. This deduction is based largely on relations in the Roslindale Syncline. The Squantum Member, striking east-west, dips 55° S and is offset 1470 feet. The east-west vertical Mt. Hope Fault is offset little or not at all. A graphic solution gives the net slip (Billings, 1972, p. 559-563).

The Dorchester Tunnel crosses the Stony Brook Fault zone (Fig. 1). The southeast end of the zone is 160 feet southeast of the main line of the Penn.R.R. The northwest end is 4700 feet to the northwest. Inasmuch as the tunnel is diagonal to the N 10° E strike of the fault, the width of the zone is about 3500 feet. Forty-nine percent of the zone is so fractured that steel support was necessary (Richardson, 1975). The rocks were highly altered and flows of groundwater were common.

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OUTLINE OF THE PLEISTOCENE GEOLOGY OF THE BOSTON BASIN

by

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Introduction

The Boston Basin is both a structural and topographic feature. Structurally, it consists of relatively unmetamorphosed folded and faulted sedimentary and volcanic rocks of Late(?) Paleozoic age, surrounded on the north, south, and west by older granites and other crystalline rocks. Eastward, the basin extends out to sea where its composition and limits have yet to be determined. It is a topographic basin largely by virtue of glacial erosion which preferrentially excavated the soft fine-grained basin rocks, such as argillite and tuff. Outcrops of the harder basin conglomerates and volcanic flowrocks, however, are at altitudes comparable to those of the surrounding rim area. On the north, the rock floor of the topographic basin lies about 50 m on the average below the surrounding uplands; on the south, it is generally less than 15 m; and on the west, the difference in elevation is barely noticeable.

There is a sharp break in the Pleistocene terrain at the margin of the topographic basin in the Boston area. Except for a few drumlins (Fig. 1), the drift on the uplands is thin and patchy and knobby rock outcrops abound. In the basin there is a subdued glacial outwash topography broken by many drumlins. Rock outcrops are rare. The surface of the plain drops below sea level to form Boston harbor with the drumlins making up most of the islands in that body of water.

Beneath the simple surface of this lowland plain there are traces of a complex geological story in the clays, sand, gravels, and sheets of till. The thousands of foundation borings made in the area and the numerous deep excavations for the foundations of large buildings have yielded evidence of a succession of glacial advances and retreats. At least two of these were in the late Wisconsin, but there are bits and pieces of evidence left by earlier glaciations that undoubtedly range back to at least Illinoian time.

The Pleistocene section is suprisingly poor in till and rich in outwash, including thick rockflour clays. There appears to be no widespread till blanket left by the full-bodied Wisconsin ice that built the large terminal moraines to the south at Cape Cod and the islands. For this reason it is difficult to place the drift-stratigraphy into the framework of these major glacial events. The geomorphology of the basin drift is only of minor value in working out the glacial story, in part due to man's success in changing the landscape by filling and grading but also due to the fact that the older surface forms have been modified, destroyed or buried by younger events and deposits.

In Boston, as anywhere else in New England, the Pleistocene geologist must think glaciologically and in four dimensions. When all the data are carefully considered, one is slowly led to conclude that some of our long-held assumptions about Pleistocene glaciology need revision. Among the concepts that first have to be formulated and then accepted with a clear conscience in order to build a coherent framework for the glacial story are: 1) glacial erosion was very variable in its effectiveness and a given glaciation did not entirely remove the deposits of earlier ice sheets; 2) the deposits of a major glacial event are not ubiquitous but rather, patchy; 3) ice sheets need not have deformed or compacted (consolidated) overridden deposits; 4) under certain conditions, sheets of preëxisting sediments were dislocated from the glacial bed and transported englacially without undergoing drastic, or even noticeable disturbance or disaggregation. As a consequence of these conditions, the recognition of the age of any drift becomes uncertain, particularly if the weathering profile has been removed by the erosion of a subsequent glaciation. Moreover, the surface drift cannot be assumed to date from the last glaciation. A study of rock lithologies of clasts in till may be helpful in separating drifts but only if flow directions of the responsible ice sheets were markedly different. Even here, however, there are difficulties because successive ice sheets reworked pebbles from older drifts, creating thereby an ever-widening fan of distribution with which to confound the geologist.

Glacial transportation of intact plates of older sediment is particularly bothersome because these may have survived glaciation in such a natural manner that one readily misreads them as being in their place of origin. A pile-up of several plates of sediment, as in the Beacon Hill moraine (Kaye, in pressB) or in the Gay Head moraine of Martha's Vineyard (Kaye, 1964a), can easily result in a stratigraphic misinterpretation where relative ages of sediments are assigned on the basis of superposition when, in fact, they may be like a well-shuffled deck of cards, where the oldest need not be on the bottom.

If the glacial geology of the Boston basin is different, or more complex, than geology seems to be in many places in the interior of New England, perhaps this can be attributed to Boston's location: first, at the margin of the marine environment and secondly, at the margin of two major ice currents, or lobes. As we shall see, the direction of ice flow at Boston varied from southwest to east, through an arc of about 135° in azimuth. Represented here are diversional interlobate currents and ice currents that were antecedent to the major Wisconsin glaciation, as well as the normal lobate currents belonging to that event.

Feeble ice flow (in comparision to that prevailing to the east and west) characterized the Boston area during much of Wisconsin time. This situation is normal to an interlobate position, for a lobe, after all, is only an expression of varying rates of glacial flow, the greatest at the center of the ice current (the lobal axis) and the least at the margins. At one time, there even appears to have been virtual ice stagnation at Boston while to the east and west ice was flowing vigorously.

Boston is at the marine shore today; and it appears to have been at, or close to, the marine limits during much of Wisconsin time. The effects of the sea on the ice sheet were many. For one, it provided bouyancy thereby relieving the bed of the ice from full bottom pressure. At times, when the ice was thin enough and the water deep enough, the ice may even have floated (shelf ice). However, the factors to be considered in determining the amount of marine bouyancy on ice at Boston are difficult to assess knowing as little as we do. The equation must include expressions for crustal (isostatic) levels, eustatic sea levels, and ice thickness.

Glacial Flow Directions

Four types of indices of glacial flow have been used: striations and grooves on bedrock, elongation of drumlin axes, lithologies of clasts in till and their probable source outcrops, deformational structures in overridden deposits. Many hundreds of striation and groove localities have been measured. It was found that all freshly exposed bedrock surfaces are well-polished, striated, or grooved and striated. Large grooves (as distinct from striations) all trend east to east southeast (S60°E). Striations, on the other hand, range through about 135° azimuth from east through south to southwest. However, these can be broken down into 4 separate striation groups representing separate glaciologic events: (1) highly variable east to southeast flow, (2) south southeast flow that varied back and forth within the range S32°E-S16°E, (3) southerly flow, and (4) southwest flow.

The elongation directions of drumlins exhibit this same broad range of orientations. However, besides the classically streamlined drumlins, there are drumlins that are rounded in plan, compound drumlins, curved and sigmoidal drumlins. Some of these represent modification of initial streamlined drumlins by later ice currents. In a few places, bedrock striations have been exposed beneath drumlins and these seem to diverge somewhat from the direction of elongation of the overlying drumlins.

In an area where much of the bedrock is covered with drift and our knowledge of the distribution of rock types is therefore limited, the use of pebble lithologies in till for establishing glacial flow patterns is difficult. Nevertheless, there are certain key rock types that as far as we know have only one outcrop, or outcrop area (viz. Quincy riebeckite granite, Blue Hills quartz porphyry, Roxbury conglomerate, Nahant gabbro, serpentinite of Lynnfield, just to list a few) and which are easily recognized in the field. Unfortunately, however, little is known about the submarine rocks offshore to the northeast and east, or even within Boston harbor. It has been found that rock suites rather than key index rocks provide a sounder way to derive the direction of glacial transport. This involves taking all of the dominant rock types and matching them with the bedrock map of the area in order to establish a "best fit" between clasts and map. Refining one's eyes to recognize rapidly the many rocks of the area and their variations is essential to the process. Fortunately, clast sampling is greatly facilitated in Boston harbor because the many drumlin islands are rimmed by beaches that consist almost entirely of pebbles and boulders from adjacent till cliffs. One has only to slowly walk these beaches to scan many thousands of pebbles in a short time. These pebbles, however, are a mixture of all horizons exposed in the cliffs. It is quite probable for example, that some of the drumlins include a complex of deposits contributed by shifting ice currents or by several distinct glacial events. Pebbles from all zones are mixed together on the beach. Two drift components of this kind have been recognized by comparing beach pebbles in front of low cliffs with those fronting high cliffs; the former giving only the last drift components, the latter both.

Complex deformational structures in the drift have been exposed in many foundation excavations in and about the city. Most of these are tied into two late glacial events, the Beacon Hill readvance and the Back Bay readvance, described in more detail below.

When all of these types of data are assembled, both from Boston and from adjacent areas, the picture of ice flow that emerges is shown in Table I. The very strong easterly flow indicated by deep, wide grooves is a particularly provoking episode. It can only be explained by the absence of a glacial lobe to the east. If this were so, then mainland ice simply followed the topographic gradient, which in the coastal zone of eastern Massachusetts is offshore to the deeper basins that lie to the east under Massachusetts Bay. Perhaps the development of the Laurentide ice cap proceeded from west to east and mainland New England was glaciated before Maine, the Maritimes and the adjacent continental shelf. Later, when the offshore lobes nad developed, glacial flow at Boston was confined to a rectilinear flow path towards the moraines of the southern shore. Here, however, we are confining our conjectures to the Wisconsin stage. Perhaps, the strong easterly flow was older; there is some evidence for this.

With glacial waning, divergent flow patterns redeveloped. The southwesterly flow is especially interesting and chronologically puzzling. To the south of Boston, in the Plymouth embayment, it probably was late Wisconsin for there is reason to think that an active ice lobe occupied Massachusetts and Cape Cod Bays after onshore ice to the west had stagnated and thinned. In Boston, the evidence for a late southwesterly flow into Boston harbor is less clear. To the north, in the lower Merrimack valley, where this flow is indicated by an alignment of drumlins that extends many kilometers to the southwest, there is some indication that it was fairly early in the Wisconsin. In any event, it is reasonable that ice flowed from the offshore lobe to onshore positions if the balance of ice in the two areas was such as to make this possible. The history of glacial fluctuations in its 4-dimensional entirety in eastern New England during the whole of the Wisconsin stage is a subject worthy of much more investigation than it has ever received. There certainly was time enough to allow substantial ice withdrawals and readvances, of changes in ice balance between lobes; and from the glimmer of insight that Boston provides, it appears almost certain that the 80,000 or so years of Wisconsin time did not pass simply with a stable ice sheet banked up first behind the outer and then the inner moraines and with a brief parting episode of minor pulsations of the ice front and the scattering of outwash over the landscape.

Table I

Glacial flow directions at Boston;

in approximate order of occurrence,

oldest on bottom

F. Lobate spreading to south and east (Back Bay readvance)

E. South (Beacon Hill readvance)

D. (?)Southwest

C. South-southeasterly (variable, mostly 32°, 22°, 16°)

B. Easterly to southeast (very variable, 80°-38°)

A. Easterly; wide, deep grooves

Drumlins

An examination of the topographic maps (Lynn, Hull, Nantasket, Boston,North, Boston South, Lexington, and Newton 7½' U.S. Geol. Survey topographic quadrangles) will show that the drumlins in the area come in many shapes and sizes. Although drumlins with the classical streamlined form are numerous enough in Boston harbor and west and south of Boston, the shapes vary so greatly that one hesitates to designate some of the hills as drumlins.

Submarine seismic profiling in the harbor and in Massachusetts Bay to the east shows many drumlins that are entirely submerged and more or less buried in later marine clays. Small drumlins, therefore, may represent only the tops of larger features that are partially submerged or buried.

The relationship between elevation of drumlins and the underlying surface of bedrock must be kept in mind. Obviously, the tops of drumlins reach higher elevation where the underlying bedrock is high than where the bedrock surface is low. This relationship seems to have a bearing on the distribution of drumlin islands and particularly on the several east northeast-bearing chains of drumlin islands in Boston harbor — for example, Peddocks Island and Long Island - which follow the strike of the bedrock and surmount ridges on the bedrock surface.

Many harbor drumlins are cliffed (Kaye, 1967) and these provide the best places to study the composition and structure of the drumlin interior. Several deep excavations in the Boston area exposed largely eroded remnants of drumlins whose existence was not suspected because they had no topographic expression. An example is the small drumlin, most of which lies buried beneath the Beacon Hill moraine and which was exposed during the building of One Beacon Street. Another is a much eroded drumlin in Cambridge, part of which underlies Harvard Yard. This was exposed in the excavations for the Pusey Library and the Cambridge St. underpass, adjacent to the Yard.

Most drumlins consist of compact, very well-graded medium greenish-gray till with a cohesive sandy clayey silt matrix. Boulders are sparse and cobbles and pebbles are predominantly of very local rock types. The top 6-15 meters of drumlins are oxidized to a characteristic light buff color; beneath this the unoxidized till is greenish to bluish gray. Layering, or stratification, has been found in all freshly-exposed drumlins. This consists of thin sandy, silty, and even gravelly layers, interbedded with till. The layers of sorted sediment range from a few centimeters to a meter or more in thickness. The spacing of these layers varies within the till. Some exposures of drumlin till show only a few of these beds of sorted sediment; others show many. In most the layers of sorted sediment are discontinuous. Gravel layers seem to grade into typical till. The thin silt interbeds not uncommonly show signs of intense shearing action. Indeed, it is not clear whether some of the fine-grained interbeds are sedimentary in origin or are of a cataclastic origin, a type of gouge that was produced during the formation of the drumlin. In fact, the entire problem of drumlin origin has been investigated but no single origin seems capable of explaining them all.

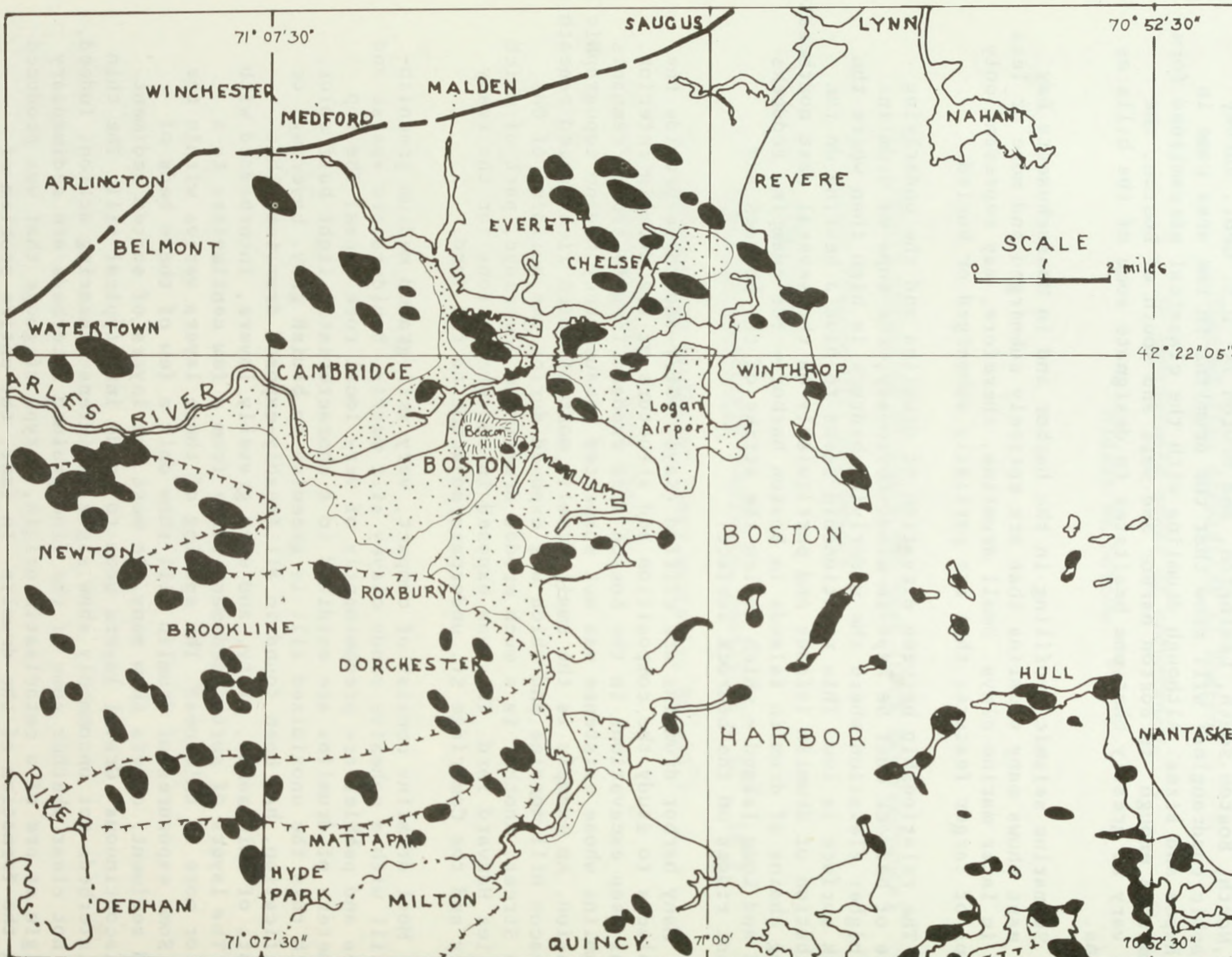

Figure 1 - Part of Boston basin showing: 1) drumlins (black); 2) boundary fault on north side of basin (heavy broken line); 3) major outcrops of conglomerate and volcanics within basin (fine dashed line, ticks towards these rocks); and 4) major areas of made-land (stippled).

One type of drumlin clearly seems different from others. These are till hills that grade laterally into stratified clay and that generally lack the simple elongate drumlin shape. Rather than the flanking clay being younger than the drumlin, both clay and drumlin seem to have been laid down at the same time. Perhaps these drumlins are simply lenticular masses of till left by large dirty icebergs stranded in the clayey bottom.

Sea cliffs show that many drumlins have an overall anticlinal structure, with the strike and dip of the layers more or less conforming to the surface of the drumlin. Some have this structure truncated thereby showing the effect of later glacial erosion. Some exhibit unconformities. The anticlinal structure may be constructional, that is, the ice having deposited till layer by till layer over an initial nuclear concentration. Or it may be the result of true arching of the ice under glacial pressures which centripetally deformed underlying or bed sediment. There are indications in the sheared silt zones that this might have occured.

Some drumlins are known to overlie bedrock directly but from borings we know that others overlie sands, gravels, or clays that appear to be earlier than the drumlins rather than interdrumlin beds. True bedrock-cored drumlins are not known here. The distribution of drumlins appears to be random relative to details of bedrock topography. The association of a few drumlins with bedrock knobs, such as the Parker Hill drumlin, is thought to be coincidental.

Interglacial Fossil Marine Shells

Fossil marine shells are found in the till in many harbor and near-harbor drumlins and in some of the outwash gravel in the same area. These fossils provoked much interest in the last century, and the last and as yet most comprehensive discussion of them was by Crosby and Ballard (1894). The total fauna listed by those authors consisted of 52 species of mollusks, 2 species of barnacles, and 1 crab. I have been able to find only a small percentage of these. The most abundant fossil by far is Mercenaria mercenaria (quahog, cherrystone, chowder clam, etc.), which always occurs as broken fragments, and to a lesser extent Venericardia borealis. Shells of the former species are unusually thick when compared to shells of the same species living in New England waters today.

Shells are found only in the gray unoxidized till, and it is quite certain that their absence from the overlying oxidized till is simply the result of weathering and leaching. The best collecting therefore is in high sea cliffs in harbor drumlins where there is ample exposure of unoxidized till. Shells were also reported by well diggers in the last century from drumlins that are located several kilometers from the harbor. It is apparent that we cannot claim to know the full distribution of fossiliferous drumlins for the simple reason that the deep interiors of most drumlins have not been exposed as have the cliffed drumlins in the harbor, or if they have been exposed, no geologist came by to notice the shells and to report them.

Suprisingly, the delicately sculptured surfaces of the shells are intact. Why the shell surfaces were not abraded when all the rock and mineral fragments that make up the till are scratched, faceted and fractured is puzzling. One wonders why the shells were spared the rough glacial milling that is evident in all the other components of the till. Perhaps the answer is that many were not spared, and we see only the exceptional few that were. Or perhaps the shells were introduced into the till mix in a different manner from the rock components. This is an intriguing conjecture but so far no suitable mechanism has come to mind.

The fauna (see Crosby and Ballard, 1894) includes temperate to cold water and shallow to deep-water species. Mercenaria mercenaria today occurs only sporadically north of Cape Cod and, as mentioned earlier, the thick shell development is more characteristic of southern coastal waters than of New England. Some of the distinctly cold-water species in the till are also found in the late Wisconsin marine clays in the Boston area and are characteristic of circumpolar seas.

What is the explanation for the faunal mixing? When and where did the organisms originate? Do they represent one or several distinct stratigraphic horizons within the drumlins? Unfortunately, none of these questions can be answered with surety. Radiocarbon dating of Mercenaria mercenaria fragments gives ages greater than 37,000 C^{14}yrs. B.P. (H-1125). Probably the temperate water species are interglacial, most probably Sangamon. There is even the possibility that they are late Tertiary, as mentioned by Crosby and Ballard (1894). These same authors also suggested that the cold-water elements represent climatic deterioration at the onset of the Wisconsin prior to the arrival of the ice sheet at Boston. There is, however, a possibility that the colder species are derived from an interstadial marine clay within the Wisconsin. We know that these exist and that the drumlins are complexed of pre-existing deposits as well as rock debris freshly plucked, rubbed, and scraped from rock ledges. If we knew just where within the drumlin the different species came from we might discover that the cold and warm species are not physically mixed but are separated into distinct zones, or strata (the stratified structure of the drumlins has been mentioned). Unfortunately, these data are lacking, principally because most shells are picked up on the talus at the foot of the slope rather than plucked from undisturbed till in the steep face of the cliff; they therefore may have come out of any of the strata exposed in the cliff.

The question of where the shells originated must be considered because of its bearing on glacial-flow directions. The distribution of fossiliferous drumlins, particularly when considered within the framework of the orientation of drumlin axes and the probable direction of dislocation of rock clasts in the till, initially suggests that the interglacial shoreline followed fairly closely the margins of the Boston topographic basin and, indeed, appears not to have deviated substantially from the present shoreline and therefore from present relative sea level. When we consider, however, the deep water species, this seems less probable for there was neither sufficient room nor the necessary depth of water within this narrow coastal strip north and west of the drumlins to provide the proper habitat.

Two possible explanations for the mixed fauna come to mind. One is that the deep water species were transported from deeper waters to the east to their present nearshore position. Even though there is evidence of such glacial flow (Table 1), the clasts of the till in which the shells are embedded and the drumlin axes strongly indicate east to southeast flow. The second, and more probable, explanation is that Sangamon sea level was higher, relative to today's sea level, by at least 30 m. This would allow a narrow zone of deep water from which the deep water species might have come to the north and west of the fossiliferous drumlins.

Pre-Wisconsin Deposits

Very much decomposed gravel is a conspicuous component of the Beacon Hill moraine (below). This deposit is dark brown in color and contains many soft, thoroughly decomposed, and manganese-stained argillite, diabase, and granitic pebbles. In places, the gravel is "openwork" (lacking in matrix) and in others the pebbles are embedded in a matrix of white silty clay. As explained below, the gravel appears to have been glacially dislocated and piled up along with less altered sediment into the moraine. The dislocation mechanism is thought to involve the freezing of the glacial sole to the bed-sediments which then become part of the glacial mass, moving when flow energy attains sufficiently high levels. The position of these gravels in the morainic pile-up is generally near, or at the top. This suggests that the true stratigraphic position of these gravels was the reverse, that is, at the bottom, for the ice appears to have dislocated underlying sediment plate-by-plate, mining progressively downward. The oldest deposit is the last to be dislocated and the last to be transported into the moraine.

The Harvard Yard drumlin may be pre-Wisconsin. As seen in the excavation for the Pusey Library, this drumlin was weathered to a depth of at least 12 meters prior to having been more or less planed down by later ice. All of the deposits in the Harvard area sequence overlie this erosional platform. As with the old gravels just described, it would appear that at least an interglacial interval was required to produce the old weathering profile that is now very much truncated.

The gravel and clay beneath drumlin till which have been found in borings may be pre-Wisconsin in age. At present there is no way of dating these deposits, or for that matter, the sorted sediment found interlayered with drumlin till. In fact, there is no way of dating any of the drift except only the most recent. To assign a Wisconsin age to part or all of these deposits is more an act of faith than of science.

Beacon Hill Moraine [1]

Beacon Hill gives us the first complex of deposits to yield a good sequential story. The hill has long been classified as a drumlin (viz. LaForge, 1932) for it has about the right shape and elongation, and it consists of drift which was presumed to be till. There is a fundamental error here, however. The shape before the 19th century was not that of a drumlin and the contents of the hill have been assumed.

Prior to 1800, when real estate developers began to grade Beacon Hill (Whitehill, 1968), the crestline was highly irregular, in profile and in plan. In profile there were three fairly isolated sharp peaks, in the east, central, and western positions (Fig. 2). In colonial times, these earned for the hill the name Trimountain, or its variants, Tramount, and Tremount. The name Beacon Hill came into usage for the entire feature only in the 19th century; before that it had sometimes denoted only the central and highest of the three peaks on which an alarm sentry, or beacon, had been built.

None of the maps of Beacon Hill that date from the time of the original three peaks give a very clear picture of the topography of the hill. The accompanying map (Fig. 2) was therefore reconstructed from available contemporary cartographic and verbal descriptions. From these we see that the original hill was somewhat arcuate in plan, concave to the north. This fact is of importance in establishing the origin of the hill because the major structural lines in the hill appear to conform to this shape.

1/ It is perhaps unfortunate that the only way to decipher the Pleistocene geology of Boston is to follow deep foundation excavations. Certainly, this is the only way to get at the stratigraphy and the structural relationships that lie beneath the surface and which contain the major clues to the story we seek. I say "unfortunate" because doing geology in this way -- a sort of looking into tiny windows opened here and there at random -- is like putting together a large and complex jigsaw puzzle in which the individual pieces by themselves throw little light on the nature of the full picture or, else, allow for a multitude of interpretations. And like a jigsaw puzzle, where the entire picture in all of its detail may allude us until almost the very end, so the geologic interpretation of the Beacon Hill morainic complex seemed forever in a state of flux. Each new excavation brought new insights and new interpretations. Each endeavor to set down the story in print later turned out to be only a description of the "state of the art." All of this is by way of an explanation, if not apology, for some of the conclusions reached in a paper on the Beacon Hill moraine that was written over two years ago and which only now is about to appear (Kaye, in press B) and which is partly at variance with what is described here.

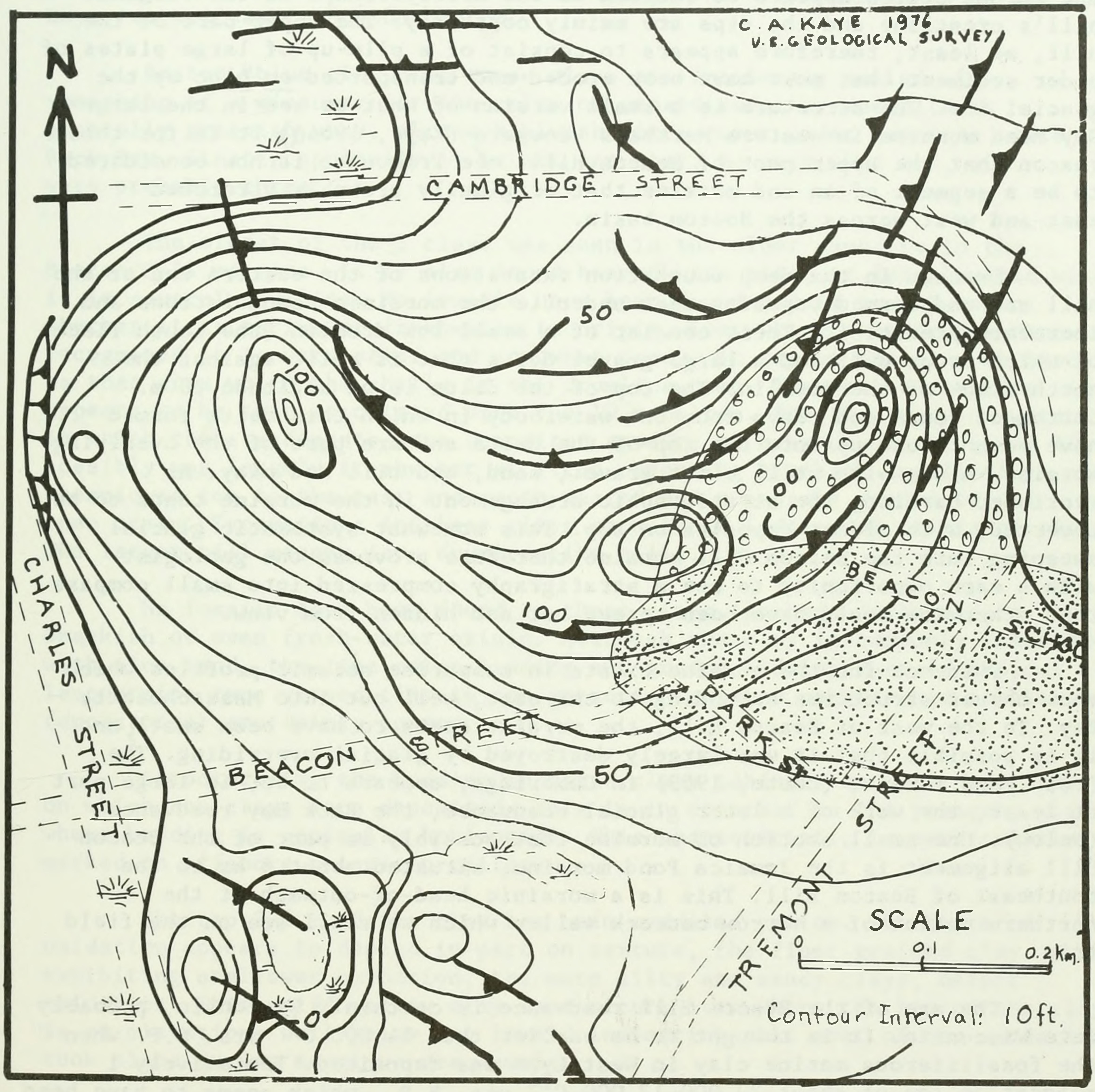

Figure 2 - Reconstructed topography of Beacon Hill and Boston Common before artificial changes. Strikes and directions of dips of thrust plates and axial planes of overturned folds in Beacon Hill and Back Bay moraines are shown by heavy-line symbols. Data for western Beacon Hill inferred. Submoraine delta shown by open circles; submoraine section of drumlin by light stipple, drumlin outcrop by dark stipple.

During the past 15 years, excavations, mostly in the eastern part of the hill, have exposed a complex of sand, gravel, clay and only minor amounts of till. The deposits tend to be in thick sheets, or plates, often separated by thrust faults. There are a variety of other kinds of structures including folds, high-angle faults, diaper intrusions, etc.. The strike of the thrust plates appears to conform to the arcuate shape of the original hill's crestline and the dips are mainly northerly. The upper part of the hill, at least, therefore appears to consist of a pile-up of large plates of older sediment that must have been eroded and transported en bloc by the glacial ice. The structure is a small version of what we see in the large Gay Head moraine in western Martha's Vineyard (Kaye, 1964a). It is for this reason that the upper part of Beacon Hill, née Trimount, is now considered to be a segment of an end moraine that originally probably stretched east and west across the Boston basin.

Exposed in the deep foundation excavations of the eastern end of the hill are undeformed deposits that underlie the morainic accumulations and therefore predate it. These consist of a small low drumlin (the south flank of which crops out) and a large gravel delta that is built against the north flank of the drumlin. The top of the delta is at altitude 10 m. Bottomset sands and clays from the waterbody in which this delta formed have been thrust up onto the top of the delta and are part of the overlying moraine, along with still older gravel, sand, and till and clay. As mentioned earlier, the stratigraphic arrangement in the moraine tends to be inverted, with oldest deposits on top. This somewhat systematic glacial sweeping into the Beacon Hill moraine therefore provides the geologist with a rare opportunity to see a stratigraphy compressed into small compass that otherwise would have been spread out and hidden from view.

Evidence for the moraine exists in submarine seismic profiles which show thrust structures extending to the east, well out into Massachusetts Bay. To the west of Beacon Hill, the moraine seems to have been small, and it is possible that it was largely destroyed by glacial overriding. The Fresh Pond moraine (Chute, 1959) in Cambridge, appears to be, in large part at least, the work of a later glacial readvance, the Back Bay readvance (below). One small section of moraine that possibly is part of the Beacon Hill alignment is the Jamaica Pond moraine, situated about 5 km to the southeast of Beacon Hill. This is a morainic head-of-outwash at the northern outlet of a narrow bedrock valley which we shall see on the field trip.

The age of the Beacon Hill readvance is certainly Wisconsin, probably late Wisconsin. It is thought to be earlier than 14,000 C^{14} yrs. B.P. when the fossiliferous marine clay in West Lynn was deposited. Tentatively I suggest an age of about 20,000-17,000 C^{14} yrs. B.P., which seems to have been the time when there was a major glacial surge to the west, down the axis of the Narragansett Bay trough and yet when the Cape Cod Bay lobe had largely melted.

The Clays

The marine clays that blanket the Maine coast extend as far south as the Boston basin. To the south of the Boston area these clays lie offshore but have not been found above sea level. Submarine seismic profiling shows that clay is widespread under Massachusetts and Cape Cod Bays, as well as in Boston harbor.

Boston "blue clay," as these clays are frequently called, is something of a misnomer for the color of unoxidized clay and silt is generally greenish gray, although bluish tints occur under sections of the Back Bay. Stratigraphically it is not one clay, however, but two, or very probably three.

The oldest of the 3 clays was seen in the older deposits in the Beacon Hill moraine. It is also found beneath the till, or interlayered with it in several drumlins. No fossils have been found and it is not known whether it is marine or freshwater in origin. Everywhere that it has been recognized it is very stiff and somewhat sandy. It may be the same horizon as that from which the shells in the drumlins came. The most widespread clay appears to be that associated with the 10 m deltas. The 10 m body of water in which these sediments were deposited appears to have been extensive. It possibly was largely freshwater at first, becoming brackish and finally oceanic as ice to the east and south wasted and a passage opened to the open ocean. Excavations in these clays show large lenticular masses of till. The larger till masses form drumlin-like hills.

No fossils have been found in these clays, perhaps reflecting a brackish or even fresh-water origin. Although the clay is commonly interbedded with fine sand, the fine color banding and graded bedding that is typical of laccustrine type varved clay is not present. Isolated pebbles and cobbles (dropstones) are fairly common.

Structurally, the bedding in these clays conforms to the topography on which the clays were deposited. This is in contrast to the youngest clay where bedding is generally horizontal. This characteristic is particularly marked on offshore seismic profiles.

The top 2-6 m of the clay has been oxidized yellow. The depth of oxidation appears to depend in part on texture, the finer grained clay exhibiting shallower oxidation, the more silty and sandy clays, deeper oxidation. This stiff yellow clay zone occurs even where the top of the clay is at elevations well below sea level, indicating that most of the oxidation took place during negative sea levels.

The youngest clay postdates the Beacon Hill moraine. It has been found to altitudes up to 15 m in the Boston area. This horizon has a sandy beach facies and the clay itself tends to be finer grained than the older clay. This clay is fossiliferous along the northern rim of the Boston basin, in the vicinity of Lynn, Revere, and Winthrop. The fauna consists of mollusks, barnacles, foraminifera and ostracods and is of a cold water type. Radiocarbon dating of fossil barnacle plates (5 dates) shows an average age of 14,000 C^{14} yrs. B.P.

Sea Levels

In discussing sea level, we must distinguish between eustatic sea level and relative sea level, or sea level in relation to some benchmark in the coastal zone. Relative sea level is a function mainly of vertical crustal movement in response to glacial loading or unloading and changes in eustatic sea level. It is the sea level we observe and measure directly.

Our data in the Boston area shows that relative sea level dropped steadily from about altitude 20 m at 14,000 C^{14}yrs. B.P. (our earliest date) to about altitude -20 m at 10,000 C^{14}yrs. B.P. (Kaye and Barghoorn, 1964). The trend was then reversed; and sea level slowly rose, attaining approximately present level about 2,000 C^{14}yrs. B.P.. Since then there appear to have been fluctuations of up to 1 m both above and below, probably largely the result of eustatic changes produced by world-wide temperature fluctuations.

Back Bay Readvance

Glacial ice seems to have occupied briefly much of the Boston basin after 14,000 C^{14}yrs. B.P.. Ice descended from the surrounding rim area via the major valleys and spread out as localized bulbous masses on the basin floor. One ice tongue flowed east through the Charles River valley and spread out over the area of the Back Bay. Another descended through the valley of the Mystic Lakes and occupied the Fresh Pond area in Cambridge (Chute, 1959). Both lobes were fed from a large stagnant relict ice cap that appears to have covered the uplands of eastern Massachusetts and Rhode Island and possibly New Hampshire as well in the years when the coastal lowlands were already ice-free and marine clay was being deposited.

Evidence for the Back Bay lobe was seen in excavations in the lower slopes of Beacon Hill and in the margins of the Back Bay. In the Beacon Hill area, the deformational structures consist of overturned folds and thrust faults that encircle the perimeter of the hill and are strongly discordant to the lobate trend of the Beacon Hill deformation (Fig. 2). In the excavation for the Common Garage, the direction of glacial deformation was to the northeast; on the north side of the hill, to the south. The Back Bay lobe appears to have squeezed up a low clay ridge at its southeastern margin to form Boston Neck, the narrow clay isthmus that was the only connection between Boston and the mainland in colonial times. In the Harvard Medical Schoool area at the southwestern margin of the lobe, clay was dragged up onto the 10 m delta. On the north side of the lobe in Cambridge, we find till and sheared clay up to altitudes of 17 m as a low, discontinuous ridge that curves around the Harvard University area and includes Dana Hill, Shady Hill, Observatory Hill, and Mount Auburn. In places, this ice lobe deposited as much as 10 m of till on top of the younger clays.

The ice lobe that flowed south out of the valley of the Mystic Lakes spread out in the basin that is now occupied by Fresh Pond. Its eastern limits have not been defined but this ice possibly was responsible for the till overlying clay that was noted by Marbut and Woodworth (1896) on Ten Pound Hill and other places along the lower valley of the Mystic River. This lobe almost coalesced with the Back Bay lobe along the line of Observatory Hill in Cambridge.

Cambridge Flood

The sudden melting of the residual ice cap and its lobate projections just described produced a rapid release of melt waters. In the Boston area, a flood of this origin came down the upper Charles River valley between present-day Newton, on the south, and Waltham and Watertown on the north. The flood was blocked by the remnant of the Back Bay lobe in the lower Charles River basin and, accordingly, was deflected north, across the low terrace of the area of Harvard University from whence it drained down the valley lying between the Shady Hill segment of the Back Bay moraine and the Somerville drumlins. The sands and gravels deposited by these floodwaters, which underlie the level plain on which most of Harvard stands, are current bedded towards this outlet.

Eolian Silt Blanket

Thin patches of soft fine sandy silt overlie the deposits of the Charles River flood and all other deposits in the area. This layer is rarely thicker than 1 m and generally is oxidized to an orange red color. It probably is a layer of windblown dust deposited at the last stage of glacial waning at a time when strong winds, blowing off the ice, picked up fine-grained sediment from the surface of the drift. This came to rest in peripheral areas, some of it perhaps trapped by grasses and low ground plants that were the vanguard of the spreading forests. The silt layer was once almost ubiquitous on the valley floors and lower slopes but owes its present patchy distribution to colonial and post-colonial man who dug it away, or allowed it to erode away, as a result of cultivation and grading.

Holocene

As sea level rose and flooded the Back Bay, silt and fine sand carried by the Charles River was deposited throughout the estuarine system. Along the channel of the river, coarser sands and gravels were laid down. The silts and fine sands of the backwaters have a high organic content as a result of the eutrophic nature of the estuarine system. During sea level rise and the deposition of these sediments, salt marshes rimmed the shore, building outward and upward (Kaye and Barghoorn, 1964). Buried in these deposits is evidence of climatic and environmental changes (Johnson, 1943, 1949).

The greatest changes, of course, have occured since the coming of the machine age in the 19th century. Large-scale filling of the shoals and salt marshes of the estuarine system have changed the modest face of Boston. The filling of the Back Bay was the largest enterprise of this kind and was accomplished in a few decades during the Civil War and post-Civil War era (Whitehill, 1968). The fill consists mostly of outwash sands and gravels dug from the extensive deposits in the valley of the Charles River at Needham, about 15 miles upstream from Cambridge. This was carried to the Back Bay by railroad and dumped to form a network of street embankments.

Most recently the site of Logan Airport was reclaimed by means of hydraulic filling. This required dredging the late Pleistocene clays from nearby harbor bottom and confining the resulting clay slurry behind levees constructed for the purpose. In a few years time the clay had settled out by natural sedimentation and had built up a clay mat sufficient to support runways and the weight of the landing aircraft. Also included in the Logan Airport fill are two drumlins, Governors Island and Apple Island, that were leveled and are now completely covered by airport fill.

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A BIBLIOGRAPHY OF THESES, DISSERTATIONS AND HONORS PAPERS ON THE GEOLOGY OF EASTERN MASSACHUSETTS

THOMAS BREWER

This bibliography is an attempt to compile a listing of works concerning the geology of Eastern Massachusetts which have not been published, but which are available at the institutions where they were written. For this purpose, Eastern Massachusetts has been defined as the area east of and including the Connecticut Valley, or east of approximate longitude 72.6^{o}. A few references have been included which appear relevant to Eastern Massachusetts problems although they have been written about field areas in adjoining states.

It is predictable that additional material (hopefully 1976 efforts) will appear after this listing is sent to the printer. With this in mind, I plan to print an additional page or two for distribution at conference registration. If you didn't get one, send a self addressed envelope to the address below, and I will see that one is mailed. Space has been left for additions at the bottom of each text page.

Geologists working in Massachusetts should also be aware of the following two bibliographies:

1) Cassidy, M. and Miller, J.P. (1962, reprinted 1968) 'A partial bibliography of the geology of Massachusetts' a publication of the Department of Geological Sciences, Harvard University, Cambridge, Mass., 02138; 90 pages.

2) Massachusetts Cooperative Geologic Program; U.S. Department of the Interior, Geological Survey; and Massachusetts Department of Public Works (1973) 'Partial list of publications and open-file reports' available from the geological survey and perhaps from the other sources named; 28 pages.

My present intention is to update this list annually and to distribute it to area institutions. I have no doubt made errors or especially omissions. Corrections and additions are welcome. My thanks go the the individuals at area institutions who took the time to compile and send me their department's references. Special thanks go to John Mahoney and Barry Cameron from B.U. who made an initial compilation of much of this material.

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