

RECENT SEDIMENTOLOGICAL INTERPRETATIONS IN THE AVALON TERRANE OF  
THE BOSTON BASIN, MASSACHUSETTS

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The depositional history of the Boston Basin remains somewhat enigmatic and controversial despite nearly over a century of research. Resolution of the basin's geologic history has remained formidable and complex due, in part, to attempts to work within the existing stratigraphy which often carried with it historic interpretations, many of which went uncontested. More importantly however, our knowledge of depositional systems and mechanisms has increased significantly over this span of time. Reinterpretations in light of these advances were not only inevitable but necessary. As a consequence of the circumstances described above, our reinvestigation into the depositional history of the Boston Basin succession, principally the Boston Bay Group, has centered on recognizing, measuring, and coding a suite of facies whose textures in many instances can be closely linked to specific depositional mechanisms responsible for the emplacement of the facies in question. From this facies analysis a preliminary depositional model for the Boston Basin has begun to emerge.

It appears that the Boston Basin originated as a rifted successor, or arc-related basin either just prior to the closure of the Cadomian Ocean or during the opening of Iapetus. The early history of the basin is marked by the presence of a suite of bimodal volcanics in the form of water-lain tuffs, dikes, sills, and flows, and coarse debris flows. Geochemical markers suggest that the basin was in contact with the open ocean very early in its history.

The next stage in the evolution of the Boston Basin was marked by the development of a rapidly prograding submarine slope/fan succession. The slope/fan setting appears to have been characterized by the deposition of ice frontal and/or ice-rafted diamictons which periodically overloaded the slope initiating sediment gravity flows which reworked and redistributed sediment downslope. During periods of more equable climate and/or tectonic quiescence, blankets of fine sand and mud were deposited. There is no evidence of a shelf or shelf-type deposits during this time.

The last stage in the evolution of the basin was the appearance of shelf sediments such as quartz and calcareous sands, and muds with abundant organic matter and shelled organisms. There is also evidence for climatic warming which is suggested to have been brought about by a tectonically-forced rise in eustatic sea-level.

L'histoire sédimentaire du Bassin de Boston soulève encore quelques énigmes et controverses et, cela, après près d'un siècle de travaux. Dans une certaine mesure, la résolution de l'histoire géologique du bassin est demeurée formidable et complexe par suite des tentatives de travailler au sein de la stratigraphie actuelle qui, elle, comportait souvent des interprétations historiques rarement mises en doute. Or, plus important est le bond en avant saisissant qu'a fait notre connaissance des systèmes et mécanismes de dépôt durant cette période. Il devint donc non seulement inévitable, mais bien nécessaire de reconsidérer les conceptions traditionnelles à la lumière de ces acquis. Pour ce faire, notre réexamen de l'histoire sédimentaire de la succession du Bassin de Boston, et surtout du Groupe de Boston Bay, s'est axé sur la reconnaissance, la mesure et le codage d'une suite de faciès dont les textures sont souvent reliées de façon intime aux mécanismes de dépôt distincts responsables de la mise en place desdits faciès. Cette analyse faciologique commence à engendrer un modèle préliminaire du dépôt dans le Bassin de Boston.

Il semble que le Bassin de Boston ait débuté sous forme d'un rift successeur ou d'un bassin allié à un arc soit juste avant le serrage de l'Océan Cadomien, soit lors de l'ouverture de L'Iapetus. L'histoire du bassin est d'abord marquée par la présence d'une suite de volcanites bimodales sous formes de tufs aquatiques, dykes, filons-couches, coulées et coulées de débris. Les marqueurs géochimiques suggèrent que le bassin était ouvert sur le large dès l'amorce de son histoire.

Le stade suivant dans l'évolution du Bassin de Boston fut marqué par le développement d'une séquence de pente et cône sous-marins à progradation rapide. L'environnement de pente et cône semble avoir été caractérisé par le dépôt de diamictons glaciaires frontaux et/ou supraglaciaires qui ont surchargé périodiquement la pente, déclenchant ainsi des écoulements gravitaires qui ont repris les sédiments et les ont redistribué en bas de pente. Les périodes de climat plus uniforme et/ou de stase tectonique donnèrent lieu à des épanchages de sable fin et de boue. On ne trouve pas trace d'une plate-forme ou de dépôts typiques d'une plate-forme lors de cette période. La dernière phase évolutive du bassin correspond à l'apparition de sédiments de plate-forme tels que des sables quartzeux et calcaires ainsi que des boues riches en matière organique et en organismes coquilliers. Certains indices témoignent d'un réchauffement climatique que l'on croit dû à une élévation eustatique du niveau marin en réponse aux sollicitations de la tectonique.

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## INTRODUCTION

The depositional setting and geologic history of the Boston Basin (Fig. 1) succession has remained in dispute for over a century. The lack of resolu-

tion and lack of agreement on the depositional history of the basin can likely be attributed to 1) paucity of continuous outcrop; 2) scarcity of subsurface lithologic information with the exception of the data compiled by Billings, his

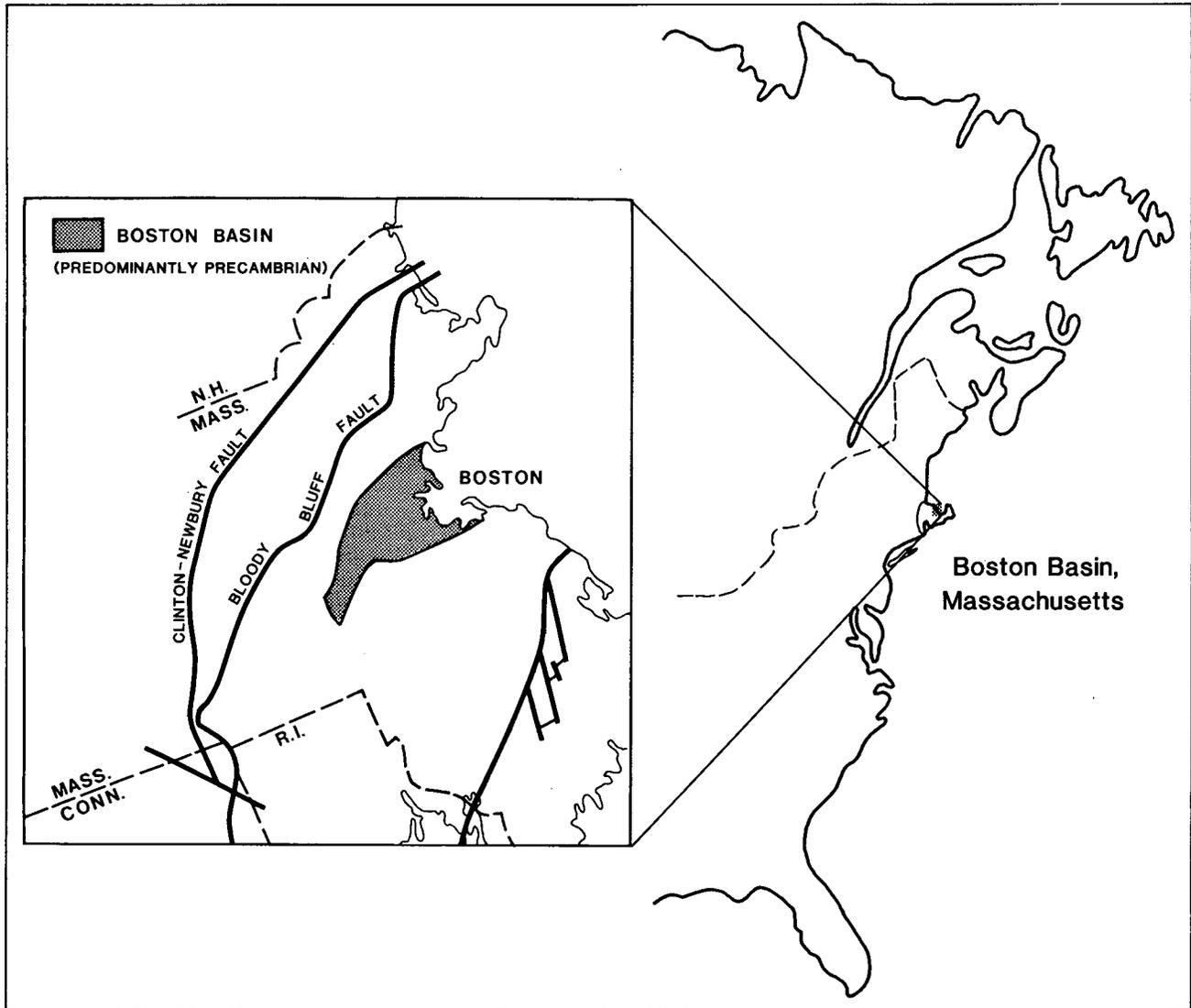


Fig. 1. Location of the Boston Basin, Massachusetts.

students, and co-workers; and 3) ambiguities housed in the original descriptions of the stratigraphic units, which appear to have led to confusion of stratigraphic units and structural relationships in the field (i.e. see LaForge, 1932). More importantly, our understanding of depositional systems, facies, and processes which has improved significantly over time necessitating re-evaluation of the Boston Basin succession. In order to circumvent a significant portion of those historic problems cited above, the authors have opted to identify and delineate facies within the basin as opposed to delineating and remapping stratigraphic units which were originally broadly defined in the mid-to-late 1800's and early 1900's. The authors have been unable to overcome completely the lack of outcrop and the lack of subsurface information, but we are attempting to resolve these problems to some extent by extending our coverage of the basin through the use of recently located exploratory cores taken from various portions of the basin.

We use the term facies in this paper in a manner analogous to Miall (1977; 1978), and Eyles *et al.* (1983), to describe a combination of lithology, nature of clast support, internal organization, and a variety of subjective features which can be used to help interpret and reconstruct the depositional system and setting. Facies is not used here as a synonym for lithology or stratigraphic unit. The information which we have gathered over the past four field seasons has yielded evidence for the emplacement and redeposition of a large volume of sediment, much of which is very coarse, by a variety of sediment gravity mechanisms as well as traction mechanisms. We have thus far amassed a substantive body of evidence which suggests that the bulk of late Precambrian sedimentary rocks in the Boston Basin was deposited on a slope (slope is used to infer only that the original depositional surface was inclined from the horizontal) within a marine basin, and that ice played a major role in the transportation and deposition of this sediment. Furthermore, the basin-fill sequence records the

tectonic evolution of the basin.

Inevitably, seismic stratigraphic techniques will have to be applied to the Boston Basin in order to document the basin type and to identify chronostratigraphic surfaces which can be traced across the basin and thereby establish a basis for testing those models such as ours which purport to explain the depositional and tectonic history of the basin.

#### HISTORIC STRUCTURAL, STRATIGRAPHIC, AND SEDIMENTOLOGIC FRAMEWORK OF THE BOSTON BASIN

The Boston Basin appears to be an extensional basin bounded by high angle reverse faults to the north, south, and west (Fig. 2). The nature of its eastern boundary, assuming one exists, is not well known. The basin's granitic basement (Dedham Granite and cogenetic Mattapan Volcanics) is suggested to have intruded older crust which appears to have been subsequently deformed during the Avalon orogeny (Skehan, 1983; Skehan and Murray, 1980a). The nature of this older crust is obscure. Perhaps the original basement constituted the Nashoba, Marlboro, and Westboro Formations or their equivalents (Rast and Skehan, 1983). The entire succession records Alleghanian deformation in the form of east-northeast striking thrust faults and northeast-trending folds (Billings, 1979a; Skehan and Murray, 1980a; 1980b). The rocks appear to have been mildly deformed during the Acadian or Taconian orogeny (Skehan and Murray, 1980a; 1980b).

Investigations into the stratigraphy of the basin date back to the mid-to-late 1800's when Hitchcock (1861), Shaler (1871), Dodge (1883), Hobbs (1899), Sayles and LaForge (1910), Sayles (1914), Emerson (1917), LaForge (1932), and Billings (1939) first used the names of the stratigraphic units which, through continued usage, achieved formal stratigraphic status and came to be known collectively as the Boston Bay Group (Fig. 3). From the base to the top, the stratigraphy of the Boston Basin begins with the calc-alkaline Dedham Granite and Lynn Volcanics (Fig. 3). The isotopic age of the Dedham is reported to be 646 - 595 Ma (Zartman and Naylor, 1984). Non-conformably overlying the granite is a suite of bimodal volcanics (Mattapan Volcanics), the later phases of which have chemical affinities with extensional tectonic settings (Hon and Hepburn, 1986). Unconformably overlying these volcanics is the Boston Bay Group whose age is bracketed between late Vendian and early Cambrian (Kaye and Zartman, 1980; Lenk *et al.*, 1982). The succession is capped by Cambro-Ordovician shales and sandstones (Weymouth Formation and Braintree Argillite) housing an Acado-Baltic trilobite-bearing fauna which links the Boston Basin to the Avalon platform. There is no agreement on the nature of the transition (conformable or unconformable) from the Boston Bay Group to the Cambro-Ordovician overlap sequence.

Historically, the lower portion of the Boston Bay Group, the Roxbury Conglomerate (Fig. 3), has perhaps been the most hotly contested, yet probably least well understood sequence within the Boston Basin (see Table 1 for a summary of historic interpretations of the Boston Bay Group). From the base up, the Boston Bay Group consists of the

Roxbury Conglomerate or Formation and the Cambridge Argillite or Slate. The Roxbury Conglomerate is composed of three members which from the base to the top are the Brookline, the Dorchester, and the Squantum. Interpretations of the Squantum Member are varied and controversial, and can be grouped into two broad general categories (Table 1): glacial (terrestrial or marine) and non-glacial (terrestrial or marine).

One of the few cross-sectional reconstructions of the Boston Bay Group (Fig. 4) is that of Marland Billings, his students, and co-workers (Rahm, 1962; Billings and Tierney, 1964; Billings and Rahm, 1966; Tierney *et al.*, 1968; Richardson, 1975; and Billings, 1975) who, over a period of 15 years (1960-1975), mapped the geology of the basin within water and sewer tunnels beneath the city of Boston.

#### LITHOFACIES OF THE BOSTON BAY GROUP

As traditional stratigraphic and analytical approaches have not led to a resolution of the depositional history of the Boston Basin succession, we have adopted a more modern approach to basin analysis, that of identifying and classifying facies on a bed-by-bed basis, for the purposes of developing an actualistic facies model for the depositional history of the basin (see Byles *et al.*, 1983; and Miall, 1978; for a discussion of these techniques). This reinvestigation is based in part on recent improvements in our understanding of sediment transport mechanisms, particularly sediment gravity mechanisms (Middleton and Hampton, 1973; 1976; Enos, 1977; Lowe, 1976a; 1976b; 1979; 1982; Hampton, 1975; 1979; Rodine and Johnson, 1976; Carter, 1975; Nardin *et al.*, 1979; and Komar, 1970). We have also abandoned traditional stratigraphic descriptions and subdivisions of the Boston Bay Group because we believe that the depositional history of the basin lies within the facies assemblages and associations, which are independent of the stratigraphy.

#### Lithofacies Descriptions

Lithofacies designations for the Boston Bay Group consist of a four letter code. The first letter of the code refers to one of three principal rock types: diamictites, sandstones, and fine-grained units (argillite), designated by the capital letters D, S, and F. The second letter of the code refers to the nature of the clast support, clast supported (c) or matrix supported (m). The third letter of the code refers to internal organization or bedding characteristics, massive and unstructured (m), stratified (s), and graded (g). The final letter of the code is bracketed, and refers to attributes of the facies that are interpretive. For example, the code (d) might be used to indicate the presence of dropstones. A list of the lithofacies types recognized in the Boston Bay Group is shown in Table 2. The non-genetic term "diamictite" is used to refer to any rock which contains a poorly to moderately sorted mixture of clasts, sand, and mud. Furthermore, the term "diamictite" does not specify the abundances of particle sizes present, yet does accommodate both matrix- and clast-supported fabrics as well as degrees of organization of clasts and matrix (stratification and grading).

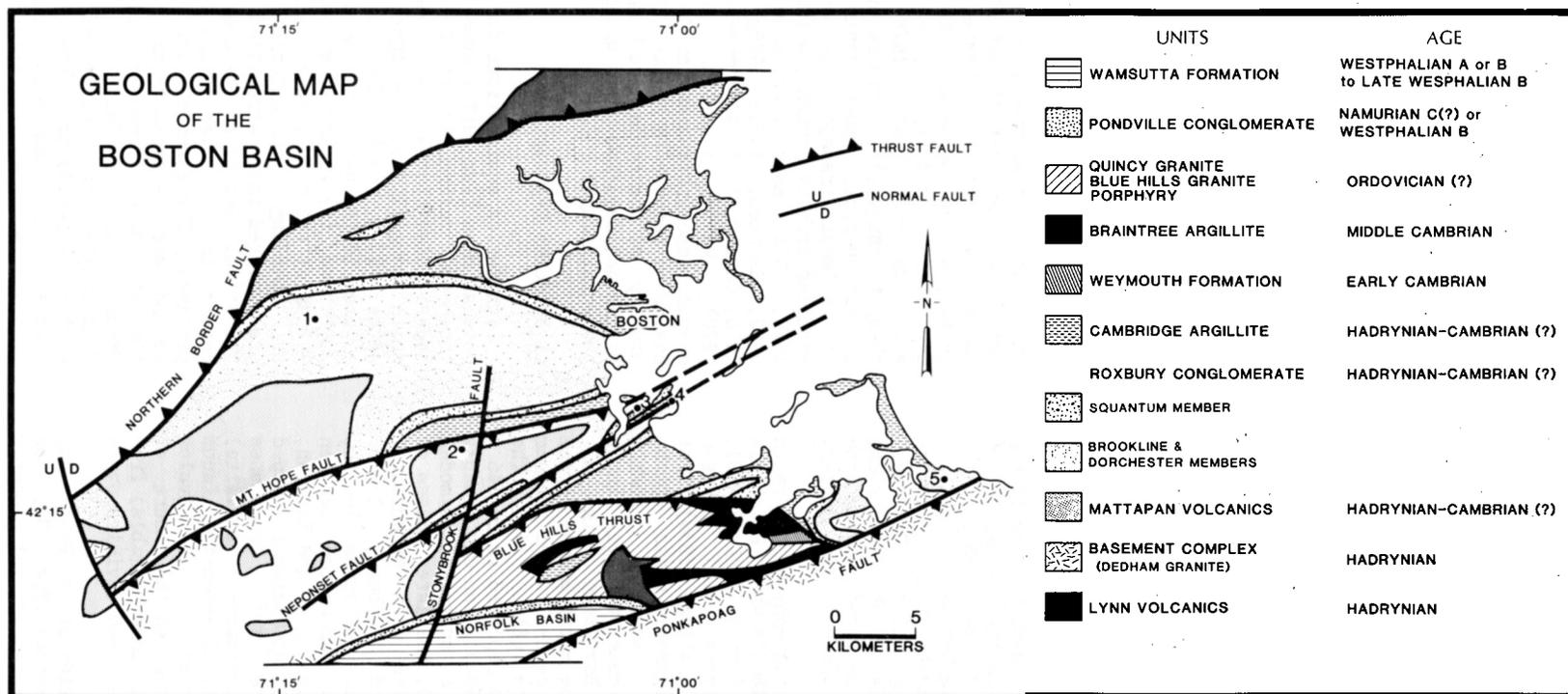


Fig. 2. Geologic map of the Boston Basin. Geology after Billings (1979a). Numbers refer to locations where stratigraphic sections were measured.

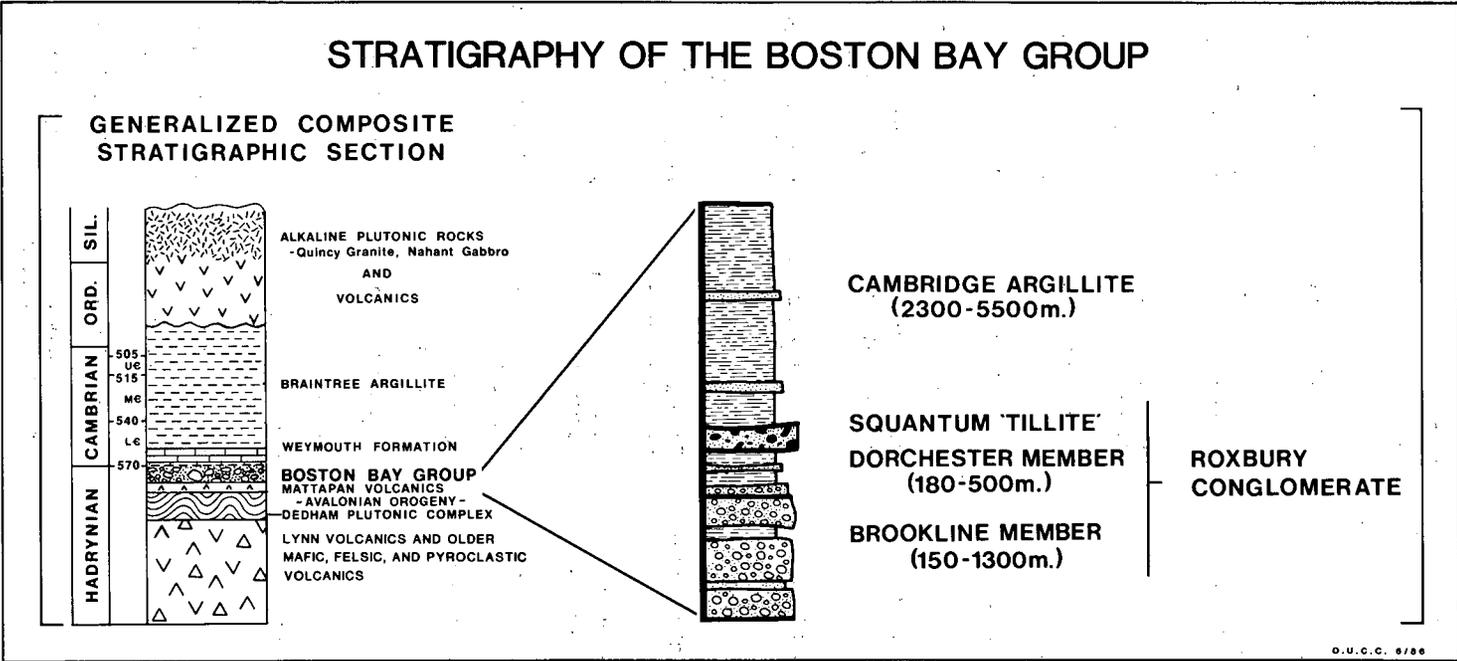


Fig. 3. Historic stratigraphic units of the Boston Basin. Approximate thicknesses are from Billings (1979a).

Table 1. A review of interpretations of the Boston Bay Group.

Interpretation	Age	Reference
Piedmont glacier/subaqueous mudflow	Ordovician-Permian	Bailey <i>et al.</i> 1976
*Transitional alluvial fan-braided stream-marine ramp.	late Precambrian-Cambrian	Bailey and Galli, 1985; Bailey, in press
*Alluvial fan-braided stream/glacial	Pennsylvanian-Permian	Billings, 1929; 1976a; 1976b; 1979a
*Alluvial fan-braided stream/glacial	late Precambrian	Billings, 1979b; pers. comm., 1985
_____	Carboniferous	Burr and Burke, 1900
Subaqueous mudflow	_____	Caldwell, 1964
Intermontane glacial/lacustrine	late Ordovician-early Silurian	Cameron and Naylor, 1976; Cameron and Jeanne, 1976
Intermontane glacial/lacustrine	late Precambrian-Cambrian(?)	Cameron, 1979a; 1979b; 1979c
* _____	Cambrian	Crosby, 1900
Subaqueous debris flow/geosynclinal	Devonian-Mississippian	Dott, 1961
*Transitional alluvial fan-fluvial-deltaic	late Precambrian-Cambrian	Kaye, 1984
* _____	late Precambrian-Cambrian	Kay and Zartman, 1980
*Alluvial fan-fluvial/glacial	Devonian-Carboniferous	LaForge, 1932
Glacial	late Paleozoic	Lahee, 1914
Mudflow	_____	Lindsay <i>et al.</i> 1970
Glacial fluvial/lacustrine	Carboniferous	Mansfield, 1906
_____	late Devonian	Naylor and Sayer, 1976
_____	Mississippian	Pollard, 1965
Glacial	Carboniferous	Rahm, 1962
*Marine/glacial	late Precambrian-late Carboniferous	Rehmer, 1981
Glacial	_____	Rehmer and Hepburn, 1974
Glacial alluvial-lacustrine/subaqueous mass flow	_____	Rehmer and Roy, 1976
Glacial	Permian	Sayles, 1914

Table 1. Continued

Interpretation	Age	Reference
*Glacial lacustrine	Permian-Carboniferous	Sayles and LaForge, 1910; 1919
* _____	late Precambrian-Cambrian	Skehan, 1979; Skehan and Murray, 1980a; 1980b
*Glacial marine slope-fan system	late Precambrian-Cambrian	Smith and Socci, 1986; <i>in press</i>
*Glacial marine slope-fan system	late Precambrian-Cambrian	Socci, 1984; 1985; Socci and Smith, 1985; 1985b; 1986a; 1986b; 1986c; 1986d; this paper
* _____	late Devonian-Permian	Tierney <i>et al.</i> 1968
Glacial	_____	Wolfe, 1976

\*Interpretations of the entire Boston Bay Group. All other interpretations pertain to the Squantum Member of the Roxbury Conglomerate.

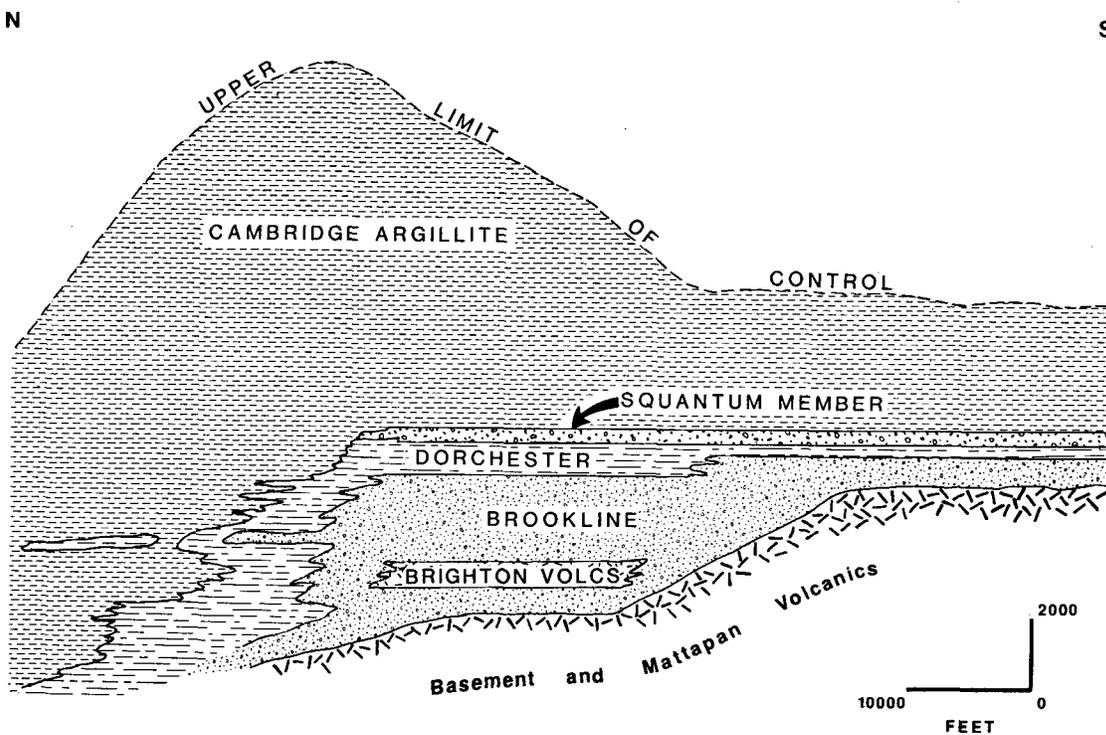


Fig. 4. Cross-sectional reconstruction of the Boston Bay Group (after Billings, 1979a).

Table 2. Lithofacies types of the Boston Bay Group.

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Diamictite (D):	poorly to moderately sorted boulder, cobble, sand, mud
Dmm	matrix-supported, massive
Dmg	matrix-supported, graded
Dms	matrix-supported, stratified
Dcm	clast-supported, massive
Dcg	clast-supported, graded
Dcs	clast-supported, stratified
Sandstone (S):	very fine to very coarse, and pebbly
Sm	massive
Sg	graded
Ss	horizontally stratified and/or cross-stratified
S-d	soft-sediment deformation
Fine-grained units (F):	mostly mud or argillite (very fine sand, silt, and clay)
Fg	graded between laminations
Fs	horizontally laminated and cross-laminated, also rippled
Fs(d)	laminated with dropstones
Fsd	laminated with soft-sediment deformation
Fgd	graded with soft-sediment deformation
Fs(d)d	laminated with soft-sediment deformation and dropstones

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A graphic log of coded measured stratigraphic sections of the Bay Group, as well as their locations, are shown in Figures 5 and 6. Unfortunately, the only controls on the locations of stratigraphic sections are outcrop availability and accessibility. Such controls do not readily lend themselves to the construction of a well-constrained sedimentological model. However, the measured sections are representative of each of the historic stratigraphic subdivisions of the Boston Bay Group. We submit therefore, that there is sufficient stratigraphic control within the measured sections to formulate a somewhat loosely constrained actualistic sedimentological model for the depositional history of the Boston Basin.

Interpretive and descriptive data for each facies is presented in Table 3. The fabric of each facies is interpreted as being representative of a specific depositional mechanism (or mechanisms) suggested to have been responsible for the emplacement of the facies in question.

#### Diamictites

The diamictites in the Boston Bay Group are composed of a range of grain sizes from mud to very large boulders, some of which are in excess of 1 m in diameter. Clasts are predominately well to moderately well rounded, although subangular and faceted clasts are not uncommon. Compositionally, these rocks are composed of granite, bimodal volcanics, quartzites, and intraclasts of massive, graded, and laminated sandstone (Sm, Sg1, Sg2, Ss1, Ss2) and mudstone (Fsd; Figure 7A), some of which show soft-sediment deformation. All of the clasts vary in undetermined proportions from place to place.

The diamictites range from clast-supported (Dc) to matrix-supported (Dm) within the same unit or within multistoried units. Massive as well as crudely to moderately well sorted, and normally and

inversely graded diamictites (D-m, D-s, and D-g) are common. Clast density is also observed to vary commonly within units. Thicknesses of diamictite units range from centimeters to tens of meters, the latter, undoubtedly, are in many cases stacked or multistoried sequences representing a multiplicity of superimposed flows some of which have extremely faint contacts with the unit above and/or below. Many diamictites also have sharp, planar/irregular, erosive, channelized and/or loaded basal contacts.

#### Sandstones

The sandstone facies within the Boston Basin range in size from fine-grained to very coarse-grained to pebbly and cobbly. Composition of the sandstones ranges from feldspathic to lithic (volcanic, plutonic, and sedimentary) to quartz-rich, becoming progressively more mature in composition as the grain size decreases. However, the relative proportion of each constituent is unknown from place to place. Individual beds vary in thickness from approximately 2 centimeters to roughly 10 centimeters where bedding contacts can be discerned. Thickness of sandstone bodies ranges from centimeters to tens of meters or more.

#### Fine-Grained Units (Argillites)

In general, the fine-grained facies consist of individual laminations which do not exceed a few millimeters to a centimeter in thickness. However, aggregate thicknesses of stacked laminae approach a meter to tens of meters.

#### Volcanic Rocks

In addition to the facies listed in Table 3, there is a suite of volcanic rocks consisting of flows, dikes, sills, and water-lain(?) tuffs, within the Boston Basin (Fig. 3). Non-conform-

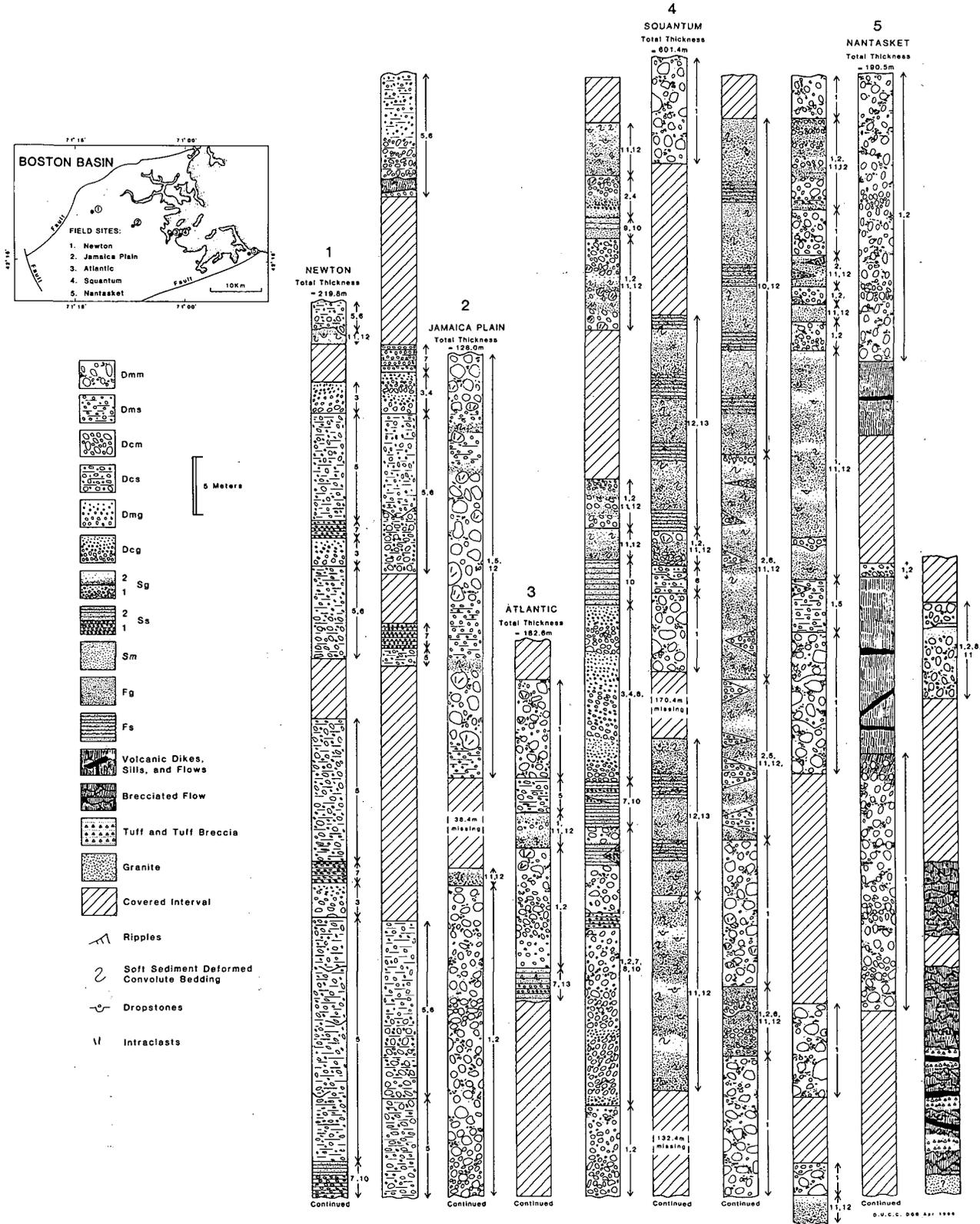


Fig. 5. Coded lithofacies logs of measured sections of the Boston Bay Group. Section numbers at the top of each section refer to the location of each section and are also keyed to Fig. 2. To the right of each section are numbers that refer to flow types which are considered responsible for the emplacement of the facies shown. Each flow type is explained in Table 3.

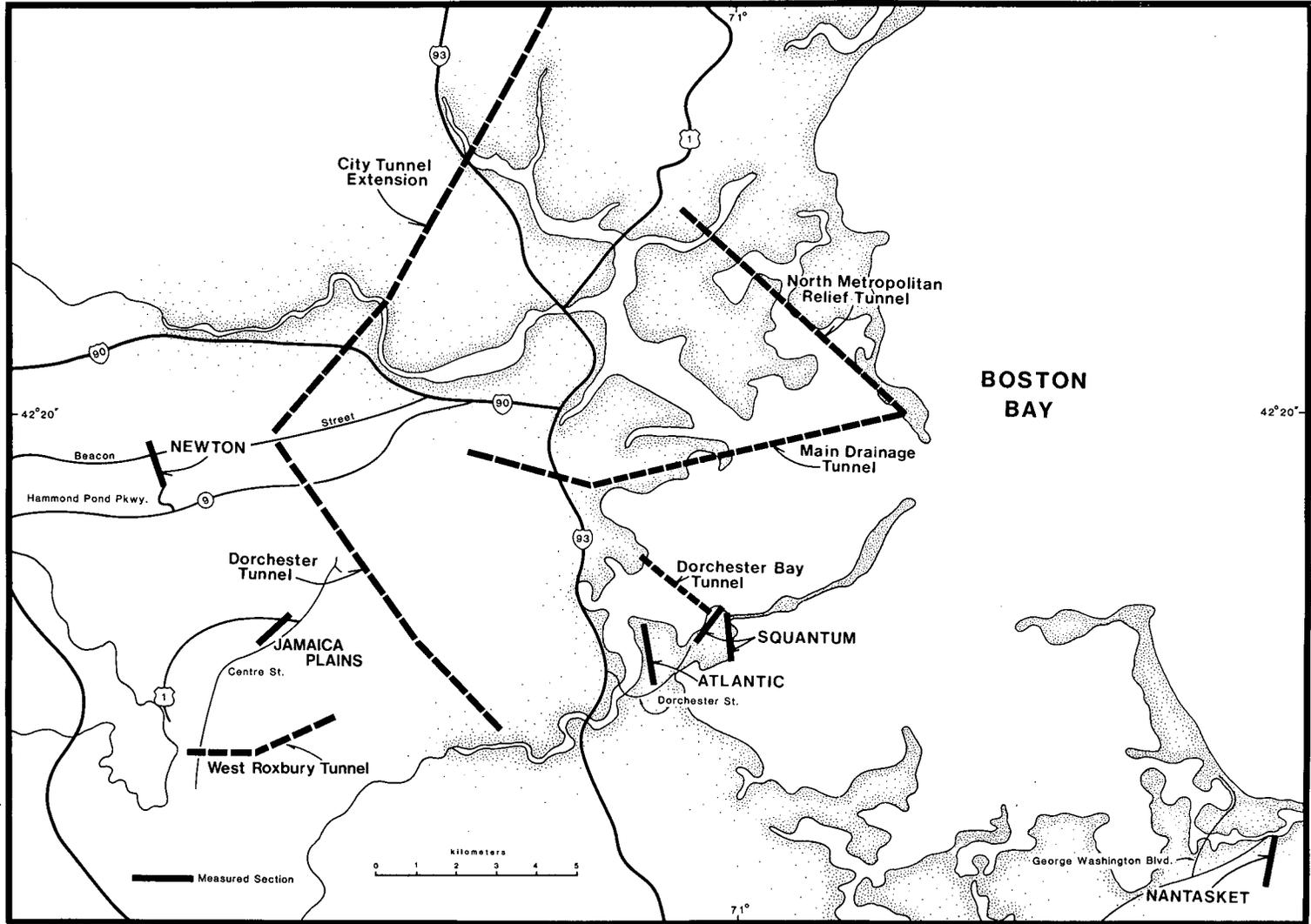


Fig. 6. Specific locations of sections shown in Fig. 5 as well as the locations of tunnels, the geologic information from which was used to construct Fig. 4.

Table 3. Classification of facies and flow types within the Boston Bay Group.

Type	Facies	Description	Interpretation
1	Dmm	Pebbles to boulders in a somewhat sorted to unsorted matrix of mud to very coarse sand and pebbles. Clasts are generally rounded but angular varieties are also present. Clast density changes often. Reverse grading at the base not common. Basal contact is generally planar-irregular, erosive or loaded with some channelling. Intraclasts present.	Unsorted to slightly sorted proximal debris flows.
2	Dcm	Similar to type 1 but clast supported. Clasts are generally slightly more sorted than those found in type 1 deposits. Matrix may also be more sorted toward the coarser sizes than type 1 deposits. Intraclasts may be present.	Clast-supported more organized proximal debris flows.
3	Dmg	Grading of clasts from boulder, cobble or pebble grades (mostly cobble and pebble) to coarse and pebbly sandstone. Reverse grading may also be present at its base. Intraclasts may be present. Planar, slightly irregular, erosive and loaded basal contacts.	Partially sorted intermediate debris flows. More sorted than types 1 and 2.
4	Dcg	Similar to type 3 but with a greater density of clasts. Loaded bases common. Intraclasts present.	Clast-rich variety of type 3 and possibly better sorted intermediate debris flows than type 3 flows.
5	Dms	Similar to type 1 but having some stratification of matrix or clasts. More sorted than type 1 deposits and stratification of clasts usually involves cobble and pebble grades. Erosional and loaded bases common. Some stratification is crossbedded cut-and-fill units. Intraclasts present.	Well-sorted proximal to distal debris flows and/or (?)traction currents.
6	Dcs	Similar to types 2 and 5 but having some stratification of clasts and/or matrix, but with a greater density of clasts than type 5. Loaded bases may be present. Crossbedding may also be present.	Well-sorted, clast-rich distal debris flows and/or (?)traction currents.
7	Ss1	Horizontally and cross-stratified pebbly (occasionally cobbly) sandstone often filling scoured depressions.	Tractive phase of high-density turbidites and/or emplacement by (?)traction currents.

Table 3. Continued

Type	Facies	Description	Interpretation
8	Sg1	Grading of unit from pebbly (occasionally cobbly) and granular sandstone to medium to fine-grained sandstone and siltstone. Basal contact is often planar and possibly erosive in places. Reverse grading at the base may also be present.	High-density (proximal) turbidites and/or possibly fluidized/liquified flows.
9	Sm	Ungraded and unbedded fine to medium grained sandstone with loaded basal contacts.	High-density (proximal) turbidites/grain flows and/or fluidized/liquified flows.
10	Ss2	Similar to type 9, but having faint to distinct strata. Different from type 8 in that the grain sizes are smaller.  Cross-stratification may also be present.	Low-density (distal) turbidites and/or possibly distal fluidized/liquified flows and/or traction currents.
11	Sg2	Medium to fine sandstone grading to fine to silty sandstone and siltstone. Bouma BCD, BCDE(?), B(?)CD, CD, and CDE(?) units present.	Low density (distal), Bouma-type turbidites.
12	Fg	Graded very fine sandstone and siltstone to siltstone and mud. Scoured and loaded bases are common. Grading usually within laminae.	Low-density (distal), Bouma-type turbidites. Possibly weak bottom currents with suspension settling.
13	Fs	Horizontal and cross-laminated argillites, including ripples. Planar and sometimes scoured basal contact.	Weak bottom currents and suspension settling.
14	Fs(d)	A variant of 13 with the additional presence of lonestones.	Variant of type 13 with dropstones suggesting sediment rain-out.
15	Fsd	A variant of types 13 and 14 with load casts and/or slump-folds.	Variant of types 13 and 14 yet also having downslope gravitational creep and rapid sedimentation on underconsolidated beds. Syn or post-depositional.
16	Fgd	A variant of type 12 but also having slump-folds and load casts.	Variant of types 12 but also having downslope gravitational creep and rapid sedimentation on underconsolidated beds. Syn or post-depositional.
17	Fs(d)d	Same as types 13, 14, and 15, but containing dropstones.	Same as types 13, 14, and 15.

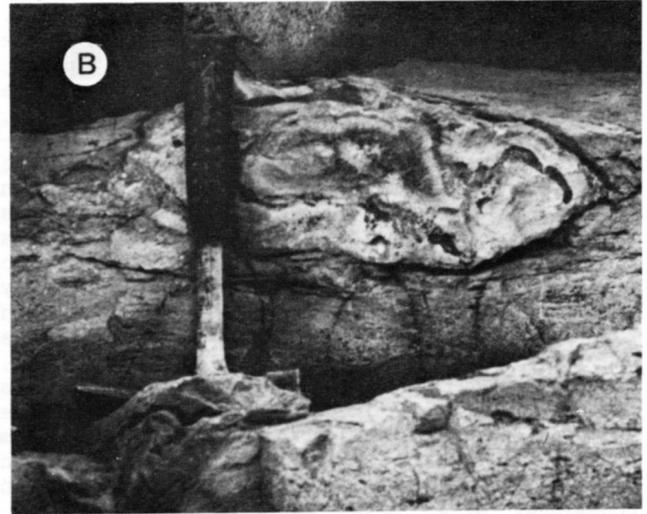


Fig. 7. Sedimentary features within the Boston Bay Group. (A) Cobble-rich diamictite (Dmm) with soft-sediment deformed argillitic (Fs) rip-ups in the upper portion of section 3. (B) Stratified water-lain? basalt/basaltic andesite tuffs containing volcanic bombs located at section 5. (C) Load-casting below the base of a proximal debris flow deposit (Dmm-Dcm facies) attributed to rapid loading of underconsolidated and fluidized sediments (Fs-Fg facies) located at section 3. Crude reverse grading is present at the base of the Dcm unit.

ably overlying the Dedham Granite basement is a suite of bimodal volcanics referred to as the Mattapan Volcanics (Fig. 3). The earliest phase of volcanic activity is recorded in a succession of felsic or rhyolitic flows and tuffs. A later phase of volcanic activity resulted in the emplacement of water-lain(?) tuffs, flows, dikes, and sills of basalt and/or basaltic andesite (LaForge, 1932; Bell, 1948; Durfee-Cardoza *et al.*, 1985; and Hon and Hepburn, 1986). These water-lain(?) tuffs, exposed in the southern part of the basin (see section 5, Fig. 5), commonly contain volcanic bombs (Fig. 7B) and terrigenous detritus. Directly overlying the tuffs is a massive (tens of meters thick) autobrecciated mafic flow which is reported to have been hydrothermally altered (LaForge, 1932; Bell, 1948). Elsewhere in the southern part of the basin terrigenous rocks and volcanics become complexly interstratified, laterally and upsection. Furthermore, there is typically a gradual increase, upsection, in the amount of terrigenous material present in the form of Dmm, Ss1, and Ss2 facies until the succession becomes completely dominated by detritus with an occasional sill, dike, or flow. Mafic dikes, sills, and flows appear to have been contemporaneous with and post-dated the deposition of the Boston Bay Group.

The geochemistry of some of the mafic flows (i.e. the Brighton Volcanics, section 1, Fig. 5) suggests spillitization (Durfee-Cardoza *et al.*, 1985; Hon and Hepburn, 1986). In general, the bimodal Mattapan Volcanics (section 5, Fig. 5) appear to represent transitional early-to-late phases of calc-alkaline-to-alkaline magmatic activity suggestive of a transition from compressional to extensional tectonic regimes (Hon and Hepburn, 1986).

#### Additional Features

In addition to those features described in the previous section, faceted clasts, confined to the D facies, and dropstones (Cameron, 1979c), observed in the S and F facies, are present throughout the Boston Bay Group. Another common feature found principally along the contacts between Dmg, Dcg, Dms, Dcm and Dmm facies and Fs and Fg facies is the presence of load features (Fig. 7C).

#### Paleocurrent and Paleoslope Analysis

Paleocurrent vectors in the Boston Basin were obtained primarily from ripples and other cross-stratified features such as scour-and-fill features wherever such features could be found and resolved either in the field or in the laboratory. Dip-corrected vectors were gathered from 24 cross-stratified units scattered throughout the basin. The rose diagram (Fig. 8) suggests that much of the material was transported from the southwest to the northeast. However, the overall dispersal pattern is rather broad. Two smaller secondary modes indicate some sediment dispersal from east to west and north to south. The paleocurrent vectors reveal a complex and varied flow pattern which reflects changing source lands and current directions through time and/or a multiplicity of contem-

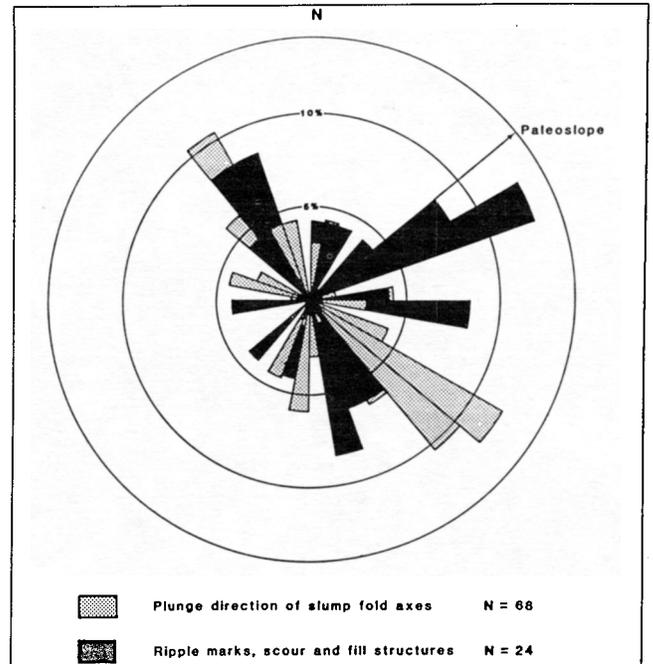


Fig. 8. Rose diagram of paleocurrent azimuths from cross-stratified units and plunge directions of slump-fold axes.

poraneous source areas and contemporaneous variably directed currents.

A total of 68 dip-corrected plunge directions obtained from slump-fold axes within the Boston Bay Group were also plotted on the rose diagram shown in Fig. 8. The diagram shows a somewhat broad distribution of plunge directions which are confined, more or less, to the northeast and southwest quadrants. When combined with the cross-section shown in Fig. 4 and the facies information in Table 3, the plunge azimuths in Fig. 8 suggest a northwest-southeast trending paleoslope somewhere to the north-northeast. There is also reason to suspect that the slope had a number of reentrants rather than being a simple linear feature.

Lindsay *et al.* (1970) had previously argued for the existence of a local paleoslope somewhere to the north-northwest based upon the orientation of the axial planes of slump folds in the vicinity of section 4 (Fig. 5). Further refinements on the paleoslope direction are probably not statistically possible given the size of the data set in this study and that of Lindsay *et al.* (1970).

It is interesting to note however, that Miall (1985) had obtained only 15 to 20 paleoflow vectors from the Gowanda Formation. Perhaps the paucity of flow vectors suggests something significant in itself regarding the nature of the depositional settings and flow mechanisms represented by the facies within the Boston Bay Group and the Gowanda Formation.

The authors make no claim as to the statistical reliability of the data in Fig. 8 since the information obtained was predicated upon outcrop availability and accessibility.

## INTERPRETATION

## Diamictites

Most of the diamictites in the Boston Bay Group are interpreted as resedimented detritus redeposited largely by sediment gravity mechanisms. Flow types 1 through 6 are interpreted as an evolutionary sequence of debris flow and turbidite facies (proximal to distal) generated on a slope as the debris flows and turbidity currents attenuated downslope producing vertical and within-flow variations in fabric.

Walker (1975; 1984) has stated that debris flows are initially disorganized in proximal settings and that as the flows move further downslope basal reverse grading in accompaniment with poor-to-moderate sorting develops in response to the establishment of dispersive pressure within the flows. As internal sorting further improves in the downslope direction, the flow may pass through a normally graded phase due to turbulence. Hampton (1972) observed that flow separation effects on debris flow noses can filter out fine sediment and produce a turbidity current which will outdistance the debris flow. Flow separation is a mechanism which improves the sorting in debris flows. In Hampton's (1972) model, turbidite sands would be the logical and genetically linked downslope facies equivalent of debris flows higher up on the slope.

Nelson and Nilsen (1984) have observed and described similar debris flow and turbidite fabrics in proximal and distal portions of submarine fans. Kurtz and Anderson (1979) and Anderson *et al.* (1983) have also described on the Antarctic shelf, diamictites, tens to hundreds of kilometers in length, in which the fabric changes downslope are analogous to the downslope (north) fabric changes within the diamictites of the Boston Basin.

Type 1 flow deposits (Table 3), facies Dmm, are unsorted, disorganized to varying degrees, matrix-supported diamictites which commonly contain boulders (Fig. 9A). These are interpreted as proximal debris flow deposits laid down on the upper reaches of a relatively steep slope. The clasts were likely supported by cohesive strength, buoyancy, and turbulence (Hampton, 1979; Lowe, 1979). In places where reverse grading is present, dispersive pressure appears to have played an important role in supporting clasts, for some unknown amount of time, at least near the base of such flows (Middleton and Hampton, 1973). Intraclasts may also be present in Dmm deposits.

Type 2 flow deposits (Dcm) are considered to be variants of type 1 deposits. The amount of matrix present is generally substantially less than that found in flow type 1, in addition to the fact that a significant proportion of the clasts are in contact or nearly in contact with other clasts. Yet the overall differences between flow types 1 and 2 are minor and are interpreted to have resulted from some degree of sorting of the matrix and the clasts due possibly to flow separation at the head of a debris flow. Consequently, the Dcm flow type is interpreted to be a more well sorted variant of a type 1 proximal debris flow deposited on a steep slope. There is a complete gradation in texture between flow types 1 and 2. Reverse grading is rarely seen at the base of Dcm deposits. Loaded

bases and intraclasts may be present in Dcm deposits.

Flow types 3 and 4 (Dmg, Dcg) are commonly characterized by changes in the density of clasts throughout the deposits (Fig. 9B), known as coarse-tail grading (Middleton and Hampton, 1973), wherein the coarsest fraction alone is normally graded and sorted due to the existence of turbulence during deposition (Lowe, 1982). These deposits may likely be the counterparts to the graded deposits described by Walker (1975; 1984) and Miall (1983; 1985), who have interpreted this fabric as representing debris flows deposited on less steep slopes than the deposits of flow types 1 and 2. This type of grading is suggested to be found in high concentration sediment-gravity flows in which turbulence has begun to diminish, while competency has changed throughout the flow (Middleton and Hampton, 1973). The distinction between clast and matrix-supported varieties of graded diamictites is difficult to make in the field due to the frequency with which clast density changes. Intraclasts are not uncommon in Dmg and Dcg deposits although basal reverse grading is common. Flow types 3 and 4 are here interpreted as intermediate debris flows which have undergone some sorting, while conceivably being deposited on less steep parts of a slope.

Flow types 5 and 6 (Dms; Dcs) represent a spectrum of stratified diamictites in which the proportion of matrix to clasts varies frequently, comprising a genetic family of facies similar to types 1 and 2 and types 3 and 4, although the entire spectrum of diamictite facies represents a broader class of genetically related deposits. Facies types 5 and 6 are interpreted as distal debris flow deposits and/or high-density turbidites having a traction carpet phase of deposition. These types of deposits have also been described and discussed by Walker (1975; 1984) and Miall (1985). Stratification types represented by these facies also include cross-stratified sequences often filling scoured depressions.

## Sandstones

Most of the sandstone lithofacies (Sg1; Sg2; Ss1; Ss2; Sm) are considered to have been emplaced by a variety of sediment-gravity flows such as high density turbidites/grain flows, low density turbidites, and liquified and/or fluidized flows, which together can account for the majority of fabrics and sedimentary structures observed in the sandstones such as normal and reversed graded bedding, cross-stratification, horizontal stratification, ripples, convolute bedding, load-casted features, and water-escape structures (see Middleton and Hampton, 1973; 1976; Lowe, 1976a; 1976b; and 1979).

In addition to interpreting the bulk of the sandstone facies as having been emplaced by sediment gravity flows, many are also suggested to have been genetically linked to proximal debris flows further up on the slope via flow separation phenomena whereby the finer sediment is continually removed from the debris flows, leaving the coarser debris flow deposits partially sorted. However, in some cases there need not have been any genetic links between sediment gravity flow mechanisms and some sandstone and diamictite facies. Sandy

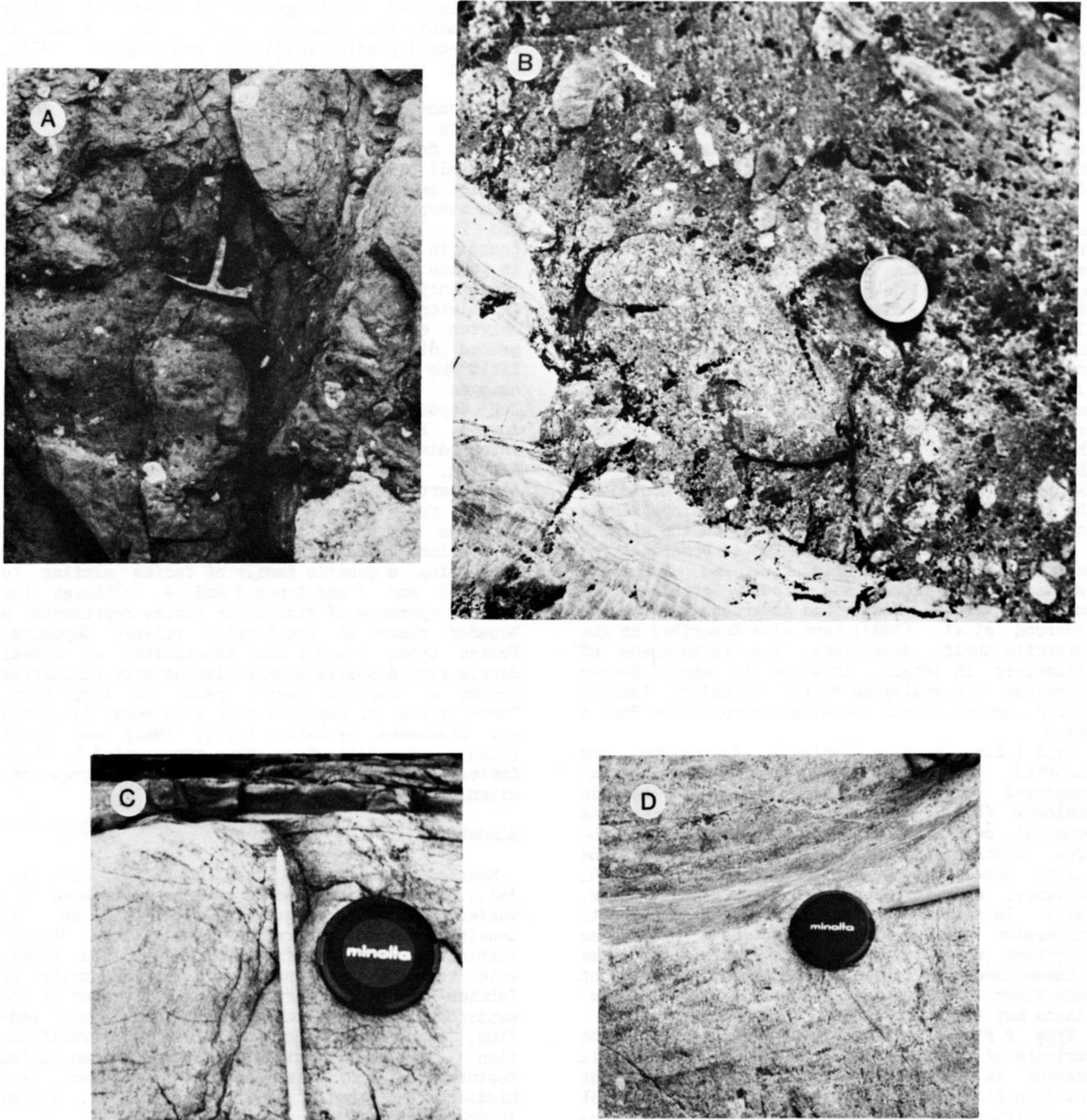


Fig. 9. Facies and flow types within the Boston Bay Group. (A) Unsorted, bouldery, matrix-supported proximal debris flow deposit (Dmm) located near the base of section 4. Faint traces of bedding within the matrix can be observed below the hammer. (B) Crudely graded, clast-poor intermediate-to-distal debris flow deposit (Dmg) overlain and underlain by argillites (Fsd) located at section 4. (C) Stacked, massive, medium-to-fine-grained sandstone (Sm), possibly graded near the top, deposited by low density turbidity currents and/or liquefied/fluidized flows located at section 3. Note the presence of concave-up fluid escape structures. (D) Medium-to-fine-grained, cross stratified, scour-filled sandstone (Ss2) possibly deposited by low-density turbidity currents and/or bottom currents located at section 3. (E) Multistoried sequence of medium-to-fine-grained, normally graded Bouma-type B(?)CD and CD turbidites (Sg2) with loaded, convolute bedding located at section 4. (F) Granitic dropstone in Fs(d) facies located at section 4. (G) Stacked sequence of graded, soft-sediment deformed argillitic units (Fgd). Individual laminations are interpreted as low-density, Bouma-type CD B?CD CDE? turbidites with erosive bases. Some reworking by bottom currents may also have occurred. Slump-folds are attributed to downslope creep.

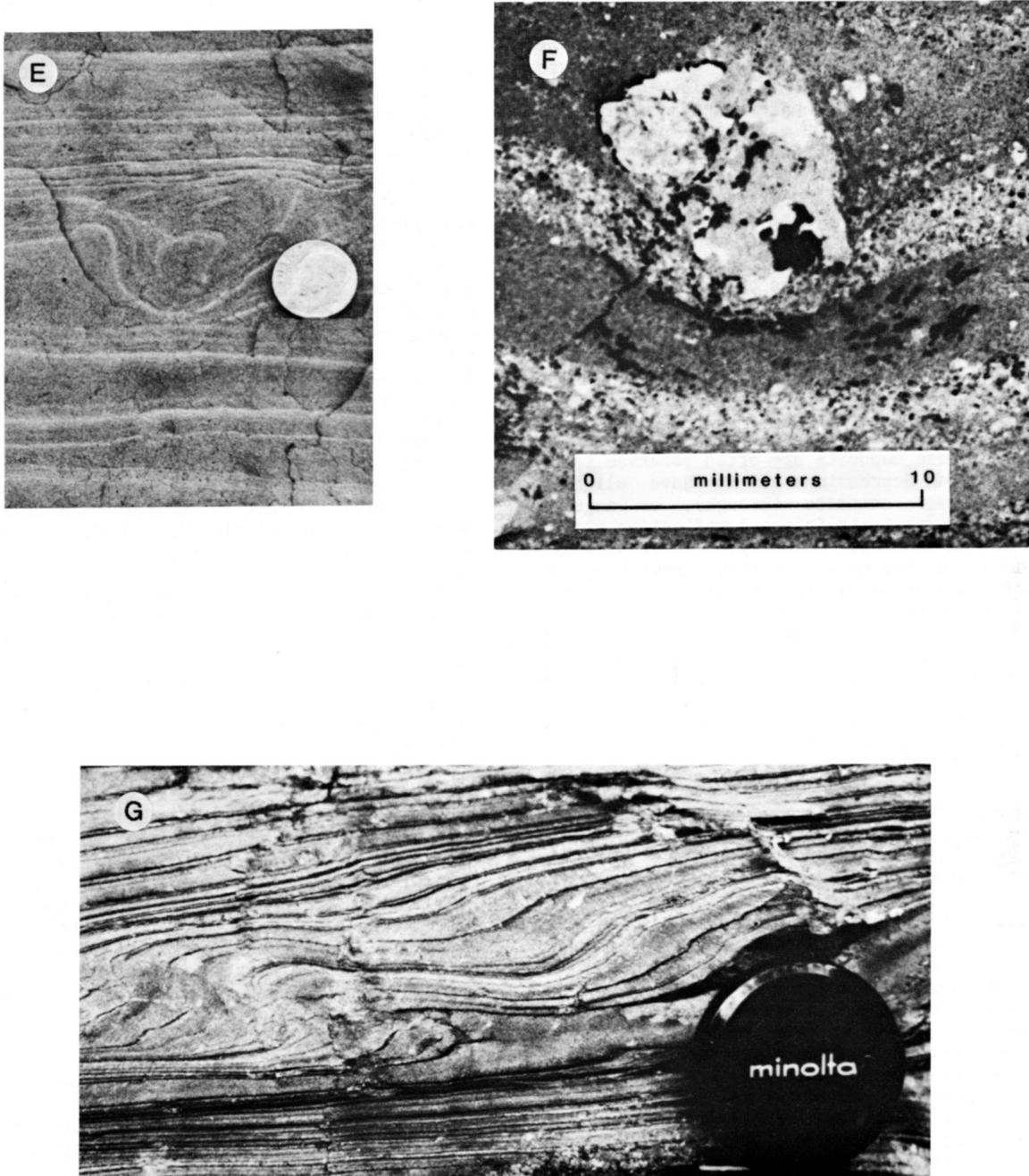


Fig. 9 Continued

sediment gravity flows for example, could have been generated independently of debris flows, and no doubt this has occurred in the Boston Basin. The intimate association of sandstones and diamictites argues for a closer association between sediment gravity flow mechanisms.

Stratified and cross-stratified sandstone facies (Ss1; Ss2) may in some cases be interpreted as having resulted from wind-driven or tide-driven bottom currents. However, one should bear in mind that sediment gravity mechanisms such as turbidity currents often pass through a tractive phase while attenuating and depositing sediment. Such mechanisms also have the capacity to transport cobble-size material. Wind-driven or tide-driven bottom currents are not considered to be sufficiently energetic in this type of setting (slope) to transport and deposit coarse clasts.

Flow type 7 (Ss1) consists of horizontally to cross-stratified pebbly, occasionally cobbly, medium-to-coarse grained sandstones. The clast compositions are similar to those reported for the diamictites. Changes in the proportions of clasts present are unknown. This facies is interpreted as representing a deposit produced during the tractive phase of a high-density turbidity current moving downslope. These deposits are often observed to be filling scoured depressions and may have slightly tangential lower contacts (trough), or angular lower and upper contacts (planar) reflecting slight variations in current velocity. Alternatively, these deposits may merely reflect reworking of previously deposited material by bottom currents. However, as stated previously, bottom currents, in the absence of turbidity currents, are generally thought to be too weak to move coarse sediment in this setting. Again, the intimate association with diamictites as well as the slightly unsorted appearance of the sandstones favor emplacement by sediment gravity mechanisms.

Flow type 8 (Sg1) is a pebbly (with occasional cobbles), granular, or coarse-grained sandstone which grades normally to a medium- to fine-grained sandstone and/or siltstone. The basal contact is planar, slightly irregular, and possibly erosive. Basal reverse grading may also rarely be present. The clast compositions are analogous to the compositions found in the diamictites, and the relative proportions of these clasts are unknown. Flow type 8 is interpreted as having been deposited on a slope during the suspension stage of a high density turbidity current. Rare reverse grading at the base is thought to have been generated by dispersive pressure during a preceding traction carpet phase (see Lowe, 1982). Alternatively, this flow type may have originated to some extent by liquified or fluidized sediment gravity flows in which particle support and motion result from rapidly escaping pore fluids leading ultimately to a tighter packing. However, the former interpretation is favored by the authors because of the coarseness of the clasts present, the absence of fluid escape features, and the presence of what appear to be erosive bases. In at least one instance the Sg1 facies was interpreted as constituting a multistoried unit deposited as a bar-like feature associated with Dmm and Dcm facies which in some instances had channelized basal contacts (see section 1, Fig. 5).

Flow type 9 deposits (Sm) are non-bedded, non-

graded, massive, medium- to fine-grained sandstones which often have loaded, non-erosional bases and are commonly associated with laminated fine-grained units (Fig. 9C). These deposits are interpreted as being generated by high-density turbidity currents during the latter stages of rapid suspension sedimentation accompanied by rapid entrainment of fluid. As the fluid subsequently escaped, the deposits were fluidized/liquefied, temporarily mobilizing or remobilizing the sediments, producing fluid escape structures. These flow types are also considered to be equivalent to the Bouma Ta division of "classical" turbidites (Lowe, 1982).

Flow type 10 deposits (Ss2) are similar to Sm flow deposits. They are composed of medium- to fine-grained, horizontally and cross-stratified sandstones (Fig. 9D). Laminations are also quite common. The cross-stratified units exhibit planar and trough type foresets and are often observed to fill scoured depressions. Small-scale ripples are also occasionally present. These stratified sandstones are interpreted as having been produced during the passage and attenuation of low density turbidity currents over the distal portions of a slope. Deposition during tractive phases is indicated by cross stratification and the presence of filled scours. In instances where only horizontal stratification is present and the nature of the basal contact is unclear, the fabric could be related to distal fluidized or liquified flows, as suggested by Miall (1985). Additionally, some of these deposits could be the result of bottom currents. However, for the coarser sandstones it is considered likely that the currents which transported them were associated with turbidity currents.

Flow type 11 deposits (Sg2) consist of normally graded medium- to fine-grained sandstones which pass upward into fine-to-silty sandstones and siltstones (Fig. 9E). Compositionally, these deposits show a marked increase in mineralogical maturity. They range from feldspathic-rich to quartz-rich with occasional lithics. These deposits are also compositionally unlike the coarser sandstone facies such as Sg1 and Ss1 which are mineralogically immature (lithic sandstones), but very similar in composition to flow types 9 and 10. Type 11 deposits are interpreted to be low density or Bouma-type (distal) turbidites laid down during the tractive and settling phases of sedimentation as turbidity currents attenuated, conceivably in the distal reaches of a slope.

Similar downslope changes in fabric and composition have also been observed in diamicton/sand, and diamictite/sandstone sequences on the present-day Antarctic Shelf (Wright and Anderson, 1982; Anderson, pers. comm., 1985) and in the Gowganda Formation (Miall, 1983; 1985), respectively. In general, the Sg2, Sm, and Ss2 facies are considered to be the mineralogically and physically sorted residuum of coarser deposits which came to rest higher (more proximally) on a slope as sediment-gravity flows moved downslope and attenuated.

#### Fine-Grained Units (Argillites)

Lithofacies type 12 deposits (Fg) consist of normally graded very fine sandstones and siltstones which pass upward into siltstones and clay. They are generally quartz rich, as are most of the F

facies types, and are interpreted to be the remnants of distal turbidites deposited from weak, low density turbidity currents during tractive and settling depositional phases as the flows attenuated downslope. Some of these deposits have scoured bases which may be related to the passage of turbidity currents, or to bottom current activity predating the passage of turbidity currents. Small-scale loaded bases with small-scale flame structures are fairly common. Some of these deposits may also have been deposited entirely from suspension, but the presence of load features suggests that sedimentation was rapid and took place upon a weakly consolidated and fluidized substrate.

Type 13 flow deposits (Fs) consist of horizontal and cross-laminated argillites whose composition is similar to type 12 deposits. Cross-laminated stratification is confined to small-scale scour-and-fill features and small-scale ripples. These deposits are interpreted as having been laid down and/or subsequently reworked by weak bottom currents independent of sediment-gravity flows. Suspension settling with reworking is also suggested to have occurred.

Type 14 flow deposits (Fs(d)) are similar to type 13 deposits, yet contain limestones which often deform and sometimes penetrate stratification planes and are interpreted as dropstones (Fig. 9F).

Types 15, 16, and 17 flow deposits (Fsd; Fgd; Fs(d)d) are similar to types Fg, Fs, and Fs(d). Yet, in addition, flow deposits 15, 16, and 17 record the presence of soft-sediment deformation such as load-casted features and slump-folds (Fig. 9G). The deformation is interpreted to have occurred during or immediately after sedimentation while the sediments were unlithified and undercompacted. Loading is thought to have resulted from rapid sedimentation upon fluidized, loosely-packed sediment with and without simultaneous downslope movement of the units. Slump-folds are considered to have been produced by the downslope creep of weakly consolidated beds under the force of gravity. Folding was also probably facilitated by poor packing resulting from undercompaction.

#### Facies Associations

Facies types 1 through 12 are considered to represent a spectrum of flow deposits laid down on a slope. The upper (proximal) region of this slope is characterized by the presence of bouldery Dmm, Dmc, and Dms facies (sections 3-5, Fig. 5) which contain soft-sediment deformed rip-ups (Fsd) and deformed, commonly laminated, matrix. This deformation and these facies are considered to be the result of sediment rain-out or basal washout from melting shelf ice or icebergs, which loaded unconsolidated sediment and overloaded the slope producing a variety of debris flows as well as other sediment-gravity flows which moved downslope generating facies 3-12 as the flows attenuated. Some Dcm and Dmm facies have channelized basal contacts whereas others have very irregular somewhat planar contacts which, in some cases, are suggested to have resulted from sediment rain-out (rapid suspension sedimentation from melting ice) rather than having been transported along the bottom. To the north and obliquely downslope the diamictites

gradually become slightly less bouldery and slightly more sorted while the matrix also undergoes some sorting (see Fig. 5). Diamictites and sandstones rarely contain stratified and graded argillitic and sandy soft-sediment deformed rip-ups in the vicinity of location 1. Stratified and graded diamictites (Dms; Dcs; Dcg; and Dmg) and stratified and graded sandstones (Ss1; Ss2; Sg1; and Sg2), as well as graded and deformed fine-grained units (Fg; Fgd), become volumetrically more important in the downslope direction to the north-northeast. Channelized features, including the presence of planar and trough crossbedded, scour-fill diamictites (Dms; and Dcs) and what appear to be bar deposits (Sg1-Sg2 facies), are prominent in the vicinity of section 1 (Fig. 5). A graded, slumped argillite sequence (Fg(d)d; Fig. 9G) at location 1 is interpreted as either a channel-fill deposit or a more regional sedimentation event marked by a lower rate of sedimentation and the presence of less competent depositional mechanisms. Dropstones occur in nearly all of the fine-grained units in the basin (Fig. 9F).

Fine-grained units gradually become volumetrically more important to the north, presumably in the lower reaches of the slope/basin where no section was measured due to the lack of outcrop but for which there exists historical information (i.e. see Fig. 4). In general, fine-grained units and sandstones are suggested to have been associated with lower sedimentation rates coupled with a significant drop in the available energy within the depositional setting (lack of competent depositional mechanisms).

There is reason to believe that as sediment gravity flows slowly moved downslope and attenuated they did not necessarily come to rest at exactly the same position on the slope. Some flows outdistanced others while other sediment gravity flows were probably remobilized several times before finally being incorporated into the stratigraphic record. The net effect of this was the generation of dramatic and abrupt facies changes in the younging direction. These facies exhibit no direct linkage to the adjacent facies (i.e. Dmm or Dmc facies directly overlying Fs or Fg facies and vice versa; see section 1, Fig. 5). Alternatively, abrupt facies changes which are, or may once have been more regional in extent prior to differential erosion, may be related to climatic changes (episodic ice growth and decay) and/or tectonic readjustments in the basin and/or the sourcelands. However, since many of the fine-grained units show varying degrees of erosion, the original extent of these units is unclear.

There is also no reason to presume that turbidity currents were, in all cases, directly linked to debris flows generated higher up on the slope. Many such flows undoubtedly originated independently of debris flows.

It should also be remembered that the principal controls on the locations of the stratigraphic sections shown in Fig. 5 were the availability and accessibility of outcrop. The sections therefore provide brief glimpses into the full range of facies present within the basin and do not permit a detailed accounting of continuous changes in fabric within flows in the downslope direction. Our only notion of lateral facies changes comes from our

understanding and application of the concept of facies development within a vertical sequence (see Visher, 1965).

#### Depositional Model for the Evolution of the Boston Basin

Historically, there appears to have been a great deal of confusion regarding the stratigraphy and hence the depositional history of the Boston Basin (i.e. see LaForge, 1932). To some extent this confusion is likely to have evolved from continued usage of the original stratigraphic subdivisions within the Boston Basin which did not adequately characterize the variety of textures present and which often came replete with an interpretation. In addition, although there are scores of published papers dealing with the stratigraphy and sedimentology of the Boston Basin, there has been little progress in inventorying and identifying the fundamental components of the Boston Bay Group (i.e. facies), while even fewer papers housed any data which could be used in combination with other data to formulate a coherent, less contentious, geologic history of the basin. The net effect has often lead to apparent misconceptions and oversimplifications of the geology and make-up of the Boston Basin succession (see Smith and Socci, in press).

Although the present authors have been able to recognize a suite of facies which can and have been used to construct a depositional model for the Boston Basin, we have found no marker beds or stratigraphic horizons which would permit the identification of lithostratigraphic or time-stratigraphic units. It is our belief, therefore, that the stratigraphy of the Boston Bay Group will be resolved through shallow and deep seismic stratigraphy and/or biostratigraphic markers.

From the information we have thus far gathered on the lithofacies of the Boston Bay Group, it appears that there is much more complexity in the make-up and distribution of lithofacies assemblages. The facies patterns are a function of the rate of subsidence due to thermal cooling, the rate of subsidence due to the rate of sedimentation, the rate of sea level change due to changes in ridge volume and sedimentation, the rate of sea level change due to climate, and the rate of sediment supply, which is a complex function of climate, rates of sea-level change, and the rate of tectonism. Of the rate controls cited above, climate and tectonics appear to have most greatly influenced the sedimentation patterns in the Boston Basin. In time however, the influence of climate on the pattern of sedimentation appears to have given way to tectonic influences on sedimentation patterns.

#### Stage 1

The Boston Basin appears to have originated as a successor (possibly arc) basin in an extensional or transtensional setting following the closing of the Cadomian(?) Ocean (Rast and Skehan, 1983) in the late Precambrian. During the subduction of Cadomian ocean crust (Avalonian Orogeny), calc-alkaline granites (Dedham and equivalents) were emplaced in a compressional or transpressional setting, into older crust (Middlesex Fells Volcanic

Complex and basement (?), the nature of which is unresolved. Subsequent deformation of the Middlesex Fells Volcanics, the Dedham Granite, the Lynn Volcanics, and older crust (?) heralded the end of the Avalon Orogeny, which also marked the closing of the Cadomian ocean. Near the end of the Precambrian, the appearance of the bimodal Mattapan Volcanics, marked by an early calc-alkaline phase of activity and a later alkaline phase (Hon and Hepburn, 1986), is suggested to have represented a transition from a compressional tectonic regime to one of extension.

Questions concerning the age of the Boston Basin, as well as the basin type, are closely tied to whether or not the Boston Bay Group (the basin fill) contains Avalonian deformation. If Avalonian deformation is not present within the Boston Bay Group, then it is reasonable to argue that the basin post-dated the closing of the Cadomian Ocean and the Avalon Orogeny, and is therefore more likely to be a successor-type basin which originated on an Andean-type active margin during an extensional tectonic regime. In time, the basin filled with locally-derived (?) plutonic, volcanic, and sedimentary detritus. Alternatively, if the Boston Bay Group does record Avalonian deformation, then it is feasible to suggest that the basin had to have formed prior to closure of the Cadomian Ocean, and is therefore more likely to have originated as an arc-type basin within a compressional tectonic regime. Presently, this question remains unresolved. The authors however, have observed cleaved clasts, principally granites, whose cleavage planes appear to be randomly oriented, with no apparent relation to the orientation of the more pervasive Alleghanian cleavages. Therefore, in the absence of any clear evidence of pervasive Avalonian deformation within the Boston Bay Group, the Boston Basin is presumed to be a successor basin which post-dated arc formation and volcanism.

Sometime during, and possibly just post-dating, the earliest (felsic or rhyolitic) and later (mafic) phases of bimodal volcanic activity, a period of erosion ensued as suggested by the presence of an unconformable surface on top of the Dedham Granite and on top of the felsic component of the Mattapan Volcanics. The nature of this unconformity is not well known nor would such a surface be required to be present everywhere. During or sometime after this erosional event, mafic volcanics in the form of stratified water-lain tuffs with volcanic bombs and occasional granitic pebbles (see section 5, Fig. 5) were deposited contemporaneously with the emplacement of dikes, sills, and flows of basalt and basaltic andesite (Fig. 10A). The presence of anomalously high sodium concentrations in these tuffs (LaForge, 1932; Bell, 1948; and Hon and Hepburn, 1986) suggests that the Boston Basin was in contact with marine waters early in its history. A later phase of mafic volcanic activity produced a thick sequence of hydrothermally altered autobrecciated flows.

The next phase of sedimentation and basin evolution was characterized by the deposition of large volumes of volcanic, plutonic, and sedimentary detritus in the form of bouldery debris flows (Dmm, Dcm) into a widening (?) and thermally subsiding (?) marine basin. These interbedded volcanic flows

and tuffs, and bouldery debris flow deposits are considered to represent the initial stages of slope progradation and aggradation within a newly emerging successor basin. Reworking of these debris flow deposits by variably directed bottom currents is suggested by the presence of multiply oriented ripples in fine-grained sandstone near the base of the succession (section 5, Fig. 5).

#### Stage 2

The next major episode in the evolution of the Boston Basin is considered to have been a period of rapid submarine slope/fan progradation and aggradation (Fig. 10B) marked by the development of complex facies associations and the appearance of large volumes of coarse detritus (diamictites). Sediment rain-out on the slope from floating shelf ice and/or icebergs led to overloading of undercompacted, fluidized sediment generating sediment gravity flows such as debris flows which moved downslope in a northerly-northeasterly direction leaving in their wake proximal debris flow deposits (Dmm, Dmc, and Dms) containing soft-sediment deformed argillites (Fgd, Fsd) representing a prior episode of slow deposition of fine-grained sediment. As the debris flows continued downslope, they slowly attenuated giving rise to other sediment gravity flows such as turbidity currents and liquified/fluidized flows which carried away the

finer materials that were originally present in the debris flows, and leaving behind sorted, stratified, and graded proximal to distal debris flow deposits and turbidites (Dms, Dcs, Dmg, Dcg). On the lower, deeper parts of the slope turbidity currents and liquified/fluidized flows produced graded, stratified, and massive sandstones (Ss1, Ss2, Sg1, Sg2, Sm) and graded argillites (Fg). In the vicinity of the toe (?) of the slope/fan and elsewhere, fine-grained sediments were reworked and redeposited by bottom currents. Channelized features were present everywhere on the slope but appear to have been more abundant some distance downslope.

There appear to have been intermittent periods of climatic amelioration conceivably brought about by Milankovitch-type orbital forcing and/or periodic rises in eustatic sea-level independent of climate. During such times sedimentation rates were significantly reduced, and the slope/fan accumulated blankets of fine-grained sediment in the absence of a mechanism (or mechanisms) capable of transporting coarse detritus into the basin (Fig. 10C). Slope failure continued during these episodes of more equable climates, but at much reduced rates presumably due the absence of coarse detritus which would ordinarily have overloaded the slope/fan with greater frequency. Abandoned channels were filled with fine-grained, graded deposits containing dropstones (Fg(d)) released

### BOSTON BASIN : (INITIAL RIFTING)

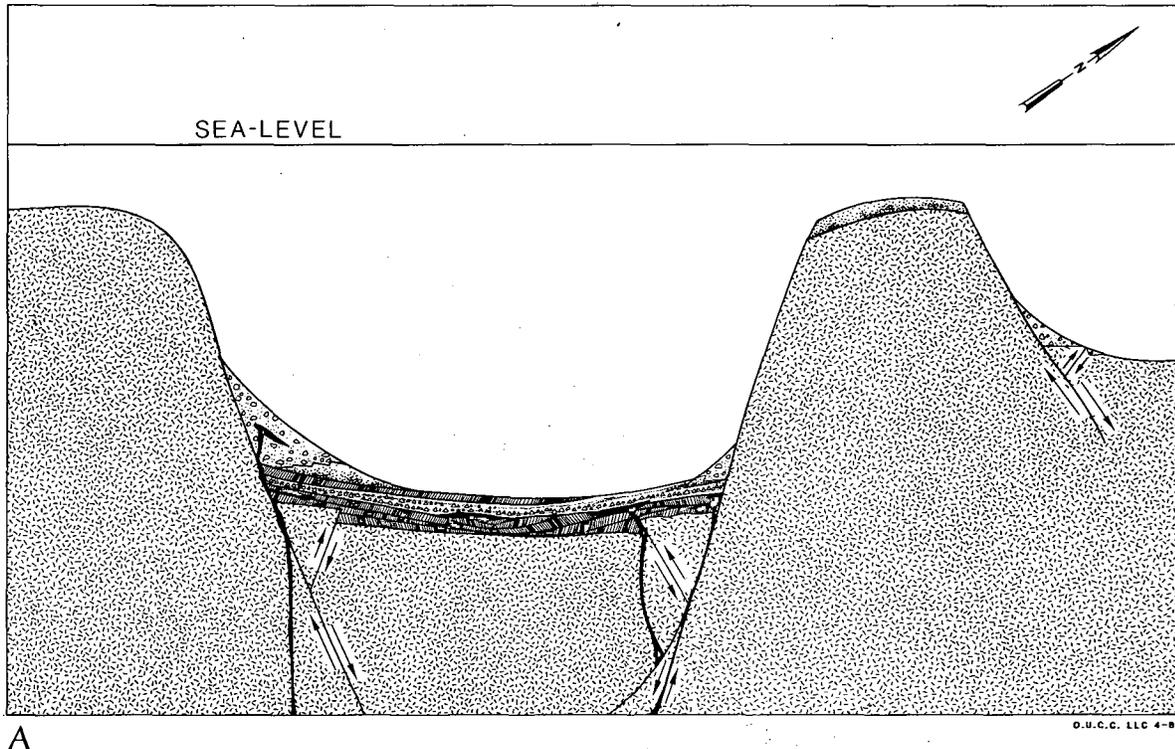
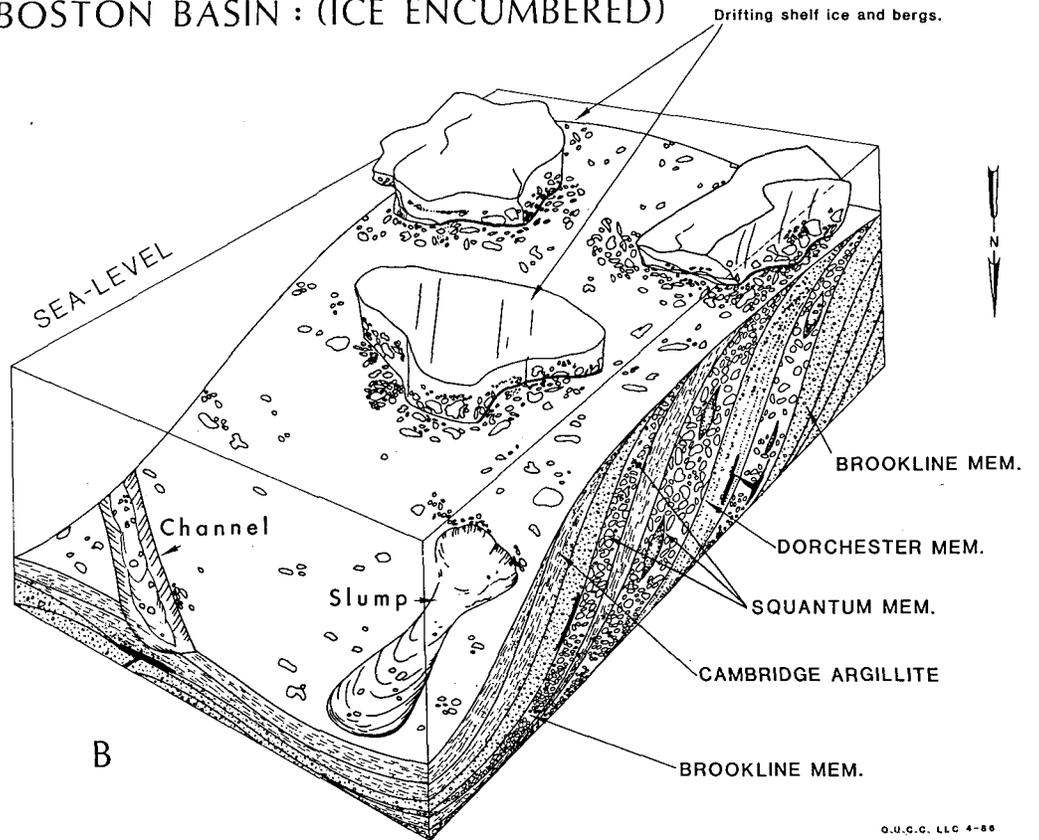


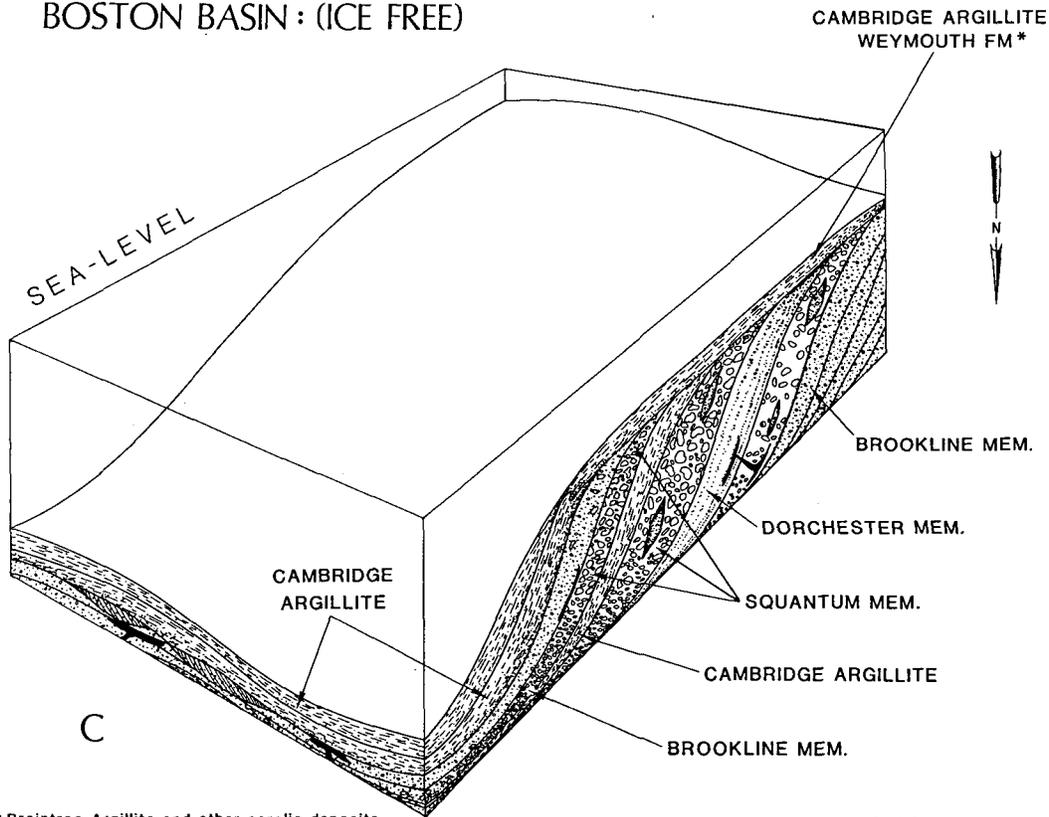
Fig. 10. Preliminary depositional model for the evolution of the Boston Basin. (A) Initial rifting phase of basin evolution with concurrent bimodal volcanism and detrital sedimentation within a marine? basin. (B) Slope building phase of basin evolution brought about by climatic controls on sedimentation. (C) Shelf building phase of basin evolution resulting from i) climate amelioration, ii) slope aggradation resulting in an elevated platform, and iii) a tectonically-driven rise in eustatic sea level. Historic stratigraphic names of the units comprising the Boston Bay Group have been assigned to stages B and C for the purpose of identifying the likely positions of those units in the context of this model.

### BOSTON BASIN : (ICE ENCUMBERED)



G.U.C.C. LLC 4-88

### BOSTON BASIN : (ICE FREE)



G.U.C.C. LLC 4-88

\*Braintree Argillite and other paralic deposits.

Fig. 10 Continued

from small, scattered icebergs. In some instances the channel fill began to creep and slump downslope probably due to slope instability and undercompaction. Bottom currents also reworked previously deposited fine-grained sediment.

In the deeper, more distal area of the slope/fan, the presence of acritarchs records evidence of pelagic sedimentation in marine waters (Knoll, pers. comm., 1986). Furthermore, the acritarch assemblage recovered by Lenk *et al.* (1982), is one that is often associated with, and may be indicative of glacially-stressed marine environments (Lenk *et al.*, 1982; Knoll *et al.*, 1981; Knoll, pers. comm., 1986). There is no evidence of a shelf or shelf-type sediments in the Boston Basin during stages 1 or 2.

There are several lines of evidence (Vail *et al.*, 1977; Fischer, 1984; and Worsley *et al.*, 1984) which suggest that throughout this episode as well as the previous episode of slope/fan deposition and basin evolution, eustatic sea-level was rising throughout the mid-to-late Precambrian and Cambrian in response to tectonic forcing (i.e. changes in ridge volume). Due to the frequent yet periodic appearance of similar facies up or down section within at least the lowermost two-thirds of the Boston Basin succession, we propose that the development of facies patterns during stages 1 and 2, was largely controlled by the rate of sediment influx into the basin, and not the tectonically driven rise in eustatic sea-level.

We further propose that the rate of sedimentation was largely controlled by climatic changes (the growth and decay of ice) at this time. Vail *et al.* (1977) have shown that during a relative rise in eustatic sea-level (i.e. late Precambrian to Cambrian), the sedimentation rate determines the geometry of sedimentary bodies. This results in the production of so-called "transgressive" and "regressive" facies assemblages, even though these assemblages need not be confined to a shelf. It is suggested therefore, that the facies patterns and sedimentary geometry produced in the Boston Basin during stage 1, and at least part of stage 2, were likely to have been source controlled. Furthermore, the rate of terrigenous influx to the basin could have been controlled by climate and/or structural adjustments during the evolution of the basin. However, structural adjustments are not sediment transport mechanisms, and as such, fail to adequately account for the presence of an apparently large volume of coarse detritus. We submit that climate (the presence of ice, for which there is substantial evidence) played a major role in transporting coarse detritus to the basin, and in the development of facies geometry and sedimentary fabric during this period of time.

There is sufficient evidence to suggest that near the termination of stage two, and possibly during the beginning of stage three, the tectonically forced late Precambrian-early Paleozoic rise in eustatic sea-level conceivably began to buffer climate globally (see Worsley *et al.*, 1984; and Fischer, 1984), thereby reducing the effect of climate (the presence of ice) on the sedimentation rate and the competence of flow mechanisms. The net effect of this change was a reduction in clast size and lower rates of sedimentation.

From the standpoint of tectonics, there is reason to believe that the basin was continuing to widen

and deepen (thermal decay of the crust) as sediments were continually being introduced into the basin. Mafic volcanic activity continued in the form of basaltic dikes, sills, and flows which appear to have been hydrothermally altered (Hon and Hepburn, 1986; Durfee-Cardoza, 1985). The flows seem to have been confined to the moderately lower, more channelized parts of the slope to the north (see section 1, Fig. 5). Anderson *et al.* (1979; 1983), Kurtz and Anderson (1979), and Miall (1983; 1985) have reported similar depositional systems on the Antarctic Shelf and slope, and for the Gowganda Formation of Canada, respectively.

### Stage 3

During the final episode of basin evolution, ice shelves and icebergs appear to have melted for the last time presumably due to a tectonically forced high stand of eustatic sea-level which ameliorated climate globally during the early Paleozoic. Fischer (1984) and Worsley *et al.* (1984) have shown that there is a non-random relationship (feedback system) between tectonically controlled fluctuations in eustatic sea-level and major glacial events in the geologic record, at least throughout the late Proterozoic and early Phanerozoic. Reduced sedimentation rates and the absence of ice resulted in the build-up of fine-grained sediment on the slope/fan over an extensive period of time. Much of the previously deposited fine-grained sediment was reworked by bottom currents during this time. Shelf and shelf-type (paralic) deposits such as quartz arenites, and calcareous sandstones and shales with abundant organic matter and shelled organisms appeared for the first time (Fig. 10C).

The shelf deposits are suggested to have been deposited landward of the slope to the south-southwest and are thought to have extended some distance into the basin on top of the previously deposited prograded and aggraded slope deposits which now acted as a platform for the accumulation of shelf-type deposits. We propose that the shelf deposits then became the shoreward facies equivalent of slope/fan deposits at the margin of the basin. Yet, at the same time, the shelf deposits accumulated unconformably on top of older slope/fan deposits, and the Dedham Granite, Lynn Volcanics, and older crust (landward) without any apparent interruption in sedimentation.

Some confusion exists, however, as to whether these shelf sediments are part of the original basin fill sequence or whether they represent an overlap sequence unrelated to the older sediments which they now overlie. Because these shelf sediments crop out to the south-southwest where shelf deposits associated with this basin would be expected to crop out, they are considered to be a genetic part of the Boston Basin succession. A more complete resolution of the nature of the shelf deposits is linked to resolution of the nature and time of emplacement of Avalon terrane.

### DISCUSSION AND CONCLUSIONS

The depositional model presented here departs in many ways from previous interpretations of the Boston Bay Group, but perhaps one of the most significant points of departure lies in our interpretation of the cross-stratified and

horizontally stratified diamictites and sandstones (Dms, Dcs, and Ssl facies) in section 1 (Fig. 5) as probable distal debris flow deposits, high-density turbidites and conceivably traction deposits which were laid down upon a moderately channelized distal submarine slope/fan. The historic and prevailing, yet largely unsubstantiated interpretation of the Boston Bay Group is that it is part of an alluvial fan/braided stream system (Billings, pers. comm., 1986; Bailey and Galli, 1985; Bailey, 1986; Bailey, pers. comm., 1986). This interpretation is apparently principally based upon the presence of rounded clasts (pebbles and cobbles), channelized contacts, and most importantly, the presence of traction-generated features such as planar and trough cross-stratified diamictites and sandstones generally confined to beds which are less than half a meter in thickness.

We would like to point out, however, that within the last ten years or more our understanding of subaqueous and submarine slope/fan systems and sediment-gravity depositional mechanisms has vastly improved. Investigations such as those of Winn and Dott (1977), Dott and Bird (1979), Damuth *et al.* (1983) and Anderson (pers. comm., 1986) have not only documented the presence of large-scale (in excess of 4 to 12 meters in thickness) trough and planar cross-stratified diamictites and sandstones, but have also shown that submarine fan and canyon deposits commonly consist of intricate networks of braided and meandering distributary systems. Were it not for the fact that these braided and meandering networks are associated with a variety of sediment gravity deposits within submarine slope/fan settings, it would be difficult at best to distinguish these deposits from terrestrial counterparts (Hein, 1984). Rounded gravel and cobbles, channelized contacts, and planar and trough cross-stratified diamictites and sandstones do not by themselves preclude the existence of a submarine fan/slope system, nor do they alone confirm the existence of an alluvial fan/braided stream system.

Within the Boston Basin there is a broad spectrum of facies ranging from predominantly poorly sorted diamictites and graded sandstones in the southern part of the basin (sections 3-5), to moderately sorted, stratified diamictites and graded sandstones in the northern part of the basin (section 1). We submit that this change in fabric is systematic, representing a transition from debris flow, turbidite, and possibly traction deposits in the south, to largely turbidite and possibly traction deposits in the north. Furthermore, we would stress that sediment gravity depositional mechanisms such as high density turbidity currents pass through a traction phase of deposition during attenuation, often resulting in the build-up of meters of cobbly, gravelly, and sandy stratified and cross-stratified deposits (Komar, 1970; Winn and Dott, 1977; and Lowe, 1982).

Additionally, the presence of spillitized basaltic andesite flows (Durfee-Cardoza *et al.*, 1984) near the top of section 1 (Fig. 5), and the presence of dropstones in sections 1, 3, and 4 (Fig. 5) suggests that these rocks were deposited below water-level in a glacial marine setting.

Another area of historic debate centers on the question of whether or not the Boston Bay Group records evidence of late Precambrian glaciation.

It is our contention that the Boston Bay Group does record evidence of late Precambrian glaciation, and that the evidence lies, in part, in the presence of dropstones, which alone is considered compelling evidence for the presence of ice (Anderson, 1983), and the presence of faceted clasts.

Several additional yet independent lines of evidence, albeit presently inferential to various degrees, also point to the presence of ice in the Boston Basin during the late Precambrian. First of all, a recently established late Precambrian-Cambrian age for the Boston Bay Group via radiometric dating of the Mattapan Volcanics (Kaye and Zartman, 1980) and the discovery of Vendian microfossils (Lenk *et al.*, 1982) coincides with a worldwide late Precambrian glaciation (Frakes, 1979). Secondly, the Vendian microfossils discovered in the Boston Basin are dominated by the probable cyanobacterium *Bavlinella faveolata* which has been found in association with glacial deposits elsewhere (Vidal, 1979; Knoll *et al.*, 1981; and Knoll, 1984). Unfortunately, these microfossils in the Boston Basin remain largely uninvestigated.

Historically, several investigators have also cited the presence of striated clasts (Lahee, 1914; Sayles, 1914; Sayles and LaForge, 1910; 1919) chattermarks on the surfaces of quartz grains (Rehmer and Hepburn, 1974), and dropstones (Cameron, 1979c) in the Roxbury Conglomerate as evidence for glaciation. However, investigators such as Dott (1961) have argued that because striated clasts can be non-glacial, their presence does not make a compelling argument for glaciation. We have also found that many clasts are cleaved and show evidence of differential rates of weathering rendering positive identification of "striations" questionable. It should be noted however, that striated clasts are not at all abundant, and in some instances, are absent from Pleistocene glacial deposits and presumably glacial deposits in general (Anderson, 1983). Furthermore, many glacial marine sequences in the geologic record are devoid of a striated pavement (Anderson, 1983) as is the case for the Boston Basin.

Bailey (1984; and pers. comm., 1986) has recently argued that what appear to be dropstones in the Boston Basin are instead isolated clasts which rolled or bounced into their present position, or were transported within a debris flow and settled down through the matrix of the debris flow and/or into the underlying surface after the debris flow had come to rest. In either instance, the limestones are suggested to be non-glacial.

We would point out however, that in the former case, it is well established that clasts which move by rolling along the bottom, are aligned with their long axes lying in the plane of the depositional surface, yet transverse to the flow direction (Sneed and Folk, 1958). Furthermore, Lindsay *et al.* (1970) plotted the orientation of the long axes of apparent dropstones from the "Squantum Tillite" in the vicinity of section 4 (Fig. 5), and found that the clast orientations exhibited an axial fabric in the form of a horizontal girdle (randomly oriented within a plane) suggesting that the lone-stone were likely to be dropstones deposited in quiet water, and subsequently unmodified by currents. Our field observations reveal that a significant number of dropstones are oriented with

their intermediate axes, and some with their long axes, perpendicular to bedding planes and projecting above the bed, draped over by laminated siltstones and sandstones.

In the latter case it can be demonstrated, from the standpoint of flow behavior (Lowe, 1982), that isolated clasts (lonestones) are rarely, if ever, likely to owe their origin to emplacement by debris flows (see Socci and Smith, in press; for a discussion of debris flow mechanics and dropstones).

The mechanisms proposed by Bailey (1984; pers. comm., 1986) to explain the presence of lone clasts in the Boston Basin by means other than having been released from melting ice, are not supported by field observations, laboratory studies, or theory. More importantly, these proposed mechanisms cannot account for the disruption of bedding associated with each of these clasts. Dropstone fabrics within the Boston Bay Group reflect the entire spectrum of dropstone fabrics found in Pleistocene subaqueous and submarine glacial deposits (see Thomas and Connell, 1985; for a review of Recent dropstone fabrics). Furthermore, we maintain that the sum of the evidence cited above formulates a compelling argument for late Precambrian glaciation in the Boston Basin.

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