FIELD GUIDE TO SEDIMENTOLOGY OF THE EDIACARAN ROXBURY CONGLOMERATE, BOSTON BAY GROUP OF EASTERN MASSACHUSETTS

By

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INTRODUCTION

Squantum head in Quincy, Massachusetts displays what is arguably one of the best known, most visited, and most frequently re-interpreted geological localities in southern New England. Its fame rests primarily on the spectacular exposure of the Squantum"tillite", a heterogeneous sequence of interbedded diamictite, mudstone, and sandstone. Detailed study of the geology of Squantum head began with R. W. Sayles in 1914 and continues to the present day (Bailey and others, 1976; Bailey, 1987; Bailey and Bland, 2001; Carto and Eyles, 2012; Bailey and Galli, 2015a, 2015b). Dick Bailey first visited Squantum in 1972 and Ken Galli, then an undergraduate at Northeastern University, began working with Bailey on the sedimentology of the Boston Bay Group in 1977. We are still at it! Many previous workers, most cited in the references above, visited and studied Squantum and Boston Basin geology for a relatively short time and therefore had to work relatively quickly. This in no way diminishes their considerable efforts and contributions; however, almost all earlier mapping and interpretations, including ours, can be improved with more detailed fieldwork. Our ideas and interpretations have also changed over nearly half a century as sedimentologic knowledge expanded, especially in our understanding of the mechanisms of formation and emplacement of sediment gravity mass flow deposits. We also know much more about the age, stratigraphy, and regional relationships of the Boston Bay Group thanks to nearly 30 years of mapping and geochronological work by Margaret Thompson (Thompson, M.D and others, 2014; Thompson, 2017) of Wellesley College. On this trip we focus on the sedimentology of the Roxbury Conglomerate.

The first two stops on the Squantum peninsula in Quincy, MA permit examination of diamictites and various facies in the Squantum Member of the Roxbury Conglomerate, including portions of interbedded strata mapped as the Cambridge Formation. The third locality to be visited in the Webster Conservation Area in Newton, MA displays conglomerates and sandstones of the Bookline Member. Exposures in these areas are among the best in the Boston basin for gaining an appreciation of the variety of lithologies and facies relationships used to interpret sedimentologic processes and possible environments of depositon.

BOSTON BAY GROUP

The Boston Bay Group consists of about 6 km of clastic sedimentary rocks and interbedded mafic lava flows preserved in a deeply eroded, folded and faulted basin bounded on the northern and southern margins by overthrust basement blocks (Fig. 1). In Billings (1976) traditional stratigraphy, coarser clastics of the Roxbury Conglomerate are comprised of the Brookline, Dorchester, and Squantum Members which are overlain and partially interbedded with mudstones and sandstones of the Cambridge (argillite) Formation. Thompson, M.D. and others (2014) and Thompson, M.D. (2017) remapped portions of the Boston basin and proposed changes in nomenclature and interpretations of portions of the basin stratigraphy. These changes do not affect interpretations of stratigraphy and sedimentology in the Brookline and Squantum outcrops to be visited on this trip. More details on the geology of the Boston Bay Group and on facies and stratigraphy are given in Bailey and Bland (2001), Thompson, M.D. and others (2014), and in Thompson, P.J. and others (2014).

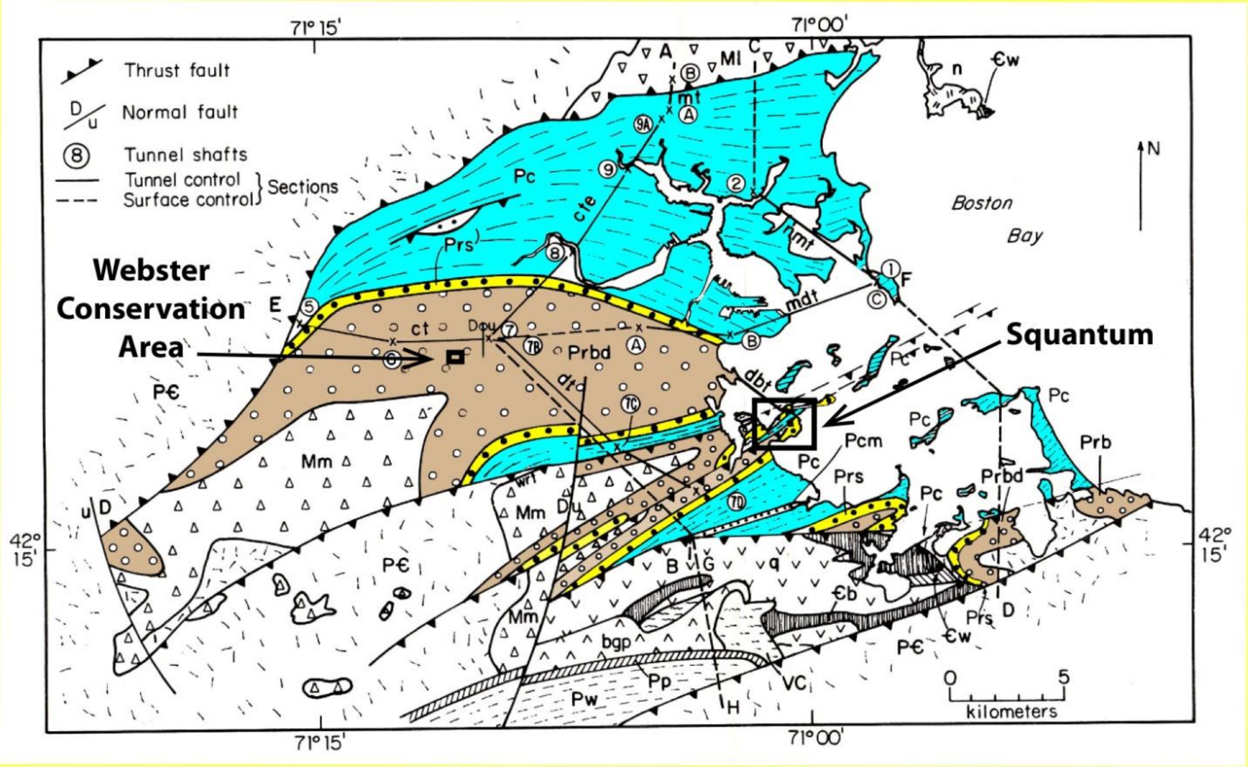


Figure 1. Geologic map of the Boston Basin and adjacent areas of eastern Massachusetts from Billings, 1976. Although many aspects of the map have been modified with recent mapping and reinterpretation, Billings map still gives a good regional representation of the Boston Bay Group strata. Tan = Roxbury Conglomerate, Yellow = Squantum Member and older diamictite horizons mapped as correlative with the Squantum Member, Blue = Cambridge Formation and older fine grained facies mapped as Cambridge Formation.

DEPOSITIONAL MODELS AND BASIN SETTING

Very coarse clastics, immature sandstones, and abrupt lithosomal changes within the Boston Bay Group are best explained by deposition in a rapidly subsiding, fault bounded basin flanked by substantial highlands (Fig. 3). Clast and grain sizes are generally coarser in more southerly portions of the basin, and paleocurrent (cross bedding, ripples, clast fabrics) and paleoslope (slump folds) indicators record a generally northerly (modern orientation) transport and paleoslope direction. Geochemistry of underlying plutonic and volcanic rocks, and of the interbedded Brighton volcanics, is compatable with a rift or wrench basin formed in the late stages of development of a subduction/magmatic arc system associated with continental basement (Cardoza and others, 1990; Thompson, 1993; Thompson and others, 1996; Thompson, M.D. and others, 2014). Rifting of an arc massif or proximal back-arc basin could produce a marine basin with high rates of subsidence and a rugged, upland sediment source area. Conglomerate clast lithologies and sandstone framework grain types indicate that granitic and volcanic bedrock currently comprising the Boston Avalon terrane was rapidly eroded and transported a short distance to the basin margin. Overall, strata of the Boston Bay Group exhibit a complex retrogradational and deepening pattern. Proximal conglomeratic facies grade up into more sandstone and mudstone-rich facies which are in turn overlain by various types of thinly laminated, muddy distal facies. Glaciation has often been considered to have been an important in direct deposition of the Boston Bay Group; however, there is a marked lack of evidence for such processes (Sayles, 1914; Socci and Smith, 1990; Carto and Eyles, 2012). Rare dropstone-like outsized clasts are present in some local facies associated with conglomerates and mass flow deposits; however, they are not present in most (virtually all) fine-grained facies many reports to the contrary notwithstanding. Although evidence for direct glacial input into the Boston basin is in our opinion lacking, it is certainly possible that both regional and global glacial affects may have influenced deposition. While there is no evidence for sub-areal or submarine glacial deposition in the preserved basin, ice caps or mountain glaciers in adjacent source areas could have moved coarse clastics into fluvial or coastal areas where they were transported farther into the basin by fluvial, coastal and shelf currents, and submarine gravity mass flow processes. Current isotopic dates for part of the Roxbury Conglomerate (ca. 580 to 585) are close to the dates for the Gaskier glacial deposits in Newfoundland and approximately coeval with similar age deposits on other continents (Eyles and Eyles, 1989; Eyles and Janusczak, 2004). Even if there was no direct affect of ice transport of sediment into the basin it is very likely that major glacioeustatic changes in sea level affected development of depositional sequences, especially those containing thick compound diamictite strata.

In Neogene and Quaternary sedimentary basins major sea level lowstands, often coincident with glacial advances, result in slope collapse and direct delivery of coarse clastics to and beyond the shelf break (Pickering and Hiscott, 2016, and many references therein). During prolonged lowstands, failure of basin margins and submarine slopes and subsequent gravity mass flow of sediment of all sizes is recorded in dramatic development of slump folded intervals, olistostromes, debrites (diamictites), and various sorts of turbidites and other mass flow deposits within more distal parts of a sedimentary basin. Much of the sediment transport is in slope channels and canyons that deliver sediment to the toe of the slope or the deep basin and submarine fans (Pickering and Hiscott, 2016). Our current hypothesis for the diamictites and associated facies at Squantum is summarized in Figures 2 and 3. Evidence to test this hypothesis is discussed in more detail in the stop descriptions and figures.

During sea level highstands, delivery of coarse clastics to the outer shelf and beyond the shelf break is much diminished because sands and conglomerates are concentrated in more proximal areas of the source area, fan deltas, and coastal regions. Finer sand, silt and clay will be bypassed to deeper parts of the shelf and slope by coastal and gravity flows. Thick unstable sequences of fine clastics accumulated on slopes are often deformed by slumping and often the slumps translated into intraclast rich debris flows, sediment rich gravity flows and very thin distal turbidity flows. The Cambridge Formation, including the fine grained facies to be seen on this trip, is dominated by very thinly laminated mudstone and sandstone with common slump folds and intraclastic debrite horizons. An array of sedimentary structures attests to these slope and deep basin processes (Bailey in Thompson, P.J. and others, 2014).

Outcrops at Squantum generally confirm this hypothesized mechanism. Diamictite sequences begin abruptly and overlie highly deformed and channeled basal contacts. As sea level gradually rose, mass flow transport diminished producing thinner and finer debrites and associated facies. Debrites give way to thick mudstone sequences during the subsequent sea level highstand which persist until the next fall in sea level perturbs the outer shelf and slope and reactivates the mass flow mechanisms. It is also true that tectonism in the source area and basin subsidence will play an important role in the basin history but sea level changes operate on a scale that seems to be of the right temporal magnitude for the Squantum succession.

Some workers (Dott, 1961; Socci and Smith, 1990; Smith and Socci, 1990) considered Billings (1929, 1976) use of the Squantum Member in correlation and mapping the Boston Bay Group to be problematic. They stated that diamictites were common and widely distributed in the Boston Bay Group therefore they had little or no chronostratigraphic significance (Dott, 1961). This is to some degree correct; however, large scale diamictite sequences, like those at Squantum, MA are not common in the Boston basin and in certain areas, as around the central anticline (Fig 1), they can be correlated. In our view Billings (1926, 1976) incorrectly correlated diamictites along the southern margin of the basin, especially those in Hingham, Ma and some nearby areas with those farther to the north. His oft reproduced reconstructed cross section of the Boston Bay Group shows a single diamictite member at the top of the Roxbury Conglomerate. Detailed mapping suggests this interpretation requires revision. Diamictites horizons would have a degree of chronostratigraphic significance if they formed during the same sea level cycle. There would be considerable facies variation in the diamictite bearing successions but a general horizon would be approximately time equivalent. This is essentially the concept that underlies our modern ideas of sequence stratigraphy.

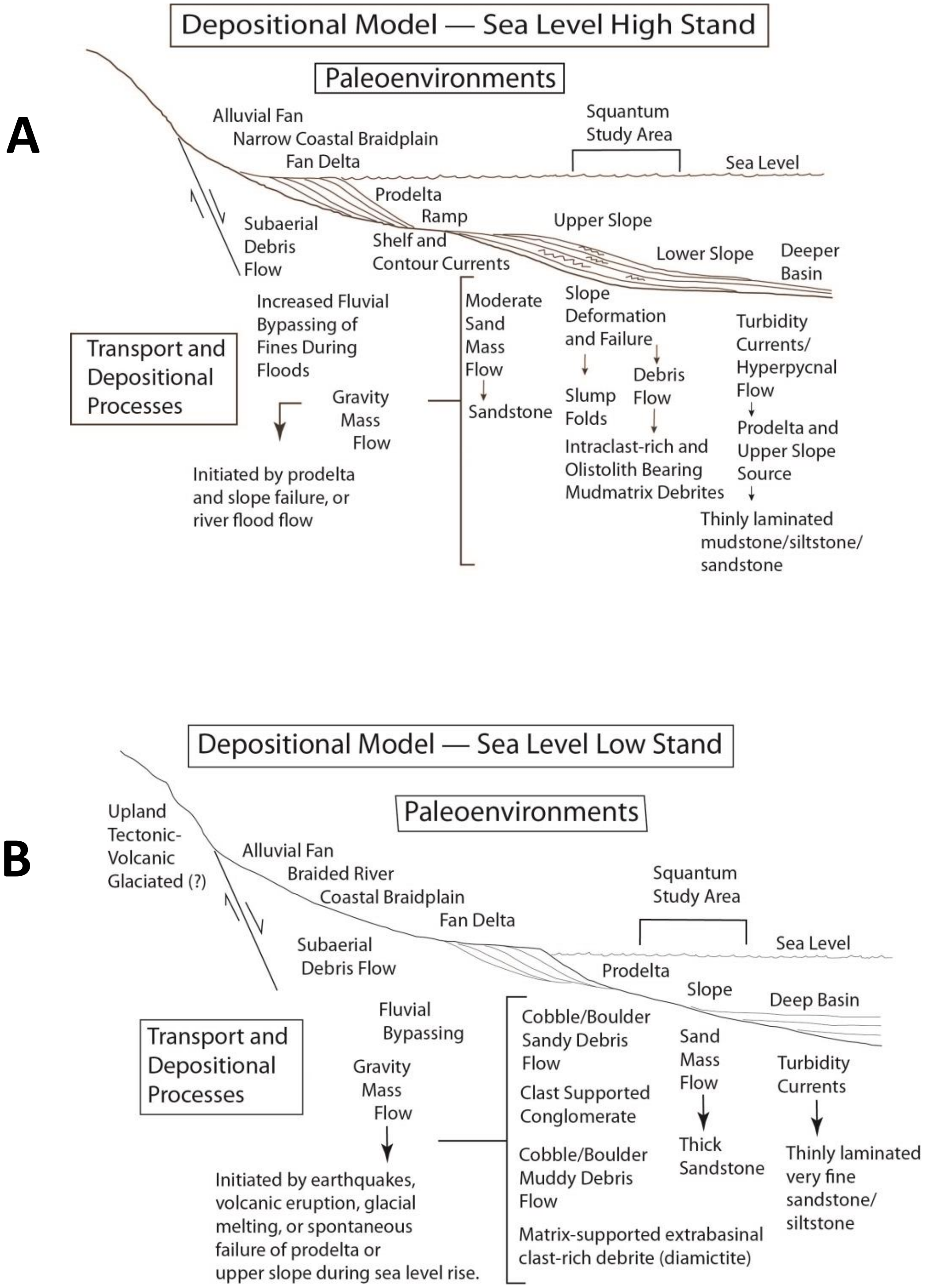


Figure 2. Depositional process models for facies associated with Squantum diamictites at Squantum, Ma. A. During sea level highstand coarser clastics are deposited closer to coast as alluvial fans or fan deltas or on a gravelly shelf. Muddy slopes are deformed and slump folded and slope failure yields mudstone intraclastic conglomerates. Deeper portions of the slope and basin receive sediment transported as sandy turbidity currents and very dilute silt/clay rich turbidites initiated on the slope or as hyperpycnal flows. B. During lowstand gravelly shelf deposits fail producing cobble/boulder bearing debris flows. These flows incorporate mud and sand intraclasts and olistoliths from slope or channel margins. Coarse clastics are transported by rivers directly to shelf break.

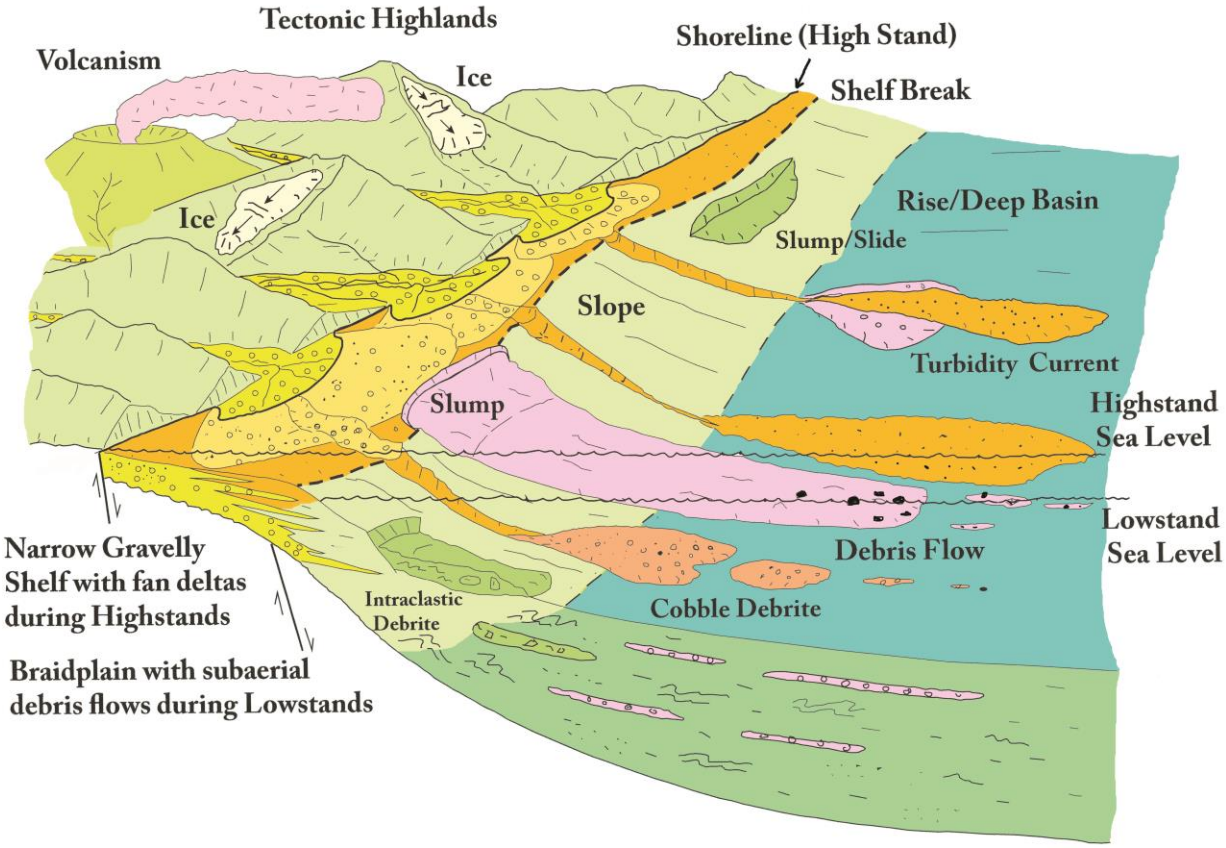


Figure 3. Highly schematic reconstruction of the Boston Basin during deposition of the Squantum style diamictites and associated facies (from Bailey and Galli, 2015a). In such a rugged basin a major fall in sea level exposes shelf and upper slope deposits and destabilizes portions of the outer shelf and upper slope. Rivers incise into the exposed shelf and upper slope and deliver coarse clastics directly into the deeper basin by an array of sediment gravity mass flow transport mechanisms. Not all facies illustrated in this diagram will be seen on this field trip. Note that this reconstruction is not appropriate for early and later stages in the evolution of the Boston basin (see Bailey and Bland, 2001 for a more complete hypothetical sequence of Boston basin tectonic evolution).

TRIP STOPS AND DESCRIPTIONS

Brief driving instructions are given for the three field stops to be visited on this trip. Nearby street addresses and lat-long coordinates permit easy location with a gps device. Note that the street addresses are near parking areas and are not the actual parking spots. See detailed instructions for stops. Stops 1 and 2 are best visited at or near low tide for complete access to rocks, but portions of all stops can be seen even at high tide. All stops are on public property and may be visited during daylight hours. Stop 3 is a conservation area and collecting is not permitted. Collecting directly from outcrops at Stops 1 and 2 is discouraged as many educational groups use these localities for study. At stops 1 and 2 there are ample specimens as rubble and loose blocks. There are no public bathrooms at any stops.

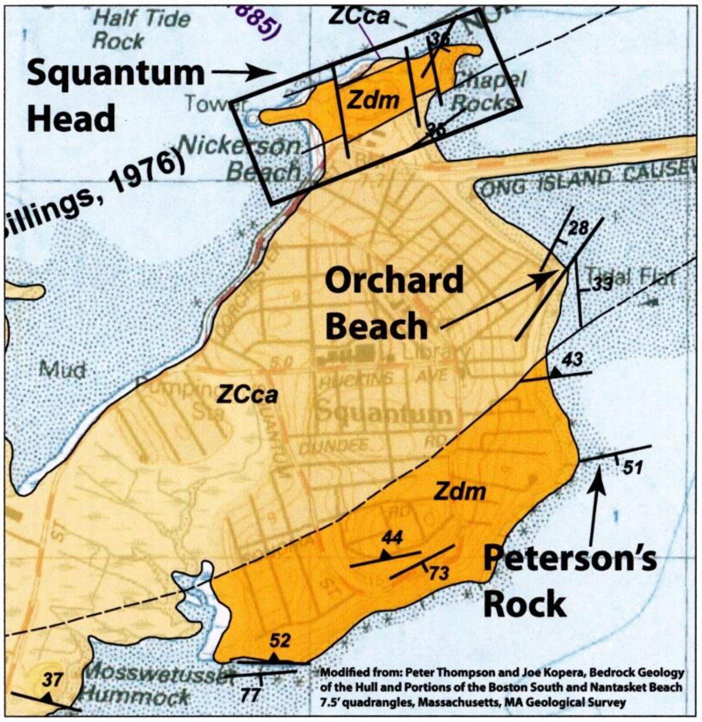
Squantum Head (Squaw Rock Park); Lat 42.302466, Long -71.011112; 20 Moon Island Road, Quincy, MA, 02171
Orchard Beach; Lat 42.298852, Long -71.005861; 105 Bayside Road, Quincy, MA 02171
Webster Conservation Area; Lat 42.330490, Long -71.179778; 492 Hammond Pond Parkway, Newton, MA, 02459

STOP 1. Squantum Member at Squantum Head, Quincy, MA

Directions to Stop 1. Take Exit 12 off I-93 south (southeast expressway); follow Gallivan Boulevard east under I-93 and bear right following signs for Massachusetts Route 3A to Quincy. Stay in left lane and bear left onto Quincy Shore Drive after crossing Neponset River Bridge. After 0.9mi turn left at stop light onto Squantum Street and bear left (following shoreline) onto Dorchester Street/Moon Island Road. Note if you are travelling north on I-93 take Exit-19 for Granite Avenue and follow Granite Avenue north to intersection with Gallivan Boulevard; at stoplight turn right onto Gallivan Boulevard and follow instructions above. Just before causeway turn left through gate into Veterans of Foreign Wars post parking area. Follow trails north and then west along shoreline to outcrop A, Fig. 5.

Stop 1. The pennisula of Squantum (Fig 4) is underlain by approximately 1 km of strata striking generally to the northeast and dipping about 40 to 70 degrees to the southeast. The lower 100 m or so of the section are comprised of the diamictite at Squantum head. The lower diamictite has a scoured and deformed transition with underlying sandstone and mudstone, mapped as the Dorchester Member of the Roxbury Formation. The upward transition into overlying sandstone and mudstone mapped as the Cambridge Argillite occurs as a series of diamictite and pebbly mudstone beds that give way to a purplish gray mudstone and siltstone. About 600 m of Cambridge mudstone underlie much of the rest of Squantum pennisula although it is very poorly exposed. Outcrops of a younger diamictite occur intermittently along the south shore of the penninsula and in sparse outcrops in the neighborhoods on the south and southeast facing slopes. The lower and upper contacts of this heterolithic diamictite are not exposed, however outcrop width indicates that it is at least 280 m thick.

The rocky headland jutting into Quincy Bay, known as Squantum head, exposes a heterolithic sequence dominated by about 90 m of an amalgamated diamictite sequence mapped as the Squantum Member of the Roxbury Formation as well as underlying sandstones and overlying mudstones. Strata along the headland strike NE and dip about 45^{o} S. A prominent cleavage, striking NE and dipping 60 to 70^{o} to the north, is well expressed in all rock units.



Modified from: Peter Thompson and Joe Kopera, Bedrock Geology of the Hull and Portions of the Boston South and Nantasket Beach 7.5' quadrangles, Massachusetts, MA Geological Survey

Figure 4. Geologic Map of Squantum Penninsula from Thompson and Kopera, 2011

Legend
Zdm = Squantum diamictite
ZCca = Cambridge Formation

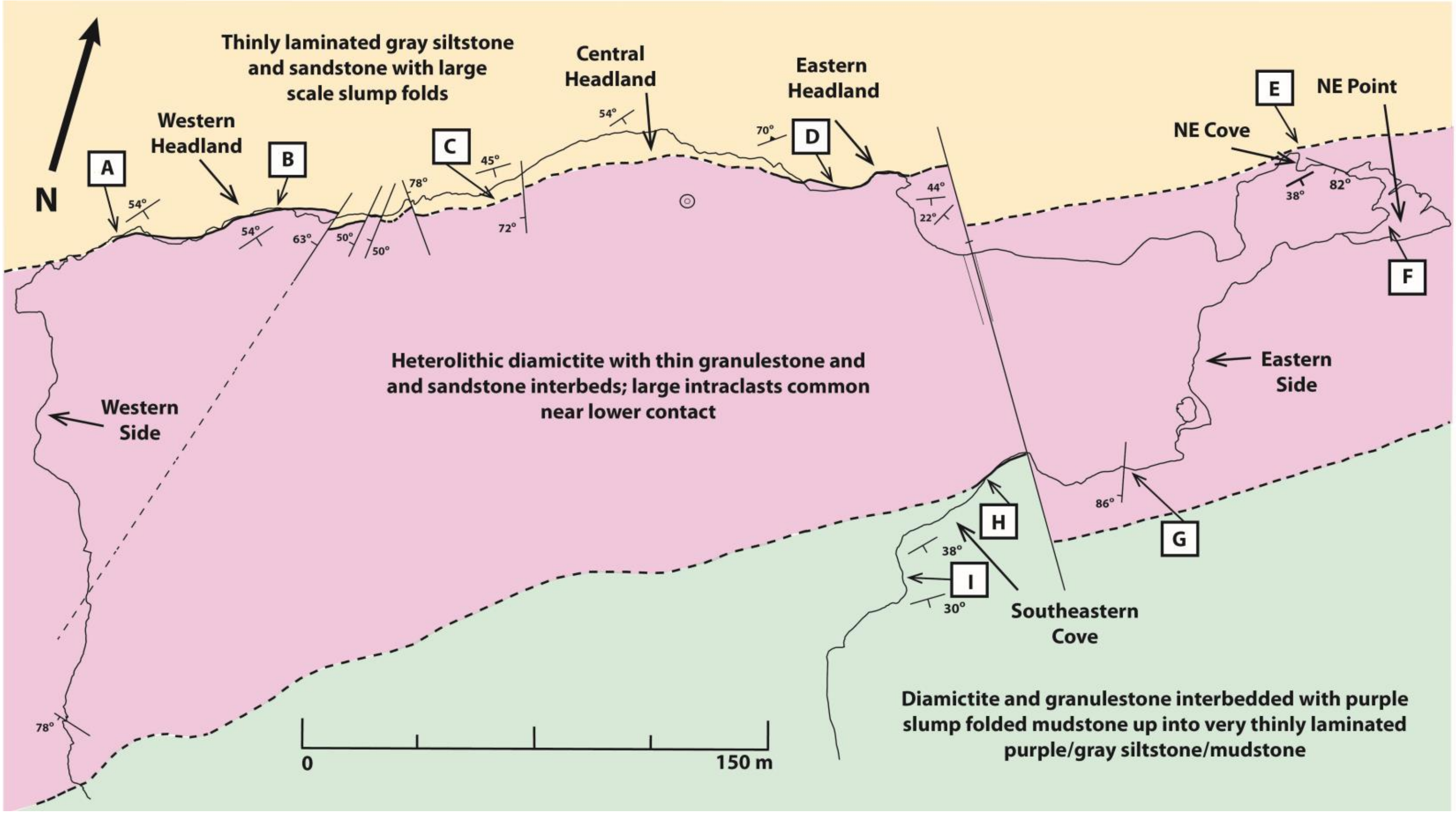


Figure 5. Geologic map of Squantum Head showing faults with dip direction and dip amount on fault trace and major stratigraphic contacts as heavy and dashed lines. Names refer to parts of the headline referred to in text and numbered boxes are locations discussed in detail and shown in illustrations.

Outcrop A. At the beginning of the western headland a portion of the basal contact of the main diamictite sequence is visible. The base of the diamictite is highly irregular and loaded onto and injected into the underlying deformed mudstone. A wide array of rounded cobbles and boulders as well as large ragged edged sandstone/mudstone intraclasts are present in the mudstone at the base of the diamictite. We interprete the sedimentary structures and proximal clast assemblage to represent a debris flow initiated higher on a submarine slope that overran and incorporated slope mud. The lack of grading or any other clear bedding in the debrite is indicative of a moderately plastic flow capable of supporting and transporting but not entirely disrupting unconsolidated sandstone and mudstone clasts; however, the precise rheology of the flow is difficult to estimate from the debrite.

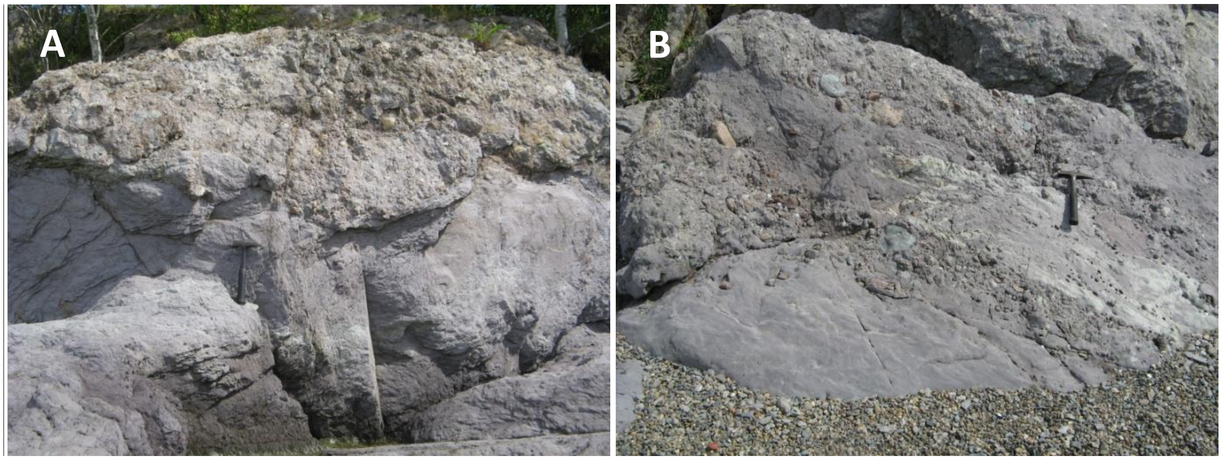


Figure 6. Field photos of outcrop A showing polymictic diamictite overlying deformed gray and purple gray mudstone (A). Chaotic pebbles and large sandstone intraclast admixed with mudstone at base of diamictite (B).

Outcrop B. The small outcrop along the eastern side of the western headland is a location that has elicited hours of discussion and debate from geologists around the world. Most of the attention is focused on the 30 to 50 cm thick thinly laminated outsized clast bed on the western side of the outcrop (yellow bed in stratigraphic panel in Fig. 7). When we returned to field work at Squantum this spring and early summer (2018) we noted that many parts of the northern side of Squantum Head had been significantly altered this past winter (2017-2018) by exceptionally high tides and wave impact. Several large blocks of the cliff were dislodged, angular rubble was transported and piled at the lower part of the beach, and weaker portions of the cliff had been quarried by wave impact. Portions of the thin outsized clast bed were significantly removed to the point where a number of the most photogenic outsized clasts and sedimentary structures were lost. Do not despair as we have dozens of images of them in our archives. Fresh exposure of several faults along the headland permitted more accurate measurement of strike and dip of the fault planes and this information is incorporated in the map in Figure 5.

The base of the outcrop B is a gray mudstone/sandstone seen below the lower diamictite at outcrop A. Here the mudstone (light tan in panel) is also extremely deformed by slump and loading and masses of similar mudstone are complexly infolded into the overlying diamictite (pale blue in panel). This lower diamictite contains large granite boulders, cobbles, and pebbles of felsic volcanic lithologies, granitic and quartzite clasts as well several large sandstone intraclasts.

On the right (western) side of the outcrop (shown in blue on panel) a lenticular sequence of laminated graded sandstone and diamictite and clast supported conglomerate fills a channel shaped unit immediately below the outsized clast bed. We interprete the lenticular sequence to represent the filling of a channel scoured into the underlying diamictite and subsequently filled with gravity mass flow sand and gravel deposits. The clast supported conglomerate at the top of the channel represents a non-cohesive mass clast flow. Such deposits are found

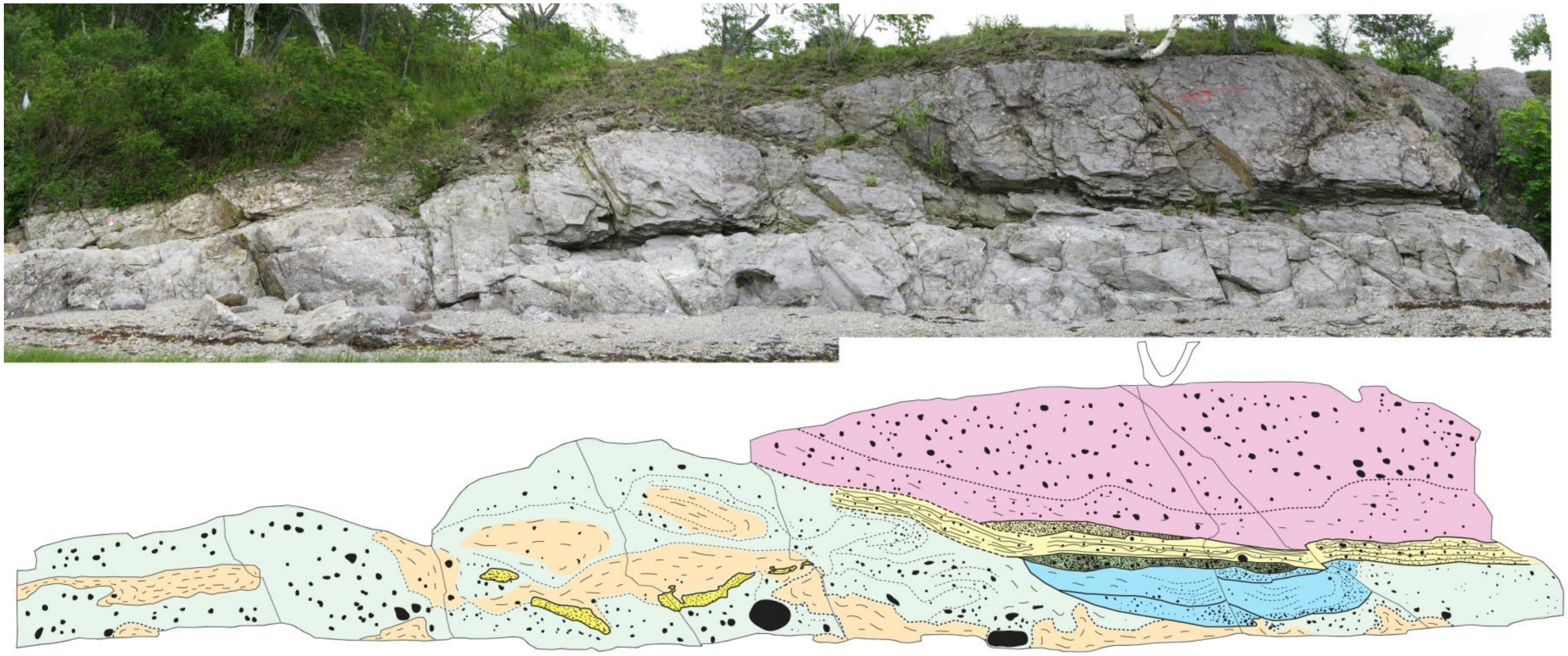


Figure 7. Outcrop B at western headland with interpreted stratigraphic panel below outcrop image. Orientation of outcrop is approximately parallel to strike of bedding. Lower contact of diamictite is highly irregular and deformed and contains boulders, large sandstone intraclasts, and irregular admixed folded mud masses. The thin yellow bed on right side of outcrop contains outsized clasts and thin graded fine sand laminations. Sedimentary structures and depositional processes are ddiscuss in detail in text.

interbedded with more typical matrix supported diamictites at Squantum and other localities. These pebble/cobble conglomerates have little fine grained matrix and clasts were probably supported by a net upward grain dispersive pressure created by intergranular vibration present during downslope transport. A characteristic feature of some of these beds is inverse grading produced by larger clasts forced preferentially to the top of the flow. These flows freeze quickly on lower slopes when downslope gradients diminish and downslope shear stress is minimal (Pickering and Hiscott, 2016). Flow transformation may occur during downslope transport due to segregation of clasts and changing rheology. Relatively matrix-free cobble/boulder flows can incorporate water and slope mud during transport and become a true plastic debris flow where clast support is provided by the high density matrix. Conversely, matrix-rich flows can become more clast rich during downslope transport as denser and larger cobbles and boulders gain momentum and velocity and move away from more matrix rich portions of the flow. Lastly, very fine sand, silt, and clay developed in the more turbulent parts of the flow, true turbidity currents, can travel away from the toe of slope and farther into the basin. While it is possible to hypothesize which mechanism of flow was most likely the cause of a mass flow deposit it is usually not possible to document the details of flow transformation and the initial condition of the flow at initiation or at different positions on the slope.

A 30 to 50 cm thick thinly bedded to thinly laminated sequence rests on the channeled units and on the lower diamictite. This laminated bed consists of thin, graded gray sandstones and very thin diamictites with larger outsized pebbles and cobbles. Some mudstones and thin diamictites in this interval exhibit small scale soft sediment folding, loading, and deformation. The outsized clasts or lonestones at this locality are often interpreted as the best dropstones in the Boston Bay Group (Socci and Smith, 1990; Smith and Socci, 1990). Despite their superficial similarity to true glacial dropstones, these outsized clasts have several features better explained by other depositional and transport mechanisms; namely, 1) outsized clasts almost all rest on scoured surfaces and within thin graded sandstones or diamictites, 2) clasts penetrate both underlying and overlying laminae suggesting that the deformation and rucking is due to differential compaction and clast rotation during dewatering and not free fall through the water column, and 3) small intraclasts within thin beds containing extrabasinal pebbles strongly indicate mass flow transport. Starting in the 1980's and continuously since, Bailey (Bailey, 1984; Bailey in Newman and others, 1993; Bailey and Bland, 2001; Bailey and Galli; 2015a, b,) argued that these clasts, although, outsized, are better explained not as dropstones, but as the result of lateral transport in very thin debris flows or as outrunner clasts just beyond the snout of the mass or debris flow or turbidity current from which they escaped (Carto and Eyles, 2012). The very thin debris flows did not originate high on the basin slope but most likely on the margins or snout of a debris flow lobe with a locally elevated and inclined surface. Remobilization of the surface of the debris flow lobe, probably adjacent to the partially exposed lenticular channel (Fig. 7), provided the gravitational impetus and the sediment and clasts to fill the local channel or depression. Further evidence for this hypothesis is seen in the geometry of the outcrop where the elevated and folded lower diamictite on the left (east) side of the outcrop appears to lift and deform the outsized clast bed. Some of this deformation could also have resulted from subsequent mobilization of the debris flow that produced the lower diamictite as it moved into the scoured channel containing the laminated bed.

The uppermost unit of outcrop B (shown in pink on the panel Fig. 7) is a somewhat homogeneous purplish gray cobble diamictite that is part of the main diamictite sequence underlying most of the headland. Clasts are dominantly angular to sub-rounded felsite volcanic lithologies and sub-rounded to well rounded granitic and quartzite (quartzarenite) cobbles and small boulders. The matrix supported texture is typical of the homogeneous diamictites in most of the Squantum outcrops.

In some prior stratigraphic sections (Sayles, 1914; Dott, 1961; Passchier and Erukanure, 2010) the diamictite exposures at outcrops A and B are shown as a separate thin diamictite horizon beneath the laminated sandstone and mudstone comprising the central headland and main diamictite sequence (Fig. 5). These sections are incorrect and the misinterpretation probably resulted from failure to note the fault to the east of outcrop B that offsets the diamictite northward so that it appears to strike beneath the laminated sandstone.

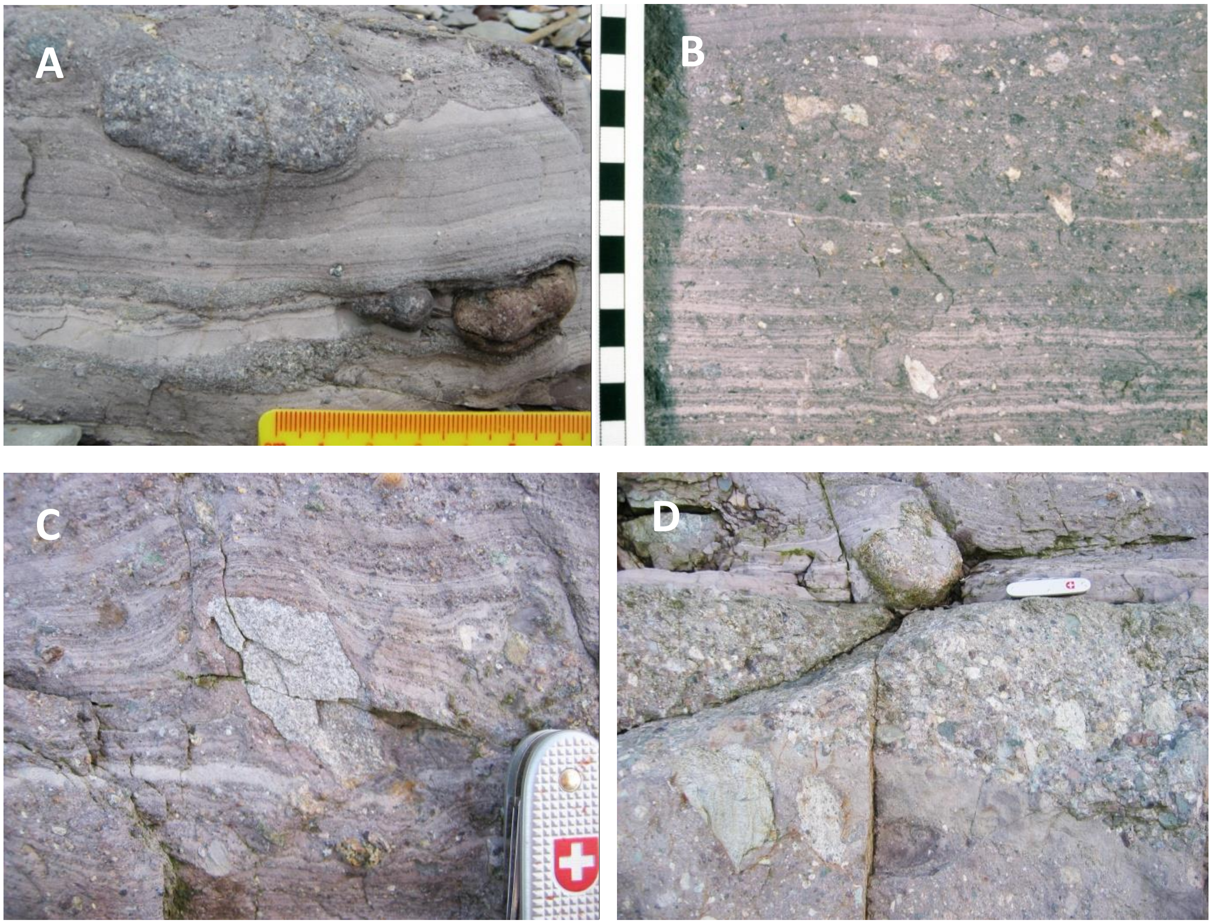


Figure 8. A, B, and C are close up photos of thinly laminated graded sandstone and diamictite beds with outsized clasts at outcrop B. The large outsized clast in A deforms underlying graded fine sandstone and mudstone. Note that this clast is contained within a very thin diamictite lamination. The cobble in D rests on the clast supported lenticular conglomerate that partially fills the upper part of the channel in Figure 7. If you inspect Figure 7 carefully you can see the clast in the photo and in the interpreted panel.

Outcrop C. Between outcrops B and D most of the cliff and wave cut bedrock terrace is comprised of very thinly laminated to thinly bedded gray sandstone, siltstone, and mudstone with abundant soft sediment folds and deformation structures ranging from 1 to 2 mm to several meters. This unit was mapped as the upper part of the Dorchester Member by Billings, 1976 and similar fine grained facies are present at a number of localities in the Boston basin.

Lamination results from numerous very fine graded sandstone/mudstone couplets**.** In sandier lamina very faint graded bedding is evident and the graded sandstone rests on a scoured surface that often truncates small scale soft sediment folds (Fig 9, A). The lamination and grading evident on the weathered outcrop is often extremely difficult to discern when viewed in thin section. We interpret this sequence to represent a lower slope or toe of slope environment where background sedimentation consisted of small scale, low energy turbidity currents probably sourced from the slope. The thinly laminated mudstones might also have resulted from numerous hyperpychnal density flows caused by river flood or shelf storm events.

The overall appearance of the outcrop suggests a rhythmic or regular episodicity to the deposition, but work under way suggests that these and similar laminated deposits do not contain a regular periodicity. Small scale sedimentary structures include soft sediment faulting and folding, thin intraclast-rich debrites, and injection, load, and flame structures (Fig. 9, B, C). Sand-rich portions of the section contain rare trough-like scour and fill structures (Fig. 9, D). Very rare small scale cross lamination is found in a few thin sand laminae.

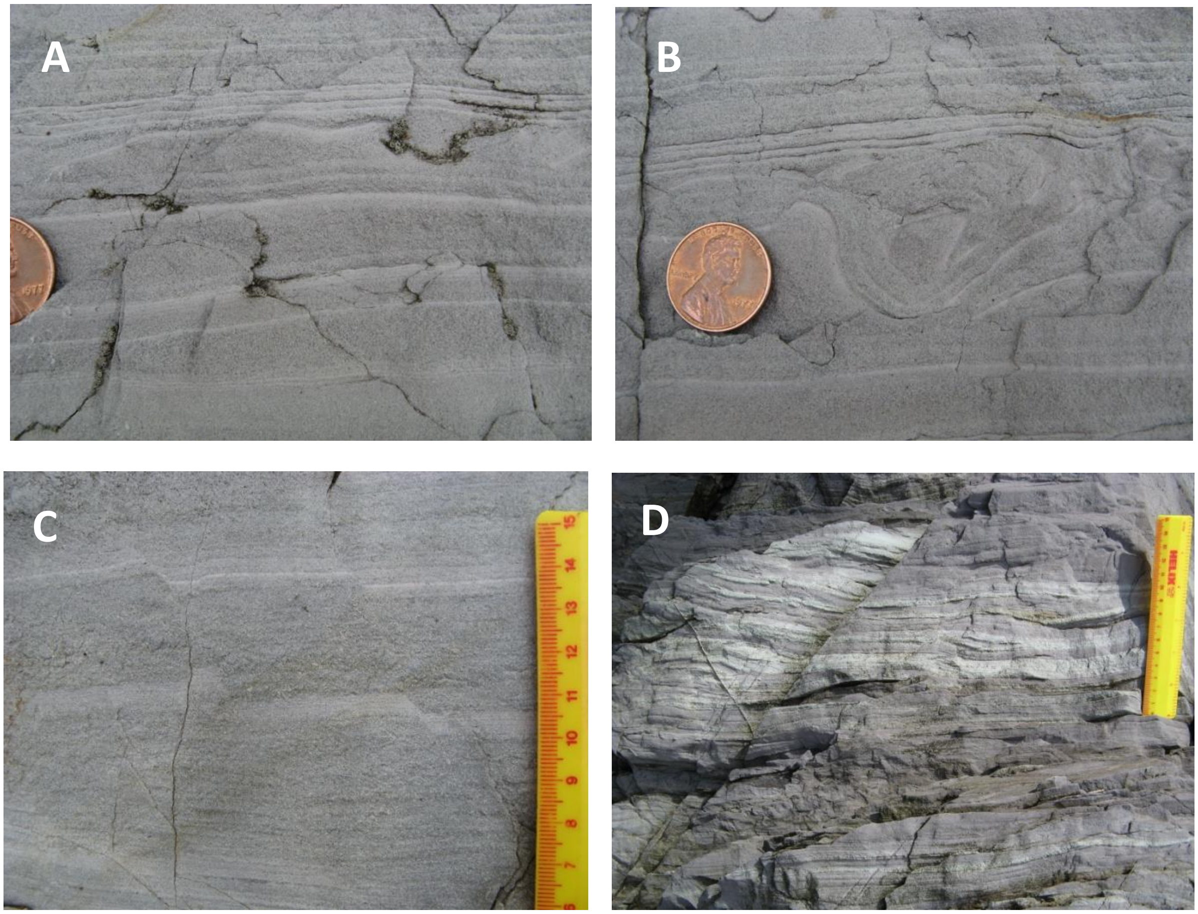


Figure 9. Small scale sedimentary structures at locality C. A. Graded couplets with very fine sand/silt grading up to very thin silt/clay couplet. B. Small intrastratal slump fold and debrite. C. soft sediment intrastratal faults. D. trough-like lenticular scour and fill structures in sandstone laminae.

Of particular note are very large outcrop-scale slump folded and deformed horizons that contort most of outcrop C (Fig. 10). This portion of the section contains large anticlinal and synclinal folds that can be traced laterally to the west into a debrite with large folded and disrupted mudstone intraclasts. This deformed unit rests on a planar sliding surface suggesting that large portions of the thinly laminated facies may have been translocated down the paleoslope as coherent glide blocks (Fig. 10). A prominent cleavage strikes to the northeast, approximately parallel to bedding, and dips about 70º to the north. In weathered portions of the exposure, where the cleavage is well expressed, it is difficult to see the southeasterly dipping primary lamination.

Figure 10. Slump folded and displaced laminated sandstone/mudstone at locality C. Upper image is highlighted to illustrate deformation. Note the large recumbent anticlinal fold and possible basal sliding surface along base of the cliff. This disturbed horizon can be traced for about 10 m to the west (right); the notch in the cliff on the east side of the outcrop is a fault that truncates stratification. This fault is the one shown in Fig. 5 to the east of outcrop C.

Outcrop D. The large reentrant on the eastern headland exposes the basal contact of the main diamictite sequence with underlying mudstone/sandstone that comprises most of the central headland. The orientation of the cliff is approximately parallel to the strike of bedding. Just to the west of this reentrant the basal contact of the diamictite is along the crest of the cliff. At the western end of the cliff this basal contact drops about 4 m to beach level near the base of the cliff. In earlier mapping this downward displacement of the contact was interpreted to be the result of fault offset (Bailey, 1976; Wolfe, 1976). Bailey (1989, 2001) and many subsequent workers (Thompson and Kopera, 2011) showed a similar fault on geologic maps (Fig. 4). Several decades of erosion and recent removal of talus and shingle from the base of the cliff permitted close examination and re-evaluation of the contact. Based on careful inspection our new interpretation is that the contact displacement is primarily due to channeling and scour into underlying mudstone/sandstone. Diamictite that subsequently filled the submarine channel, abuts and is partially interbedded with the underlying unit. On the right side of the diamictite (Fig. 11), thin continuous diamictite layers and stringers from the main diamictite bed pinch laterally into the mudstone/sandstone so no fault can be present.

The contact along the base of the cliff in the reentrant is highly irregular, loaded, and deformed. Large intraclasts and blocks of underlying mudstone occur along the basal contact (Fig. 11). You can examine a dip section of the stratigraphy by carefully rounding the eastern headland and walking toward the shingle beach. The diamictite contains cobbles, boulders, and deformed intraclasts in a mudstone matrix. A coarse feldspathic litharenite interbed about 3 m thick is present near the top of the headland sections (Fig. 12, A). This homogeneous bed is best explained as a high density mass sand flow deposit. The sand in such a deposit was not transported by turbidity currents with turbulence providing grain support but rather as a highly sheared, inflated sediment gravity flow with grain support resulting from grain interaction and upward fluid flow (Pickering and Hiscott, 2016).

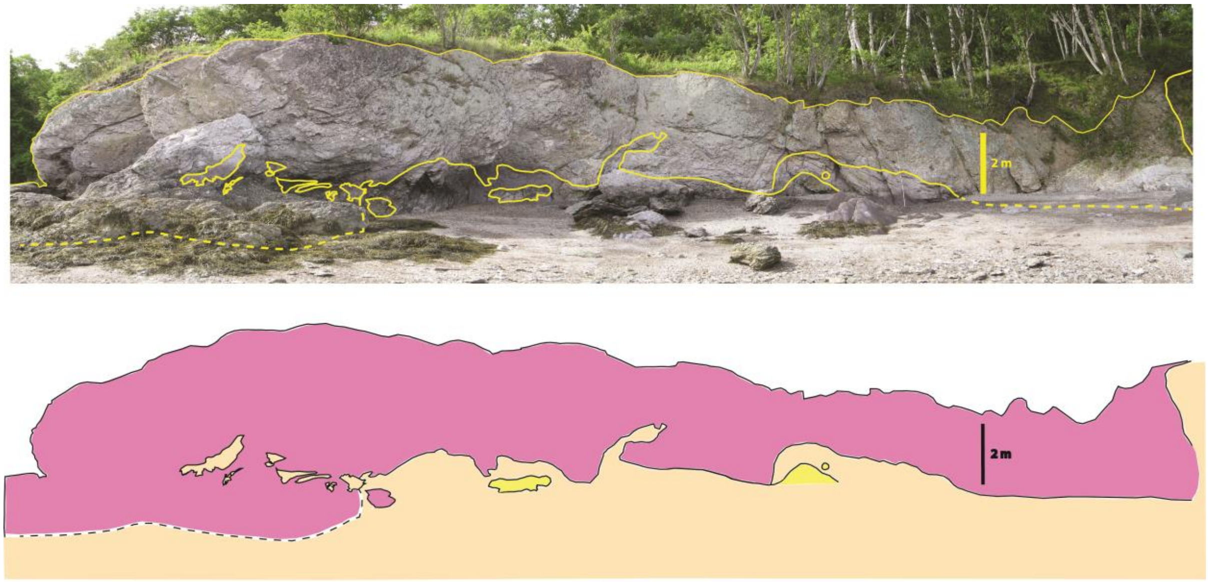


Figure 11. Outcrop D at eastern headland and cliff reentrant. Diamictite (pink) resting on highly deformed basal contact with underlying mudstone/sandstone (tan). Large intraclasts and deformed sandstone masses are shown in yellow. Note the incision into underlying rocks on west (right) side of exposure where diamictite abuts channel margin.

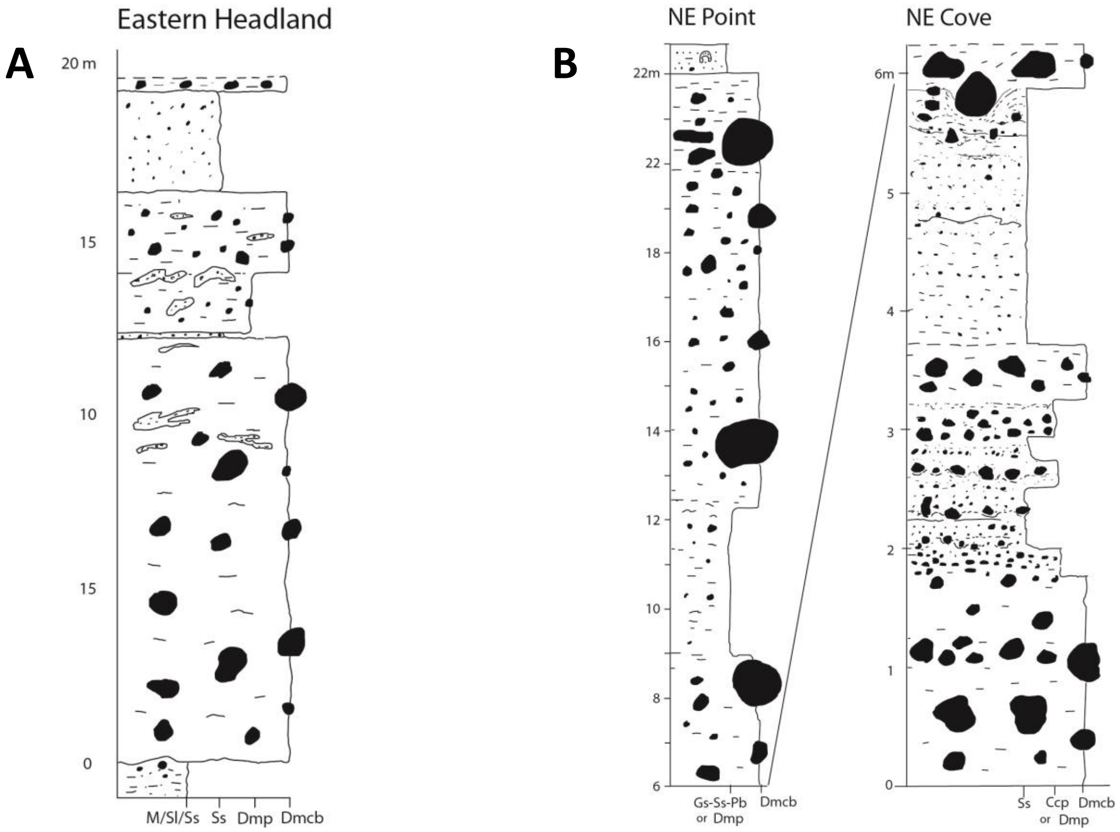


Figure 12. Stratigraphic sections at eastern headland (A) and northeast cove and northeast point (B).

Outcrops E and F. The northeast point and narrow slot-like reentrant into the cliff (northeast cove) expose a heterolithic stratigraphic sequence near the base of the main Squantum horizon (Fig. 12, B). The portion of the section in the cove between about 1.8 and 3.6 m is comprised of sand-rich, clast and matrix supported conglomerate interbedded with medium to coarse, moderately to well sorted sandstone. These rocks appear to be typical diamictite at first glance, but they have textures and bedding styles that are significantly different from typical Squantum diamictites. Similar intervals are also associated with diamictites in other parts the Boston Bay Group.

Conglomerate and sandstone beds in this interval exhibit normal or poorly developed reverse (inverse) grading. Normal grading in mass flow deposits is typically explained by segregation of coarser grains toward the base and snout of the moving sediment mass. When flow velocity diminishes the coarser grains or clasts are deposited first followed by grains of decreasing sizes (Fig. A, B). Inverse grading (Fig. 13, C) is well documented in deposits where the coarse clasts in a mass flow are supported by clast collisions and vibration resulting in a grain dispersive pressure within the flowing mass (see earlier discussion for outcrop B). In a cobble flow greatest dispersive pressure is near the base of the flow and this pressure drives larger clasts to the top of the flow while smaller clasts preferentially move nearer the base of the flow. This process has been named kinetic sieving because it is only effective when the flow is moving. When the paleoslope decreases the flow loses momentum and the flow freezes preserving the inverse clast distribution (Pickering and Hiscott, 2016). In this particular deposit possible inverse grading is subtle but much better examples occur at other localities.

The largest clasts observed in mudstone matrix supported diamictite strata at Squantum head occur at northeast point. Several subrounded 0.8 to 1.2 m granite boulders occur in the deposit and boulders in the 0.3 to 0.6 m range are common (Fig. 13, E). A 1.0 m diameter quartzite boulder was present near the base of the northeast point sequence but it was plucked from the cliff and destroyed in the early 1990's. All of the extrabasinal clasts form a rather disorganized unsorted fabric and typically lack clear bedding or clast orientation. The most common clasts are angular to subrounded felsites including flow banded rhyolite, various porphyritic felsites, and crystal and lithic tuffs all of which are typical of the Mattapan Volcanic Suite. Mafic volcanic clasts are present but are much less common. Plutonic clasts, especially medium to coarse grained Dedham Granite, are common, and well-rounded to subrounded quartzite or quartzarenite clasts similar to the Westboro Quartzite are least common (Fig 13, D). Other very rare clast lithologies have been observed and collected. Several small carbonate clasts and a few lithified (not intraclastic) sedimentary clasts have been noted. Despite nearly half a century of search we have never found any faceted and/or striated clasts typical of glacial transport.

The well rounded extrabasinal clasts strongly suggest a significant fluvial transport history before they were resedimented by sediment gravity flows. It has been suggested (Dott, 1961) that the Squantum extrabasinal clasts were derived from clast supported roundstone conglomerates of more proximal conglomeratic facies (Franklin Park and Brookline Members) of the older Roxbury Formation (Thompson, M.D. 2017). This is unlikely as there are textural differences in the conglomerates (Bailey and others, 1976). Given the stratigraphic position of the Squantum diamictites it is much more likely that the proximal facies from which Squantum clasts were derived is not preserved in the currently outcropping Boston Bay Group. The clast assemblages are similar because all of the conglomerates share the same basic source. Even though diamictite outcrops often appear homogeneous, interbedded lithosomes of mudstone, conglomerate, and sandstone demonstrate that multiple debris flows were amalgamated to produce the thicker diamictite sequence. The debris flows were rich in plastic mudstone/water matrix that provided buoyancy to support the very large clasts during transport. The mud matrix was probably incorporated quickly into the slumping or sliding material as it moved down the slope or channels eroded into the slope. Material collapsing from the margins of canyons or deep channels during a sea level low stand would start as relatively cobble or sand rich flows and become progressively more plastic as mud was admixed. Abundant sandstone and mudstone intraclasts attest to this mixing process during transport (Fig 13, F).

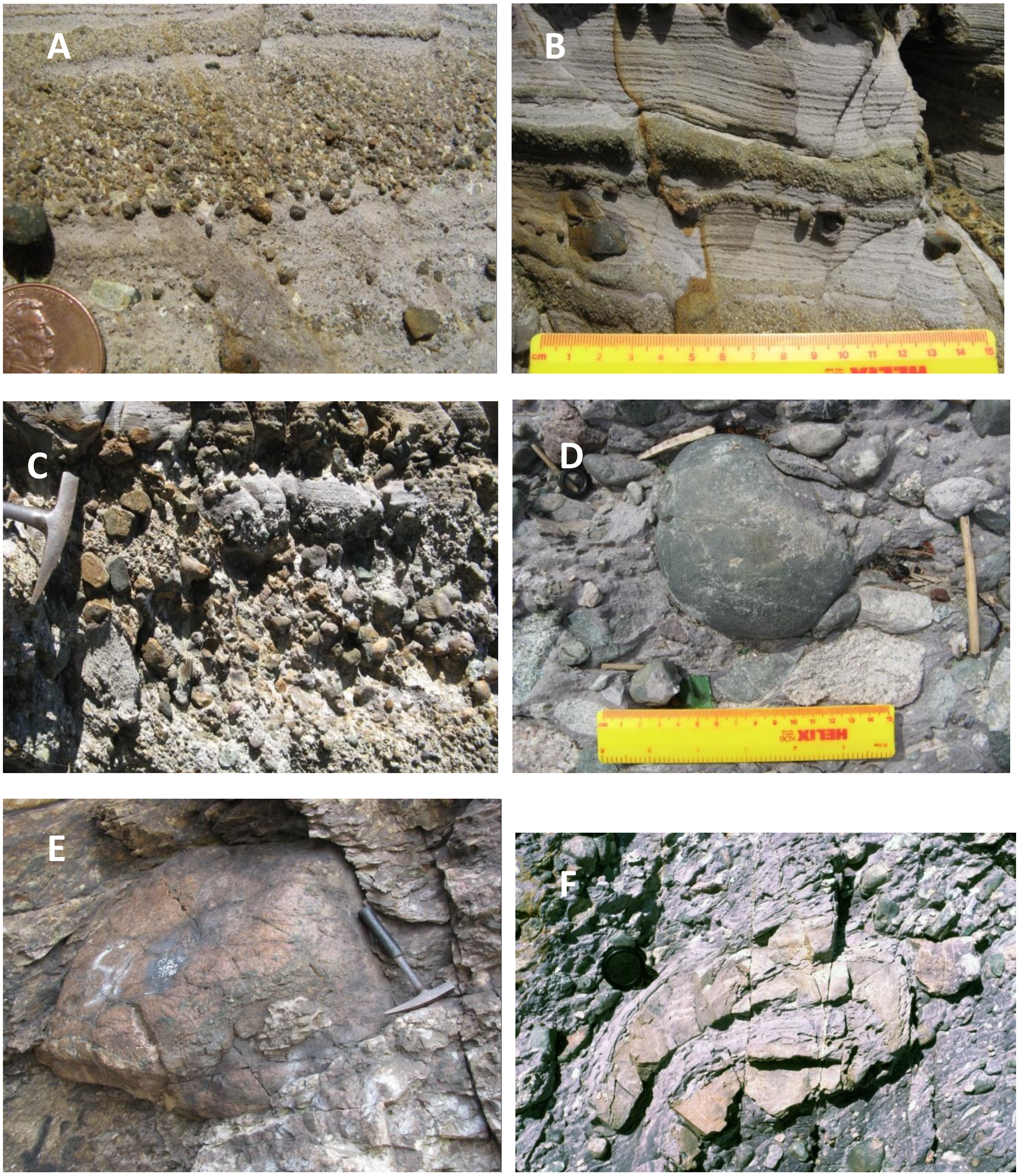


Figure 13. Images of structures and clasts on northeast point. A. Thin normally graded granulestone and coarse sandstone laminae typical of cohesionless mass flow. B. Normally graded laminated sandstone with outsized clasts resting on scour surfaces. C. Crudely stratified possibly inversely graded sand-rich mass flow conglomerate. D. Well rounded quartzite clast. E. 1.2 m diameter granite boulder in lower part of northeast point sequence. F. Folded quartzose sandstone intraclast in diamictite, upper portion of northeast point sequence, this clast is shown at the 22.5 m position in the stratigraphic section in Fig 12, B.

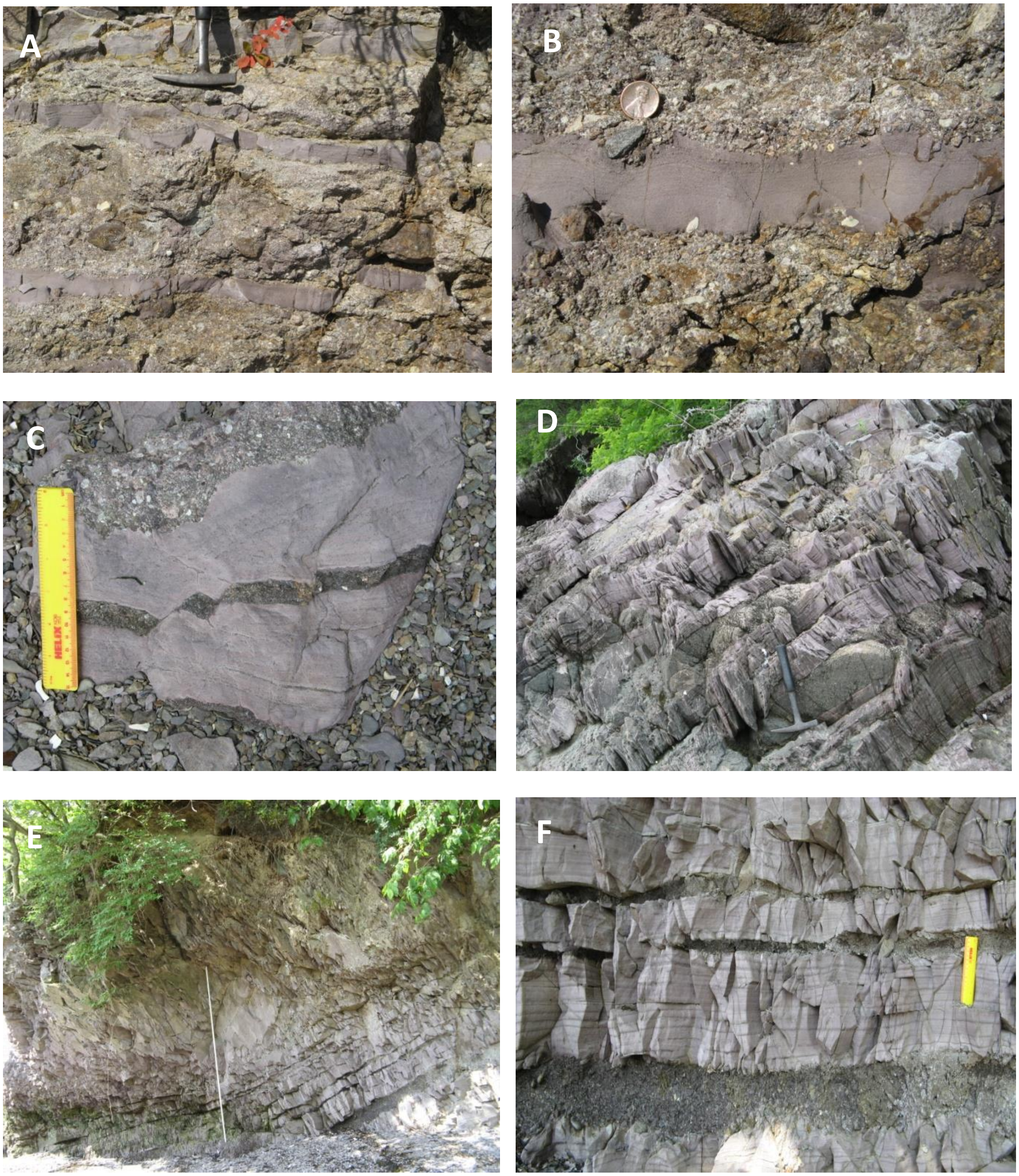


Figure 14. Images of structures at outcrops G, H, and I (southeast cove). A. Interbedded pebbly granulestone and mudstone at G. B. Detailed of mudstone bed at G, note clast forced into the plastic bed and soft sediment deformation. C. Soft sediment boudinage produced by extension of mudstone and interbedded sandstone sliding downslope, slab on beach at H. D. Folded and pillowed masses of pebbly sandstone and granulstone produced by downslope slumping and sliding at H. E. Laminated purple mudstone (locality I) and disrupted sandstone overlain by debris flow; to the right of the 1.6 m rule is a rotated mudstone intraclast. F. Laminated mudstone and highly weathered granulestone and fine debrites to right of rule in E, these beds are tilted but image is rotated to horizontal.

Outcrop G. The upper part of the diamictite sequence is similar to areas already observed and described. The modal size of clasts is somewhat smaller but boulders are present at many horizons. A fault at outcrop G offsets part of the conglomerate and an interbedded interval of 5 to 10 cm thick purple mudstones and pebbly feldspathic and lithic granulestone (Fig 14 A, B). These deformed, laminated mudstones, pebbly and cobbly diamictites, and granulestones demonstrate quiescent pauses in larger scale debris flow deposition (note interval from 60 to 61 m, Fig. 15, A). The mud and larger clasts may have sloughed into a low local basin on the surface of a debrite as small localized sediment gravity flows.

Outcrop H. The low cliff along the shoreline from G to I in southeast cove is approximately parallel to strike of bedding and the southward facing outcrops are dip slopes or cut across dip at a low oblique angle. There are no thick diamictite horizons with large boulders west of outcrop G. Purple gray mudstone is interbedded with 2 to 30 cm thick beds of feldspathic and lithic grannulestone and sandstone and pebble conglomerate. The coarser beds have been highly disrupted, folded, and extended into lenticular and pillow shaped sediment masses or boudins (Fig 14 C, D). Some of the horizons were laterally translocated to the point where they disintegrated into irregular embayed intraclasts (Fig. 15, B). Much of this sequence must have moved down the paleoslope during or shortly after or during deposition.

Outcrop I. The vertical wall at the end of southeast cove is location I. Here you can see a section approximately parallel to bed dip. Interbedded laminated mudstone and coarser beds are lenticular and disturbed (fig. 15, B). A debrite with a 1 m intraclast sits above the well bedded portion of the section (Fig. 14, E, F). The cliff around the corner from I displays the last thick debrites and diamictites in the Squantum head section. The diamictites and interbedded mudstones are highly distorted and disrupted as described above and mudstone is injected into and fragmented and incorporated within the diamictites. Dott (1961) interpreted the coarser beds in this sequence as lapilli tuffs and later workers have followed this terminology (see Carto and Eyles, 2012). Thin section and megascopic examination of these beds reveals pebbles of quartzite, granite, feldspar, and various felsite lithologies in a very coarse feldspathic arenite. No accretionary lapilli or any other sorts of airfall or reworked tephra were observed. We interprete these units as coarse immature sedimentary clastics that have been misinterpreted as tuffs because they are extremely thoroughly weathered with feldspars and unstable rock fragments altered to clays.

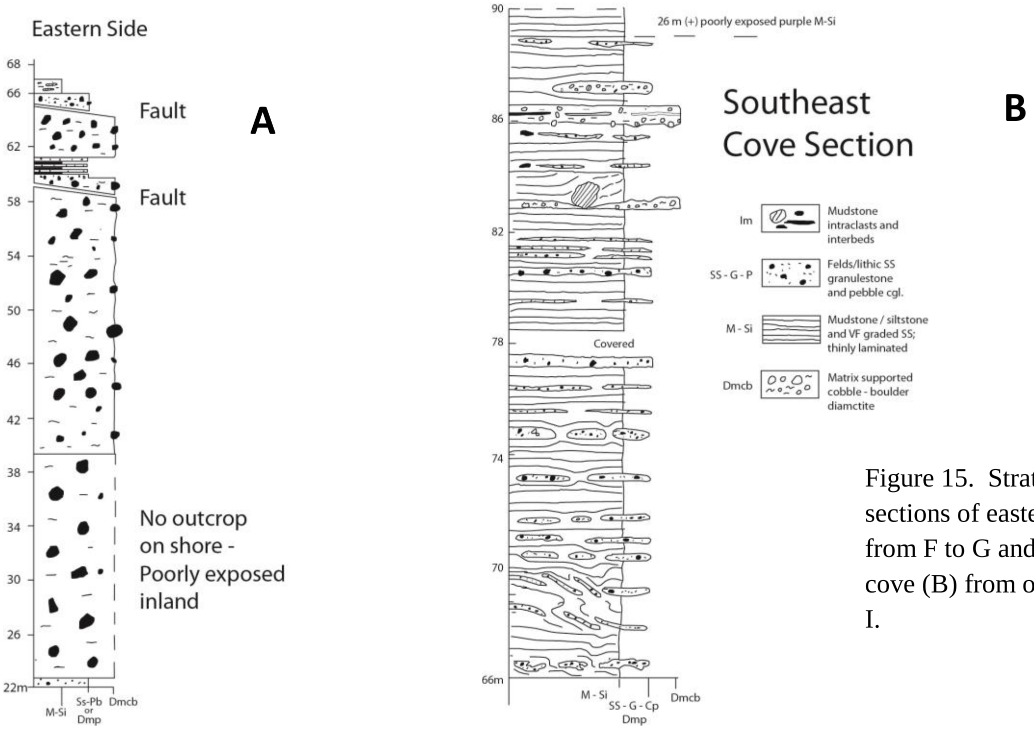


Figure 15. Stratigraphic sections of eastern side (A) from F to G and southeast cove (B) from outcrops H to I.

Stop 2. Debris flow and outcrops of Cambridge Formation at Orchard Beach, Quincy, MA

Directions to stop 2. Retrace your route back toward Quincy (turn right from the parking lot). Go 0.2 miles and turn left on Bellevue Road. After 0.6 miles turn left on Brunswick Street and follow it for 0.8 miles to the seawall. Turn right and park along the beach at the north end of the seawall. Walk to the north end of the beach, where large granite blocks are stacked, and onto the small outcrop.

STOP 2: North Orchard Beach Debris Flow and Interbedded Mudstone This small outcrop exposes a debris flow deposit or debrite about 2 to 4 m thick (fig. 16 A). The exact thickness is difficult to determine because underlying and overlying mudstone is intimately contorted into the debrite. The entire debris flow is deformed by slump folds and the orientations of several of the larger folds are shown in Figure 17. The matrix of the debrite is a grayish mudstone with patches of fine sandstone and siltstone. Intraclasts are abundant at all scales and range from small mudstone or sandstone blebs or clots to a purplish sandy mudstone olistolith several meters on a side (Fig. 16, B). About 5 m from the beginning of the outcrop there is a 1.5 m long bedded sandstone/mudstone block entirely enclosed within the matrix (Fig. 16, C). Black sandstone intraclasts with very ragged and deformed margins are very distinctive.

One intraclast (Fig. 16 D) has been identified in the literature as a stromatolite head (Passchier and Erukanure, 2010), but it is a deformed siliciclastic mudstone intraclast. Extrabasinal clasts are primarily felsites, with rare granitic and quartzite pebbles or cobbles. As you walk to the northeast corner of the outcrop near the large concrete vent, the outcrop is a distinctive purple, different from the gray matrix of the debrite. The margins of the purple block are faulted or tectonized but it seems to be a large olistolith entrained by the debris flow. As you walk northwest parallel to the shoreline you traverse about 40 m of gray thinly laminated mudstone (Fig. 16, A). Beyond the last outcrop of deformed mudstone the section is covered until you get near the top of the lower diamictite on the north side of the causeway, north of the meeting point. Please do not try to cross the causeway from the beach, as permission is required from the Boston Police Department to be on the causeway to Moon Island. Walk back south along the beach.

This debrite is different from the very coarse, clast rich diamictites present at Squantum head in that it is mostly highly deformed matrix with sparse extrabasinal clasts. Most large clasts are blocks of coherent laminated sandstone and mudstone. Smaller intraclasts are typically deformed, embayed and ragged edged indicating significant disruption during transport. The largest clasts remained relatively intact and were supported by the plastic matrix. The largest intraclast or olistolith is a large purple mudstone that has been intensively folded (Fig. 16, B and Fig. 17). This large block has the purplish gray color of some portions of the Cambridge Formation, but this is not the mudstone that immediately underlies this debrite implying a significant transport distance for the block. If sea level fall caused destabilization of the self edge and slope in the basin then perhaps this debris flow was a precursor to the much greater instability recorded by the thick overlying diamictite sequence exposed on the south side of the Squantum peninsula (Fig. 4).

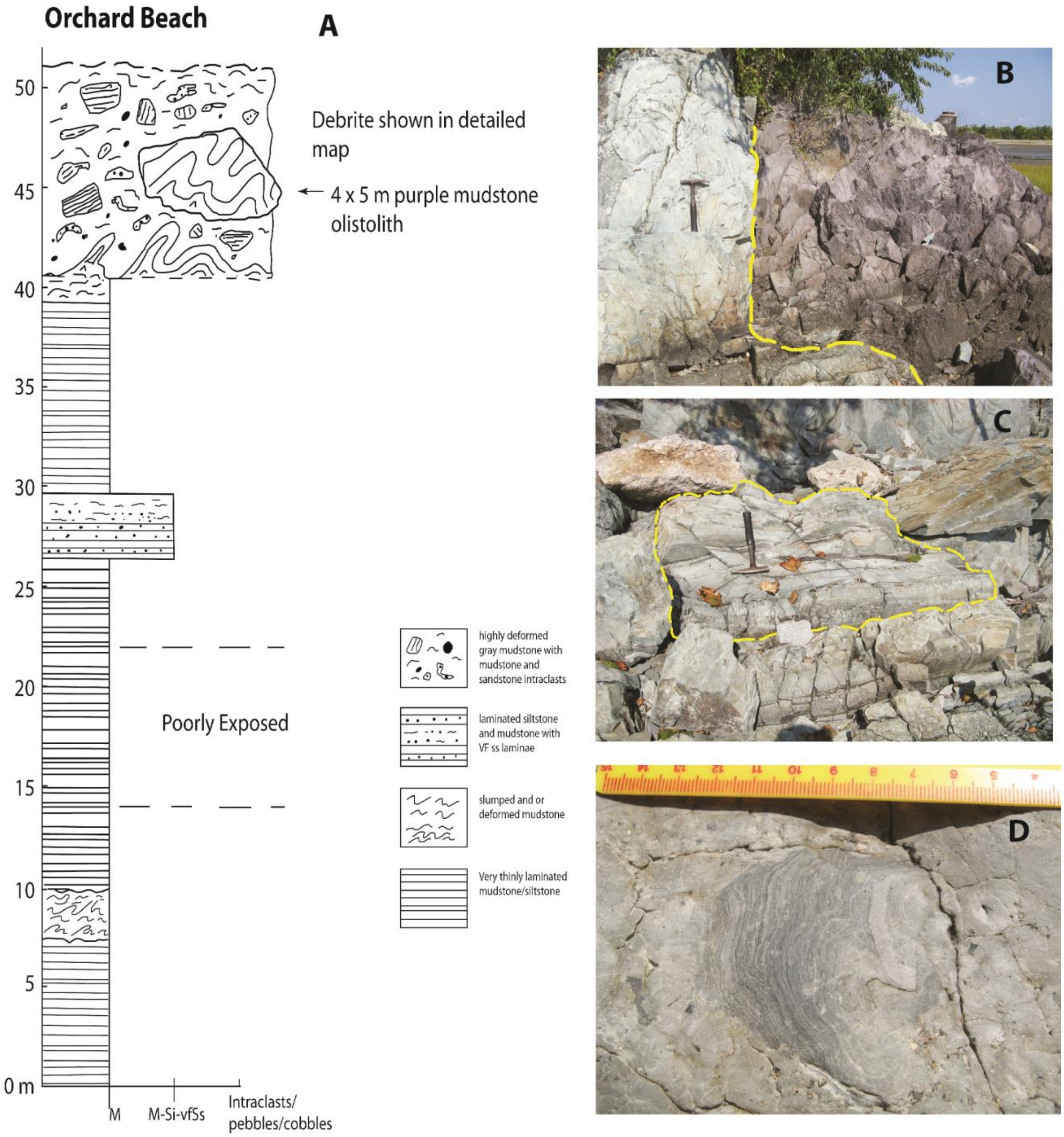


Figure 16. A. Stratigraphic section of debrite and underlying mudstone mapped as Cambridge Formation (see Fig. 4). B. Large slump folded olistolith in debrite. C. Gray mudstone/sandstone intraclast in debrite. D. thinly laminated and deformed mudstone intraclast in debrite.

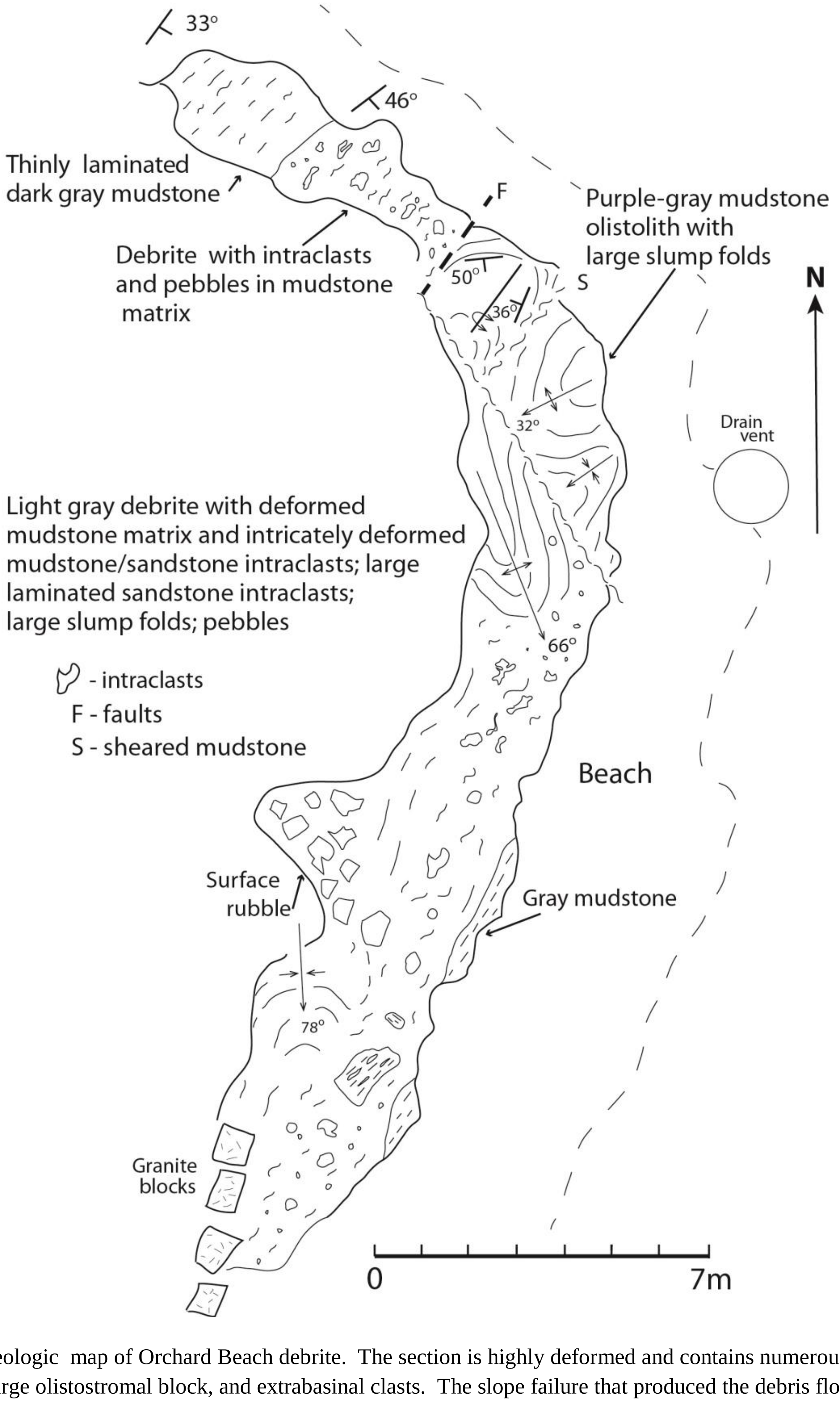


Figure 17. Geologic map of Orchard Beach debrite. The section is highly deformed and contains numerous intraclasts, a large olistostromal block, and extrabasinal clasts. The slope failure that produced the debris flow incorporated materials from both the slope and extrabasinal clast bearing deposits.

STOP 3. Roxbury Conglomerate, Brookline Member and Brighton Igneous Suite (volcanic) at Webster Conservation Area, Newton, MA

Directions to Stop 3. Drive north on Hammond Pond Parkway from Route 9 and very carefully make a u-turn just before stoplight at intersection with Beacon Street or drive south on Hammond Pond Parkway from Beacon Street and park on shoulder on west side of parkway about 200 m south of Beacon Street intersection next to sign marking trail entrance to Webster Conservation Area. Take the trail into the woods (west) and follow the right branch of the trail past the cliffs on the north (left) to the old chain link fence. Watch out for Poison Ivy and use insect repellent as necessary.

Stop 3. The geology of this location was mapped and described in detail by Rehmer and Roy (1976). Figure 18A is based in part on work by Rehmer and Roy (1976) and on unpublished work by R. H. Bailey. Part of the following discussion is modified from Bailey in Hepburn and Bailey, 1998. About 58 m of conglomerate, sandstone, siltstone and shale, as well as an interbedded basalt flow are exposed in the woods and on 3 south facing scarps in the conservation area (Fig. 18, A). Additional outcrops are directly north of Beacon Street, just west of the intersection of Beacon Street and Hammond Pond Parkway (Rehmer and Roy, 1976). We will not visit these outcrops nor are they included in the following discussion of Figure 18. Strata in the conservation area dip 25° to 35° north and strike to the W/NW.

The top of the low scarp south of the trail at the fence is the upper 7 m of a 12 m thick basalt flow (Fig. 18, A) mapped as part of the Brighton volcanics. The uppermost 2-3 m of the flow is highly vesicular and deformed siltstone inclusions are present about 3m below the top of the flow. The irregular upper contact of the flow with fine reddish sandstone is visible for about 15m along the top of the scarp. Blocks and pebbles of scoriaceous basalt up to 15 x 20 cm are incorporated into gray to reddish gray, deformed siltstones and fine sandstone (Fig 18, C). The lower contact of the flow is not exposed, but an underlying conglomerate is visible in the scarp below the trail and to the west of the fence (Fig. 18. A). Based on the lack of pillows and the nature of the upper contact, we consider this to be a subaerial lava flow; however, the paleoenvironmental setting is uncertain.

Follow the fence to the north across a bench (underlain by the upper portion of the sandstone over the basalt and an overlying conglomerate sequence) to the third scarp about 7m high at this locality. The face of the cliff to the east of the fence displays 10 to 50 cm thick beds of pebbly feldspathic litharenite and layers of small cobbles and pebbles with their maximum axes parallel to bedding. The cobble horizons clearly define bedding units and in some areas are slightly imbricated. Very faint cross bedding is present in some sets and the upper, more conglomeratic beds, have scours or troughs filled with cobble lags grading up into fine pebbly sandstone. Pebbles and cobbles are predominantly felsite, granite, and quartzite or quartzarenite.

Take the trail back to the east to the high overhanging ledge. A sandstone bed, exposed for about 45m along the face of the cliff (Fig. 18, A), has been channeled down from about 4 m to 10 cm from east to west (Fig. 18, A). Filling the incised channel and overlying the sandstone is a sequence of pebble and cobble-rich sandstones and clast-supported conglomerates. Just below the sandstone is a 2 m sequence of conglomerate, sandstone and reddish siltstone with symmetrical (oscillation?) ripples. Rippled horizons are at the top of thin sandstone beds with small scale cross lamination and are in turn draped by thin reddish mudstones. The 4 m thick sandstone is a series of amalgamated, cross-bedded, feldspathic litharenites. Sedimentary structures in the sandstones indicate north-northeast paleoflow (Fig 18, D). These sandstone beds grade upward into sandy conglomerates.

Descend back to the main trail and follow the first branching trail left (north) into an old quarry to the top of the ridge above the sandstone interval. This polymictic, clast-supported, roundstone conglomerate with a sandstone matrix has a texture and fabric typical of many Roxbury Conglomerate outcrops. Similar extensive homogeneous outcrops typically lack discernable bedding and are very difficult to interpret. A cobble fabric analysis in these beds revealed that 63% of 219 a-b planes of cobbles plunge to the south indicating a general

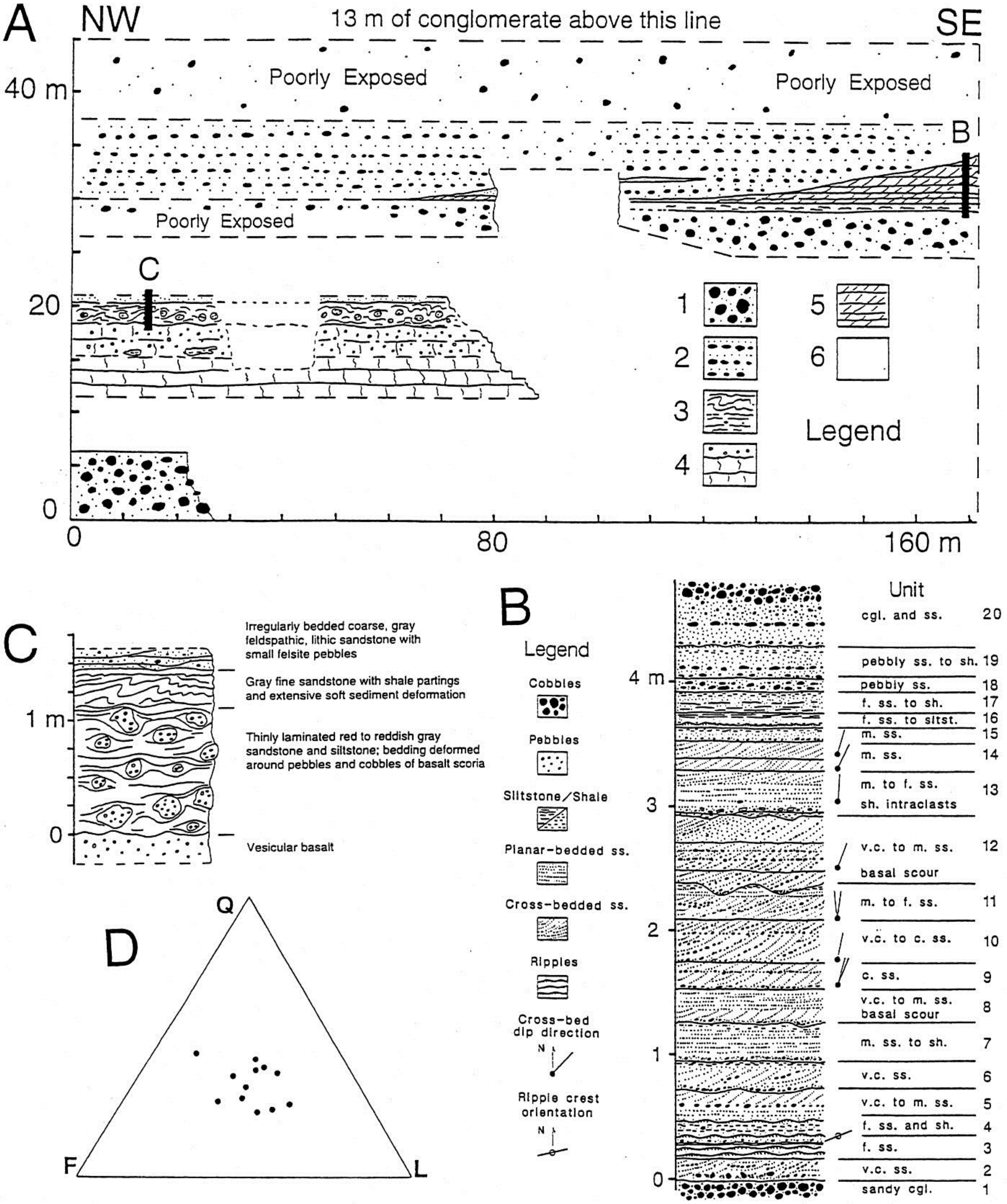


Figure 18. A. Stratigraphy of a portion of Brookline Member of Roxbury Conglomerate in Webster Conservation Area. B. Detailed stratigraphic section of sandstone bed shown at B in diagram (A) above. C. Detailed section of upper contact of basalt flow at shown at (C) in diagram above. D. Quartz, feldspar and Lithic proportions in 12 sandstones from sandstone bed B. Legend for symbols in A; 1-clast supported cobble conglomerate; 2-pebble and cobble rich sandstone; 3-deformed and/or rippled fine sandstone and siltstone; 4-basalt flow; 5-cross bedded feldspathic litharenite; 6-covered.

northerly paleoflow confirming the flow direction determined by cross bedding in the underlying sandstone unit (Yuan Ming Hsu, unpublished senior thesis, Northeastern University).

This is a unique locality in the Boston basin because the architectural geometry of beds is well displayed. Large channels of the sort displayed in these outcrops are rarely seen at other localities. Even after many years of study we are still somewhat uncertain as to the exact nature of depositional mechanisms and paleoenvironments needed to explain this sequence. Proposed environments of deposition for these beds have ranged from braided non-marine rivers to resedimented deep water conglomerates associated with submarine fans. A paleoenvironment dominated by a coastal braid plain and associated fan delta, sandy and silty prodelta, and gravelly sandy shelf best explains the structures and bedding relationships displayed here. The planar bedded, pebbly sandstones somewhat resemble those from better known undoubted shallow marine sequences and the low amplitude symmetrical ripples suggest oscillatory currents in a shallow marine environment. Similarly, gravelly tidal environments produce planar bedded sandy conglomerates associated with channels, but diagnostic sedimentary structures are not present. The major channel scour surfaces may represent sequence or parasequence boundaries produced by sea level and/or tectonic cycles.

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