A Tour of Avalonia in "Greater Brookline"

A Brookline Rocks! Self-Guided Tour
October 25, 2021

This tour visits Neoproterozoic-age deposits in the "greater Brookline area." Outcrops in Brookline area are mainly composed of the Brookline Member of the Roxbury Conglomerate, but other rocks can also be found, including an "open air" museum of Brighton Igneous rocks at Dane Park. There are 8 stops of this tour. **Figure 1** below shows the tour stops on a street map combined with a map of the basement geology of the area (Thompson *et al.* 2014).

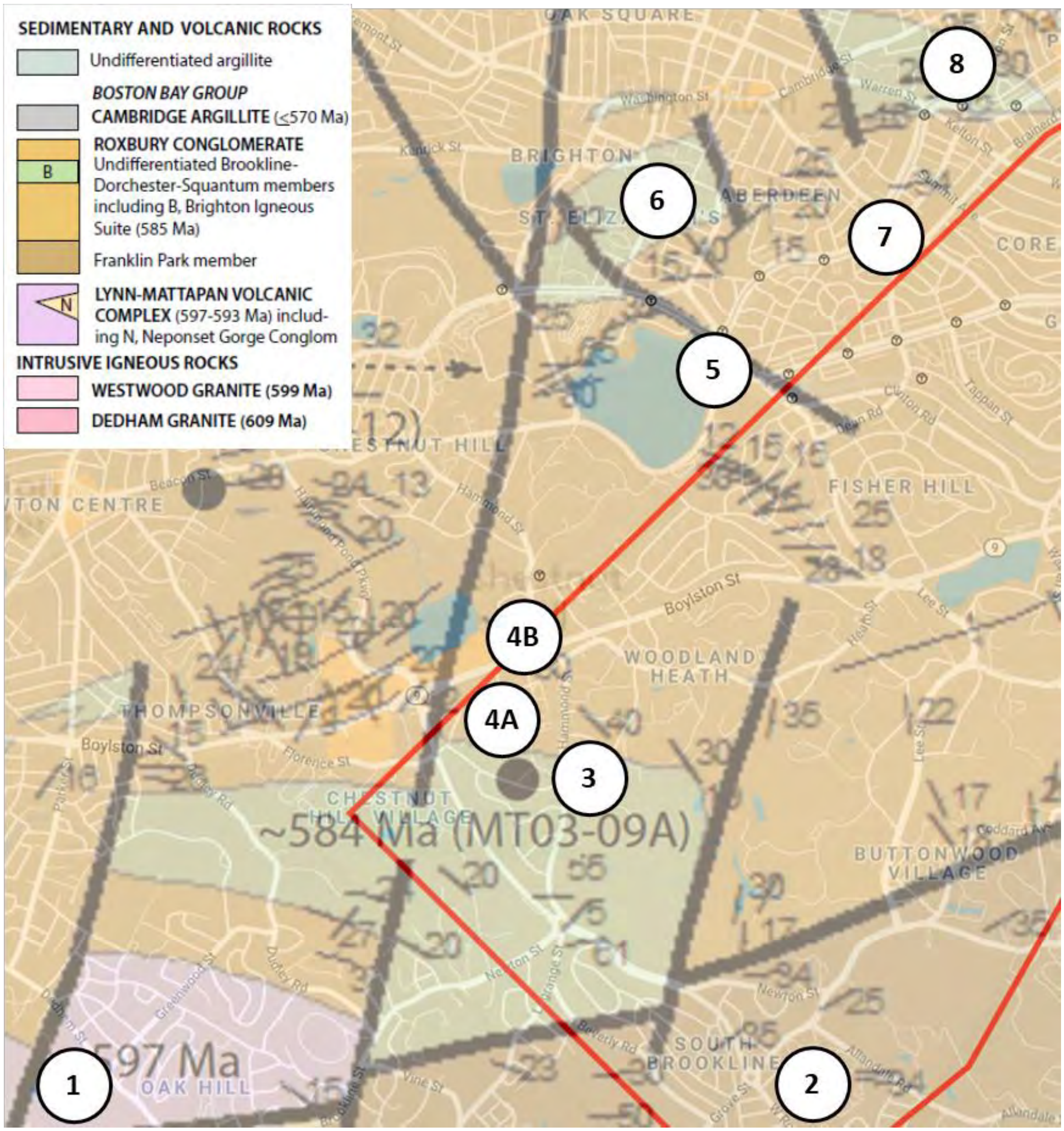


Figure 1: The tour stops shown with a superimposed map of basement geology of the area. Thick black lines mark major faults within the area. Small lines denote strike of deposits and numbers represent dip. Longer lines with arrows show the axis for folds. Red outline shows borders of Brookline.

Please note that some of these stops are in private property, city parks and wooded areas. In private property, please be respectful of the rights of the property owners. In parks and reservations, please do not use hammers on samples or take anything with you but memories and pictures. In the wooded areas, watch out for poison ivy and use insect repellant to avoid tick bites! Finally, if you are following directions in your car, keep your eyes on the road. Pull off to check directions, use GPS, or have someone help guide you.

Geological Summary

The rocks to be viewed during this field were likely deposited over a 15-million-year period between 600 and 585 million years ago ("Ma"), at the end of the "magmatic arc" period of Western Avalonia. During this time, the microcontinent of West Avalonia lay at the margin of the supercontinent of Gondwana, near what is now the northern coast of South America. This period preceded what geologists posit as the collision between the front edge of the Avalonian microcontinent and the oceanic ridge that had been generating the basaltic crust that had been subducted under the Avalonian margin for over 100 million years. This "trench-ridge collision" is interpreted as occurring around 580-590 million years ago in the West Avalonian region (Murphy *et al.* 1999, Thompson and Crowley 2020), and it converted the leading margin of Avalonia from an active subduction zone with consequent magmatic activity to a transform fault zone that brought an end to magmatic activity in West Avalonia for about the next 140 million years (**Figure 2**).

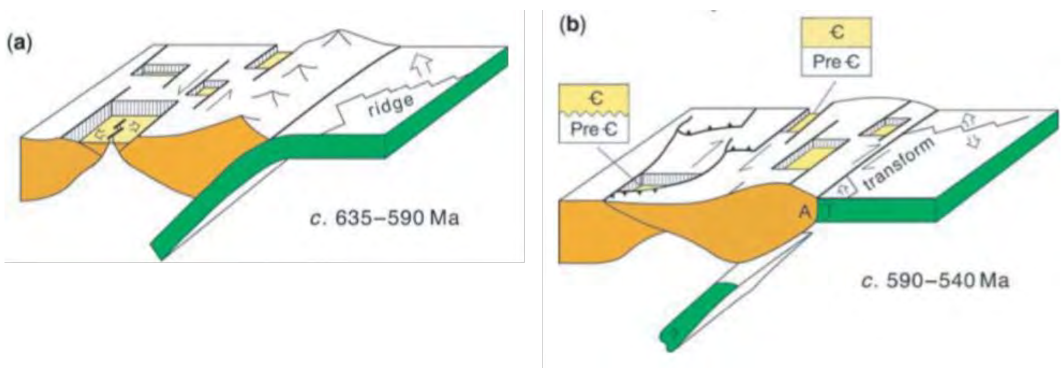


Figure 2: Model for the late Neoproterozoic tectonic evolution of West Avalonia. (a) Oblique subduction during the interval *c*. 635–590 Ma produces the main arc phase of Avalonian magmatism and opens a variety of volcanic arc basins in response to sinistral motion on basin-bounding faults. The Boston Basin was one of these. (b) Ridge–trench collision results in the termination of subduction at *c*. 590–540 Ma and the progressive development of a dextral continental transform fault € = Cambrian; Pre = Precambrian; A = away; T = towards. (Image from: Nance *et al.* 2008)

The igneous rocks included in this tour likely are the oldest and youngest of the rocks that will be seen on this tour. The Mattapan Volcanics in Newton were produced around the time the Boston Basin was formed, and the Brighton Igneous Suite rocks were likely deposited around the time when subduction in West Avalonia began to cease. In addition, in the Walnut Hill Cemetery we can see an igneous dike that may date from the early Mesozoic, about 250 million years ago.

The sedimentary rocks on the tour are all part of the Roxbury Conglomerate unit. Two specific members are represented: the massive, poorly sorted conglomerates of the earlier Franklin Park Member, which may reflect "debris flow" type of deposits formed closer to the source rock, and the later Brookline Member, which are characterized by smaller conglomerate clasts, more evidence of sorting, and variations of sediment type including conglomerates, sandstones and mudstones.

In its current orientation, the Boston Basin opens to the northeast. There is evidence that a major portion of the Boston Basin was under water during its formation, suggesting the basin perhaps opened into a shallow sea. This is typical for this kind of island arc basin. Some of the volcanics in the area (Dane Park) show evidence of being deposited under water. In general, basin sediments become finer as one moves north. While in general, rocks in the southern part of the map are older than rocks in the northern part, the vertical displacements of rock caused by the faults (black lines in map above) often changes where outcrops of specific rocks appear. Radioisotopic dating of these rocks (some sampling sites with attendant dates are shown with large black dots), accomplished over a 20-year period by Dr. Margaret Thompson's group (Wellesley College) in collaboration with the MIT Radiogenic Isotope Laboratory, has helped provide a context for interpretation of the geological history of the area.

Figure 3 below provides an illustration for the possible environment of deposition for most of the rocks on the tour. It is likely that the shoreline of the basin area changed with the progress of erosion, the development of new volcanoes or basaltic eruptions, and the rise or drop in sea level, in part due to periods of glaciation. In the past, many geologists attributed the deposition of sedimentary rocks in the Boston Basin to glacial activity. That is in part because much of the Roxbury Conglomerates are poorly sorted conglomerates in a fine matrix reminiscent of what are called glacial tillites. In addition, during the deposition of these rocks, the location of West Avalonia was near the south pole. During the period of Avalonia's formation—a time called the Neoproterozoic Era—there were several regional and global ice ages. One of these periods of global glaciation, called the Marinoan, lasted from about 650-635 Ma, and around 579 Ma there was a regional glaciation called the Gaskiers (Pu *et al.* 2016)—probably after the end of the deposition of the sedimentary rocks on this tour. In spite of the relationship of these deposits with one or more glaciations, the current consensus is that clear evidence of direct glacial influence on the formation of these sedimentary deposits is lacking. However, glaciation may have occurred even locally, and would have contributed to erosion of the source rock and feeding the streams that carried sediments into the sea. This nuance is captured in the diagram of deposition below.

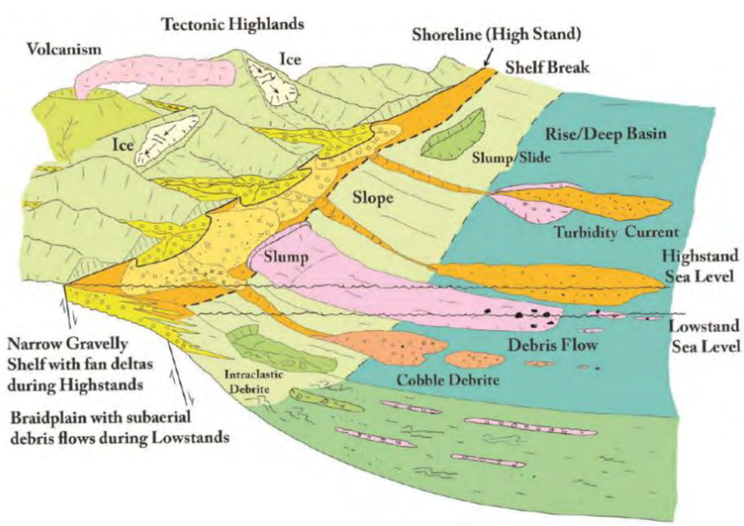


Figure 3: Diagram of the depositional environment of the Boston Basin during the Neoproterozoic. Volcanic highlands provide erosional material for the basin. Coarser debris flows exist nearer to the source. Some deposits were made on land, others in what was likely a shallow marine basin. Changes in sea-level shifted the environment and type of deposits. Source: Galli and Bailey 2018.

Over the last 600 million years, the rocks of the Boston Basin have been subject to tectonic stresses that have fractured, faulted, and folded the deposits and produced metamorphic modifications to the original rocks. The many major faults that cut through the area can be seen in the area geological map above. Evidence of these alterations will be noted at many of the stops. It is likely that many of the faults in the area occurred during the 15-million year period of the deposit of these rocks. Other changes that can be seen in the rock are evidence of a series of collisions endured by the Avalonian microcontinent—first with other microcontinents, then with Laurentia (ancient North America) during its initial amalgamation to the continent, and finally its being crushed between Laurentia and Gondwana as the supercontinent of Pangea formed, with Avalonia then buried beneath miles of rock eroded from the mountains formed by these collisions. After all this time, erosion has finally re-exposed the Boston Basin to the surface, providing us an opportunity to explore some of these remains of ancient Avalonia.

One stress feature seen in these rocks is called cleavage. Compared to a bedding plane, which shows the orientation at which sediments were originally laid down, cleavage is an orientation of the rock constituents that results from intense and extensive stress exerted on the rocks after their formation. Such stresses occurred during the collision between Avalonia and Laurentia, but were far more extensive when Avalonia was caught in the middle of the collision between Gondwana with Laurentia during the formation of Pangea about 280 Ma. These collisions happened at a geological scale, involving the impact between trillions of tons of crustal material moving toward each other at about an inch per year and lasting tens of millions of years. Such impacts exposed the buried Avalonian rocks to prolonged periods of elevated temperature and pressure sufficient to cause the constituent materials inside the rock to begin to re-orient, and for cleavage layers form orthogonally (at right angles) to the pressure (see **Figure 4**). In many of the rocks to be viewed on this tour, a near-vertical cleavage with a generally north-south trend can be seen, suggestive of compression from east-west. In some of the conglomerates, the clasts within the matrix also flattened out along the cleavage plane. The cleavage plane in the rock forms a natural weakness along which the rock may tend to fracture at a later time. These fracture planes can be seen at several of the stops and uniformly strike to the north regardless of the location or type of rock.

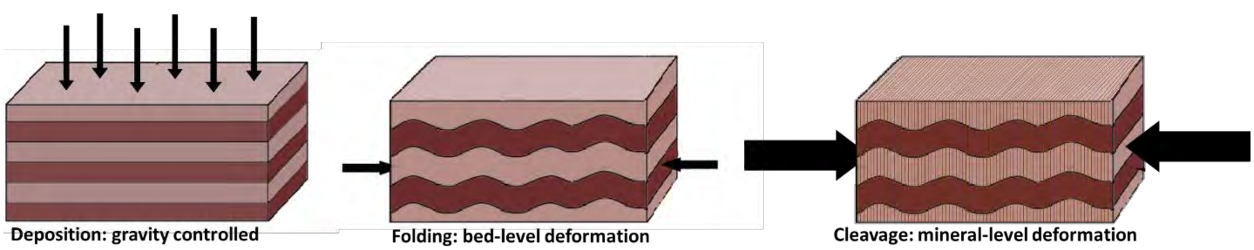


Figure 4: Alteration of initial deposits. Left: Original bedding determined by gravity and often is nearly horizontal. Middle: moderate compressional stress can cause folding of the rock layers, but does not alter the minerals in the rock themselves. Right: High, sustained compressional stress can result in the re-orientation of rock minerals and components at right angles to the direction of stress, producing cleavage layers. Note that the angles of bedding, folding, and cleavage may all be different.

Finally, the combination of heat and pressure on these rocks have transformed them into metamorphic versions of the original igneous and sedimentary rocks. In the conglomerates of the Roxbury Puddingstone, this metamorphic alteration has not destroyed the original features but has served to weld the rock together into an incredibly strong and resilient stone sufficient for use in building. As a result, it has found its way into literally hundreds of buildings in the Boston area.

Field Trip

Stop 1: Mattapan Volcanics

Charles River Country Club, 483 Dedham Street, Newton MA
(42°18'20.7"N, 71°11'44.8"W)

Directions
The entrance to the country club is located on the south side of Dedham Street.
After you enter the drive to the country club, look for the first parking lot on the left about 500 feet up. Turn right.
Park in one of the open spots and then walk back to the road.
You will see deposits of the Mattapan Volcanics ahead and to the right. Walk about 20 feet up the road to a small cart path going off to the right. It will take you back to the area of the outcrop.

This is private property. Follow instructions on signs and be respectful of the property. Do not use rock hammers on any samples within this area.

This tour starts somewhat outside of the borders of Brookline, but it is worth it to see an outcrop of the Mattapan Volcanics, which are typically found further to the south and east. However, faulting in the area has brought this rock up to the same level as younger rocks to the north (the Dane Park igneous rocks north of these deposits are almost 13 million years younger).

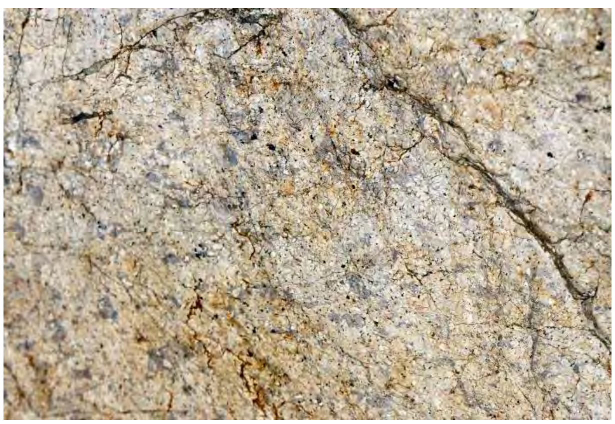
The Mattapan Volcanics are eruptive rocks that likely accompanied the rifting and opening of the Boston Basin. While in other parts of the Boston area there are more extensive volcanic flows, here the outcrops are mostly formed from aerial deposition from volcanic vents or shield volcanoes. The outcrops near the tennis courts across from the parking lot are for the most part examples of what are called tuff, which are deposits of volcanic ash. Fine-grained aerial eruptions from volcanoes are called ash falls, while larger sized pieces are called volcanic bombs. Eruptions may eject both kinds of rock. If the temperature of the ejected ash is hot enough, instead of forming tuff deposits, the ash can fuse together after falling to the ground. This is called welded tuff.

Left: view of ash flow outcrops near the tennis courts across from the parking lot. Left: view down one of the fairways showing additional outcrops of volcanics.

The ash flow deposits show larger bedding structure (see picture above left) but finer bedding of the ash fall can sometimes be seen (below left). In some of the outcrops, one can see inter-bedded darker deposits that appear to be lavas.


Left: Ash-flow tuff showing fine layering. Key fob is 3 inches for scale. Right: Darker layers of lava at the base of ash flow. One can see gas vesicles in the lava.

The ash flows found at this stop show a variety of textures. Some are composed of small granules, which may include rounded glass fragments. Others contain small chunks of ejecta. One can see ash flows with larger, embedded volcanic bombs.




Different consistencies in ash flow deposits. Top left: small, granular texture with glass-like inclusions. Top right and bottom left: Small chunks included in the ash. Bottom image inclusions are darker than the other ash matrix. Bottom righ: larger bombs included in the ash (see arrow). Key fob included for scale is 3 inches.

At this first stop as well as other stops, we can see the fingerprints of different geological forces that shaped area rocks. The original volcanic deposits were formed by ejection from volcanoes or open vents and the original plane of deposition may have had substantial slope. Currently, however, these rocks are generally tilted with a northward dip that may represent large-scale folding in the rock. In addition, these rocks show fracturing along cleavage planes that resulted from being subjected to tremendous compressional stress at depth. The fracturing is nearly vertical and trends north-south.


Left: hillside outcrop showing the depositional bedding sloping up toward the right and the fracturing nearly vertical and moving directly away from the camera. Right: an outcrop of darker lava near the walkway.

Stop 2: Roxbury Conglomerates, Franklin Park Member, Mesozoic (?) Dike

Walnut Hill Cemetery, 96 Grove Street, Brookline (42°18'18.1"N, 71°08'55.3"W)

Directions
Return to Dedham Street and turn right.
Follow Dedham Street for 0.7 miles past the Newton Fire Station and take the next left at Brookline Street/Newton Street.
Follow Brookline/Newton Street 1.5 miles until the rotary and take the second right on West Roxbury Parkway.
Follow West Roxbury Parkway 0.4 miles to another rotary.
Take the third exit onto Grove Street.
Follow Grove Street 0.2 miles; look for the cemetery entrance on the right.
Enter the cemetery and park at the lot just inside the entrance.

This is private property. Follow instructions on signs and be respectful of the grave areas. Do not use rock hammers on any samples within this area.

The Franklin Park Member is, based on stratigraphic position, the oldest of the members of the Roxbury Conglomerate group (Figure next page). Radioisotope dating of zircons within the clasts of the conglomerate set its upper limit of age to about 595 Ma (Thompson *et al.* 2014). In general, the Franklin Park Member is a poorly sorted diamictite, which Wikipedia defines as “a type of lithified sedimentary rock that consists of nonsorted to poorly-sorted terrigenous sediment containing particles that range in size from clay to boulders, suspended in a matrix of mudstone or sandstone.”

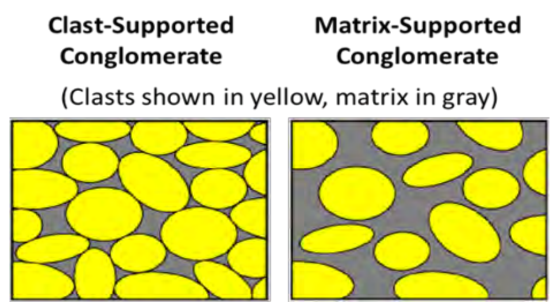
The Franklin Park Member generally contains a much greater range of clast size in the matrix compared to the Brookline member, and the matrix tends to be coarser—often a coarse sand matrix compared to a fine sand/mud matrix found in the Brookline Member.

Roxbury Conglomerate/Squantum Member (> 580 Ma)	
Roxbury Conglomerate/ Brookline Member (595-585 Ma?)	Brighton Igneous (584-585 Ma)
Roxbury Conglomerate/Franklin Park Member (< 595 Ma)	
Mattapan Volcanics (595-597 Ma)	

Estimated chronologic ages for original deposition of the sedimentary (yellow/gold/ orange) and the igneous (gray) rocks of the Boston Basin seen on this tour.

The large size of the biggest cobbles suggests deposition occurred closer to the source of erosion, as larger rocks tend to be deposited closer to the source of erosion than smaller ones. Most of the clasts have some degree of rounding, providing evidence of transportational smoothing. The Franklin Park Member contains few interbedded sandstone or mudstones.

After parking at the entrance, walk back out of the cemetery to Grove Street and to the right. Large outcrops are apparent on both sides of the road. One can see the high variability of the clast size. In general, the matrix of the Franklin Park rocks can be considered “clast supported” as opposed to “matrix supported” (see Figure right). These deposits are debris flows that occurred either on land or under the water, such as in a braided stream environment or in turbidite deposits close to shore.



Clast-supported conglomerate vs. matrix-supported conglomerate.

Walk back into cemetery parking lot and drive into the cemetery. Take the first right, Willow Lane. You will see an outcrop on the left with the large tree growing out of it. Here one can see the variable size of the clasts, the coarse sand matrix, and the lack of clast alignment. At the south end of the outcrop you can see a contrast between the bedding of the outcrop and the cleavage. The bedding can be seen toward the bottom, where it consistently dips toward the east at 35-45°. The cleavage here is about 80-85° and strikes north-northeast.

Left and middle: variable size clasts and coarse matrix in the Franklin Park Member conglomerate. Glasses are 5.25 inches for scale. Right: south edge of the outcrop shows bedding dipping about 35-45 degrees east, while the cleavage is nearly vertical and strikes N-NE.

Take the right just south of the outcrop, Beech Avenue, and follow to the east and toward the south. On the left, a low outcrop running roughly NW-SE can be seen. Look at the outcrop face from the south. Here lensing in the bedding can be seen showing the undulating bedding surface. The beds here dip gently toward the south.

Figures: undulating bedding in a southward-dipping conglomerate outcrop. In close up on the right, the distinction between beds is shown by different matrix colors. The matrix of the bottom bed is greener than the browner bed above.

Continue to follow Beech Avenue south toward the southern end of the cemetery. The road will swing east and then south, intersecting with Downing Avenue. To the right of this intersection is an outcrop. About 10-12 feet up on the rock, two sandstone layers several inches thick show the bedding of the outcrop. Here the dip is 30° SE. On the side of the outcrop signs of glacial scoring of the rock can be seen. Further southeast of this outcrop is a longer ridge that contains other similarly oriented beds.

Figure left: Location of two sand layers on the outcrop near Downing Avenue (black arrows). Right: close-up shows bottom and top of sand layer (see top and bottom black arrow), which forms a shelf on the deposit. Eroded layers can be seen at the far right (red arrow). Above the shelf, scratches on the rock can be seen that is probably glacial scoring (white arrows). Glasses shown for scale are 5.25 inches.

Continue on Downing, which swings to the east and goes past a number of outcrops to the south. It then turns north toward the cemetery entrance. Across from Spruce Avenue is a footpath called Bow Avenue. Stop the car and walk up the hill. Behind a row of four graves is an outcrop that contains a profile of a channel fill bed. In this outcrop the left side of the channel is seen most clearly, cutting almost 90 degrees at the top and flattening out toward the bottom. The channel is filled with sand with a different bedding angle from the channel border. The sandstone has been modified by stress and has near vertical cleavage surfaces that can be seen on closer examination.

Figure left: view of the channel fill, with the contact between the sand layer and the conglomerate shown with dotted line. Right: close-up of bedding transition shows layering of sand above and to the right of the conglomerate layer.

Beyond this outcrop, additional sand beds can be found at the top of the nearby hill with a north 30 east dip.

Return to the car and continue north on Mt. Walley Avenue. A hundred feet up the road or so, look for a marker on the side of the rock marking Stearns burial area. A final interesting outcrop in the cemetery runs through here. This is a mafic igneous dike that trends north and cuts the conglomerate in several places. The dike runs northward from the Stearns burial area for a couple hundred feet.

Figure left: mafic dike (trend shown in white arrows) cuts between conglomerate along the cleavage, trending northward. As the image shows, the dike rock has been more easily eroded than the conglomerate, which appears as ridges in between. Middle: small gas vesicles can be seen in the igneous rock. Right: A xenolith of a conglomerate clast (just below and to the right of the glasses) was plucked out from the conglomerate rock and trapped in the basalt matrix.

The dike appears to have intruded along the almost vertical, northward striking cleavage layers that we saw earlier on entering the cemetery (see Figure above). This suggests the igneous rock was intruded after the cleavage was formed. If the cleavage occurred as a result of stresses exerted on the Franklin Park Member rock during the formation of Pangea when Gondwana and Laurentia collided, trapping West Avalonia in between, the dike must have been intruded later. In the Boston area, as well as all along the eastern seaboard of the United States, evidence of the magmatic upwelling that finally resulted in the formation of the modern Atlantic Ocean can be seen in the form of rift basins (Connecticut River Valley in western Massachusetts), border faults, and dikes. Dikes formed when the push from hot magma below caused extensional stress in the rocks, allowing some of the magma from below to intrude up into the older rock.

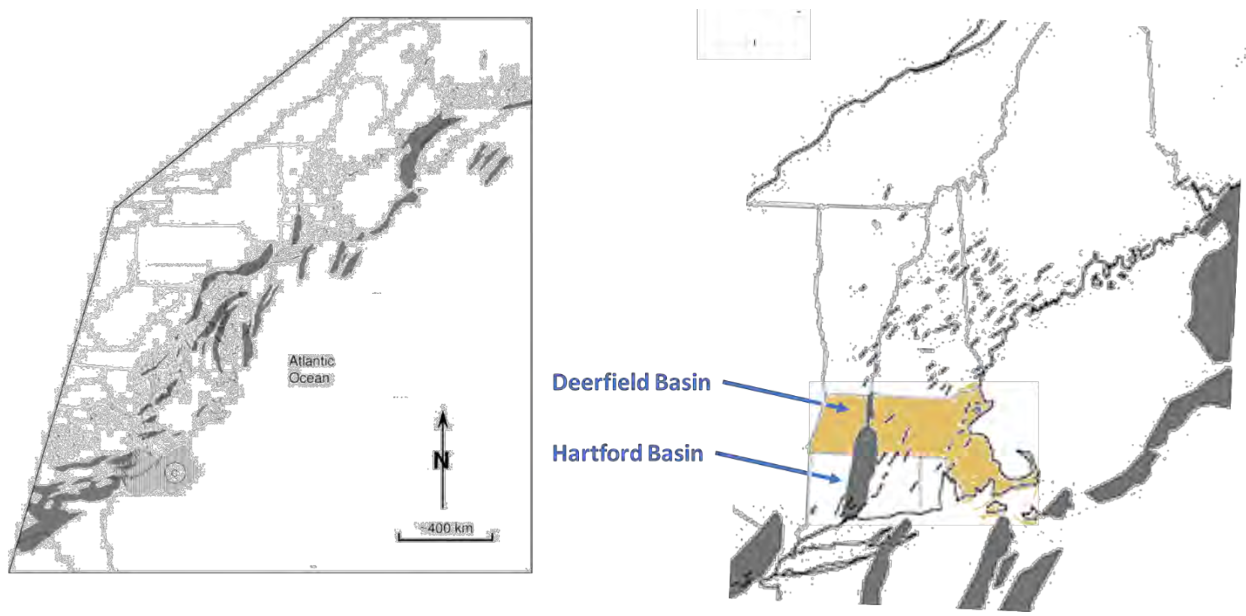


Figure: Early Jurassic-age diabase dikes (thin black lines) in eastern North America. Rift basins are shown in gray. Image from: Schlische *et al.* 2002.

Return to the car and exit the cemetery to the north.

Stop 3: Brighton Igneous Suite

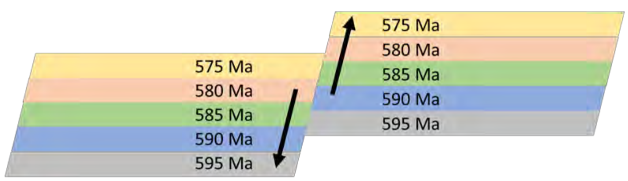
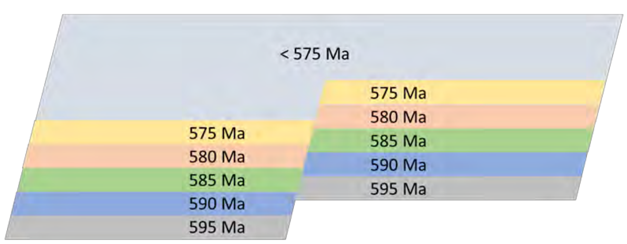
Dane Park, Hammond Street, Brookline (42°19'03.2" N; 71°09'46.7 W)

<u>Directions</u>
Exit from the cemetery, turning left on Grove Street.
Stay on Grove Street 0.2 miles until you come to the rotary, take the first right onto West Roxbury Parkway.
Follow West Roxbury Parkway for 0.3 miles; the Parkway merges into and becomes Newton Street.
Follow Newton Street another 0.5 miles. You will pass the Robert T Lynch golf course.
Take the first right on the rotary (practically going straight here), onto Hammond Street.
Follow Hammond Pond Parkway 0.5 miles. You will pass by the Brookline Country Club golf course on the right. Dane Park is adjacent to the golf course.
Go past the entrance to Dane Park on the right and then turn right on Woodland Street.

Park off the side of the road near the fence. The entrance of Dane Park is a short walk back Hammond Street.

Dane Park presents an opportunity to see a variety of both intrusive and extrusive igneous rocks in a relatively small space. The park contains examples of lava, ash beds, and volcanic bombs. Several of the lava flows show evidence of either underwater extrusion or contact with water after eruption. This is a public park. Follow instructions on signs and do not use rock hammers on any samples within this area.

These deposits are identified as part of the Brighton Igneous Suite. Thompson *et al.* (2014) dated these igneous rocks at about 584 million years old ("Ma"). The informational sign at Dane Park suggests that the rocks are closer to 600 Ma, but it is likely the sign was put up before the data reported by Thompson. The Thompson dates for these rocks are 10 million years younger than the Franklin Park Member rocks just south of here. How is that possible? Going back to map at the start of this document, you will notice from the map that the area of Dane Park is surrounded by faults with the east-west Savin Hill fault lying between Walnut Hills Cemetery and Dane Park. This means that the ground at Dane Park has moved (here mostly vertically) compared to the ground at Walnut Hills. The diagram below shows how this could happen. It is not clear when this faulting actually occurred but it may have occurred during the time the basin was forming, a time when the area was tectonically active.

	Over time, a number of different rock layers are deposited.
	Stress on the rock layers causes faulting, with some of the layers displaced vertically relative to the others.
	Subsequent layers of rock are deposited on top of the faulted units.
	Over a long period, the overlying rock is eroded. This erosion eventually exposes rocks of different ages next to each other.

In the diagram above, the rock on the right in the bottom panel could represent the Franklin Park Member conglomerate, while the rock on the right could be the Dane Park volcanics.

Entering the park, follow the path immediately to the left. There will be an elongated outcrop to the right of the path. This shows two types of volcanism. The nearest rocks has been identified as lapilli, which are aerially-deposited volcanic rocks, while the majority of the rock appears to be either a basaltic lava flow or intrusion. There appears to be a fault between the two types of rock that may have resulted in the incongruous displacement, but as the rocks at Charles River Golf Course showed, lava flows can be interbedded with aerial deposits like ash flows or the lapilli deposits found here. Layering of the lapilli is evident at the outcrop, and high-angle, northward striking fracturing that likely follows cleavage planes in the rock.


Left image: basaltic lava at the left side showing nearly vertical fracture planes that strike northward. On the right the lapilli outcrop is shown. A tree grows out of what appears to be the fault between the two types of rock. Right: Close-up of the fault area, showing the layering of the lapilli dipping northward.


Close up of the two kinds of rocks. At left, the basaltic lava/intrusion shows a fine-grained texture with blocky faulting. At right, the layering of the coarser lapilli.

Returning to the main entrance, go up the main pathway past the informational sign and proceed to the left. Here a sign indicates the rock is an intrusive basalt that may have formed in the throat of a volcano. The rock, which has been identified as a gabbro, which is the intrusive equivalent of basalt. The gabbro has a relatively fine-grained matrix and the presence of gas vesicles is minimal. The lack of pronounced mineralization suggests that the gabbro solidified relatively rapidly.

Figure left: gabbro outcrop. Not glacial smoothing of the top of the deposit. Figure middle: close up of gabbro shows relatively fine-grained matrix with some light-colored larger minerals. Key fob is 3 inches for scale. Figure right: portions of the gabbro have been post-depositionally modified, with deposition of quartz along cracks in the rock.

Somewhat further down the path is an interesting juxtaposition of Brookline Avalonian rocks. Here a small boulder of Roxbury Puddingstone sits atop the gabbrodiorite. In this area, there are no deposits of such Puddingstone. The size of the cobbles within the rock, and the distinct bedding of the cobbles, indicate this is Brookline Member rock. The boulder is an example of a glacial erratic. The boulder was picked up by the last glaciers that covered the area more than 12,000 years ago. It was likely plucked from a Brookline Member deposit somewhere north. As the edge of the ice sheet melted back, the boulder was deposited here atop the basalt. If one climbs to the top of the igneous deposit and look carefully, one can see the signs of glacial sculpting of the rock, including striations made from rocks embedded in the ice.

Traveling back to the informational sign, follow the path to the south from that location. This path takes you by examples of both land- and water-deposited volcanics. The first deposit shows examples of pillow lava. This is lava that was extruded under water. When the hot lava comes in contact with the water, it cools rapidly. As a result, instead of bedding as continuous flow, it forms a series of these rounded, “pillow” structures (see Figure right). These deposits are evidence that a portion of Dane Park was underwater at the time of the formation of these rocks.

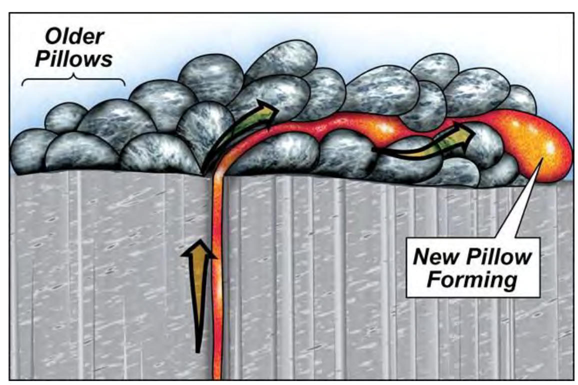


Diagram of formation of pillow basalts by extrusion of lava under water. Figure from U.S. National Park Services.

A bit further down the path are examples of large chunks of rock that were ejected from volcanoes or volcanic vents. These lava chunks, called bombs, were ejected along with the finer ash that was erupted along with them. While the outline of the bombs can be seen, the deposit as a whole was welded together as the ash and rock cooled.

Figure left: pillow lava outcrop. The rounded outlines of the lava pillows can be seen in the rock. Figure right: ash bed containing blocky volcanic bombs. The bombs are a slightly darker color than the surrounding ash. Glove is about 6.5 inches in length for scale.

If one moves further down the path, there is an outcrop that is another example of an ash flow lapilli. A close examination of the deposit shows the ash was deposited on top of a lava flow.

Figure top left: ash flow beds overlying a lava flow. The lava can be seen on the lower left of the picture. Figure top right: Close up of contact between lava flow below and ash bed above. Granulation of the ash flow can be seen. Gas vesicles can be seen in the lava. Bottom left: view of the lapilli ash from the west side. Outlines of large volcanic bombs can be seen. Bottom right: close up of lapilli showing coarse texture of the ash flow.

Stop 4: Brighton Igneous and Early Roxbury Conglomerate, Brookline Member

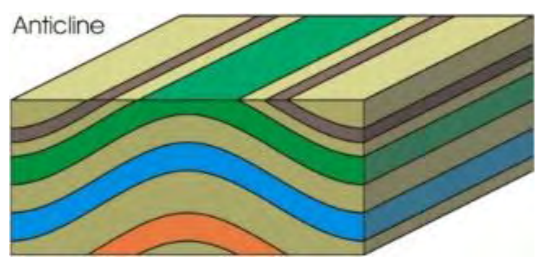
Holyhood Cemetery, Heath Street, Brookline and Chestnut Hill Mall/Star Market, Brookline

Stop 4A: Holyhood Cemetery (42°19'08.8"N; 71°09'56.8"W)

Directions
Depart Dane Park. Turn around to get back to Hammond Street, turn right.
Follow Hammond Street 0.4 miles to the intersection at Heath Street. Turn left.
Follow Heath Street 0.1 miles to entrance of cemetery on left. Turn left.
Follow road about 50-60 feet south to the intersection, turn right then left (Eastern Ave).
Follow road past Fenwick Street and curve to the right.
Look for marker of Donovan grave (a bronze angel) at a fork in the road. Park at the right fork.

This is private property. Follow instructions on signs and be respectful of the grave areas. Do not use rock hammers on any samples within this area.

This location is unusual in three respects. First, it represents an area where Brighton Igneous rocks transition to Roxbury Conglomerate. The two types of outcrops are only a few dozen feet apart here. Second, it is near the top of an anticline in the area. An anticline is the top of a fold in a folded rock formation. Looking at the map at the top of the document, one can see the Brookline Anticline (line with arrows pointing away from it) running just south of the Brookline Reservoir. The Brookline Anticline trends ENE, and Route 9 parallels the fold axis at this location. Rocks exposed at the top of an anticline are older than those further away from the fold top (see Figure left). If we imagine the green layer of the figure as being the axis of the Brookline Anticline, then rocks to the left (north) and right (south) will be younger.



Therefore, the third unusual aspect of this stop is that the sedimentary rocks here, identified as being part of the Brookline Member of the Roxbury Conglomerate, are among the older representatives of the Brookline Member. As we shall see, they have characteristics of both Franklin Park Member and Brookline Member rocks.

Starting with the igneous rocks on the south branch of the road, we can see that the rock transitions from a basaltic lava at the east end to a lapilli ash flow at the west end. The contact between the two is not obvious but may be at the ledge shown in the picture below. The basalt is relatively fine grained, and the lapilli is also relatively fine. The lapilli shows an 18° degree dip about 70NE. Like the rock in Dane Park, it shows almost vertical fracturing along the cleavage plane running 60NE. This outcrop may be a continuation of the lava flow/lapilli visited in Dane Park.

Figure left: lava overlain by ash lapilli. Ridge (in shadow) running horizontally toward the right may mark contact between the two. Right: lapilli at right side shows fracturing along the cleavage striking 60NE.

Going back to the north branch of the road, one can see a large outcrop of Brookline Member running east to west. A small chapel sits at the top. This rock shows an interesting combination of characteristics from both the Franklin Park Member and Brookline Park Member. Like the Franklin Park Member seen at Walnut Hill Cemetery, the conglomerate is poorly sorted with very large cobbles or small boulders included the rock. In the wall, the larger rocks are typically 11-14 inches and the largest rock seen had a diameter of almost 20 inches. Much of the rock was also clast-supported, and the matrix was coarse sand.

However, in contrast to the Franklin Park Member, many of the outcrops seen in this area (including here, the one along Hammond Street near Glenoe Street, and the outcrops at the Star Market just north of here) show clear bedding even in the absence of sandstone layers. The elongated portions of the rocks have a clear alignment. In general, the beds here dip toward the east (beds on Hammond Street were measured dipping east at about 30°).

Figure left: portion of the outcrop showing large cobbles (left one about 12 inches), alignment of clasts along bedding layer, and coarse sand matrix. Right: undulating bedding horizon of the conglomerate can be seen at the lower part of the outcrop.

The picture this outcrop paints is a transition between the depositional environment of the Franklin Park Member and that of much of Brookline Member. It is still near the source of erosion and could be characterized as debris flows. However, the deposits are less massive and depositional layers more distinct. As such, it may represent slope-based, possibly turbiditie-like deposits where periodic sediment slump or outwash occurred.

Stop 4B: Chestnut Hill Mall/Star Market (42°19'26.9"N; 71°09'57.3"W)

Directions
Depart cemetery at same entrance. Go across Heath Street to Holly Lane.
Follow Holly Lane one block to Boylston Street/Route 9. Turn left.
Move into the inside lane and take the left into the parking lot of the Star Market.
Head for the large rock wall behind the store. Park near the rock outcrop

This outcrop shows a transition toward more typical Brookline Member conglomerates. The large cobbles or small boulders seen in the cemetery are missing. Here the largest clasts are about 5-6 inches. The layering of the rock seen in the cemetery is retained here. Here and along Hamond Street at the supermarket entrance the rock dips about 20-30° in the 30-40° NE direction. The variability of bedding dip likely reflects variability of the angle at which the conglomerates were originally deposited. Unlike the rocks at the Hollyhood Cemetery, the conglomerate here is more matrix supported and the grain size of the matrix is much smaller.

Stop 5: Roxbury Conglomerate, Brookline Member

Chestnut Hill Reservoir, Boston (42°20'11.6"N; 71°09'15.0"W)

Directions
Depart cemetery and turn left on Hammond Street.
Follow Hammond Street 0.5 miles until the intersection with Reservoir Avenue (signal light). Turn right.
Follow Reservoir Avenue 1.2 miles. The road will wind around the Chestnut Hill Reservoir to the south and become Beacon Street.
On the left you will see the Reilly Memorial Ice Rink and a parking lot. Park either on the street or in the lot. The outcrops of interest are to the north of the parking lot and next to the Reservoir walking path.
Climb the hill to the Reservoir walking path at the north end of the outcrop

This stop shows classical Brookline Member conglomerate. Here the clast sizes in the rock is smaller, with most clasts smaller than 3 inches. The bedding of the conglomerate can sometimes be seen with the alignment of the clasts. At the edge of the outcrop here, one can again see the north-striking fracturing of the rock that follows the cleavage of the rock.

Figure left: Smaller size of conglomerate clasts. Key fob shown for scale is 3 inches. Right: steep dip of the beds in this area can be seen in the slates at the lower right.

The bedding in this area is fairly steep with a dip angle around 50° oriented 30-40° NE. The dip of beds in this part of the Reservoir is, in general, much steeper than on the western side of the Reservoir, and may reflect local folding of the rock. However, the original bedding contours likely varied significantly. This can be seen further to the north where a wedge of slaty mudstone can be found in between two layers of conglomerate. The dip of the mudstone is consistent with the dip of the conglomerate elsewhere, but the curved lower and upper edges of the bedding suggests that there was scouring of the mudstone when the next layers were deposited. Here a significant change in environmental conditions occurred after the first conglomerate layer was laid down, leading to a quiet period where fine layers of mud were laid down over time before the next layer of conglomerate was deposited.

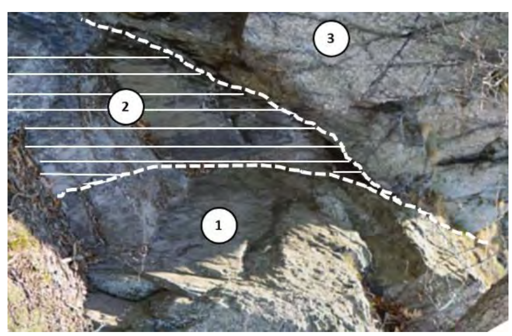


Figure left: A wedge of slaty mudstone between two convergent layers of conglomerate. Top Right: The conglomerate at the top cuts across the bedding angle of the mudstone, suggesting that the turbid flow scoured a channel in the slate deposit. Bottom right: In this reconstruction 1) the first conglomerate bed was laid down, leaving a rounded surface; 2) the mud was deposited on top of this bed in a relatively horizontal orientation; and 3) the top conglomerate cut a channel across the profile of the mud and the previous conglomerate layer.

Stop 7: Roxbury Conglomerate, Brookline Member and Brighton Igneous

Foster Street Rock, 188 Foster Street, Brighton (42°20'35.2"N 71°09'28.3"W)

Directions

Depart parking lot to Beacon Street. Turn left. Stay on the inside lane of the street.
At the light, turn left on Chestnut Hill Avenue and stay on the inside lane of the street.
At the next light, cross the T tracks and turn left on Commonwealth Avenue.
Follow Commonwealth Avenue and proceed 0.4 miles.
Foster Street will be on the right. Turn right.
Follow Foster Street about 0.3 miles.
You will see a large, rounded rock outcrop on the right, with the parking lot of the St. Peter Faber Jesuit Community directly after it.
Park on the street next to the rock outcrop.

This is a park. Please be respectful of the property and do not use rock hammers.

This stop captures the disruption of a portion of the Brookline Member by intruded igneous rock, probably basalt. The proximity of this outcrop to other outcrops of the Brighton Igneous Suite, as well as the characteristics of this deposit, suggest it is part of the Brighton Igneous Suite. This is one of the few outcrops in the area where the contact between the conglomerate and the basalt is visible.

At the west end of the outcrop, near the street, the sedimentary rock is conglomerate. Toward the east, the sedimentary rock is slate/mudstone. In addition to the intruded basalt, which cut dikes in two different locations, other features appear to show faulting of the rock. It is possible that there was vertical thrusting of the rock during this intrusion, now juxtaposing the mudstone next to the conglomerate.

Figure left: conglomerate near street. The top of the outcrop has been smoothed and scratched by glacial passage. A cluster of clasts can be seen in the lower right. Figure right: slaty mudstone at eastern end of the outcrop (relatively horizontal lines mark bottom of the bed).

As one moves east along the outcrop, the mudstone layers above are bowed, likely by the pressure of the injected magma beneath. At the west end the dip of the mudstone is about 18-19° almost to the west, but at the east end the dip is about 30° toward the north. This distortion of the bed at a relatively small scale suggests that magma was intruded before the layers of mud were fully lithified, and that the intrusion occurred relatively soon (from a geological perspective) after deposition of the sediments.



Figures left and middle: dikes cutting the conglomerate and the slaty mudstone. Figure right: an apparent fault in the conglomerate.



Figure left: The eastern part of the outcrop, showing the bowing of the slaty bed (arched dashed line). The basalt is below the slate beds. Figure middle: The basalt surrounds the slaty mudstone as both a dike to the right and a sill underneath. Figure right: Contact between the basalt (left) and the conglomerate (right).

One interesting aspect of this outcrop is that the slaty mudstone preserves a record of the surface of the bed at the time of deposition. The bottom of one of the layers preserves casts of the scouring of the mud surface by the next layer. This provides evidence that the mud was likely deposited as turbidites, disturbing the mud layer below as they were deposited. Even more interesting, these marks preserve the direction of the turbidite flow, which appears to be northwest.

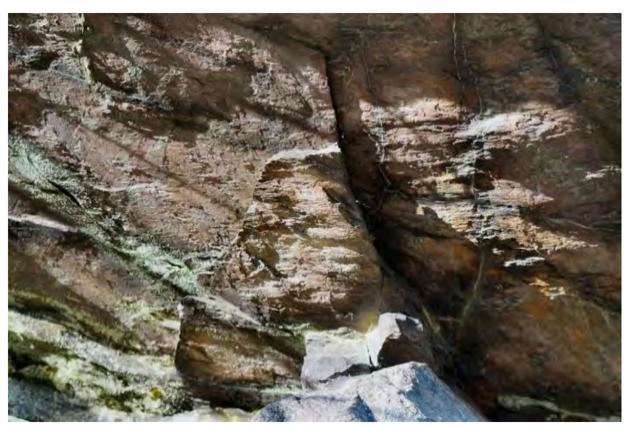



Figure left: The intrusion of the basalt ripped clasts from the conglomerate and they ended up in the basalt matrix as xenoliths. Figure right: the underside of some of the slaty mudstones preserve casts of the sediment flow over the layers below. Note the scour features at the right.

Stop 7: Roxbury Conglomerate, Brookline Member

Irving B. Matross Covenant House, Egremont Road, Brighton

<u>Directions</u>
Turn around and head south on Foster Street back to Commonwealth Avenue.
Follow Foster about 0.2 miles until Kirkwood Street. Turn left.
Follow Kirkwood Street 0.2 miles until Chestnut Hill Avenue. Turn left.
Take the very next right, Strathmore road.
Follow Strathmore Road 0.2 miles to Commonwealth Avenue. Turn left.
Follow Commonwealth Avenue 0.7 miles to Washington Street. Turn right.
One block down the street, turn right on Egremont Street.
As you turn, the Irving B. Matross Covenant House will be on the right. About halfway along the building there is an entrance to the right into a parking lot. Park on the street nearby and enter the parking lot.
You will see a rock wall in front of you.

This is private property. Please be respectful and make only observations.

This stop is an opportunity to see what is likely a series of turbidite beds composed of conglomerate. Here there is no interbedding of sandstone or mudstone layers like in other areas. The size of the conglomerate clasts is relatively uniform throughout the outcrop, with a maximum size of 3-4 inches. The clasts are suspended in a relatively fine matrix. The bedding on the east side of the outcrop (closest to the building) is fairly uniform. A layer at the base of the outcrop shows a dip of 29° 10N.

An interesting feature in this large, exposed wall is the undulating, sweeping layers of the rock. These are suggestive of turbidites that scoured out the bedding surface below. Turbidites are relatively disordered because the turbidity caused by the movement of the sediment can cause the mixing of larger sized sediment (the “clasts’) with the finer, often muddy matrix. Here, the majority of the turbidite flow is composed of mud, with a suspension of larger clasts. If this material had been deposited in a stream or river, sorting of the sediments would more likely occur, resulting in segregation of the larger and smaller components.

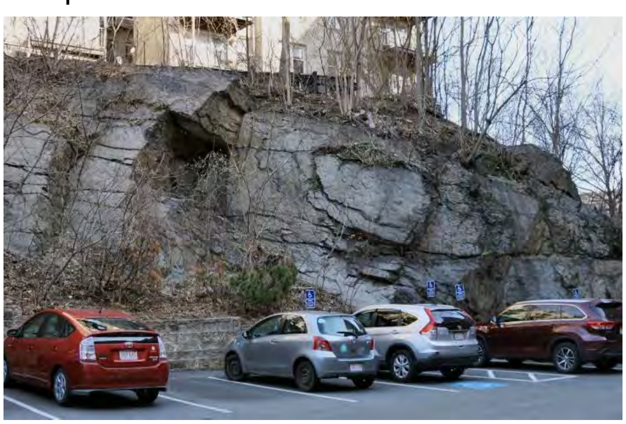


Figure left: a view of the turbidite bedding at Egremont. The scour beds are seen mainly in profile, suggesting that the turbidites were being deposited in a northward direction (away from the parking lot). Right: close up of the curved contour of the bedding.

In some turbidites, the flow may be so chaotic that larger clasts are left in random orientation within the sediment. Here, however, it appears that the larger clasts have managed to be oriented parallel to the bedding.

At the far left of the outcrop, near the garden area, one can see another igneous dike. This intrusion is likely part of the Brighton Igneous. Its contact with the adjacent conglomerate strikes almost due west, a quite different direction from the northward-striking cleavage throughout the area. Second, there is again evidence of distortion of the nearby conglomerate bed, which suggests emplacement before the full lithification of the rock. Compared to the beds at the east side that dip northward, these beds are dipping 34° in the direction 80°E.

Figure left: basaltic igneous dike within the conglomerate. Contact between the two types of rock is well defined (arrow). Right: close-up of the contact surface shows chlorite weathering of the rock (green).

Stop 8: Brighton Igneous

Ringer Park, Allston Street, Brighton MA (42°21'01.6"N 71°08'14.8"W)

<u>Directions</u>
Head back east on Egremont to Washington Street. Turn right.
Take the immediate next right, Allston Street.
Follow Allston Street 0.5 miles. passing over Commonwealth Avenue.
You will see the West End House Boys and Girls Club on the left at 105 Allston St.
Turn into the parking lot and park in a visitor’s spot.
You will see a stairs going up to the right of the building. Take that stairs.

This is a public park. Please show more respect to the grounds than apparently many of the users have.

Ringer Park is dominated by a large deposit of Brighton Igneous rock at the east end of the park, transitioning to a mixture of igneous and sedimentary rock at the west end capped with igneous rock. The dominant sedimentary rocks are fine-grained sandstones and mudstones.

At the top of the stairs next to West End Boys and Girls Club, you can again see fracturing in the igneous rock that, like at other locations, is northward-striking and almost vertical (80°). This pervasive and uniform fracture orientation in most of the rocks visited on this tour provides evidence of a regional metamorphism of the Boston Basin that occurred after deposition and folding.



Figure left: Igneous rock next to stairs shows almost vertical fractures striking northward, similar to fracture along cleavage seen in other stops. Middle: Igneous rock capping hilltop at the west end of the pavilion area, displaying contemporary art. Right: Over the crest of the hill, outcrops of slaty mudstone can be seen below the igneous rock.

Head around the pavilion and cross the top of the hill toward the west. Ahead you will see a series of outcrops facing west with paths winding among them. The cap rock at the top (which evidently provides perches for local partiers) is again igneous rock. At some point down the hill, the rock transitions to sedimentary. At this upper area, it is mostly mudstone, but further down the hill toward the bottom are alternating layers of fine sandstone and mudstone. The mudstones that jut out of the hill just below the basalt are tilted at about 32° dipping 43NE. On some of the mudstones, ripple marks can be seen. These are both indicative of relatively quiescent deposition. Ripples could have been formed on the bottom of a deeper part of the basin, further from shore. Alternatively, they could have formed in a quieter intra-tidal environment.



Figure left: Slaty mudstone dipping to the northeast exposed on the southwest side of the hill. Middle: Close up shows fine bedding of the mudstones. Right: View from the top shows some surfaces show ripple marks. Rock is cut by fractures filled with quartz.

Further investigation of the basalt near the top of the hill shows that it is a dike, cutting the mudstone almost vertically. The contact between the basalt and the mudstone strikes 34NE. Based on the strike directions and positions of the dikes here and at Egremont, this may be the same dike. Like the dike at Egremont, the intrusion here has also altered the bedding orientation of the adjacent mudstones. Near the contact with the basalt, bed dips 44° almost directly north. The alteration of the dip of the bed suggest that the intrusion may have occurred before the mudstones were fully lithified. The mudstones here also demonstrate the same fracturing along the cleavage plane, dipping 80° 43NE.

Figure left: Basalt dike cuts the mudstone almost vertically. Figure right: contact between the mudstone (reddish brown left) and the basalt (right side). The dip of mudstone here has been disturbed by the intrusion of the dike, dipping must more steeply northward instead of northeast in the beds a few dozen feet away.

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