SELF-GUIDED GEOLOGICAL TOURS IN EASTERN AND CENTRAL MASSACHUSETTS

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INTRODUCTION

This guidebook describes the geology of six locations in Massachusetts, all but one of them inside Route 128. It's written for students who have some background in geology and want to learn more about how to look at, and think about, rock units and their relationships in the field. It was conceived as a substitute for field trips accompanied by the instructor (me), so the text is quite detailed. I hope I've anticipated a great many of the questions that will occur to users when they're on the outcrop.

For each locality, the rock units and geologic features to be seen are listed just below the heading. As an aid to those who want to try to develop their own ideas before being presented with mine, I've tried to arrange the text so that paragraphs end with a sentence, usually unrelated to previous material, telling the user where to go next and what to look for. I implore the serious user to resist the temptation to read the text beyond the section on location before looking at the rocks.

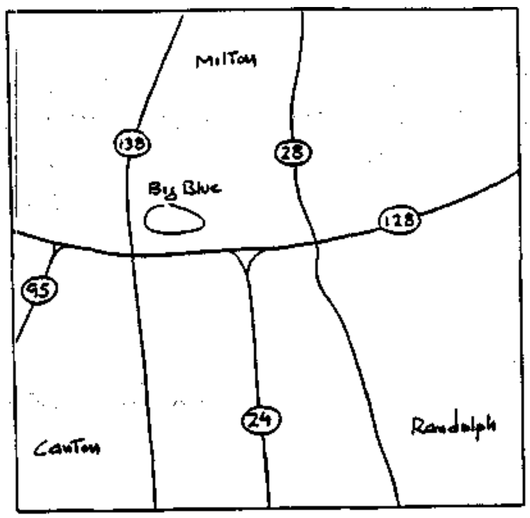
Users' comments on clarity of presentation, with respect to both outcrop location and outcrop geology, are most welcome; I'm sure that numerous inadequacies still reside in the text. I'm greatly indebted to Vicky Dounias for helping with the typing and organization of this guidebook.

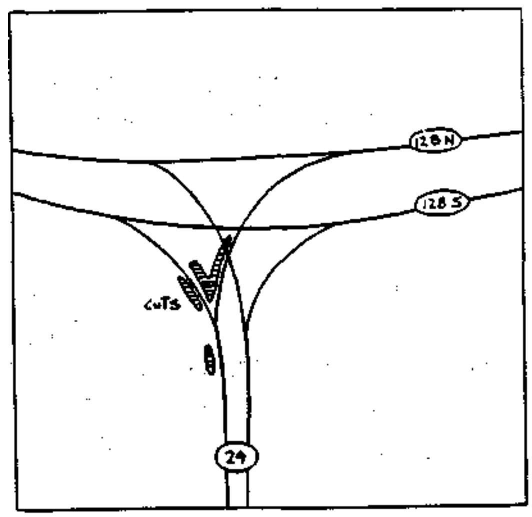
CONTENTS

CANTON, ROUTES 128 AND 24
(Blue Hills Quadrangle)

Wamsutta Formation (Pennsylvanian)

sandstone; mudstone; conglomerate; cross-stratification; graded bedding; desiccation cracks; folding; axial-plane cleavage





This locality is on one of the connectors between Route 128 and Route 24, south of Boston. It can be reached easily by car. The cuts are all in a small area, so you won't have much walking to do. There's quite a lot of traffic noise here, but since the shoulders are wide you're well away from passing cars and you won't feel overwhelmed by the traffic. Sunday mornings are least unpleasant here.

LOCATION

The rocks of this locality are in cuts at the intersection of Route 128 and Route 24, south of Boston. Route 24 extends almost due south from Route 128, which runs east-west here. The cuts are along two of the four broadly curving connectors between the two highways. The best approach is to drive "south" (actually east) on Route 128 and take the Route 24 exit. Route 24 goes only south from Route 128, so there's no possibility of going in the wrong direction here. The cuts are far along the connector, almost to where the two connectors merge to form Route 24 south. There's plenty of space to park on a wide, grassy shoulder. There are cuts not only on this connector but also the one just to the east, but I suggest that you spend most of your time on this western connector. The rocks are better exposed on the left side of the road as you head toward Route 24. The best time to examine these cuts and take pictures is in the morning or in the afternoon, when one cut is in full sun and the other is in full shade. In most respects it's harder to examine and photograph the cuts in the middle of the day, because then the sun illuminates the rock surfaces at a low angle.

GEOLOGY

The first thing you'll notice about the rocks as you walk up to them is that they are red—a kind of purplish or pinkish red. This is a very common sedimentary-rock color, although many pyroclastic volcanic rocks show a similar color. Red-colored sedimentary rocks in a stratigraphic sequence are usually called red beds. The first thing you should try to do here is locate the stratification.

Seeing the stratification is not especially easy in the first cuts you come to on either side of the road, but if you walk along the outcrop a short way on the east side, the stratification should become apparent. The strata strike approximately across the road and dip south at a moderate angle of about forty degrees, so as you walk south you're walking up through the section—provided that the beds are upright and not overturned. Examine the section on the east side for composition, texture, and sedimentary structures.

There are two thin covered intervals on the east here, but the section is almost completely exposed. For convenience in specifying positions along the outcrop, note that the cuts on the east begin about at a lamppost. There's another lamppost at an outcrop with covered intervals above and below, and a third nearer the southern end of the cut on this side. At the southernmost end of the cut is the low-to-ground base of a fourth lamppost that was sheared off by some wayward vehicle. It would be a good idea to walk up and down the section a few times to get a general idea of what it's like, and then go back and look in more detail at certain features.

Most of the section consists of mudstone or shale. In these rocks the sediment particles are too fine to see with the unaided eye, so you can't tell the percentages of clay, silt, and sand in these beds. Except for the very finest, many if not most of these finer beds are probably siltstone. Some beds are sandstone, however, and a few are coarse enough to be classified as conglomerate. On the average the grain size of the section decreases upward: the sandstone and conglomerate beds are more numerous in the lower part of the section. Although all the beds have a red or pink color, the coarser beds are lighter in color than the finer beds; this is common in red-bed sequences. Start by examining the sandstones.

Most of the sandstone beds show sharp lower contacts, which in some cases clearly truncate underlying strata. This is conclusive evidence that the section is upright. Some of the sandstone beds grade upward to finer grain sizes, and pass smoothly into mudstone. Other sandstone beds don't show such graded bedding, and are succeeded rather sharply by finer beds. Lamination within the sandstones ranges from indistinct (or even nonexistent) to well defined, but it's somewhat crude and on a scale of several millimeters. Many of the sandstones are cross-stratified, and commonly you can see internal truncation surfaces that separate individual sets of laminae. If you "untilted" the sandstone beds by rotating them along their strike line to bring them back to their original almost horizontal attitude, the cross-laminae would for the most part dip to the west. This untilted dip direction shows the current direction at the time of deposition (called the paleocurrent direction), because such cross-laminae are usually deposited on the downcurrent slopes of downcurrent-moving bed forms like dunes or sand waves. An interesting feature of this cross-stratification is that in many beds the laminae are oversteepened, in that they dip at angles considerably greater than the approximately 30° angle of repose of loose sands in air or water. On the reasonable assumption that the laminae couldn't have been deposited at such steep angles, we can invoke two possibilities for the oversteepened dips. The first is that shortly after deposition the sands became flowy or "quick" by rearrangement of packing while in the saturated state, whereupon they flowed like quicksand. This is common in rapidly deposited sands, and can easily be reproduced in laboratory experiments. The other possibility is that the section is pervasively sheared at some angle to the stratification, thus changing the angular relationships of all linear and planar features in the rock that aren't parallel to that shearing direction. Since only some of the cross-stratified sandstone beds are oversteepened, this might not seem as reasonable a possibility—although the extent of oversteepening (or understeepening, which would be unremarkable and thus would likely escape attention) depends on the relationship between the direction of dip and the sense of shearing, and anyway there's no reason to expect uniform shearing of all the beds. I won't make any pronouncements on this oversteepening because I don't understand it.

There are three prominent conglomerate beds in the section: two in the east cut, and one at the very top of the section in the west cut, not very accessible to close observation. The lower conglomerate in the east cut is about halfway between the second and third lampposts (counting from the one at the base of the section) and the upper is just short of the third lamppost. These beds, a meter or so thick, show sharp and erosional lower contacts, little or no internal stratification, and a general but unspectacular upward decrease in grain size. Try to ascertain the composition of the clasts in these conglomerates.

Each of the conglomerate beds contains small and large clasts of mudstone and siltstone whose lithology looks similar to the underlying fine beds. These clasts, usually called rip-up clasts, probably represent pieces of only slightly older sediment only partly consolidated, that were eroded nearby and then transported along with the other sediment to the site of deposition of the gravels. The lowest conglomerate is especially rich in rip-up clasts. Also present as coarse clasts are rounded fragments of various rock types that probably were derived from outcrops of much older rock in a distant source area. Among such farther-traveled clasts you should be able to spot pieces of vein quartz, red chert, tough sandstone or quartzite of various colors, and what looks like fine-grained volcanic rock. The sand-size material in these conglomerates, on the other hand, seems to be mostly quartz and potassium feldspar. The greenish color of the beds is probably due to the content of potassium feldspar.

A striking feature of the sequence, especially in the upper part, above the upper conglomerate, is the presence of thin mudstone beds, rich dark red in color and ranging in thickness from about a centimeter to several centimeters. Some of these beds are continuous, but most are segmented, with coarse lighter-colored sediment in the gaps between the segments. This can best be seen on joint surfaces that are almost vertical and strike southwest across the road. The only reasonable explanation for the segmentation is that the sediments were deposited as mud beds and were later broken apart. In many if not most of these broken beds one gets the impression that the pieces are all of about the same length and are curled upward slightly at their edges. We could invoke two causes for this: the mud beds could have been broken by desiccation cracks (also called mud cracks or shrinkage cracks) during subaerial exposure and then engulfed by later deposition of sediment, or they could have been broken by upward flow of water-saturated sand around them. I haven't yet resolved in my mind which is the right explanation—or combination of explanations. The regularity in size within each of the beds is more likely to result from desiccation cracking, although the wispy thinning and termination of the individual pieces in many of the beds suggests soft-sediment flow rather than desiccation cracking. Moreover, you can't rule out the possibility that the present geometry of the mudstone beds is partly or even largely the result of the same pervasive deformation that was mentioned above in connection with the oversteepened cross-stratification in the sandstone beds. Another feature of the fragmented red mudstone beds that casts doubt on a simple desiccation-cracking origin is that the gaps between the fragments are relatively large, in some cases as great as the width of the fragments themselves. Finally, in just a few places you can see overlying sandstone beds cutting down into the red mudstone beds; this shows that strong currents cut shallow channels into the fine sediment before depositing the sands. If you search carefully you'll discover just a few places where the sandstone filling between the red mudstone fragments is itself truncated by erosion along with the upper parts of the mudstone fragments and overlain by another sandstone bed; this is good evidence that whatever the change in geometry caused by later deformation, the cracking of the mud beds and the filling of the cracks by sand is a primary feature, unrelated to deformation after burial while either still unconsolidated sediment or hard rock.

The rocks in this section have a pronounced cleavage that's visible not only in the finer rocks but also to some extent in the sandstones, presumably because of clay content. The cleavage planes strike about northwest and dips at a steep angle, about 70° to the northeast, so that they cut the stratification almost at right angles. The cleavage is not nearly strong enough for the rocks to be called slates, but it's strong enough that the rock tends to break along cleavage planes rather than along bedding planes. You'll see presently that this cleavage is axial-plane cleavage that must have developed during folding, but you can't assume that just from this one set of cuts, because they are not extensive enough to define the geometry of folding.

The cuts in the other connector, just to the east (to get there, walk in the direction of traffic and make a sharp left around the corner of the cut) look just the same. These cuts expose rocks lower in the section, but the exposures aren't as good and you won't get much out of looking at them. (There are also cuts in generally the same part of the section along the connector from Route 24 north to Route 128 south, but I haven't looked at them closely.) If you're ambitious you could try tracing the sequence of beds from one connector to the other—a distance of a few tens of meters in straight-line distance. If you measured and described the stratigraphic sections in each of the four cuts on the two connectors and then plotted them in vertical columns, using some system for symbolizing rock type and noteworthy features, you'd probably find that at least some if not most of the beds can be traced from cut to cut. (I haven't tried to do this.) An exercise like this would give you a good idea of the lateral persistence of the various kinds of beds, which in turn gives indirect evidence on depositional environments. Finally, you should walk south along the west side of Route 24 for about a hundred meters past the point where the two connectors merge to look at the next outcrop, after a long covered interval.

Note that the attitude of stratification is different here: it ranges from almost horizontal at the northern end of the outcrop, to gently north-dipping in the middle of the outcrop, back to horizontal again a little farther along, and finally to south-dipping at 20-25° at the southern end of the outcrop. The cleavage, however, has about the same attitude as in the cuts on the connectors, and doesn't vary in attitude the way the stratification does. If you stand back a ways from the outcrop (keep your eye out for traffic) you can use the changes in attitude of stratification along the outcrop to help you perceive a pattern of gentle folding, with the cleavage about parallel to the axial planes of the folds. It looks as though the fold axes are about horizontal and strike about east-west here. It seems as though this outcrop is stratigraphically above the cuts on the connectors, but we don't really know that because of the possibility of folding or faulting, or both, in the covered interval between. This southern outcrop has more sandstone and less mudstone than the cuts to the north, but the rock types and sedimentary features are generally the same. Some of the sandstone beds here are cross-stratified on a fairly large scale, and the nearly vertical cleavage is again prominent not only in the mudstone but also in the sandstone and even the conglomerate.

A noteworthy feature of the pebbly sandstones and conglomerates in this outcrop (present also in the earlier outcrops but less pronounced) is a strong tendency for the scattered red mudstone rip-up clasts to have the shape of irregular plates and chips that are oriented along the cleavage and at a large angle to the stratification. Where you can get a three-dimensional view of the outcrop you'll get the impression that the shortest diameter of these clasts is always just about perpendicular to the cleavage. It's as if these clasts have been sheared out or extended along the cleavage to give them their present shapes. It's highly unlikely that these clasts were originally deposited in their present orientation, with its regular relation to the cleavage and variable relation to the stratification, so they must have been deformed somehow into this orientation after deposition. It's noteworthy also that the accompanying clasts of quartz and tough fine-grained rock have not been affected by this deformation.

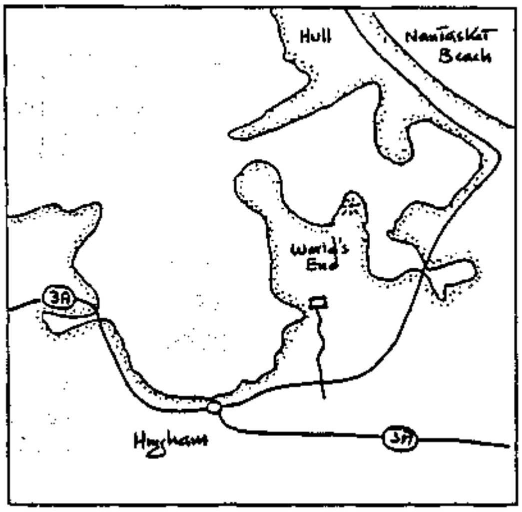
Several inferences can be made about the environment of deposition of this: sequence. The presence of the conglomerate beds tells us that the site of deposition was subjected to occasional very strong currents. The large-scale cross-stratification in the sandstones tells us that the sands were transported by moderate to strong unidirectional currents and molded into large-scale ripple bed forms of some kind. Well stratified conglomerates like this are usually thought to have been deposited by river flows. The mudstones were most probably deposited by slow-moving water. The desiccation cracks in the mudstones are good evidence of at least occasional subaerial exposure and drying. The environment most sedimentologists would deduce from such features is that of a fluvial plain, with one or more major shifting sand-bed channels with floodplain areas between. The red color in the rocks, produced by the presence of fine-grained hematite, is usually associated with fluvial environments rather than marine environments, because the ferric iron is much more likely to be reduced after deposition in marine environment. For further details on interpretation of fluvial environments, see the discussion of the Turner's Falls locality, which probably represents a generally similar depositional environment.

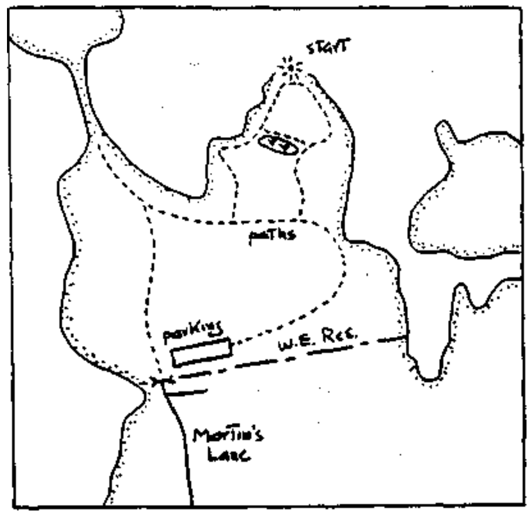
HINGHAM, WORLD'S END RESERVATION

(Nantasket Beach Quadrangle)

Boston Bay Group (Proterozoic); **Dedham Granite** (Proterozoic)

conglomerate; mafic dikes; batholith; fault; unconformity; glacial striae





This is perhaps the best locality around Boston for diversity of geological relationships in a small area. The geology at this locality is spread out over an area of about a quarter of a mile on each side, but the walking is easy along grassy roads and paths in the pleasant surroundings of a park managed by the Trustees of Reservations. You have to walk almost a mile from the parking lot to get to the area of outcrops. Much of the geology is best seen at low tide, and most of the benefit of the trip would be lost if you're there at full high tide. Parking costs $2.00 per person—unless you're lucky enough to get one of the few parking spaces outside the gates. The large parking area inside the gates can become full on weekend afternoons in nice weather. This locality would be a great place for a picnic, but park regulations don't allow it.

LOCATION

Make your way on Route 3A to Hingham. Near the center of town and overlooking the harbor is a rotary on Route 3A. If you're coming from the west from Quincy or Boston, go straight through the rotary toward Hull and Nantasket. If you're coming from the south from Cohasset, it's a right turn at the rotary. About half a mile from the rotary is a traffic signal at crest of a hill. Turn left onto Martin's Lane and drive for 0.7 miles until you can't go any farther. The street ends at the entrance to World's End Reservation. Pay the warden at the toll station, bear right onto the gravel road, and drive about 0.1 mile to the last parking area. (If the warden isn't there and the gate is closed, you can walk in free, but parking outside the date is limited. I don't know what their schedule is, or even if there is one. If in doubt call the headquarters of the Trustees of Reservations in Milton.)

To get to the guidebook locality you have a pleasant walk of almost a mile through the woods along the unpaved road (more a path than a road, but used by maintenance vehicles) that continues from the parking area. The road eventually curves to the left and comes out into the open with a narrow branch of the Weir River on your right. Watch for another unpaved road to the right just beyond this point. Follow that road for a few tenths of a mile until you reach the northern tip of the peninsula. You'll know you've arrived when the road curves sharply to the left once and for all and you have a good view of Hull across the wide water to the north. Use the sketch map as a guide. This is the best place to start looking at rocks. The geology described below is all within an area of a small fraction of a square mile in the northern part of the peninsula. Except in a very few places the walking is easy. Since many of the important outcrops are along the shore and inaccessible at high tide, plan this trip for a time of low tide. Keep in mind also that the tip of the peninsula, where there's a lot of geology to look at, can be surprisingly cold and windswept.

GEOLOGY

At the northern tip of the peninsula and southward along both shores are numerous exposures separated by gravelly pocket beaches. Spend some time examining the rocks within a few tens of meters in both directions from the tip of the peninsula.

Much of the rock here should strike you as a conglomerate with clasts up to a few tens of centimeters in size. The clasts are composed almost entirely of fine-grained igneous rock. In the lower part of the outcrop these volcanic clasts are mafic, and in the upper part they are felsic. Some of the felsic clasts are porphyritic, and others are flow-banded. Look for stratification features in the outcrop.

You can get a good idea of the stratification here both from the overall arrangement of strata with the two different clast compositions, and from the attitude of the finer interbeds in the conglomerate. The contact between the mafic-clast conglomerate and the felsic-clast conglomerate is abrupt and well defined, although not obviously erosional; it can be followed all along the steep face of the outcrop well above the high-tide line into the swale just west of the major outcrop surface of the point, and it reappears in the little knob of conglomerate just before the shoreline bends out of sight to the south. The approximate correspondence between the topographic contours and the trace of the contact implies that the contact surface has a gentle dip. But you don't need to rely on this evidence, because the felsic-clast conglomerate shows considerable variation in clast size from bed to bed: some beds are mostly gravel, but others are mostly sand, with only scattered pebbles. Look especially at the way the crude lamination in the sandy beds wraps around differently oriented joint planes in the outcrop; this allows you to fit planes in your imagination to the stratification. You should be able to convince yourself that the strata here strike approximately east-west (the two tall towers across the water lie almost due north) and dip gently south at 15 to 20 degrees.

Is the section upright or overturned here? This is one of the questions that should naturally occur to you when you look at a sequence of sedimentary rocks. Since the dips are so gentle, it's natural to assume that the section is upright. But the only way to know for sure is to see features in the rocks themselves that give evidence of top and bottom. Near the east end of the outcrop is one small joint plane, facing out across the water, that shows erosional truncation of laminae. Although it's not ideally clear here, the geometry of the stratification shows that already-deposited laminae were truncated at a low angle by erosion and then more sediment of the same kind was deposited conformably on that erosion surface. This shows definitively that the strata are upright. Also, you can see in some places that the felsic-clast conglomerate beds rest with sharp lower contact on finer, sandier beds, and in just a few places you can see fairly clear evidence of erosional truncation of the finer beds by the conglomerates—but you have to hunt around on the outcrop to see such evidence.

The clasts in the felsic-clast conglomerate are almost all well rounded. Rounding of clasts that started out this tough can only be the result of abrasion during transportation by water, either in streams or on beaches. This doesn't mean, however, that the sediments were deposited right at this point by streams or shallow-marine currents: they could have been deposited temporarily in shallow water and then transported to deeper water by sediment gravity flows of some kind.

The mafic clasts in the underlying deposits are rounded too, but there's some interesting evidence in the stratification that casts serious doubt on the idea that these too were transported by running water. This evidence is best exposed around the little western knob of conglomerate. Note the presence of sinuous cream-colored or buff-colored beds, up to ten centimeters thick and delicately laminated, irregularly interbedded with the coarse conglomerates. Similar but thinner laminated beds also wrap under and over individual large mafic clasts. It's not easy to think of plausible ways to account for this kind of stratification. If it were just a matter of accounting for the presence the thicker and continuous interbeds, we could invoke deposition of the fine material by quiet-water deposition and subsequent deformation by emplacement of subaqueous debris-flow deposits. The existence of the thinner beds of fine sediment among the larger clasts is more difficult to explain. It's conceivable that this is a glaciomarine deposit: the large clasts settled as dropstones after being melted out of floating ice, and fine sediment deposited by continuous quiet-water settling was bowed down by the impacts and then more fine sediment was draped over the fallen clasts. Indeed, a glacial origin has been proposed for parts of the Boston Bay Group for a hundred years. One might also appeal to the fall of large basaltic volcanic bombs, ejected violently from a volcanic vent somewhere nearby. The bombs might have fallen, either in air or ultimately through water, onto a depositional surface on which fine sediment, perhaps largely volcanic ash, was settling at the same time. Both of these hypotheses might strike you as far-fetched, but both phenomena are well known, and anyway I can't think of a better one. I lean toward the latter explanation, but I can't cite any convincing evidence. Now walk to the western end of the outcrop and look for rock types other than sedimentary.

You'll see two places where the rock is different from the conglomerates described above. These outcrops are just below the grassy soil cover that rests on top of the entire outcrop here. The rock is dark greenish gray, fine grained, and uniform, and if you look closely at the weathered surface you'll see small and randomly oriented crystals, elongated and light colored, surrounded by darker material. This is the texture you typically see in a basalt or a fine gabbro. The light crystals are plagioclase and the darker material is probably augite. Search for the contacts between this basalt and the conglomerate.

You should be able to locate the contacts fairly easily. They are sharp and approximately planar, and the grain size in the basalt decreases toward the contacts. This is an excellent example of chilled margins in a pluton. The contact relationships are best exposed in the northern of these two exposures. Contacts are approximately planar and parallel in each pluton, showing that you're dealing with dikes, which here are between one and two meters thick. If you stand on the exposures of the dikes and look west you'll see narrow passes in the brown-stained bedrock marking the surface trace of the dikes. The rock surface of the dikes is lower because the dike rock weathers more readily than the conglomerate it intrudes. The strike of the dikes is about east-west, almost the same as that of the conglomerates, but the dip is steeply north. So the dikes are just about perpendicular to the strata they intrude. Around the bend of the shoreline to the south there's a third dike, a little thicker than the other two. Near the contacts of this dike (and to a lesser extent of the other two) the conglomerate is cut by closely spaced, almost planar fractures. These fractures are somehow related to the emplacement of the dike, but cause and effect are hard to sort out: did emplacement of the dike cause the fractures, or was the dike emplaced along one of a number of preexisting fractures in a shear zone of some kind?

At the westernmost knob of conglomerate at the the of the peninsula, just before the shoreline bends to the south, there's clear evidence of minor faulting that cuts strata in the conglomerate and offsets them short distances. In some cases it's easy to see the magnitude of the separation, because you can match up strata on the two sides of the fault. Now go back and examine the eastern end of the outcrop for still another rock unit.

At the eastern end of the outcrop, and continuing for some distance along the shore to the south, is another dark-greenish-gray rock not much different on a small scale from the dike rock you just looked at but a little finer grained. A prominent feature is the presence of rounded, irregular, light-colored masses, isolated or semiconnected. At least the smaller of these bodies are amygdules, showing that this rock (probably basalt, but possibly andesite; that's a matter for microscopic work) is a lava flow and not an intrusion. Degassing to form vesicles (which upon mineralization are called amygdules) is especially common at and near the tops of lava flows. In many places the amygdules merge into irregular, thicker, semiconnected bodies that stretch horizontally across the outcrop. These bodies seem to be arranged as sheets whose attitude is approximately the same as that of the strata in the conglomerates. These sheetlike bodies may have been minicaves formed near the top of the lava flow by collection and merging of volcanic gas bubbles, or in part by crusting and draining of lava. These cavities could have been filled either by precipitation of material by circulating waters long after solidification of the flow, or by washing in of fine sediment by flowing water, perhaps much earlier—or both. When the larger of these bodies are weathered in the right way they show delicate layering that in most places is approximately parallel tn the overall attitude of the bodies. This layering might well be sedimentary; see below.

To trace the contact between the conglomerate and the mafic volcanic rock at the point of the peninsula, wait for low tide and then walk down the east-sloping ramp of bedrock toward the waterline and look at the almost vertical face of mafic rock on the right (to the south) as you go down the ramp. On that face, try to trace out in detail the contact between the mafic rock, which is on your left as you face south away from the water, and the conglomerate, which is on your right. The contact is almost continuously exposed in this face, from the soil cover at the top down to the waterline. In the lower part of the outcrop, however, it's difficult to see because of the water stains on the rock. Where you can see the contact well you'll get the impression that it's extremely irregular: it meanders back and forth, with the conglomerate projecting deeply into the volcanic rock and the volcanic rock projecting deeply into the conglomerate. If you examine the contact very carefully in the upper, western part of the rock face you get the impression that the stratification strikes directly into a wall of volcanic rock, with no evidence of faulting, and if you trace the conglomerate downward in the outcrop at this point you'll see that it fills a crack or crevice downward to the left in the volcanic rock. (You can see this same thing a meter or two to the west also.) One gets the impression that these two rock units must have been deposited at about the same time; perhaps the nose or margin of the lava flow was advancing with a component to the right on this face while sediment was being deposited against it by a current of some kind. That's the only explanation I can advance for this interesting and rather unusual contact relationship. If this interpretation is correct, it shows how wrong you can be if you assume layer-cake stratigraphy. That said, however, it will soon become clear that on a larger scale, that of the entire peninsula, the basalt overlies the conglomerate.

Another significant feature of the contact is that you can trace the fine greenish-cream-colored crevice-filling in the conglomerate continuously into the; irregular cavity-fillings in the volcanic rock. This seems incontrovertible evidence that the finely laminated filling of the cavities, perhaps fine volcanic ash, was indeed washed in by water through open and interconnected cavities and pores in the volcanic rock, and so is clastic and not precipitated. If this sounds fantastic, keep in mind that flow rates are known to be high in modern highly porous basalts. You can even get an impression of cross-lamination in the filling of some of the larger cavities. Many of the smaller cavity fillings an; different in that they consist of white (quartz), green (epidote) and orange (potassium feldspar) crystalline material: this is consistent with the idea that many of the smaller cavities were closed and therefore inaccessible to flow, and presumably were filled much more slowly by precipitation. It's these small cavities to which the term amygdule should be applied. Some of these smaller amygdules show crudely concentric zonation, with two or three of these minerals in the succession quartz-epidote-feldspar from center to periphery. Now walk south along the east side of the peninsula, keeping track of the rock you're walking through.

As you walk, you'll see more outcrops of the amygdaloidal basalt. If we can assume that the basalt continues to have the same attitude of stratification as the conglomerate, you'll be walking up through the stratigraphic section. Some of the basalt shows none of the amygdules and sheetlike masses described above, suggesting that there is more than one flow in the sequence—but I've never spent the time trying to figure out how many flows might be present. Eventually, after a covered interval of a few tens of meters along a pebbly beach, you'll reach another outcrop of conglomerate. Examine this conglomerate carefully for the following features: composition, size, shape, roundness, and packing of the clasts; attitude of stratification; and sequence of strata within the outcrop.

The clasts are composed almost entirely of various kinds of felsic volcanic rock rather similar to the felsic clasts in the conglomerate at the point. Some are homogeneous, but others show pronounced flow banding. Many also contain small feldspar phenocrysts. Most of the clasts are well rounded, and many seem to have a discoidal shape. Again, such good rounding can come about only by transportation by strong flows of water. It's believed that discoidal pebble shapes tend to develop by transport on beaches rather than in rivers, but we can't say definitively just by looking at this outcrop that we're dealing with clasts derived from a beach. Note also that the conglomerate is clast-supported, in the sense that the gravel-size clasts are in contact with one another, with the intervening spaces filled with finer sediment. This suggests strongly that the sediment was deposited by fairly clear turbulent water flows, as in rivers or shallow marine environments, and not by thick slurrylike debris flows.

It's hard to perceive the stratification in this outcrop because the rock is so uniform: nowhere in the outcrop is there any discernible differentiation of strata by grain size or clast composition. If you look closely, however, you'll notice that the discoidal or elongated clasts tend to show a preferred orientation such that the long axes all lie in approximately the same plane. At first you may not be able to convince yourself that there is indeed such a preferred clast orientation, but once you see it, it will be unmistakable. This preferred orientation presumably reflects deposition of the clasts on a well defined sediment-water interface, and it therefore defines the stratification. The stratification thus revealed seems to have approximately the same attitude as that at the point, lower in the section, so it seems as though we're still in a conformable stratigraphic sequence, although we can't be sure because there's always the possibility of faulting in the covered intervals between outcrops. In the following, this conglomerate will be called the upper conglomerate.

If we're right in our assumption that we're dealing with a conformable sequence, we should be able to walk out the basalt unit and the upper conglomerate unit along strike—that is, trace them west across the peninsula and find them exposed on the opposite shore. But before you run off to try mat, think about where their contact should be located, based on the intersection of a gently dipping plane with an irregular land surface. Since the units dip gently south and the peninsula is high ground relative to the east and west shorelines, in map view the contact between the units should bulge northward as it's traced across the peninsula. Now find your way across the low ridge of the peninsula and try to trace out the contact between the basalt and the upper conglomerate unit.

The upper conglomerate unit occupies the first high ground of the peninsula south of the point where you started out. On ledges below this high ground you'll find the same basalt as along the shore. In a few places the contact between the basalt and the upper conglomerate is actually exposed; it's abrupt but conformable. It's not as easy to study the conglomerate in these landlocked outcrops, because the weathering is not nearly as favorable: the rock surfaces are not washed clean by storm waves, and lichen obscures much of the rock. In confirmation of the hypothesis that the contact between the basalt and the upper conglomerate unit bulges north as it crosses the peninsula, you'll find that when you stand at the contact here you're only a short distance, a few tens of meters, from the tip of the peninsula. Now continue to follow (or bracket) the contact all the way to the western shore—or if you don't feel like beating through the underbrush go back to the road and follow it along the shore.

On the western side of the peninsula you'll be able to locate the contact between the basalt and the upper conglomerate fairly well by looking at the low outcrops along the road, although the contact itself is not actually exposed there. As the contact comes out on the western shoreline it's lost in a deep outcropless reentrant, where the beach consists of well packed plant material and. lots of mankind's rubbish. The basalt forms a prominent point to the north, and conglomerate outcrops end far short of the waterline. If you stand at the beach and face south you'll be looking at a cliff of light-colored rock. Even from a distance you can see that the cliff doesn't look like the conglomerate you've been following, so you should be on your guard for some monkey business here: the basalt strikes right into this wall of different rock. Examine the rocks in this cliff (easy at low tide, impractical at high tide) and think about how they relate to the conglomerate unit you were following across the peninsula.

The rock in the cliff is light colored, crystalline, coarse grained, and homogeneous, so it's likely to be an intrusive igneous rock. Most of the rock consists of feldspar, which by its orange color is probably potassium feldspar, although there may be a fair amount of plagioclase here also. There's also some quartz, and if you look high enough above the waterline you'll see a small percentage of a ferromagnesian mineral, probably hornblende or biotite. Let's provisionally call this rock a granite, although technically it could be a quartz monzonite, depending on the proportions of potassium feldspar and plagioclase. This rock is better exposed just above the waterline around the point, but to get there you have to scramble up a steep little path up the; cliff or go back to the road and take the long way around. But before you do that, spend some time looking for other rock types at the base of the cliff and thinking about their relationships to the granite.

At the edge of the little beach below the cliff is a low outcrop of fine-grained mafic rock that should strike you as looking much like the basalt unit that comes out to the water just a few steps away at the other end of the beach. On the reasonable assumption that this rock belongs to the same unit, search carefully for its contact with the granite in the cliff. Toward the cliff the mafic rock becomes more sheared and fractured, and it's in contact with the granite in a weathered vertical reentrant where the rock is loose and finely crushed. This is a well exposed and fairly well defined fault that puts the mafic rock in contact with granite. Very small faults often show a single well defined plane along which movement has taken place, with subsequent healing of the fracture so that there is no preferential weathering at the fault contact. But in larger faults like this one there is often a crushed and fractured zone of weaker rock causing the fault zone to weather back and be poorly or not at all exposed. We're lucky to see the fault zone exposed here. This fault zone, one or two meters wide, would appear as a very thin line on a geological map of usual scale. You can get a good idea of the attitude of the fault plane: it strikes approximately east-west, appearing to head east across the peninsula, and is almost vertical. The nature of the displacement is a different matter, however, because we have no evidence for the direction of movement and thus none for the magnitude of the displacement. Now clamber up the hill, or walk around by way of the road, and examine the granite more closely down near the waterline at the end of the little point where the cliff ends.

Look first at the feldspars. Much and perhaps most of the feldspar in the rock is represented by coarse crystals of an orange feldspar that's most likely potassium feldspar. There is also a light-gray feldspar that's probably plagioclase. This rock should probably be classified officially as granite, although if it turns out to have about equal proportions of plagioclase and potassium feldspar it should be called a quartz monzonite. Note that down close to the waterline the ferromagnesian minerals weather preferentially, leaving cavities on the rock surface. Higher up, however, you can see weathered femags on the rock surface. These form only a very small percentage of the rock.

There are a few other features worth noting in this outcrop. Look closely at the outcrop surface and you will see well defined small and rounded bodies of darker rock completely surrounded by the granite. These are xenoliths—fragments of the wall rock that were incorporated into the magma as it moved and were carried along to the site of final cooling and solidification. Owing to thermal metamorphism the rock type in these xenoliths may not be very representative of the wall rock. Note also that the margins of the xenoliths seem a little blurred or frayed on a scale of individual grains; this suggests that these xenoliths were undergoing assimilation by the magma. This is one of the ways that felsic magma is changed in composition, or contaminated, as it rises through the crust. The xenoliths are very small here, but in a situation like this you shouldn't be surprised to see much larger ones—even so large that you wouldn't be able to see then in a single outcrop but would have to map them. You'll also see in this outcrop that the granite is cut by veins that seem to have about the same composition as the granite itself. These are probably late-stage intrusions associated with the emplacement of the magma. Now walk up the slope toward the road that curves around the hill near the crest, and watch for a change in rock type.

By the time you get up to the road you'll be in an area underlain by conglomerate. There's a nice flat outcrop of this conglomerate right in the road, and the knoll on the upslope side of the road consists entirely of conglomerate. This conglomerate is similar to the one at the tip of the peninsula: most of the clasts are felsic volcanics and fairly well rounded, and sorting is very poor. Now try to develop some hypotheses about the relationship between the conglomerate and the granite, and comb the slope below the road to try to locate the contact and find evidence in support of one or another hypothesis.

When a sedimentary rock and a plutonic igneous rock are juxtaposed, there are three possibilities for the nature of the contact: it could be a fault contact, an intrusive contact, or an unconformable contact. You should be able to bracket the position of the contact within a few meters in a belt or swath of ground wrapping around the hillslope just a short distance downslope from the road, but you won't be able to find a sharp and well defined contact between the two rock types: the granite grades imperceptibly into the conglomerate. In the absence of clear evidence for faulting, the best way to explain this gradation is that it represents what's called a graded unconformity. This develops by prolonged and deep weathering of a granitic land surface, to develop a layer of regolith grading downward into unweathered rock, and then deposition of coarse sedimentary material on that surface, buirying the mantle of regolith. Burial and relithification of the regolith results in a smooth transition from granite to conglomerate. Moreover, if the conglomerate rests unconformably on the granite in this way, it shouldn't surprise you to find clasts of the granite in the conglomerate. In the outcrop in the road, mentioned above, are several large, rounded boulders of granite that look identical to the underlying granite. This is further evidence for an unconformity, although we can't prove that these granite clasts are derived from the same granite. If they're indeed the same, they couldn't have been derived from the granite directly underneath, because of the layer of regolith discussed above; they might have been eroded from an outcrop some distance away and then transported and deposited with the sediment mantling the granite here.

It's difficult to see the stratification in the conglomerate on the knoll above the road. There are just a few places in the outcrop where you get a sense of the stratification on the basis of grain-size variations and preferred orientation of clasts. The attitude of stratification determined in this way, striking east or northeast and dipping very gently south, seems to be similar to that of the unconformity surface itself, of which you can get a crude idea by imagining a plane through the curving contact zone that wraps around the ridge below the road.

The strong similarity between the conglomerate resting on the granite here and the first conglomerate you saw at the tip of the peninsula makes it highly likely that these two conglomerates are part of the same stratigraphic sequence, and it's even tempting to speculate that they belong to the same rock unit in that sequence. If so, granite should underlie the conglomerate back at the point, but the outcrop doesn't allow us to ascertain that. The other side of the coin is that if the two conglomerates are indeed the same, the conglomerate here is likely to be overlain by the mafic volcanic unit. That's not necessarily the case, however, because of the possibility of lateral facies changes in the units. I'll leave it to you to investigate this possibility by reconnoitering the broad and low ridge that stretches east from this point toward the opposite shore of the peninsula. You'd find that to be a difficult task, because the outcrop surfaces are badly weathered and lichen-covered, and not nearly as easy to study as the shore exposures.

One more thing you might do before you leave is to try your skill in tracing a large mafic dike all the way across the peninsula. From where you studied the unconformity, walk south down the road to the edge of an elongated ephemeral pond, and turn left onto a path that runs east along the edge of the pond. When you get to a complicated grassy intersection, bear left a little, and then after about fifty meters cut to the right through the open woods and make your way to the east shore of the peninsula. Look along the shoreline for three or four very large, washing-machine-size blocks of dark rock. The southernmost bedrock outcrop along the east shore of the peninsula, in the form of a low wall of rock facing the water, is near these blocks. On this face you'll see a vertical contact, distinct and sharp, between lighter-weathering rock on the south and a darker-weathering rock on the north. The rock on the south, as you face away from the water, looks the same as the mafic dikes you saw at the tip of the peninsula. The rock on the right is a little messier, but it too is fine grained and dark gray. It turns out that the rock on the left is part of a mafic dike that seems to belong to the same set as the three at the northern tip of the peninsula. Its southern contact is not well exposed here, but you can bracket the position of the contact fairly well; the dike is a couple of meters thick. Now try to walk out this dike along strike to the west across the peninsula. If you're interested in trying this for yourself without any coaching, do so before reading the next paragraph. The only hint I'll give you is that it can indeed be traced all the way across. It's easy to trace the dike from the shoreline back to the road. There are two or three large, low-to-the-ground outcrops between the shore and the road that expose the dike and one or both of its contacts well. The contrast in color between the weathered surfaces of the dike and the wall rock is almost nil in these woodland outcrops, but the contrast in surface texture of the outcrop is considerable: the dike has smooth surfaces, but the wall rock has rough and jagged surfaces. It's not as easy to follow the dike on beyond the road. You can do some bushwhacking to try to find the next outcrop, or you can go directly to the next paragraph.

The next good outcrop of the dike is along the path along the north edge of the pond, in the steep slope about halfway down the path. There the dike is in contact with about the same kind of rock as before. The strike and thickness of the dike are about the same, but the dip is different. The dike has a little side branch here, a few tens of centimeters thick, on the upper (northern) side. It's not uncommon for dikes to branch or split; sometimes the branches rejoin, and sometimes they splay out and disappear. A sightline along strike from this outcrop passes diagonally across the west end of the pond toward high ground near the west shore, where you'll find the dike next. There, in a steep north-facing cliff of granite (you're just south across the water from the little point where you first looked at the granite) the dike has about the same dip as the face of the cliff itself; the dike is plastered against the cliff, with a large piece of the granite of the hanging wall still attached. You can keep on following this dike until it finally strikes out into the water farther along the shoreline to the south (it cuts overland to get there, so you couldn't follow it along the water even if you were willing to do some swimming along the base of the cliff) but it's not very accessible for study there.

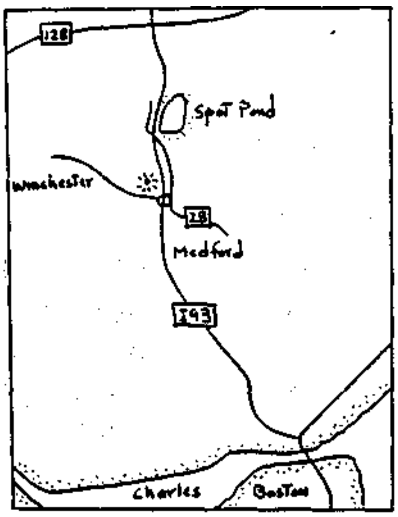
The interbedded conglomerates and volcanics constitute the base of the Boston Bay Group, a thick sequence of coarse and fine clastics that occupies the Boston Basin. The age of the Boston Bay Group was controversial for many decades, until very recently when fossils of the Latest Proterozoic age were found in the Boston Bay in the excavations for the Red Line extension from Harvard Square to Porter Square. The Boston Bay Group unconformably overlies the Dedham Granite, which elsewhere has been dated isotopically at about 600 million years. So not a lot of time—millions to a few tens of millions of years—intervened between the emplacement of the Dedham and the deposition of the Boston Bay.

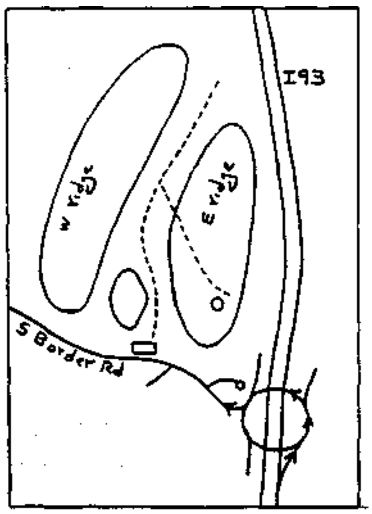
MEDFORD, MIDDLESEX FELLS RESERVATION

(Boston North Quadrangle)

Dedham Granite (Proterozoic), Lynn Volcanics (Proterozoic?), Medford Diabase (Jurassic)

Thick dike; crosscutting intrusions; pyroclastic volcanics





This area is very easy to reach by car from Boston. The geology is spread out over a fairly large area, but the walking is easy, mostly along unpaved roads and marked trails. This is strictly an igneous trip: you'll see rocks of two plutons, one mafic (an enormous dike) and the other felsic, and lots of felsic volcanic rock. In the area is a low stone tower that affords a fine view of the Boston Basin, so you might bring binoculars.

LOCATION

Take I93 north from Boston by heading north on the Central Artery and bearing left just after you pass by North Station. Keep your eye out for a stone tower on the ridge that stretches east and west in front of you as you drive north across the lowlands around the Mystic River; the wooded hill-slopes around the tower are where you're heading. Get off at Exit 7, labeled Mass. Route 28, a little short of 5 miles north of the start of I93. At the end of the offramp bear left over I93 and take what's called the South Border Road west toward Winchester. There's a parking area on the right less than 0.2 miles from I93. The parking area is sometimes open and sometimes not, but you can always find a place to pull off along the road itself. Walk north along the unpaved road that leaves the northeast corner of the parking area at a large metal gate. There's a shallow pond on your left, and woods to the right. You'll be walking straight toward the tower on the hill you saw as you drove north on I93, but you can't see the tower through the trees.

GEOLOGY

Where the road curves upward to the left, at a low stone wall that overlooks the pond, there are some outcrops in what seems to be a small abandoned quarry on the right. Along the upper edge of the outcrop you'll see the little drill holes that were used to split blocks away from the rock face. You won't see any fresh surfaces here, but you'll be able to see that the rock is uniform, crystalline, and coarse grained, with about equal percentages of feldspar and ferromagnesian minerals. So you know you're dealing with a mafic intrusive igneous rock; it might be a monzonite, a diorite, or a gabbro.

The only other outcrop in the immediate vicinity is a low and rounded rock surface that pokes up from the surface of the pond just below the stone wall—and you can't even be sure it's in-place bedrock. But it has the same smoothly curving weathering surface as the rock surface that's right at your feet in the road by the stone wall, which in turn looks the same as the undoubted bedrock in the little quarry. So tentatively you can think of this as a group of outcrops that represent some connected rock mass, or rock unit.

You won't find the contacts of this intrusive igneous rock unit anywhere in the immediate vicinity. But if you look over to the west side of the pond you'll see a long cliff of jagged and irregular outcrop that even from this distance looks different from the smooth and rounded surfaces of the outcrops at your feet. If you take a few more steps up along the road you'll see a trail leading up the steep hill to the right. Just a short detour up this path (not all the way up to the stone tower at the crest of the hill) brings you into jagged outcrops of light-weathering, very fine-grained rock entirely different from the mafic intrusive rock—but the contact is not exposed here.

What you've seen so far gives you enough evidence to frame the tentative hypothesis that you're dealing with an intrusive body with approximately tabular shape and appreciable width, of the order of a hundred meters, that occupies the lowland between two ridges, one on the west and one on the east. A natural thing to do to test this hypothesis is to continue north along the road, up the little valley that seems to be occupied by this intrusive rock, to see if this relationship is maintained, and also to try to locate the contacts of the intrusive body. I suggest that you defer any further inspection of the rocks to the east and west; you'll reach the hill with the tower and the fine-grained light rock later by a more instructive route.

The first place you get another chance to look at the coarse-grained igneous rock right at the road is where another road branches sharply back to the right (to the southeast) and ascends toward the tower. At this point there's a large, rounded outcrop at the road intersection, where in white paint we learn that Julie Q. loves Johnny N. Here some of the edges of the rock have been chipped off by earlier geologists, and you can see better the texture and composition of the rock. Take a detour by that road to look at the geology around the tower.

The road forms the upper edge of a large overgrown quarry. On your left, just a short distance up the road, is a good outcrop of the same coarse-grained mafic igneous rock, crumbling by granular disintegration. The disaggregation at the surface is presumably caused by expansion of the grains upon incipient chemical weathering. The base of the outcrop is mantled by piles of mineral grains and loose, broken rock. On the crumbly surfaces of this outcrop it's a little easier to see the texture of the rock. The area to the left of the road as you ascend is a good place to look for the eastern contact of the coarse-grained igneous rock. A good way to do this is to walk directly east from the crumbly outcrop along the road until you encounter different rock. Search for the contact, walking to your left and right if necessary, to bracket the position of the contact and find a point where it's actually exposed. Be sure to look only at genuine bedrock; factor out any loose blocks and boulders.

While working on this hillslope, don't get discouraged about trying to identify the rock type. The outcrops are covered by green lichen and mossy growth, making it difficult to find good rock surfaces. But if you use the same criterion we developed before—the overall texture of the rock surface—you can usually tell readily which rock type you're looking at here.

Within several meters you'll run into bedrock that looks finer grained and much more jagged on the surface. But the contact here (at the base of some big trees, one of them dead) is not well exposed. I suggest that you walk south (that is, to your right as you face away from the road) to find better contact relationships. As you walk, try to keep the finer-grained igneous rock on you right. In the very next set of outcrops you'll find the contact fairly well exposed. It's sharp and well defined, although somewhat irregular on a large scale. You can get the impression that the igneous rock is finer grained right at the contact; such a chilled margin suggests that the igneous rock is intrusive into the finer rock, but the nature of the weathered surface makes it hard to study this in detail here. On an even larger scale, from outcrop to outcrop, the contact seems extremely irregular, with salients of the igneous rock projecting deeply into the finer rock in the little valleys and the finer rock projecting into the igneous rock in the little spurs or ridges along the slope.

If you follow out some of the east-pointing salients of the igneous rock in the little swales or valleys you'll find what seem to be branch dikes or thick apophyses extending into the finer rock from the main body of the intrusion. Even in their centers these thinner dikes are noticeably finer grained than the main intrusion. This makes sense, because these thinner dikes must have cooled much more rapidly than the main intrusion. Now go back to the road and. continue south for the last hundred meters until you reach the tower. Around the tower is the best place to examine the finer, intruded rock.

By the time you get to the tower you'll be entirely within the finer rock. (If it's a clear day be sure to climb the tower to yet a magnificent view of the Boston area. Binoculars would be advantageous. You can survey all of the major topographic features of the area, all the way south to the Blue Hills.) Almost all the rock in the vicinity of the tower is of one kind: it's gray to almost cream-colored on weathered surfaces, dark gray on fresh surfaces, very fine grained, and tough. One of its most striking features is the presence of small (1-2 mm) light-weathering chunks or crystals that look like weathered feldspars. Also present, more abundant in some places than others, are larger clasts or fragments of various fine-grained rock types. One of the most distinctive of these is what looks like fine-grained and very pure quartzite, white to light-gray weathering, but there are several other hard-to-identify rock types. You have to decide whether this rock is igneous or sedimentary: is it a conglomerate or a volcanic rock? And if it's the latter, is it a lava flow or a pyroclastic deposit?

The extremely fine grain size, the toughness (probably the result of abundant finely crystalline feldspar and quartz), the light weathering color, and the presence of feldspar crystal clasts all suggest a volcanic rock. In fact this rock is a classic and very characteristic-looking felsic volcanic rock. But is it a lava flow or an ash deposit? You could imagine it to be a lava flow, in which case the rock fragments are xenoliths broken off the wall rock and incorporated in the magma. On the other hand, you can just as easily imagine it to be an ash fall or an ash flow, in which case the rock fragments are chunks of preexisting rock that were explosively blown out of a volcanic vent. The presence of the abundant feldspar crystals can be explained by either hypothesis: they are either phenocrysts in a lava or crystal fragments in a tuff. It's difficult to distinguish between these two possibilities on the outcrop, w' hout the benefit of thin-section work. Even in thin section it might be difficult to tell, because recrystallization tends to obliterate the textural details by which the two kinds of rock differ. The great abundance and variety of rock fragments, together with their uniform distribution, suggest a pyroclastic rock rather than a lava flow. Another piece of evidence along this line is the total absence of any flow structure in the rock. There's no obvious stratification, either, and if this is a pyroclastic rock, that points toward its being an ash flow rather than an ash fall. As luck would have it, the only bit of evidence for stratification I've been able to find anywhere around the tower is in a block that's not actually part of the outcrop. It sits on the right-hand side of the little set of steps that leads to the door of the tower. If you look closely on the east face of that block you'll see a little packet of laminae bowing down to fill a depression in the underlying rock. This looks like a thin interbed of stratified volcanic ash, perhaps separating two thicker beds. Unfortunately, I haven't found any other such beds as in-place bedrock. Another noticeable feature of the volcanic rocks can be seen in a little knob on the other side of the road from the tower, to the north. There's a body of much lighter-weathering and finer-grained rock, roughly tabular in shape and the greater part of a meter thick, that cuts through the felsic volcanic rock in an east-west direction and dips steeply to the north.

Both of its contacts with the volcanic rock are sharp and irregular. It seems to be about the same in composition as the felsic volcanic rock, but it doesn't contain any of the coarser clasts. The geometry of the contact relations suggests that this rock intrudes the volcanic rock: you can see apophyses of this finer rock extending into volcanic rock, which here weathers a bit darker than at other points. This body might well have been a little feeder dike at very shallow depths supplying some later volcanic activity.

Just south of the base of the tower is a thin mafic dike that shows sharp intrusive contacts with the felsic volcanic rock. Its attitude is about east-west, and you can imagine it being another one of those offshoot dikes from the main dike to the west, although to prove that you'd have to walk it out to the west.

Leading north from the tower is a trail marked by white blazes. Follow it, and you'll soon cross another east-west mafic dike, four or five meters thick, on which have been carefully hewn some very old dates and initials. If you follow this dike west down to the road, just several meters away, you can see that this is one of the dikes that branch off from the main mafic intrusion. There's another similar dike just to the north, with a sliver of the fine-grained volcanic rock caught between the two mafic dikes.

Now go back down to the main north-south road in the valley, by either the road from the tower or the white-blazed trail. Continue north up the road in the direction you were originally heading before detouring to the tower. From this point on, the quarry workings on the right side of the road become more numerous. Soon you'll pass a clearing on your left that's floored by a large, low mound of crushed rock that must have been dumped during the

the little pass you'll find yourself crossing an easy-to-miss trail marked with white blazes on trees. Take the trail to the right (to the north). Walk along this trail for a couple of hundred meters until you reach a bluff that overlooks I93, whereupon the trail angles sharply down and to the left. This is a good place to start looking at the rocks in this western ridge, west of the thick mafic dike.

Although much of the outcrop surface here is badly weathered and stained dark gray, there are lots of places to see fairly fresh surfaces that show details of texture, composition, and structures. You'll see that this rock is indeed a coarse-grained felsic igneous rock, with abundant feldspar, both orange-colored and white, a fair percentage of quartz, and a small percentage of femags. This might be a granite, a quartz monzonite, or a granodiorite, depending on the feldspar composition; I'll use the term granite for it, just as a field term. Look around this outcrop, and see what other rock types you can identify, because not all of the rock here is granite.

There are numerous bodies of much finer-grained rock that seem to be completely enclosed in the granite and show sharp and irregular contacts with it. They range from bodies no larger than the size of your fist to bodies some meters across. It's clear that these are xenoliths in the granite. The grain size in these xenoliths varies from very fine to medium. The rock weathers light-gray to almost pinkish or orangish, and where you can see fresh surfaces (where previous investigators have kindly chipped off material with a hammer) the color is uniformly medium-gray. On favorably weathered surfaces you'll see that much if not most of these xenoliths show uneven grain size: they show very light, almost white-weathering crystals a millimeter to a few millimeters across surrounded by a finer mass of light and dark material. Some of these xenoliths, however, are finer grained and more grayish, and show a sense of stratification or perhaps foliation.

Do these xenoliths look like anything you've seen so far in this area? Remember that most probably this granite some has to be in contact with the fine-grained light-weathering rock you saw back at the tower, because that rock extends northward along the eastern ridge to a point just opposite your present location, so if you closed the dike back up the two rock types would be close together. The outstanding characteristic of the fine-grained rock at the tower is the presence of prominent feldspar crystals in a very fine-grained groundmass. Most of the xenoliths here are texturally rather similar, in that they show coarse, very light-weathering crystals that look like weathered feldspars surrounded by finer material, although that finer material is coarser than back at the tower. You can suppose as a working hypothesis that these xenoliths are the same as the rock at the tower except that they have been slightly thermally metamorphosed by close contact with the hot granitic magma and have therefore become slightly coarser. According to that

In the granite along the east side of the path just a few meters beyond the southern contact of this dike is a large xenolith, white weathering, very fine grained, and brittle-looking. This could be a quartzite, although it might also be a felsic volcanic rock. Interestingly, in the next large xenolith, right in the path, which is of the kind described earlier, you'll see a few small inclusions of what looks like the same tough, very fine-grained, white-weathering quartzite or felsite. It may well be that what we're seeing here is a xenolith within a xenolith, and the xenolith within the xenolith came from the same rock unit as the other large xenolith (just described) in the outcrop. But we can't really prove that.

When you get to the little swale that the path crosses, and you walk south, you encounter another dike of the same kind as the last, again with sharp contact and chilled margins against the granite. Some of the rock surfaces on the west side of this path show remnants of glacial striations. Now cross the rock-strewn path in the little pass by which you first reached the white-blazed trail, and continue south along the trail.

Once you get across the swale and up onto the next set of outcrops along the white-blazed trail you can see right away that the rock is entirely different from the granite: it's finer grained and has a more complicated structure, involving a mixture of what seem to be different rock types that weather differently. There is rough-weathering, fine-grained, seemingly crystalline rock that can't be studied very easily, and intermixed with this rock is light-weathering and smoother-weathering, very fine-grained rock that looks a bit like a quartzite or a felsite, but it's very hard to sort out the relationships of these two rock types in the outcrops here. The rocks are cut by numerous thin minor veins, running this way and that, that tend to weather out in relief. What's the relationship between the granite and this new finer-grained rock?

First of all, you might try to compare the look of this rock with the xenoliths seen earlier in the granite. It should strike you that they are similar, but not similar enough for you to be able to say definitely at this point that they are the same. If they are indeed the same, then it's likely that the granite intruded this rock and incorporated some of it as xenoliths. If this rock is not the same as those xenoliths, however, then you don't know anything about the nature of the contact. These rocks, which almost by a process of elimination must be volcanic rocks, could then rest unconformably on the granite. Or the two could be in fault contact. Even if a fault does run through the swale, either of the other two possibilities for the nature of the contact (intrusive or unconformable) could still hold, although you'd be lucky to see any contact except the fault contact.

One strategy, when you are faced with really messy rocks and relationships like these, is to walk the rocks out and see if they grade over into outcrops of rock types that are easier to study. It turns out that this strategy works well here. Walk directly south along the ridge, finally leaving the white-blazed trail as it goes downslope to the left into the valley, and stop at the south-facing end of the ridge, where it slopes sharply down to the south and you get a good view of Boston.

Here the rocks are clearly all felsic volcanics. There seem to be two rock types. One, with very rough weathering surfaces, is relatively dark; its color on weathered surfaces is gray with a suggestion of orange. The texture of the rock on weathered surfaces shows clearly that the rock is pyroclastic. The other rock type in the outcrop, with much smoother weathering surfaces, weathers uniformly very light gray with a slight tan cast. Its texture is less obvious, but on favorably weathered surfaces it too looks pyroclastic. The weathering of the lighter phase is irregular, in that any given area of the outcrop shows some areas that weather much rougher and darker, with miniature islands or buttes of smooth-surface weathering surrounded irregularly by areas with rough-surface weathering. Where the surfaces are rougher the texture is more clearly pyroclastic. This difference in weathering surface is probably caused not so much by underlying lithology as by randomness of weathering. On a larger scale it's clear that the rougher, darker-weathering rock occupies the southern half of the outcrop and the smoother, lighter-weathering rock occupies the northern half. I can convince myself that the contact between the two rock types is broadly planar and strikes east-west across the outcrop and dips at a moderate angle to the south. But this contact is complicated in detail. Moreover, it's clear that in the southern half of the outcrop there are larger irregular masses of the smooth light rock surrounded by the rough dark rock. We're probably dealing here with pyroclastic stratification, but the nature of the stratification is not clear. The irregularities might be explicable entirely by the differences in weathering behavior, or we may have to appeal to some primary effect like churning of the material during deposition, or incorporation of large masses or clasts of earlier pyroclastic material in later pyroclastic flows of some kind. I haven't yet come close to working out these details in my own mind.

If you look closely at favorably weathered surfaces of the rough dark rock, and also at the few fresh surfaces in the outcrop that have been exposed by hammering, you'll see that the rock consists of an irregular and very poorly sorted jumble of clasts that consist partly of crystals (feldspar is prominent) and partly of what seems to be preexisting, very fine-grained volcanic rock. It's harder to say anything about the light smooth rock, although on some weathered surface; one gets the impression of the same jumble of feldspar crystals and fine-grained rock fragments.

There's an extremely interesting rock surface on this outcrop you should hunt for and study. Just south of the highest point on the knob, and just south of the contact between the two rock types, there's a little west-facing slope underneath an overhang where fresh rock has been exposed by hammering over an area a few square feet in size. Some charcoal from a campfire rests on the flat rock surface below. Here you'll see clasts up to several centimeters across of what looks very much like the granite that you saw farther north along the ridge. If these clasts are indeed of that granite, then these volcanic rocks must overlie the granite unconformably. But of course the clasts could have been derived from a similar but different granite, of a different age.

A few tens of meters north along the ridge from the large expanse of outcrop at the southern end is a small low-to-the- ground outcrop (you'll have to search for it) where a mafic dike showing a chilled margin against the dark rough volcanics cuts an earlier mafic dike, seemingly identical in composition, which itself cuts the volcanics and shows a long tongue or apophysis into the volcanics. In the later dike especially, but also to some extent in the earlier dike, there's a suggestion of flow structure right near the contact.

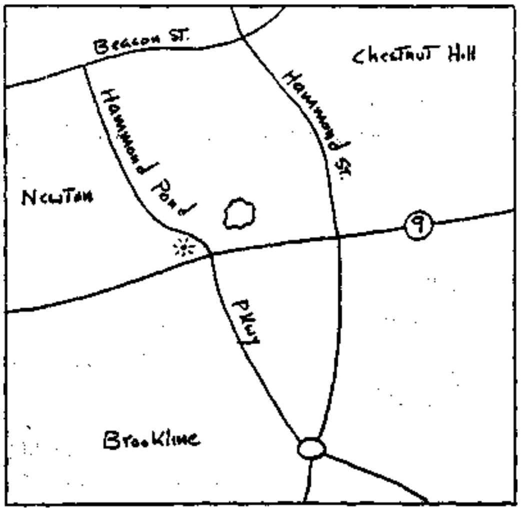
Now, as you trace the volcanics back to the north along the ridge, in the direction of the contact with the granite, you can see that these rocks we formerly had so much difficulty with are in fact very similar to the clear-cut volcanic south end of the ridge. They are not as well exposed, the weathered surfaces are messier, and the rock seems more sheared and more mixed—but the same rock types are clearly there. So now we know that we are dealing with volcanics in contact with the granite. But since we don't see apophyses of the granite cutting the volcanics, we don't yet know whether the granite intruded the volcanics or the volcanics rest unconformably on the volcanics. But now that you've seen all those volcanic rocks south of the little pass, you should get the distinct impression that the xenoliths in the granite are very similar to these volcanics—although we can't prove that by just what we see on the outcrop. It seems likely to me that the xenoliths are the same as the volcanics to the south, meaning that the granite intrudes the volcanics. The granite clasts we saw in the volcanics at the south end of the ridge seem to contradict this, but remember that those granite clasts could represent some earlier granite, perhaps unrelated to the one we see here.

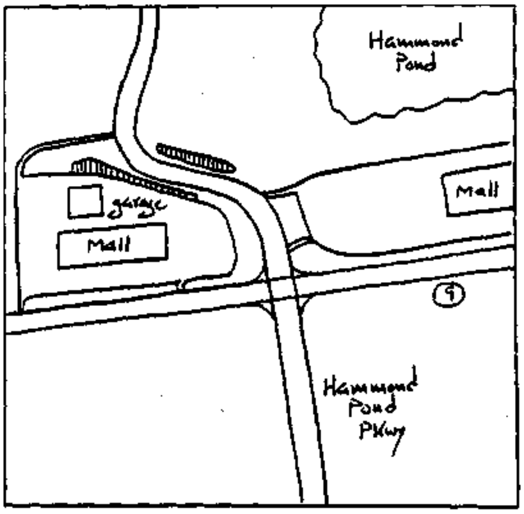
The big dike in this area is the Medford Diabase Dike (diabase is a petrographic term for a mafic igneous rock with a particular kind of grain-to-grain texture), and is shown on the bedrock map of Massachusetts as being of Jurassic age. The granite cut by the dike can reasonably be considered to be equivalent to the Dedham Granite, which is so widespread around Boston. The volcanics are traditionally included in the Lynn Volcanics. Whether these volcanics are older or younger than the Dedham here depends crucially on the kind of contact relationship discussed above. Perhaps in a nearby area you might find a more definitive contact exposed, but just on the basis of what you've seen here you can't say anything about the age of the volcanics except that they are pre-Jurassic, which doesn't help much.

NEWTON, CHESTNUT HILL MALL
(Newton Quadrangle)

Roxbury Conglomerate (Proterozoic)

conglomerate; sandstone; cross-stratification; mafic dike; glacial striae





This locality is easily accessible, not only by car but also by trolley (Green Line, Riverside D branch). It offers excellent exposures of the Roxbury Conglomerate, whose age and depositional environment have been controversial for many decades. The exposures are in cuts along the edge of Filene's parking lot at the new mall at Chestnut Hill. The most peaceful time to examine the cuts is on a Sunday morning, when the place is deserted. This trip requires the least physical exertion of any described in the guidebook.

LOCATION

This stop is at the northwest corner of the intersection between Route 9 and Hammond Pond Parkway in Newton. The outcrops are along the northern edge of the upper-level parking lot next to Filene's at the Chestnut Hill Mall. You can enter the Mall either by turning west off Hammond Pond Parkway at a traffic signal a short distance north of Route 9, or by turning north off Route 9 a short distance west of the bridge over Hammond Pond Parkway. Make your way to the northernmost part of the parking lot, farthest from Route 9. Stand at the foot of the parking garage next to Filene's and face north, away from Filene's; you'll see an almost continuous low cut extending along the edge of the parking lot for almost a hundred meters. Across Hammond Pond Parkway, which is only a few steps behind the cut, there are good older roadcuts in the trees.

You can reach the locality easily on the MBTA Red Line. Take a Riverside car, marked D, outbound from Boston and get off at Chestnut Hill. Walk south on Hammond Street, which crosses over the tracks just beyond the station, to Route 9, just a few blocks away. Walk along Route 9 for a few tenths of a mile until you come to Hammond Pond Parkway. Bear right (north) on the Hammond Pond Parkway for a few hundred feet to where a footpath leads up a rock-lined slope from the "old mall" (the one you just passed) and the "new mall." Stay along the northern edge of the parking lot of the new mall until you come to the cuts just opposite the multistory garage.

GEOLOGY

Start with the conglomerate at the west end of the cut, to your left as you face the cut from the parking lot. First of all, see if you can spot the attitude of stratification. Look for differences in composition or texture from stratum to stratum, or for preferred orientation of clasts.

You'll probably soon give up in frustration, because there are few stratification features in the entire outcrop. Upon close examination you might be able to convince yourself that there's a subtle preferred orientation of the gravel clasts, and also a few thin and discontinuous sandy beds in the outcrop; on this basis, it looks as though the stratification strikes about east-west and dips gently north. (Once you see the obvious stratification farther along the outcrop, and then come back to the conglomerate, you'll be much more comfortable about this.) Now look at the gravel clasts themselves.

The clasts are all fairly well rounded. We have to assume that to be so well rounded they must have been transported by currents, either in a river or on a beach. For clasts this size it doesn't take too great a distance of transport—kilometers to tens of kilometers—to attain this degree of rounding. Note also that the conglomerate is clast-supported: the gravel clasts are packed so as to be just about touching, rather than floating freely in a matrix of finer material. (The material in the interstices is finer grained: sand and perhaps even mud.) This has implications for the mechanism of deposition: the sediment must have been deposited by free-flowing, turbulent currents rather than being "poured" into place as debris flows—which we know by direct observation on land and by inference under the sea to be important in the deposition of matrix-supported gravels.

clast-supported. Alternatively, the conditions of deposition by a turbulent current might just have happened to be extremely uniform; then the minor differences in texture from bed to bed could have been obliterated by subsequent diagenesis, and the result now looks completely homogeneous to us. We can't really choose between these two possibilities just by looking at this outcrop—although I suspect that the latter is the case.

This conglomerate is one of a great number of similar outcrops of the Roxbury Conglomerate—the familiar "puddingstone"—in a large area southwest of Boston. The formation consists of a large number of individual conglomerate bodies interbedded with less resistant sandstones, which are much less often seen in outcrop. The entire sequence of Boston Bay Group clastics, which consists of interbedded conglomerate, sandstone, argillite, and mafic volcanics, thins and becomes finer grained from south to north, implying a southerly source for the material. That's not something you see from just one outcrop, though; extensive mapping is needed to establish such things. The finer part of the sequence, the Cambridge Argillite (also called the Cambridge Slate), is especially poorly exposed. Much of our information on the stratigraphy of the Boston Bay Group comes from the subsurface, from water-supply tunnels and sewage tunnels driven earlier in this century. Now walk east along the edge of the parking lot. There's a break in the outcrop between the conglomerate and the next cut to the east.

The rocks in the cuts to the east are finer grained than the conglomerate, and are mainly sandstone. They show no striking difference in weathering color from bed to bed, but even so the stratification here is much more obvious than in the conglomerate because there are substantial variations in grain size from bed to bed. Aside from the rock surfaces produced by blasting during construction of the parking lot, there are two kinds of rock surface in the outcrop: there's more than one set of joint planes, mainly steeply dipping, and also parting planes along the stratification. The stratification clearly dips gently north, about the same as we thought in the conglomerate. If there's no monkey business between these outcrops and the conglomerate, that means that the sandstone dips underneath, and therefore underlies, the conglomerate. These same sandstones are well exposed in cuts along the east side of Hammond Pond Parkway, just a stone's throw away, and there you can actually see the contact between the sandstone and the conglomerate. Now take a close look at the stratification features in the sandstone along the parking lot.

Lamination in the sandstone is very faint, but at least in places discernible, especially on certain joint planes. On one large joint plane—it's slightly overhanging and sometimes covered with a little dried mud you'll have to dust off—you can see distinct sections through small-scale ripple cross-lamination. Also, there's just a suggestion that some of the exposed bedding surfaces are rippled—that is, they show the actual geometry of the ripples. On these bedding surfaces there's a thin film of red mudstone that helps define the shape of the ripples. There are several thin red mudstone interbeds in the section. The ripples aren't well enough preserved to say definitively whether they are current ripples or oscillation ripples, but I'm inclined to think that they are oscillation ripples. These rippled bedding surfaces are better exposed in the cuts on Hammond Pond Parkway. So at least we know that the sandstones, if not the conglomerates, were transported and deposited by turbulent movements, oscillatory or unidirectional, of relatively clear water.

Interbedding of sandstone and conglomerate on a scale of meters to tens of meters is characteristic of much of the Roxbury southwest of Boston. The thick conglomerates are abundantly exposed, both naturally and in roadcuts. The finer-grained intervals of the section, however, are seldom seen in outcrop, so one gets an unrepresentative idea of the section. This is a common problem in looking at sedimentary sequences; always think about what you might be seeing in the covered intervals.

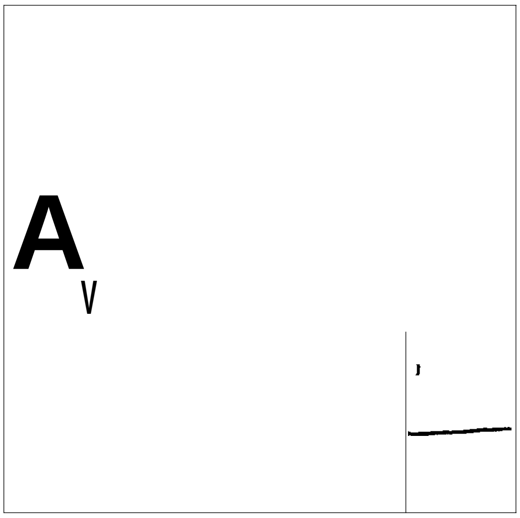
Another good and easily accessible place to see the sandstones of the Roxbury is at the intersection of Hammond Pond Parkway and Beacon Street, less than a mile north of the Mall. Along the north side of Beacon Street just west of the intersection are wooded cliffs with houses above. The sandstones are well exposed at the base of the cliffs, along the path that serves as the sidewalk. You'll see distinct lamination and just a suggestion of broad and low ripples on some of the rock faces near to the ground. Overlying these sandstones, higher in the cliffs, is a conglomerate closely similar to the one at the parking lot.

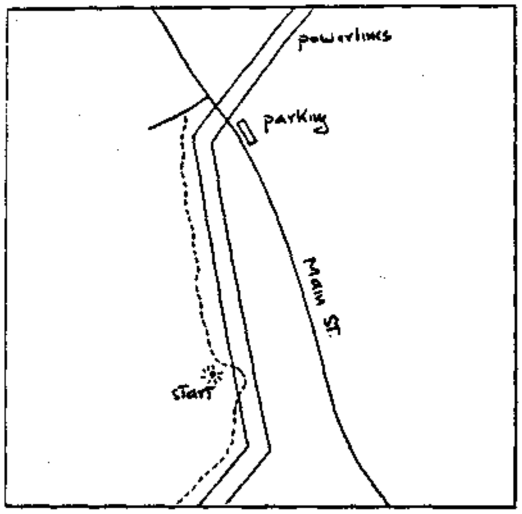
A similar extra outcrop is at the intersection of Route 9 and Route 128. Take Route 9 west from the Mall, and turn onto the Route 128 north onramp. Park on the grassy strip alongside the onramp and walk back around the curve onto Route 9. In the upper part of the cut just before the onramp is Roxbury conglomerate, and low in the cut, just inside the guard rail, is soft-weathering, well stratified sandstone underlying the conglomerate. The contact between the sandstone and the conglomerate is well exposed here. There is substantial relief on the contact: the contact cuts up and down through the previously deposited sandstone. This tells us that there was a period of erosion of the sandstone before the conglomerate was deposited.

SAUGUS, POWERLINE AREA
(Boston North Quadrangle)

Westboro Formation (Proterozoic), **Dedham Granite** (Proterozoic), Lynn **Volcanics** (Proterozoic?)

sedimentary structures; cross-cutting intrusions; low-grade metamorphic rocks; felsic volcanics





This locality is most easily reached by car, but you could also cycle there from Boston. You have to walk the greater part of a mile from where you park to where you look at the rocks, so bring everything with you. The outcrops are along a cleared powerline route, so the area is open and scrubby, and I imagine that it can be unpleasantly hot in the summer.

LOCATION

Take Route 1 north from Boston, and get off at Main Street West in Saugus. It's as if you were turning left from Route 1. To do so you have to pass under the Main Street overpass before taking the offramp. After 0.8 miles you'll cross the Lynn Fells Parkway at a traffic light. This a substantial intersection but is poorly marked. (If you're coming from the north on Route 1, before you get to Main Street you can bear right onto the Lynn Fells Parkway, which departs to the southwest from Route 1 at about a 45° angle at a traffic light, and proceed just about a mile to the intersection with Main

Street.) From the intersection of Main Street and the Lynn Fells Parkway, drive north on Main Street for 1.2 miles through thinly settled country until you see powerlines that cross the road at right angles. There's plenty of room to pull off and park on either side of the road just before you pass under the powerlines.

A short distance west of where they cross the road the powerlines bend left and then run straight south. To get to where I want you to start looking at rocks you need to walk south along the powerlines for about half a mile, about to where they make their next bend to the west. To do that, walk under the powerlines along the west side of the road and turn left onto a little side road called Harmon Road just beyond the powerlines. After just a few hundred feet, turn left again (south) onto the hilly and winding powerline road. Try to ignore all the outcrops you could be looking at, and walk about half a mile down the powerline road (which runs near the western edge of the treeless powerline swath) until the road turns sharply left down a steep slope and then hooks sharply right into a little grassy lowland. Here the towers of the easternmost powerline are stout green metal columns, and those of the other two are metal trusswork towers. The middle powerline tower, where I want you to start, is named T146267.

GEOLOGY

Start by examining the large, rambling outcrop west of the base of the westernmost tower. This outcrop, just south of the bend and slope in the road, has a steep but accessible south slope down into an open grassy swale. It contains a lot of information, so it's worth quite some time. See how many rock units you can identify, and think about their relationships.

Most of this outcrop is a stratified rock ranging from medium gray to darker greenish gray in color. The stratification, which you may have to hunt for but which is clear once perceived, is on two scales: an alternation of two intergrading major rock types on a scale of the order of a meter, and lamination in the darker beds, on a scale of the order of a millimeter. The stratification strikes about east-west and dips steeply south. The south slope of the outcrop is approximately a dip slope: various parts of the rock surface on the slope represent actual bedding planes in the finer, darker rock. Now examine these stratified rocks in detail.

The lighter beds, which are coarser grained, are classic pure quartzites; you'd see in thin section that they are almost 100% quartz, uniform in size and well sutured. They must have started out as well sorted and therefore well washed pure quartz sand. These quartzites are massive and unlaminated. (It's uncommon for pure quartzites to be otherwise, because lamination in pure quartz sands is always a subtle matter, visible mostly by slight differences in resistance to weathering, and metamorphism tends to obliterate these differences.)

The darker beds, some of which are well laminated, are finer grained, and on the outcrop you can only guess at their composition. They probably started out as silts and muds, and perhaps even very fine sands, and mild metamorphism has not only thoroughly reorganized the phyllosilicates but also converted some or even most of them into chunky minerals like amphiboles. (This is presumably why these rocks show no cleavage at all.) Although a bit interpretive, a good field term for these rocks would be metasiltstone.

Here, and also in other nearby outcrops of this same unit a short distance north, certain parts of the outcrop show clearer stratification than other parts, on both the smaller and the larger scales; this could be due either to partial disruption of the deposited sediment while still fairly soft, or to much later rock deformation localized in certain places, or both. This question will have to be addressed later.

These quartzites and metasiltstones are considered to be part of the Westboro Formation, a rock unit that crops out in a long, narrow, discontinuous belt extending southwest through eastern Massachusetts; see the geologic map of Massachusetts. To the southwest the metamorphic grade is higher, and no primary sedimentary features can be recognized. This locality is therefore the very best place to try to gain some insight into the original nature and depositional setting of this fascinating and (as will presently be discussed) very old rock unit.

Whenever you encounter a sequence of strata it's important to try to establish tops and bottoms, especially when dips are steep and the rocks have had a long and complicated history. Scour this outcrop for primary sedimentary features that give evidence of tops and bottoms.

Almost all of the visible lamination here is even and parallel, but on one rock surface on the upper part of the outcrop you can trace what looks like a low-angle truncation surface that a seems to cut down through about a centimeter of laminae over a distance of the greater part of a meter. Although not ideally clear, this truncation suggests that tops are to the south, so the strata are upright and not overturned. Keep this in mind as a working hypothesis, with the hope that more definitive evidence will be found in another outcrop. Often in a situation like this, with limited outcrop of rocks not well endowed in sedimentary structures, you have to scour the available outcrops to find just one or a few good indicators, and sometimes they're just not there; finding the evidence you need can be a very chancy thing.

This outcrop of the Westboro is cut by several small intrusions of coarse, almost pegmatitic granitic rock with very irregular geometry. In this same outcrop the Westboro is also cut by a thicker dike of fine-grained mafic igneous rock with sharp and clearly exposed contacts. The margins of the dike are chilled, and in one place near a dike margin you can observe clear flow layering parallel to the contact, caused by orientation of preexisting crystals by shear in the flowing magma. You may have to search for a while to find evidence on the relative age of the two kinds of intrusions, but at one point, just about halfway between the western side of the westernmost tower and a separate wooden electric pole, you can see that the mafic dike cuts one of the granitic intrusions.

In a nearby outcrop on the other side of the road, and just north of the bend in the road, a much thicker mafic dike is well exposed. Its contacts with the Westboro, although exposed in only a few places, are constrained well enough by the locations of nearby outcrops for you to see that the strike of the dike is more or less east-west. The rock type looks about the same as that of the thinner mafic dike in the previous outcrop, but the rock is somewhat coaxser grained. It would be nice to know which dike cuts and is therefore younger than the other, but they seem nowhere to be exposed in contact, so we don't know. If I had to guess, I would say that the thicker dike is younger, because the outcrop surface is smoother and less disturbed than that of the thinner dike, but that's not a very reliable criterion, because often the thinner and finer-grained members of the same generation of dikes end up looking more disturbed than the thicker and coarser-grained members. And even if we could demonstrate here that one of these dikes cuts the other (remember it's also possible that the thinner dike is just an offshoot of the thicker) we still wouldn't know whether they are members of the same generation of dikes, and therefore of almost the same age, or unrelated and therefore probably greatly different in age. (Some petrographic and geochemical work back in the laboratory would be helpful on this score, but not necessarily definitive.) In a great many areas in eastern Massachusetts there are demonstrably three or more sets of mafic dikes of greatly different ages, ranging from Precambrian to Jurassic.

Now spend a while examining the numerous low-to-ground outcrops of the Westboro to the north along both sides of the road, to a point well beyond the next set of towers (the middle one is labelled T146266). Try to ascertain whether the rock types are the same or different, and whether the attitude of stratification remains the same or changes. Look especially for further and better evidence for tops and bottoms.

The best place I've found for top-and-bottom features and style of stratification in the Westboro is in a large and almost ground-level exposure a few steps west of the road at a point a few tens of meters north of the bend in the road at Tower 6267. Five or six quartzite beds, each the greater part of a meter thick, strike about perpendicular to the road and dip steeply south. Interbedded with the quartzites are the same darker-weathering, better-laminated, and finer-grained rocks, called metasiltstones at the first outcrop. It's clear here that at least some of the quartzite beds show sharp northern and gradational southern contacts with the metasiltstone, although the differences are not striking. Graded bedding of this kind suggests again that tops are south, because sand-depositing currents usually are strong and erosive at first and then deposit finer and finer sediment as they wane. At just one point, a little to the west of the center of the outcrop, you should be able to find a small area, about the size of your hand, that shows clear and unmistakable small-scale cross-stratification in the darker rock just above one of the quartzite beds. Later-deposited laminae cut earlier-deposited laminae at appreciable angles of up to 20°, showing definitively that tops are south. I haven't found such clear cross-stratification anywhere else in the Westboro in this area. If the glacier had chosen to cover this particular outcrop with till, the available evidence on the facing direction of these strata would be much less substantial.

Another good outcrop to visit, a few tens of meters north on the east side of the road, is marked by a little cairn that someone built on top of the outcrop. This outcrop shows the same rock types as before, and some additional features. Just east of the cairn is a quartzite bed that contains a large angular clast of well laminated finer rock and many smaller chips. These clasts might be now-metamorphosed rip-up clasts of about the same original lithology as the intervening finer beds. In this outcrop, as in many others in the vicinity, the stratification is not as regular on a large scale as in the two outcrops described already. In places the bedding is twisted and disrupted, and in some places irregular masses of quartzite a fraction of a meter across are surrounded by finer-grained rock. Examine this and neighboring outcrops to get as clear a picture as possible of the geometry of deformation—not an easy task, because in many places the strata are badly scrambled. There are two more good and accessible outcrops, one along the eastern edge of the road a few of meters north of Tower T146266 and another a bit farther north along the western edge of the road. It's hard for me to describe to you the features of geometry to look for in deciding whether the strata were deformed while still soft—even before lithification—or much later, as hard rocks, but the lack of well defined sets of planar and brittle fractures offsetting the strata points to soft-sediment deformation. It's important to try to decide this question, because soft-sediment deformation implies deposition on a slope—most probably a submarine slope—and that's important in interpreting the depositional environment.

Along the east side of the road about 50 m north of Tower T146265 is a low, glacially sculptured outcrop of a thick dike of the same unsheared mafic igneous rock as at the bend in the road to the south. This outcrop shows nice glacial striations, as do many of the low and recently uncovered outcrops along the powerline road. You can see the striations best in the morning, when the sun is low. (This prompts a comment about outcrop illumination: outcrop features like surface grain texture, striations, and relief of laminae are best seen in low-angle sun, whereas subtle differences in color and shade between grains or laminae are best seen in high-angle sun or bright shade. One does different things in outcrops as the lighting changes.)

If you're curious about what's up section in the Westboro, go back to the first outcrop at the bend in the road at Tower T146267 and then walk south or southwest along the powerline route, in what should be the up-section direction. After a covered interval there are abundant outcrops, especially along the west side of the powerline swath. These outcrops represent more of the Westboro (not as easy to study, and you're not likely to see anything new), extensively intruded by the same coarse-grained granitic igneous rock. The much greater abundance of granite over such a short distance should lead you to suspect the existence of a fault in the covered interval, but it would take careful mapping of the entire area to check this possibility.

As you head back from the Westboro outcrops toward your car, examine some of the numerous outcrops on the broad low hill the powerlines cross to the north. Most of these outcrops are very fine-grained and very tough rock that's dark gray on fresh surfaces but uniformly light gray on weathered surfaces. The abundant little angular crystals scattered through the rock are probably feldspar phenocrysts. This is felsic volcanic rock, probably a series of thick lava flows, that belongs to the Lynn volcanics, a complex and controversial volcanic unit that's extensively exposed north of the Boston Basin. The age of the Lynn Volcanics is not entirely clear, but in many if not most places it's clearly late Proterozoic. At least at this locality it's impossible to find clear evidence of stratification, or even of flow layering—although I haven't looked as carefully at the Lynn here as at the Westboro. These volcanics are intruded by numerous mafic dikes of the same kind and scale as intrude the Westboro.

It's important to think about the contact relationship of the Westboro and the Lynn here. Since we know from the cross-stratification that the Westboro faces south, the Lynn either underlies the Westboro or is in fault contact with it. If the latter is the case, we can't say anything about the relative age of the Lynn and the Westboro here. You won't find the contact exposed, but you can at least try to bracket its location by walking back and forth across the powerline swath t locate the lowest outcrops of the Westboro and then all the nearest outcrops of the Lynn on the other side of the unexposed area where the contact must lie. This takes some flailing around in the underbrush, but it's worth the effort. In this way you'll find that you can constrain the strike of the contact to be at a fairly high angle to the strike of the bedding in the Westboro. Since it's unlikely in the extreme that the strata of the Westboro were deposited against such a steep surface of the Lynn, you can safely assume a fault contact here.

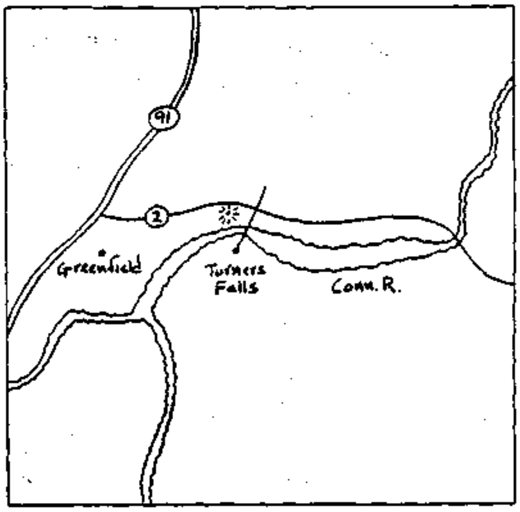
Before you leave, you might think a little about the depositional environment of the Westboro here. Usually the most fruitful evidence for depositional environment of a terrigenous sedimentary rock lies in features of stratification and its vertical sequence. Your ability to observe these in the available outcrops here is limited, but the impression is one of rather even and regular stratification (if you factor out the later deformation; discussed earlier) and an alternation of coarse and fine beds. Of itself, this could be suggestive of an environment that's fluvial, or nearshore shallow marine (subtidal or even intertidal, as in an estuary or on a tidal flat), or deep marine. Ordinarily the details of the stratification and vertical sequence would give at least some evidence from which to choose among these possibilities, but here we can't even see anything of the original internal stratification of the quartzites. But we have two additional pieces of evidence to help us. First, the almost pure quartz composition of the quartzites points to a marine environment, because sands coming down river systems usually haven't had the less resistant components like feldspar and rock fragments weeded out by weathering and abrasion—unless the source itself is a preexisting pure quartz sandstone. Pure quartz sandstones (technically called quartz arenites) are usually associated with shallow marine environments. Second, the likelihood that the deformation and disruption of stratification described earlier is soft-sediment deformation that occurred not long after deposition points to deposition on a slope. The most reasonable scenario seems to me to be the following: mature and well washed quartz sand from near shore (perhaps cycled many times through beaches) found its way to an unstable temporary resting place at a shelf edge and was then carried sporadically down a slope in the form of sediment gravity flows to become interbedded with finer slope sediment. But keep in mind that this is all just intelligent guesswork.

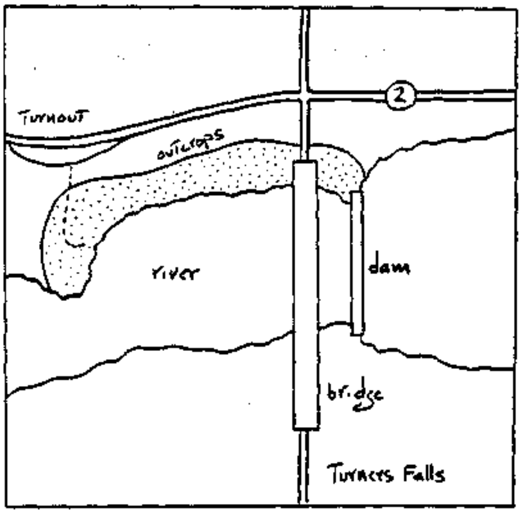
The granite that intrudes the Westboro here and in many other places in this area is part of a large and complicated pluton (or, what's probably a more accurate way of putting it, a closely related series of plutons) that are generally similar to the Dedham Granite of latest Proterozoic age, south and west of Boston. So the Westboro is older than about six hundred million years, but there's no way of knowing how much older. I'm told by Dick Bailey at Northeastern, the man who's the authority on the Westboro, that detrital zircons in the Westboro have been dated at 1.5 billion years or older. It's interesting that at present one has to look far afield—many hundreds of miles—to find crystalline basement rocks that old. The part of Westboro you've seen here is just about the oldest rock unit in New England that can be studied as a sedimentary rock. It affords just a tantalizing peek into a stage in the development of New England about which almost nothing is known.

TURNERS FALLS

Turners Falls Sandstone (Jurassic)

sandstone; mudstone; red beds; sedimentary structures; lava flow





This locality is the farthest from Boston; it's halfway across Massachusetts. There may be a way of getting there by bus (is there a bus that runs along Route 2 and stops at or near Turners Falls?) but it's far easier by car. The locality is on the rocky right bank of the Connecticut River just below the dam at Turners Falls. It's a sheltered location, so it's a good place to do some geology on a raw and windy day in spring or fall. If the weather is nice it's a good place for a picnic.

LOCATION

Drive west on Route 2 almost to Greenfield. A few miles before Greenfield is an undesignated cross road at a traffic signal. If you turned left there, you'd cross a long, high bridge across the Connecticut River (which flows directly west here) into the town of Turners Falls. Drive straight through the traffic light on Route 2 for about a tenth of a mile. Watch for a large, paved turnout and rest area on the left. Park there, hop the guard rail at the sign warning you about sudden rises in water level caused by the release of water from the dam just upstream of the bridge (don't worry; it doesn't happen often, they announce it beforehand, and the water doesn't rise much anyway), and make your way down a short, steep path to the river, keeping as far to the left as possible.

GEOLOGY

Look first at the rock you crossed on the way down to the river. It's dark gray, fine grained, and uniform, and on favorably weathered surfaces you can see that it consists of abundant, very small, white-weathering, lath-shaped plagioclase crystals surrounded by a dark mineral, probably augite. It's a rather standard looking basalt. As you walk upstream (toward the bridges and the dam beyond) from where the path leads you down to the river, within just a few meters you'll begin to see abundant dark-colored amygdules in the rock. These masses, which are rounded and irregular and distributed irregularly through the rock, are evidence that you're looking at a lava flow rather than an intrusive rock. Amygdules tend to be most common at and near the tops of flows, where dissolved gases bubble out of the lava most profusely. Now walk farther toward the bridge and watch for a change in rock type.

The path you walked down is on a spur or ridge of rock that projects downward toward the river. The open eastern (upstream) slope of this spur shows the amygdaloidal basalt. At the base of this slope is a sharp contact with red mudstone. This contact, which extends about perpendicular to the river, is very well exposed, and in places you can even put your finger on it. If you trace it carefully you'll see that it's planar on a large scale but rather irregular on a scale of a meter or so. In places along the contact the mudstone fills depressions in the basalt. The best interpretation here is that the contact represents the irregular top of a lava flow (tops of basalt flows are very often irregular) onto which mud was eventually deposited. Consistent with the idea that this is a top of a flow is the generally reddish and more weathered look of the basalt within a meter or two of the contact. As you stand at the contact, look east toward the bridge and survey the wide area of almost continuously exposed sedimentary rock in front of you. Even cursory inspection of the exposures just ahead of you shows that the strata strike perpendicular to the river and dip toward the bridge at about 30°. So you're standing at the base of the sedimentary sequence and looking "up section."

This is your chance to practice subdivision of a sedimentary sequence. Walk slowly through this section all the way to the dam, examining the rocks carefully as you go, and then think back about the section you've seen, from the standpoint of whether it should all be placed in the same rock unit or subdivided into two or more units. Are you a lumper or a splitter? That is, would you like to lump all the rocks into one broad rock unit, or would you prefer to split the section into perhaps a number of thinner rock units that differ in lithology in certain respects from unit to unit? It would even be a good idea to cruise the section more than once while you're thinking about subdivision.

A useful note here: with gently dipping strata, you can see different kinds of features by walking up section and down section. As you walk up section you get a good view of the rocks on surfaces perpendicular to the stratification, and that's the best way to see stratification features. As you walk down section you see mainly stratification surfaces, or surfaces almost parallel thereto, and you can better see the various features (like desiccation cracks and parting lineation) displayed on such surfaces. So be sure to walk in both directions while you're examining the rocks. If you want to pursue this exercise, do so before reading the following paragraphs, which describe the features seen and make some points about subdivision.

One question you might address at the very outset is whether the section is indeed upright, as seems to be the case from the relation between the basalt and the mudstone—and also simply because it's not highly deformed and it's dipping at a fairly small angle. If you keep your eyes peeled for top-and-bottom indicators, in places you'll see two kinds of such features that show definitively that the section is indeed upright: (i) erosional truncation of earlier-deposited strata and later deposition on that truncation surface, and (ii) desiccation cracks. Erosional truncation is seen in two situations: at the bases of many of the sandstone beds, which rest erosionally on mudstone, and as cross-stratification within some of the sandstone beds. Desiccation cracks are common, but in only a few places is the evidence definitive. The very best place to see desiccation cracks in cross section is on an almost vertical joint surface near the overhanging top of the prominent outcrop salient just down-river from the bridge. If you search assiduously you'll see one place, about at eye level, where a layer about half a centimeter thick at the top of a thick bed was cracked by desiccation, and the cracked pieces, several centimeters across, curled upward at the edges without breaking away from the substrate at their centers. Later sediment buried this desiccation-cracked bed and filled the spaces around and underneath the curled pieces. Most of the other examples of desiccation cracking are seen on stratification surfaces rather than in cross section; what you usually see is an irregular network of cracks filled in by later deposition, and it's usually difficult to tell tops and bottoms without seeing a cross-sectional view as well.

Another good top-and-bottom indicator you might watch for is raindrop impressions. These are little craters a few millimeters across, with upraised rims. They are found on single bedding planes, usually on those covered with a film of mudstone, and are often associated with desiccation cracks. They record passing rain showers on subaerially exposed but still soft mud surfaces. The concavity of the craters tells you which way is up. I've seen one good example in this section, but only on a loose piece, so I can't give you any clues about where to look. The lower two thirds of the section consists mainly of red sandstone and mudstone with a few interbeds of conglomerate. The sandstone beds, usually some tens of centimeters thick, form perhaps only a quarter of the total section thickness, but because they ars more resistant to weathering than the mudstone they tend to form prominent little ridges or ledges on the outcrop. They are mostly too fine to see much by way of mineral composition. They are prominently stratified, showing both even stratification and small-scale cross-stratification. The sandstone beds tend to have sharp and sometimes demonstrably erosional lower contacts with the mudstone, and in many cases it's clear that they grade into the mudstone.

The most common vertical sequence of structures in the sandstone beds is perfectly even and planar lamination in the lower part passing up into climbing-current-ripple cross-lamination in the upper part, although often the entire bed is parallel-laminated, or the sequence of structures is irregular. From experiments in laboratory channels, current ripples in sands are known to be formed by currents of moderate velocity, and planar lamination, by stronger currents—so the sequence of structures in the sandstones implies a waning current, and that's consistent with the upward decrease in grain size. In the parts of the sandstone beds that show small-scale cross-lamination you can often recognize complete vertical profiles of current ripples. These are preserved when the rate of deposition of new sediment onto the bed by settling is not small relative to the speed of downcurrent movement of the ripples. When the rate of deposition is very small relative to the rate of advance of the ripples the cross-lamination is more complicated in geometry, with little packets of foreset laminae separated by curving and irregular erosion surfaces. You usually don't see the current ripples on bedding surfaces, only in cross section, although if you hunt around you'll see a few places where ripples are exposed on bedding surfaces. One of the best examples is right next to a giant slab of concrete lying loose on the outcrop, just downstream of the bridge. Look at the outcrop surface on the side of this block away from the river and you'll see a few partly exposed surfaces that show current ripples.

Where the sandstones part along the parallel stratification you'll see on the parting surfaces abundant flakes of muscovite, the greater part of a millimeter in size. (The weakness the mica flakes produce is what causes the rock to split along these planes in the first place.) In many cases you'll also see on these parting surfaces a subtle lineation, called parting lineation, that's believed to be produced by crude alignment of the sand grains in little streaks by the turbulent flow that transports the sediment on the bed surface during deposition. It's an excellent indicator of the orientation of the depositing current, although unfortunately not the direction. The very tops of the sandstones are commonly capped by a thin film of bright red mudstone, often desiccation-cracked. This is further evidence that the sandstones were laid down by some brief event of strong current, and as the current died down and before the area became emergent a film of mud was deposited by quiet-water settling on the sand surface.

It's not only igneous rock that can be intrusive: under certain conditions, already-deposited sediment can also flow and be intruded into other sediment. In just one place, near the base of the section, is such a sedimentary intrusion, called a clastic dike. It might not be easy for you to find. Stand on the large boulder of basalt that sits right on the contact between the basalt and the mudstone about halfway between the water line and the steep bank, look about 45° to the left of the direction that's directly up section, and walk in that direction a little more than halfway to the edge of the woods. You'll then be standing fairly near the clastic dike, in a low area underlain mostly by red mudstone with prominent ledges of sandstone behind you and in front of you. At your feet is another low ledge of sandstone that cuts diagonally through the red mudstone. This sandstone shows no noticeable stratification, but it contains numerous little rip-up clasts of the same red mudstone that surrounds it. When traced down section this sandstone seems to merge into the sandstone bed below, and when traced up section it ends abruptly before the next sandstone bed is reached. This body of sandstone must have been injected as a flowy mixture of sand and water from the underlying sand bed along a fracture plane after burial, but long before lithification.

The mudstone tends to be darker red and less resistant than the sandstone. Some is prominently laminated, but some shows only subtle stratification. Even lamination in sediment this fine is probably formed by settling of sediment from still or slow-moving water. The mudstone is ubiquitously disrupted by little strips and marks with color and texture slightly different from the rest of the rock. This represents disruption of sediment by the life activities of organisms: plants or animals living in and/or on the sediment left tracks, trails, burrows, or root marks as fossils of a sort. The process of disruption is called bioturbation, and the results are called trace fossils (in contrast to body fossils, which show the actual form of the organisms).

At a point about halfway from the basalt to the bridge is a prominent bed of conglomerate about a meter thick. At the end of the outcrop away from the river the conglomerate rests with sharp contact on a sandstone bed which itself rests on red mudstone. Toward the river along the contact the conglomerate cuts down through the sandstone at a noticeable angle, finally to rest directly on the mudstone. So the sharp base of the conglomerate is demonstrably erosional. It's clear that an extensive bed of sand was deposited on mud by an initially erosive current, and then at some later time another strong current eroded away part or all of the sand bed and deposited gravel on both sand and mud. You won't see much by way of internal stratification features in the conglomerate, but you should be able to convince yourself that the bed is graded from slightly coarser below to slightly finer above. Graded bedding of this kind comes about either by setting of finer and finer material onto a depositional surface or by transport of finer and finer material past a point on the bed as deposition proceeds; given the coarseness of the material, the latter was most probably the case here. The gravel-size clasts in the conglomerate consist of vein quartz, fragments of various kinds of preexisting rock (see what you can identify), and chunks of potassium feldspar. In the sand sizes, quartz and potassium feldspar seem most abundant. In the lower part of the bed at a few points you'll see red mudstone rip-up clasts that look identical to the underlying mudstone. These are pieces of mud, probably only partly consolidated, torn up from the bed by the current and then deposited along with the far-traveled sand and gravel. Similar rip-up clasts are present in many of the sandstone beds in this section as well.

As you get closer to the bridge, thicker sandstone beds a meter or more thick become more common, although there is still plenty of fine, bright red, thin-bedded mudstone between. Some of this red mudstone (probably mainly siltstone) is prominently current-rippled.

Just a few tens of meters before you pass under the bridge you reach a higher and more prominent outcrop, gray instead of red, that juts out into the water to your right. Up near the tree line some of the mudstone below this sandstone ledge is gray rather than red. If you look closely you'll see that between the gray mudstone and the overlying sandstone is a bed of fine-grained rock 10-20 cm thick that weathers uniformly tan or brown. If you squirt a little dilute hydrochloric acid (which admittedly you're not likely to have with you) on this rock it won't fizz, but if you powder a bit of the rock surface with a knife it then fizzes. This shows that the bed consists of dolostone. Now walk toward the water along the base of this prominent sandstone ledge and see if you can spot the offset on a minor fault.

About two-thirds of the way from the trees to the water you'll find that the base of the sandstone ledge is offset, with a stratigraphic separation of about a meter. The sense of the separation is such that the block nearer the water moved east (toward the dam) relative to the other block. You can trace the fault line by its topographic expression to the northeast, diagonally upriver toward the woods. Since there's nothing on the fault plane to indicate the orientation of the displacement, you can't say anything about the magnitude of the displacement, but you can safely assume that this is only a minor fault. If you combed the area you'd find a few other faults as well. The importance of observing these is that they might give evidence of the orientation and nature of movement on larger faults in the area.

Most of the section from the base of this sandstone ledge to underneath the bridge consists of red and gray sandstone with some thinner mudstone interbeds of the same kind you saw before. Except that they're thicker, these sandstone beds are generally similar to those lower in the section: they rest with sharp contact on mudstone and commonly contain rip-up clasts in the lower part. If you look closely you'll see that many of these sandstones show large-scale cross-stratification as well as even stratification. This is especially clear in the sandstone beds directly beneath and just down section from the bridge. (Be sure to factor out the red and green paint speckles on the rock surfaces just under the bridge.) Look for sets of curved, low-angle, concave-upward laminae that truncate underlying sets of similar laminae at a fairly low angle. Almost directly under the bridge you'll encounter another prominent conglomerate bed.

The outcrop ends a short distance upstream of the bridge, and there is a covered interval of several meters of section thickness before you get to the final set of outcrops, at and near the base of the hillslope to the left of the dam. Above the covered interval you see no more of the red sediment: instead it's all dark gray to light gray. The finer-grained beds could again be described as mudstone or shale. This shale becomes finer grained, darker gray, and more prominently stratified upward. In the gray shale just beneath the prominent ledge of sandstone in the next cliff you'll see continuous beds and also discontinuous nodular layers of the same tan-weathering dolostone you saw lower in the section. Succeeding the dark gray shale is a thick unit of sandstone, several meters thick, pebbly near the base, that shows both even stratification and cross-stratification. Its contact with the underlying dolomitic shale is sharp and probably erosional. Variations in grain size in this sandstone unit suggest it's a composite unit, with several sandstone beds emplaced at different times. The upper part of the unit is a good place to look for large-scale cross-stratification. An even better place is in a gigantic planar-faced boulder of interbedded sandstone and conglomerate (we know not where from) that sits on the outcrop just above the sandstone unit. Here you can get a good three-dimensional conception of the stratification by following individual sandstone beds around the corners of the boulder. In particular, there's one 15-20 cm sandstone bed that's prominently cross-stratified.

Above the sandstone is another interval of gray shale, very similar to the last, that shows the same tendency to become finer, darker, and more dolomitic upward. This shale is succeeded in turn by another thick, coarse sandstone unit that forms the final cliff next to the dam. Are the two shale-sandstone pairs in the uppermost part of the section really different, or do they represent repetition of the same pair by faulting? It's clear from the continuity of the outcrop here that they're different, but in many situations like this an obscure fault nearly parallel to bedding planes can be invoked to account for the apparent doubling of a single unit.

Now that you've examined the entire section, there are two related questions you might attempt to address: (i) how would you split up the section into useful rock units (useful in the sense that they might be traceable or recognizable from outcrop to outcrop area), and (ii) what was the environment of deposition of this sedimentary sequence?

With regard to subdivision of the section, remember that recognition of rock units is partly on the basis of natural and significant changes in lithology but also partly a matter of the geologist's judgment. It's perhaps most natural here to subdivide the section into two units, with the contact drawn at the first appearance of the gray dolomitic shale and thick gray sandstone. Above that point there are at least three cycles consisting of dolomitic gray shale succeeded by sharp-based, thick, fining-upward sandstone. The upper two cycles are best developed here. But it's also clear that the upper and lower parts of the entire section show many features in common, and there seems not to be any sharp break between them. It may therefore be preferable to leave them as one thick unit.

With regard to environment of deposition, abundant evidence is at hand. Look first at the sandstone beds throughout the section. Their lower contacts are almost always sharp and often erosional. Usually they fine upward and are capped by mudstone drapes, and they tend to show even stratification in the lower part and small-scale cross-stratification, often clearly produced by movement of current ripples, in the upper part. All of these features are indicative of deposition by brief and strong episodes of current while sand was being deposited from the current. This kind of thing can happen in either rivers or shallow seas. Now think about the mudstones. They mostly show even stratification that suggests deposition from very weak currents, and in places they show desiccation cracks that are excellent evidence for occasional subaerial exposure. One could think in terms of an intertidal marine environment or a river floodplain. The evidence is in favor of the latter, because of the dominantly unidirectional currents and the presence of a few much thicker bed coarser conglomerate beds. This sequence is very similar to many that are considered to be fluvial. You can picture shallow flows in broad channels on a river plain depositing the coarser beds, and then slow-moving or stagnant water on the surrounding floodplain depositing the mud beds. Remember that for a section to be deposited in the first place the river had to be aggrading its bed. This net aggradation, together with irregular shifting of channels on the plain, is what gives rise to the vertical alternation of sand and mud beds you see in the section.

The dolomitic shales beneath the thick sand bodies are not as easy to interpret. We could speculate about the presence of shallow floodplain lakes or swamps in which dark muds were deposited. The dolomite could be evaporitic, suggesting an arid climate, but the dark color suggests an abundance of organic matter that escaped oxidation, suggesting a humid climate. Perhaps a climate with seasonally strongly variable rainfall is the answer. The sand bodies might be point-bar deposits of meandering channels that cut into the already-deposited muds. It would be nice to be able to trace these sand bodies laterally to see if they end in clay plugs, as would happen when a meandering channel is finally abandoned and then filled in slowly by overbank muds, but the outcrop doesn't give us that opportunity.

The nonmarine nature of similar Triassic and Jurassic rocks elsewhere in the Connecticut Valley is definitively revealed by the presence of plant fossils and dinosaur tracks. Although I haven't seen either of the latter in the section here at Turners Falls, it wouldn't surprise me. If you find dinosaur tracks, let me know. Rocks thought to represent lake deposits are common as well in other places in the Connecticut Valley. Nonmarine fish fossils have been found here at Turners Falls in the dark gray shales underlying the thick sandstones, but don't bust up the outcrop too much trying to find some.

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