Self-Guided Geologic Tour of the full Rock Circuit Trail in the Middlesex Fells Reservation

Prepared by Jack Ridge, Professor, Dept. of Earth and Climate Sciences at Tufts University, Medford, MA

Some general information before starting a tour in the Middlesex Fells:

1. The Rock Circuit tour has been broken into three parts. However, this tour guide does the whole trail in one trip as ~5-6 twisting miles (62 stops!) or about 8-10 km. It's recommended that you do parts of the tour in order, Part 1 to Part 3. The beginning of each part is at the end of another part. Each tour and its stops are marked on the geologic maps with each part. PLEASE FOLLOW the maps as you go. ***It will be handy to have a sense of direction from the sun, remembering that at noon the sun is due South, in the morning it is to the southeast, and by late afternoon it is to the southwest.***

2. At many times of the year and on weekends, parking areas fill, especially along the Fellsway East, so start early.

3. The tours require hiking over some steep and rocky trails, so plan ahead. It is recommended that you have sturdy hiking or trail shoes. I don't recommend sandals or heeled shoes.

4. Make sure you have enough food and water with you. In the Fells, there is nowhere to get water and the spring water is NOT drinkable.

5. In compliance with DCR rules, please stay on official marked trails as indicated on DCR maps. This is also a way of avoiding poison ivy and ticks. In making the geologic map, special permission was obtained from the DCR to go off the trails. See the DCR's official Middlesex Fells Reservation Trail Map (last updated in March 2020). This map accurately shows trails, except where they have been refurbished, and it has the numbered intersection designations indicated in the guide. The DCR map is online at: https://www.mass.gov/doc/middlesex-fells-reservation-trail-map/download and it is sometimes available at kiosks at Fells parking areas.

6. In wet or winter weather, some rock surfaces are slippery. DO NOT venture out onto frozen ponds and reservoirs. The ice may be too thin to support your weight and it is unpredictable!

7. Do not collect rocks on the tour or deface outcrops by writing on them. It is against DCR regulations. Please remove your own trash and follow other DCR rules. Leave no trace!

Some Fundamental Geology to Get Started:

1. The self-guided tours of the Fells focus primarily on **bedrock geology**. This is a characterization of the solid rock that occurs beneath our feet as viewed from above. Exposures of the **bedrock** surface are called **outcrops**. Loose rock debris (or **float**), sediment, and soils on top of the bedrock comprise the **surficial geology**.

2. **Rocks** are naturally occurring solids made of minerals and non-mineral materials. **Minerals** are naturally-occurring, inorganic, crystalline solids that have a specific chemical formula and unique properties that allow us to tell them apart. A **crystalline material** is one in which atoms have a repeated regular pattern (i.e., crystals or crystal structure). Minerals have names in addition to their chemical formulas. For example, sodium chloride ($NaCl$), which is the main ingredient of table salt, is known as the mineral **halite**, while silicon dioxide (SiO_2) is **quartz**. The most common mineral at Earth's surface is **feldspar**, an aluminosilicate containing sodium, potassium, and calcium. Non-mineral materials in rocks include organically-produced materials and **natural glass**, which is non-crystalline.

3. Rocks are divided into three main types:

   Igneous rocks – rocks formed by the solidification of molten rock, or **magma**. Magmas can invade older rock units in the subsurface and then crystallize to form **intrusions** or **intrusive igneous rocks**, which may later be exposed by erosion at Earth's surface. Magma can also escape to Earth's surface before hardening to form **extrusive** or **volcanic igneous rocks**. Examples of these are **lava flows** or magma explosively ejected into the air that later settles to produce **pyroclastic rocks**.

   Sedimentary rocks – rocks formed by the accumulation or deposition of particles produced by the breakdown and erosion of older rocks. This often happens in oceans and lakes or on river flood plains. Sedimentary rocks also include the accumulation of organically-produced sediment, such as clam shells and coral reefs (limestone) and plant material (coal), or chemical precipitates such as salt beds. **Fossils** occur in sedimentary rocks.

Metamorphic rocks – rocks resulting from exposure of existing rocks to increased temperatures or pressures that change the mineral composition and arrangement of mineral grains. We say these rocks are **metamorphosed**.

4. Solid materials (rocks and minerals) have been in existence on Earth for at least 4 billion years. This time in Earth's history defines the expanse of **geologic time**. Geologic time (**geologic time scale**) is subdivided based on past events represented by changes preserved in the rock record. Radiometric dating techniques are then used to place precise numerical ages on rock units and time unit boundaries. A geologic time scale can be found at: https://www.geosociety.org/documents/gsa/timescale/timescl.pdf.

5. On a geologic map, bedrock is classified into units known as **formations**, characterized by rock types and age. Formations have proper names from a place where they are well exposed or first defined. Sometimes, single formations are split into a sequence of mappable units called **members**. The boundaries between geologic units are known as **contacts**. On geologic maps, formations and members are given their own colors and patterns so they can be distinguished from each other. They also have abbreviations that consist of a capital letter for the unit's geologic time period (when it was formed) and lower-case letters that abbreviate for the unit's name. For example, "Zsg" = the Late Proterozoic (Z) Spot Pond Granodiorite (sg). Time period abbreviations in the Fells are Z (Late Proterozoic), P (Pennsylvanian), and Q (Quaternary). If a rock unit does not have a known age or formal name, only lower-case letters are used as an abbreviation. (For example: "d" stands for dolerite). Also shown on maps of the Fells are areas where the geology is concealed by human-made deposits, defined as **artificial fill** (af).

6. On the geologic maps in this guide, geographic north is shown with an arrow. **Compass directions** are given in the guide as degrees W or E of either N or S. For example, N50°E is 50 degrees east of north.

7. **Geologic symbols** on the maps are used to convey information; for example, on the maps here, the blue lines are faults. Symbols at stops on the tour are explained, but a complete description of all rock units and a listing of symbols on the map are given in map explanations at: https://sites.tufts.edu/fellsgeology/

8. The maps in the guide present detailed mapping of the Fells and introduce new formation names. It is an ongoing research project. Things will likely change with more field work and age determinations. Updates of the bedrock map, its explanation, and associated surficial geologic map and tours will be posted as they occur. We welcome feedback at: https://sites.tufts.edu/fellsgeology/.

Rock Circuit Trail in the Middlesex Fells Reservation version: January 13, 2024

Tufts UNIVERSITY

Part 1: Fellsway East to Pinnacle Rock and back to the Cross Fells Trail

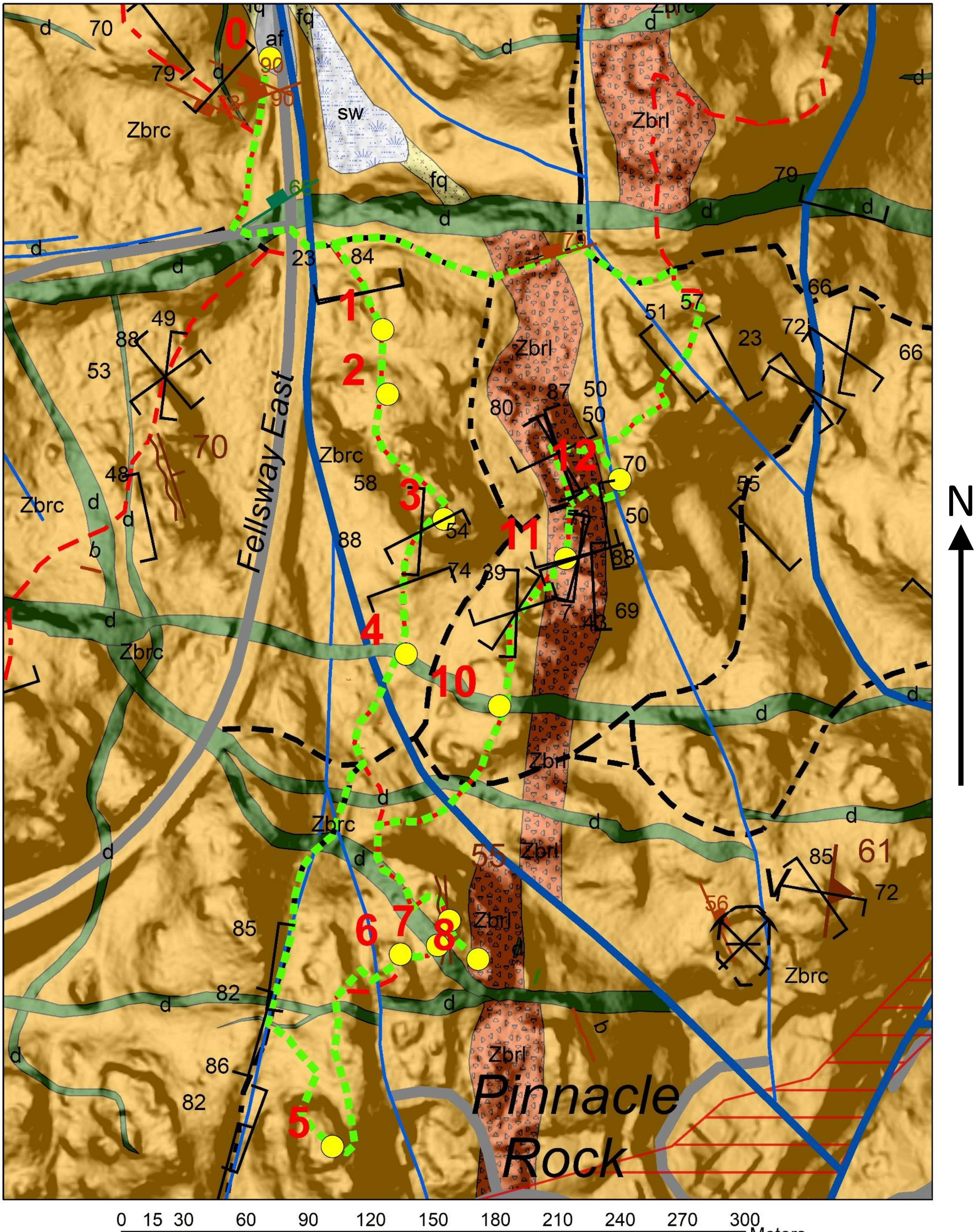
Total distance: about 2 km round trip. This part of the Rock Circuit Trail tour is relatively short, but it involves some steep slopes.) Prepared by Jack Ridge, Professor, Dept. of Earth and Climate Sciences, Tufts University

Starting point: Parking Area on Fellsway East near Gate no. 53 (see Map RC-1, Stop 0). Head south from the parking area kiosk to Gate no. 53 at Jerry Jingle Road (crossing fractured outcrops of the Boojum Rock Tuff). Cross over Fellsway East to Gate no. 52, where the tour begins at the Rock Circuit/Cross Fells trail junction. **Follow the trail on the geologic maps as you go**. Stops on the tour are yellow circles with red numbers on the geologic maps. Follow the white trail markers in the field and dashed green path on the map. In the guide, DCR trail junction numbers are given that are marked with signs in the park. This is the shortest of the three segments of the tour of the Rock Circuit Trail. Having a hand lens or magnifying glass can be helpful. Enjoy the geology! Have fun!!

This trip focuses on Neoproterozoic volcanic rocks of the Boojum Rock Tuff of the Lynn Volcanic Complex and younger dolerite dikes, which underlie the southeastern Fells. The Neoproterozoic Era was 1000 to 541 million years ago. The trip will also point out how the rocks were deformed by faults and fractures, and you will see some glacial features.

NOTE: Polished rock images are cut rock slabs photographed under water. Scale bars are in centimeters. In pictures of rock surfaces there is often a camera lens cap, pencil, or rock hammer for scale.

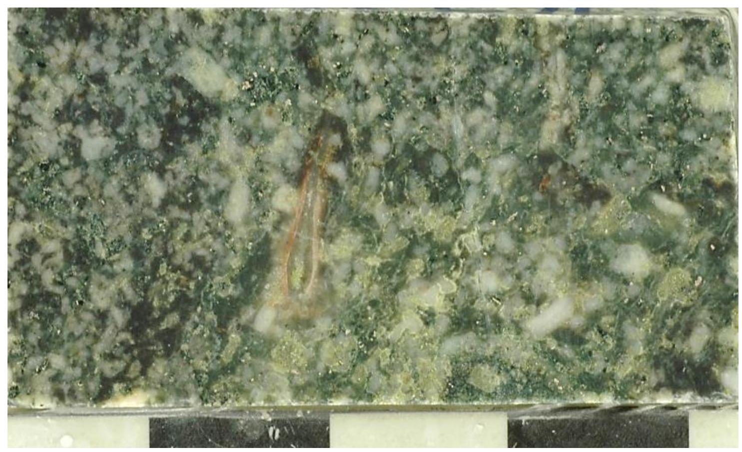
Map RC-1



Fellsway East
Pinnacle Rock
Zbrc
Zbrl
sw
fq
af
N
0 15 30 60 90 120 150 180 210 240 270 300 Meters

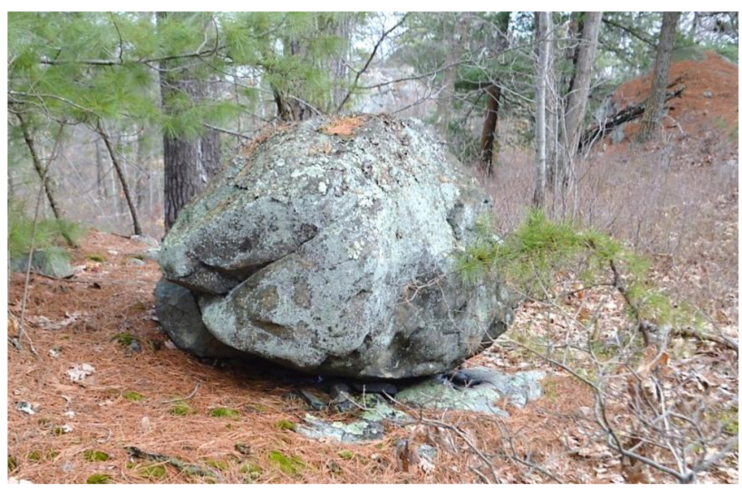
Follow map RC-1. Proceed to Gate no. 53 and cross the Fellsway East. You are crossing two geologic features: 1) a major fault running N-S along the Fellsway East, and 2) a large, E-W trending dolerite dike, which on the west side of the Fellsway forms a linear hill and runs along the south side of Jerry Jingle Road (more on these dikes later). After crossing the Fellsway East, the dike is on the north (left) side of the Cross Fells Trail. After crossing through Gate no. 52 follow the Rock Circuit Trail (white markers) up the hillslope to the south (right) toward Pinnacle Rock.

STOP 1: On the left at the first bench in the hillslope are outcrops of the Boojum Rock Tuff in the Lynn Volcanic Complex (Zbrc on map), which covers the southeastern corner of the Fells. Part 1 of the tour is entirely in the Boojum Rock Tuff! It has a huge outcrop area on the geologic map and extends into Malden and Melrose. This unit is a pyroclastic volcanic rock, meaning it was ejected into the air prior to accumulating on the land surface. Pyroclastic rocks can have 4 components in them: 1) ash, or fine, broken glass shards that may have still been molten when they landed; 2) crystals which were mineral grains that had started to crystallize in the magma prior to eruption; 3) large pieces of glass and pumice (bubbly glass), which may still have been molten when they landed; and 4) lithic fragments, which are fragments of pre-existing rock, either from prior volcanic eruptions or any older rocks through which the magma passed in the subsurface. The rocks exposed here are welded crystal tuff. Tuff is any pyroclastic rock with ash in it. The term welded refers to the fact that the ash and glass/pumice fragments were at least partly molten (liquid), allowing them to adhere to each other when they landed. The tuff here has abundant crystals in it, which occur as small (up to 2 mm) white plagioclase feldspar grains that are often broken (image below to right). This unit is noteworthy among volcanic rock units in the Fells because it lacks quartz crystals and has a very consistent composition over its large outcrop area. In an outcrop, you may see occasional small lithic fragments, but you will not see glassy materials for two reasons: the glassy ash particles are too small to see without a microscope, and glass that remains at high temperatures after it solidifies will slowly convert to a crystalline solid composed of very fine-grained quartz and feldspar. This change of hardened glass to a crystalline material is called devitrification. The devitrified glass gives the rock its overall greenish-gray color on fresh surfaces. The larger glass and pumice fragments are up to 5 mm and were soft when they landed. As a result, they were flattened under the weight of accumulating material before they hardened and devitrified. The flattened fragments, best seen in a microscope, blend in with surrounding devitrified ash.



Continue toward the top of the hill.

STOP 2: On the left, you will pass a glacially transported boulder resting on the Boojum Rock Tuff. The boulder is a piece of the Stoneham Granodiorite (Zst), transported from the northern Spot Pond area and left here when the last glacier receded or melted away about 17,000 yr ago. Granodiorite is an intrusive, coarse-grained igneous rock almost entirely made of plagioclase feldspar and quartz with lesser alkali feldspar and scattered to sometimes abundant mafic (dark) minerals. An intrusion is a body of magma that invaded other rocks in the subsurface and then crystallized. The boulder is a glacial erratic. To be a glacial erratic a rock must be glacially transported and end up resting on a different bedrock unit than the one it came from. Boulders like this are common throughout the Fells.



Continue south on the trail to the highest point on the hill.

STOP 3: On the hilltop just before the steep slope to the valley below is an outcrop of the Boojum Rock Tuff (Zbrc) with closely-spaced, parallel fractures (cracks). Fractures like this are common throughout the rock unit and are formed due to compression of the rocks. Fracture orientations in the Boojum Rock Tuff have been measured at hundreds of places. On the map you will see a black bracket symbol (**[**), which shows fracture orientations. The small bars on the bracket point in the direction in which a fracture dips downward. The nearby number indicates the dip in degrees away from horizontal. Two fracture sets were measured at the top of this hill. The fracture data from the southeast Fells shows a clustering in specific orientations. This demonstrates that the fractures aren't just cracks with random directions, but instead were created by well-organized stresses exerted on the rocks in a particular orientation. **Descend the steep hill to a lowland.**

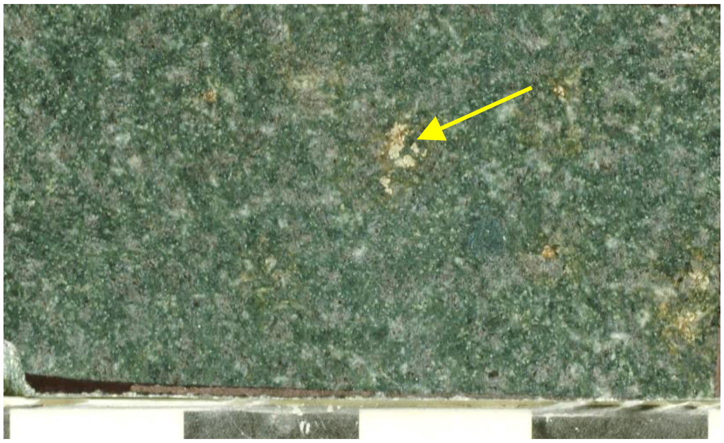
STOP 4: About 30-40 m after the lowest spot in the lowland is a bump and rock rubble on the trail, which is a 5-10 m wide, E-W trending dolerite dike (d on the map, no image). We will discuss the dark minerals that occur in dolerite dikes in more detail at Stop 7. A dike is an intrusion of magma that filled a fracture in the subsurface. Later, on our return from Pinnacle Rock, you will see this dike again at Stop 10.
Continue south to a wide path at junction F5-11. Recently, the Rock Circuit Trail south of here was reconfigured, so it does not match the current DCR map. Follow the Rock Circuit Trail as it shifts to the right before heading up the hill southward (left) on Pinnacle Path. Do not turn to the left, or go straight ahead from junction F5-11, which is close to the return trail from Pinnacle Rock.

STOP 5: Pinnacle Path follows a fault, which cuts across a low spot in the crest of the hill. A fault is nothing more than a crack that separates two bodies of rock that moved relative to each other. Beyond the crest of the hill, the trail then turns off to the east (left) and climbs the first pinnacle in this area. Looking to the south from this spot is a great view of Boston. Shortly, we will see some even better views. Note that the Boojum Rock Tuff is heavily fractured in this area, and, on the map, you will see small faults (blue lines) nearby. After leaving the pinnacle and heading north (reversing direction), the trail goes by two abandoned concrete radio tower platforms. If you look adjacent to the first platform, you will see broken rock debris of crystal tuff in the Boojum Rock Tuff (Zbrc). This debris has relatively fresh surfaces that show its greenish-gray interior color and small white to gray plagioclase feldspar crystals.
A short ways after the abandoned concrete platforms, the trail crosses a small valley and then ascends a steep slope to a ridge crest.

STOP 6: Where the trail makes a sharp turn east (right) and a few meters south you can see a cluster of boulders perched on the Boojum Rock Tuff (image to right). These boulders are pieces of the underlying tuff, so they are not glacial erratics, though they were glacially transported. The boulders seem to have been a single boulder that fell apart after it came to rest on the hilltop. The far boulder has blackish-gray, specular hematite veins exposed on its northern face (red arrow). The veins were fractures in which hematite (iron oxide, Fe_2O_3) precipitated from hydrothermal (hot water) solutions passing through the fractures. Just below the boulder at the sharp turn in the trail (yellow arrow) is a polished and striated rock surface with striations oriented S23°E. Striations are scratches produced by a glacier sliding across the rock surface, recording the direction in which the last glacier was moving. These were created during the last ice age, when glacial ice covered this area about 35,000-17,000 years ago.

After making the sharp right turn (east), you will cross a small valley toward Pinnacle Rock.

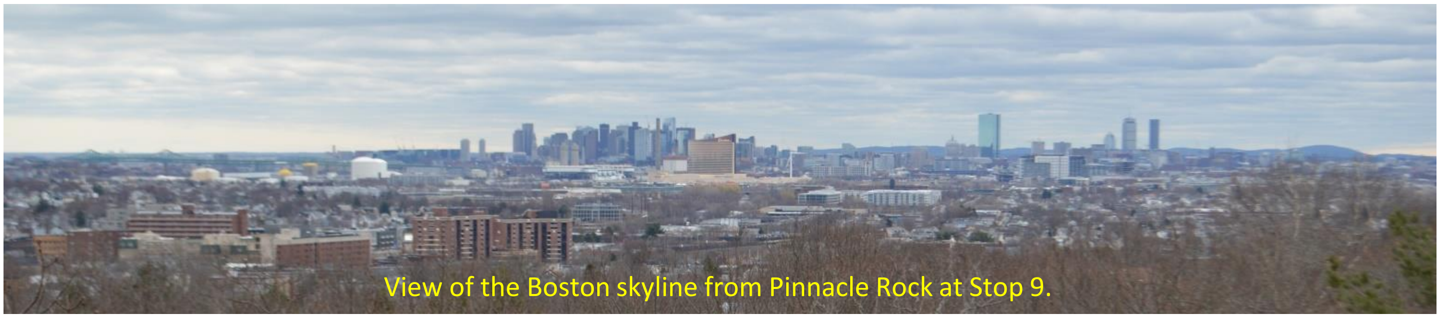
STOP 7: As you cross the far end of the small valley, the trail crosses a N-S trending dolerite dike that runs along the flank of Pinnacle Rock (image below on left, view east). Dolerite is an igneous rock of intermediate (sand size) grains made of mafic (dark-colored) minerals and plagioclase feldspar. Usually, these dikes contain the minerals pyroxene and magnetite. The pyroxene may be partly altered to chlorite and amphibole. This is a good opportunity to see the rusty surface produced by the weathering of iron-bearing minerals in the rock. The high iron content of the rock gives it a dark color on fresh surfaces, which is easily seen on a cut rock sample (image below on right). The faintly purplish-green grains are pyroxene while the plagioclase is gray. This dike also contains pyrite, an iron sulfide mineral, sometimes called fool's gold, with a metallic brassy color (arrow on image). This dike has the same chemistry as lava flows in Hawaii and Iceland, but it was formed as an intrusion that filled a fracture.



STOP 8: Before climbing up the steep face of Pinnacle Rock, look at the rock surface about 15 m to the south (image below left, arrow shows position of image on right). Exposed here is welded lithic crystal tuff (Zbrl), which forms a N-S trending and eastward dipping layer within the Boojum Rock Tuff. This is the same volcanic rock we have seen so far, welded crystal tuff, but with the addition of many lithic fragments (image below right). Almost all of the lithic fragments are gray, angular volcanic rock types. There are also occasional metasandstone lithic fragments from a much older metamorphic rock formation exposed north of here, called the Westboro Formation (Zvwq). This exposure tells us that the magma erupted through volcanic rocks from earlier eruptions associated with the Boojum Rock Tuff, and that deeper in the crust the magma encountered older metamorphic rocks. The unit is steeply dipping to the east; this appears to be the orientation of an ancient volcanic land surface that was later tilted.

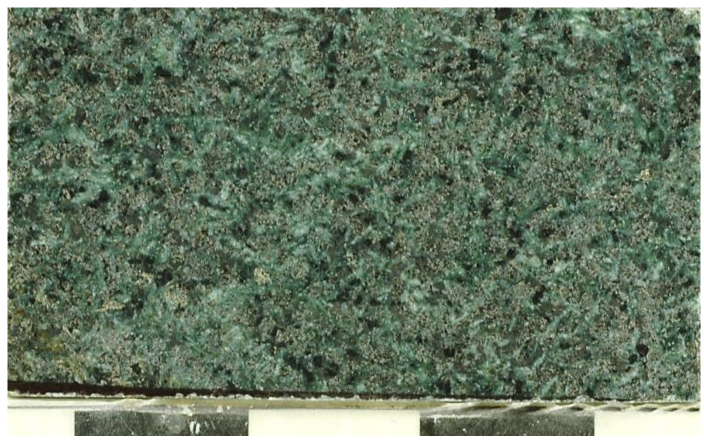
STOP 9: At the top of Pinnacle Rock is an excellent view of the Boston skyline (panorama at top of next page). Visible from east to west (left to right) are the Mystic Tobin Bridge, downtown Boston, and the Back Bay skyline. The top of Pinnacle Rock is crystal tuff (Zbrc) and is just west of the contact with the lithic crystal tuff (Zbrl) seen at Stop 8. Where the trail heads down from the ridge crest, you may see small orange (iron)-stained patches of smooth, highly polished rock, which is what remains of a glacially striated surface.

From here the trail heads downhill to where it crosses East Path in the valley below. Before reaching East Path, the trail bends to the east (right) and crosses a wet area on wooden planks. East Path is marked as a fire road (bike symbol). Cross East Path and head upslope a short distance.



View of the Boston skyline from Pinnacle Rock at Stop 9.

STOP 10: The trail crosses the E-W trending dolerite dike we saw earlier at Stop 4, but here, it is much better exposed. The dike forms an E-W trending ridge (image to right taken in winter) because of its resistance to weathering and erosion relative to the surrounding highly fractured crystal tuff (Zbrc). The dike is not as fractured and crosscuts fractures in the tuff, which means that the dike intruded after the tuff was fractured. Also note the rusty color and fine grain size of the dike (image below right). On this image, the faintly purplish-green areas are pyroxene, and the less conspicuous gray grains are plagioclase feldspar. In another 40-50 m, the trail ascends a steep slope onto a small hill of fractured crystal tuff, which has several orange (iron)–stained, polished glacial striation and groove remnants that trend S24°E. The trail then descends into a small valley before ascending another hill to Stop 11. The contact between crystal tuff (Zbrc) and lithic crystal tuff (Zbrl) within the Boojum Rock Tuff is in the small valley.



Continue across the small valley onto the next steep-sided pinnacle.

STOP 11: This pinnacle is one of the best places to see lithic crystal tuff of the <u>Boojum Rock Tuff</u> (Zbrl). Like at Pinnacle Rock, the lithic fragments are almost entirely gray, angular volcanic rocks with very sparse metasandstone fragments (image to right). On the map, this unit continues north from Pinnacle Rock. About halfway up to the top of this pinnacle is a highly polished, tan platform that has striations oriented S17°E. Ice flow here was about 10 degrees more southerly than at nearby sites because it was deflected by the western steep face of the hill.

After this stop, the trail descends into a valley to trail junction G5-8. There are two options here as the trail splits and later rejoins, to provide an alternative to the very steep slope directly ahead.

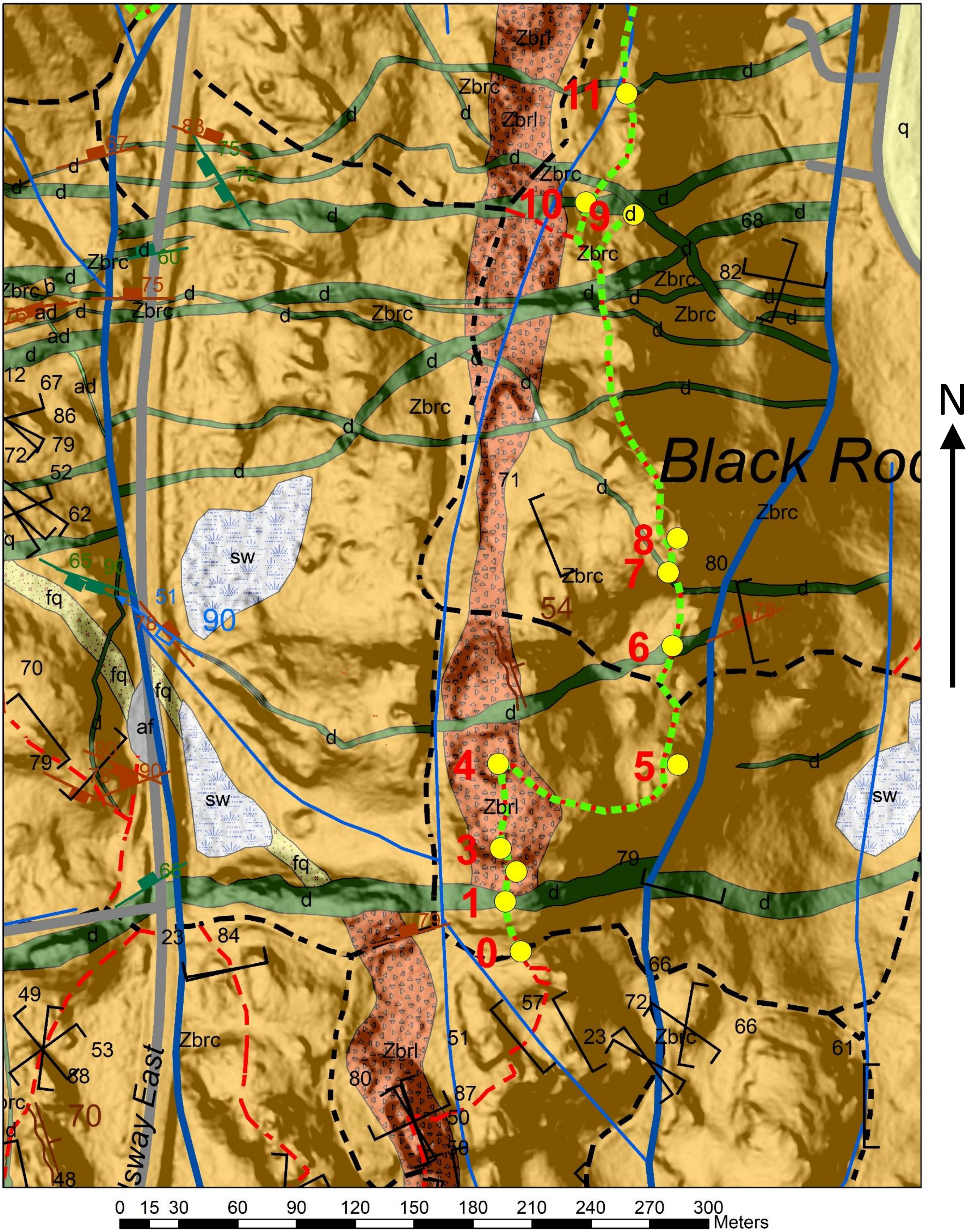
STOP 12: Option 1 (up steep face): From junction G5-8, climb up the steep face directly ahead onto the hill composed of lithic crystal tuff (Zbrl). On the hill's north (far) side, the trail heads down into a ravine and then sharply turns east (right) down a steep face to a trail junction in the valley below. This valley is a N-S trending fault. The Rock Circuit Trail continues straight to the east, but if you want to explore the fault valley, head south (right) at the trail junction. The fault is described in Option 2.

STOP 12: Option 2 (into valley to east): From junction G5-8, head down the slope to the east (right) into a hollow bounded by steep faces. The hollow runs along a N-S trending fault. From the valley bottom, follow the trail north (left) up the rubbly slope. This is fractured rock along the fault (along dashed line on image to right) that continues north through a small valley.

When you arrive at the junction with the trail from Option 1, head east (right) to continue on the Rock Circuit Trail. Continue east (right) on the trail across a wetland, where the rock is heavily fractured in the fault zone. Upward seepage of groundwater along fractures is the source of the wetland. The trail heads up onto a steep knob that is back in the crystal tuff (Zbrc) of the Boojum Rock Tuff. Follow the trail north (left) to the Cross Fells Trail (blue markers) at junction G5-5. This spot is the beginning of Part 2 of the tour.

Continue to Part 2 of the Rock Circuit Tour. Stop numbers start over at 1.

Map RC-2A


Zbrl
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5
4
3
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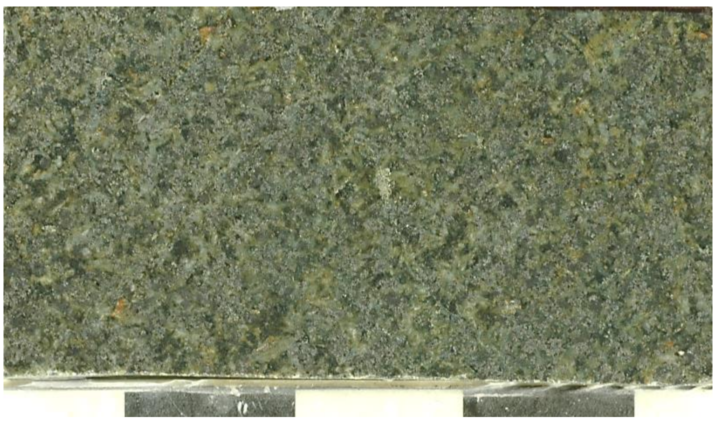
0 15 30 60 90 120 150 180 210 240 270 300
Meters

PART 2 (Stop numbers start over at 1.)

At junction G5-5 (Stop 0 on map RC-2A), follow the Rock Circuit Trail (white markers) up the slope to the north (left) toward Black Rock for about 30-40 m.

STOP 1: The trail crosses a wide, E-W trending dolerite dike (d on the map). Look for the rusty, weathered surface of this unit. This was the same dike mentioned at the beginning of Part 1, that can be seen when crossing the Fellsway East. A dike is an intrusion of magma that fills a fracture and then crystallizes, in this case producing dolerite. Dolerite is an igneous rock of intermediate (sand size) grains made of mafic (dark-colored) minerals and plagioclase feldspar (gray, image below on left). Usually, these dikes have the mafic minerals pyroxene (faintly purplish-green mineral in image), which is partly altered to chlorite and amphibole, and magnetite. A high iron content gives the rock sample a dark color. The rusty surface of outcrops is from the oxidation of iron. Just a few meters west (left) of the trail, the rock surface has glacial grooves created by the last glacier sliding across the land surface (image below right). As the base of the glacier slid across the rock, it dragged rocks and sand across the surface and scratched and gouged the dolerite. The grooved surface is not polished because dolerite weathers too quickly, which removes the polish and fine scratches, but faint grooves are still preserved. The orientation of the grooves (red arrow) at S29°E indicates the flow direction of the generally south-southeast moving ice sheet. During the last glaciation (ice age) the glacier covered the land surface from about 35,000 to 17,000 yr ago.



STOP 2: 10 m uphill from the dike and on the east (right) side of the trail is an example of flake weathering exhibited by the Boojum Rock Tuff (image to right). This gives the rock surface a patchy mosaic-like coloration pattern. The rock here is welded lithic crystal tuff (Zbrl, see Stop 3). Flake weathering results from initial chemical weathering that produces a light tan-colored outer weathered zone, or weathering rind, that is usually 2-3 mm thick, which likely creates very fine pore spaces in the otherwise solid rock. The pores may allow lichen growth and water to penetrate and freeze in the rock, causing expansion. Other mechanisms are likely involved, such as periodic fires, but we don't yet know what role they play. Flake weathering is widespread on the Boojum Rock Tuff but does not occur on any other volcanic units in the Fells.

STOP 3: 10-15 m uphill from the last stop and on the west (left) side of the trail is a good exposure of welded lithic crystal tuff in the Boojum Rock Tuff (Zbrl, image below on left). This unit is exposed across the top of the hill and is the same unit that we traced northward from Pinnacle Rock on Part 1 of the tour. This unit is a pyroclastic volcanic rock, meaning it was ejected into the air prior to accumulating upon landing. Pyroclastic rocks can have 4 components in them: 1) ash, or fine (microscopic), broken glass shards that may have still been molten when they landed; 2) crystals which are mineral grains that had started to crystallize in the magma prior to eruption; 3) large pieces of glass and pumice (bubbly glass), which may still have been molten when they landed; and 4) lithic fragments, which are fragments of pre-existing rock, either from prior volcanic eruptions or any older rocks through which the magma passed in the subsurface. The rocks exposed here are welded lithic crystal tuff. Tuff is any pyroclastic rock with ash in it. The term welded means that the ash and glass/pumice fragments were at least partly molten (liquid), so they adhered to each other when they landed. The tuff here has crystals, which are small (usually 1-3 mm), broken, white plagioclase feldspar grains, as well as abundant, sub-centimeter lithic fragments, which are volcanic and occasionally metasandstone (image below on right). Also, glass that remains at high temperatures after it solidifies will slowly convert to a crystalline solid composed of very fine-grained quartz and feldspar. This change of hardened glass to very fine quartz and feldspar (crystalline material) is called devitrification, and this material gives the rock its greenish-gray color on fresh surfaces. The larger devitrified glass fragments, including pumice, that are up to 2 cm, were also soft when they landed. As a result, they were flattened under the weight of accumulating material above. The flattened fragments, best seen in a microscope, blend in with the surrounding devitrified ash.

Continue uphill. At the top of the hill, the trail makes a sharp bend to the east (right).

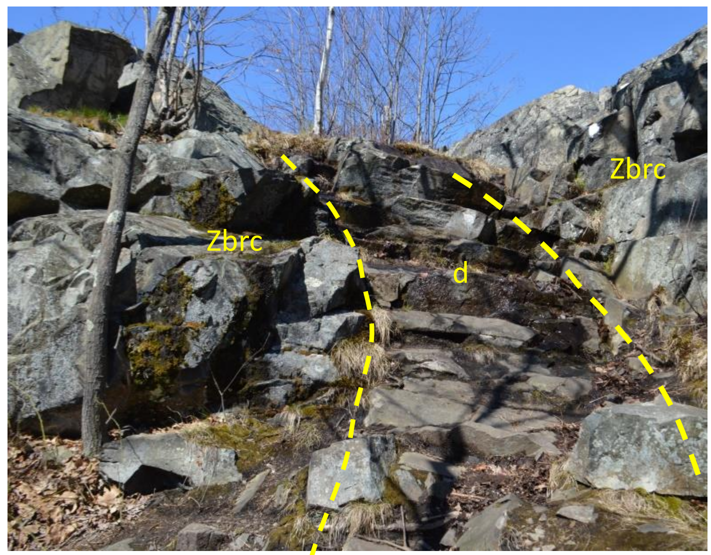
STOP 4: At the bend, you can see a broken glacial erratic from the Stoneham Granodiorite (Zst, image to right), a rock formation in the northern Spot Pond area. Granodiorite is an intrusive, coarse-grained igneous rock almost entirely made of plagioclase feldspar and quartz with lesser alkali (potassium) feldspar and scattered to sometimes abundant mafic (dark) minerals. To be a glacial erratic the boulder must be glacially transported and also end up on a different rock formation than the one it came from. Here, the underlying rock is the same lithic crystal tuff as at Stop 3. The erratic has been broken, to reveal fresh, unweathered surfaces. The granodiorite contains dark patches called inclusions. When the magma that would later form the granodiorite intruded subsurface rocks, pieces of another rock formation with a mafic composition (basalt) broke off into the magma and were later frozen into the granodiorite. The inclusions indicate that the mafic rocks are older than the granodiorite.

After the sharp turn east (right) the trail descends a steep slope to a bare knob.

STOP 5: The bare knob (no image) is made of welded crystal tuff in the Boojum Rock Tuff (Zbrc). This rock is similar to the welded lithic crystal tuff at Stop 3, but without the abundant lithic fragments. We will discuss this rock unit more thoroughly at Stop 7. The tuff here is heavily fractured near the major faults that run along the base of the cliff that forms the eastern edge of the hill. This is essentially the eastern boundary of the Fells. From this spot you can see the athletic fields and Pine Banks Park in Malden and Melrose. You may also hear the Orange Line at Oak Grove Station.

Follow the trail downhill (north) to a dirt road at junction G5-2. The trail follows the road a short distance west (left) before continuing north (right) in the woods.

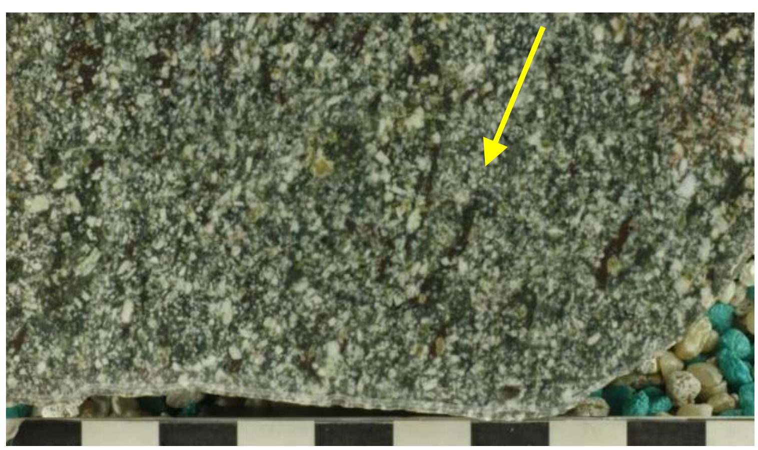
STOP 6: The trail crosses a small E-W trending dolerite dike (image to right) that forms a knob in the trail. This dike is similar to the dike at Stop 1.
Continue north to a steep rock face, which is the southern end of Black Rock.



STOP 7: The trail heads up the face on what looks like a crude staircase (image to right). This is a small, NW-SE trending dolerite dike, but with a finer grain size than the dikes at Stops 1 and 6. Fractures crossing the dike perpendicular to its sides have a different orientation and density than fractures in the surrounding crystal tuff and do not cross into the tuff. The fractures are cooling joints that resulted from contraction of the dolerite as it continued to cool. Intrusion of the magma to form this dike took advantage of large fractures in the surrounding tuff. The dike has been traced about 700 m to the northwest before it pinches out; it is cut off by a fault to the southeast. When you arrive at the top of the hill, look for the dike heading off to the northwest.

Follow the trail up the steep slope of the dike and then to the highest point on Black Rock.

STOP 8: At the top of Black Rock is a great view of north suburban Boston and a great exposure of welded crystal tuff in the Boojum Rock Tuff (Zbrc). If you find a freshly exposed face, you can see many white plagioclase feldspar crystals surrounded by very fine, greenish-gray devitrified glass and occasional dark lithic fragments (image below left). If you find a fresh vertical face that is trending E-W you may also see some parallel, dark reddish-gray remnants of what were flattened glass or pumice fragments that dip downward to the east. These fragments are very hard to see on an outcrop face (image below left, parallel to arrow). The elongated fragments are more easily seen in a rock surface cut vertically and trending E-W (image below at arrow).

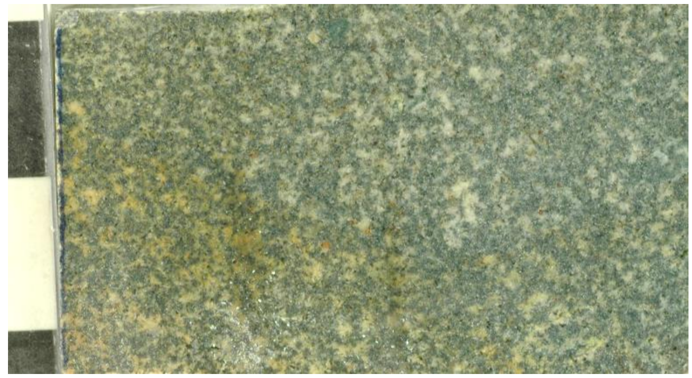


Descend Black Rock northward to the center of the broad valley below where you will eventually see a small trail marked with yellow markers that leads down to a waterfall called "The Cascade" at junction G4-4.

STOP 9: About 12 m before the small trail, the trail crosses an E-W trending ridge that is a dolerite dike. The waterfall is formed over intersecting, heavily fractured dolerite dikes. The fractures allowed easier erosion by a small intermittent stream that drains wetlands to the west. You can go down to see the waterfall, but **BE CARFUL!! The wet rock here can be slippery in the winter because of ice and in the summer because of algae**. In most summers, the stream and waterfall are almost dry. The waterfall can also be approached from the other side of the stream.

After seeing the waterfall, return to the Rock Circuit Trail and continue north over the small bridge crossing the stream. Continue for another 15-20 m.

STOP 10: At this position is one of the dikes that intersects at the waterfall. This dike is badly fractured, so several boulders have broken off it. It has a lighter, grayer, less rusty color than most dolerite dikes in the Fells (image to right), and a higher plagioclase percentage. Most of the original pyroxene has been altered to chlorite and biotite.

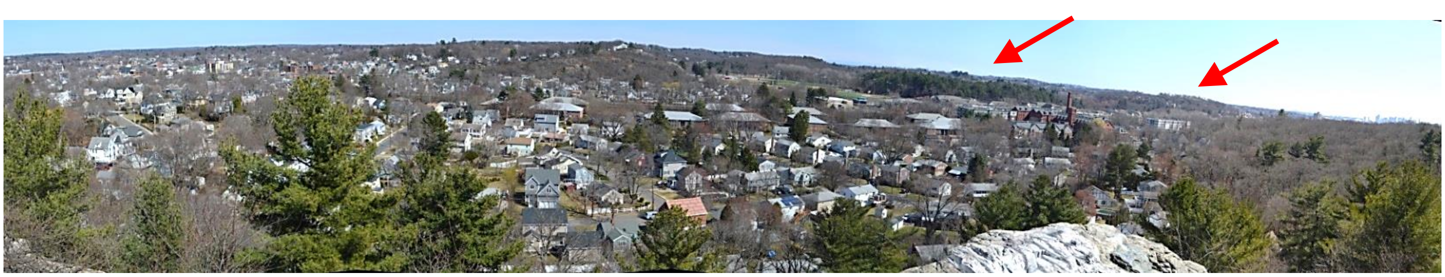


Continue the tour north on Map RC-2B.

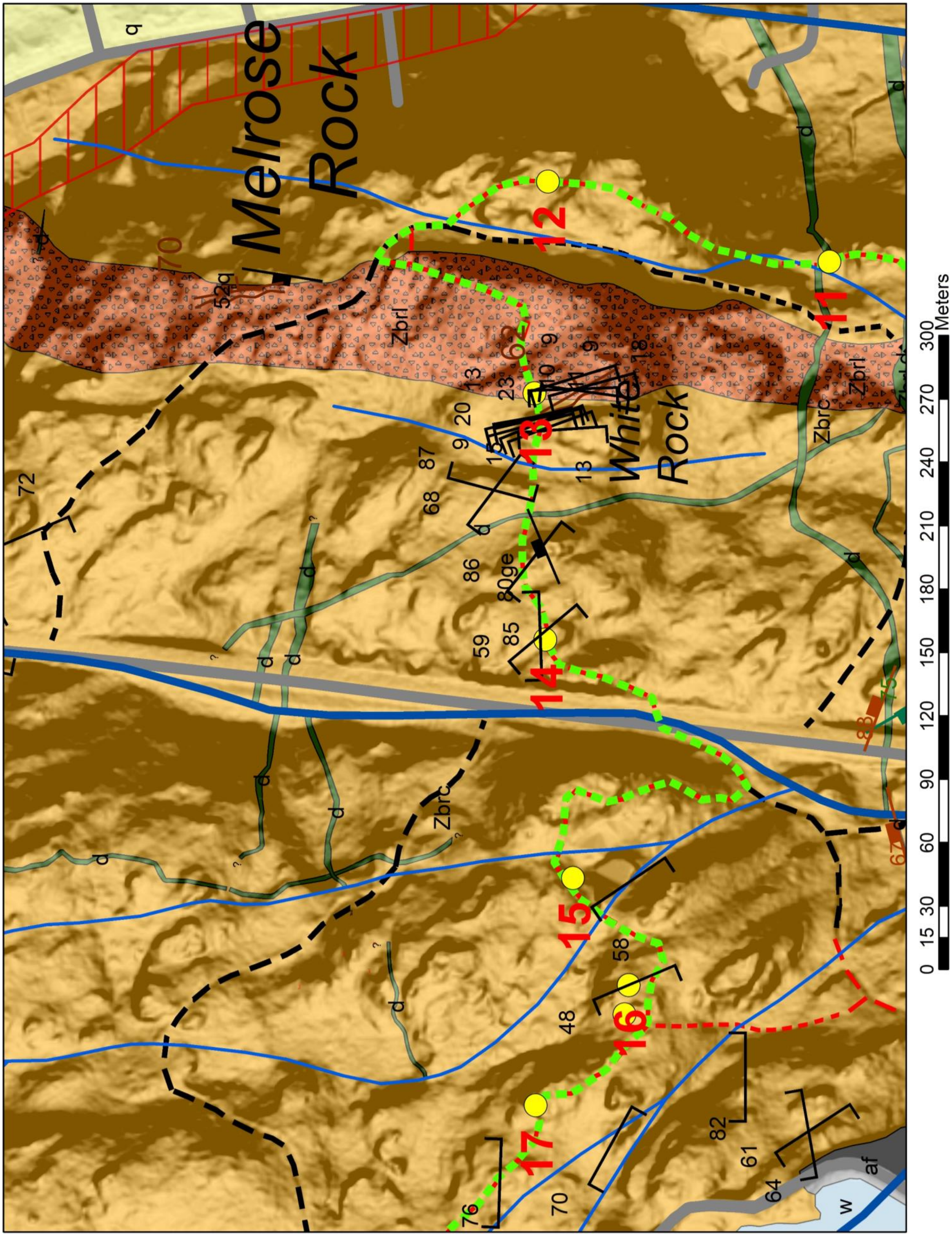
STOP 11: In a short distance, the trail ascends a ledge of welded crystal tuff in the Boojum Rock Tuff (Zbrc). On fresh surfaces, this is a good spot to look for the white plagioclase crystals surrounded by fine, greenish-gray, devitrified glass. At the north end of the outcrop, the trail descends a small, steep face and lands on another dolerite dike (image to right) The circular holes in this dike are gas bubbles or vesicles.

Continue north on the trail across a valley and then up the steep southern slope of Melrose Rock.

STOP 12: Melrose Rock is heavily-fractured, welded crystal tuff in the Boojum Rock Tuff (Zbrc). Fractures on Melrose Rock frequently have a sparkly, metallic, steely-gray mineral on their surfaces (image to right). This is specular hematite, which is formed by precipitation of iron oxide (Fe_2O_3) from hydrothermal (hot water) solutions that circulated through the fractures. Hematite is common in the Boojum Rock Tuff and occurs in many parts of the Fells. It post-dates the Neoproterozoic rock formations, having formed at a time either during or after the rocks were fractured. I have not seen hematite in fractures in the dolerite dikes, so it may predate them. Melrose Rock also has a spectacular view across Melrose to the north all the way to the Boston skyline in the south (panoramic view below). Near the middle is a pine covered hill (left arrow). This is Pine Banks Park in Malden and Melrose. Further south (right arrow) is Waitts Mount in Malden.

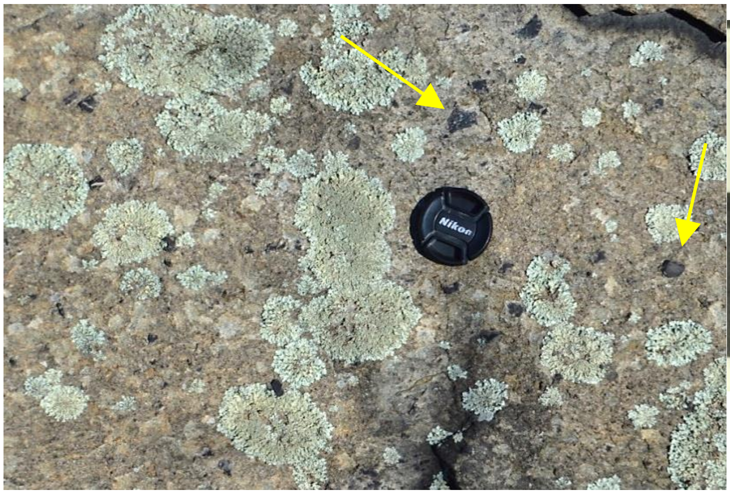
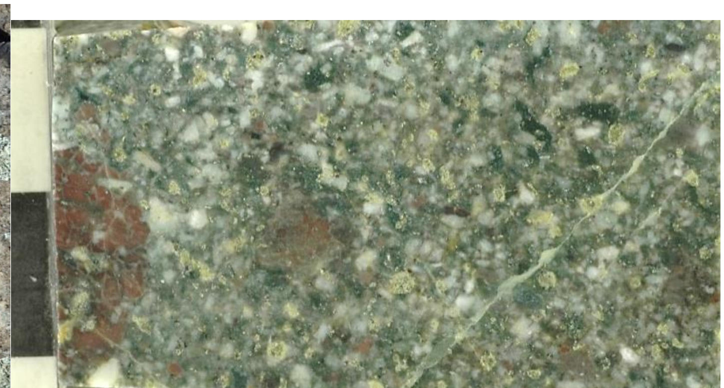


Map RC-2B


N
Melrose Rock
White Rock
Zbrl
Zbrc
11
12
13
14
15
16
17
q
w
af
0 15 30 60 90 120 150 180 210 240 270 300
Meters

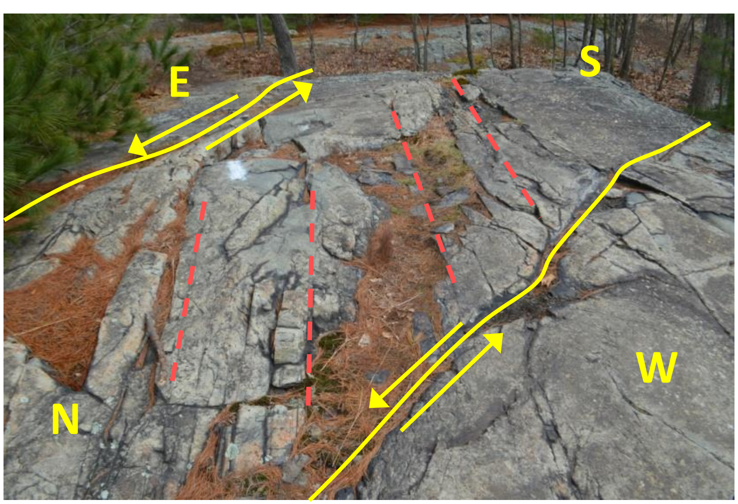
Head down the steep north (far) side of Melrose Rock to White Rock Path (junction G4-2), which follows a fault. Continue north on the path to junction B4-1. Head west (left) to the top of White Rock, which looks down (east) over Melrose Rock. The rock here is the same lithic crystal tuff unit (Zbrl) seen at Stop 3. From the top of White Rock head west (right) down into a linear hollow formed by fractures and then up the gentler opposite side.

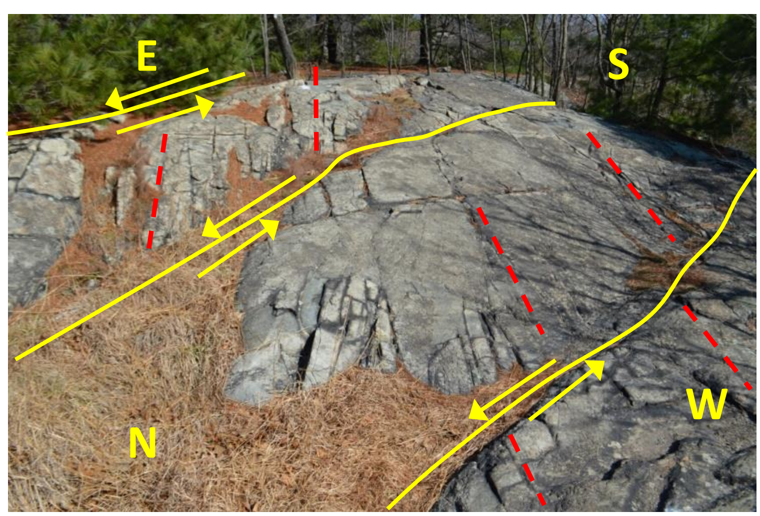
STOP 13: Close to the next hilltop and at a slight bench, the trail crosses the contact of lithic crystal tuff (Zbrl) to the east and crystal tuff (Zbrc) to the west, both in the Boojum Rock Tuff. Note on the map that the lithic crystal tuff has been traced from the southern end of the Fells (see Part 1) to here. The lithic tuff is a N-S trending, steeply east-dipping layer in the tuff. Just before reaching the crest of the hill, the exposed bench to the south (left) and east is lithic crystal tuff. Walking out onto this high spot you will notice that the volcanic lithic fragments (image below to left at arrows) project above the weathered surface of the rock because they are more resistant to weathering. They appear black in the field, but on cut rock surfaces, many of the fragments are dark reddish-brown (image below on right). The ridge top to the west (ahead on the trail) has none of these fragments and is underlain by the crystal tuff.

Continue west into the next ravine, which follows a fault, and up to the top of the next hill. After crossing the crest of the hill, you will cross an irregular platform. Before descending into a narrow, steep-sided hollow, the west end of the hilltop has some interesting fracture patterns.

STOP 14: The top of this hill has sets of parallel fractures angled between sets of longer N-S trending fractures that run the length of the hill. This fracture pattern is known as Riedel shears and is caused by the fracturing of rock between two separate but parallel shear or displacement planes. On the images below (views back to east), the larger shear planes are outlined in yellow with arrows showing relative displacement on opposite sides of them. Dashed red lines show the fractures in between the larger shear planes. Letters indicate compass directions. This configuration indicates that areas to the west are moving south relative to areas to the east or there is left lateral displacement in which areas viewed across a shear are moving to the left. In addition to occurring in association with N-S trending faults in this area, Riedel shears occur across the entire area of the Boojum Rock Tuff where there are other major N-S trending faults .





Follow the trail across the Fellsway East, and after about 30 m make a sharp turn to the north (right), to the top of a steep knob.

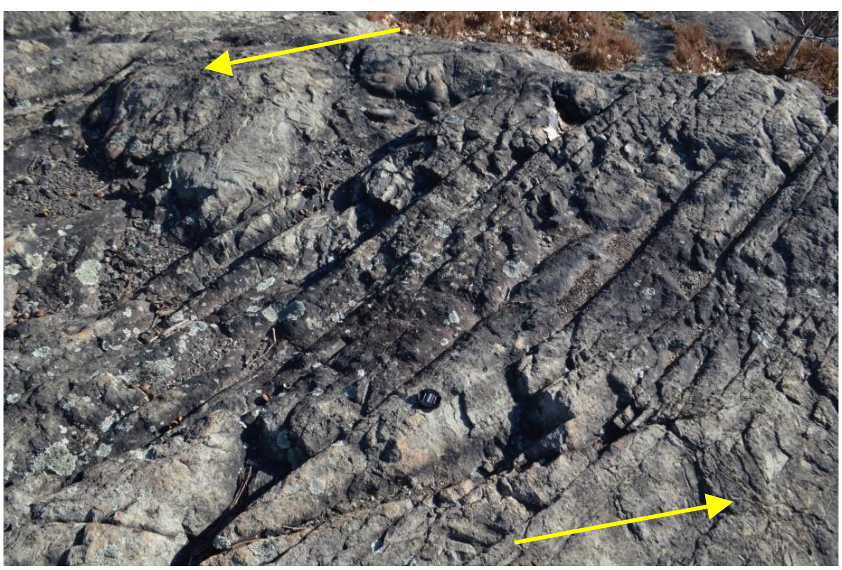
STOP 15: The knob overlooks the Fellsway to the east, which follows a major fault. The knob is heavily fractured crystal tuff in the Boojum Rock Tuff (Zbrc). The trail continues west and descends into a fault valley with a vernal pool. Vernal means seasonal (in the spring). However, water stays in this pool through most summers because it is constantly being fed by groundwater seepage from the upland to the west.

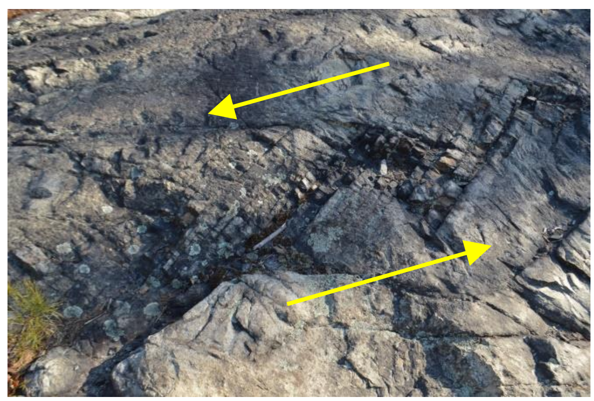
From the vernal pool, the trail climbs westward and then makes a bend northward (right) on a relatively flat bench.

STOP 16: After the bend there is a small knob shaped by fractures dipping to the west (image to right, view ahead). As you make your way past the knob and view it to the right (image below right), look for the tannish orange, highly polished, glacially striated surface (arrow). We have seen striation patches before, but this one is unusual because of the direction of the striations. Striations on nearby surfaces to the north and south are S32-37°E, while this surface has striations at S73°E. The striations are best seen when the rock surface is wet. It remains uncertain, but this may be a set of striations preserved from a glaciation that pre-dates the last one, when an ice sheet had a more easterly flow. It does not look like ice flow during the last glaciation (SSE) was deflected at this site, and the very hard tuff may have resisted weathering, which allowed long-term preservation of older striations.

Continue north (ahead) on the trail to a large, gently tilted bench.

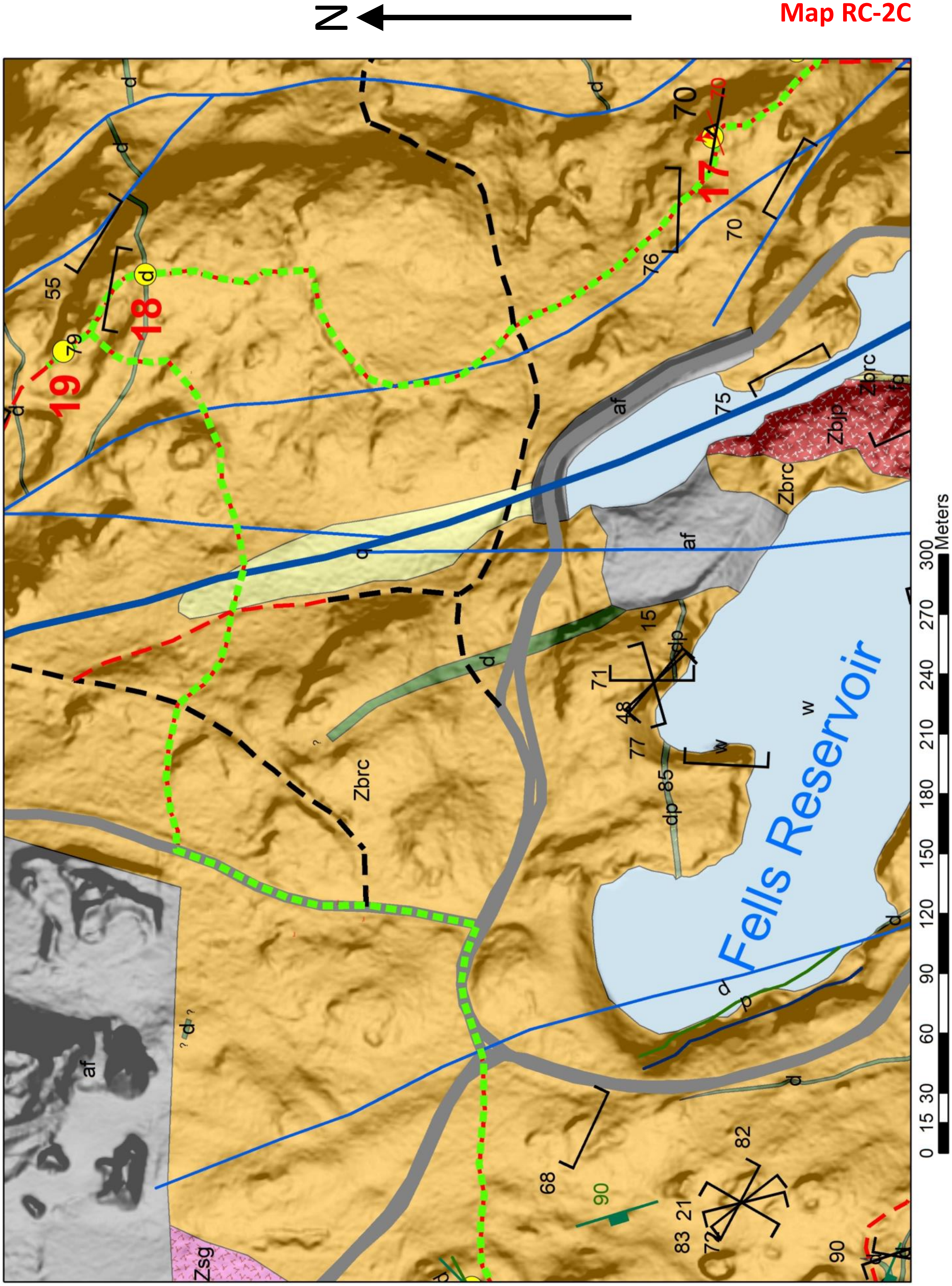
STOP 17: On the bench are several sets of closely spaced, parallel fractures. The fractures are in the form of parallel sets of tension gashes (images on right) in response to shear (arrows). They are like the Riedel shears at Stop 14 but without the major N-S shear planes. There are finer sets of parallel fractures perpendicular to and between the larger gashes (below right). On the east side of the outcrop and further from the trail) are angled fractures of what appear to be Riedel shears (below). This outcrop also has small, remnant patches with glacial striations.





Continue tour on Map RC-2C.

Map RC-2C


N
Fells Reservoir
Zbrc
Zbjp
Zsg
af
dp
17
18
19
0 15 30 60 90 120 150 180 210 240 270 300
Meters

Continue north on the trail and cross Wyoming Path at junction F4-8 to a relatively flat area on crystal tuff (Zbrc). The trail winds through outcrops as it makes its way north.

STOP 18: The trail eventually comes to a large, split metasandstone boulder (image to right). This is a glacial erratic from the Westboro Formation, which occurs north of here in Virginia Wood. The north (far) end of the boulder is also resting on a small dolerite dike that is hard to trace. **Continue beyond the boulder for about 30-40 m to a bench.**

STOP 19: The bench is crystal tuff in the Boojum Rock Tuff (Zbrc). Scattered across the top of the bench are remnant, orange (iron)–stained, polished striation surfaces with striations oriented S30°E. A little further west along the last 30 m of the Crystal Spring Trail (red markers) where it joins the Rock Circuit Trail (junction F4-4) from the north (image to right) are striations oriented S55°E that represent ice flow deflected eastward as the glacier tried to move up the slope.

From this site continue west on the Rock Circuit Trail down a steep slope into a valley. Follow the trail through an area of heavily fractured and faulted rock in the crystal tuff with deep linear hollows (faults) and isolated knobs covered by angular rock debris. Continue west crossing a wood walkway, a trail, and a road (Melrose Path, junction F4-2). The trail then joins Pipeline Road at the edge of the Fells (junction F4-1). Follow Pipeline Road north (left) to Wyoming Path. Follow Wyoming Path west (right) to junction F4-5, where the trail heads into a wooded area.

Continue the tour on Map RC-2D.

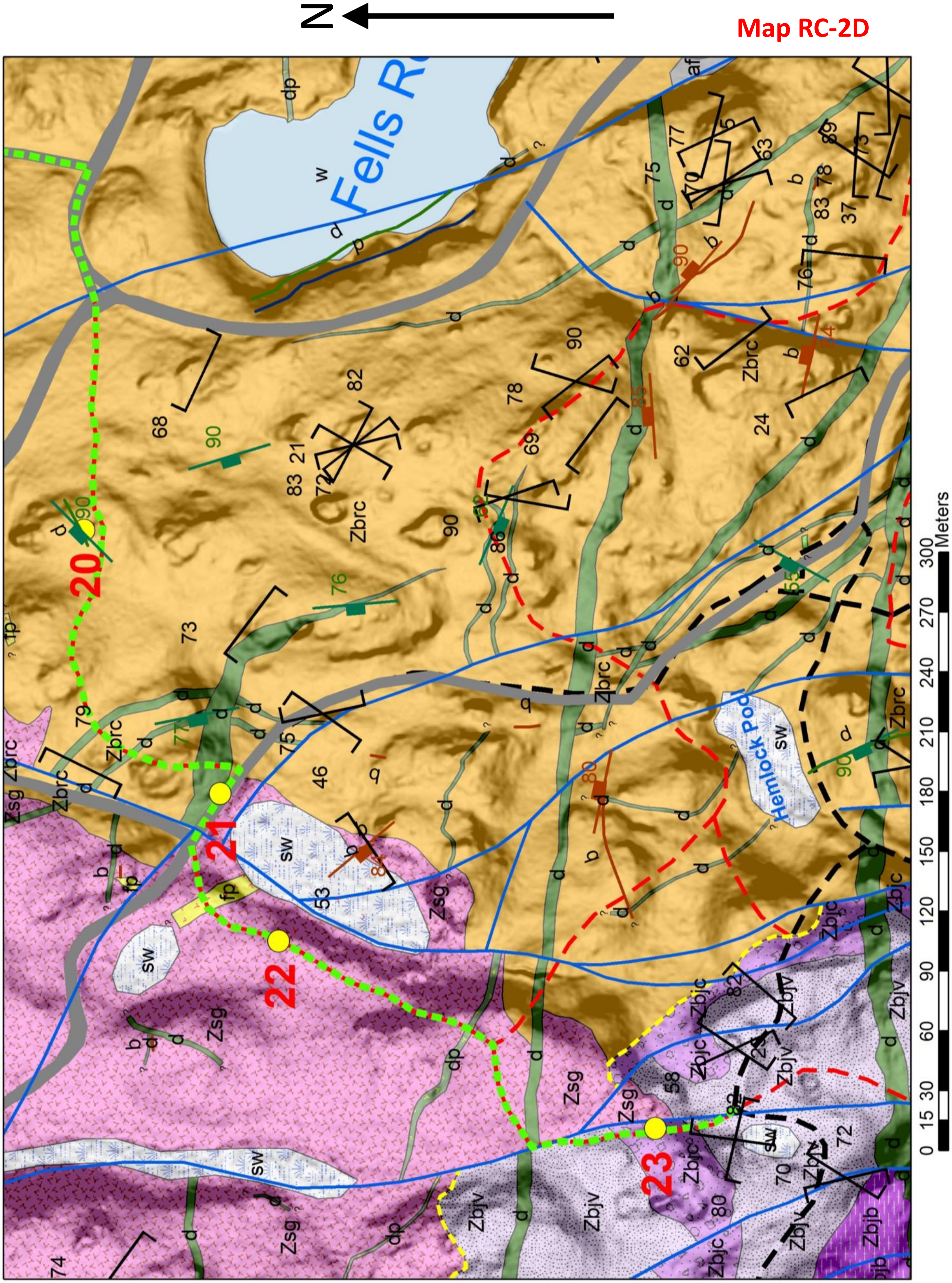
STOP 20: After crossing a wooden walkway, the trail curves around a mound, which is a porphyritic dolerite dike. Porphyritic rocks have two distinct grain sizes: fine crystals that make up most of the rock, or the ground mass, and a second set of larger crystals called phenocrysts. In this dike, the phenocrysts are slender, white plagioclase feldspar (image to right). You will have to look closely to see the them. Although we haven't yet seen any porphyritic dikes along the Rock Circuit Trail, they are common in the Fells.

Continue west (ahead) on the trail. As the trail starts to bend to the south (left), rocks across the road below are the Spot Pond Granodiorite (Zsg). The trail descends a steep slope to Hemlock Pool Road at junction E4-5. The trail joins the road and heads northwest (right).

STOP 21: Shortly after junction E4-5 on the northeast (right) side of the road is a dolerite dike with many holes (image to right). The holes are vesicles, or gas bubbles that were trapped in the cooling magma.

The road bends to the west (left) at the next road junction, and a little way after, the trail branches off to the south (left) at junction E4-4. Continue south.

Map RC-2D

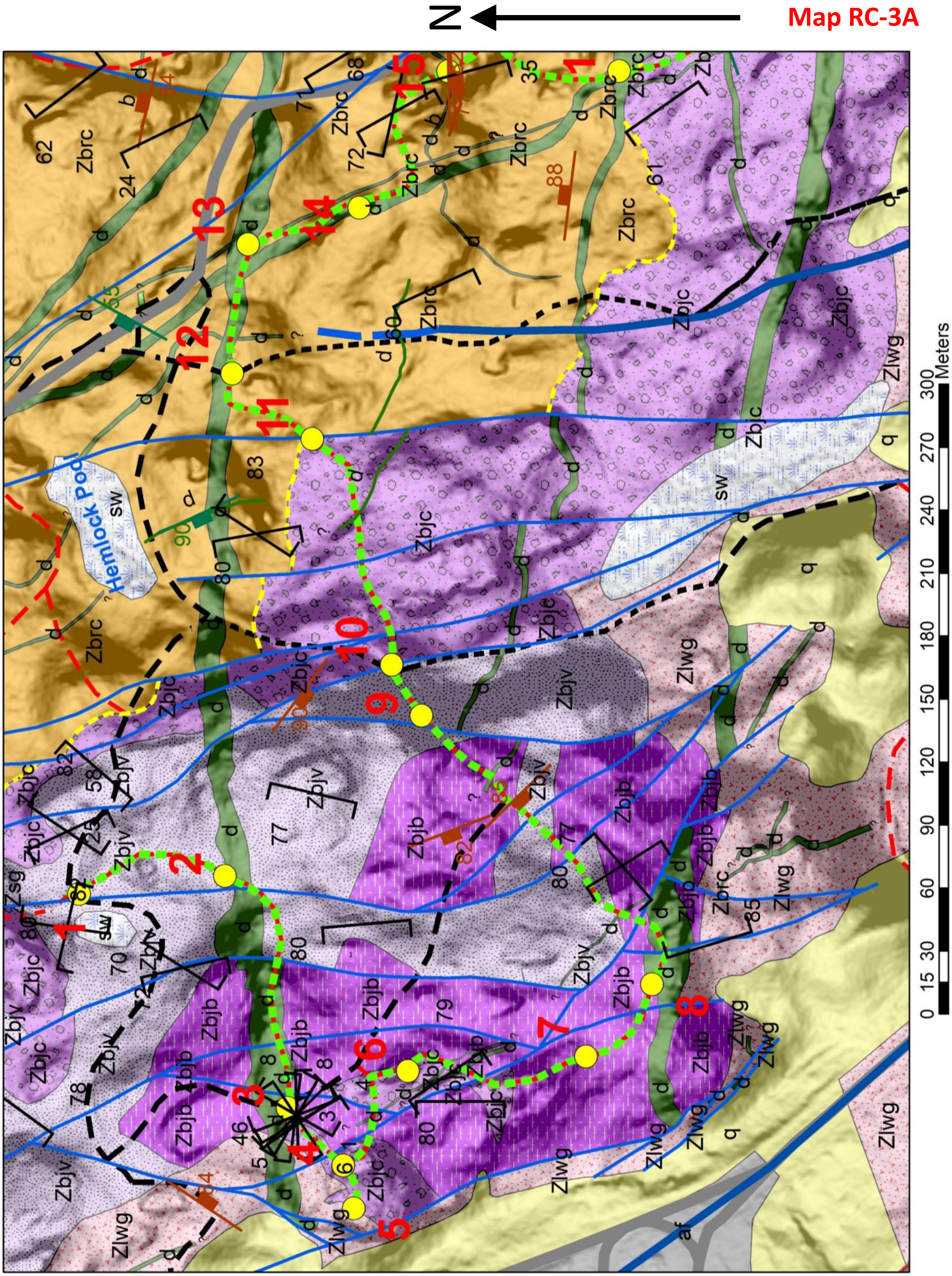

N
Zbrc
Zsg
Zbjc
Zbjv
Zbjb
sw
fp
dp
20
21
22
23
0 15 30 60 90 120 150 180 210 240 270 300 Meters

STOP 22: The first outcrops ahead on the trail are in the Spot Pond Granodiorite (Zsg). This area is recognizable by the somewhat rounded, glacially streamlined outcrops and lower fracture density (image below to left). Granodiorite is a coarse-grained intrusive rock in which the light-colored minerals are mostly quartz and plagioclase feldspar with smaller amounts of alkali (potassium) feldspar. Alkali feldspar is easy to spot because of its pink color. When the rock surface weathers, it develops a knobby surface (image below to right), because the quartz crystals tend to resist weathering more than feldspar. The Spot Pond Granodiorite is exposed over large areas at the southern end of Spot Pond and in the southern Fells west of Rt. 93. Although the contact between the Spot Pond Granodiorite and Boojum Rock Tuff is exposed here the contact is difficult to interpret for relative ages of the units. However, radiometric ages for the units, the granodiorite being 609 Ma and the tuff being 596 Ma, indicate that the tuff is younger.
Continue ahead to junction E4-9 and then turn west (right). After about 50 m the trail turns south (left) in a small valley.

STOP 23: The small valley is the location of a fault that separates the Spot Pond Granodiorite (Zsg) on its east (left) side from tuff in the Lynn Volcanic Complex (Zbjc) on its west (right) side that is a younger part of the Lynn than the Boojum Rock Tuff. The younger volcanic rocks of the Lynn will be explored in detail on Part 3 of the tour. The trail passes a steep E-W trending scarp on the east (left) side of the trail that marks the contact between the granodiorite to the north and the volcanic rocks to the south. On the west (right) side of the trail, only the volcanic rocks are exposed. The image to the right shows the fault valley viewed from the south near Woodland Path (back up the trail). The dashed line shows the approximate location of the fault separating the two rock units.

END of Part 2: Part 2 ends at Woodland Path (junction E4-8), which is where Part 3 begins. To start Part 3, cross over Woodland Path and continue to follow the Rock Circuit Trail.

Map RC-3A

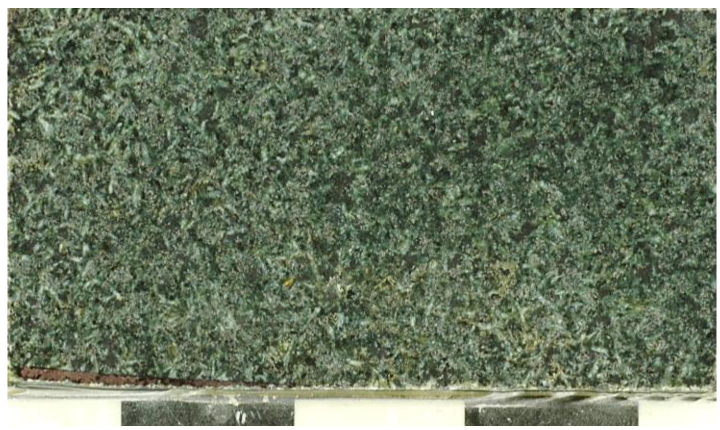

N
Hemlock Pond
Zbrc
Zbjc
Zbjv
Zbjb
Zlwg
Zsg
sw
af
q
d
0 15 30 60 90 120 150 180 210 240 270 300
Meters

PART 3 (Stop numbers start over with 1.)

Follow Map RC-3A. From the Cross Fells Trail (Woodland Path) follow the Rock Circuit Trail (white markers) up the hillslope to the south toward the Boojum Rock area.

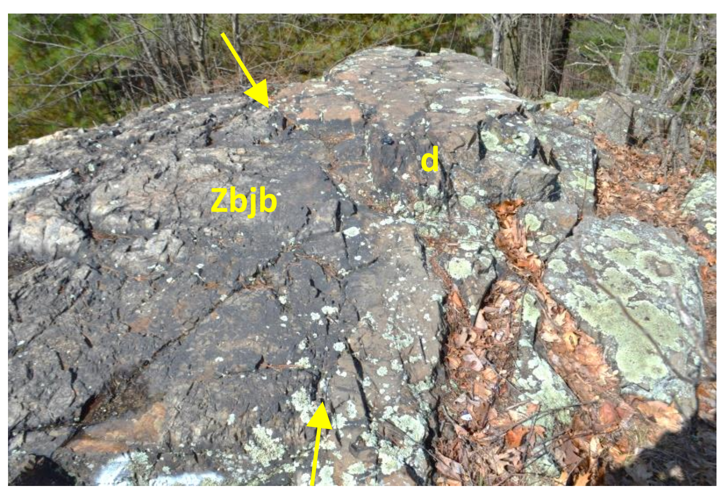
STOP 1: A meter or two from junction E4-8 is a glacially striated and grooved rock surface on an outcrop of the Lynn Volcanic Complex (image to right). We will investigate these volcanic rocks in more detail in a few stops. The striations and grooves, which are common in the Fells, were created by the last glacier moving across the land surface. As the glacier slid, the underlying rock was scratched, gouged, and polished by rock fragments and sand being dragged at the base of the glacier. The orientation of the grooves at S21°E (red arrow) indicates the flow direction of the generally south-southeast moving ice sheet. The last glacier covered the southern Fells from about 35,000 to 17,000 yr ago.

STOP 2: In about 80 m, the trail crosses a wide, E-W trending dolerite dike. Note the smooth and rounded forms of dolerite outcrops (image below left) as compared to the heavily fractured and angular outcrops of adjacent volcanic rocks. A dike is an intrusion of magma that fills a fracture, in this case producing dolerite. Dolerite is an igneous rock of intermediate (sand size) grains made of mafic (dark-colored) minerals and plagioclase feldspar. These dikes usually contain the minerals pyroxene, that may be partly altered to chlorite and amphibole, and magnetite. The high iron content of the rock gives it a dark color, as is easily seen on the cut rock sample (image below right). The faintly purplish-green grains are pyroxene, and the gray grains are plagioclase. The rusty surface of dolerite outcrops is due to the weathering (oxidation) of iron-bearing minerals.



The trail continues along the dike after bending to the west (right) in another 50 m. The trail crosses to the south side of the dolerite dike and crosses a road at junction E4-16.

STOP 3: Across the road is an excellent exposure of the contact of the south (left) side of the dike and the Lynn Volcanic Complex (Zbjb, image to right, arrows point to contact). Note the smoother surface and rusty color of the dike. It also has a finer grain size along the contact than towards the center because the magma cooled more quickly along its margin with the volcanic rock, forming a chill zone. Glacial grooves on the dike are oriented at S22°E.

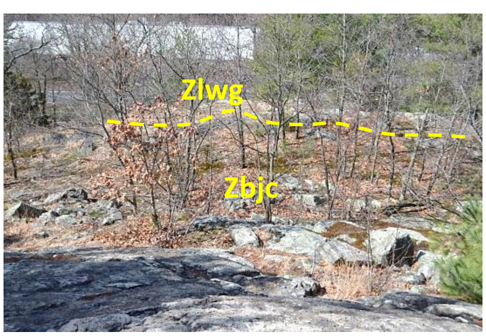


The trail drops into a hollow that is a <u>fault zone</u>. A fault is nothing more than a fracture that separates rocks that have moved relative to each other. The trail then climbs a bench.

<u>STOP 4</u>: On the bench is <u>volcanic breccia</u> in the Lynn Volcanic Complex (Zbjc). A <u>breccia</u> is any rock containing coarse angular fragments. The breccia here is a volcanic or sedimentary unit made almost entirely of large blocks of volcanic rock in finer olive-gray (light-colored) fine sediment (the matrix), which is rusty when weathered (images below). The unit may be landslide deposit formed from already deposited volcanic debris mixed with other rock types or just a coarse sedimentary deposit (conglomerate) with a high percentage of volcanic material. This is the bottom unit of the Lynn Volcanic Complex in the Boojum Rock area which overlies the Boojum Rock Tuff to the southeast. The image below on the left shows a volcanic boulder in the breccia surrounded by an olive-gray matrix weathered to a rusty color. In addition to <u>volcanic fragments</u>, there are also occasional blocks of <u>granite</u> in the breccia (image below on right, red arrow). Some granite boulders are rich in pink feldspar and others are pieces of the Spot Pond Granodiorite. This relationship proves that this part of the Lynn Volcanic Complex is younger than the Spot Pond. The breccia ends on a bench below (Stop 5), where it is in contact with an intrusive igneous rock unit.

Scramble down the incline at Stop 4 and out to the flat bench below (left image below, viewed from above in early spring). Note the roof of the ice rink in the distance, which may be concealed when there are leaves on the trees.

<u>STOP 5</u>: On the bench is the <u>contact</u> of <u>volcanic breccia</u> (dark unit in 2 images on right below) in the Lynn Volcanic Complex (Zbjc) and the Lawrence Woods Granophyre (Zlwg, light tannish-pink unit). Note the sharp contact (dashed line) between the two units at various scales. A <u>granophyre</u> is a fine-grained <u>granite</u> (quartz with roughly equal amounts of plagioclase and alkali feldspars) with a granophyric texture. A <u>granophyric texture</u> occurs when feldspar, in this case <u>alkali feldspar</u>, and <u>quartz</u> crystallize rapidly and simultaneously to produce irregular, intermingling crystal growths of the two minerals. This texture is only visible in a microscope, but it occurs throughout the unit and over a wide area from Lynn, across North Medford, and all the way to Medford High School. The granophyre represents a magma chamber close to the land surface, referred to as a <u>subvolcanic intrusion</u>. The granophyre intrusion appears to be closely related to the Lynn Volcanic Complex, which would be its surface (volcanic) equivalent.



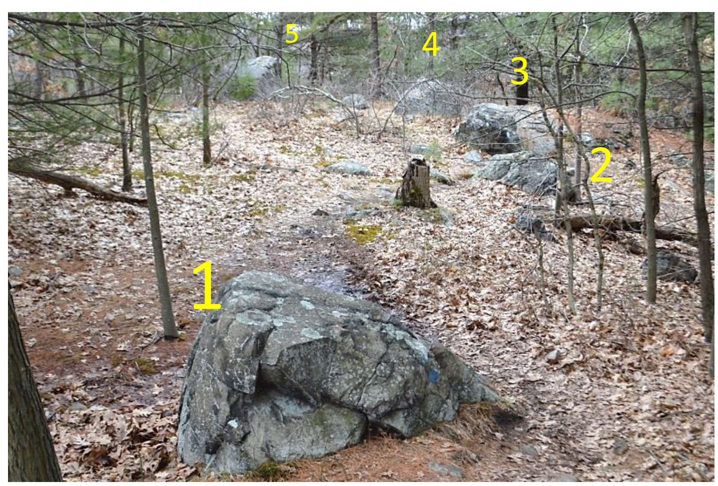
Climb back up the steep face of the breccia, keeping an eye out for granite boulders and faint layering or banding within volcanic blocks, which represent layers of ash and glass fragments. Continue south (right) on the Rock Circuit Trail. After about 40 m, a side trail joins from the dirt road to the east (left, from junction E4-18) and the trail climbs onto another bench.

STOP 6: The bench is an exposure of volcanic breccia (Zbjc) and on its south (far) end is welded crystal tuff (Zbjb) all in the Lynn Volcanic Complex. The north (near) end of the bench is part of the volcanic breccia (Zbjc) seen at Stops 4-5 with a few large volcanic blocks. The crystal tuff is a pyroclastic volcanic rock, meaning it was ejected into the air prior to accumulating upon landing. Pyroclastic rocks can have 4 components in them: 1) ash, or fine, broken glass shards that may have still been molten when they landed; 2) crystals which are mineral grains that had started to crystallize in the magma prior to eruption; 3) large pieces of glass and pumice (bubbly glass), which may still have been molten when they landed; and 4) lithic fragments, which are fragments of pre-existing rock, either from prior volcanic eruptions or any older rocks through which the magma passed in the subsurface. The rocks exposed here are welded crystal and lithic tuff. Tuff is any pyroclastic rock with ash in it. The term welded refers to the fact that the ash and glass/pumice fragments were at least partly molten (liquid), allowing them to adhere to each other when they landed. In an outcrop, you may see occasional small lithic fragments, but you will not see glassy materials for two reasons: the glassy ash particles are too small to see without a microscope, and glass that remains at high temperatures after it solidifies will slowly convert to a crystalline solid composed of very fine-grained quartz and feldspar. Change of hardened glass to a crystalline material is called devitrification and this material gives the rock its light to purplish-gray color. The tuff here has crystals of quartz and plagioclase feldspar that are often broken and not easy to see because of their fine grain size. At the south end of the bench, right where the trail drops down, are black flattened pumice fragments (image below left). The flattening was due to the weight of accumulating material squeezing the soft, still-molten pumice. The rock also has zones of volcanic lithic fragments, some which are very large (up to 0.5 m). 3 m east (left when looking ahead on trail) of the flattened pumice fragments are angular, pink volcanic lithic fragments along the small cliff (image below center). Some of the lithic fragments have faint pyroclastic banding, which is layering produced by deposition of ash layers. Moving about 5-6 m back to the north on the trail is an area of tan rocks with dark lithic fragments (image below right). This is volcanic breccia with volcanic fragments in fine ash. 2-3 m south (beyond) of the end of the bench is a large purple boulder that is crystal tuff with faint banding.



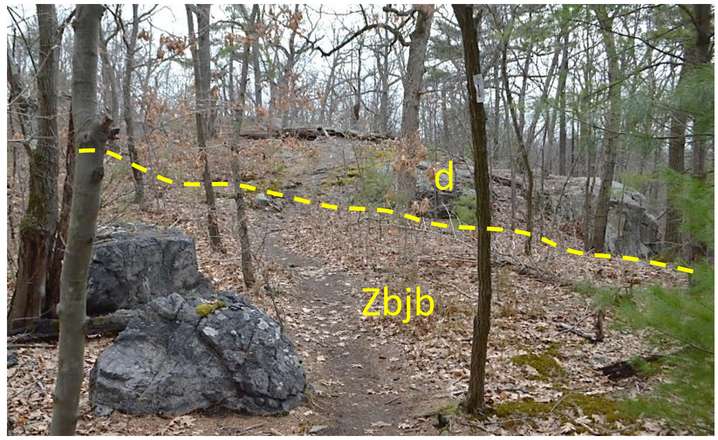
Beyond the boulder, the trail climbs over another knob of crystal tuff with a vernal pool on its east side. A vernal pool is a seasonal, or ephemeral, body of water. In the Northeast, these pools are usually at their fullest in the spring, when snowmelt and a seasonally high water table fill them. In the Fells, some of these pools last through the summer because of upward seepage of groundwater through fractures. After descending from the last knob and passing the vernal pool, you will be directly above the Elm Street/Woodland Road rotary to the west.

STOP 7: Along the trail is a collection of 5 large glacial boulders (image to right in early spring). Boulders no. 1 and 5 on the image are glacial erratics of the Stoneham Granodiorite from the northern Spot Pond area. Granodiorite is an intrusive, coarse-grained igneous rock almost entirely made of plagioclase feldspar and quartz with lesser alkali (potassium) feldspar and scattered to sometimes abundant mafic (dark) minerals. To be a glacial erratic, a boulder must be glacially transported and different than the underlying rock, which here is the Lynn Volcanic Complex. Boulders no. 2-4 are purplish-gray pieces of the underlying Lynn Volcanic Complex (Zbjb), so while they have been glacially transported, they are not technically erratics.



Continue south on the trail to two more large purplish-gray tuff (Zbjb) boulders.

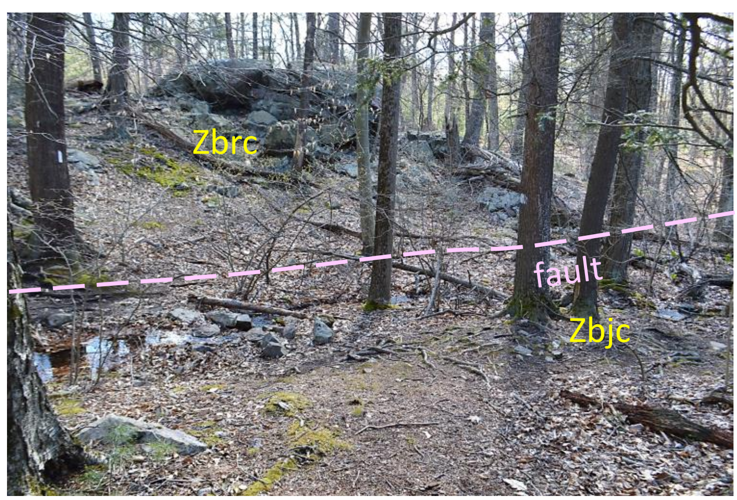
STOP 8: At the boulders (lower left on image to right, view in early spring), the trail comes to a knob underlain by an E-W trending dolerite dike (d) like at Stops 2 and 3. At the base of the knob is the contact between the Lynn Volcanic Complex (Zbjb) to the north and the dolerite to the south. The trail bends to the east (left) and crosses a second double knob, which is also part of the dolerite dike. The dike is cut into separate blocks by several small faults. After passing the second set of knobs, the trail bends to the left and crosses a third knob underlain by the crystal tuff of the Lynn Volcanic Complex (Zbjb). **After passing a trail on the left (junction E5-1, same trail crossed at Stop 3), the Rock Circuit Trail steeply descends into a deep valley.**



STOP 9: While descending the hill there are large angular blocks of rock along the trail to the left from upslope, which are crystal tuff (Zbjb) and vitric tuff (Zbjv) in the Lynn Volcanic Complex. Vitric tuff is tuff made of ash with few crystals or lithic fragments. Along the trail, boulders of the vitric tuff are light gray with no apparent crystals. You will also see boulders of the breccia from Stops 4, 5 and 6. About halfway down the trail to the valley below, look for boulders of a peculiar mixture of orangish-pink crystal tuff in a light gray vitric tuff (image to right). **The trail crosses a road in the valley bottom at junction E5-2.**

STOP 10: Just beyond the road and along the flank of the hill across the valley is where a fault runs through volcanic breccia in the Lynn Volcanic Complex (Zbjc). This valley (no image) has a series of faults with associated fractures as is evident from all the angular fractured boulders lying in the valley. The hill continues over the next ridge, which is underlain by the easternmost occurrence of volcanic breccia in the Lynn Volcanic Complex. Be on the lookout for not only boulders of breccia but also less frequent conglomerate with rounded granite, sandstone, and volcanic pebbles. The conglomerate is well exposed on the southern end (to right) of the ridge that is crossed by the trail and is mapped as part of the volcanic breccia in the Lynn Volcanic Complex. **Continue east on the trail.**

STOP 11: After crossing the ridge described at Stop 10, the trail crosses another fault valley with some wetlands and a small stream (image on right, pink line is fault). The fault brings the volcanic breccia of the Lynn Volcanic Complex (Zbjc) on the west (near) side in contact with older crystal tuff of the Boojum Rock Tuff (Zbrc), also in the Lynn, on the east side. The volcanic breccia is highly fractured, while the Boojum Rock Tuff occurs as large, bold outcrops east of the fault with a lower fracture density. The breccia also has abundant quartz crystals and lithic fragments while the Boojum Rock has abundant 2-3 mm, broken plagioclase crystals, sparse lithic fragments, and no quartz crystals. If you look at map RC-3A, you will also see that, north of here, the volcanic breccia rests on an unconformity (yellow dashed line on map) on the older Boojum Rock Tuff. An unconformity is a surface that represents a gap in the geologic record and is also overlain by a sedimentary or volcanic unit. Here the unconformity is an erosion surface cut into the Boojum Rock Tuff that was later covered by the breccia. For more on unconformities see: Unconformities.

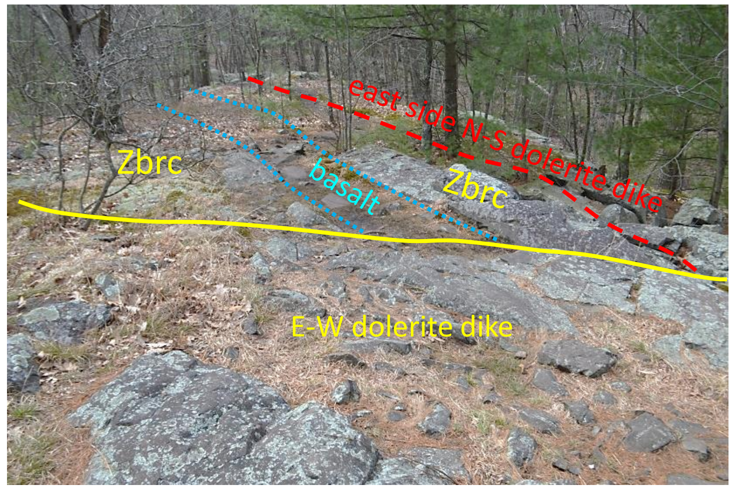


After crossing the small stream and heading uphill the trail cuts across a road at junction E4-17.

STOP 12: At the road, the trail crosses the south side of a large, E-W trending dolerite dike (d, image to right). This is the same dike seen at Stops 2 and 3, but here it is in contact with the Boojum Rock Tuff (Zbrc). The trail begins to follow the dike, which is also exposed in the road. Note the relatively smooth surfaces, low fracture density, and rusty color of the dike as compared to the adjacent volcanic rock.

In a short distance the trail bends to the south-southeast (right) and enters an open area.

STOP 13: In the open area, the large, E-W trending dolerite dike cuts across a large, N-S trending dolerite dike, which forms a west-facing ledge, and a smaller, N-S trending basalt dike (image to right). Basalt is compositionally like dolerite, but fine-grained. This site is important because it helps establish the age relationships between dikes of different trends. For much of the Rock Circuit tour, we have encountered large, E-W trending dolerite dikes that are parallel to each other (Stops 2, 3 and 8). Wherever we see dikes of a N-S trend, they are crosscut by the large E-W trending dikes. Thus, the E-W dikes are younger.



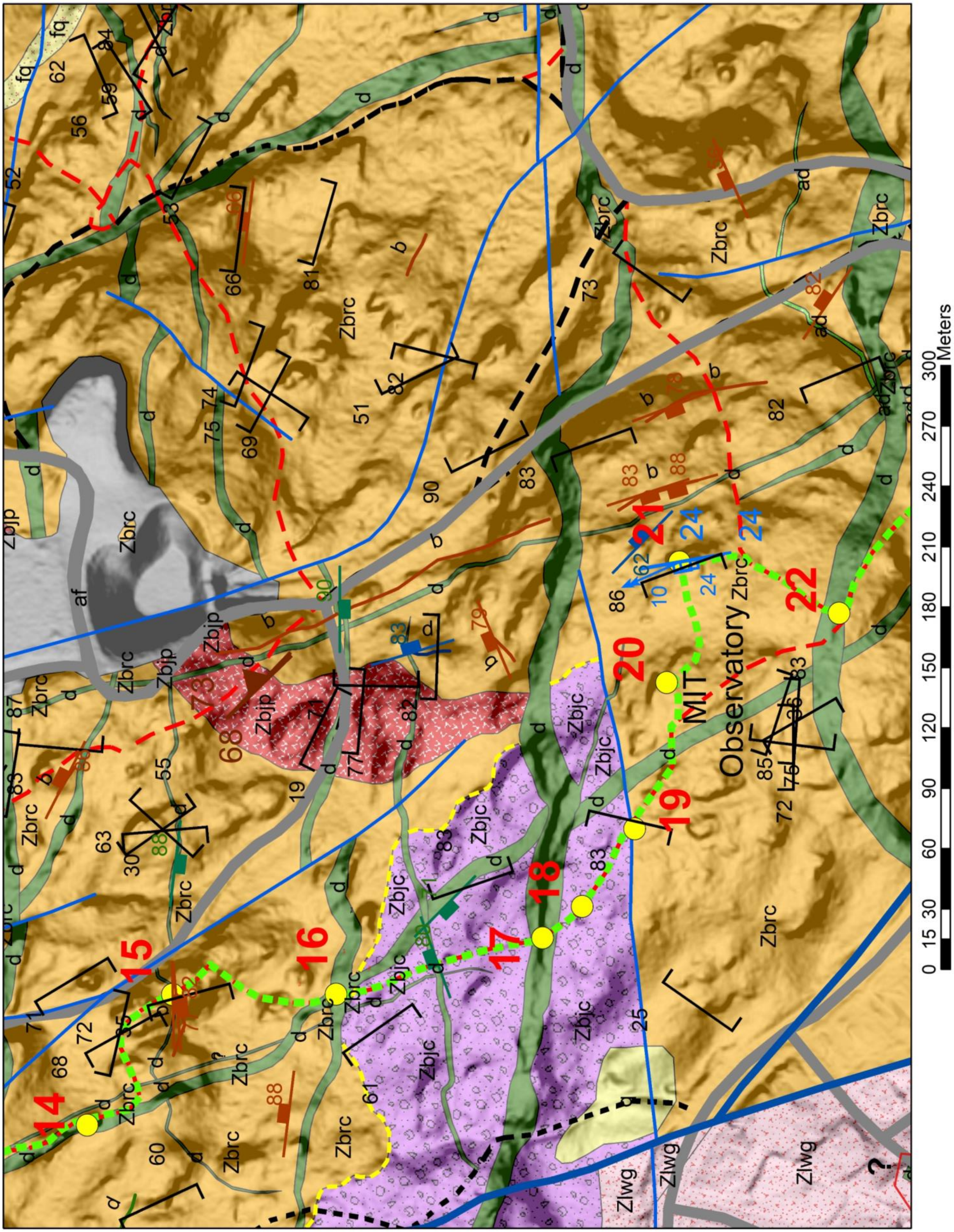
Continue the tour on Map RC-3B.

The trail continues south following the N-S trending dikes to a prominent point formed by the larger N-S trending dike.

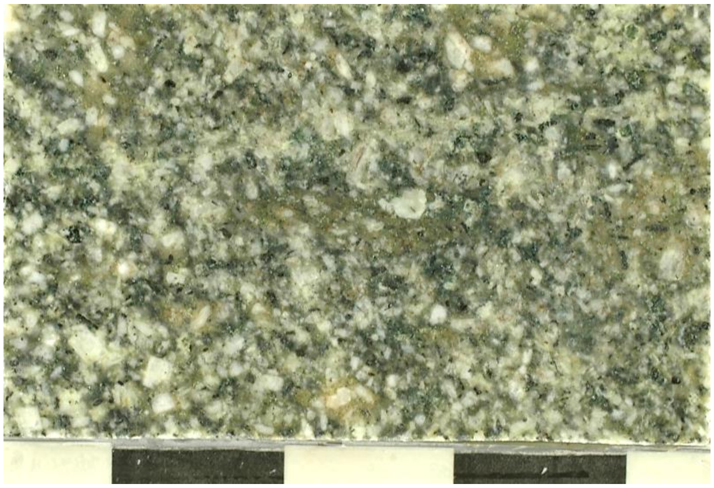
STOP 14: At the point underlain by the large N-S dolerite dike is a platform with preserved glacial grooves (image to right, parallel to hammer). The grooves are oriented at S36°E. If you look closely at this surface, you will also see some subtle, streamlined (smoothed) knobs that were more resistant to glacial erosion (X's on image below to right). South of the knobs (to left on image), the less resistant rock was protected from glacial erosion and formed broad tails. These features are called rattails, and they indicate the absolute flow direction (azimuth) of the ice flow (e.g., N to S instead of S to N), not just the trend of flow indicated by striations and grooves.

The trail continues south. After crossing the outlet of a vernal pool, it cuts sharply to the east (left) where it climbs to the top of a N-S trending ridge.

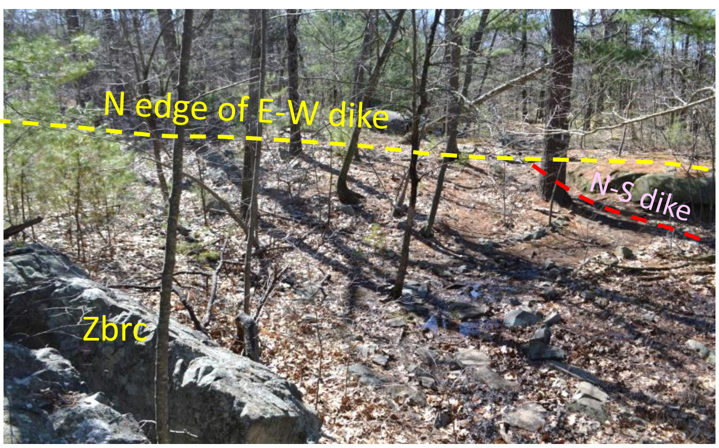
Map RC-3B


N
Meters
0 15 30 60 90 120 150 180 210 240 270 300
MIT
Observatory
14
15
16
17
18
19
20
21
22
Zbrc
Zbjc
Zbjp
Zlwg
af
fq
ad
d
b

STOP 15: The N-S trending ridge is underlain by welded crystal tuff of the Boojum Rock Tuff (Zbrc). The tuff is a pyroclastic volcanic rock, meaning it was ejected into the air prior to accumulating upon landing. The term welded refers to the fact that the ash and glass/pumice fragments were at least partly molten, and they adhered to each other when they landed. The unit is composed of fine ash particles surrounding abundant, mostly broken, white crystals of plagioclase feldspar (image below left). There are also glass and pumice (bubbly glass) fragments that were soft when they landed and were subsequently flattened beneath the weight of accumulating material. The fragments are small (up to 5 mm) and hard to see in outcrop. Both the glassy ash and glass fragments were devitrified to very fine intergrown quartz and feldspar. You may also see occasional small lithic fragments, but they are not common. Across the top of this ridge are scattered orange (iron)-stained and polished remnant patches of glacial striations (image below right). The striations here are oriented S28°E. To see the very fine scratches, it helps to wet the rock surface. Moving past a small cluster of trees at the center of the ridge, there is a thin, E-W trending basalt dike (image at bottom right). Basalt is basically fine-grained dolerite. Because of fractures in the dike, it eroded more rapidly than the tuff that it intruded, and this has left a channel across the ridge. The road that you can see below to the east (left) is Hemlock Pool Road.



The trail continues south, heading down a steep slope to a low area, and crosses an area that is usually wet.



Stop 16: After the wet area is a large E-W trending dolerite dike ridge. The E-W trending dike cuts across a N-S trending dolerite dike (image above on left, view from top of knob of tuff on east side of trail in early spring). This represents the same relative age relationship that was seen at Stop 13 with the E-W trending dike being younger than the N-S trending dike. This area is also where the surrounding rock changes from the Boojum Rock Tuff (Zbrc) to the north to younger breccia in the Lynn Volcanic Complex (Zbjc) to the south of the E-W trending dike. The breccia rests on the Boojum Rock in this area on an unconformity (yellow dashed line on map). For more on unconformities see: Unconformities.

After the dike, the trail slowly ascends to the Boojum Rock area through breccia the Lynn Volcanic Complex and arrives at a steep face.

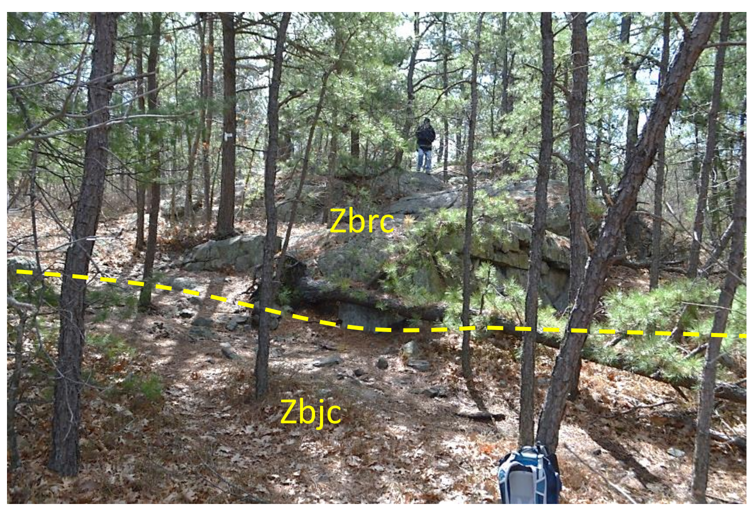
STOP 17: The steep face (image below left) is the north side of a wide, E-W trending dolerite dike. This is the same dike seen at Stop 8 of this tour, at Gate no. 53 at the beginning of Part 1, and at Stop 1 on Part 2. It is also like the dikes seen at Stops 2, 3, and 12 on this tour. The steep ledge here is a product of differential glacial erosion, where the heavily fractured volcanic rocks to the north are less resistant to erosion by southward flowing glacial ice than the dolerite dike. Glacial striations and grooves are found at the top of the ledge (image below right) and are oriented at S13°E, defining the local flow direction of the last ice sheet that covered this area. The ice was deflected slightly to the south as it tried to slide across a low spot in the dike ridge.

After about 15-20 m, the trail crosses the south side of the E-W trending dolerite dike and heads across a bare, lichen-covered surface.

STOP 18: The bare surface is an exposure of the volcanic breccia of the Lynn Volcanic Complex (Zbjc). This exposure is the same unit seen at Stops 4-5. Although it is a struggle to see features in some parts of the outcrop because of lichen growth, the unit consists of mostly purplish-gray lithic tuff containing large angular blocks of light gray to pink volcanic lithic fragments (image to right). East of here this unit with its green sandstone matrix rests on the same unconformity that occurs to the north near Stop 11. Thus far, only volcanic lithic fragments have been found here.

After about 30-40 m, the trail leaves the breccia in the Lynn Volcanic Complex (Zbjc) and climbs a ledge.

STOP 19: The ledge here is welded crystal tuff of the Boojum Rock Tuff (Zbrc) that underlies most of the Boojum Rock area (image to right, view to south). The contact with the volcanic breccia in the Lynn Volcanic Complex (Zbjc) is a small E-W trending fault (dashed line on image). The ledge at this stop is a scarp, or sudden break in slope, formed along the fault. Areas to the south have moved upward to expose the Boojum Rock Tuff, but the scarp is not a result of fault displacement. Rather, it is the result of different erosion rates across the fault. The breccia was less resistant to glacial erosion than the Boojum Rock Tuff. Many hundreds of meters have been eroded from both sides of the fault since it was last active. On Map RC-3B, you will notice that, if you follow the fault further east, a small branch of the large dolerite dike we saw at Stop 17 crosscuts the fault, indicating that the dike is younger than the fault. Further east, the large dike also crosscuts the fault and intruded the fault plane. Just north of the current stop, the dolerite dike from Stop 17 also crosscuts a N-S trending dolerite dike.



After leaving the fault, the trail heads east across a small valley and then up on a ridge where you will see a sign board.

STOP 20: The ridge is composed of crystal tuff in the Boojum Rock Tuff (Zbrc). The preceding small valley has the N-S trending dolerite dike that is crosscut by the dike at Stop 17 (see map RC-3B). Unfortunately, the N-S dike is poorly exposed in the trail area. On top of the ridge, you will see the ruins of the MIT Observatory, which was an early geodetic survey station set up in 1899 by what is now the Dept. of Earth, Atmospheric, and Planetary Sciences at MIT (image to upper right). Geodesy is the study of Earth's shape as it relates to gravity. The observatory was set up with very accurate telescopic surveying devices used to locate markers on hilltops, miles away. When the observatory was active, primarily as a teaching facility, there was far less tree cover. Measurements allowed the early geodesists to teach and refine surveying methods and to determine very subtle differences in land surface movements (tilt). This was state-of-the-art in the late 1899 and today is replaced by laser and satellite technology.

Leaving the observatory, the trail heads down a rocky surface in the crystal tuff in which fractures are coated with the pistachio green mineral epidote (image to right). This mineral is common in fractures in all rock units across the Fells and is the result of precipitation by hydrothermal (hot water) solutions that traveled along the fractures.

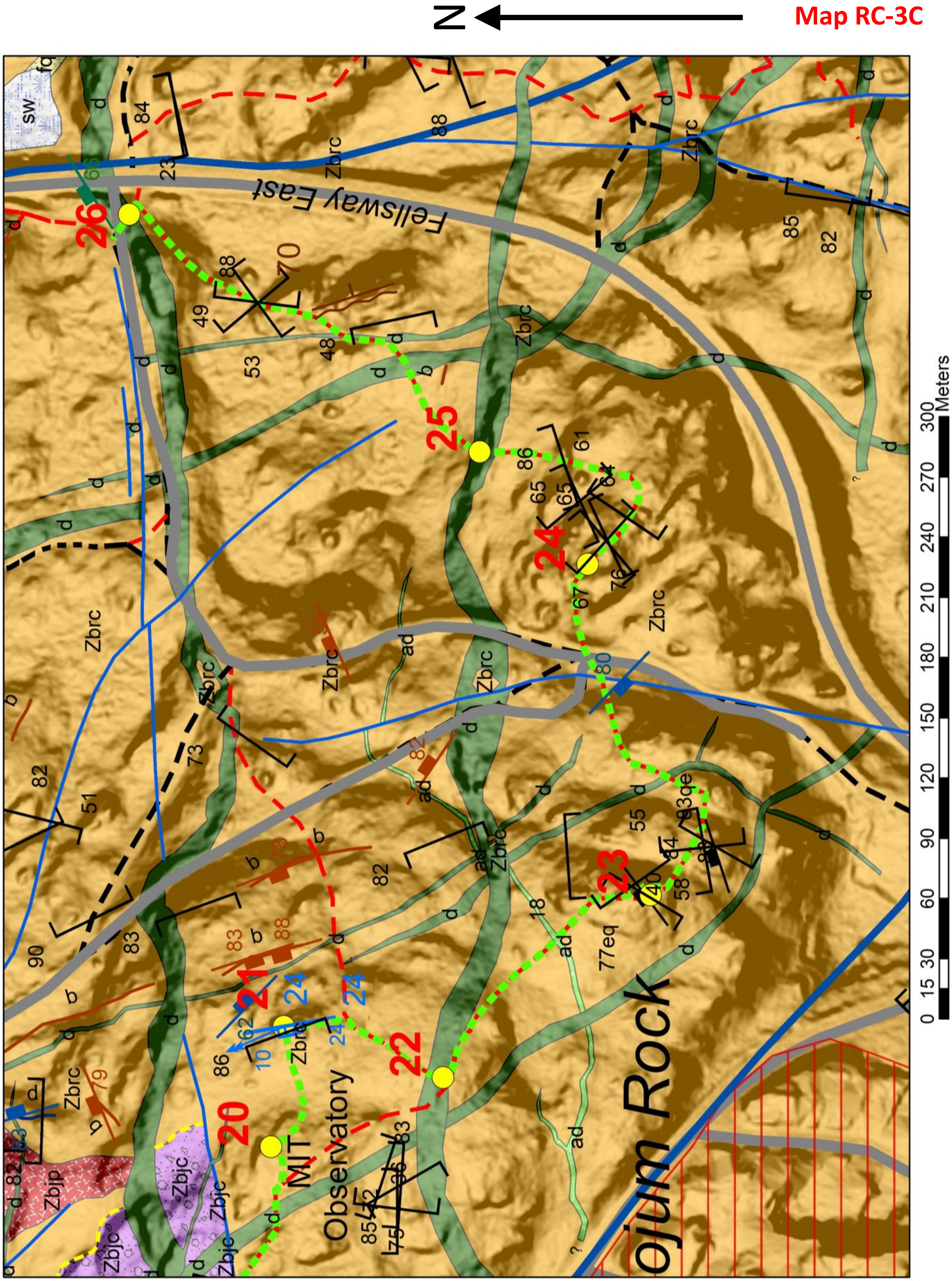
Continue the tour on Map RC-3C.

Continue on the Rock Circuit Trail to junction F5-8 where it intersects the Rock Circuit Connecter (orange trail markers).

STOP 21: At junction F5-8 is a knob of crystal tuff in the Boojum Rock Tuff (Zbrc) that has slickensides with hematite mineralization (image to right). Slickensides are polished, striated, and grooved surfaces created by displacement along faults. In this case, hematite, an iron oxide with a metallic, steely gray color, grew along the fault planes. It grew as a result of hydrothermal fluid circulation when the faults were active and is striated. There is also minor epidote on this outcrop. The striations and grooves indicate the displacement direction of the faults. They are different than glacial striations because they extend into the rock along a fracture rather than just existing on the rock surface and are generated by different processes. The fault surfaces here are wavy, but on average they dip gently to the west and the slickenside striations are oriented NNW (arrow). Displacement on the slickenside surface is indicated by minor steps that face north showing that the rock above the slickensides moved north relative to rock below. A blue symbol on the map shows the orientation of the slickensided surface and orientation of the striations on this surface. At the top of the knob at this stop, look for the bronze geodetic survey marker mounted in the rock surface.

Follow the Rock Circuit Trail south (right) from junction F5-8 for about 75 m to a sharp turn east (left).

Map RC-3C


N
Fellsway East
MIT
Observatory
Zbrc
Zbjp
Zbjc
sw
20
21
22
23
24
25
26
0 15 30 60 90 120 150 180 210 240 270 300
Meters

STOP 22: At the sharp turn, the trail begins to follow yet another wide, rusty weathering, E-W trending dolerite dike that is related to the dikes seen at Stops 2, 3, 8, 12, 13, 16 and 17. This is the same dike seen at Stops 4 and 10 of Part 1 of the Rock Circuit tour. On the south side of this dike, look for the contact of the dike with crystal tuff in the Boojum Rock Tuff (Zbrc, image to right). The grain size along the margin of the dike is finer and does not have the salt and pepper appearance of the coarse-grained center. The fine-grained edge of the dike is its chill zone, where magma cooled quickly next to the crystal tuff.

The trail follows the dolerite dike east for about 30 m before turning southeast (right) and descending into a valley. After the valley, the trail climbs to the summit of Boojum Rock.

STOP 23: Boojum Rock has one of the best views of Boston from the Fells (image below). The rock here is again welded crystal tuff in the Boojum Rock Tuff (Zbrc). Leaving the summit, the trail skirts the east side of Boojum Rock.

Descend southward along the east slope of Boojum Rock to a bench where the trail turns east (left).

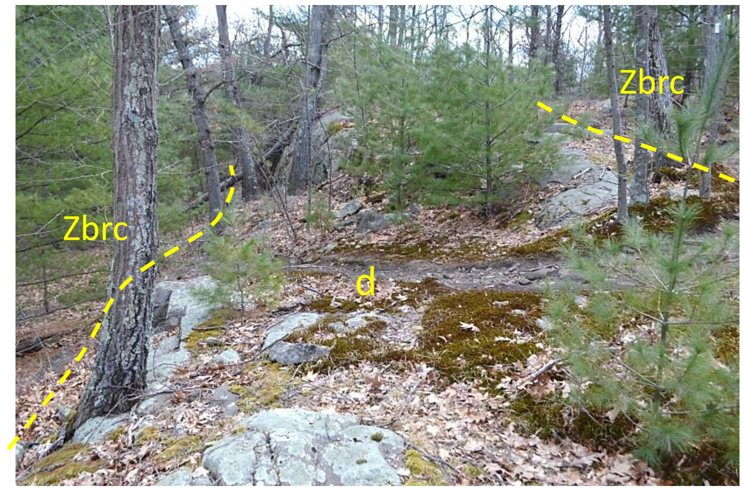
STOP 24: The bench has a great example of flake weathering exhibited by the Boojum Rock Tuff (Zbrc). This unit peels or pops off in flakes, giving the rock surface a splotchy coloration pattern. Flake weathering appears to result from initial chemical weathering of the rock surface, producing a light tan-colored outer weathered zone, or weathering rind, that is usually 2-3 mm thick. This likely creates very fine pore spaces, in the otherwise hard, solid rock. The pores may allow lichen growth and water to penetrate the rock, causing expansion when the water freezes. Other mechanisms are likely involved such as periodic fires, but we don't yet know what role they play. This type of weathering is widespread on the Boojum Rock Tuff, but it does not occur on any other rock units in the Fells.

The trail continues east and crosses Jerry Jingle Road near its intersection with another road at junction F5-9. Across the road, the trail climbs the steep face of East Boojum Rock.

STOP 25: At the top of East Boojum Rock, the crystal tuff of the Boojum Rock Tuff (Zbrc) is crossed by several sets of parallel fractures (image to right). Note the bracket symbols (**[**) on the map that show the dip direction of the fracture planes and the nearby number indicating the degree of dip away from horizontal. From here you can see areas south to Boston and hawk migration in the fall months.

After leaving the top of East Boojum Rock, the trail descends to the south, bends to the east (left), and then goes north (left again). The trail crosses two steep slopes at prominent scarps.

STOP 26: The second steep slope is where the trail crosses a rusty, E-W trending dolerite dike (image to right, view east across trail). This is the same dike seen at Stop 22 near Boojum Rock and Stops 4 and 10 of Part 1 of the Rock Circuit tour. This is yet another example of differential glacial erosion: the dolerite dike has a steep northern face because of its greater resistance to glacial erosion than the more heavily fractured volcanic rock to the north. At the bottom of the scarp, the trail heads northeast (right) and crosses two N-S trending dikes, which are not easy to trace in the field, and are crosscut by the larger E-W trending dikes in the area.



Continue into the lowland below where the trail bends east (right). On the way to the next stop, you will see many long, flat fracture surfaces in the Boojum Rock Tuff. The trail runs next to and then crosses over a ridge of the Boojum Rock Tuff before crossing a wooden bridge over an outlet stream from a wetland to the west (left). The trail then ascends a slope up to Jerry Jingle Road at near Gate no. 53.

STOP 27: The slope before Jerry Jingle Road is the south side of a large E-W trending dolerite dike (d). This is the same dike seen at Stop 17 near the MIT Observatory. From Jerry Jingle Road is a view to the west (up the road) of the northern flank of the dolerite dike, which parallels the road (image to right, view west). This is another example of glacial, differential erosion leaving the dike as a high ridge.

END of Part 3.

The Fellsway East parking area is just to the north of Jerry Jingle Road along the Fellsway East. To reach it, follow the Cross Fells Trail (blue markers, see arrow on image above). Where the Cross Fells Trail cuts away to the west (left) continue straight ahead to the parking area.