THE BENNIES BROOK SLIDE:
A WINDOW INTO THE CORE OF THE MARCY ANORTHOSITE

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INTRODUCTION

The Marcy anorthosite massif forms the core of the Adirondack High Peaks region and is the geographic center of the associated topographic dome. On the State Geological Map (Adirondack Sheet, 1:250,000) it is depicted as a single rock type consisting of meta-anorthosite. However, this is a simplification and, in detail, numerous lithologies occur within the massif and display complex relations. This trip is designed to introduce participants to a 1.5 km, near continuous, linear landslide exposure which follows the course of Bennies Brook on the northern flank of Lower Wolf Jaw Mountain. Saturated conditions associated with Hurricane Irene in August of 2011 resulted in the most recent of landslide events along the course of Bennies Brook and additional exposure. The features unearthed here provide an unprecedented view into the interior of the massif and demonstrate its geological complexity.

GEOLOGICAL SETTING

The Marcy Massif is one of a number of variably sized anorthosite massifs in the Grenville Province (Figure 1). These enigmatic rocks, largely restricted to the Proterozoic, vary in age but are nowhere near as volumetrically significant as in the Grenville Province. Long collectively regarded as anorogenic, recent geochronological constraints demonstrate a close temporal relationship with orogenic activity in some cases. For example, the Marcy Massif was intruded at ca. 1160 Ma at a time corresponding to the close of the Shawinigan Orogeny. Observations made on this trip will demonstrate deformation at granulite grade, generally along lithologic discontinuities, in spite of exceptionally well preserved igneous features in adjacent rocks.

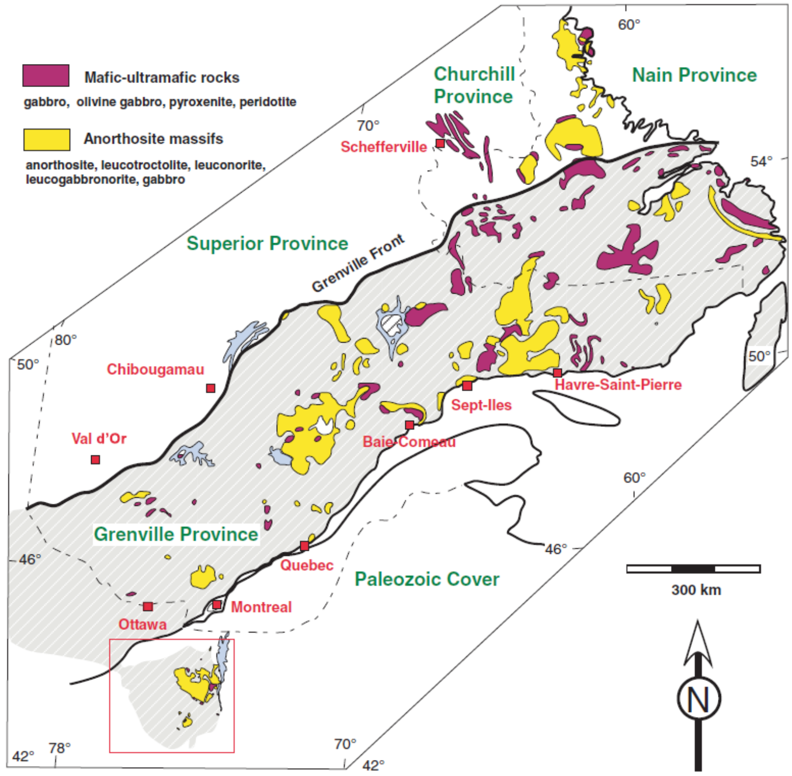


Figure 1. Map of the Grenville Province showing the distribution of anorthosite (yellow) and gabbroic (red) bodies throughout the region (modified from Corriveau et al., 2007).

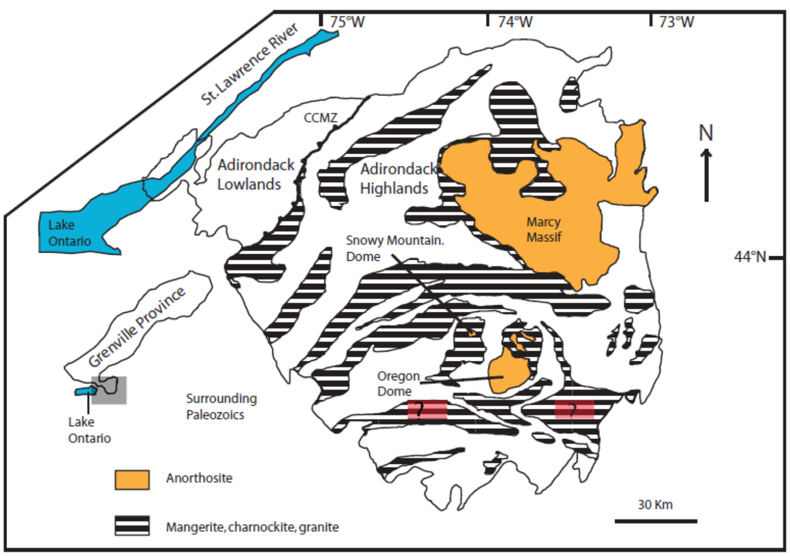


Figure 2. Simplified geologic map displaying the distribution of anorthosite-mangerite-charnockite-granite (AMCG) rocks within the Adirondack Highlands (modified from McLelland et al., 2004). Question marks represent the Piseco Lake shear zone; this granitic gneiss has been previously interpreted as a member of the AMCG suite, but this association is currently under review (Chiarenzelli and Valentino, 2008). CCMZ—Carthage-Colton mylonite zone.

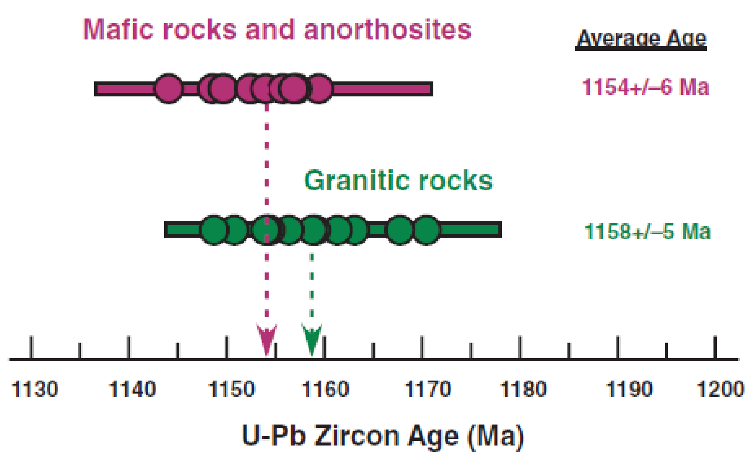
Massif anorthosites are also geographically associated with a variety of other coeval igneous rocks including granitic and orthopyroxene-bearing granitoids (Figure 2). Collectively known as the AMCG Suite (Anorthosite-Mangerite-Charnockite-Granite Suite) these rocks are not considered comagmatic with the anorthosite but rather to represent the thermal effects of voluminous gabbroic melts at, or within, the base of the lower crust. Crustal melting of the deep crust and subsequent rise of coeval granitic melts is envisioned to explain the spatial association. Massif anorthosites are also associated with, and grade into, a variety of gabbroic rocks, ilmenite-rich ores, and hybrid rocks known as ferrodiorites or jotunites with andesine megacrysts, presumably derived from the anorthosite itself.

Metamorphism to granulite facies is shown by the development of garnet coronas on pyroxenes and oxides. These minerals are concentrated in shear zones and often shown evidence of intense ductile deformation while the anorthosite wall rocks often show little or no sign of deformation. In fact, igneous features such as xenoliths, chill margins, ophitic texture, flow alignment of plagioclase, cumulate layering, block structure, and multiple intrusions are readily observed where exposures permit and these are plentiful and readily observed on the Bennies Brook slide. These features suggest the interior of the large anorthosite bodies, including the Marcy Massif, show repeat intrusions of varied composition and behaved as large rigid blocks during subsequent tectonism. Preservation of such features occur despite the profound deformation in the surrounding granitoid and metasedimentary country rocks exposed primarily as east-west trending belts crossing the Highlands (Figure 2).

AGE OF THE ROCKS

Several studies have addressed the age of the Marcy Massif, smaller Adirondack Massifs, and spatially related rocks (Figure 3). The most recent of these using the sensitive high-resolution ion microprobe (McLelland et al., 2004) suggests that the bulk of the anorthosite crystallized at ca. 1154 Ma, while associated granitoids are slightly older (ca. 1158 Ma). Perhaps a more accurate way of summarizing the data, including the errors reported, would be to state there are a range of overlapping ages within a relatively limited timeframe; basically they are more or less coeval.

Figure 3. U-Pb zircon ages from dated rocks of the anorthosite-mangerite-charnockite-granite (AMCG) suite throughout the Adirondacks. Note the overlapping age range of anorthositic and quartz-bearing members, suggesting a coeval, but not comagmatic origin (after McLelland et al., 2004).



Abundant field evidence also confirms that the lithologies were intruded more or less synchronously. Within the boundary of the massifs themselves, however, a general sequence of extremely coarse "Marcy" type anorthosite (Kemp, 1920), followed by slightly more mafic anorthositic rocks of more moderate grain-size, gabbroic, and andesine-bearing, ferrodioritic rocks is observed. Granitoids including mangerites, syenites, aplites, and granitic pegmatites of lesser abundance and dike-like geometry are commonly observed but are not volumetrically significant. The total elapsed time represented by all of these events is unknown but is thought relatively limited. However, it is observed that ferrodioritic lithologies are chilled against anorthosite and undeformed along their margins on the Bennies Brook slide.

COMPOSITION AND ORIGIN

While the Marcy anorthosite massif does show a wide range of rock-types of variable composition, by far, it is composed of coarse-grained anorthosite *sensu stricto*. Gradation into, inclusion of, and or intrusion by rocks with slightly more mafic minerals such as anorthositic gabbro or gabbroic anorthosite, or in some cases, gabbronorite, is common. Distinctive gabbroic pegmatites, coronitic metagabbros, oxide-rich gabbros with or without apatite, pyroxenites, and ilmenite-rich, sometimes with apatite (i. e. nelsonite), ores also occur but in much lesser volume. Many workers regard these rocks as natural variants of gabbro fractionation, residual fluids or cumulates, parental magmas, and/or a variety of ore formation processes. Most or all of these rocks are thought to have a dominant mantle component with variable amounts of crustal contamination. Among these rocks coronitic metagabbros have the most primitive Nd-systematics, crystallized olivine, and are interpreted to be the parental magma from which the bulk of the anorthosite and gabbro rocks crystallized in the Adirondack region (Regan et al., 2012).

Distinct from these rocks are those of granitic composition with variable ratios of hornblende to orthopyroxene including mangerites, charnockites, and granites. As presented elsewhere, opx-bearing rocks include charnockites and mangerites and pyroxene syenites. They are generally thought of as dominantly crustally derived via melting of the lower crust during intrusion and staging of the parental magma of anorthosite at the base of the crust. Often they contain zircon xenocrysts and have neodymium whole rock systematics and hafnium-zircon signatures compatible with derivation from an arc terrane of similar age (1300-1400 Ma) and composition to that exposed in the southern Adirondacks. Thus, although not comagmatic, the anorthositic and gabbroic rocks and spatially associated felsic magmatic rocks are coeval and likely genetically linked. This association is seen throughout the Grenville Province and beyond and may represent thermal conditions on Earth restricted largely to the Mesoproterozoic.

Ferrodioritic rocks, also called jotunites, appear to have large components derived from both mantle and crustal sources and have been invoked as the parental magma for both anorthosite and granitic members of the suite. Their mineral assemblage often includes two pyroxenes, quartz, k-spar, plagioclase, apatite, and zircon, although many variants exist and provide strong arguments for a hybrid origin. There is clear field evidence, well exposed at Bennies Brook, supporting the contention that the megacrystic andesines found in them are derived from intrusion into the anorthosite. The andesines can vary from as much as half the rock volume to sparse or rare. The ferrodiorites often show chill margins against the anorthosite suggesting intrusion relatively late in the sequence.

On the slide, granitoid rocks are relatively rare but ubiquitously exposed as thin (1-10 cm) dikes cross-cutting anorthositic and gabbroic lithologies. They have remarkably straight-walled, vertical boundaries and include sugary aplites, granitic pegmatites, and syenitic variants. Most show extreme ductile strain parallel to the walls of the dike itself and trend 110^{o}. In a few examples, deformation can be traced into the surrounding anorthosite but generally not for any considerably distance, with most anorthosite remaining undeformed right up to the contact. The intruding lithologies, particularly gabbroic pegmatites, have taken up the strain preferentially and show the bulk of metamorphic mineral growth.

OTHER FEATURES

The exposures on Bennie Brook document several other events in the geologic history of the region. The anorthosite and associated rocks are cut by a variety of basaltic dikes up to 2 m wide. Rarely the dikes are compound with felsic, largely trachytic, parallel intrusions within the basalt. While the age of these dikes is not known at this locality, similar dike swarms throughout extensive parts of the Grenville basement elsewhere yield Neoproterozoic ages. Nearby at Dannemora a trachytic dike, included in a swarm of basaltic dikes, yielded a U-Pb zircon age of 643±4 Ma. Although found elsewhere, Cretaceous-aged intrusions thought synchronous related to opening of the Atlantic Ocean were not noted here.

While the vast bulk of rocks exposed on the slide are undeformed, despite high-grade metamorphism and deformation, thin shear zones are common. The development of these shear zones occurred at high-grade conditions and where they cross-cut gabbroic and anorthositic rocks there is extensive development of garnet and pyroxene, which are also highly strained. Most shear zones occur along near vertical, lithologic discontinuities such as granitic dikes and gabbroic pegmatites. The vast major of shear zones record left-lateral shear. Displacement is moderate on small shears but collectively, based on the number of shear zones, considerable left-lateral displacement appears to have been accommodated. Where lineation is visible and well developed, it plunges shallowly at 100-120^{o}. Dextral shear is recorded in cross-cutting ductile shear zones which warp/fold pre-existing sinistral shears. In this slide, as well as others nearby, brittle deformation occurs in narrow zones up to several meters wide. Most often it consists of sets of closely spaced fractures, some of which intersect and brecciate the rock. Often these areas are highly altered to lower greenschist facies assemblages, bleached, and/or weathered.

SUGGESTIONS FOR THE TRIP

What follows is a number of waypoints along the slide starting at the intersection of Bennies Brook with the South Side trail just above confluence with Johns Brook. Because this area is within the Adirondack Park and highly traveled, and it is illegal to do so, we did not mark specific points of interest. A GPS is essential to retrace our route up the slide and stop at key locations. However, rest assured that the exposure is good enough that whatever route you take you will see all of the key features and likely many we haven't mentioned here.

Each of the waypoints was selected to point out specific features that occur in abundance or are particularly well developed in that area of the slide. You will note some progressive changes as you proceed upward in the proportions of lithologies and the structural features you observe. On a warm fall day the slide is very inviting and generally fairly dry. On a wet, overcast day it can be treacherous with red-brown algal films that virtually eliminate friction. It requires only moderate climbing to reach the ~2900' elevation just before where the slide forks, past this point, it steepens considerably to the head wall. Those without experience on steep slides may wish to return from here and avoid the steepest portions. Please remember it is illegal to collect rocks from the Adirondack Park without a permit and day use groups in the High Peaks are limited to 15. **The trip is weather dependent.**

ACKNOWLEDGMENTS

The senior author would like to thank Mr. Kevin MacKenzie for introducing him to Adirondack slides and the wonderful features they expose. He would also like to thank students Sam Hecklau and Paxton Rountree-Jabin for participating in the study of Adirondack slides. They were supported by the James S. Street Fund at St. Lawrence University. Last, but not least, he would like to thank Dr. James McLelland for his mentorship and tireless efforts to understand how the Adirondack Region was formed and evolved over time.

SLIDE GUIDE

Departure Point: Other than Saturday of the 2015 NYSGA meeting this is a self-guided field trip. Access to Bennie's Brook Slide can be had via the Garden of the Gods Parking Lot Keene Valley, New York. The parking lot is at the end of Johns Brook Lane. Note: This lot tends to be full on the weekends; however, there are shuttles and parking lots in town during the busy season. Drive time to Keene Valley from Plattsburgh is one hour; please factor this into your dinner (banquet) plans.

Departure Point Coordinates: Parking Lot - N44° 11' 20.6" W73° 48' 59.0" (Figure 4)

Meeting Point Coordinates: I will meet trip attendees at the cairn where Bennies Brook meets the Southside Trail at 10 am. N44° 09' 56.4" W73° 50' 43.4"

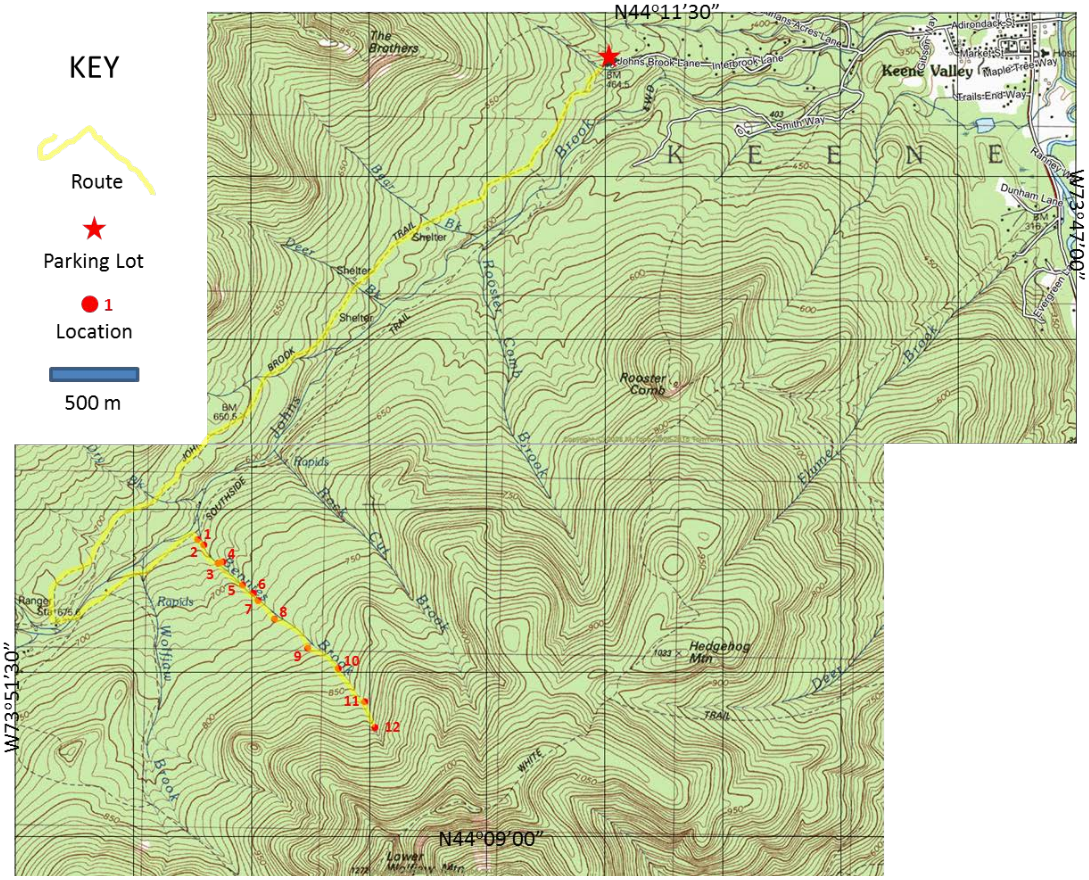


Figure 4. Topographic map showing route from Garden of the Gods parking lot to the Bennies Brook Slide.

Trip Length: The hike to the base of the slide is ~3.5 miles (6 km). The trip up the slide is approximately 1 mile (1.6 km) to the recommended turn around point. The total round trip distance is ~9.0 miles (14 km) of moderately strenuous walking and climbing. Allow at least eight hours of day light to complete your trip. Wet conditions will likely extend the time required.

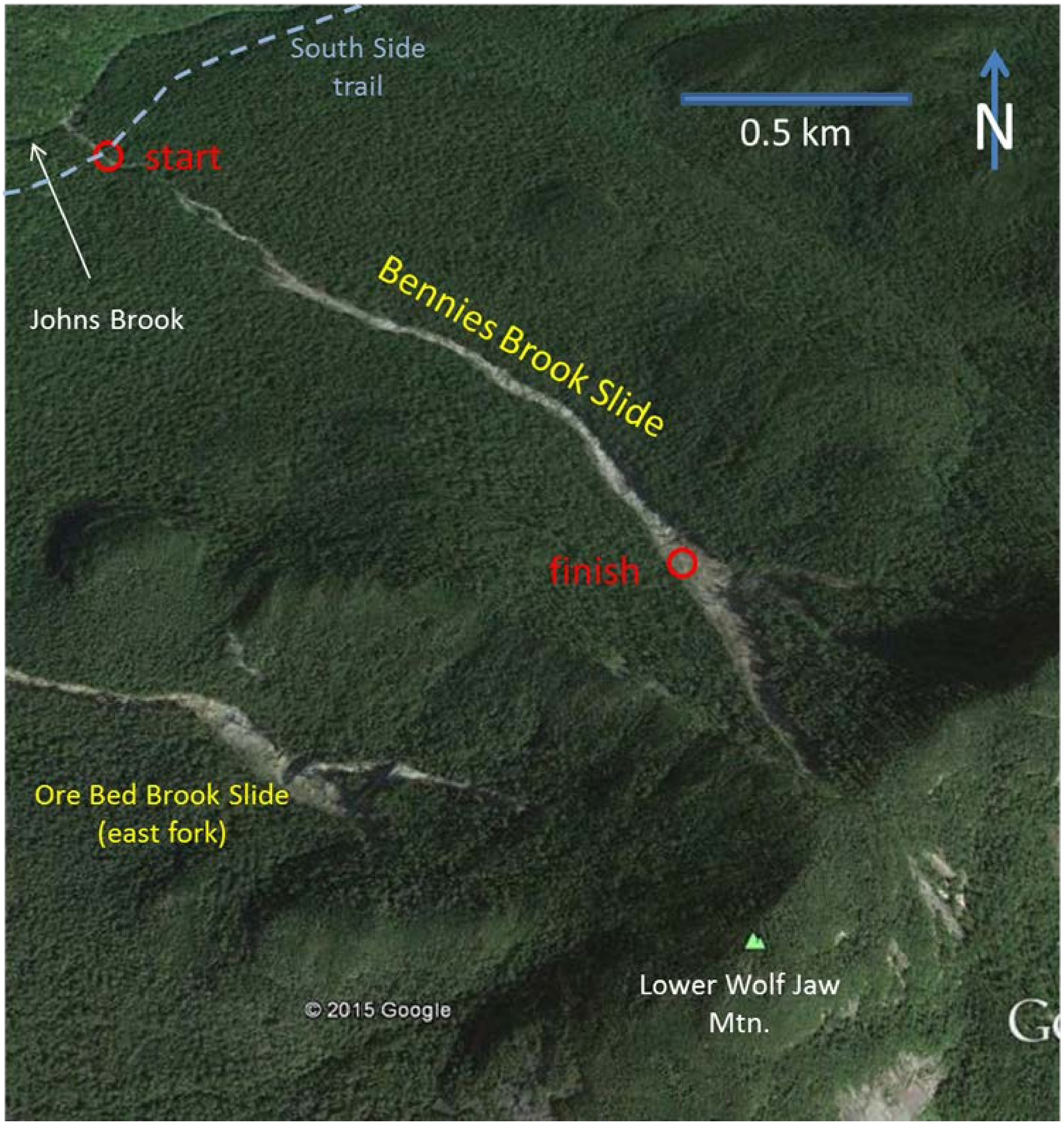


Figure 5. Google Earth imagery showing the location of the Bennies Brook Slide on the northern slope of lower Wolf Jaw Mountain. Note the older, grown over forks of the bennies Brook slide and the new more southerly extension due to Hurricane Irene. Starting and finishing points shown by red circles.

Directions:

0.00 miles (0.00 km) Garden of the Gods Parking Lot (N44° 11' 20.6" W73° 48' 59.0"). Follow the Johns Brook Trail southwest to the Ranger Station (~4.6 km).

2.85 miles (4.6 km) Johns Brook Ranger Station (N44° 09' 38.9" W73° 51' 19.5"). From the Ranger Station follow the trail east over Johns Brook for approximately 150 m to its intersection with the South Side Trail. Follow the South Side Trail to the northeast. Pass the first major creek (~440 m), Wolf Jaw Brook until you reach the intersection of Bennies Brook and the South Side Trail (~410 m). The slide is to your right, proceed uphill towards the south up the north side of Lower Wolf Jaw Mountain.

3.46 miles (5.6 km) Bennies Brook Slide and start of trip (N44° 09' 56.4" W73° 50' 43.4")

4.43 miles (7.1 km) Turn-around point at base of steep head wall (N44° 19' 18.4" W73° 49' 57.7"). See Figure 5 below.

BB-1 Intersection of Bennies Brook Slide and South Side Trail. (N44° 09' 56.4" W73° 50' 43.4" – 633 m)

→ Features: 1) typical Marcy-type anorthosite; 2) garnet coronas; 3) small ductile shear zones; 4) sub-meter scale north-trending joints

The South Side trail follows John's Brook and was severely damaged during the flooding associated with Hurricane Irene. The trail crosses the slide a few hundred meters above the confluence of Bennies Brook with Johns Brook. A stone cairn marks the intersection (Figure 6). *If you don't see the stone cairn you are at one of the other nearby slides in drainages on the north side of the range and this guidebook won't be of much use.* If you look to the north towards Johns Brook you can see a variety of woody debris and boulders from the slide (Figure 7).

Exposed in the bed and banks of Bennies Brook is typical Marcy type anorthosite (Figure 8). Here it consists mostly of 90% or more of darker andesine, some reaching lengths of 5 cm or more; mere pikers compared to what is to come. The lighter colored matrix is also plagioclase, much of which shows bent twins and other features indicative of some type of strain (recrystallization or auto brecciation?) during or just after final emplacement. Other minerals include pyroxene (often of both persuasions), oxides (magnetite and/or ilmenite), and trace minerals including biotite, hornblende, and garnet. Close examination reveals that much of the garnet rims mafic minerals and provides evidence of high-grade metamorphism. Throughout the outcrop proportions of minerals and grain-size vary.

Here cm-wide shear zones are developed. Some concentrate and deform garnets and pyroxenes and this will be much more evident and convincing as you proceed upwards. They are generally subvertical and trend about 340° here. A set of parallel joints are developed slightly oblique to the ductile shear zones and trend 352° 90°.

Figure 6. Co-author Marian Lupulescu at stone cairn where the Bennies Brook Slide intersection the South Side trail.

Figure 7. Looking north towards debris from Hurricane Irene landslide in the bed of Bennies Brook just below its intersection with the South Side trail.

Figure 8. Typical features of the Marcy type anorthosite. Notice large bluish andesine crystals set in a finer-grained matrix of plagioclase. Pyroxene-rich gabbroic rock cross-cuts anorthosite filling in an angular interstice to the left of blue pen.

BB-2 Heavy Minerals in Bennies Brook and Garnet Coronas (N44° 09' 53.4" W73° 50' 41.8" – 638 m)

→ Features: 1) garnet and heavy mineral-rich sand in brook; 2) garnet coronas

There are deposits of reddish and black sand exposed in the bed of Bennies Brook, often forming layers or ripples or other bed forms (Figure 9). These are derived primarily from within the drainage basin and show the relative abundance, and density, of garnet, pyroxene, and oxides. A sample of this sand has been collected and will be characterized by SEM and detrital zircon studies.

Figure 9. Heavy mineral bands in sand in the bed of Bennies Brook. The heavy mineral population of the sand is dominated by garnet, pyroxene, and magnetite and has a distinctive red color.

Wandering up from this location for the next 50 m or so will show some excellent examples of garnet coronas. Coronas are developed upon mafic minerals such as pyroxene and olivine, as well as, on oxide minerals (Figure 10). Some form delicate single grain necklaces or chains. In many cases they may represent the only metamorphic reaction visible in the rock. Davidson and Van Breeman (1988) showed similar zircon coronas on baddeleyite in Grenville mafic dikes. The zircon gave ages 100 million years younger than the baddeleyite cores documenting both igneous crystallization (1150 Ma) and Metamorphism (1050 Ma). In shear zones garnets are deformed and particularly abundant indicative of deformation and high-grade conditions and the abundance of the residual components needed for it to form (i.e. Fe, Al, Si).

Figure 10. Thin garnet coronas developed around large pyroxenes and oxides (in circle) in gabbro pegmatite. Note the sheared boundary between the gabbro and anorthosite at the top of the photograph. Photograph compliments of Doug Reed.

BB-3 Altered Anorthosite and Brittle Structures (N44° 09' 50.0" W73° 50' 38.1" – 659 m)

→ Features: 1) alteration zones in anorthosite; 2) closely spaced fractures and brittle faults; 3) tiny carbonate veins

While typically fresh, and well preserved, some anorthositic rocks have experienced numerous lower grade alteration events. While the exact nature and timing of events is currently unknown many appear to be associated with low-temperature hydrothermal alteration associated with areas of high fracture density and brittle faults. Typically bluish grey when fresh, anorthosite often appears chalky white to pale green where altered and rusty where also weathered (Figures 11 and 12). In these zones andesine is nearly completely altered to epidote, pumpellyite, clinozoisite, chlorite, carbonate, and other secondary minerals.

At this locality there are composite alteration zones and veins that range in color from white to pink to pale green (Figure 11). They appear to be in close proximity and best developed where brittle faults occur (Figure 12). In addition, to these features the rock is heavily laced with thin (mm-scale) white calcite veins. Secondary calcite in microfractures is ubiquitous within the anorthosite (Morrison and Valley, 1988). A similar mineralized alteration zone up to several meters wide, cutting anorthosite, has been studied by the senior author and colleagues at SUNY Potsdam.

Figure 11. Example of extreme hydrothermal alteration in anorthosite; note the distinctive pale green color of the host rock.

Figure 12. Brecciated fault zone with closely spaced fractures and alteration cutting anorthosite. Note sharp boundary between altered anorthosite and fracture rock near center of photograph. The zone trends $255^o 90^o$.

BB-4 Xenoliths in Anorthosite (N44º 09' 50.3" W73º 50' 37.0" – 666 m)

→ Features: 1) xenoliths; 2) white, finer-grained anorthosite

In this stretch of the slide there are a number of xenoliths. This is not uncommon for the anorthositic rocks to include well documented metasedimentary country rock lithologies (Valley and Essene, 1980) and also igneous xenoliths (McLelland). Here their origin is debatable, although some display a deep green clinopyroxene, possibly diopside (Figure 13). Many of the xenoliths are highly disrupted and partially assimilated into the anorthosite. In some areas the anorthosite appears to be chilled against larger xenoliths resulting in white, fine-grained regions in the anorthosite where in contact with the xenoliths. However, white finer-grained anorthosite also appears to have intrusive relationship with fresh anorthosite as well.

Figure 13. Clinopyroxene-rich layer with white, finer-grained anorthosite. The whitish anorthosite may be a consequence of assimilation of xenoliths and/or chilling against them or intrusion by another magma batch.

BB-5 Dikes and Shear Zones (N44º 09' 46.1" W73º 50' 32.1" - 695m)

→ Features: 1) intrusive granitic dikes; 2) narrow ductile shear zones

In this section of the slide, as elsewhere, you will note a number of straight-walled and narrow 5-10 cm granite and pegmatite dike-like intrusions into the anorthosite. On closer inspection, shearing and mylonitic fabrics parallel to the boundaries of dikes are noted (Figure 14). Quite often the surrounding anorthosite is completely unaffected by the strain. Most of these shear zones trend nearly 110º, coincident with the major east-west trending Shawinigan-aged Piseco Lake Shear Zone in the southern Adirondacks. Where observable the shear zones display left-lateral kinematics. Many such dikes can be traced for 10's of meters across the slide.

Figure 14. Co-author Sean Regan investigating the mylonitic fabric in an aplitic dike cutting the anorthosite.

BB-6 Complex Shear Zone (N44° 09' 44.6" W73° 50' 29.2" – 715 m)

→ Features: 1) gabbroic pegmatite; 2) sinistral shear zone modified by late dextral motion; 3) relative age relations

At this stop a spectacular example of complex shearing, lithologic variation, and relative age relationships can be seen. Shown in Figure 15 there is a contact between Marcy-type anorthosite (left-hand side) and gabbro (right hand side). This contact was intruded by a gabbroic pegmatite with crystals approaching 10 centimeters in length. All three of these rocks were intruded by a thin aplitic granite trending 110°. After intrusion both the gabbroic pegmatite and aplite show strong left-lateral displacement parallel to the aplite margins. After cessation of left-lateral motion the rocks were affected by right -lateral shear (200°), deflecting the contact and the previously developed left-lateral shear fabric. Where observed elsewhere dextral shear also follows earlier sinistral shearing at 110° but also appears to have operated at high-grade metamorphic conditions.

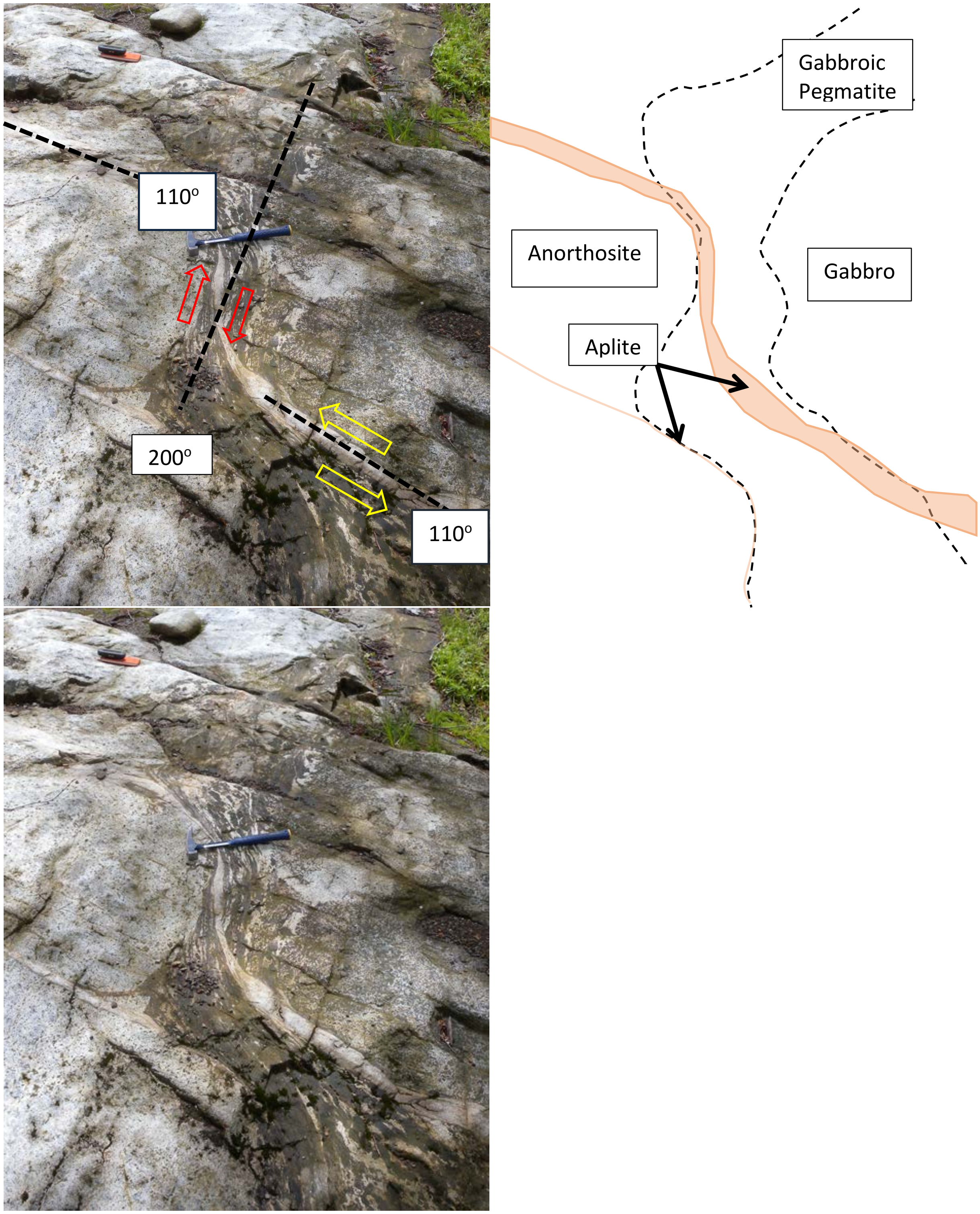


Figure 15. Diagram showing offset direction and trace of lithologic contacts of complex shear zone. Right had photograph: Left lateral shear shown by yellow arrows; right-lateral by red arrows. Left hand photograph: margins of gabbroic pegmatite shown by black dashed lines; margins of aplites shown by pink transparent overlay.

BB-7 High-grade Sinistral Shearing in Anorthositic Rocks (N44º 09' 43.4" W73º 50' 28.0" – 721 m)

→ Features: 1) large sinistral shear in anorthosite; 2) pyroxene kinematic indicator; 3) shear in granitic pegmatite

As observed at the previous location and elsewhere on the Bennies Brook slide a large number of small sinistral shear zones developed along lithologic discontinuities occur. In most cases the strain is taken up in the dike or pegmatite and is parallel to the dike walls and often is completely absent in the anorthositic wall rocks. At this location you will see a ~2m shear in anorthositic rocks indicating deformation of sufficient magnitude to affect a relatively rigid lithology (Figure 16). Also in the same shear zone you will see evidence of the high-grade nature of the shear zone in the form of sinistral pyroxene "fish-shaped" kinematic indicators (Figure 17). Finally, you will see evidence for opening of fractures approximately perpendicular to dike margins, followed by shearing parallel to the contact (Figure 18). This appears to indicate a nearly 90º change in stress direction after anorthosite intrusion.

These features provide clues to the overall kinematic history of the High Peaks region, when deformation occurred, and the relative age of events. Here they are clearly exposed without ambiguity. The trend of the shear zone is 114º82º and a brittle fault is developed parallel to its margin. A well- developed lineation in the ductile shear zone has the orientation of 115º 16º.

Figure 16. Approximately 2m wide shear zone developed in anorthosite.

Figure 17. Dolphin-shaped, pyroxene kinematic indicator just to the right of the dime. Note sinistral sense of off-set.

Figure 18. Zoned pegmatite dike with internal sinistral shear zone.

BB-8 Neoproterozoic dikes (N44° 09' 40.0" W73° 50' 24.0" – 744 m)

→ Features: 1) Neoproterozoic Dikes; 2) Magmatic layering in anorthosite

Straight walled Neoproterozoic dikes are common in the Adirondack Region but rarely exceed a meter or two in thickness. They are believed to be part of the extension and mafic magmatism associated with the opening of the Iapetus Ocean. The dikes cut Grenville rocks over a large area from the Appalachian inliers to Newfoundland, with ages ranging between ~570-640 Ma. Here a variety of dikes ranging in size from a few cm's to a few meters are found. Most are vertical and northeast (~40°). Some appear to be composite (Figure 19) and higher up in the slide relatively rare felsic trachytic dikes intrude the basalts, allowing the possibility of U-Pb dating.

In many areas anorthositic rocks subtle but regular changes in grain-size and mineral proportions are readily observable with the naked eye. Some are so subtle that only a vague meter-scale alteration of color demarks them (Figure 20). Others have finer layering and contain considerably more mafic minerals. While these layers are nowhere nearly as well developed as in mafic-ultramafic intrusions, they are believed to represent original magmatic, perhaps cumulate, layering with the anorthosite.

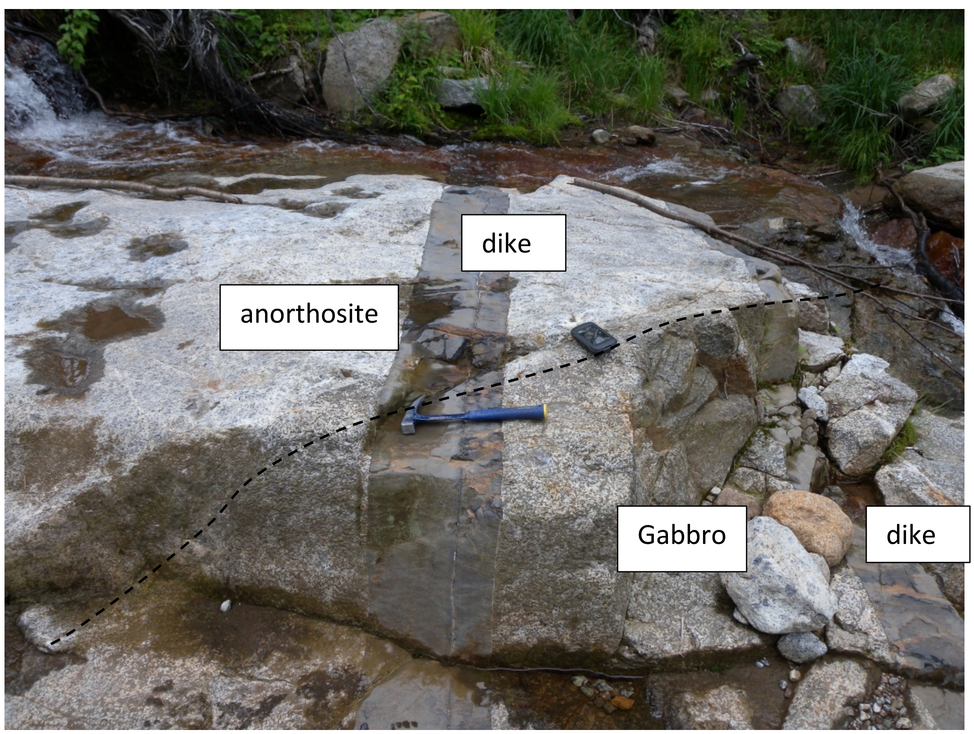


Figure 19. Possible composite Neoproterozoic dike cutting contact between anorthosite and gabbro (contact dashed). The trend of the dike is 40°90°.

Figure 20. Subtle, meter-scale, compositional layering in anorthosite. The trend of the contacts between the layers is 57°62°.

BB-9 Ferrodiorite Contact (N44° 09' 34.7" W73° 50' 15.5" – 782 m)

→ Features: 1) giant andesines; 2) raft of coarse Marcy type anorthosite; 3) ferrodiorite contact with anorthosite

The anorthosite within the massif is often a true pegmatite in terms of its grain-size and exceptionally large andesines can be found as xenoliths and rafts in other lithologies. At this locality large andesines up to 20cm or more can be found included in anorthosite of more moderate grain-size (Figure 21). In addition, a large raft of exceptional coarse anorthosite can also be seen (Figure 22). The raft has minimum dimension of 2 x 3 meters and consists of large andesine crystals with few other minerals. In an upcoming stop we will see exceptionally large pyroxenes as well.

On the upper portions of the Bennies Brook slide ferrodiorite or jotunite becomes a dominant rock type intruding the anorthosite and related rocks (Figure 23). Travelling up the slide another 20 meters or so reveals ferrodiorite as a network of thin, box-like dikes around anorthosite blocks and as large intrusive sheets. It is invariably chilled against the anorthosite and has scalloped or complex margins. In some cases andesine megacrysts can be seen increasing in abundance towards the contact and are often aligned along their long axis. The ferrodiorite is demonstratively one of the last intrusive phases as it cuts gabbroic pegmatites which have been previously deformed (Figure 24), indicating intrusion after ductile deformation.

Figure 21. Large andesine (30cm) xenocryst in anorthosite. The xenocryst is crossed by numerous alteration veinlets. Note gabbroic pegmatite and minor shear zone to right of hammer.

Figure 22. Co-author Doug Reed explores a large raft of exceptionally coarse Marcy-type anorthosite.

Figure 23. Irregular contact between ferrodiorite and anorthosite. Note fining of grain-size towards anorthosite indicating chilling of the ferrodiorite against the anorthosite and the lack deformation along the contact.

Figure 24. Crunch, the handsome geology dog, sniffs out an outcrop displaying a dike of ferrodiorite along a shear zone in a previously deformed gabbroic pegmatite. Relationships such as these establish the ferrodiorite as one of the last intrusive phases seen along Bennies Brook.

BB-10 Pyroxenite Block (N44° 09' 30.5" W73° 50' 7.8" – 822 m)

→ Features: 1) numerous xenoliths; 2) pyroxenite block; 3) composite shear zone

As previously noted a wide variety of xenoliths can be found in the anorthositic rocks including metasedimentary country rocks of the Grenville Supergroup (Valley and Essene, 1980) and those of igneous parentage. Those of igneous origin are generally assumed to be related to the anorthosite and related rocks. At this locality a large meter-scale block of coarse-grained pyroxenite can be observed (Figure 25). If the anorthosite did develop by fractional crystallization from gabbroic magma, then it is lacking in requisite mafic minerals. One way to explain this dearth of Fe and Mg-bearing silicates, is to separate the anorthosite by density differences. Perhaps this pyroxenite was entrained as a rising mass of anorthosite made its way higher into the crust?

Also at this locality is a second photogenic example of a composite shear zone with sinistral movement modified by a later dextral shear (Figure 26). This example is developed in a gabbroic pegmatite cutting anorthosite. The sinistral shear trends ~110°, while the dextral shear, larger of the two in this case, trends ~350°. This confirms the sequence of deformation described previously and suggests both sinistral and dextral components of late deformation affected the rocks exposed in the High Peaks.

Figure 25. A large pyroxenite block (xenolith) included in anorthosite. Individual pyroxene grains range from 2-3 cm in diameter.

Figure 26. Composite shear zone developed in gabbroic pegmatite showing initial sinistral motion modified by later dextral deformation. Hammer head points to the north.

BB-11 More Ferrodiorite (N44° 09’ 24.6” W73° 50’ 1.1” – 868 m)

→ Features: 1) ferrodiorite defining block structure in anorthosite; 2) giant pyroxenes; 3) off-set of chill margin

At this point on the slide ferrodiorite is a major rock type and it occurs on all scales from small dikes (2-3 cm across) to large sheets intruding anorthosite. At several locations irregular dikes of various orientations and sizes and shapes define anorthosite blocks in a jig-saw fashion (Figure 27). Also exposed is a meter-scale xenolith with giant pyroxenes up to 20 cm or more in diameter (Figure 28). It is engulfed in anorthosite, and both are cut by ferrodiorite. An offset contact between anorthosite and an andesine xenocryst-rich ferrodiorite or ferrogabbro is also exposed. The offset appears to be brittle and right lateral (Figure 29). However, the origin of the rock at the contact can be debated. Is it a contact chill margin or a layered dike that intruded along the contact or the wall of a magma chamber? We will let your group argue over how best to interpret and test the origin of this enigmatic exposure.

Figure 27. Ferodiorite intrusive dikes defining block structure in anorthosite. Note the seemingly random orientation, irregular shape of dikes, and connections. All of these features appear to argue for intrusion into a jig-saw pattern of anorthosite blocks. Did the anorthosite fracture first allowing rise of the magma or did the intrusion of the ferrodiorite cause the fracturing?

Figure 28. Pyroxenite xenolith with individual pyroxenes up to 20 cm in diameter. Note the contact with the andesine-rich darker rock on the right hand side of the photograph.

Figure 29. Dextral off-set of contact between anorthosite and ferrodioritic to gabbroic rock. What is the the origin of the layered rock at the contact?

BB-12 The End (N44° 09' 19.8" W73° 49' 58.5" – 913 m)

→ Features: 1) magmatic layering in xenolith; 2) composite bimodal Neoproterozoic dike

This is the final stop just before the splitting of the slide into three individual forks of different ages. Here the route steepens as you approach the head wall and it is an excellent place to turn around and descend. Two unique features are exposed in this section of the slide and include a layered mafic intrusion and a composite dike.

The layered mafic intrusion shows rhythmically cm-scale alteration in the proportion of mafic minerals (Figure 30). Its overall composition suggests it may be a variety of ferrodiorite; however, further work is needed to confirm this. Nonetheless it is striking in its difference from the bulk of the ferrodiorite and other rocks and testifies to the variety of igneous textures possible in this situation.

A number of small basaltic dikes occur at this elevation on the slide. One reaches a width of 2m and has an orientation of 50°90°. What is unique here, though, is a few small felsic dikes (Figure 31) that appear to concordantly intrude the basaltic dikes. This suggests that they are broadly coeval. A similar trachytic dike intruding in a swarm of Neoproterozoic basaltic dikes near Dannemora yielded zircon. This zircon gave a concordant U-Pb zircon age of 643±4 Ma. Work is in progress to date this dike as well.

Figure 30. Possible magmatic layering in mafic dike intruding anorthosite. Note alteration of layers on the cm-scale.

Figure 31. Composite Neoproterozoic dike cutting anorthosite. Note the upper felsic portion which appears to intrude the basalt.

Figure 32. Co-author Sean Regan, caught in geologic action pose, contemplates which way is up near where the slide steepens and forks beneath the summit of Lower Wolf Jaw Mountain.

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