TRIP A-3: CRYSTALLINE MEGABOUDINS ALONG THE LEADING EDGE OF THE TACONIC THRUST SHEET, ORANGE COUNTY, NY

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INTRODUCTION

As rocks are extended during deformation and break into fragments, they are termed boudins and the spaces between are gaps. However, in some geological settings, theses boudins can be quite large and are considered megaboudins or megalenses (Tricart and Lemoine, 1986). Typically, these terms were reserved for plate boundaries and highly active tectonic situations. However, large lenses of rock can form within actively deforming belts outboard of a plate boundary. This is the situation with the Monroe megaboudins of Orange County, southeastern New York which are the subject of this field trip.

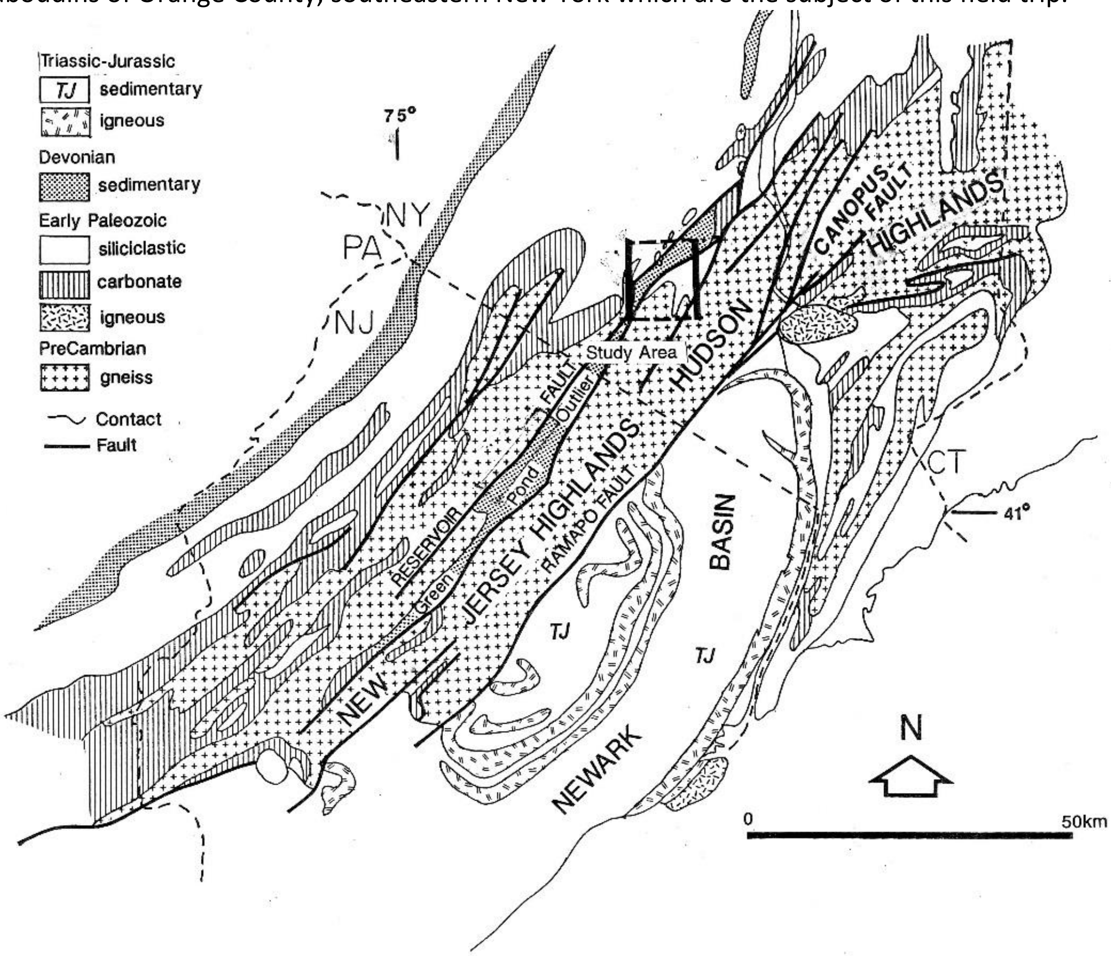


Figure 1. Geologic map of the NJ-NY border area. Box shows Monroe 7.5 minute quadrangle.

The Monroe area encompasses parts of the western Hudson Highlands, an extension of the Reading Prong, the Valley and Ridge province and the Green Pond Outlier (Figure 1) (Offield, 1967; Jaffee and Jaffee, 1973; Gates and Valentino, 2000; Gates and Kush, 2007; Gates and Valentino, 2014). The Hudson Highlands are composed of 1.0-1.3 Ga Grenville ridge forming igneous and high grade metamorphic rocks of the Rodinian tectonic cycle (Gates et al, 2001; Gates et al, 2006; Gates and Valentino, 2014). The Valley and Ridge rocks in southeastern New York are composed of Cambrian to Silurian unmetamorphosed sedimentary rocks of the Pangean cycle (Rodgers, 1970; Gates and Valentino, 2014). The Green Pond outlier is a belt of unmetamorphosed Silurian-Devonian sedimentary rocks that are equivalent to the Valley and Ridge units but which occur within the Grenville rocks of the Highlands (Herman and Mitchell, 1991).

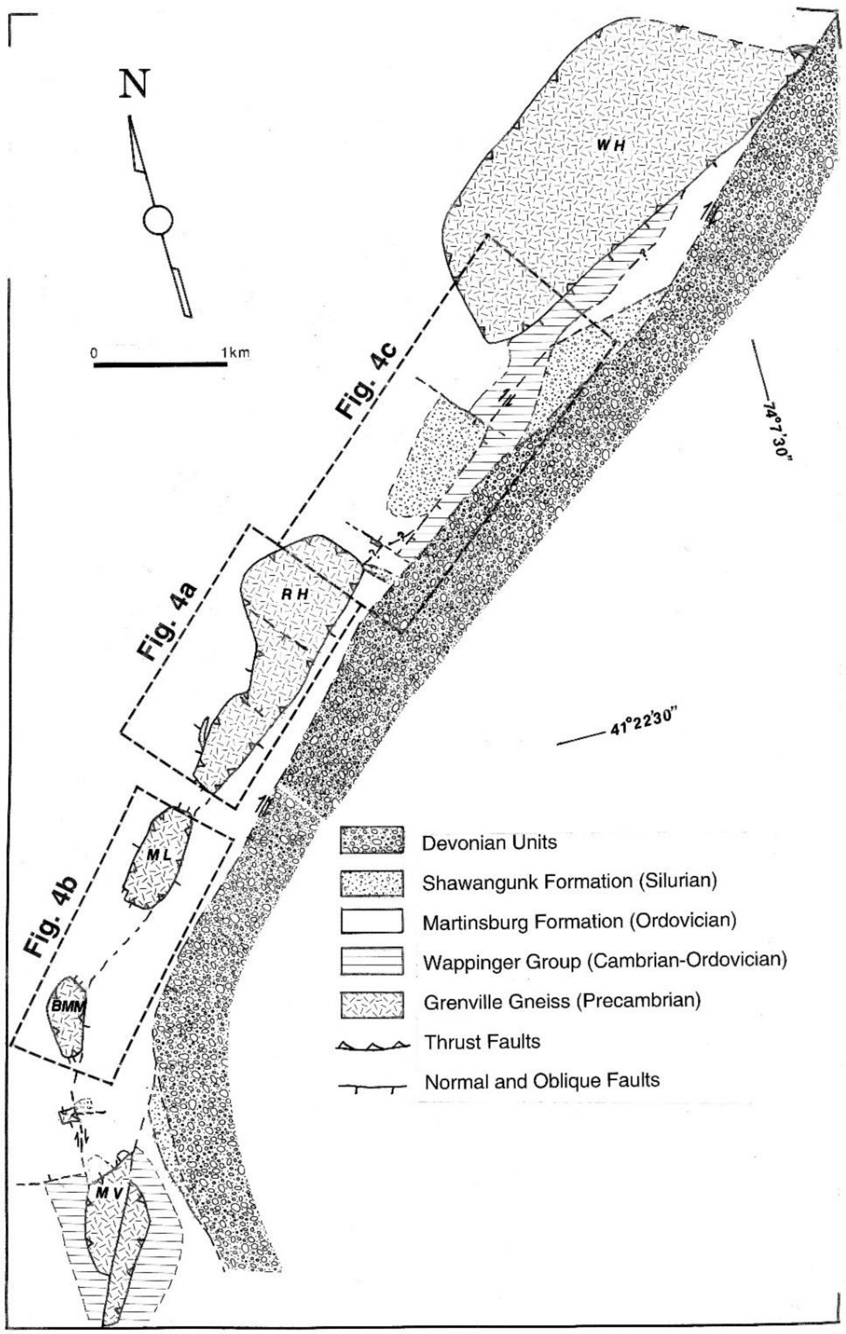


Figure 2. Geologic map of the Monroe megaboudin chain showing locations of figures. MV = Museum Village, BMM = Bull Mine Mountain, ML= Merriewold Lake, RH=Round Hill, WH=Woodcock Hill.

The Monroe megaboudins form a chain of small hills of 50-100 m elevation in an otherwise relatively flat terrain of ±20 m relief (Figure 2). The megaboudins range in size from 50 m on an edge to as large as 1.2 X 3 km with northeast trending long axes parallel to the regional structural grain and the chain. There is no pattern to the size order. The gaps between the boudins are as large as 2 km but generally decrease towards the southwest. Jaffee and Jaffee (1973) interpreted the megaboudins to be klippe that were erosionally separated from the Highlands massif to the southeast but Gates (1996) showed that they are megaboudins. To the northwest, the area is completely underlain by shales of the Martinsburg Formation.

STRATIGRAPHY

<u>Grenville Rocks</u>

Metasedimentary Gneiss

The metasedimentary gneiss includes granulite facies rocks with protoliths that were likely sedimentary (Gundersen, 1986; Gates et al., 2001; Gates et al., 2006). This unit includes pelitic and semipelitic to psammitic gneiss, and calcsilicate with minor quartzite and marble. The metapelite-psammite consists of medium to coarse-grained biotite-garnet gneiss with quartz, plagioclase, K-feldspar and local sillimanite, and cordierite. Thin zones of graphite-pyrite-garnet gneiss with biotite, quartz, K-feldspar, plagioclase, and minor sillimanite occur locally. Some metapelites are migmatitic with biotite-garnet gneiss melanosomes and thin layers of medium-coarse granite. The pelitic gneiss is interlayered with semipelitic and psammitic gneiss and local discontinuous quartzite, diopside and diopside-garnet marble, and calcsilicate gneiss. The calcsilicate gneiss is commonly migmatitic and quartzofeldspathic with K-spar, salite, plagioclase and hornblende with minor apatite, titanite and scapolite. Most of these gneisses include intrafolial pegmatites that exhibit rootless isoclinal folding. The contacts with quartzofeldspathic and metavolcanic gneiss can be sharp or gradational.

Metavolcanic Gneiss

The metavolcanic gneiss that are made up of interlayered black metamafic and gray metaintermediate bands at centimeter to meter scale (Gundersen, 1986; Gates et al., 2001; Gates et al., 2006). The mafic gneiss is medium to coarse grained with well-developed foliation defined by aligned augite, hornblende, plagioclase, ortho and clinopyroxene, and local concentrations of magnetite. The intermediate gneiss consists of medium to coarse-grained plagioclase, quartz, and minor hornblende and/or biotite. These lithologies include minor layers of felsic gneiss consisting of quartz, K-feldspar, plagioclase with minor hornblende.

The gneissic banding ranges in thickness from 5 cm to 1.5 m. These rocks were interpreted to have a volcanic origin based on the diverse range of rock compositions that are dominated by mafic and intermediate lithologies, and supporting bulk and trace element geochemistry (Gates et al., 2006). Local interlayers of quartzite and calcsilicate gneiss also occur. The contact of the metavolcanic gneiss unit quartzofeldspathic gneiss and metasedimentary gneiss are generally gradational but can be sharp locally.

Metavolcaniclastic Lithofacies

Much of the western Hudson Highlands is underlain by medium to coarse grained gray quartzofeldspathic gneiss Gates et al. (2001). The gneiss is characterized by massive to layered quartz-plagioclase aggregates with minor amounts of biotite, and/or hornblende, and trace magnetite, K-feldspar, or garnet locally. Compositional layering is defined by differences in the proportion of mafic minerals. Quartzofelspathic gneiss locally contains interlayers of amphibolite that are parallel to compositional layering and pervasive foliation. The gneiss is interlayered with quartzite and amphibolite layers near the contacts with the metavolcanic and metasedimentary gneiss, respectively in an interstratal gradational contact. Commonly small pockets of granite occur between foliation boudins in the gneiss and the unit hosts younger cross cutting pegmatites ranging from decimeter to several meters thick. Based on the mineral composition and the occurrence of compositional layers in the quartzofeldspatic gneiss, the unit is interpreted to represent a sequence of volcaniclastic metasedimentary rocks.

Paleozoic Rocks

Poquag Formation

The Poughquag Formation is a Cambrian fluvial to shallow marine sandstone to conglomerate deposit with trilobites and variably sized worm burrows that lies directly on Grenville basement rocks. This unit is called the Hardyston Formation in New Jersey. The rock ranges from feldspathic sandstone to arenite that can contain iron cementation. It commonly contains trough cross beds and forms channels into the basement rocks. Bed thickness ranges from about 20 cm to 1-2 m but is highly variable, thinning laterally in many areas. The thickness of the unit is variable and it is commonly missing in which case, the Wappinger Group rests directly on basement.

Wappinger Group

The Wappinger Group of limestone and dolomite units overlie the Poughquag Formation or lie directly on basement in many areas. The basal unit is dolomite that can be interlayered with Poughquag sandstone at the contact. It contains flaser and lenticular bedding with herringbone cross stratification near the base and nodular chert in much of the lower unit. Bed thickness in the lower part ranges from 10 cm to 50 cm in repeating cycles. The upper unit is a limestone that contains stromatolites, tempestites and oolitic packstones. Bedding thickness ranges from 10 to 30 cm and exhibits regular erosional surfaces filled with intraclast breccia. In New Jersey, this group also contains the Jacksonburg Formation of limey shale but the unit has not been identified in the field area. The Cambrian to Ordovician age Wappinger Group is equivalent to the Kittatiny Group in New Jersey.

Martinsburg Formation

The up to 3,000 m-thick, Ordovician age Martinsburg Formation overlies the Wappinger Group and exhibits a coarsening upward sequence. There are two members of the Martinsburg in the study area including the basal Bushkill shale member and the Ramseyburg sandstone member. The Bushkill member is primarily black shale with thin 1-10 cm silt and fine sand layers that occur in rhythmic cycles. The sand layers are thicker higher in the member and contain ripple and hummocky cross stratification. There is a gradational contact with the overlying Ramseyburg member which is composed of gray sandstone interlayered with shale grading into pure sandstone that is fossiliferous. Bedding ranges from 10 to 50 cm and is locally trough cross bedded.

Shawangunk Formation

There is an angular unconformity between the Martinsburg Formation and the overlying Silurian Schawangunk Formation so the contact is sharp. The unit is an interlayered quartz pebble to cobble conglomerate, quartzite and sandstone in a fining upward sequence. The rocks range in color from white to tan and red. The upper unit contains thinly (10-20 cm) bedded sections of arenitic sandstone with trough cross bedding, shale rip-up clasts and pebble lags. The lower unit contains interlayered trough cross bedded lithic sandstone with lithic and quartz pebble-cobble conglomerate and conglomeratic sandstone. The conglomerate locally displays reverse grading and weathered rinds on cobbles. The Schawangunk is so resistant to weathering that it forms prominent ridges from New York to Alabama. An equivalent unit of the Schawangunk Formation is the Green Pond Formation which occurs in the Green Pond Outlier, a sequence of Paleozoic rocks that bisects the western Hudson and New Jersey Highlands.

Esopus Formation

The Devonian Esopus Formation is a gray to black shale that overlies both the Schawangunk Formation and the Green Pond Formation within the Green Pond Outlier. It displays a coarsening upward sequence. The lower section ranges from massive to rhythmically interlayered with 1-2 cm tan silt to fine sand laminae to beds. The upper part of the formation contains thicker gray sandstone beds of 10-20 cm and normally graded with local cross bedding. The shale locally contains large trilobites and other fossils.

Bellvale Formation

The Devonian Bellvale Formation is in gradational contact with the underlying Esopus Formation. It is a trough cross bedded to massive lithic greywacke sandstone with bedding thickness ranging from 20 cm to 2 m. The lower unit contains 5-25 cm-thick shale interbeds with sharp contacts. Some sandstone layers have local quartz pebble concentrations along the lower contacts. The unit can be locally fossiliferous including terrestrial fossils.

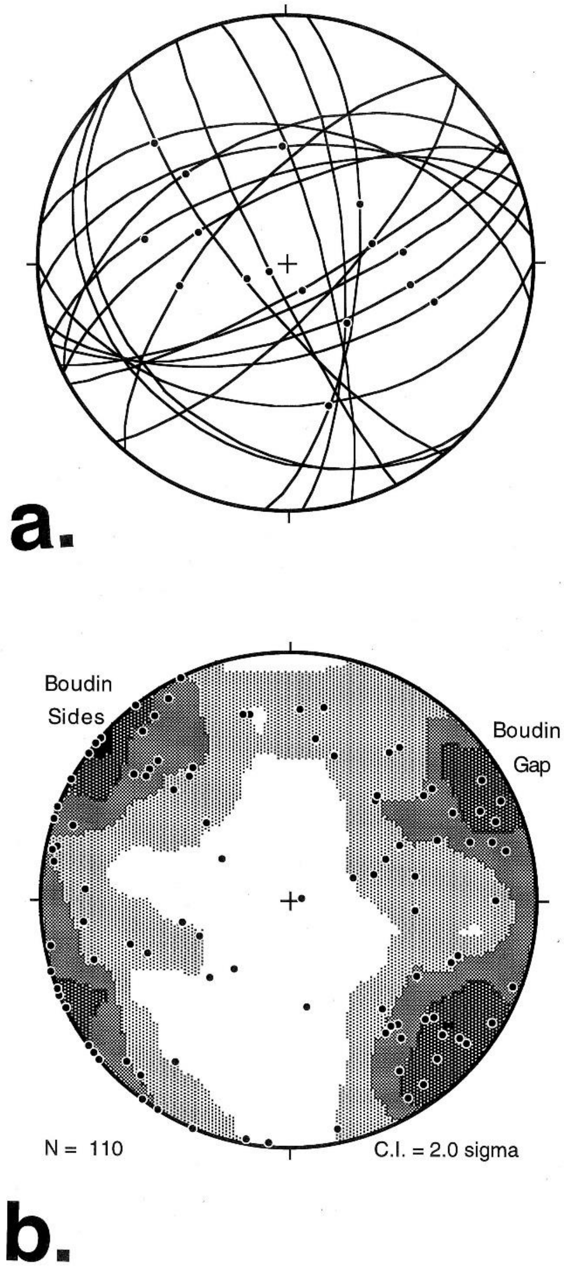
Schunemunk Formation

The top unit in the sequence is the Devonian Schunemunk Formation which is a red-purple conglomerate, quartzite and sandstone. This unit is gradational with the underlying Bellvale Formation and the transition is marked by the appearance of red in the otherwise gray sandstone. This is succeeded by red siltstone and minor shale. The lithic and quartz pebble to cobble conglomerate that characterizes the Schunemunk lies in sharp contact with the finer lithologies. The conglomerate and conglomeratic sandstone is trough cross bedded and contains imbricated clasts locally. It is interlayered with trough cross bedded sandstone. Beds in this section are about 1 m thick.

STRUCTURAL GEOLOGY OF THE MEGABOUDINS

The megaboudins of Grenville gneiss form a 35 km long, northeast trending chain along the northwest edge of the western Hudson Highlands massif (Figure 1). A 12 km long segment in the central part of this chain is relatively well-exposed and display complex structural relations (Figure 2). Northwest of the chain, the Martinsburg Formation contains two cleavages. The S_2 foliation is a spaced crenulation cleavage that is locally continuous in shale but absent in the sandier lithologies. Poles to S_2 are tightly clustered with an orientation of 044 73 SE. The earlier S_1 cleavage was folded during the formation of S_2 and defines a fold axis of 10/047 with a spread in orientations of 46°. Similarly, the poles to S_0 bedding define a fold axis of 2/047. Locally, NE-trending tight to isoclinal folds of bedding are visible (Gates, 1996).

The bedding and cleavages in the Martinsburg Formation can be seen dipping beneath the crystalline basement in an overthrust contact. The fault contact exhibits extensive fracturing and multiple slicken-



side surfaces primarily with thrust and reverse motion in both the gneiss and shale. The faults primarily dip shallowly to moderately southeast and less commonly to the northwest. The gneiss also contains epidote and quartz veins as well as pockets of chloritic breccia 5-15 cm long.

Figure 3. Equal area plot of a. Normal faults (great circles) with slickensides (dots) (n=19) and b. contour diagram of poles to joints.

The Round Hill megalens forms an hourglass map pattern with the thinned or necked area characterized by extensive normal faulting, jointing and epidote-chlorite alteration (Figure 3). Individual fractures cannot be assigned to a deformational even but fracture orientation maxima in the gneiss and cover rocks are consistent with lateral extension. Faults in the gneiss form individual planes with chlorite or epidote coating containing grooved slickensides with tapered prod marks (Means, 1987), R criteria of Petit (1987) and rare fibrous slickensides documenting kinematics. All crystalline blocks in the chain exhibit two sets of steeply dipping normal faults with northeast and northwest trends.

There are many orientations of joints in the area but there are two maxima with steep northwest and northeast orientations. The density of both the joints and normal faults is higher in the necked area of Round Hill (Figure 4a). This area also contains steep Northeast and Southwest dipping faults that offset the basement cover contact. Normal faults also occur along the northeast-trending margins of the megalens. Extensive jointing and steep slickensides are especially common along the northwest margins. At the southwest corner, Martinsburg Formation has been juxtaposed with gneiss creating a repeated succession of gneiss and shale separated by a normal fault.

The bedding and cleavage in the shale are parallel to the NE-trending block margins but are rotated towards the NW in the thinned and gap areas where they are small. In Round Hill, the rotation of the bedding into the gap area to the south is through 61^{o} and defines a fold axis of 37/064 (Figure 5a). Cleavage orientation spread defines a similar axis but there is less rotation. Slickensides and foliation drag defines strike slip shearing such that on the northwest side of the gap, the northern corner shows sinistral motion and the southern corner shows dextral motion.

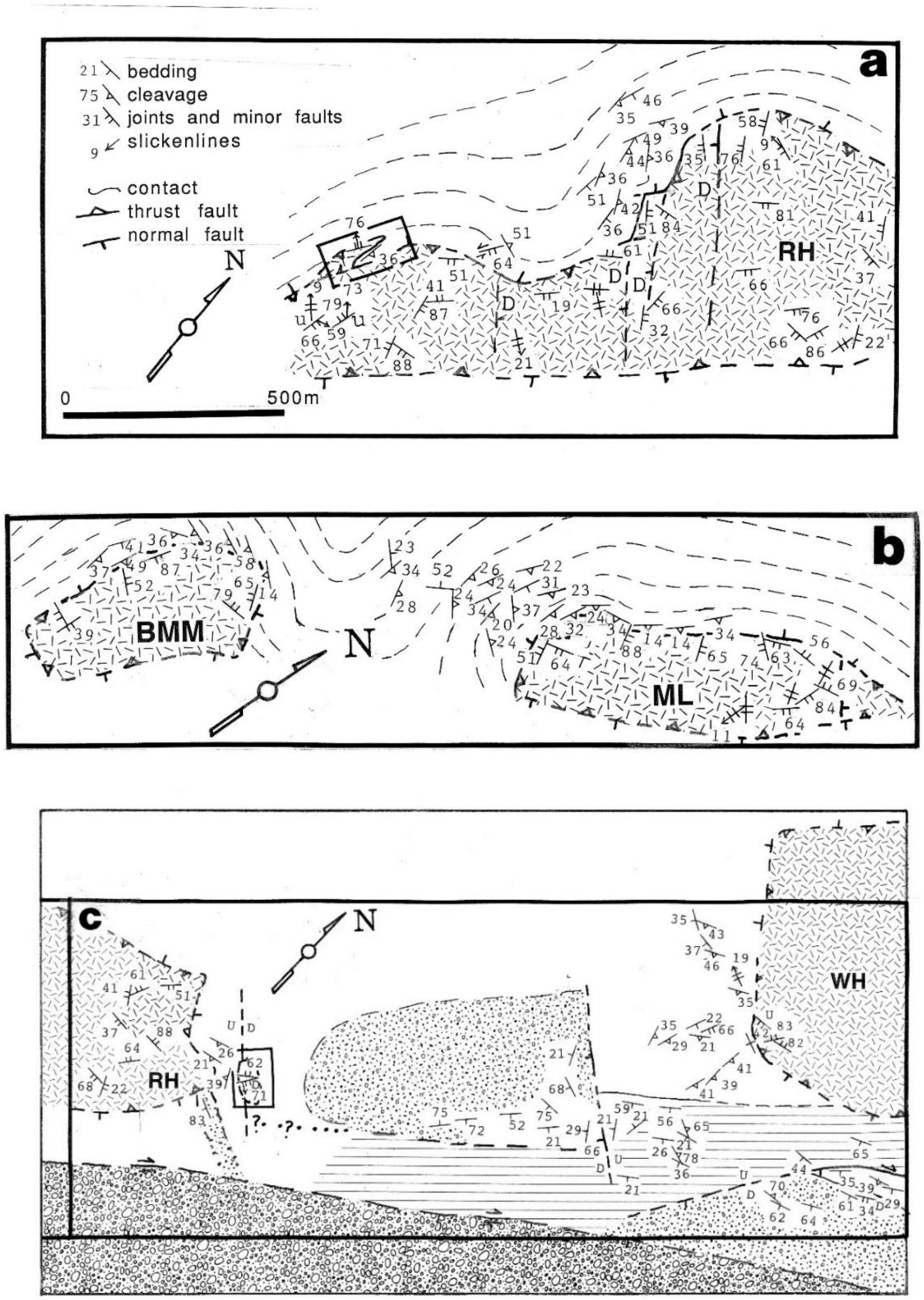


Figure 4. Geologic map of megaboudins and gaps between them. Boxed areas show normal fault offset fragments. a) Round Hill (RH), b. Bull Mine Mountain (BMM) and Merriewold Lake and gap and c. Woodcock Hill-Round Hill gap.

The gap between the Bull Mine Mountain and Merriewold Lake megaboudins is much larger (Figure 4b). The contacts between the gneiss of the megalenses and the Martinsburg shale in the gap is sharp along NW-striking, near vertical planes. Cleavage orientation swings about 77^{o} from NE-striking along the northwest margins of the Bull Mine megalens to NW-striking in the gap. The fold axis produced by this swing in orientation is 23/149 (Figure 5b). On the north side of the gap, cleavage swings 69^{o} from NE-striking along the NW margin of the Merriewold Lake lens trhough N-S and towards the NW producing a fold axis oriented 16/052 (Figure 5c). Crenulation cleavage S_2 is well developed in this area and also swings through 74^{o}, producing a fold axis of 14/052 (Figure 5d) similar to that of S_1 both in this gap and in the thinned area of Round Hill. This swing is in sharp contrast to the S_2 away from the megalenses which has a consistent orientation.

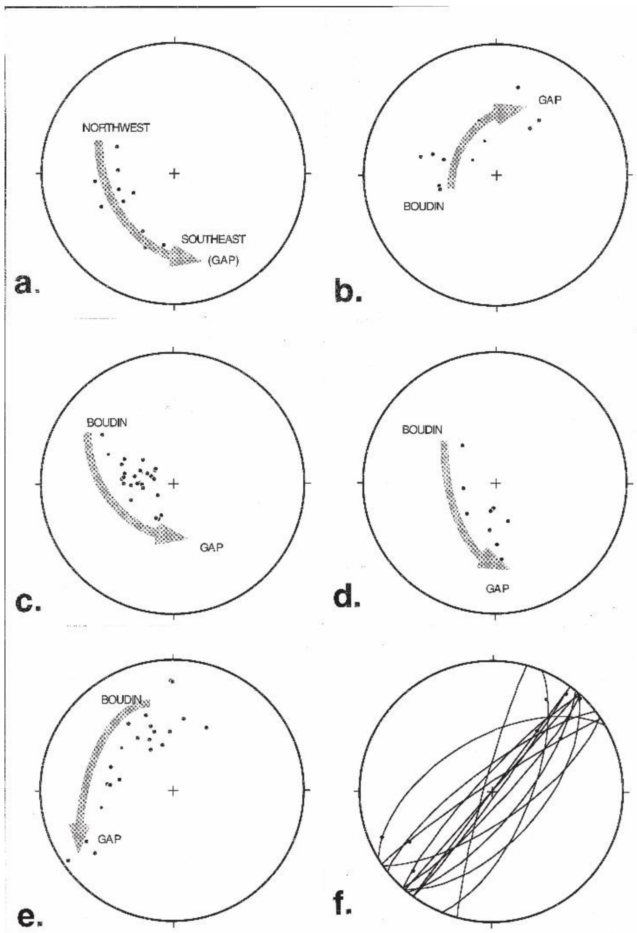


Figure 5Equal area plots of poles to cleavage in Martinsburg shale (dots) around megaboudins with arrows showing wrapping of cleavage from sides and into gaps. a. S1 in center of Round Hill. b. S1 on NW Bull Mine Mountain and N into gap. c. S1 on NW Merriewold Lake and S into gap. d. S2 on NW Merriewold Lake and S into gap. e. S1 around W and SW Woodcock Hill. f. dextral strike-slip faults along the SW side of the chain. Great circles=faults; dots=slickenside lineations

The area of deviation of cleavage from regional trend around the lenses is not symmetric across the gap (Figure 4b). The area of deflected cleavage southwest of the Merriewold Lake lens is much larger than the area of deflection to the northeast of the Bull Mine Mountain megalens. The geometric center of the cleavage deviation in the gap is significantly closer to the Bull Mine Mountain lens.

The widest gap in the chain occurs between the Round Hill and Woodcock Hill blocks (Figure 4c). Cleavage in the Martinsburg Formation shows a similar wrapping pattern around the blocks and into the gap area. The deviation in cleavage from NE regional trend through N-S and towards the NW in the gap to the southwest of Woodcock Hill indicates 115^o of rotation. It defines a fold axis of 35/122 (Figure 5e). There are only four appropriate outcrops of Martinsburg Formation on the north side of Round Hill and into the gap. The fold axis defined by this small amount of data is 22/186 but it is not considered representative. Unlike the other gaps, there is a block of Silurian Shawangunk Formation within the Round Hill-Woodcock Hill gap. The northeast contact of the Shawangunk quartzite and conglomerate is a steep, NW-striking, steeply SE-dipping normal fault that is visibly juxtaposes it against Cambrian Wappinger Group limestone. The fault surface is composed of weathered brecciated limestone with anastomosing fibrous and polished slickensides. The fault crosses a NE-striking conformable contact between Martinsburg shale and Wappinger limestone in the footwall to the northwest. The southwest edge of the fault block of Shawangunk Formation is not exposed but a moderately NE-dipping normal fault offsets a small block of brecciated gneiss from the Round Hill megalens and into the gap. A thin band of Martinsburg shale between Round Hill and the brecciated gneiss. The breccia is sericitized and sausseritized.

The cross-trend normal faults form a graben within the Round Hill-Woodcock Hill gap area. The Shawangunk Formation within the graben block exhibits folds that are truncated by the normal faults and therefore predate them. These shallowly SE-plunging folds resemble typical Alleghanian folds in the Green Pond outlier (Jaffee and Jaffee, 1973; Mitchell and Forsythe, 1988) and those in the Valley and Ridge in the area (Drake and Lyttle, 1981).

Wappinger Group and locally Martinsburg Formation rocks are juxtaposed against Precambrian gneiss on the SE-side of the Museum Village and Goose Pond megaboudins by normal faulting. Shawangunk Formation is also juxtaposed with gneiss along the southeast side of the small unnamed megaboudin between Museum Village and Bull Mine Mountain. There was certainly some normal movement along this contact but slickensides and drag folds in the Shawangunk Formation show right lateral strike-slip kinematics. A thin EW-trending band of Shawangunk quartzite extends from the southeast side of Round Hill and appears to have strike-slip offset. A similar EW-trending band of Shawangunk Formation is faulted against Wappinger carbonates and Martinsburg shale at the north end of Woodcock Hill. Slickensides and pockets of breccia along these contacts consistently show strike-slip movement though significant normal movement is also required to achieve the current geometry.

MEGABOUDIN FORMATION

The interpreted Taconic westward thrusting of the Highlands massif over the Martinsburg Formation (Offield, 1967; Rodgers, 1970; Jaffee and Jaffee, 1973; Drake and Lyttle, 1981) is well displayed by the rocks in the Monroe area. The band of gneiss that was stretched into the megaboudin chain may have been an erosionally separated klippe from the main sheet or an infold in the Martinsburg Formation. During Alleghanian compression, the shale of the Martinsburge Formation extended laterally along strike in pure shear deformation. The high competency contrast between the gneiss and shale resulted in ductile flowing of the shale matrix and brittle fracturing of the gneiss. The points where the gaps developed experienced a higher degree of strain but the reason for the locations of the breaks is unclear. There could have been preexisting weaknesses but there could also have been some periodicity to the separations. As the megaboudins separated and the gaps widened, the shale was able to flow into the gaps and ultimately, cross-strike normal faults developed locally.

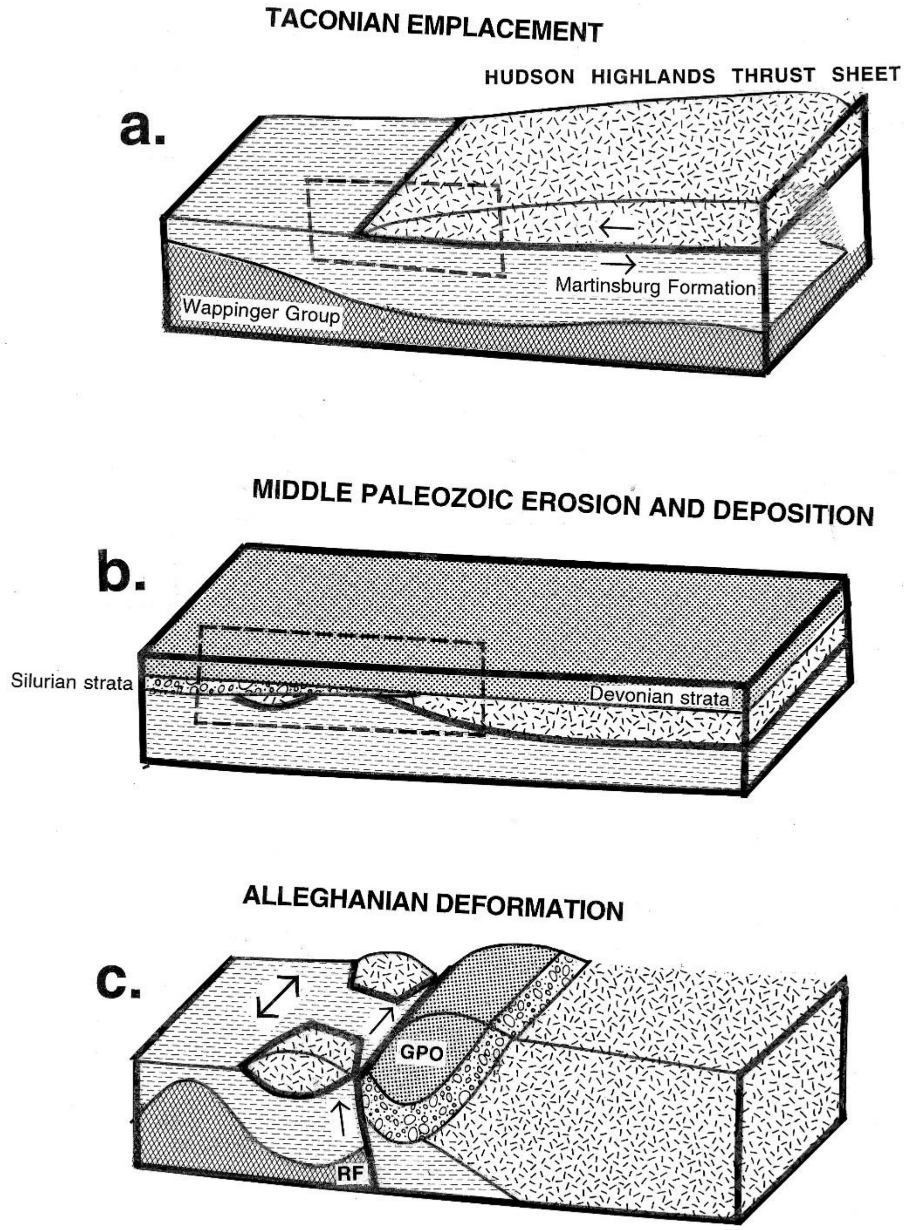


Figure 6. Model for megaboudin formation. a. Taconian emplacement of Hudson Highlands sheet. b. Silurian-Devonian erosion and deposition of sedimentary rocks. c. Alleghanian deformation and megaboudin formation. RF=Reservoir Fault; GPO=Green Pond Outlier.

The cleavage and bedding in the Martinsburg shale rotated from NE-striking to NW-striking as the rock flowed into the gaps. However, it rotated clockwise on the north side of the megaboudins and counterclockwise on the south sides. This opposing direction of rotation produced contrasting fold axes on the north versus the south side of the gaps. The S_2 foliation is also reoriented into the gap whereas it is consistent on a regional scale. This means that the boudin formation post-dated the S_2 fabric to some degree.

The size of the megaboudins and their gaps vary considerably (Figure 2). The mapped area on the unnamed megaboudin (smallest) between Museum Village and Bull Mine Mountain is only 0.1 km^2 in contrast to Woodcock Hill which is 5 km^2. Others in the chain are even larger. The megaboudin gaps similarly vary considerably. Ferguson (1981) and Ferguson and Lloyd (1984) have shown that gap aperture in a boudin chain commonly reflects the duration of opening. Applying this theory to the megaboudin chain indicates that the gaps initiated at various times during the deformational event. The Woodcock Hill-Round Hill gap would be the earliest formed and the nascent separation of the two halves of Round Hill would be the youngest. Smith (1975) proposed that the gaps in boudin chains reflect points of weakness or stress nodes. Such an evaluation is not possible in the megaboudin chain.

The asymmetry of the cleavage-bedding flow patterns in Martinsburg shale within the Bull Mine Mountain-Merriewold Lake gap complicates a simple explanation of passive boudinage. A possible explanation for this asymmetry is that both megaboudins may have moved northeastward during separation. In pure shear fracture boudins (Cloos, 1947; Rast, 1956), all boudins separate in opposite directions as the chain elongates. Material is transported from the high stress sides of the boudins into the gaps which are low stress areas in the system (Ramberg, 1955; Stromberg, 1973). This produces a wrapping geometry in the transported material. As the gaps widen, the material in the gap is flattened perpendicular to the maximum stress direction as the shielding by the rigid boudin becomes less effective. However, if adjacent boudins move in the same direction, once initial opening takes place, the gap will only be filled behind the leading boudin and produce an asymmetric gap fill. In this scenario, the trailing boudin would compress the material in the gap area and may even overthrust it. Such a process could be considered extrusion boudinage (Gates, 1996). There is no definitive evidence to support this in the megaboudin chain though it cannot be ruled out. The staggered opening times of the gaps between the megaboudins may have created a complex pattern of deformation in the gap areas. A symmetric fill pattern could have become asymmetric if subsequent opening of a gap in an adjacent boudin created asymmetric motion and a leading-trailing boudin situation.

The opening of the gaps between the megaboudins is marked by extensive fracturing and normal faulting. In some cases, extension formed a saddle-like graben across the spine of the megaboudin producing a sag in the topography and normal fault offset of the gneiss-shale contact. In other gaps, the separation is abrupt along NW-striking, vertical fractures. Once the gaps opened, shale flowed into them. Fullagar (1980) describes the type of flow around the megaboudins in terms of vorticity. The strike-slip shearing around the megaboudins further documents this vorticity in the horizontal direction. However, the normal faulting around the megaboudins demonstrates vorticity in the vertical plane as well thus suggesting three-dimensional vorticity.

Vertical movements appear to have become more important in the wider gaps. In the wide Round Hill-Woodcock Hill gap, after the gap opened and the shale flowed in from the sides, cross-strike conjugate normal faults formed a graben that juxtaposed Shawangunk Formation rocks with older rocks in the gap.

The sequential progression of deformation dominated by horizontal flow of shale into the gap to that dominated by vertical displacement of conglomerate into the gap appears to be the result of deformation of a layered sequence with contrasting competencies (Figure 7) . In the early stages of boudin development, the weak and ductile shale quickly flowed into the gap. The overlying conglomerate and quartzite may have deformed within its stratigraphic level but the rigidity of the rock prevented it from moving into another horizon. Only when the gap achieved a critical aperture was the rigid layer able to drop into the gap area. There are several instances of normal faulting juxtaposing rock from a higher horizon into the gap both by clipping off the leading edge of the crystalline boudin and by normal faulting of Shawangunk Formation.

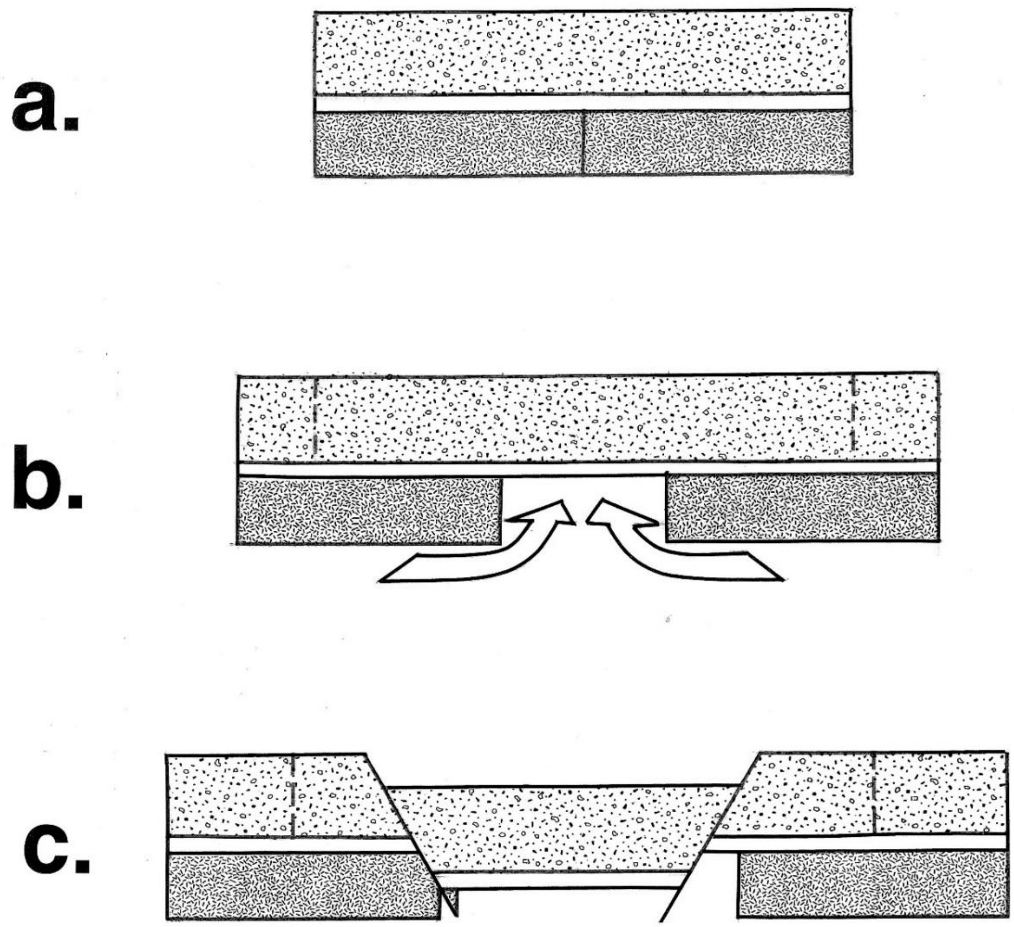


Figure 7. Model showing sequential development of boudin gaps in a rheologically layered sequence. a. Rigid block (stippled) with incipient break encased in incompetent material (white). b.Opening of gap and flow of incompetent material along horizontal plane into gap. c. Normal faulting and vertical displacement of overlying competent material into gap.

Map reconstruction of the crystalline megaboudins yields a gap length of 3.6 km along the 12 km-long chain. There may have been some internal brittle extension within the crystalline rock that cannot be accounted. The exposure along the chain is only fair and small pieces of crystalline rock may have been clipped by normal faults like on the north side of Round Hill but that are not exposed. Late vertical motion on the chain may further have shifted deformational horizons so that the current level of exposure may not reflect a single deformational horizon. All of these factors may result in some missing crystalline rock from the reconstruction and therefore introduce error into calculations. Nonetheless, a ⍰ = 3.3 was calculated using the strain reversal method of Ferguson (1981). The Martinsburg Formation had a much higher amount of strain because it undoubtedly extended laterally well before the crystalline body began to fracture into the megaboudins.

The right-lateral faulting along the southeast margin of the megaboudin chain could have resulted from variable lateral extension of the belts in response to compression. The thick sandstones and conglomerates of the Green Pond outlier (Herman and Mitchell, 1991) to the southeast of the megaboudins are likely more rigid and less prone to pure shear extrusion than the Martinsburg Formation. The difference in lateral expansion would account for the faulting between the two making it a stretching fault (Means, 1989; 1990). On the other hand, it may be part of the larger Alleghanian dextral strike-slip system in the Appalachians (Gates, 1996).

REFERENCES CITED

Cloos, E., 1947, Boudinage; Transactions of the American Geophysical Union, vol. 28, p. 626-632.

Drake, A.A., Jr., 1984, The Reading Prong of New Jersey and eastern Pennsylvania: An appraisal of rock relations and chemistry of a major Proterozoic terrane in the Appalachians, in Bartholemew, M. J. (ed) The Grenville Event in the Appalachians and Related Topics; Geological Society of America Special Paper 194, p. 75-109.

Drake, A.A., Jr. and Lyttle, P.T., 1981, Alleghanian thrust faults in the Kittatinny Valley, New Jersey, in Manspeizer, W., (ed) Field Studies of New Jersey Geology and Guide to Field Trips, New York State Geological Association vol. 52, p. 278-311.

Ferguson, C.C., 1981, A strain reversal method for estimating extension from fragmented rigid inclusions; Tectonophysics, vol. 79, p. T43-T52.

Ferguson, C.C. and Lloyd, G.E., 1984, Extension analysis of stretched belemnites: a comparison of methods; Tectonophysics, vol. 101, p. 199-206.

Fullagar, P.K., 1980, A description of nucleation of folds and boudins in terms of vorticity; Tectonophysics, vol. 65, p. 39-55.

Gates, A.E., 1996, Megaboudins and lateral extension along the leading edge of a crystalline thrust sheet, Hudson Highlands, New York, USA; Journal of Structural Geology, vol. 18, p. 1205-1216.

Gates, A.E., and Kush, E., 2007, Geologic map of the Maywood 7.5 minute quadrangle, NY; New York State Geological Survey Open-file Report, 2507.

Gates, A.E. and Valentino, D.W., 2000, Geologic map of the Monroe 7.5 minute quadrangle, NY; New York State Geological Survey Open-file Report No 1g1436,

Gates, A.E. and Valentino, D.W., 2011, Bedrock Geology of the Highlands Province, Connecticut, New York, New Jersey And Pennsylvania, in Lathrop, R. G. (ed), The Highlands: Treasured Landscapes, Critical Resources, Rutgers University Press, p. 9-25.

Gates, A.E., Valentino, D.W., Chiarenzelli, J., Gorring, M., and Hamilton, M., 2001, The Assembly of the Supercontinent Rodinia in the western Hudson Highlands, New York State Geological Association Field Trip Guidebook, vol. 73, p. 174-204.

Gates, A.E., Valentino, D.W., Gorring, M., Thern, E. and Chiarenzelli, J., 2006, Rodinian collisional and escape tectonics in the Hudson Highlands, New York, in Pazzaglia, F.J., ed., Excursions in Geology and History: Field Trips in the Middle Atlantic States: Geological Society of America Field Guide 8, p. 65-82.

Gundersen, L.C., 1986, Geology and geochemistry of the Precambrian rocks of the Reading Prong of New York and New Jersey – Implications for the genesis of iron-uranium-rare earth deposits, in Carter, L.M.H. (ed) USGS Research on Energy Resources; U.S. Geological Survey Circular 974.

Herman, G.C. and Mitchell, J.P., 1991, Geologic map of the Green Pond Mountain region from Dover to Greenwood Lake, New Jersey; N.J. Geological Survey, Geologic Map Series 91-92.

Jaffee, H.W. and Jaffee, E.B., 1973, Bedrock Geology of the Monroe Quadrangle, Orange County, New York; N.Y State Museum and Science Service, Map and Chart Series vol. 20, 74 p.

Jaffee, H.W. and Jaffee, E.B., 1989, Structure and petrology of the Precambriam allochthon, autochthon, and Paleozoic sediments of the Monroe area, New York. New York State Geological Association Guidebook, vol. 61, p. 29-50.

Means, W.D., 1987, A newly recognized type of slickenside striation; Journal of Structural Geology, vol. 9, p. 585-590.

Means, W.D., 1989, Stretching faults; Geology, vol. 17, p. 893-896.

Means, W.D., 1990, One dimensional kinematics of stretching faults; Journal of Structural Geology, vol. 12, p. 267-272.

Mitchell, J.P. and Forsythe, R., 1988, Late Paleozoic non-coaxial deformation in the Green Pond Outlier, New Jersey Highlands; Geological Society of America Bulletin, vol. 100, p. 45-59.

Offield, T.W., 1967, Bedrock Geology of the Goshen-Greenwood Lake area, N.Y., N.Y State Museum and Science Service, Map and Chart Series vol. 9, 78 p.

Petit, J.P., 1987, Criteria for the sense of movement on fault surfaces in brittle rocks; Journal of Structural Geology, vol. 9, p. 597-608.

Ramberg, H., 1955, Natural and experimental boudinage and pinch and swell structures; Journal of Geology, vol. 63, p. 512-526.

Rast, N., 1956, The origin and significance of boudinage; Geological Magazine, vol. 93, p. 401-408.

Rodgers, J., 1970, Tectonics of the Appalachians, J.W. Wiley and Sons, New York.

Smith, R.B., 1975, Unified theory of the onset of folding, boudinage and mullion structure; Geological Society of America Bulletin, vol. 86, p. 1601-1609.

Stromgard, K.E., 1973, Stress distribution during the formation of boudinage and pressure shadows; Tectonophysics, vol. 16, p. 215-248.

Tricart, P. and Lemoine, M., 1986, From faulted blocks to megamullions and megaboudins: Tethyan heritage in the structure of the western Alps; Tectonics, vol. 5, p. 95-118.

FIELD GUIDE AND ROAD LOG

NOTE: Most of these exposures are on private property and the owners are protective of their privacy. Please respect their property both during this trip and in subsequent visits.

Meeting Point: West parking lot of the Double Tree Inn, located at 425 NY-59, Nanuet, NY, 10954.

Meeting Point Coordinates: 18T 0584372mE, 4549264mN

Meeting Time: 8:30 AM

Distance in Miles (km) Cumulative	Point to Point	Route Description
0.0 (0.0)	0.0 (0.0)	Assemble in the western parking lot of the Double Tree Inn in Nanuet, NY.
0.3 (0.5)	0.3 (0.5)	Head East on NY-59 E toward Rose Rd.
0.5 (0.8)	0.2 (0.3)	Use the right lane to take the ramp to Palisades County Rd N.
16 (25.6)	15.5 (24.8)	Merge onto Palisades Interstate Parkway N.
16.2 (25.9)	0.2 (0.3)	Take exit 18 toward US-6, NY-17, I-87.
26.7 (42.7)	10.5(16.8)	At circle, take 2nd exit onto US-6.
26.8 (42.9)	0.1 (0.2)	Take Exit 129 toward Museum Village and merge onto Curly Rd.
26.9 (43.0)	0.1 (0.2)	Turn left on Museum Village Rd.
		Park on the corner of Museum Village Rd. and Old Mansion Rd.

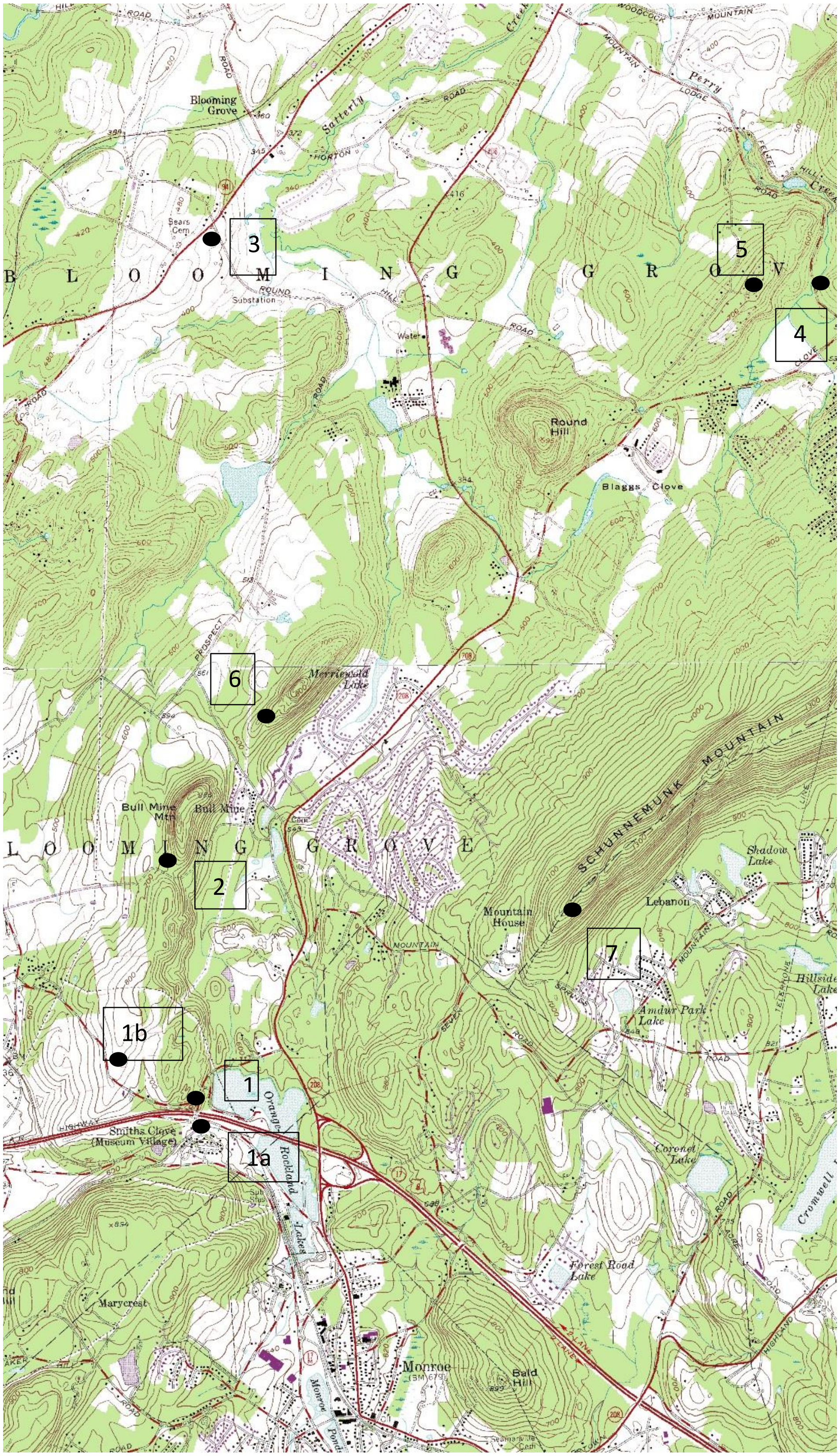
STOP 1: Traverse through the Museum Village megaboudin

Location Coordinates: 41°20’31”N 74°12’00.93”W

Quartzofeldspathic gneiss with intense fracturing and alteration. The entire span of the megaboudin can be observed on the transect exposed in the Rt 17/6 road cut. Rock types and structures are observed near the Museum Village Rd overpass. The gneiss shows chlorite and hematite alteration on most fracture faces and the rock is altered throughout. Fracturing is more intense along the edges of the megaboudin and is multidirectional. Many surfaces exhibit both fibrous and polished slickensides that primarily show reverse motion but locally show many directions.

Distance in Miles (km) Cumulative	Point to Point	Route Description
27.0 (43.2)	0.1 (0.2)	Continue on Museum Village Rd. across highway overpass to stop sign
27.1 (43.4)	0.1 (0.2)	Turn left on Orange & Rockland Rd. and turn into parking lot on right
		Park in the Heritage trail lot for hikers and walk west about 200 feet to the underpass outcrop is around the bridgeworks.

STOP 1a: Wappinger Group Limestone on the Museum Village megaboudin


3
5
4
6
2
7
1b
1
1a
Blooming Grove
Round Hill
Blaggs Clove
Merriewold Lake
Bull Mine Mtn
Bull Mine
SCHUNNEMUNK MOUNTAIN
Mountain House
Lebanon
Shadow Lake
Amdur Park Lake
Smiths Clove (Museum Village)
Orange-Rockland Lakes
Coronet Lake
Forest Road Lake
Marycrest
Monroe
Bald Hill
Cromwell

Location Coordinates: 41°20'48.19"N 74°12'01.42"W

Small outcrop of bedded Cambrian limestone with nodular chert layers. This rock lies unconformably above the gneiss. Note the lack of intense jointing seen in the gneiss and the gentle deformation. This is a small outcrop for reference. Limestone occurs both above and beneath the megaboudins because it is structurally repeated.

Distance in Miles (km) Cumulative	Point to Point	Route Description
27.2 (43.5)	0.1 (0.2)	Return to Station 1
27.5 (44.0)	0.3 (0.5)	Turn left on Old Mansion Rd.
		Stop at intersection of Old Mansion Rd. and Mediacom Way

<u>STOP 1b: Martinsburg Formation and view of the Goose Pond megaboudin</u>

Location Coordinates: 41°20'06.38"N 74°12'28.6"W

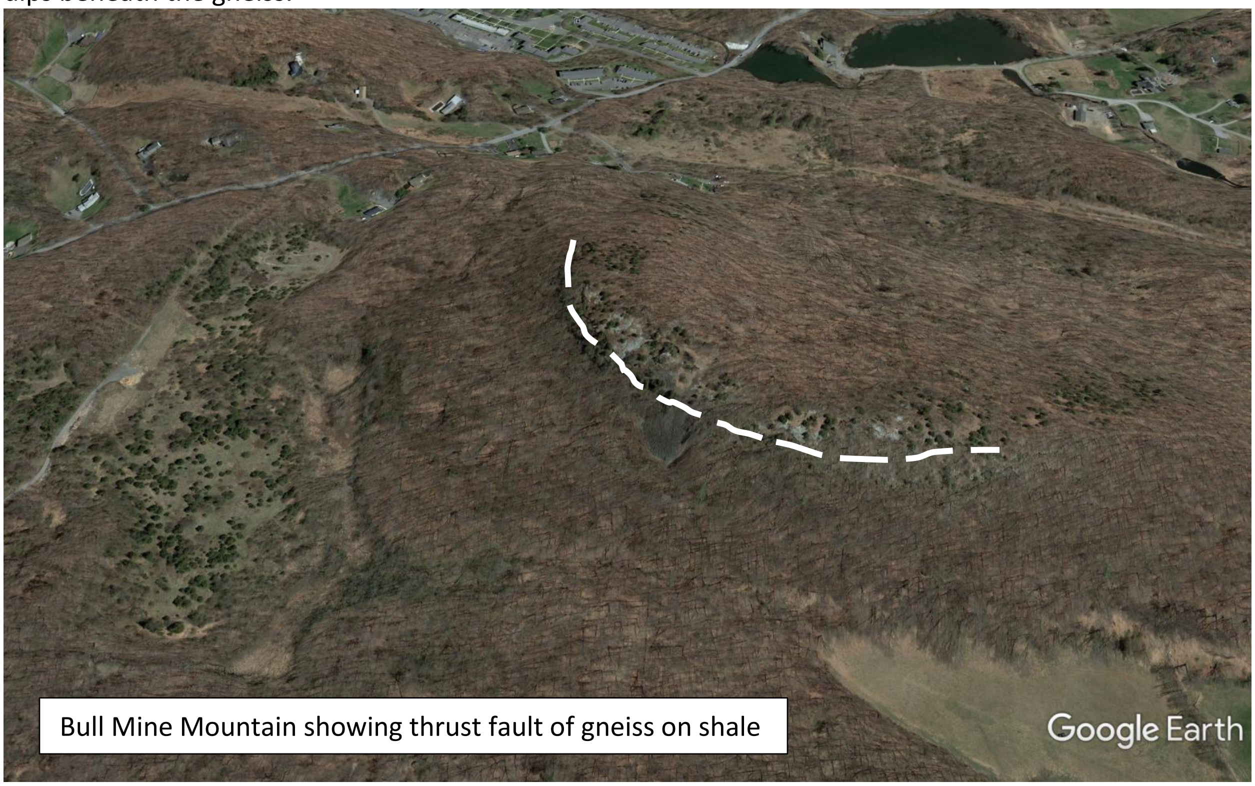
The Goose Pond megaboudin is the next south from the Museum Village megaboudin in the chain. It is located far to the west of the rest of the chain. This is because the E-W trending Monroe Fault offsets the megaboudin by approximately 1 mile in a dextral strike-slip sense. The Monroe Fault is interpreted as a Cretaceous fault but appears to be currently active with several recent epicenters located along its western extension. Several hundred feet west of the parking area are outcrops of Martinsburg shale. This shows the western contact of the Museum Village megaboudin is with lower Martinsburg Formation (Bushkill Member) and indicating a loss of section.

Distance in Miles (km) Cumulative	Point to Point	Route Description
28.2 (45.1)	0.7 (1.1)	Continue on Old Mansion Rd. to Craigville Rd.
28.5 (45.6)	0.3 (0.5)	Turn right on Craigville Rd.
29.0 (46.4)	0.5 (0.8)	Turn right on Bull Mine Rd. Park at circle
		Walk up road to right pass through gate and continue along dirt road to circle and crossing path. Follow path to left and visit mine and dump. NOTE: be careful of hidden adits in underbrush. Continue north along west face of hill to outcrops of gneiss overlying Martinsburg Shale. These slopes can be slippery.

<u>STOP 2: Bull Mine Mountain megaboudin</u>

Location Coordinates: 41°20'42.12"N 74°12'19.27"W

Bull Mine is a magnetite (iron) mine in the Bull Mine Mountain megaboudin. There are several adits and shafts within the mine complex and a tailings pile with large quantities of ore. The host gneiss for this iron deposit is largely metavolcanic gneiss but is also metasedimentary including calcsilicates. The mine is accessible and the dump contains a significant amount of ore. Farther along the western slope of the Bull Mine Mountain megaboudin, gneiss can be seen directly overlying Martinsburg shale in an overthrust contact. Both the gneiss and shale are highly fractured and contain slickensides showing thrust and reverse movement. The shale is highly cleaved and shows foliation and some bedding that dips beneath the gneiss.



Bull Mine Mountain showing thrust fault of gneiss on shale

Distance in Miles (km) Cumulative	Point to Point	Route Description
29.5 (47.2)	0.5 (0.8)	Drive back down Bull Mine Rd. and turn right on Craigville Rd.
33.1 (53.0)	3.6 (5.8)	Drive northwest on Craigville Rd. and turn right on Rt. 94.
		Stop in the gravel area on the corner of Rt. 94 and Round Hill Rd.

STOP 3: View of Round Hill megaboudin

Location Coordinates: 41°24’7.8”N 74°11’53.75”W

The Round Hill megaboudin has a saddle in the middle where it began to separate but never developed a gap. The gneiss is continuous across the megaboudin but at a much lower elevation where intense fracturing made it subject to erosion. From this location, the abrupt hill of the weakly to unfractured gneiss in the northern part of the Round Hill megaboudin can be seen in the other low lying shale plain. To the south of Round Hill Rd. the southern elevated part of the Round Hill megaboudin can be seen.

There are outcrops of Martinsburg shale along Round Hill Rd. and an abrupt contact with gneiss at the megaboudin saddle.

Possible stop on Rt 94 (if time permits) to view Martinsburg Formation outside the influence of the megaboudins for comparison. Outcrop is beneath Railroad trestle.

Location Coordinates: 41°23’38.83”N 74°13’03.65”W

Distance in Miles (km) Cumulative	Point to Point	Route Description
33.8 (54.1)	0.7 (1.1)	Continue on Round Hill Rd. to Rt. 208
34.9 (55.8)	1.1 (1.8)	Turn right on Rt. 208 to Clove Rd.
35.8 (57.3)	0.9 (1.4)	Turn left on Clove Rd.
36.4 (58.2)	0.6 (1.0)	Turn Left on Mountain Lodge Rd.
		Park at bridge over stream. Outcrops of limestone occur along road and in stream to the southwest of the road. Walk up road to northwest to view outcrops of Martinsburg formation to quarry on the left side of the road.

STOP 4: Wappinger Group and Martinsburg Fm. In the Round Hill-Woodcock Hill gap

Location Coordinates: 41°23’54.78”N 74°08’55.1”W

At the stream is Wappinger Group limestone with nodular chert beds. Bedding is well developed but outcrops are weathered and difficult to see in many cases. Good cliff outcrops of limestone along stream bed to the southwest. Continue along the road to the west to observe a good section of the Martinsburg shale that is not excessively deformed near the carbonate but is progressively deformed up the hill and towards the quarry. Just 200 feet northwest of this entire section, are the rugged slopes and gneiss of the Woodcock Hill megaboudin.

Distance in Miles (km) Cumulative	Point to Point	Route Description
36.9 (59.0)	0.5 (0.8)	Continue on Mountain Lodge Rd. to Helms Hill Rd.
37.5 (60.0)	0.6 (1.0)	Turn left on Helms Hill Rd.
37.6 (60.2)	0.1 (0.2)	Turn left on Calvert Dr.
37.6 (60.2)	0.05 (0.1)	Quick turn on Mandy Dr.
		Park at cul-de-sac. Outcrop is on the road leading up on north side.

STOP 5: Shawangunk Formation infilling the gap

Location Coordinates: 41°23’57.57”N 74°09’11.43”W

Large exposure of classic Shawangunk Formation conglomerate and quartzite. Thick bedded quartz pebble to cobble conglomerate with lithic sparse clasts. Some imbrication of cobbles and reverse graded beds. Sandstone is arenitic and locally cross bedded. Minor slickensides show strike-slip and normal offset. This rock is juxtaposed directly against the carbonate of Stop 4 along a visible normal fault in the stream below this point.

Distance in Miles (km) Cumulative	Point to Point	Route Description
37.8 (60.4)	0.1 (0.2)	Return to Calvert Dr. and turn right
38.3 (61.2)	0.5 (0.8)	Return to Helms Hill Rd. and turn left to the end
38.3 (61.3)	0.05 (0.1)	Turn left on Round Hill Rd.
40.7 (65.1)	2.4 (3.8)	Turn right on Clove Rd
41.6 (66.6)	0.9 (1.4)	Turn right on Rt. 208
42.2 (67.5)	0.6 (1.0)	Turn right on Peddler Hill Rd.
		Turn right into private driveway and park Hike up the hill through the woods to the east to rock exposures.

<u>STOP 6: Northern contact of the Merriewold Lake megaboudin</u>

Location Coordinates: 41°22'27.26"N 74°11'40.5"W

This exposure shows the sharp contact of the gneiss with mobilized Martinsburg shale. Blocks of quartzofeldspathic gneiss of the Merriewold Lake megaboudin have sharp southern terminations along NW-striking planes. Martinsburg shale shows progressive strikes from NE along the northwest side of the megaboudin towards the NW in the gap to the southwest. It has well-developed cleavage and crenulation cleavage that demonstrate this swing in orientation. This stop may not be available or it may be too late in the day. There are two other exposures that clearly demonstrate the swing in orientation of fabric in the Martinsburg Formation from deformation.

This exposure on Prospect Rd. shows very shallowly southeast dipping fabric in Martinsburg shale reflecting the overthrusting of the Highlands massif and subsequent deformation.

Location Coordinates: 41°22'15"N 74°11'49.83"W

This exposure is on Peddler Hill Rd. and shows Martinsburg Formation with a clear northwest strike. This rock demonstrates the reorientation of the fabric from NE-striking to NW-striking through nearly 90° as a result of flow into the gap between the Merriewold Lake and Bull Mine Mountain megaboudins.

Location Coordinates: 41°22'20.47"N 74°12'16.64"W

Distance in Miles (km) Cumulative	Point to Point	Route Description
42.8 (68.5)	0.6 (1.0)	Return to Peddler Hill Rd and drive east to Rt 208

43.3 (69.3)	0.5 (0.8)	Turn left (south) on Rt. 208
43.8 (70.1)	0.5 (0.8)	Turn left on Mountain Rd.
44.1 (70.6)	0.3 (0.5)	Turn left on Seven Springs Rd.
		Park at trailhead for Skunnemunk Mountain. Hike up trail about ¼ mile until the megaboudin chain can be clearly seen to the west at the base of the hill.

STOP 7: View of the megaboudin chain

Location Coordinates: 41°21’36.01”N 74°10’37.39”W

The walk to the vantage point is on Bellvale Sandstone up Skunnemunk Mountain. Look to west to see the entire observed megaboudin chain sitting in the plain underlain by Martinsburg shale.

Distance in Miles (km)		
Cumulative	Point to Point	Route Description
44.4 (71.0)	0.3 (0.5)	Take Seven Springs Rd. to Mountain Road
45.0 (72.0)	0.6 (1.0)	Turn right on Mountain Springs Rd. towards Rt. 208
45.9 (73.4)	0.9 (1.4)	Turn left on Rt 208 (south).
56.4 (90.2)	10.5 (16.8)	Take ramp onto Rt. 17/6 East.
71.9 (115.0)	15.5 (24.8)	At traffic circle, take second right to Palisades Interstate Parkway South
72.2 (115.5)	0.3 (0.5)	Exit 8W at Rt 59 West in Nanuet towards Spring Valley.
72.4 (115.8)	0.2 (0.3)	Reverse direction on Rt. 59 at Smith Rd. to the left
		Return to Double Tree Inn at 425 New York 59, Nanuet, NY, 10954. Destination will be on the right. END OF TRIP