FIELD TRIP TO
THE WESTERN HUDSON HIGHLANDS, NEW YORK

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Introduction

The Reading Prong province is a Grenville massif that links the Blue Ridge and the Green Mountain provinces to form the spine of the U.S. Appalachians (Figure 1). The Hudson Highlands comprises the northern extent of the Reading Prong in southeastern New York and Connecticut (Figure 2). The details of the Grenvillian orogeny in the Appalachians are commonly difficult to decipher because of complex structural relations, lack of exposure, and pervasive granulite facies metamorphism, as well as extensive structural and metamorphic overprinting during the Paleozoic and Mesozoic locally (Ratcliffe *et al.*, 1972; Bartholomew and Lewis, 1988; Krol et al., 1992; Krol and Zeitler, 1994).

Any granulite crystalline massifs, or with an isotopic age between ca. 1,300 Ma (Mose, 1982) and 893 Ma (Ratcliffe *et al.*, 1972) age in the Reading Prong of the north-central Appalachians (Figure 1) has been assigned to the Grenville orogeny. Middle Proterozoic tectonism in the Canadian and Adirondack Grenville rocks have been subdivided into three to four orogenic events (Easton, 1986). McLelland (1986) suggested that the older Grenvillian ages are related to anorogenic plutonism in the Adirondacks of New York. McLelland and Isachsen (1980) and Whitney (1983) proposed a three-stage tectonic model for the deformation and metamorphism in the Adirondacks. Virtually all studies concur that the culmination of the Grenvillian event occurred about 1,100 - 1,000 Ma, approximately equivalent to the Ottawan orogeny (Easton, 1986).

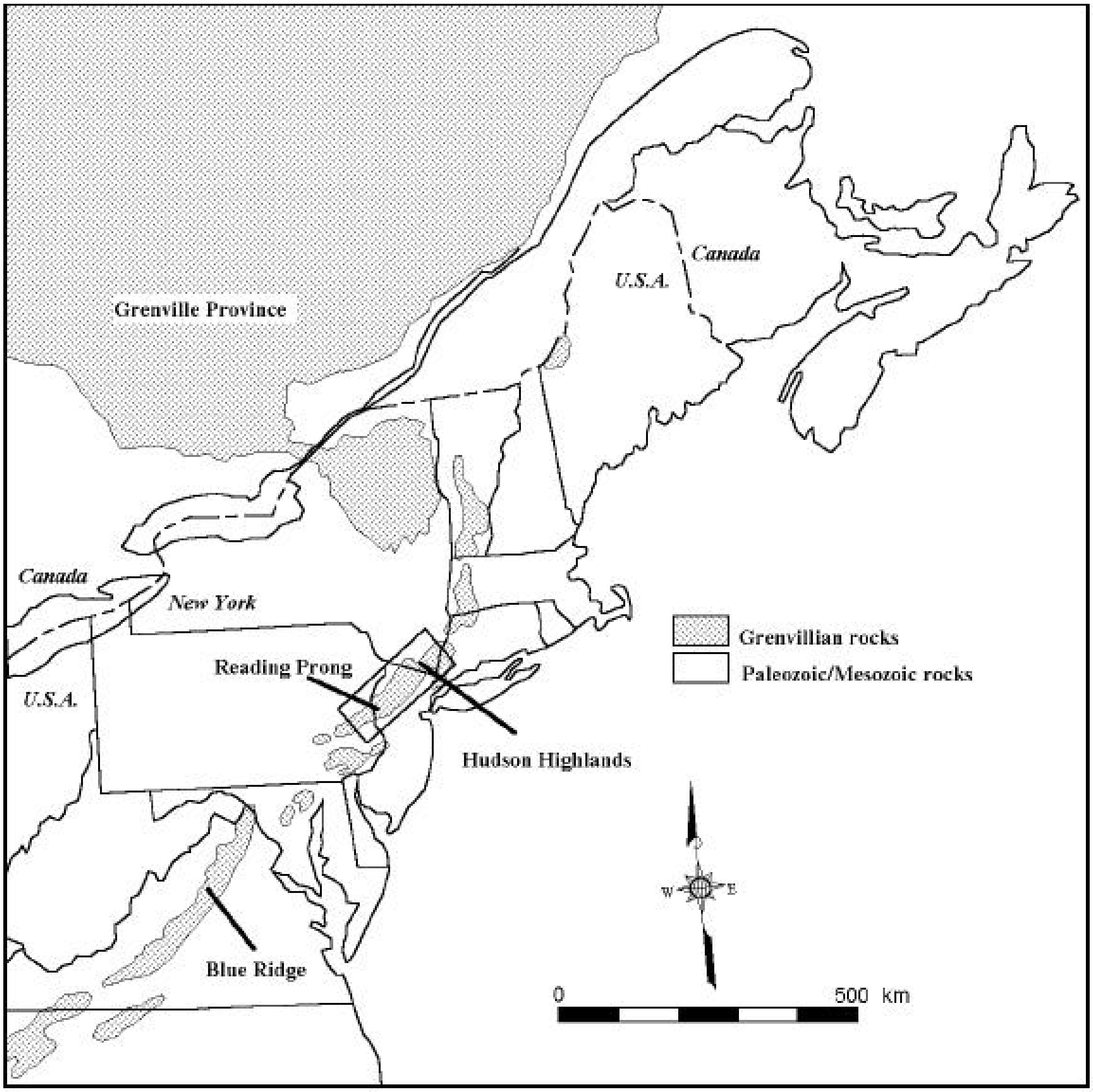

Figure 1. Regional map of eastern United States and Canada showing the geographic distribution of Grenville rocks. The area of Figure 2 is outlined by a rectangle.

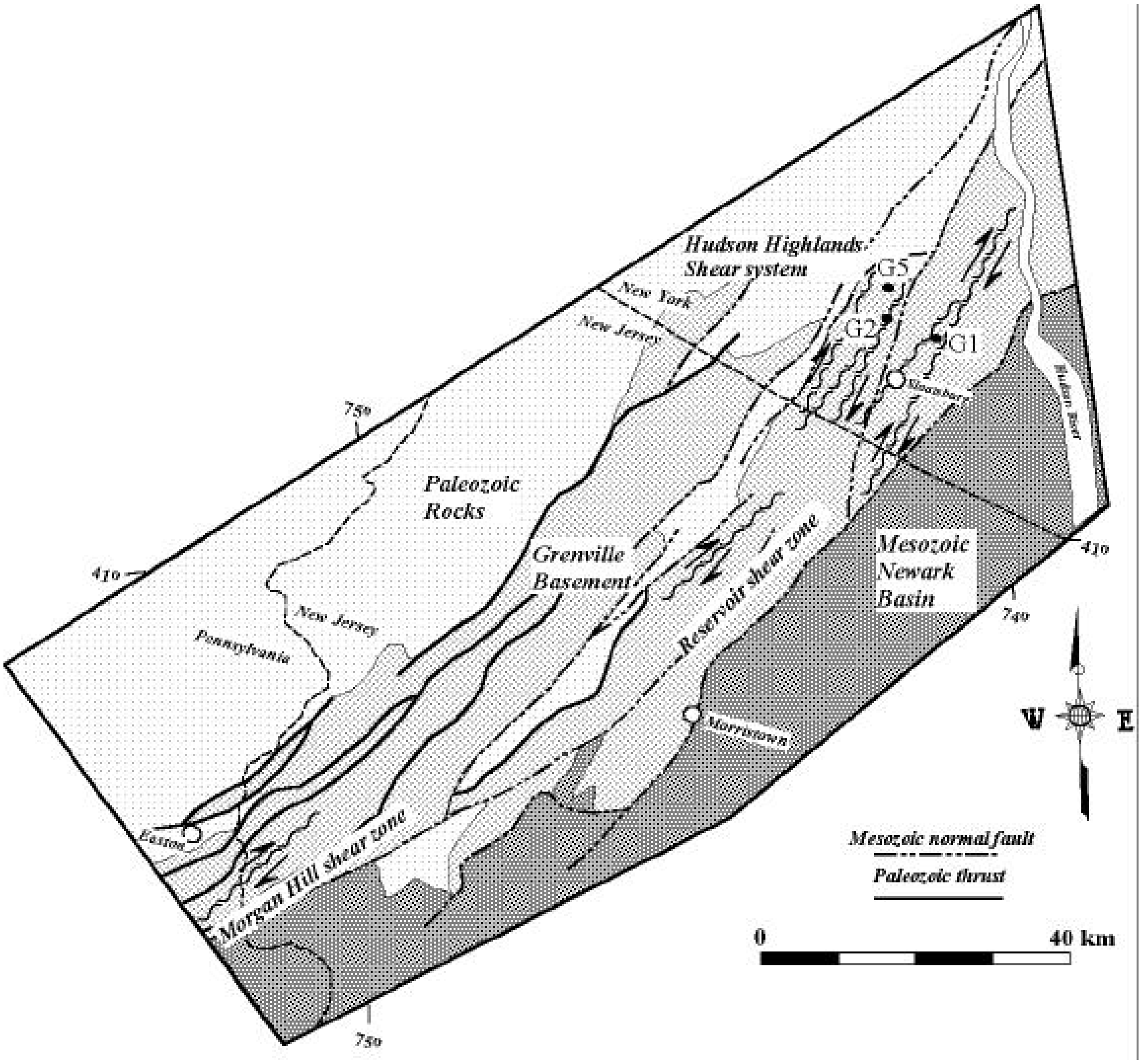

Figure 2. General geologic map of the Reading Prong and Hudson Highlands. The study area, in southern New York State, is outlined.

The thermal and deformational peak in the Hudson Highlands and the entire Reading Prong occurred around 1,150-1,050 Ma (Silver, 1969; Ratcliffe *et al.*, 1972; Mose, 1982; Weiner *et al.*, 1984; Drake, 1984).

Gates (1995) and Gates and Costa (1999) proposed a major late Grenvillian dextral strike-slip shearing event in the Reading Prong. This shearing was constrained to discrete faults, such as the Ramapo and Reservoir Faults (Figure 2), which were active well after peak Grenville tectonism and to much lower temperatures. A Middle Proterozoic escape tectonic (Tapponnier *et al.*, 1982) event in the central Appalachians resulting from accretion to the north is interpreted to have produced this deformation.

Stratigraphy

This field trip area is located in parts of the Sloatsburg, Thiells, Monroe, and Popolopen Lake quadrangles west of the Hudson River within the central Hudson Highlands, NY (Gates et al., 2001) (Figures 2 and 3). Previous mapping in this area, subdivided the rock units by rock types down to the varietal mafic mineral (Dodd, 1965; Dallmeyer, 1974). Considering that about 80% of the rocks are quartz-feldspar gneisses, this system is useful for geologic maps but not for purposes of tectonic reconstructions. It is also rather confusing with the vast number of rock types using this system. Gundersen (1986) suggested that lithologic and stratigraphic associations and sequences should be grouped as units in a kind of sequence stratigraphy for metamorphic rocks. This system of grouping lithologies is adopted for this field guide.

Metasedimentary Lithofacies

Throughout the western Hudson Higlands there are belts of rock considered to have sedimentary protoliths including pelitic-, psammitic-, calcsilicate-gneisses, quartzite and marble. Belts of rock up to two kilometers wide may contain all or some of these lithologies interlayered at the scale of meters to 100's of meters. These rocks have been included in the metasedimentary lithofacies (Figure 3). The metapelite consists of interlayered biotite-garnet gneiss with medium to coarse quartz, plagioclase, K-spar and local sillimanite, and cordierite with quartzofeldspathic layers. Within the metapelite are zones of graphite-pyrite-garnet gneiss with biotite, quartz, K-spar, plagioclase, and sillimanite locally. Quartzite layers of 10-50cm thickness also occur within this unit as do rare and discontinuous layers of diopside and diopside-garnet marble to calcsilicate of 10 cm to 2 m thickness. The calc-silicate is quartzofeldspathic with salite, apatite, sphene, scapolite, and hornblende. It is commonly migmatitic with white quartz-K-spar leucosome. There is also a rare quartz-garnet granofels. Common intrafolial pegmatites exhibit rootless isoclinal folding. The contacts with the quartzofeldspathic gneiss and rocks of the metavolcanic lithofacies are commonly gradational.

Metavolcanic Lithofacies

Sequences of strongly banded interlayered gneisses with mafic, intermediate and felsic compositions are interpreted to represent rocks with volcanic protoliths. The mafic gneiss domains are medium to coarse grained with aligned hornblende, plagioclase, clinopyroxene and hypersthene and local concentrations of magnetite. The intermediate and felsic gneiss bands contain medium to coarse-grained plagioclase, quartz, and minor hornblende, biotite, clinopyroxene and hypersthene. Banding ranges in thickness from 5 cm to 5m with varying proportions of each rock type. There are local interlayers of quartzite and calcsilicate gneiss. The contacts with the quartzofeldspathic gneiss and rocks of the metasedimentary lithofacies are gradational. Migmatites occur locally in this lithofacies (Figure 3).

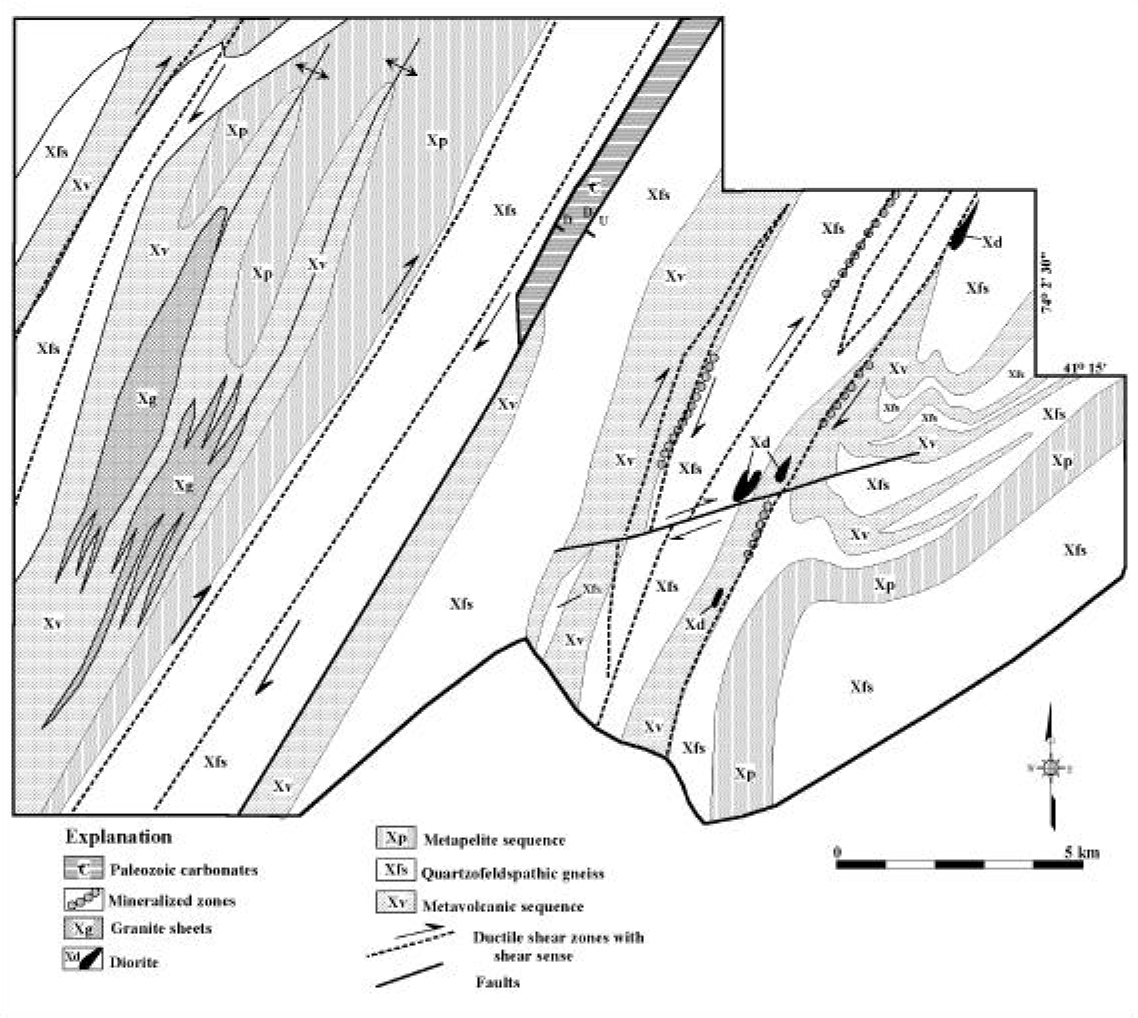

Figure 3. Geologic map of the area of Harriman State Park and Sterling State Forest (from Gates et al, 2001).

Quartzofeldspathic Gneiss

The quartzofeldspathic gneiss ranges from massive to layered quartz-plagioclase gneiss and quartz-k-feldspar-plagioclase gneiss with minor amounts of clinopyroxene, hypersthene, hornblende and/or biotite depending upon the layer. Locally, this unit contains magnetite or garnet in trace amounts. Compositional layering is defined by the proportion and type of the mafic mineral component. Locally, this unit contains apparent fining upward sequences by an increase in the amount of mica and decrease in layer spacing with sharp contacts between sequences. However, such relict sequences in granulite terranes are difficult to interpret. It is locally interlayered with quartzite and with mafic gneiss at the contact with the metavolcanic lithofacies. The gradational contacts with the metavocanic and metasedimentary lithofacies,and the internal compositional layering suggests the quartzofeldspathic units represent a volcaniclastic sequence. However, the occurrence of relict plagioclase grains in the main body west of the New York State Thruway suggests an intrusive origin for some of the rocks (Figure 3).

Granite Sheets

A series of granite sheets intruded rocks of the metavolanic and metasedimentary lithoficies and the quartzofeldspathic gneiss. The sheets range in thickness from 5 to 200 m and are laterally continuous for several kilometers. The granite is typically medium to coarse grained, locally megacrystaic, and generally lacking in foliation. However, locally granite sheets are foliated where intersected by later ductile shear zones. The granite sheets are leucocratic with K-spar, quartz, plagioclase, minor biotite, apatite, and titanite. The texture is equigranular with subhedral to anhedral interlocking grains, and locally they contain xenoliths of country rock. Where the granite sheets are mylonitic, the contact with the quartzofeldspathic gneiss is difficult to determine.

East of the New York Thruway there are isolated occurrences of granite sheets. One of the more famous outcrops at Claudia Smith's Den immediately east of the New York Thruway. In the central part of the Sterling Forest there are numerous granite sheets that strike northeast and dip moderately southeast (Figure 3). The sheet thickness varies considerably, however, the granite sheets in Sterling Forest extend from two tabular shaped bodies of granite. One is central to Hogback Mountain and the other is located in Bare and Tiger Mountains. These two bodies of granite and sheet appendages occur within parallel antiforms that can be traced from the Monroe quadrangle southward.

Diorite

Coarse- to very coarse-grained black and white speckled diorite occurs as dikes and small bodies throughout the field area. Because the bodies tend to be concentrated in certain zones, it is possible that larger bodies exist at depth. The diorite is composed of plagioclase, ortho- and clinopyroxene, hornblende, and biotite locally. Armoring of these mafic minerals reflects progressive crystallization through Bowens Reaction Series. The diorite grades to pyroxene-poor anorthositic compositions locally. Texture ranges from granoblastic to foliated and mylonitic with S-C fabric. The diorite locally contains xenoliths of country rock with ductile contacts that are partially melted to form a rind of coarse to pegmatitic granite around them and filling fractures in the diorite that opened after it crystallized but while the granite was still liquid (Figure 3). The softened and partially melted xenoliths indicate that the diorite was deeply emplaced.

Pegmatite Dikes

There are two generations of pegmatite dikes. Early dikes are white and contain K-spar, quartz, muscovite, and garnet locally. They are largely parallel to subparallel gneissic foliation (concordant), commonly boudinaged, and contain internal foliation and deformed grains. Thickness ranges from 10cm to 1m. Many are associated with granite sheets. The late dikes are pink, and very coarse grained with K-spar, quartz, and locally muscovite, hornblende, magnetite, pyroxene, titanite, and/or garnet depending upon the rock intruded. They are highly discordant, commonly within brittle faults, and contain xenoliths of fault rocks. They exhibit minor to no deformational fabric. Thickness ranges from 1m to 10m. They are locally associated with small granite bodies.

Mineralized Zones

Late stage concordant to slightly discordant brittle fracture zones occur within several of the late mylonite zones and are mineralized. They contain skarn of randomly oriented, coarse to megacrystic intergrowths of scapolite, salite and phlogopite followed by magnetite and cemented by calcite in areas of marble. Other zones contain hornblende and clinopyroxene followed by magnetite that are cemented with massive quartz. Zones that connect the magnetite deposits are thinner and typically composed of randomly oriented to aligned clinopyroxene with only minor magnetite, phlogopite and/or quartz. The zones are commonly intruded by late pegmatite dikes that contain mineralized rock as xenoliths. Thicknesses of the zones range from 2m to 15m.

Deformation

There are at least two major Precambrian deformational events recorded in the crystalline rocks of the western Hudson Highlands (Gates et al., 2001). The structural features produced during these events are described and placed in the context of the metamorphic evolution.

First Deformation Event

The first identifiable deformational event is regional in extent, penetrative and found in most rock units. A pervasive gneissosity formed during this event in every unit except the diorite and granite sheets which are younger. This gneissosity is defined by virtually all minerals but especially by platy and elongate minerals. Biotite, amphibole, sillimanite, and pyroxene are aligned in the strongly foliated quartz-feldspar matrix. Additionally, aggregates of quartz and feldspar define layering in some lithologies. Pegmatites are commonly parallel to subparallel to the gneissosity and exhibit well developed pinch and swell structures. These pinch and swell pegmatites are locally asymmetric indicating a component of simple shear in their formation. Amphibole and pyroxene clots show similar rotation textures forming δ porphyroclasts (Passchier and Simpson, 1986). Some pelitic rocks contain garnet-fish structures, and locally, some rocks contain intrafolial asymmetric isoclinal folds 5 to 20 cm thick though larger map scale folds may also exist.

Mesoscopic and megascopic folds produced during this event are recumbent to shallowly reclined. They are tight to isoclinal and commonly asymmetric with the lower limbs sheared out. This asymmetry consistently indicates northwestward transport and emplacement of fold nappes. The weak and sparse kinematic indicators described above support this shear sense. Thinner layers in these folds contain mesoscopic parasitic folds that are especially well developed on the upper limb. The occurrences of the granite sheets is in the hinge region of two of the map-scale isoclinal folds. Undeformed diorite contains xenoliths of deformed gneiss constraining the age of the first deformational event to pre-diorite intrusion.

Second Deformation Event

The second deformational event is characterized by a $\geq$ 35 km-wide band of anastomosing shear zones across the area (Figures 2 and 3). These shear zones overprint the features of the first deformational event. The shear zones strike northeast and are vertical or steeply northwest to southeast dipping. They range from 0.5 to 2 km in thickness though the boundaries are diffuse and difficult to determine in some areas. The shear zones are marked by well-developed type II S-C mylonite (Lister and Snoke, 1986) with shallowly northeast plunging mineral lineations. The dominant lithology within the mylonite is quartzofeldspathic gneiss but some rocks of the metavolcanic and metasedimentary lithofacies are also sheared. Diorite also locally forms S-C mylonite constraining the time of emplacement to pre-kinematic with regard to this event. Kinematic indicators within the mylonite include S-C fabric, rotated porphyroclasts, shear bands, asymmetric boudins and flattened asymmetric intrafolial folds. There are well-developed mesoscopic sheath folds with shallow northeast plunge, and megascopic drag folds adjacent to the main shear zone around Little Long Pond and Lake Tiorati respectively. All kinematic indicators show a consistent dextral strike-slip sense of shear. Minerals within the sheared rocks include amphibole and biotite as well as quartz and feldspar, all of which show plastic deformation but with full recovery. By texture and mechanical response of the minerals (Simpson, 1985), metamorphic conditions must have been upper amphibolite to granulite facies.

Late in the movement history, the shear zones became dilational. One to 6 km long mineralized veins occur along the shear zones (Figure 2). The veins parallel the zones but clearly cut the mylonitic foliation with ragged to planar contacts. The veins were progressively filled with salite and scapolite locally followed by magnetite as described previously.

Mesoscopic gentle to open upright folds also occur adjacent to the shear zones locally. These folds plunge gently from due north to north-northeast. The folds occur in well-layered metavolcanic sequences and within 150 m of the shear zone boundary. They locally appear en echelon.

A pervasive steeply northwest-dipping crenulation cleavage occurs throughout the area. It is best developed in the metapelitic and thin layered metavolcanic units. Intersection lineations with the gneissic foliation produced in the early event are generally parallel to the stretching lineations in the mylonite.

Geo-Thermochronology

Ar/Ar thermochronology

Ar/Ar thermochronology was performed on hornblende and biotite samples from the area around the Hogencamp mine (Gates and Krol, 1998). Samples were collected along the southeastern margin of a major dextral strike-slip shear zone. Mineral separates were prepared and analyzed at the Ar/Ar thermochronology lab at Massachusetts Institute of Technology using standard incremental heating procedures. All uncertainties in the ages are quoted at the 1 sigma-level and include the error associated with the J-value.

Hornblende from the gangue minerals in the Hogencamp mine HSP-2A and HSP-2B yield ages of 914 ± 3.6 Ma and 922 ± 3.4 Ma respectively. Hornblende from an undeformed granitic pegmatite that intruded mineralized vein material yielded an age of 923 ± 2.8 Ma. Biotite from the gangue minerals (HSP-2A) yields an age of 840 ± 5.0 Ma whereas biotite from the pegmatite yielded 794 ± 3.0 Ma.

The closure temperature for argon diffusion in hornblende is 500 - 550° C depending upon the cooling rate. The ages obtained for hornblende from the pegmatite and the veins may represent either the initial emplacement and crystallization or cooling ages. The relations among the rocks and their ages presents a complex picture. The source of fluids for mineralization may have been related to the pegmatite magmatism. However, the pegmatites may have been emplaced when the regional metamorphic temperatures still exceeded to closure temperature for hornblende.

The Reservoir fault, a related dextral strike-slip shear zone, was active until 876 ± 5 Ma (Gates and Krol, 1998). Therefore, the fault could have been active after pegmatite intrusion and the 914 Ma age is explainable as crystallization or deformation. In some areas, the vein rock is sheared.

The closure temperature for biotite is about 300 ° C. Therefore, cooling through 200-250 ° C took at least 74 Ma and up to 134 Ma. This duration for a small change in temperature represents very slow cooling on the order of 1.5-3.5° C/m.y. Slow cooling rates suggest that the interval between 920 and 786 Ma does not represent a major period of crustal thickening but instead there was slow unroofing and lateral movement.

U-Pb Geochronology

Zircons from three samples of gneiss from the field area analyzed at the SHRIMP lab at the Geological Survey of Canada to obtain U-Pb ages (Gates et al. 2001, 2003). Sample G-5 is from a semi-pelitic gneiss layer within the metasedimentary lithofacies, sample G-2 is from the quartzofeldspathic gneiss body located west of the New York Thruway, and sample G-1 was collected from a small diorite body (Lake Tiorati Diorite). All uncertainties in the ages are quoted at the 1 sigma-level.

The zircons from the semi-pelitic gneiss are strongly zoned with distinct cores and rims (Figure 4a). We interpret the cores of these zircons to be detrital in origin whereas the clear rims are probably associated with high-grade metamorphism. Analyses from zircon cores and rims are shown on Figures 5a and 5b. Zircon cores yielded a range of ages from 1200 to 2000 Ma, whereas the rims yielded ages from 1000 to 1030 Ma with the bulk of the ages centered on 1020 Ma.

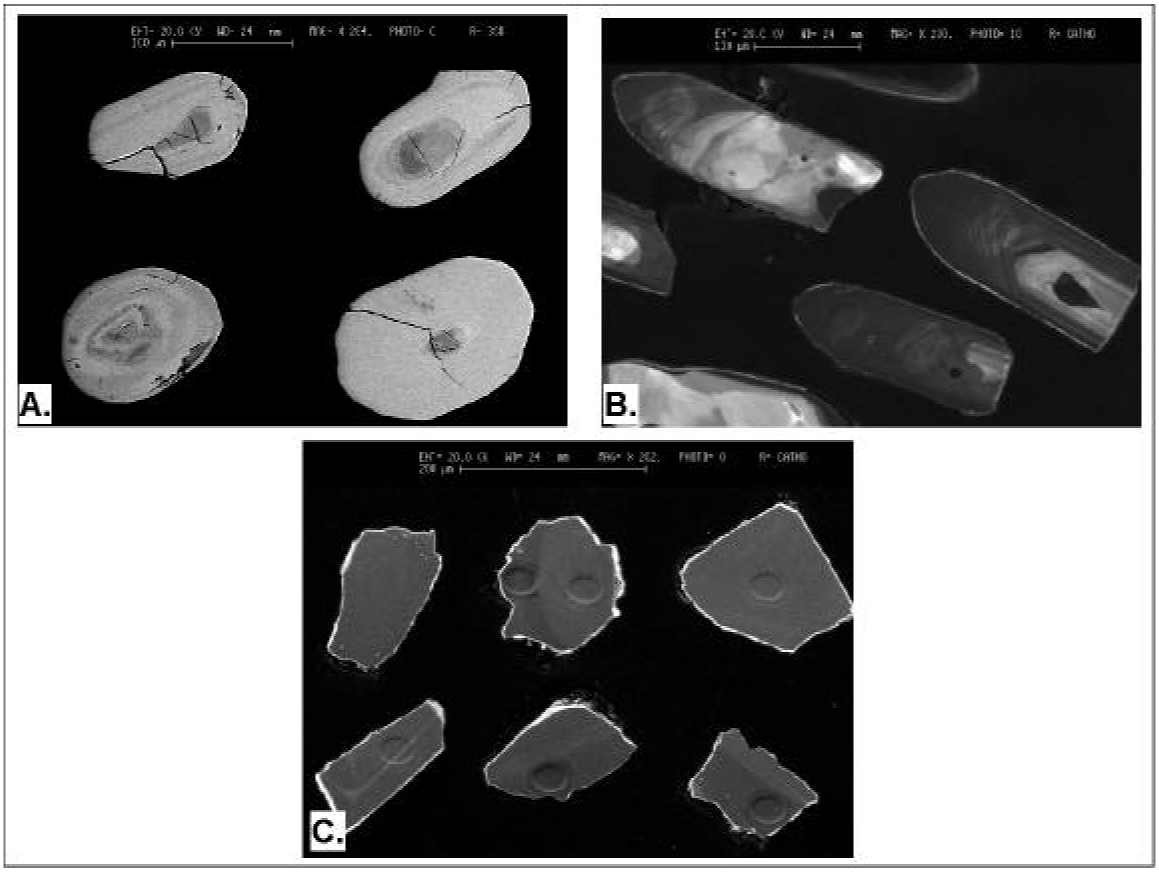

Figure 4. Representative cathodoluminescence images of zircons that were analyzed using the SHRIMP. A. Zircons from metasedimentary rocks showing complexly zoned cores and metamorphic overgrowths. B. Zircons from metavolcanic rocks showing igneous cores and metamorphic overgrowths. C. Zircons from diorite with no zonation.

The quartzofeldspatic gneiss contains zircons with rhythmically zoned cores and clear rims (Figure 4b). Analyses of the cores and rims produced two clusters of concordant ages (Figure 5c). The cores range from 1160 to 1220 Ma, and the rims exhibit a range of ages from 1000 to 1080 Ma. We interpret the zoned cores and associated ages to represent the original igneous history of this rock, and the rims to represent the regional metamorphic overprint.

The Lake Tioroti diorite body contain small subhedral zircons with minimal zoning to no zoning (Figure 4c). Analyses of these zircons yield a cluster of concordant ages averaging 1008 +/- 4 Ma (Figure 5d). Because this pluton is partially deformed in a dextral strike-slip shear zone, this age provides an upper limit to the local strike-slip event.

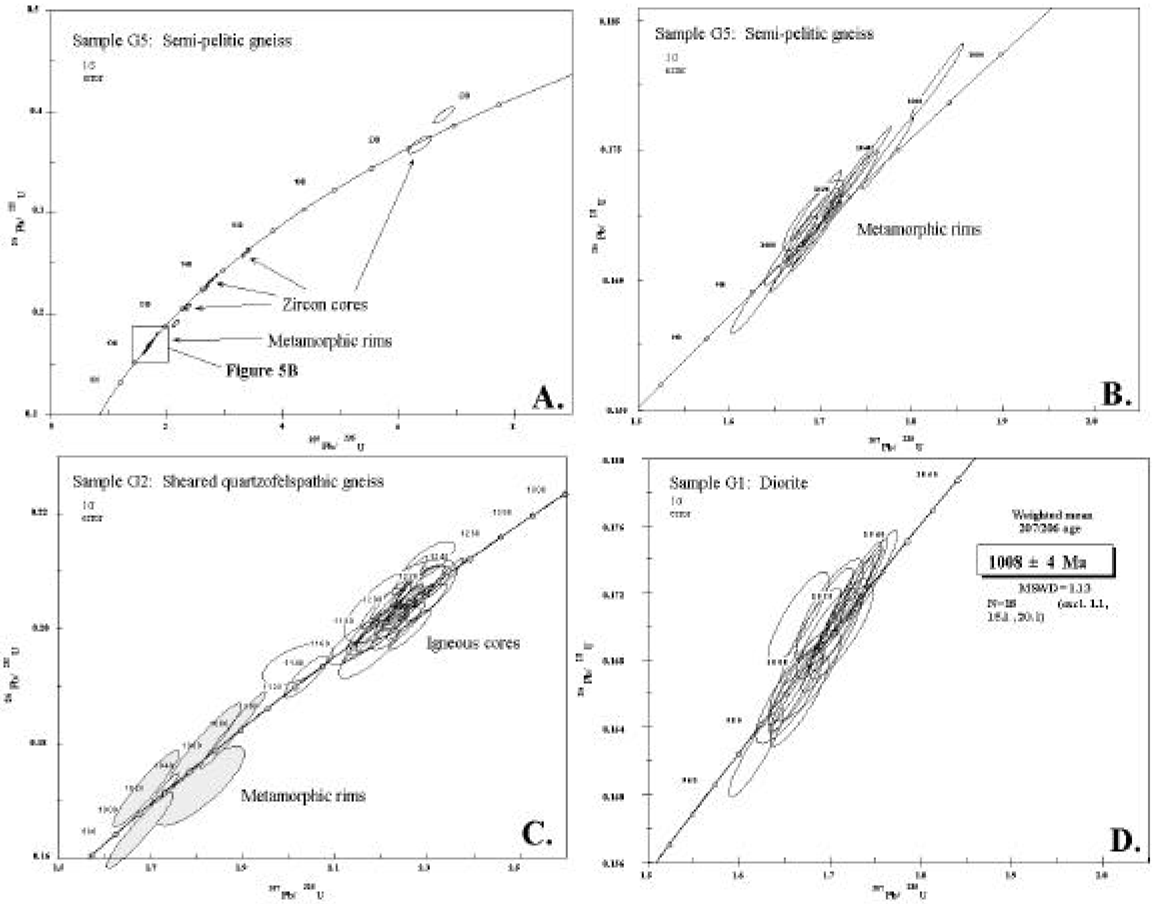

Figure 5. Concordia plots for SHRIMP analyses completed on zircons from Hudson Highlands rocks. A. and B. from semi-pelitic gneiss (B is a detailed view of A); C. from sheared quartzofeldspathic gneiss; and D. Lake Tioroti diorite body.

Geochemistry

Recent geochemical, structural, and geochronological investigations in the southwestern Hudson Highlands, NY has identified at least four discrete tectonomagmatic events (Gates et al., 2001). The earliest igneous events are represented by a sequence of metavolcanic (mafic and intermediate, quartz-plagioclase gneisses) and quartzofeldspathic gneisses (meta-plutonic and/or metavolcanoclastic). The metavolcanic unit consists of interlayered mafic (amphibolites) and intermediate to felsic (quartz-plagioclase) gneisses that are variably HFSE-depleted and LREE-enriched and are interpreted to have erupted in volcanic arc and back-arc setting. The second event (examples of which will not be displayed on this trip) is represented by metaplutonic, hornblende granite with A-type chemistry that is correlated with the Byram Intrusive Suite (~1095 Ma, Drake et al., 1991; ~1100 Ma, Volkert et al., 2000). The third magmatic event generated a suite of syn- to late-orogenic alaskite sheets (granite sheets on Figure 3) that have syn-COLG granite signatures and depleted HREE contents indicative of deep crustal melting in a thickened crust. The fourth magmatic event in this region is represented by the diorite plutons. These rocks have strong depletions in HFSE and high HREE and Y contents indicating shallow partial melting (<65 km) of asthenospheric or arc-modified lithospheric mantle with subsequent crustal contamination.

Metavolcanic lithofacies and the quartzofeldspathic gneiss

Mafic gneisses have major and trace element compositions broadly similar to tholeiitic to calc-alkaline basalts and thus, support a mafic volcanic protolith for these rocks. This is illustrated on a classification diagram based on High Field Strength Elements (HFSE), where mafic gneisses plot within and overlap the fields for tholeiitic and calc-alkaline basalts (Figure 6A). Rare Earth Element (REE) patterns are quite variable (Figure 6B); however, most samples have slightly LREE-enriched (La/Yb_N = 1.5 to 2) to almost MORB-like, LREE-depleted (La/Yb_N = 0.8) patterns with minor negative Eu anomalies (Eu/Eu* = 0.9 to 1.0) (Figure 7). Sample LT-5 is an exception with a distinct LREE-enriched pattern (La/Yb_N = 10) with a significant negative Eu anomaly (Eu/Eu* = 0.7). The lack of strong LREE/HREE fractionation and relatively high concentrations of HREE (~8-12x chondrite) in all samples indicates melt generation occurred at relatively shallow mantle depths above stability field of garnet peridotite (e.g. <60 km depth). These rocks also show variable HFSE depletions and on tectonic discrimination diagrams they consistently plot in overlapping fields defined by volcanic arc basalts and/or MORB (Figures 6C-D). Based on this data, we interpret these rocks to have erupted in an oceanic island arc/ back-arc setting or perhaps a continental arc built on attenuated crust. Mafic gneisses of similar chemistry have also been reported in the Central Metasedimentary Belt of the Grenville Province in SE Ontario (Tudor Volcanics, Turriff Volcanics, and Belmont Lake Volcanics; Smith and Holm, 1990; Harnois and Moore, 1991; Smith et al., 1996) and have similar tectonic interpretations.

Geochemical data for intermediate and felsic gneisses are also supportive of a volcanic protolith for this unit. Based on major elements, these rocks are most similar to calc-alkaline, low-K rhyodacites. Mineralogically, these rocks are tonalites (Figure 6A). They have moderately LREE-enriched patterns (La/Yb_N = 5 to 7) with relatively small negative Eu anomaly (Eu/Eu* = 0.7 to 0.9) for rocks of this silica content (68 to 70%) (Figure 6E). Similar to the mafic gneisses of this unit, intermediate and felsic gneisses lack strong LREE/HREE fractionation and have relatively high HREE abundances (8-10x chondrite) indicating crustal melting in the absence of residual garnet in crustal source rocks. HFSE depletion in these rocks is variable, but overall most samples have strong depletions in Nb, Ta, P, Hf, and Ti that are characteristic of calc-alkaline, volcanic arc rocks. They are mineralogically and chemically very similar to other tonalitic to trondhjemitic gneisses found in the New Jersey Highlands (Losee Metamorphic Suite; Volkert and Drake, 1999). Similar rocks also occur in the Green Mountains, VT (Mount Holly Complex; Ratcliffe et al., 1991) and in the Adirondacks (McLelland and Chiarenzelli, 1990) that have U-Pb zircon ages between 1300 and 1350 Ma. The data on these rocks are consistent with the interlayered mafic gneisses and again, suggest an island arc and/or continental arc on attenuated crust tectonic setting.

Lake Tioroti diorite

Major element chemistry of coarse-grained, relatively undeformed samples of the Lake Tiorati Diorite indicate they are uniformly mafic plutonic rocks that have moderate to strong calc-alkaline geochemical signatures (Figure 6A). REE patterns of most samples are weak to moderately LREE-enriched (La/Yb_N = 1.5 to 5) and have slightly concave upward or "dished", MREE-depleted patterns (Figure 6F). They also have variable negative Eu anomalies (Eu/Eu* = 0.6 to 1.0). The mafic, calc-alkaline composition, relative strong negative Eu anomalies and slight MREE depletions in some samples suggests that significant plagioclase ± hornblende crystallization was important in the petrogenesis of these rocks before final emplacement. The lack of strong HREE and Y depletions relative to other trace elements indicates mantle melting occurred at relatively shallow depths above the garnet stability field (e.g. <65 km). All samples have very strong HFSE depletions and on plot well within volcanic arc fields on tectonic discrimination diagrams characteristic of calc-alkaline rocks associated with subduction zones (Figures 6C-D). These rocks were emplaced synchronously with a major right-lateral, ductile shearing event and thus, the strong calc-alkaline, arc-like signatures are somewhat enigmatic. We interpret the arc signature in these rocks to have been inherited from lithospheric mantle sources that had been metasomatized by prior subduction events and/or extensive crustal contamination during emplacement in the crust.

Quartzofeldspathic gneiss

The protolith for the quartzofeldspathic gneiss is somewhat controversial. At least parts of this unit have good textural and field evidence for being meta-plutonic rocks (e.g., feldspar augen; mafic gneiss xenoliths), whereas other parts are layered and interpreted as metamorphosed metavolcanoclastics. It is likely, that this unit contains rocks of both intrusive and volcaniclastic origin. Mineralogically and chemically, the quartzofeldspathic gneisses can be characterized as K_2O-rich, metaluminous (ASI ~ 0.9) hornblende-biotite granites (Figure 7A). They have distinctly A-type granite chemical characteristics defined by high K_2O/Na_2O (~2), Ba/Sr (~6), Fe/(Fe+Mg) (~0.90), total REE (~500-600 ppm), Ba (~500 ppm), Zr (400-500 ppm), Nb (20-30 ppm), Y (100-150 ppm), and low Sr, (~100 ppm), MgO (<0.5%), CaO (<2%), Cr and Ni (<5 ppm). On tectonic discrimination diagrams, they form tight clusters well within the within-plate granite (WPG) field (Figures 7E-F). REE patterns are LREE-enriched (La/Yb_N = 10), but flat through the MREE and HREE, and with strong negative Eu anomalies (Eu/Eu* ~0.30) (Figure 7B). Total REE content is very high with LREE at ~300x chondrite and HREE at ~30-40x chondrite. The lack of strong HREE depletion relative to LREE and the strong negative Eu anomalies are consistent with melting of plagioclase-bearing, garnet-free, mafic source rocks. These rocks are strikingly similar (essentially identical) in terms of mineralogy and chemistry to less deformed, A-type hornblende granites and granitic gneisses exposed 5-10 km to the west in the Greenwood Lake Quadrangle (Sonzogni et al., 2001), to the Byram Granite of the northern NJ Highlands (Volkert et al. 2000), and to the Storm King Granite in the northeastern Hudson Highlands (Rankin et al., 1993). These rocks are also chemically similar to mildy A-type granite gneisses of the AMCG and Hawkeye suites of the Adirondacks (McLelland and Whitney, 1986). The A-type affinity and similarity to AMCG suites suggests a similar origin by shallow crustal heating during syn- and post-Elzevirian lithospheric delamination and orogenic collapse.

Granite sheets

The granite sheets are high SiO_2 (~75%), leucocratic, hornblende-bearing granitoids with <5% modal mafic minerals (Figure 7A). They are metaluminous to slightly peraluminous (ASI = 0.95 to 1.1) and have highly variable K_2O/Na_2O (0.3 to 3.3) reflecting variability in the modal abundance of K-feldspar and/or Na-plagioclase as the dominant feldspar. Trace element chemistry of these rocks are distinctive from the granitic gneisses of the quartzofeldspathic unit in that the have overall much lower concentrations of most trace elements (e.g., total REE = 25-100; Y = 2-30 ppm; Zr = <125 ppm; Nb <3 ppm). This difference is also reflected on REE diagrams (Figures 7C-D) and tectonic discrimination diagrams, where the granite sheets plot scattered along the boundary between fields for syn-collisional (syn-COLG) and volcanic arc (VAG) granitoids (Figures 7E-F). These rocks are divided into two chemically distinct groups based on REE patterns. The first group has higher concentrations of total REE's, modest negative Eu anomalies (Eu/Eu* = 0.35 to 1) and either LREE enriched patterns or concave upward, "dished" MREE-depleted patterns (Figure 7C). The second group is defined by very low total REE's, strong LREE enrichment, depleted and flat MREE to HREE, and extreme positive Eu anomalies (Eu/Eu* up to 3.5) (Figure 7D). The sheets exposed at Stop 6 are of the latter type and are best interpreted as partial melts of plagioclase-free source rocks with abundant residual amphibole ± garnet coupled with fractional crystallization of quartz + feldspars ± trace element-rich accessory phases (e.g., zircon, apatite, monazite, allanite). The garnet-bearing, plagioclase-free source mineralogy implies melt generation probably occurred at deep crustal levels. In comparison, granite sheets with distinctly "dished" REE patterns clearly were generated by partial melting of garnet-free source rocks and hence melt generation probably occurred at shallower crustal levels. These two groups of granite sheets have similar field relations and appear to be part of the same magmatic event, thus crustal melting apparently occurred at various crustal levels. Based on these geochemical data, and on based on field and textural relations, we tentatively interpret these as a syn- to post-Ottawan (~1050 Ma) magmatic event related to a Himalayan-type continent-continent collision.

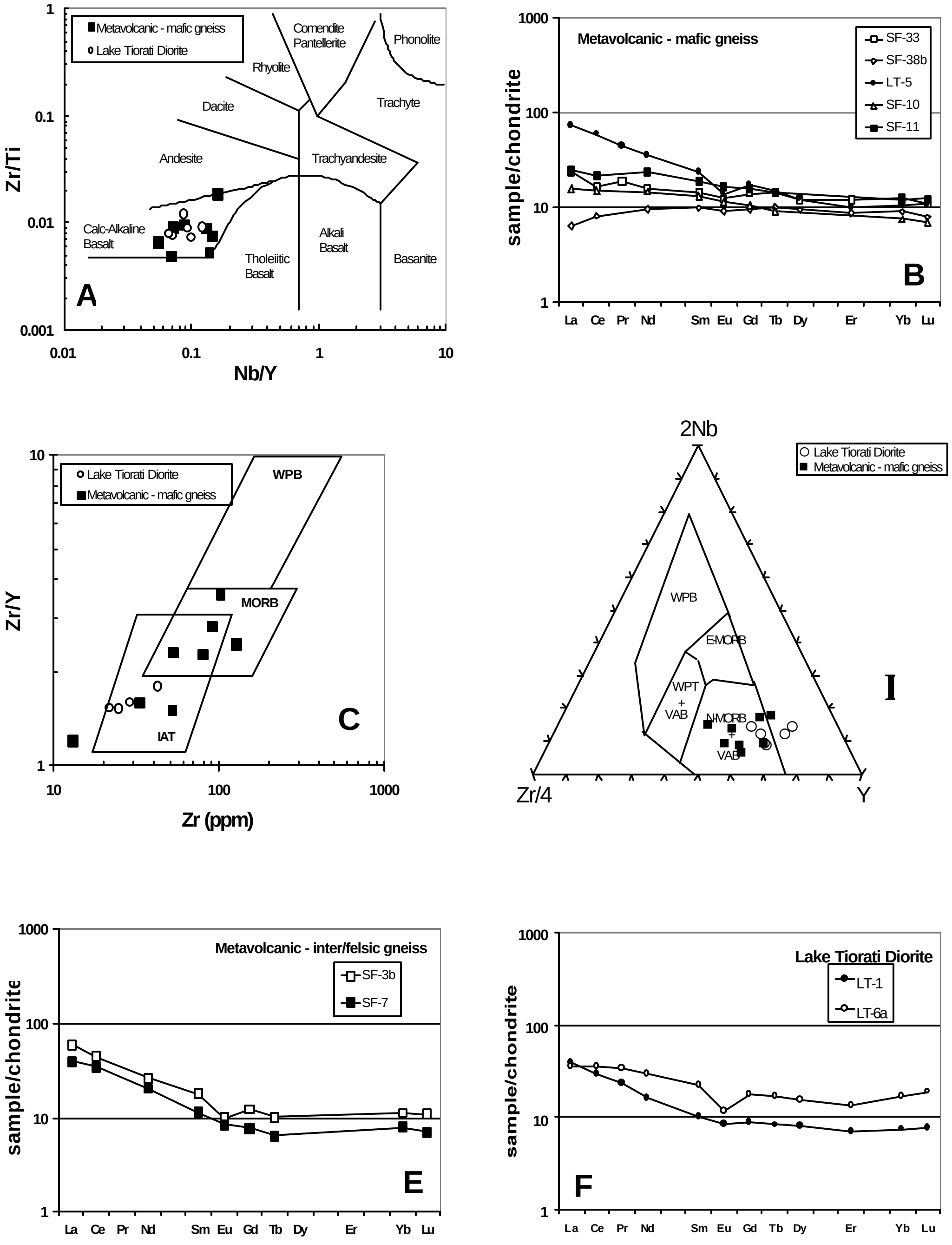

Figure 6 (A-F). Geochemical plots for amphibolites and quartz-plagioclase gneiss within the Metavolcanic Unit and diorite.

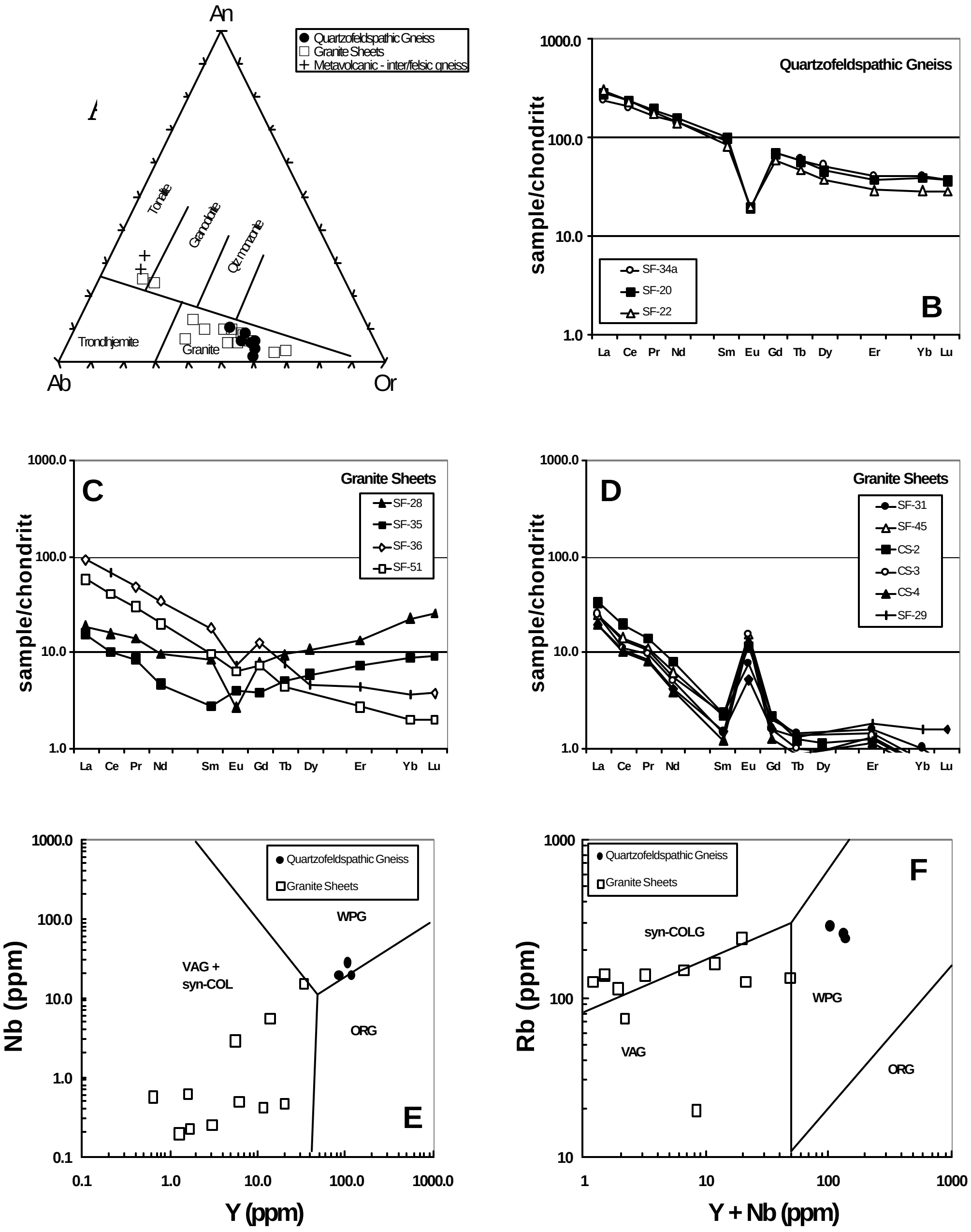

Figure 7 (A-F). Geochemical plots for the granitic gneisses within Quartzofeldspathic Unit and the Granite Sheets.

Tectonic History

A subduction zone developed in the current study area about 1.2 Ga. A volcanic pile was formed in an island arc or marine magmatic arc setting consisting of interlayered mafic and intermediate rocks as well as associated plutons (Gates et al., 2001). Submarine aprons of volcaniclastic material formed along the volcanic islands and were interlayered with the volcanic rocks. These units tapered away from the source. The coarse-grained volcaniclastic rocks varied in composition depending upon proximity to the volcanic source and the amount of volcanic material subject to erosion. The pelitic and calcareous rocks are in uncertain relation with the other units. By virtue of the abundance of graphite-sulfide rocks, they are interpreted to reflect a restricted and euxinic marine basin. Whether they formed during periods of volcanic dormancy, were synchronous but distant or represent a temporally separate sequence, is not clear. They are commonly interlayered with metamafic rocks. It is possible that they are back-arc basin deposits. Zircons from some of these sediments contain detrital cores with a variety of ages including possible Pinwarian (1.45 Ga) and trans-Amazonian (2.05 Ga) affinities.

The subduction sequence terminated in a collision between the volcanic or magmatic arc and another continent, likely proto-South America (Dalziel, 1991), about 1020 Ma. This collision is the Grenville orogeny (Ottawan phase) and was a Himalayan type event (Windley, 1985). It also produced severe deformation and heating of the rocks at temperatures in excess of 700^{o} C and pressures in excess of 6.5 kbars (Young and Cuthbertson, 1994). Anatexis occured locally producing the migmatites, granite sheets and the early pegmatite dikes that occur throughout the area. The intense orogenesis caused the rocks to become gneissic and produced the recumbent folds. These mesoscopic folds reflect large-scale fold nappes that were emplaced westward across the area.

Subsequent to the intense tectonism, there was intrusion of dioritic melts. Exposed in and around the study area, these bodies are dikes and small stocks. The diorite locally grades into anorthosite. SHRIMP U/Pb age determinations of zircons indicate that this event occurred at 1,008 ± 4 Ma. Geochemical data are consistent with this magmatic activity between the events having resulted from mantle delamination at the termination of the first event or the early dilational stages of the later strike-slip event.

The second event is characterized by dextral strike-slip movement during a period of rapid uplift and unroofing at approximately 1,008 Ma to 924 Ma in the study area (Gates and Krol, 1998). Thick zones of ductile deformation formed during this event and overprinted all previous features to varying degrees. Judging by the number and thickness of shear zones and the drag of some units into one of the zones, offset was significant (100s of kilometers). Late in their history, these faults were mineralized with magnetite and related minerals (uranium minerals, scapolite, pyroxene). Sheath folds within the fault and open upright folds adjacent to the fault are associated with this event. The entire area was intruded by granitic pegmatites as fault activity waned. The pegmatites are concentrated along the faults suggesting a genetic relationship. The early folds in contrast to the late dilation in the fault zones may indicate a transition from transpression to transtension during the event. A component of gravitational collapse is also possible. This second event could reflect another accretionary event but far to the north of the Hudson Highlands. A collision in the area of the Canadian Appalachians and Scandinavia may have generated tectonic escape (Tapponnier *et al.*, 1982; Burke and Sengor, 1986) of eastern Laurentia to the south along large dextral strike-slip faults that are well displayed in the Hudson Highlands (Gates, 1995). It could also just be tectonic escape as a second phase of the continental collision with proto South America similar to the scenario in the modern Himalayas. There, strike-slip overprints the contractional features produced at the onset of the collision.

Early and Middle Proterozoic were times of compressional tectonics on a global scale (Hoffman, 1988; Dalziel, 1991; Borg and DePaolo, 1994). As the Proterozoic supercontinent of Rodinia was built by the accretion of continental fragments, contractional orogens were built all along the margins and then nested into the interiors. Each accretion event reactivated adjacent old contractional zones of weakness as strike-slip faults. In this way, lithotectonic terranes escaped in directions away from the collision zones. Such extensive escape tectonism similarly occurred during the building of Pangea during the Late Paleozoic as well as in the Alpine-Zagros-Himalayan orogeny today (Burke and Sengor, 1986). If the strike-slip event in the Reading Prong-Hudson Highlands formed by tectonic escape, the locus of a major continental collision would have taken place somewhere to the present northeast of the study area. This collision would likely be the Ottawan event, a Himalayan-type collision (Windley, 1986). All terranes to the east of the dextral strike-slip faults therefore escaped to the south. A conjugate E-W striking left-lateral shear system appears to have formed synchronously in the Adirondacks of northern New York. We propose that these two systems may form a deep crustal syntaxis analogous to that which is observed in the Himalayan orogen (Gates et. al, 2001; 2003).

Conclusions

The Grenville event in the Hudson Highlands of the north-central Appalachians was formed in a four-fold tectonic scenario.

1) Deposition of volcanic, volcaniclastic sediment, and pelite-carbonate sediment within a subduction zone complex about 1.2 Ga.
2) Continental collision of the arc with another continent to the east during the building of the Rodinian supercontinent occured at about 1050-1020 Ma. Granulite facies metamorphism, extensive pegmatite intrusion, and westward directed fold nappe emplacement accompanied this event.
3) After orogenesis ceased, dioritic to anorthositic melts intruded the area, about 1,008 Ma. Their origin is unclear but an accompanying period of extension or mantle delamination would be consistent.
4) Strike-slip shearing resulting from tectonic escape probably lasted from 1,008 to 900 Ma or later. There was a rapid decrease in temperature during this event resulting in the shear zones crossing the brittle-ductile transition and becoming dilational. Extensive mineralization occured within these dilational fractures.

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FIELD LOG

STOP 1: Metapelites and Graphite-sulfide Gneiss

(7 Lakes Drive at Lake Sebago Dam)

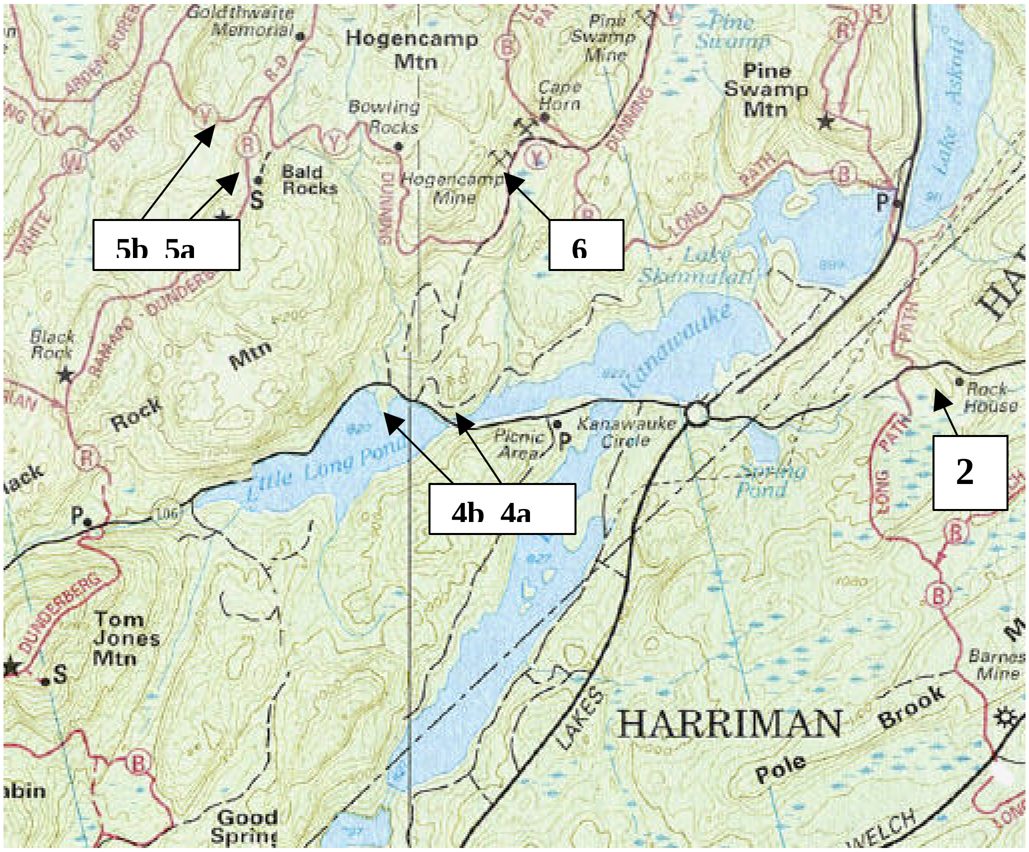
The rocks at this stop include sillimanite-garnet gneiss, cordierite-sillimanite gneiss, garnet-biotite gneiss, all of these are locally migmatitic, garnet-quartz granofels, graphite-pyrite or marcasite gneiss, and quartzofeldspathic gneiss. The sulfide bearing rocks weather to a red rust color on the surface. The deformation state ranges from somewhat randomly oriented grains to mylonitic. Late warping to gentle folding can be seen on the layer surfaces. They have shallowly northeast-plunging fold axes that parallel the mineral lineation.

These rocks are representative of the low energy deposits of the sequence. They are interpreted to have formed in a restricted marine basin that was likely euxinic and with a significant volcanic input. In other areas, these rocks can contain biotite gneiss with 55% garnets, thin marble lenses, and layers of pyroxene-plagioclase gneiss that are interpreted to be of volcanic origin.

STOP 2: Nappe-Stage Folds

Tight to locally isoclinal recumbent folds are displayed within biotite and hornblende quartzofeldspathic gneiss. The folds trend shallowly to the northeast and have a sheared out lower limb. Parasitic folds are common. The gneiss is interlayered and is dominated by biotite quartzofeldspathic gneiss which locally contains garnet. One outcrop shows a progressive change from biotite-poor to biotite-rich gneiss over a 2 m interval with an abrupt contact to biotite-poor quartzofeldspathic gneiss. There are local granitic veins which are also folded.

The rock is interpreted to be metamorphosed sedimentary to volcaniclastic rock that was deposited in a high energy environment. The hornblende-rich rock reflects volcanic input. The apparent fining upward sequence might reflect a prograding fan or delta or shifting channel sequence. The folds were generated during westward directed fold nappe emplacement. These recumbent folds are observed at all scales. They appear to accompany peak metamorphic conditions. This tectonic event is interpreted to have been a Himalayan type continental collision.



STOP 3: Diorite Intrusion

(7 Lakes Drive at Lake Tiorati, across from small rock island past Cedar Pond Camp and before PIPC camping office)

Pluton of coarse to very coarse-grained black and white speckled diorite. On the south side of the outcrop, the diorite is equigranular in texture with random grain orientation. It contains a roof pendant of well-foliated biotite quartzofeldspathic gneiss that exhibits crenulation cleavage. The xenolith contains drag folds along it's contact with the diorite. It also contains a rim of granitic pegmatite that connects to pegmatite and quartz veins within the diorite. The diorite contains plagioclase and hornblende and clinopyroxene but with brown cores of orthopyroxene. Other phases include magnetite and ilmenite. In the northern part of the exposure, the diorite is crossed my anastomosing mylonite bands. The mylonite strikes northeast and is near vertical. Lineations plunge shallowly to the northeast. Kinematic indicators include rotated porphyroclasts and S-C fabric. Where it can be determined, shear sense is consistently dextral.

Subsequent to the first tectonic event which included the nappe emplacement and granulite facies metamorphism, there was a period of intermediate plutonism. The xenolith was deformed and metamorphosed prior to intrusion. The xenolith became more ductile as a result of the heat of the pluton. Thus drag folds formed along its edges as it fell into the magma. The magma was hot enough to cause partial melting of the rim of the xenolith, producing a granitic melt. The diorite crystallized at higher temperature than the granitic melt. Fractures opened in the newly crystallized rock and the remaining granitic melt squeezed into them forming the veins. Later deformation produced the mylonitic fabric in the diorite. This outcrop is at the eastern edge of a large dextral strike-slip shear zone with similar orientation.

STOP 4a: Migmatitic Metavolcanics

Black and white, strongly interlayered mafic and intermediate gneiss with migmatitic veins. The mafic layers in the melanosome are composed of clinopyroxene, hornblende, plagioclase, magnetite, sphene and apatite. The intermediate layers are dominantly plagioclase with minor quartz, K-spar locally, apatite, hornblende and biotite. The leucosome is composed of coarse interlocking plagioclase, quartz, and K-spar and form net veins and clots. Minerals are aligned in the gneiss and granular in the leucosome.

The interlayered mafic-intermediate gneiss are interpreted as metavolcanics of island arc affinity. During the nappe emplacement event, metamorphism achieved granulite facies. Locally, the gneiss underwent anatexis and formed migmatite. Note that this rock still preserves the evidence of the first tectonic event with no overprinting. Contrast this rock with Stop 4b.

Across the Shear Zone Boundary

Sheared

Unsheared

STOP 4b: Tectonic Blocks

Lozenges of mafic gneiss contained within contorted layered biotite and hornblende quartzofeldspathic gneiss. The mafic gneiss is the same as in Stop 4a but it contains magnetite veins and contorted folds. The quartzofeldspathic gneiss is layered as defined by variations in biotite content and locally hornblende content. The layering is also contorted and wraps around the lozenges. The fold axes and long axes of the lozenges are parallel and plunge shallowly to the northeast.

Stops 4a and 4b are grouped together because the compositions are similar and interpreted to be part of the same sequence. There is a large dextral strike-slip shear zone to the northwest. This deformation postdates the nappe emplacement phase. The rocks in stop 4a are considered to have been unaffected or only mildly affected by this later deformation. Deformation progressively increases towards the northwest as tracked by the progressive increase in linear fabric and steepening of the foliation.

STOP 5a: Mylonite Zone and Folds

The rock is a quartzofeldspathic mylonitic gneiss with interlayers of biotite gneiss locally. The mylonite is well foliated and lineated and composed of plagioclase, quartz, K-spar, and biotite. The biotite gneiss is composed of biotite, quartz, plagioclase, magnetite, and hornblende locally. It is well foliated and commonly folded into open to tight shallowly northeast-plunging asymmetric folds. There are pegmatite dikes that are parallel to mylonitic foliation and which commonly displays pinch and swell. There are also late pegmatites that form in "gaps" in the mylonite.

Based upon kinematic indicators, the mylonite zone the zone appears dextral but with a significant component of pure shear. There is a macroscopic drag fold to the southeast side of the shear zone that is consistent with dextral strike slip shear with offset of at least 3-4 km.

STOP 5b: Transpressional Folds

Open upright, shallowly north to northeast-plunging folds in layered quartzofeldspathic and mafic gneiss. The amplitude of the folds range from 0.5 to 2 m and the wavelength is 2 to 8 m. These folds are only adjacent to the shear zones and only locally developed in layered rocks. The rocks are part of the metavolcanic sequence. They are dominated by mafic rocks.

The folds are interpreted as transpressional structures related to dextral shearing on the adjacent shear zone. They appear to have formed at the same point in the deformational sequence and under the same metamorphic conditions. Gentle to open folds plunge shallowly towards the north to north-northeast. Tighter folds are more northeast-trending. There appears to be rotation of the structures with tightening. These folds are restricted to a thin band adjacent to the shear zone both to the southeast and northwest. Some are en-echelon.

STOP 6: Hogencamp Mine

The Hogencamp mine was active in the 18th and 19th centuries. Magnetite was mined from the mineralized veins. The vein that hosts the Hogencamp deposit is about 6 km long and ranges in thickness from about 2 to 15 m. The wall rock is mylonitic and in this area, it is composed of quartzofeldspathic calcsilicate, amphibole-pyroxene gneiss (metavolcanic), and diopside marble. The contact of the vein with the wall rock is sharp and generally parallel to mylonitic foliation. On the small scale, however, it crosses foliation and generally the vein appears to eat into the wall rock. There is a bleached zone in the wall rock at the contact with the vein. In quartzofeldspathic rock, the bleached zone is marked by retrogression of feldspar to mica and pyroxene to amphibole. It also contains scapolite, calcite locally and apatite. The vein is composed of distinct compositional band characterized by mineral assemblages. Nearest the wall rock, there is pargasite, scapolite, K-spar, and phlogopitic biotite. The next zone in contains mainly biotite pargasite and salite. The next band is salite and pargasite. Minerals in interior zones are salite, magnetite, and calcite in that order. The salite and locally magnetite crystallized in cavities because they are euhedral and locally form doubly terminated crystals. The bulk composition of the salite and pargasite rich zones is identical to an ultramafic rock. These are metamorphically produced ultramafic rocks. The mineralized veins are intruded by very coarse grained pegmatites which locally contain xenoliths of vein material. Ar/Ar dating of the hornblende in these deposits yields 924 Ma.

The veins are interpreted to have formed in dilational joints and fractures during the waning stages of dextral strike-slip shearing. Metamorphic fluids flushed through these fractures and reacted with the wall rock. The fluids mobilized elements from the reactions with the wall rock. These reactions buffered the composition of the fluids. When these fluids encountered the right conditions either physically or chemically, they deposited the ore and gaunge minerals. With the banding of different assemblages and compositions reflects the changing chemistries of the fluids. These changes may reflect changes in flux, fluid source, or physical conditions. The pegmatites may have intruded along the same pathways as the fluids.

STOP 7a: Refolded Fold

(Town of Tuxedo, park at Ramapo River fisherman access and walk on road towards thruway, outcrop is about ¼ mile up the road)

Interlayered pyroxene amphibolite and biotite quartzofeldspathic gneiss forms a recumbent fold that is refolded about an upright shallowly northeast plunging fold. It also produces a type 3 refold. The rocks are strongly lineated. The lineations plunge shallowly towards the northeast. There is tectonic thinning of the mafic layer on the limbs of the recumbent fold.

These rocks are from the metavolcanic sequence. They exhibit evidence of both the first and second deformational events but are distal to the high strain zones of the second event. The refold geometry is reflective of the emerging macroscopic geometry of the area.

STOP 7b: Granite Sheet

(Claudius Smith den on PIPC or NY/NJ Trail Conference hiking map (near Tuxedo))

Concordant leucogranite sheet intruding interlayered biotite quartzofeldspathic gneiss and amphibole-pyroxene gneiss. The granite contains K-spar, quartz and plagioclase, with minor biotite and muscovite locally. It is foliated and exhibits interlocking subhedral to anhedral grains. The pluton is folded with roof rock forming shallowly northeast-plunging open folds. It contains screens of gneiss that are folded and xenoliths with faulted margins.

Granite sheets appear to have formed during the peak of the first event. Their texture suggests that they are minimum melts and are interpreted to have been locally derived. They are concordant to the gneissic foliation and appear to have been emplaced during peak metamorphic-deformational conditions. On the other hand, the presence of xenoliths with sharply truncated edges suggest that intrusion may have been forceful. The lineation and folding indicates that the sheets predate the second deformation event.

STOP 8: Mylonite Zone

(Rt 17A near Sloatsburg, outcrop is on the north side of the westbound lane just before the first left turn lane to the west of Rt. 17)

The rock is a biotite quartzofeldspathic mylonitic gneiss with interlayers of biotite gneiss locally. The mylonite is well foliated and lineated and composed of plagioclase, quartz, K-spar, and biotite. This mylonite exhibits well developed kinematic indicators including S-C fabric, reverse shear cleavage (RSC), rotated porphyroclasts, and shear bands. These kinematic indicators show a consistent dextral shear sense. The width of the zone and low S-C angle indicate significant offset.

Because this shear zone developed in a biotite-rich gneiss, it displays kinematic indicators better than most zones. It is another in the series of anastomosing dextral shear zones that were produced during the second event. The gneiss is interpreted to have a volcaniclastic origin.