Bedrock geology, geochemistry and geochronology of the Grenville Province in the western Hudson Highlands, New York

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Abstract

New integrated field, regional, geochemical and geochronological studies in the western Hudson Highlands yield a detailed history of the building of the supercontinent of Rodinia during the Middle Proterozoic. An early volcano-plutonic complex formed in a ca. 1.2 to 1.1 Ga island arc or oceanic magmatic arc. The arc was rimmed by aprons of volcaniclastic detritus in uncertain relation with euxinic clastic>carbonate sedimentary basins. Collision likely with the proto-South American continent peaked at ca. 1020 Ma and resulted in granulite facies metamorphism, local felsic plutonism, pervasive gneissic foliation, and westward to northwestward directed fold nappe emplacement. A dioritic to bimodal plutonic event closely followed the peak conditions at 1,008 Ma. An extensive dextral strike-slip event then overprinted the area forming a 35 km-wide anastomosing system of mylonite zones. These mylonites display abundant kinematic indicators and are fringed by mesoscopic sheath folds and asymmetric boudins and well as transpressional folds and drag folds. Late in the deformational history, the zones became dilational and hydrothermal fluids mineralized them with local magnetite deposits within a locally buffered gangue assemblage. This strike-slip system has a synchronous conjugate system of the same magnitude in the Adirondacks of New York. Together they form a deep seated syntaxis analogous to that in the Himalayan orogen of southern Asia.

Introduction

The Reading Prong 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 (Figure 2). The details of the Grenvillian orogeny in the Appalachians are difficult to decipher because of complex structural relations, lack of exposure, and pervasive granulite facies metamorphism, as well as extensive overprinting during the Paleozoic and Mesozoic locally (Ratcliffe *et al.*, 1972; Bartholomew and Lewis, 1988; Krol et al., 1992; Krol and Zeitler, 1994). Any

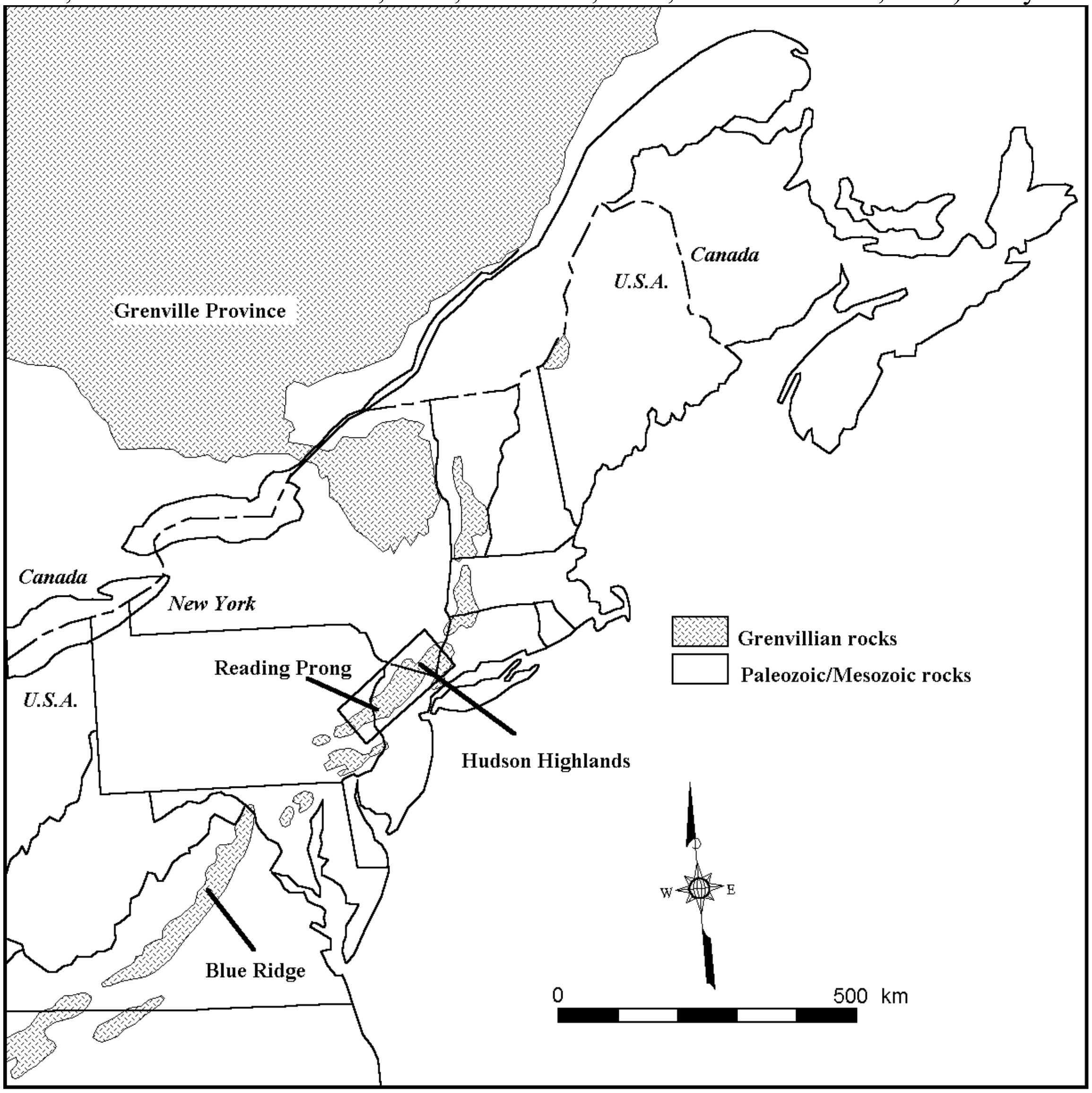

Figure 1. Regional map of eastern United States and Canada showing the geographic distribution of Grenville rocks. The area of Figure 2 is outlined by a rectangle.

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) was 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,

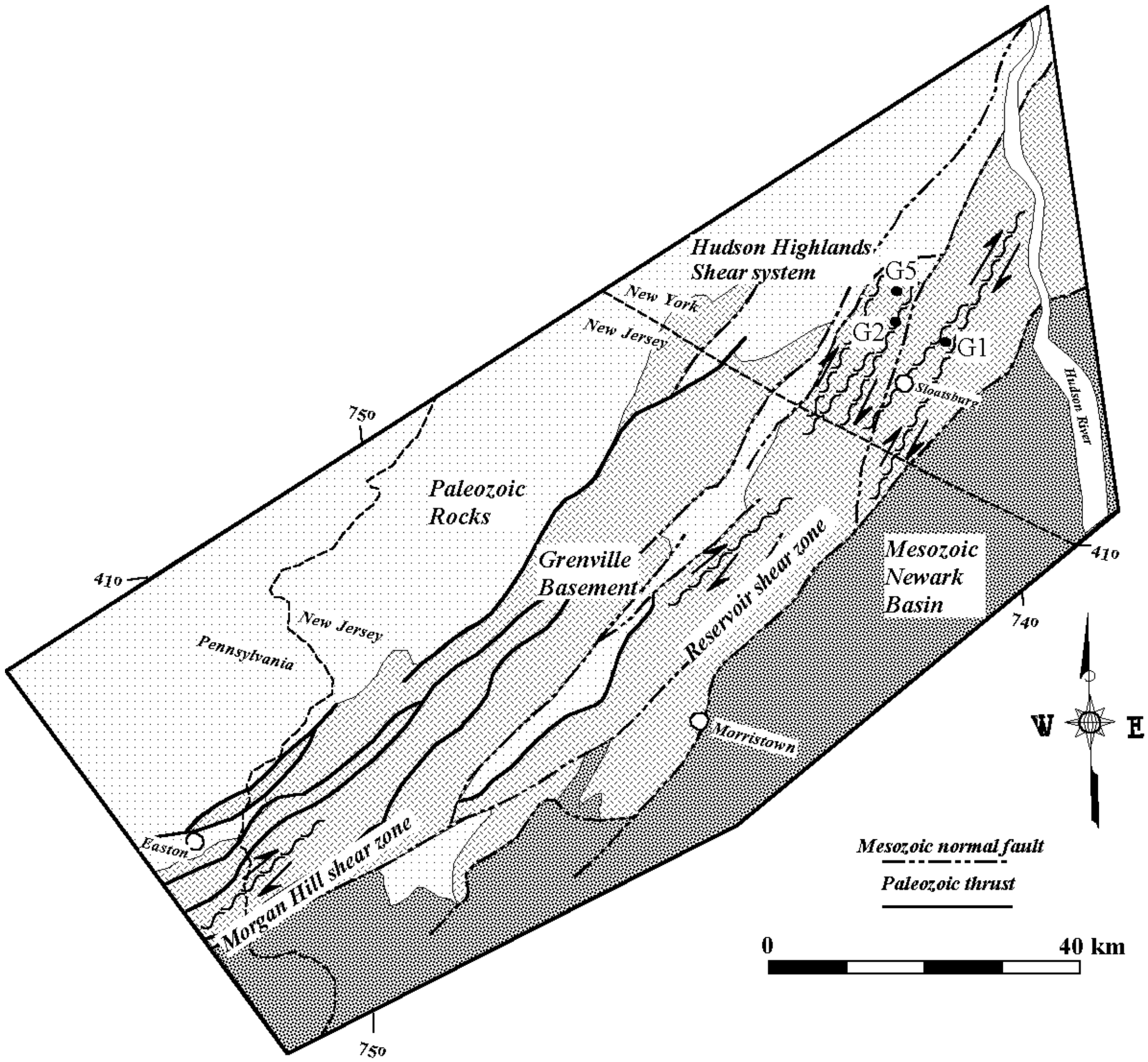

Figure 2. General geologic map of the Reading Prong and Hudson Highlands. The study area, in southern New York State, is outlined.

approximately equivalent to the Ottawan orogeny (Easton, 1986). 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

The 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 (Figures 2 and 3). Previous mapping in this area, divided the units by rock types (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. 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 upward of a few 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. 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 usually 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 and aligned hornblende, plagioclase, clinopyroxene and hypersthene with 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).

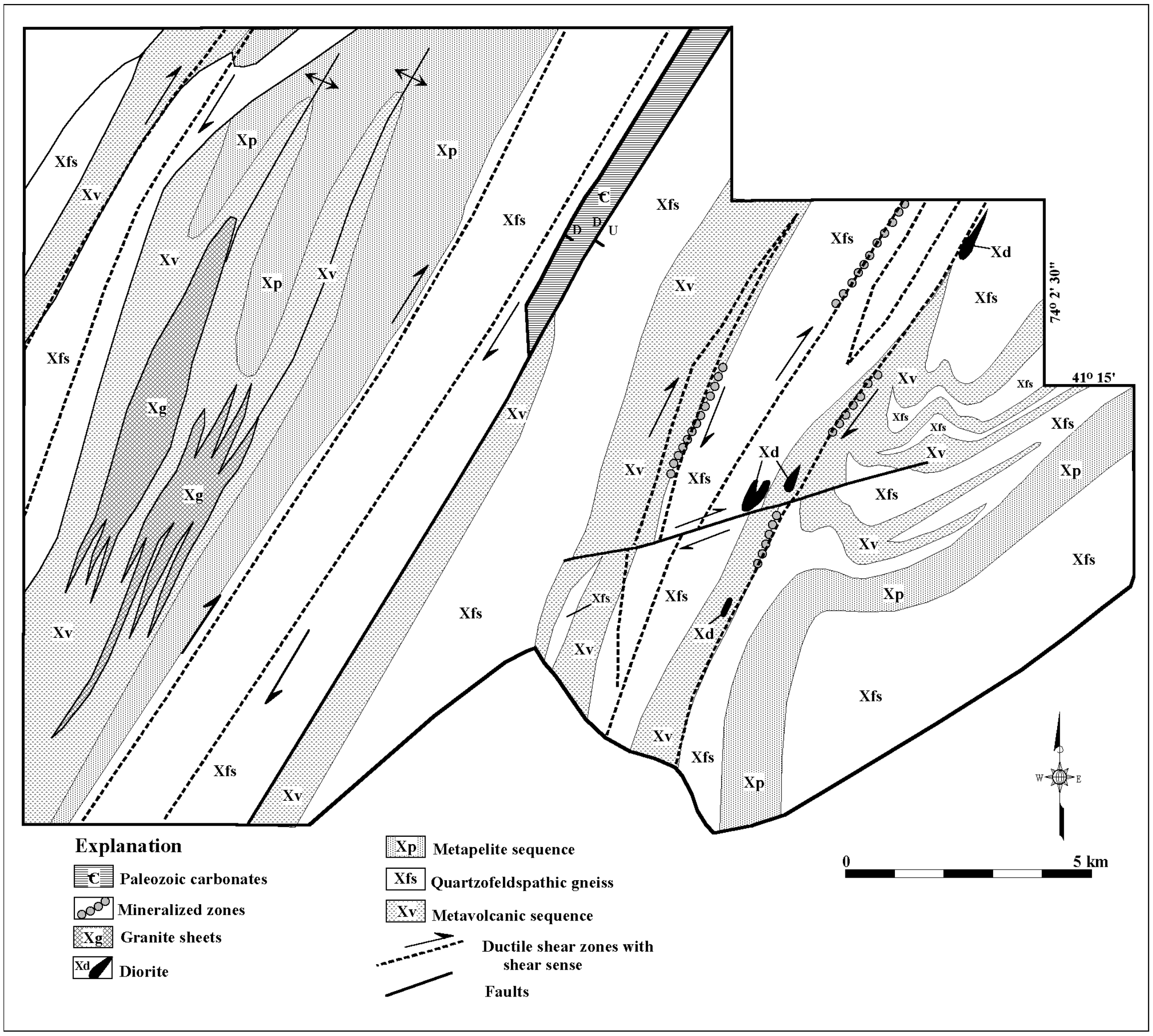

Figure 3. Geologic map of the area of Harriman State Park and Sterling State Forest.

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. 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 lacking foliations. 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 very 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 northest-southwest and dip moderately southeast (Figure 3). As previously stated, sheet thickness varies considerably, however, the granite sheets in Sterling Forest extend out 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 contains plagioclase, pyroxene, hornblende, and biotite locally. The diorite grades to lower pyroxene, 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 (Figure 3).

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 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 mylonite zones and are mineralized. They contain 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 contained within 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. They are commonly intruded by late pegmatites 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. The structural features produced during these events are described and placed in the context of the metamorphic conditions.

First Deformation Event

The first 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. 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. 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. 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 group 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 either 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 C/S 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 earlier.

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.

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 $\pm$ 3.6 Ma and 922 $\pm$ 3.4 Ma respectively. Hornblende from an undeformed granitic pegmatite that intruded mineralized vein material yielded an age of 923 $\pm$ 2.8 Ma. Biotite from the gangue minerals (HSP-2A) yields an age of 840 $\pm$ 5.0 Ma whereas biotite from the pegmatite yielded 794 $\pm$ 3.0 Ma.

The closure temperature for argon diffusion in hornblende is 500 - 550^{o} 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. Generally, it is clear that the mineralization and pegmatite intrusions occurred at about the same time. The pegmatite must have closely followed the mineralization where they intrude the veins. The source of fluids for mineralization may have been related to the pegmatite magmatism.

The Reservoir fault, a related dextral strike-slip shear zone, was active until 876 $\pm$ 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^{o} C. Therefore, cooling through 200-250^{o} 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^{o} 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 minor 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. The first sample was from a semi-pelitic gneiss layer within the metasedimentary lithofacies, the second sample was from the quartzofeldspathic gneiss body located west of the New York Thruway, and the third sample 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 wheras the clear rims are probably associated with the high-grade metamorphism. Numerous 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 analyses centered on 1020 Ma.

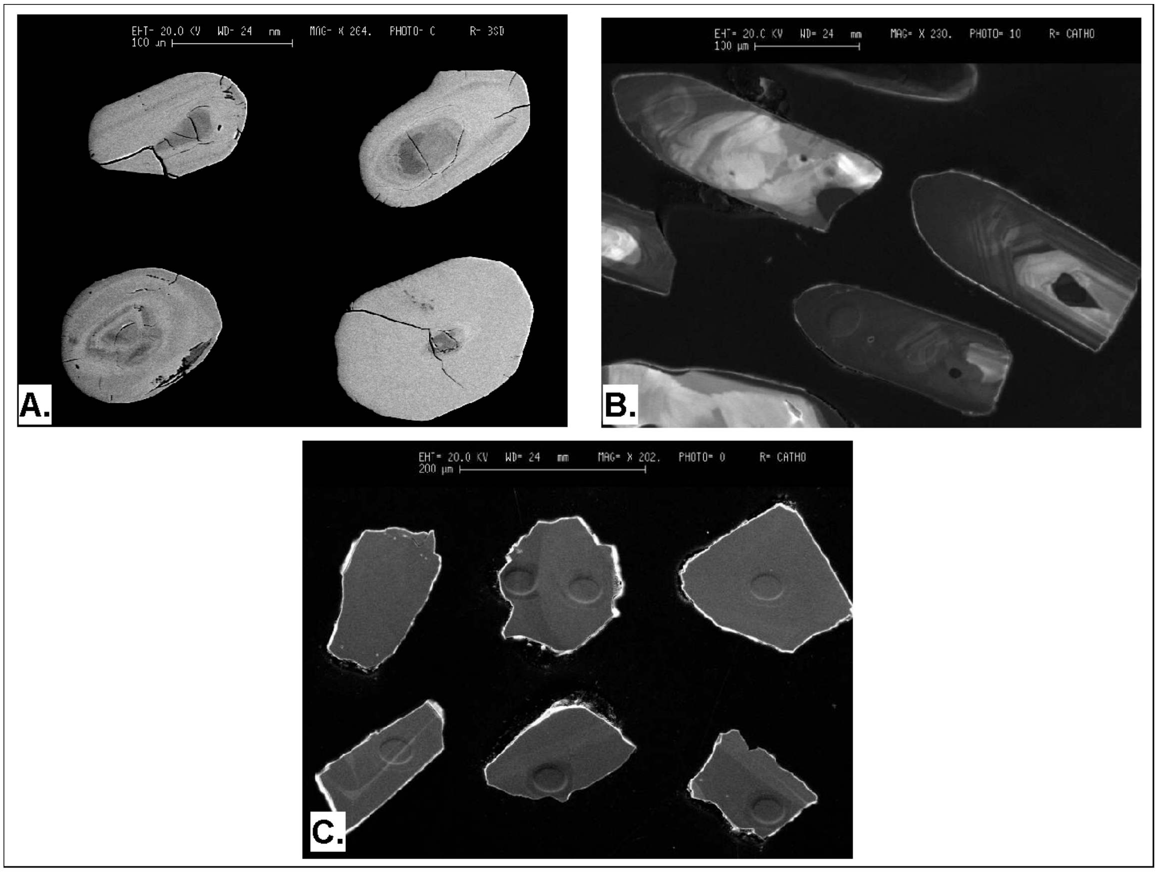

Figure 4. Representative cathodoluminescence images of zircons that were analyzed using the SHRIMP. A. Zircons from metasedimentary rocks showing complexly zoned cores and metamorphic overgrowths. B. Zircons from metavolcanic rocks showing igneous cores and metamorphic overgrowths. C. Zircons from diorite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

The quartzofeldspatic gneiss produced 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 produced small subhedral zircons with minimal zoning (Figure 4c). Analyses of these zircons yielded 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.

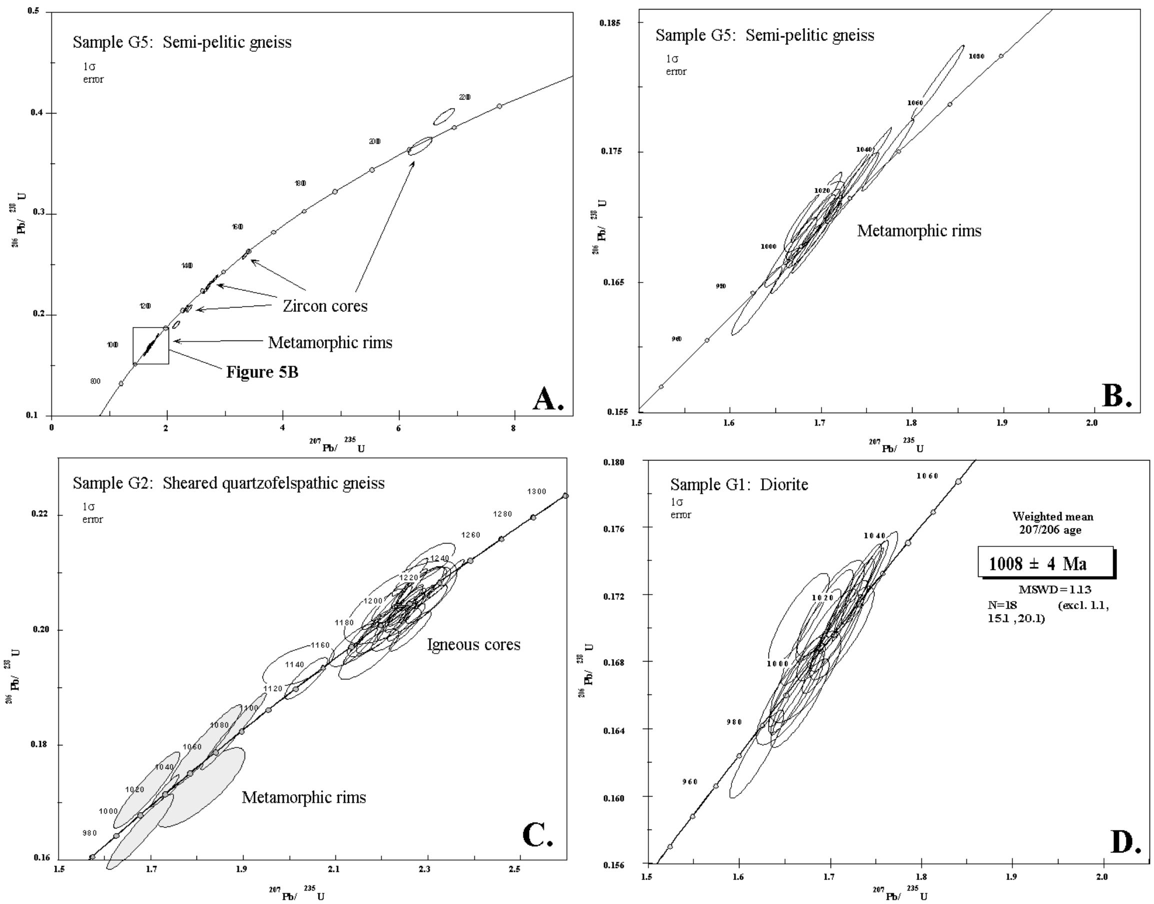

Figure 5. Concordia plots for SHRIMP analyses completed on zircons from Hudson Highlands rocks. A. and B. from semi-pelitic gneiss (B is a detailed view of A); C. from sheared quartzofeldspathic gneiss; and D. Lake Tioroti diorite body.

Geochemistry

Recent geochemical, structural, and geochronological investigations in the southwestern Hudson Highlands, NY has identified at least four discrete tectonomagmatic events. 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 small, diorite pluton. 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 Greens Mtns, 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 exact protolith for the quartzofeldspathic rocks 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), while other parts are interpreted as metamorphosed metavolcanoclastics. It is likely, that this unit contains rocks of intrusive and extrusive 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.

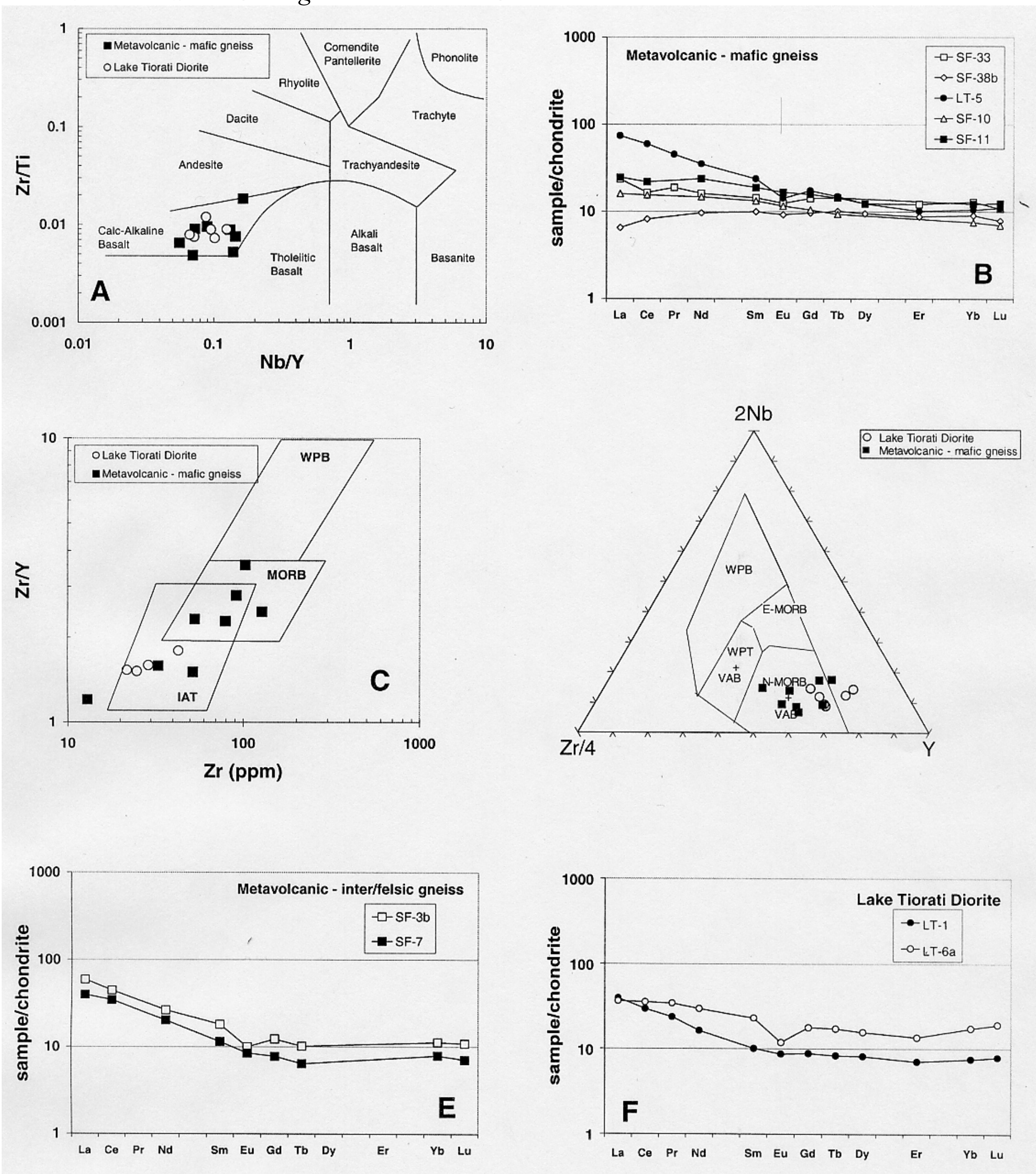

Figure 6 (A-F). Geochemical plots for amphibolites and quartz-plagioclase gneiss within the Metavolcanic Unit and diorite.

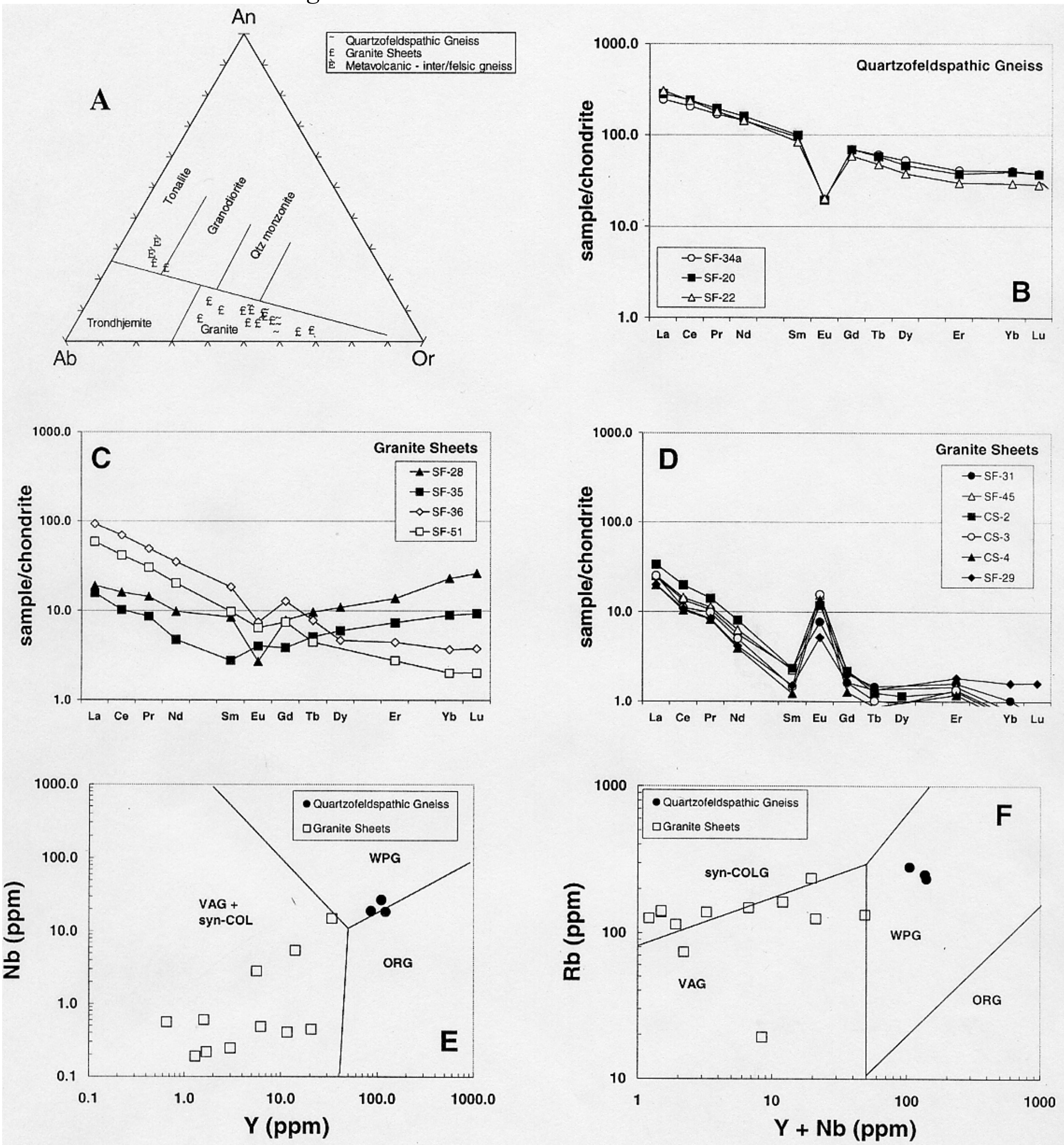

Figure 7. Geochemical plots for granite sheets and quartzofeldspathic gneiss.

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 consisting of interlayered mafic and intermediate rocks as well as associated plutons. Submarine aprons of volcaniclastic material formed along the volcanic islands and were interlayered with the volcanic rocks. These units taper 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 $\pm$ 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).

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 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. 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.

References

Bartholomew, M.J., and Lewis, S.E. (1988) Peregrination of Middle Proterozoic massifs and terranes within the Appalachian orogen, eastern U.S.A. *Trabajos de Geologia*, **17**, 155-165.

Borg, S.C., and DePaolo, D.J. (1994) Laurentia, Australia, and Antarctica as a Late Proterozoic supercontinent: Constraints from isotopic mapping. *Geol*., **22**, 307-310.

Burke, K., and Sengor, C. (1986) Tectonic escape in the evolution of the continental crust, In *Reflection Seismology: The Continental Crust* (Barazangi, M., and Brown, L., eds.), Am. Geophys. Union Geodyn. Ser., vol. 14, 41-53, Washington, D.C.

Dallmeyer, R. D. (1974) Metamorphic history of the northeastern Reading Prong, New York and Northern New Jersey, *Jour. of Petrology,* **15**, 325-359.

Dalziel, I.W.D. (1991) Pacific margins of Laurentia and East Antarctica-Australia as a conjugate rift pair: Evidence and implications for an Eocambrian supercontinent. *Geol*., **19**, 598-601.

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 *The Grenville Event in the Appalachians and Related Topics* (Bartholomew, M.J., ed.), Geol. Soc. Am. Spec. Pap. **194**, 75-109.

Drake, A.A., Jr., Aleinikoff, J.N., and Volkert, R.A. (1991) The Byram intrusive suite of the Reading Prong - Age and tectonic setting, In *Contributions to New Jersey Geology* (Drake, A.A., Jr., ed.), U.S. Geol. Surv. Bull., **1952**, D1-D14.

Drake, A.A., Jr., Volkert, R.A. (1991) The Byram Intrusive Suite of the Reading Prong: Age and tectonic environment. In: Drake, A.A. Jr. (Ed.), Contributions to New Jersey Geology. U.S. Geol. Surv. (1952), D1-D14.

Easton, R.M. (1986) Geochronology of the Grenville Province. In *The Grenville Province* (J.M. Moore, A. Davidson and A.J. Baer, eds.), Geol. Assoc. Can. Spec. Pap., **31**, 127-173.

Gates, A.E. (1995) Middle Proterozoic dextral strike-slip event in the central Appalachians: Evidence from the Reservoir fault, NJ, *J. Geodynamics,* **19**, 195-212.

Gates, A.E. (1998) Early compression and late dextral transpression within the Grenvillian Event of the Hudson Highlands, NY, USA, in Sinha, A.K. (ed.), *Basement Tectonics 13*; Dordrecht, The Netherlands, Kluwer Academic Publishers, 85-98.

Gates, A.E., and Costa, R.E. (1998) Multiple reactivations of rigid basement block margins: Examples in the northern Reading Prong, USA, in Gilbert, M. C. and Hogan, J.P. (eds.), *Basement Tectonics 12: Central North America and Other Regions*; Dordrecht, The Netherlands, Kluwer Academic Publishers, 123-153.

Gates, A.E., and Krol, M.A. (1998) Kinematics and thermochronology of late Grenville escape tectonics from the central Appalachians, *Geol. Soc. America Abstracts with Programs*, **30**

Gates, A.E., Valentino, D.W., Chairenzelli, J., and Hamilton, M., 2001, Deep-Seated Himalayan-type Syntaxis in the Grenville orogen, NY-NJ-PA, *Geol. Soc. America Abstracts with Programs*, **33**.

Gundersen, L.C. (1986) Geology and geochemistry of the Precambrian rocks of the Reading Prong, New York and New Jersey - Implications for the genesis of iron-uranium-rare earth deposits, In *USGS Research on Energy Resources - 1986 Programs and Abstracts* (Carter, L.M.H., ed.), U.S. Geol. Surv. Circular **974**, 19.

Harnois, L., Moore, J.M. (1991) Geochemistry of two metavolcanic arc suites from the Central Metasedimentary Belt of the Grenville Province, southeastern Ontario, Canada. Can. J. Earth Sci., 28, 1429-1443.

Harrison, T.M., Duncan, I.J., and McDougall, J. (1985) Diffusion of ^{40}Ar in biotite: Temperature, pressure and compositional effects. *Geochim. Cosmochim. Acta*, **49**, 2461-2468.

Helenek, H.L. (1987) Possible Late Proterozoic wrench tectonic in the Reading Prong, New York - New Jersey - Pennsylvania, *Northeastern Geology,* **9**, 211-222.

Helenek, H.L., and Mose, D.G. (1984) Geology and geochronology of Canada Hill Granite and its bearing on the timing of Grenvillian events in the Hudson Highlands, New York, In *Grenville Events and Related Topics in the Appalachians* (Bartholomew, M.J., ed.), Geol. Soc. Am. Spec. Pap., **194**, 57-73.

Hoffman, P.F. (1988) United plates of America, the birth of a craton: Early Proterozoic assembly and growth of Laurentia. *Ann. Rev. Earth Planet. Sci.,* **16**, 543-604

Krol, M.A. and Zeitler, P.K. (1994) 40Ar/39Ar Constraints on Regional Thermal Resetting of Alkali Feldspars from the Newark Basin and Adjacent Reading Prong, Eighth International Conference on Geochronology, Cosmochronology and Isotope Geology, *U.S. Geological Survey Circular* **1107**, 180.

Krol, M.A., Gosse, J., Hedlund, C., Messina, T., Tenore-Nortrup, J., Winslow, D., & Zeitler, P. (1992) 40Ar/39Ar Constraints in the Extent of Both Paleozoic and Mesozoic Thermal Overprinting of Reading Prong Basement Adjacent to the Newark Basin, *EOS Transactions, American Geophysical Union Abstracts with Programs*, **73**, 279.

Lister, G. S. and Snoke, A. W. (1984) S-C mylonites: *J. Struct. Geol.,* **6**, 617-638.

McLelland, J.M. (1986) Pre-Grenvillian history of the Adirondacks as an anorogenic, bimodal caldera complex of mid-Proterozoic age. *Geol*., **14**, 229-233.

McLelland, J.M., and Isachsen, Y.W. (1980) Structural synthesis of the southern and central Adirondacks: A model for the Adirondacks as a whole and plate tectonic interpretations. *Geol. Soc. Am. Bull.*, **91**, 208-292.

McLelland, J., Whitney, P. (1986) Anorogenic, bimodal emplacement of anorthositic, charnokitic, and related rocks in the Adirondack Mountains, New York. Geol. Soc. Amer. Spec. Pap. 246, 301-315.

McLelland, J., Chiarenzelli, J. (1990) Geochronological studies in the Adirondack Mts. and the implications of a Middle Proterozoic tonalitic suite. In: Gower, C., Rivers, T., Ryan, C. (Eds.), Mid-Proterozoic Laurentia-Baltica. Geol. Ass. Can., Spec. Pap., 38, 175-194.

Mose, D.G. (1982) 1,300-million-year-old rocks in the Appalachians. *Geol. Soc. Am. Bull.*, **93**, 391-399.

Passchier, C.W., and Simpson, C. (1986) Porphyroclast systems as kinematic indicators. *J. Struct. Geol*., **8**, 831-843.

Rankin, D.W., Drake, A.A., Jr., and Ratcliffe, N.M. (1993) Proterozoic North American (Laurentian) rocks of the Appalachian orogen. In *Precambrian Conterminous U.S.* (eds. J.C. Reed and others): Geology of North America Series, v. C2, Geol. Soc. Am., Boulder, Colorado, 378-403.

Rankin, D.W., Chiarenzelli, J.R., Drake, A.A. Jr., Goldsmith, R., Hall, L.M., Hinze, W.J., Isachsen, Y.W., Lidiak, E.G., McLelland, J.M., Mosher, S., Ratcliffe, N.M., Secor, D.T. Jr., Whitney, P.R. (1993) Proterozoic rocks east and southeast of the Grenville front. In: Reed, J.C. Jr., Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., Van Schmus, W.R. (Eds.), Precambrian: Conterminous US. The Geology of North America. Geol. Soc. Am., C-2, 335-461.

Ratcliffe, N.M., Aleinikoff, J.N., Burton, W.C., Karabinos, P. (1991) Trondhjemitic, 1.35-1.31 Ga gneisses of the Mount Holly Complex of Vermont: evidence for an Elzevirian event in the Grenville Basement of the United State Appalachians. Can. J. Earth Sci., 28, 77-93.

Ratcliffe, N.M., Armstrong, R.L., Chai, B.H., and Senechal, R.G. (1972) K-Ar and Rb-Sr geochronology of the Canopus pluton, Hudson Highlands, New York. *Geol. Soc. Am. Bull.*, **83**, 523-530.

Silver, L.T. (1969) A geochronologic investigation of the anorthosite complex, Adirondack Mountains, New York, In *Origin of Anorthosites and related rocks* (Isachsen, Y.W., ed.), New York State Museum and Science Service, Mem. 18, 233-252.

Simpson, C. (1985) Deformation of granitic rocks across the brittle-ductile transition, *J. Struct. Geol.* **7**, 503-511.

Smith, T.E., and Holm, P.E. (1990) The petrogenesis of mafic minor intrusions and volcanics of the Central Metasedimentary Belt, Grenville Province, Canada: MORB and OIB sources. Precambr. Res., 48, 361-373.

Smith, T.E., Holm, P.E., Dennison, N.M., Harris, M.J. (1996) Crustal assimilation in the Burnt Lake metavolcanics, Grenville Province, southeastern Ontario, and its tectonic significance. Can. J. Earth Sci., 34, 1272-1285.

Sonzogni, B., Gorring, M.L., Gates, A.E., and Valentino, D. (2001) Middle Proterozoic A-type granite plutonism in the western Hudson Highlands, New York. Geol. Soc. Amer. Northeastern Section Meeting, 33-1, A-8, Burlington, VT.

Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armigo, R., and Cobbold, P. (1982) Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine. *Geol.*, **10**, 611-616.

Volkert, R.A., Drake, A.A. Jr. (1999) Geochemistry and stratigraphic relations of Middle Proterozoic rocks of the New Jersey Highlands. In: Drake, A.A. Jr. (Ed.), Geologic Studies in New Jersey and Eastern Pennsylvania. U.S. Geol. Surv. Prof. Pap. 1565-C, 77 p.

Volkert, R.A., Feigenson, M.D., Patino, L.C., Delaney, J.S., Drake, A.A. Jr. (2000) Sr and Nd isotopic composition, age and petrogenesis of A-type granitoids of the Vernon Supersuite, New Jersey Highlands, USA. Lithos, 50, 325-347.

Weiner, R.W., McLelland, J.M., Isachsen, Y.W., and Hall, L.M. (1984) Stratigraphy and structural geology of the Adirondack Mountains, New York: Review and synthesis, In *Grenville Events and Related Topics in the Appalachians* (Bartholomew, M.J., ed.), Geol. Soc. Am. Spec. Pap., **194**, 1-55.

Whitney, P. R. (1983) A three-stage model for the tectonic history of the Adirondack region, New York. *Northeastern Geol.*, **5**, 61-72.

Windley, B.F. (1986) Comparative tectonics of the western Grenville and the western Himalaya, In *The Grenville Province* (J.M. Moore, A. Davidson and A.J. Baer, eds.), Geol. Assoc. Can. Spec. Pap., **31**, 341-348.

Road Log

0.0	Start from Parking Lot at Lamont-Doherty Earth Observatory Palisades, NY
0.1	Left on Route 9W
0.3	Right on Palisades Interstate Parkway Northbound
8.7	Exit 13 on New York State Thruway North
19.4	Exit 15A on Route 17 North. Pass through town of Sloatsburg to second stop light.
21.5	Right on Seven Lakes Drive
22.5	Right into Parking Lot at Reeves Meadow Visitors Center. Starting point for field trip. Permission for trip is required from Palisades Interstate Park Commission. See website http://harrimanrocks.rutgers.edu for a permit and a virtual field trip of these rocks.

0.0	Turn Right on Seven Lakes Drive North.
1.8	Large cut on both sides of road. Camp road at north end of outcrop (left) and spillway for Lake Sebago. Park along roadside.

STOP 1: Rocks of the metasedimentary lithofacies

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.

1.8	Continue North on Seven Lakes Drive.
9.1	Park on roadside just past Cedar Pond campground on right. Lake Tiorati is on the right. There is a small rock island directly across from outcrop which is on the left (west) side of the road.


Mountain
Lake Stahahe
Stahahe High Peak
Carr Pond Mtn
Valley of Boulders
Green Pond Mtn
Arden
Black Rock Mtn
Black Rock
Boston Mine
Garfield Mine
Island Pond
Lemon Squeezer
Island Pond Mtn
Harris Mine
Echo Mtn
Surebridge
Goldthwaite Memorial
Bald Rocks
Bowling Rocks
Hogencamp Mtn
Hogencamp Mine
Ship Rock
Surebridge Swamp
Surebridge Mine
Mountain
Little Long Pond
3
4
Picnic Area
Kanawauke Circle
Lake Kanawauke
Cape Horn
Pine Swamp Mine
Times Square
Pothole
Greenwood Mine
Pine Swamp Mtn
Fingerboard
SEVEN LAKES DRIVE
Lake Askoti
Rock House
HARRIMAN
Rockhouse Mtn
Camp Thendara
Cedar Pond (Group Camping)
2
Picnic Area

STOP 2: Diorite Intrusion

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. The dioritic Canopus pluton in the eastern Hudson Highlands is proposed to be synchronous with dextral strike-slip movement. It is dated at 1065 Ma by Rb/Sr whole rock methods (Ratcliffe et al., 1972).

9.2	Turn around at the maintenance office 200 m to the North and drive south on Seven Lakes Drive.
11.7	Drive ¼ way around Kanawauke Circle to first right, Rt. 106 west.
12.4	Park on left (south) side of road on small pull off and walk west about 100 m. Outcrop is on right (north) side of road just past bridge over the neck between Lake Kanawauke (east) and Little Long Pond (west).

STOP 3: Rocks of the metavolcanic lithofacies

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.

12.4 Continue west on Route 106.

12.6 Find Parking along roadside and hike up paved service road through gate (wire). After 0.8 miles, woodland road (no unpaved) will join with Dunning Trail with yellow trail markers (turn right). After 0.2 miles mine workings will be on the left and tailings pile on the right. Mine workings extend for several hundred yards.

STOP 4: 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.

12.6 Return to vehicles. Continue west on Route 106.

18.1 Route 106 changes to 4-lane highway Route 17A across Route 17. Stop at the west end of first outcrop with rocks on both the median and westbound lanes of the highway. Park to the right along Route 17A.

STOP 5: Sheared quartzofeldspathic gneiss

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. At this locality there is a dike of coarse grained granite (few meters thick) with large crystals of hornblende that for radiating and linear aggretates.

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. Locally there are small sinistral shear zones that crosscut the main foliation and are interpreted to be conjugate. The sheared quartzofeldspathic rocks at this locality occur within the Indian Hill shear zone (Figure 3), which is only one of the zones in the anatomizing system of ductile shear zones that occurs in the Hudson Highlands.

18.3	Immediately get into the left lane of Route 17A westbound and turn left onto Eagle Valley Road from the left turn lane.
19.5	After two ponds on right (west) side of road, the first large outcrop is a road cut on the west side of the road (faces an excavated area on the east side). Park along the road.

STOP 6: Granite Sheet

Concordant leucogranite sheets intruded the quartzofeldspathic gneiss, and the rocks of the metasedimentary facies and metavolcanic lithofacies. The granite sheets range from a few meter up to 100 meters thick and contains K-spar, quartz and plagioclase, with minor hornblende, biotite and muscovite locally. Most exhibit interlocking subhedral to anhedral grains, and they are only locally foliated where the granite sheets occur near dextral shear zones. The granite at this locality is not foliated.

Most granite sheets occur within two domains inside the area of Sterling Forest. These two domains correspond to the hinge regions of map-scale upright antiforms (Figure 3). Some small granite sheets occur east of the NY Thruway.

19.5	Turn around and drive north on Eagle Valley Road.
20.7	Return to Route 17A and turn right (east), returning the way you came.
22.1	Turn left at Route 17 junction onto the service road to Route 17 North and continue onto Route 17.
23.4	Turn left onto Orange Turnpike (gas station and deli). Road will split after about one mile (large furnace on right) where the left (west) fork is Lake Mombasha Road. Remain on Orange Turnpike to right (east).

25.9 Large fresh roadcut on right (east) side of road on a right (east)-curving decline in the road.

STOP 7: Calcsilicate rocks of the metasedimentary lithofacies

Melanosome of calc-silicate gneiss is of diopside, plagioclase, quartz, K-spar and phlogopite and leucosome of pink granite veins. The rock is strongly foliated and the leucosome veins are parallel to the foliation. Later deformation is minimal. The rock is interpreted to have been a very dirty carbonate mud within the metasedimentary sequence. That sequence is dominated by metapelite. It was metamorphosed to the point of anatexis during the first tectonic event, hence the foliation in this rock is associated with the first deformation event.

25.9 Turn around and return to Route 17 South to end the trip.