The nature and significance of the Carthage-Colton Shear Zone and related late-to-post tectonic granites and ore deposits; Adirondack Mountains, New York

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Friends of the Grenville Annual Field Trip – September 30 – October 2, 2005

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This trip will examine the nature and geologic significance of the Carthage-Colton Shear Zone (CCSZ) which forms the boundary between the Adirondack Highlands Central Granulite Terrane and the Adirondack Lowlands Central Metasedimentary Belt. Recent field mapping, petrologic and geochronologic studies provide critical new data that constrains the ca. 1070-1030 Ma history of ductile and brittle deformation along the CCSZ and its relationship to the collisional tectonism of the Ma Ottawan Orogeny, strike-slip motion along the shear zone and later extensional orogenic collapse (Johnson, et al 2004). Leucogranites of the Lyon Mountain Granite suite are common along the Highlands portion of the CCSZ and intruded synchronously with extensional motion on the CCSZ (Selleck, et al 2005). Low-Ti magnetite ores are found in association with these leucogranites, suggesting that some ore mineralization occurred during motion along the CCSZ. Cl-scapolite and Cl-amphibole mineralization is also associated with the high-strain features within CCSZ.

The trip will visit a series of key exposures along the CCSZ that illustrate the range of lithologies and structural features of the zone, and provide a framework for discussion of geothermometric and geochronologic relationships and implications for the evolution of the Grenville Orogen. Stops will include mylonites, ultramylonites and pseudotachylites and ore deposits that are associated with intrusion of ca. 1045 Ma leucogranite, shear zones in the Diana Complex (Baird and MacDonald, 2004), the Valentine wollastonite deposit (Gerdes, 1994), Cl-scapolite/amphibole vein mineralization in the Dana Hill (Johnson, et al 2004) and other metagabbro bodies, Jayville low-Ti magnetite with associated Fe-borate mineralization that may represent the deep-seated zone of an IOCG system, synkinematic 1045 Ma quartz-sillimanite nodular leucogranite (McLelland, et al 2002), and additional localities that illustrate the range of intrusive relationships, deformation fabrics and ore deposits that are topics of on-going research.

Introduction:

Mesoproterozoic rocks south and east of the Grenville Front Tectonic Zone are subdivided into a number of terranes on the basis of different tectonothermal histories and are separated by ductile shear zones (Davidson, 1986; Rivers, et al 1989). Using the terminology of Wynne-Edwards (1972) and Davidson (1986; 1998) these terranes, from west to east are the Central Gneiss Belt (CGB), the Central Metasedimentary Belt (CMB) consisting of the Bancroft, Elzevir, Mazinaw, Frontenac and Adirondack Lowlands Terranes and the Adirondack Highlands Terrane of the Central Granulite Terrane (CG). Carr, et al (2000) divide the Ontario/Quebec/New York Grenville Province into three zones: the pre-Grenville Laurentian Margin, the Composite Arc Terrane and the Frontenac-Adirondack Belt. We will utilize the terminology of Wynne-Edwards (1972) and Davidson (1998) in this report.
The terrane-bounding ductile shear zones within the Grenville Province carry metamorphic assemblages that range from granulite to greenschist facies and are critical to understanding the tectonic assembly and evolution of the orogen and its ultimate cratonization. On this trip we will examine structural and intrusive features in the Carthage-Colton Shear Zone (CCSZ), which separates rocks belonging to the Central Granulite Terrane (Adirondack Highlands) and the Central Metasedimentary Belt (Adirondack Lowlands).

Geologic/tectonic relationships between the CMB and CGT and the role of the CCSZ have been a matter of some debate. Geraghty et al (1981) and Isachsen and Geraghty (1986) interpreted the CCSZ as a crustal-scale shear zone along which the CMB (Adirondack Lowlands) was thrust over the CGT (Adirondack Highlands). Wiener (1983) interpreted the CCSZ as the lower limb of a large fold-thrust nappe with no significance as a terrane boundary. Isotope data (U/Pb, $^{40}$Ar/$^{39}$Ar) document different thermal histories for the CMB and CGT and strongly support the assertion that the CCSZ is a major crustal boundary (McLelland, et al 1993; Mezger et al 1993). Isotopic evidences show the Adirondack Highlands (CGT) reached granulite facies conditions during the ca. 1050-1070 Ma Ottawan Orogeny (McLelland, et al 2001; McLelland and Chiranzelli, 1990) whereas temperatures at this time in the Adirondack Lowlands (CMB) did not generally exceed 400°C (Mezger et al 1993; McLelland et al 1993). However, ca. 1155 Ma AMCG (anorthosite-mangerite-charnockite-granite) suite magmatic rocks are present in both terranes, leading to the possibility that the CMB and CGT terranes were juxtaposed prior to and during the ca. 1155 event, separate during the 1050-1070 Ottawan Orogeny, and then reunited following the Ottawan. Mezger, et al (1992) interpreted the CCSZ as a major crustal collapse structure that brought the CMB and CGT rocks into their current configuration syn- to post-Ottawan (ca. 1030 Ma). Mezger et al (1992) further proposed that the CMB and CGT were separated by the opening of a small ocean basin following ca. 1155 Ma magmatism, allowing for different P-T-t paths for the terranes during the Ottawan followed by crustal suturing in late Ottawan and subsequent orogenic collapse. An alternative interpretation is that the CMB and CGT rocks have been part of the same crustal entity since 1155 Ma magmatism, but the CMB rocks were at a higher, and thus cooler crustal level during the 1050-1070 Ma Ottawan Orogeny. In this model, late to syn-Ottawan collapse along the CCSZ juxtaposes the two terranes at their current structural level (Mezger, et al., 1992, McLelland, et al 1993). Mineralization associated with zones of ductile deformation within the Diana Complex, a CMB lithology, contain titanite with U-Pb ages spanning the interval 1073-1016 Ma suggesting prolonged syn- to late-Ottawan motion (Heumann, et al 2004). Lower temperature conditions in the Diana Complex shear zones suggest slow uplift and cooling at temperatures of 550-400°C and pressures of 3 to 5 kb (Lamb, 1993). Zhao et al. (1997) and Martignole and Reynolds (1997) report granulite-grade mineral assemblages associated with strike-slip motion on the Labelle and Morin Shear Zones in Quebec. Hamner et al. (2000) report 1.09-1.06 Ga oblique sinistral motion on the Tawachiche Shear Zone, and Streepey et al (2001) and Johnson et al (2004) report oblique dextral movement along the CCSZ introducing the possibility that lateral displacements may be important during the Ottawan deformational phase. In all of these models, the precise role of the CCSZ (and Labelle Shear Zone/Tawachiche Shear Zone) is the critic link to understanding the relationship between the CMB and CGT.

Excellent exposures of deformed and metamorphosed rocks belonging to the CMB (Adirondack Lowlands) and CGT (Adirondack Highlands) along the CCSZ form the basis of this field trip. We will cross the CCSZ at several locations and examine the relationship among high-strain fabrics and structures, metamorphic recrystallization, igneous intrusion and hydrothermal mineralization in the Harrisville, Fine, South Edwards, Hermon, West Pierrepont and Albert Marsh 7.5’ quadrangles. The CCSZ in this region is not a simple boundary but rather consists of meter to kilometer wide zones of intensely strained rock with intervening relatively less highly strained lithologies. In addition, the CCSZ has been partially dissected and offset by later, post-Ottawan ductile and brittle shear. We will examine a number of examples of these discrete shear
zones and discuss their possible relationship to economic mineralization in the region. This trip will also address the wealth of geochronologic data that has been recently collected along the CCSZ, including new and previously unpublished U/Pb and Ar/Ar dates.

These new observations and data allow refinement of existing models for the role of the CCSZ and relationships between the Adirondack Highlands and Lowlands Terranes during the tectonic evolution of this part of the Grenville Province. One area of controversy is the exact timing of the juxtaposition of the Highlands and Lowlands. Critical to this discussion is the nature and timing of widespread metasomatic alteration of rocks in both the Highlands and Lowlands near the CCSZ detachment surface. This alteration is marked by widespread scapolite replacement of plagioclase feldspar and the emplacement of hornblende+scapolite and scapolite veins in both the footwall (Highlands) and hanging wall (Lowlands) of the CCSZ. This metasomatism is critical to understanding the relationship between the Highlands and the Lowlands terranes during late Ottawan history because it marks a common event for both terranes. In the Dana Hill Gabbro (Highlands), scapolite growth corresponds with the formation of hornblende veins related to fluid injection that occurred prior to 1020 Ma, as constrained by U/Pb dating. In the Diana Complex (Lowlands), scapolite growth occurs in shear zones dated to 1052-1040 Ma. These data argue that the Highlands and Lowlands terranes were near to a common structural level as early as 1050 Ma. At this time, the terranes would have had quite different thermal structures with a thermal gradient of at least 100°C across the CCSZ until ca. 1000 Ma.

At several locations on the trip we will examine granite intrusions that decorate the footwall (Highlands) side of the CCSZ. These granite bodies intrude rocks deformed by ductile shear within the CCSZ and are themselves deformed by CCSZ ductile strain. U/Pb SHRIMP II geochronological studies of these granites suggest synkinematic intrusion at ca. 1045 Ma (Selleck, et al 2005). Petrologic signatures including extreme potassic compositions and presence of hydrothermal quartz-sillimanite mineral segregations, and U/Pb zircon ages strongly suggest affinity of these granites to the Lyon Mountain Granite suite of the Adirondack Highlands (McLelland, et al 2001). The relationship of the granites of the CCMZ to the hornblende+scapolite mineralization noted above, and to the occurrence of magnetite deposits in the nearby Adirondack Highlands will be a topic of discussion on this trip. The abundance of these granite bodies near to and along the CCSZ suggests that a causal relationship may exist between CCSZ motion and granite emplacement, with granite melts generated within the footwall rocks of the Adirondack Highlands and emplaced in zones of extension adjacent to the main detachment of the CCSZ. The heat and magmatic fluids provided by these magmas drove high-temperature hydrothermal systems responsible for lo-Ti magnetite deposits and related mineralization, and including, perhaps the Cl-amphibole/scapolite mineralization along the detachment zone.

The Tectonic Framework

Field, isotopic and petrologic data suggest that the tectonic framework for the evolution of the CCSZ was very similar to that proposed for the rapidly exhumed granulite core terranes of the modern day Himalayan Mountains (Wobus, et al 2003). Zeitler et al (2001) describe the rapidly exhumed granulites of Nanga Parbat as tectonic aneurisms triggered by orogenic compression coupled with rapid surface denudation. Pronounced (>100°C) thermal contrasts exist across the bounding shear zones, and the exhuming granulate core is the source of A-type granite melts. The granites intrude along the bounding shear zones during active tectonic denudation. In the Himalaya and adjacent Tibetan Plateau, generation of leucogranite began ca. 20 Ma (Miocene High Himalaya leucogranites; Fort, 1975) some 35–25 Ma after the initial collision of India with southern Asia at 55–45 Ma (Besse et al., 1984; Patriat and Achache, 1984). Geophysical surveys of the southern Tibetan Plateau suggest that leucogranite melts occur at 15–
20 km depth (Gaillard, et al. 2004). In the Adirondack Highlands collisional tectonism and metamorphism of the Ottawan began after ca. 1090 (Ma McLelland, et al. 2001). Widespread deformation ceased by ca. 1040 Ma, as ca. 1040 Ma leucogranite generally lacks penetrative fabrics except within the CCSZ. The time span from initiation of collisional Ottawan tectonism at ca. 1090 Ma until generation of Lyon Mountain Granite (LMG) leucogranite at ca. 1050 Ma is thus similar to the Himalayan analogue, ca. 40 Ma. The generation of the LMG melts within the Highlands may have caused weakening of the rheologically strong Highlands core thus promoting ductile extension in the adjacent CCSZ.

Because of rapid exhumation, rocks across the shear zone boundaries in the Himalayan orogenic belt record very different thermal histories, as observed along the CCSZ. We suggest that the CCSZ system represents the top of a “crustal channel” system that developed during peak Ottawan collisional tectonism and continued through the late to post-Ottawan phase. In this model, the Highlands and Lowlands were vertically juxtaposed ca. 1100 Ma but relatively soon thereafter, during or immediately following emplacement of the ca. 1090-1070 Hawkeye Granite suite (McLelland, et al. 2001), the granulite rocks of the Highlands were displaced outward and deformed into the large Ottawan fold nappes best defined in the southern and eastern Highlands. Ottawan penetrative fabrics and granulite facies mineral assemblages developed at this time. The CCSZ was initiated as a deep crustal detachment that permitted ductile flow of the Highlands granulite terrane under the cooler and relatively immobile Lowlands. The emplacement of granites of the LMG suite followed most penetrative deformation in the rocks of the Highlands, but strong ductile shear zone fabrics along the CCSZ continued to develop as the Lowland hanging wall rocks moved down to the current northwest. The emplacement of granite melts in syn- to late-Ottawan time also drove local hydrothermal circulation leading to mineralization, some of economic significance. Where high strain rates or brittle lithologies permitted, fracture systems opened at relatively high temperature to promote movement of fluids and metasomatic vein mineralization. As shown below, this model explains many of the salient features of the CCSZ and the age relationships and thermal history of the CMB and CGT rocks of the Lowlands and Highlands terranes.
Figure 1. Tectonic cross-sections illustrating the evolution of the Adirondack Region and development of a crustal channel during Ottawa orogenesis. LL = Adirondack Lowlands Terrane; HL = Adirondack Highlands Terrane.
Figure 3. Generalized geologic map showing stops on day 1. Note that stop 4 on day 2 is also shown. The map position of the CCSZ is approximate and based on brittle fracture GIS data from the New York State Geological Survey. Uncolored map areas are mixed metasedimentary and metaigneous rocks.

**Field guide road log day 1**

<table>
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<tr>
<th>Cum. Mi.</th>
<th>Description</th>
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<td>0.0</td>
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<tr>
<td>3.3</td>
<td>Route 3 west to intersection with Rt. 812. Turn left (south) onto Rt. 812</td>
</tr>
<tr>
<td>15.6</td>
<td>Stop 1 – Road cut on east side of Route 812. Park on right shoulder heading south</td>
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Stop 1: **Intrusive relationships Indian River Road**  
*Indian River Road near Croghan, NY (UTM 18T, 495212E, 4920802N)*

This roadcut exposes dikes of leucogranite intruding mafic syenite. The location is south of the mapped extent of the CCSZ and thus we are within the Adirondack Highlands. This outcrop and nearby exposures represent a zone of extension within the lower plate (Highlands side) of the CCSZ that accommodated granite emplacement. The undeformed (lacking grain-shape fabric) quartz mesoperthite leucogranite dikes crosscut foliation in the syenite and contain xenoliths of the mafic country rock. The outcrop is also crosscut by later hematite-stained quartz-
feldspar-calcite veins that resemble the late mineralized veins associated with the Lyon Mountain Granite elsewhere in the Adirondack Highlands.

![Figure 4. Ca. 1039 Ma leucogranite intruding foliated mafic syenite at Stop 1, Day 1. Note xenolith of foliated mafic rock in leucogranite (arrow)](image)

![Figure 5a. Concordia plot of U-Pb SHRIMP data from leucogranite at stop 1.](image)

![Figure 5b. BSE image of zircon from leucogranite. The finely zoned overgrowth is interpreted as igneous. Darker (lower U content) cores from this suite are older and represent xenocrysts.](image)

This site was sampled for U-Pb SHRIMP age determination (Selleck, et al, 2005). Zircons from the leucogranite are subequant to elongate with faintly zoned cores and finely-zoned rims. Cores and well-developed oscillatory-zoned rims were selected for analyses. Data (figure 5)
from four reliable core analyses yield an upper intercept age of 1195 ± 11 Ma (MSDW = 1.3). Six analyses of zoned rims on yielded 1039 ± 10 Ma with MSDW of 0.63. The core ages are older than zircons dating intrusion of the Diana Complex (1154 ± 11 Ma) but overlap the ages of some older cores (1180–1190 Ma) in the Diana reported by Hamilton, et al (2004). The rim material represents igneous overgrowths on xenocrysts, as observed in other studies of the Lyon Mountain Granite suite in the Adirondack Highlands (McLelland, et al 2001). This age determination fixes the minimum age of penetrative deformation in this part of the Adirondack Highlands at ca. 1035 Ma, as the undeformed granite crosscuts foliated country rock.

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<tr>
<td>27.9</td>
<td>Intersection of Rt. 3 and Hermitage Road; turn right (north).</td>
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<tr>
<td>28.4</td>
<td>Stop 2 – Valentine Mine – Park on right shoulder of Hermitage Road</td>
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Stop 2: Valentine Wollastonite Mine

*Hermitage Road near Harrisville, NY* (UTM 18T 4885511N 469800E)

This long-exploited deposit of massive wollastonite is a high temperature skarn deposit formed between the western boundary of the Diana Syenite body and Gouverneur-type Adirondack Lowlands marble. Diopside, graphite (well developed hexagonal crystals) and sphene (titanite) are common in a wollastonite/calcite matrix. Blue calcite fills fractures and voids in the ore and veins of prehnite and calcite in the ore are common. Wollastonite in the main ore body is massive and typically lacks a deformational overprint. The Diana Syenite in and around this location exhibits a moderate to strong deformational fabric related to motion along the CCSZ. According to Gerdes and Valley (1994) skarn mineralization was driven either by intrusion of the hot (>1000°C and dry) Diana Syenite magma into the lowlands marble followed by upper amphibolite facies metamorphism, or mineralization was driven by fluids focused along the CCSZ during exhumation while the rocks were at temperatures ~675°C. Oxygen isotope values within the wollastonite and marble preserve high gradients across marble skarn contacts indicating that the marbles were not infiltrated by large quantities of fluid, however mass balance calculations require large volumes of fluid to produce the skarn. Late, fine-grained ‘retrograde’ wollastonite has isotopic signatures that suggest local infiltration of meteoric water along shear zones in the deposit (Gerdes and Valley, 1994).

Irregardless of whether the Diana Syenite intrusion drove wollastonite formation, here we see direct evidence for the 1155 Ma AMCG event in the Adirondack Lowlands coeval with the intrusion of voluminous amounts of AMCG magmas in the Adirondack Highlands terrane now located to the east. The lack of a deformational fabric in the deposit in conjunction with the moderate CCSZ deformational fabric noted in the Diana Syenite Body indicates that this deposit formed or recrystallized (grain coarsening) at the waning stages of CCSZ deformation, or occupied a protected position and escaped subsequent deformation. The latter explanation is less satisfactory. This is not the only skarn deposit to ‘escape’ Ottawan and CCSZ deformation that we will see today. Both the Jayville magnetite-vonseinite deposit and the Edwards diopsidite skarn (Stops 4 and 7) also show relatively minor deformation fabric in contrast to the surrounding granite gneisses which are strongly deformed. The lack of strong deformational fabrics in many, obviously fluid-driven mineralization zones underscore the importance of late (post Ottawan), fluid migration in and across the CCSZ.
Stop 3 – Mineralized Shear Zones in Diana Syenite
_Rt. 3 near Harrisville, NY_ (UTM 18T 4888498N 474283E)

The host Diana Syenite is moderately deformed at this location, with multiple cm- to dm-width shear zones with mylonitic to ultramylonitic fabric development. This outcrop also offers an opportunity to examine pegmatites/vein fill associated with the shear zones. These shear zones contain minerals documenting active shearing at temperatures ranging from upper amphibolite facies to greenschist facies with lower temperature shears active during the later stages of CCSZ deformation. The whole-rock oxygen isotope signatures of the mylonitic shear zones suggest high-temperature (upper amphibolite facies) equilibrium between shear zone minerals and host Diana Syenite (Cartwright and Valley, 1993). The pegmatite/vein fill in this outcrop contains large (0.2 m long) clinopyroxene crystals which can be identified easily by the

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<td>28.6</td>
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<td>29.1</td>
<td>Remington Corners intersection of Rts. 3 and 812; continue east on Rt. 3</td>
</tr>
<tr>
<td>31.6</td>
<td>Stop 3 – Diana Syenite – Park on shoulder of side road off E end of large roadcut.</td>
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Figure 6. Titanite-bearing pegmatite from Diana Syenite at Stop 3 (left) and sectioned titanite crystal showing U/Pb TIMS ages (from Heumann, et al 2004).
well defined basal partings. Along with cpx, large crystal masses of microcline and sphene (titane) are common. The large veins with associated pegmatites exhibit fabrics that range from undeformed to ultramylonite. Titanite from this outcrop has been dated (U/Pb) and yields a range of ages that span nearly the entire history of the Ottawan Orogeny from ca. 1080 to ca 1020 Ma. (Heumann, et al 2005; figure 6). Cm- to mm-thick pseudotachylite veins cut earlier foliation and shear zone fabrics, and are best seen on weathered surfaces at the east end of the outcrop on the north side of Rt. 3.

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<td>31.6</td>
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<tr>
<td>32.4</td>
<td>Bridge over Oswegatchie River in Harrisville. Continue east on Rt. 3</td>
</tr>
<tr>
<td>35.8</td>
<td>Intersection of Rt. 3 and Jayville Road. Turn right (south) onto Jayville Road</td>
</tr>
<tr>
<td>42.0</td>
<td>Mine dump and ore piles of Jayville Mine. Park on right adjacent to gravel pit.</td>
</tr>
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</table>

Stop 4 – **Jayville Iron Mine**
Jayville, NY (UTM 18T 4889739N 484888E)

Iron ore extraction at the Jayville mine began in 1854 and was all but abandoned by 1888 as operations under the Benson Corporation moved to the larger Star Lake deposit (Benson Mine) (Leonard and Buddington 1964). Today we will examine one of the old mine (Benson #1) shafts, and the piles of “concentrate” left on the roadside. The deposit was described by Leonard and Buddington (1964) as a skarn type deposit and in many ways this deposit is similar to the one at Clifton to the northeast. Magnetite deposits throughout the northwest Adirondacks are typically associated with late Ottawan (Lyon Mountain) granite intrusions into pyroxene-bearing calc-silicate gneisses (pyroxene granulites of Buddington, 1962).

**Mineralogy of the Jayville Deposit**

The ore at Jayville is concentrated in what Leonard and Buddington (1964) describe as biotite sköl and amphibole (ferrohastingsite)-ferrosilite skarn ores. These ores are hosted in massive amphibolite xenoliths hosted in perthitic hornblende granite (Jayville Granite). The “xenoliths” form a series of lenticular bodies that may have maintained structural continuity as the orientation of these folded amphibolite bodies parallel the foliation measured in a well-exposed xenolith of Irish Hill Gneiss located approximately 2 km to the east. Leonard and Buddington (1964) recognize at least two generations of ore deposition with the ore-rich biotite skölS having formed after the main amphibolitic skarn.

The mineralogy of this deposit is complex (see table below) and is the only locality in the world were the borate mineral vonsenite ($Fe^{2+}Fe^{3+}2BO_3$) belonging to the ludwigite series is found in great abundance. Leonard and Buddington (1964) report that in some samples vonsenite comprises 40 to 60% of the mined ore. In hand sample, vonsenite is nearly impossible to differentiate from magnetite and the two minerals are always in close association at this locality. Biotite-rich samples are the most likely to contain abundant vonsenite. Figure 7a-b show backscattered electron (BSE) images of vonsenite in an amphibole skarn (sample ADF) collected from the concentrate/spoil piles. These images show vonsenite grains that are partially replaced by magnetite (figure 7). Figure 7b shows a thin rind of magnetite separating vonsenite from amphibole. This image along with figure 8 show the growth of late biotite that is in turn replaced...
along the (001) cleavage by magnetite. A lighter colored rind of anthophyllite separates biotite from amphibole. In amphibolite skarns, magnetite is commonly included in amphibole grains as interstitial fill between amphibole grains and filling fractures in amphibole. These relationships indicate multiple generations of magnetite growth in these skarns. In addition to magnetite, amphibole, and vonsenite, the amphibolite skarns frequently contain biotite (usually secondary to amphibole), minor plagioclase feldspar and fluorite (included in amphibole). In the so-called biotite sköls, large biotite flakes and magnetite dominate the mineralogy. Magnetite is often found in planes (foliation?) that cut the sample separating biotite-rich regions. Biotite grains in these samples show little to no preferred orientation, are light in color and lack strong pleochroism/adsorption. Biotite in both the amphibolite skarns and biotite sköls is fluorine rich ranging from 2.3 to 5.8 wt % F. The fluorine content decreases as the host “skarn” grades from amphibole to biotite rich varieties.

Figure 7a. Backscattered electron image of vonsenite magnetite relationships in sample ADF.

Figure 7b. Backscattered electron images of magnetite replacing vonsenite and biotite in sample ADF.

Biotite-rich samples which Leonard and Buddington (1964) interpret to have formed after the amphibolite skarn ores contain a variety of minerals including large (mm) long flakes of biotite (fluorine 2-3 wt. %) with random orientations, magnetite, vonsenite, minor plagioclase feldspar, amphibole (incl. secondary anthophyllite), quartz (minor), chlorite and calcite as late fracture/vein filling material. Accessory phases include the zinc spinel gahnite, titanite, cassiterite, molybendite, and sphalerite. In thin section, magnetite invades biotite along disrupted (001) cleavage traces and occurs as interstitial grains (figure 7b). These samples represent the most evolved ore.

Conditions of ore emplacement at Jayville.

In many skarn and biotite sköls samples, magnetite growth along disrupted cleavage traces, fractures and as replacement of vonsenite indicate several episodes of magnetite growth. In addition to secondary magnetite, subhedral grains of magnetite are common as are magnetite grains included in amphibole. Texturally, magnetite is a member of the high grade (upper amphibolite-granulite facies) assemblage as well as a secondary mineral.
The temperatures for equilibration in amphibolite “skarns” at Jayville are constrained by plagioclase-hornblende geothermometer of Holland and Blundy (1994). P-T conditions for samples ABD (amphibolite ore) and ADE (amphibolite), based on the quartz absent edenite-richterite thermobarometer are presented in figure 9. Examination of these results show that these samples clearly record granulite facies to magmatic conditions and are well above the minimum melt conditions for the boron-bearing granite system (see figure 9). Since the ore contains vonsenite and fluorite, it is reasonable that the granite intrusive (Jayville Granite) was boron- and fluorine-bearing (see section on ore fluid chemistry). Temperatures of 720 - 745°C may represent a localized thermal excursion caused by intrusion of the Jayville Granite although recent work in the western Adirondacks (south of this location) show that peak Ottawan temperatures may have reached as high as 850°C at 6.6 kbar (Florence, 2005). These conditions, therefore, may reflect the regional peak or post peak of Ottawan metamorphism. Furthermore, these conditions are well within those needed to form granitic melts, especially if the protolith is rich in boron and/or fluorine. Streepey et al. (2001) report recrystallization temperatures for the Dana Hill Metagabbro (Stop 8) of over 720°C so these temperatures seem reasonable in terms of the regional thermal structure of the Adirondack Highlands during the Ottawan Orogeny.

**Fluid Chemistry at Jayville**

The ore deposit at Jayville was developed by multiple influxes of fluid through the granite and the xenolithic and country-rock calcsilicate gneisses. The nature of this fluid differs from an early episode of HF/HCl and Boron-rich fluid of likely magmatic origin through a subsequent fluxing of a H2O-CO2 (CO2-rich) fluid of more regional extent. This latter fluid infiltration is noted by several authors (Tyler, 1981, Streepey et. al. 2001, Johnson et al. 2004, Selleck et al. 2005) and drives widespread scapolite replacement of plagioclase in and along the CCSZ. At Jayville, this event is marked by scapolite and calcite growth in the skarn, granite, and calcsilicate gneiss.
Early fluid infiltration (related to granite emplacement)

Early fluids were Hf+HCl and boron-rich and similar in character to those of many exhalative ore deposits associated with granitic magmatism (see figure 10). The fact that the Jayville Deposit contains relatively minor sulfide minerals relative to magnetite indicates that the ore forming system was oxidizing in nature. The fluorine content of biotite varies greatly from sample to sample and overall, these samples do not obey the Fe-F avoidance rule (Munoz, 1984) indicating that the biotite may have been altered or partially reequilibrated by later fluids. Figure 10B shows that the fluorine content of biotite is fairly consistent for a given sample. One exception is sample ADB which is a hornblende “skarn” for which biotite compositions break into two distinct chemical groupings (see figure 10a, b). These groups represent different generations of biotite growth that equilibrated with distinct fluids. The shift in log (fHf/FCl) vs. log (fH2O/fHCl) for ABD biotite cannot be due to a simple change in temperature showing that, for this sample at least, biotite growth took place in the presence of an evolving fluid system(s).

Late fluid history

An informative symplectite intergrowth of low-Al calcic amphibole+quartz+calcite after diopside from the Irish Hill Gneiss is shown in figure 11. Symplectite intergrowths typically form when a mineral is rapidly driven out of its stability field. In this instance the cause for this reaction texture is most likely due to the infiltration of a CO$_2$-bearing fluid. A drop in temperature is not likely to be the cause as thermal change would be too slow to generate symplectite formation. This reaction occurs at temperature (at 5 kbar) at or below ~550°C and is clearly a post-Ottawan retrograde reaction. It does provide direct evidence for the infiltration of a CO$_2$-bearing fluid into the IHG. This infiltration event may also be responsible for the secondary calcite observed at the Jayville Deposit. The surrounding k-feldspar also marks a fluid infiltration event as it forms a patchy replacement of plagioclase feldspar. It is unknown if this classic potassium metasomatic texture pre- or post-dates symplectite formation in this sample.

A third retrograde reaction texture can be seen in figure 11 where rinds of pumpellyite and hornblende separate the low Al amphibole of the symplectite from the adjacent altered...
feldspar. This reaction resulted in the formation of a rind of hornblende (light rind on the BSE image in figure 11). This hornblende has higher K, Fe, and Al than the darker symplectite amphibole. The pumpellyite rind separates metasomatically produced kspar (expense of plagioclase) from symplectitic amphibole. This texture suggests a link between the plagioclase replacement and the pumpellyite forming reactions and appear to mark a still later infiltration of aqueous and potassium rich fluid into the sample late in the recrystallization history.

Figure 10a. Log (fHF/fHCl) vs. Log (H2O/HCl) plot for fluids in equilibrium with F-rich biotite from the Jayville Deposit. The calculations are based on the model of Zhu and Sverjensky (1991). Figure 10b. wt% F versus XMg (=Mg/(Mg+Fe+Ti+Mn)) in biotite. The Jayville samples do not show strict adherence to the Fe-F avoidance rule of Munoz (1984). These biotite grains may have suffered partial reequilibration. Note that sample ABD shows two populations of biotite based on F-Fe chemistry.
Bulk Chemistry of the Jayville Deposit

The bulk chemistry of the Jayville deposit cannot be discussed without an examination of the bulk chemistries of the surrounding granite and country rock calc-silicate gneiss (Irish Hill Type). In thin section, the Jayville granite contains perthite, plagioclase, quartz, and hornblende. Biotite is typically formed as a retrograde product after hornblende. Textures range from pristine igneous to moderately deformed. Flame mymerkite is common in many samples indicating some deformation even when no penetrative fabric is in evidence. Grain size and abundance of hornblende increase toward the center of the body. Two kilometers to the east of this stop a large xenolith of Irish Hill Gneiss structurally parallels the “skarn” xenoliths at the Jayville Mine. Further to the east (~2 km), the granite is in contact with Irish Hill Calcisilicate Gneiss. The western boundary is truncated by the Carthage Colton Shear Zone and/or Kalurah Lineament. Compositionally, the Jayville granite is a subalkaline metaluminous to peraluminous I to A-type granite. K2O contents tend to be lower than typically reported by McLelland et al. (2001) for Lyon Mountain Granite Gneiss but these rocks are otherwise similar in chemistry and are nearly identical in composition to Lyon Mountain Granite at the Benson Mine. REE and spider plots for the Jayville Granite are consistent with an anorogenic origin (Johnson et al. 2004). Sodic granite lenses and dikes are present.
Noting the preservation of igneous textures, LaMark et al. (2003) used the aluminum in hornblende geobarometer of Hollister to recover crystallization pressures for this granite body. LaMark et al. (2003) reports crystallization pressures of 3.7-4.2 +/- 1 kbar for the body. These conditions are similar to those reported by Florence (1995) for anatexis of gneisses at Port Lyden, New York and are well below the 6.6 kbar of peak Ottawan-aged metamorphism. These results suggest that the Jayville Granite may be late Ottawan and as suggested by Johnson et al. (2003) may represent pressure release melts formed during exhumation of the Adirondack Highlands along the Carthage Colton Shear Zone.

Figure 12. E-W cross section through the Jayville locality showing an interpretation of the subsurface relationships between the Jayville Granite (JG), Jayville Deposit, and the surrounding country rock (Irish Hill Gneiss). The coarse-grained and igneous textured granite is labeled HbG. Other symbols: mb: lowlands marble, Dia: Diana Syenite Body, CCSZ: Carthage Colton Mylonite Zone.

Intrusion dates for the younger granites (Lyon Mountain Series) in the Adirondacks range from ca. 1040 to 1030 Ma and although the granite at this locality has not been dated, the observation that in places the Jayville Granite lacks a strong penetrative deformation coupled with chemical (bulk and trace) similarities of this granite with known Lyon Mountain Granite elsewhere in the northwestern Adirondack Highlands support a late Ottawan age for this body as well. Since intrusion of the Jayville Granite resulted in (at least in part) the formation of the Jayville iron ore deposit, a late to post-Ottawan origin is consistent with the coarse texture and lack of deformation recorded by most of the “skarns” and ores at this location.

To the east, the Jayville Granite is in contact with calcisilicate rocks mapped as the Irish Hill Gneiss. The Irish Hill Gneiss was described by Buddington (1964) and lumped into a mapping unit referred to as the pyroxene granulite gneiss which appears on the current New York State Map (Adirondack Sheet) as mu (metamorphic undifferentiated, or csm (calcsilicate marble). Hall (1984) named the unit the Whippoorwill Corners Gneiss in recognition of a large road cut at the Corners. The best and most characteristic outcrop of this unit, however, is exposed at the intersection of the Degrasse-Fine Road and Irish Hill Road leading Johnson (2003) to rename the unit. In outcrop, the Irish Hill Gneiss is compact foliated and grey green in color. In most locations, the unit is cut by pink granitic pegmatite ranging from stringers to m-scale pods to large masses. In thin-section, the gneiss is composed of apple-green diopside + plagioclase + microcline (perthite) + quartz + titanite (sphene) +/- vesuvianite + apatite + monazite + zircon +/- calcite +/- pyrite +/- scapolite. Amphibole (hornblende to tremolite and anthophyllite), biotite, chlorite, calcite, pumpellyite and epidote are common as secondary/alteration minerals. Pegmatite stringers in the IHG contain perthite (microcline host) + quartz + minor hornblende.

Figure 13a presents a series of Harker-type variation diagrams for the rock types present in and around the Jayville mine. These diagrams include analyses of the Jayville ore taken from
Leonard and Buddington (1964). The simple chemical trends between the Irish Hill Gneiss, amphibolite “skarn”, “skarn ore”, biotite-rich (Sköl), and ore samples suggest that the ore-bearing units were produced via metasomatic alteration of the Irish Hill Gneiss. Ore formation was driven in part by the introduction of boron and fluorine rich (aqueous?) fluid driven into IHG xenoliths upon introduction and subsequent crystallization of the Jayville Granite. Johnson et al. (2005) demonstrates that the observed chemical variations between the IHG and the ore can be explained via a series of incongruent dissolution reactions involving the replacement of diopside and feldspar by amphibole and subsequent replacement of amphibole by biotite (Mg-rich, F rich) and magnetite.

Figure 13b shows variations in chemistry between the Irish Hill Gneiss and the ores. The linear behavior for Si vs Na and Si vs. the plagioclase compositional vector (2Ca+3Na) indicate that the skarn and sköl ores are related to the surrounding Irish Hill Gneiss and that the removal of plagioclase feldspar was an important factor in the ore forming process.
Figure 13a. Variation diagrams for bulk oxides (Harker type) showing relationships between Irish Hill Gneiss (country rock), various “skarn”, and ore at the Jayville Mine.
Figure 13b. Variation plots on a molar basis showing chemical trends between the Irish Hill Gneiss (IHG) and the various “skarn”, “skarn Ore” Biotite Sköl and ore at the Jayville Deposit. Note the 2.5:1 slope for Na vs. Si. Y axis on the second plot is a feldspar vector and the linear relationship shown by the data strongly indicates the importance of the mobilization/breakdown of plagioclase in the ore forming process. (no sodium data were available for the ore analyses)

Figure 14 shows the relative additions to and subtractions (molar basis for each cation) from the Irish Hill Gneiss composition (average) to produce the “skarn” ores. The large addition of iron is compensated largely by loss of silica. It is interesting to note that potassium remains little changed in this process while sodium exhibits a progressive depletion. In addition, magnesium is added to all but one of the skarn ores. The reactions leading to “skarn” and ore formation involve the breakdown via the progressive and incongruent dissolution of the original mineralogy of the Irish Hill Gneiss. These reactions result in a large volume loss (excess of 70%) of the original IHG xenolith.
Figure 14. Ore-bearing “skarn” from the Jayville Deposit normalized to the bulk composition of the enclosing Irish Hill Gneiss (pyroxene-granulite of Buddington). The chart is plotted on a molar (cation) basis and values represent molar% ore-molar% Irish Hill Gneiss. The chart shows that relative to the IHG, ore bearing skarns show marked addition of Fe and Mg with losses of Si, Al, and Na. Potassium remains little changed between protolith and ore.

NOTE: Although Leonard and Buddington (1964) view the Jayville Deposit as a skarn-type mineralization, this deposit does not fit the classic definition of a skarn. At Jayville, the granite does not intrude into a marble, but rather a calc-silicate gneiss that is at or near to granulite facies conditions. The strong temperature gradient associated with classic skarn mineralization is not present. This deposit is the result of high temperature metasomatism within a regional granulite grade event. The mineralization is due more to high integrated fluid:rock ratios over the waning stages of the Ottawan Orogeny. The interesting question here is where, did these fluids originate, as the Adirondack Highlands remains one of the classic examples of fluid absent metamorphism! The low intrusion pressures recorded by the Jayville Granite and the proximity of the deposit to the Adirondack Lowlands (across the Carthage-Colton Shear Zone (CCSZ)) may provide the answer. If this deposit was formed (in part) at the waning stages of the Ottawan Orogeny at a time when the Adirondack Highlands were being exhumed along the CCSZ, this region may have served as a locus of fluid flow along and across the CCSZ with the introduction of fluid from the Lowlands (hanging wall) block.
Table 1. Chemical composition of the main minerals from the iron ore (provided by Marian Lupulescu)

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1. Magnetite; 2. Hedenbergite (Wo45.17En30.31Fs21.46Ac3.07); 3. Diopside (Wo60.87En0.23Fs38.89); 4. Diopside (Wo46.85En8.78Fs41.22Ac3.14); 5. Diopside (Wo47.79En8.26Fs40.52Ac3.42); 6. Andradite (And57.46Gro25.77Alm10.09Sps3.36Pyr0.12Mor3.19); 7. Potassium fluorian ferro-edenite; 8. Andradite (And54.94Gro25.78Alm12.74Sps4.41Pyr0.36Mor1.76); 9. Potassium fluorian hastingsite; 10. Potassium fluorian hastingsite; 11. Potassium fluorian ferro-edenite; 12. *Vonsenite (Leonard & Vlasidis, 1961) – Empirical formula: (Fe²⁺₁.₉₂Mn₀.₀₁Mg₀.₀₄)Σ₁.₉₇(Fe³⁺₀.₉₆Al₀.₀₇Ti₀.₀₀₄)Σ₁.₀₃B₀.₉₆O₅; Fe₂O₃ and H₂O were calculated from stoichiometry.
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<th>Cum. Mi.</th>
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<td>42.0</td>
<td>Intersection of Jayville Road and Rt. 3; turn right (east) onto Rt. 3</td>
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<tr>
<td>48.2</td>
<td>Intersection of Rt. 3 and Rt. 58; turn left (northwest) onto Rt. 58. After driving through the hamlet of Fine, we will pass several large outcrops of Irish Hill Gneiss and of pink leucogranitic gneiss. The leucogranitic gneisses are highly deformed. As we proceed west on Rt. 58, we will pass through outcrops of hornblende granite gneiss (Eastern Granite Gneiss of Hall, 1984). The Highlands-Lowlands boundary is constrained between the last outcrop of Eastern Mountain Granite Gneiss and the first outcrop of Diana Syenite, which is also a pink granitic gneiss along Rt. 58. The Diana Syenite can be identified by the presence of abundant rounded augens of grey plagioclase feldspar.</td>
</tr>
<tr>
<td>55.7</td>
<td>Stop 4 – Tectonites of the CCSZ in Diana Complex granitoids. Park on right shoulder.</td>
</tr>
<tr>
<td>60.7</td>
<td>STOP 5 Carthage-Colton Shear Zone mylonites in Diana Complex Granitoid: Route 58 near Edwards, NY (UTM 18T 4903228N; 483644E)</td>
</tr>
<tr>
<td></td>
<td>Diana Syenite (granitic phase) shows strong ductile deformation with well developed c/s and l/s tectonites. A range of mylonitic fabrics are present. A near-vertical late brittle fault zone contains angular blocks of country rock in a calcite + quartz matrix. This fabric suggests relatively high fluid pressure in the fault zone during deformation. Note also the strong brittle overprint as marked by the abundant and closely spaced joints sets. We are once again crossing the boundary between the Adirondack Highlands and the Lowlands. Kinematic indicators are present in the c/s and l/s tectonites.</td>
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<td>Continue west on Rt. 58.</td>
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<td>Intersection with Harmon Rd. Turn right (northeast) onto Harmon Road.</td>
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<tr>
<td>63.4</td>
<td>Stop 5 – Park the vehicles off to the right at the junction of Harmon Road and Stammerville Road. Proceed to the small outcrops on either side of the roadway.</td>
</tr>
</tbody>
</table>

Stop 6 – Shear zones in Diana Complex syenite
*Harmon Road near Edwards NY* (UTM 18T 4905968N, 482850E)

The outcrop on the north side of the road shows numerous anastomosing shear zones. Sheared syenite contains hornblende (Cl-rich) + biotite + plagioclase + perthite + quartz + titanite ± Fe-Ti oxide minerals. Relict clinopyroxene rimmed by amphibole and amphibole + chlorite is common, as is scapolite replacement of some plagioclase crystals.
Figure 15. Two-feldspar geothermometry of shear zone samples from Stop 6.

Figure 15c and 15d show backscattered electron images of feldspar pairs used for two feldspar geothermometry. Both samples (SE-TF-8 SE TF-11) were collected from the cores of shear zones in these outcrops. Re-integration of the perthite was accomplished using electron microprobe analyses using a 5 micron (SE-TF-8) and 10 micron (SE-TF-11) beam size over an analyses grid. The 150 analyses (grid points) were used to reintegrate the composition for SE-TF-11 and 45 analyses (grid points) were used for SE-TF-8 (note scale differences, figures 15e and 15e). Temperatures were calculated using SOLVCALC and the thermodynamic model of Elkins and Grove (1990). Temperatures calculated for reintegrated feldspar compositions are 454-467°C for sample SE-TF-8 and 419-461°C for sample SE TF 11 (for pressures of 3-6 kbar). These results are similar to those reported by Lamb (1993) for shear zones in the Diana Syenite Complex to the south near Harrisville, New York. Two feldspar geothermometry is plagued by resetting and so these temperatures are considered to represent minimums. The presence of biotite and chlorite which is not retrograde to the deformation in these shear zones indicates that shearing took place at upper greenschist to lower amphibolite facies.

Samples SE-TF-8 and SE TF-11 have been dated by EJ using U/Pb titanite and ^{39}Ar/^{40}Ar for hornblende. The intrusion age for the Diana Syenite Complex has been dated to 1155 ± 4 Ma (Grant et. al. 1986). In shear zones, titanite replaces Fe-Ti Oxides probably via a reaction involving plagioclase feldspar, and calcic amphibole. Titanite is also found in the syenite outside of these shear zones but it is rare. Away from the shear zones, Fe-Ti oxides are common while they are nearly absent in the shear zones. These observations suggest that titanite growth accompanied recrystallization during shearing, and since the recrystallization conditions during...
shear zone formation range only to the lower amphibolite facies and probably well below the 600-650°C closure temperature for Pb in titanite, U/Pb ages are interpreted to represent growth ages and hence the time of shearing.

<table>
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<tr>
<th>U/Pb titanite (sphene) SE TF 8</th>
<th>39Ar/40Ar Hornblende SE TF 8</th>
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<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
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<tr>
<td>Weighted Mean: 207Pb/235U age 1041.3 +/- 1.7 Ma 206Pb/238U age 1042.1 +/- 1.8 Ma</td>
<td>Plateau age = 979.6 ± 8.6 Ma (1σ) MSWD = 0.16, probability = 0.998 Includes 100% of the 39Ar</td>
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</table>

Figure 16 – U-Pb and Ar-Ar geochronology for titanite at stop 6.

The U/Pb ages for titanite are concordant and constrain the time of titanite growth during shearing to ~1041 Ma (see figure 16). 39Ar/40Ar data for amphibole from this sample yield a flat spectrum with a plateau age of 979.8 +/- 8.6 Ma. The closure temperature for Ar in hornblende is 500-550°C, and these ages are interpreted to represent cooling ages. Note the flat release spectra which are characteristic of rapidly cooled systems.

Sample SE-TF 11: (Same outcrop as SE-TF-8) Geochronology data for the SETF-11 is shown in figure 17. Three fractions prepared from this sample all yield concordant ages that range from 1054 to 1034 Ma. These ages are interpreted to represent multiple generations of titanite (sphene) growth in the shear zone. The range in ages determined for SE-TF-11 are similar to those found at Stop 3 near Harrisville, but occur in multiple titanite crystals. Once again interpretation U/Pb geochronological results suggest a prolonged period of titanite growth and/or recrystallization along the CCSZ.

<table>
<thead>
<tr>
<th>Cum. Mi.</th>
<th>Turn around to head west on Harmon Road to Rt. 58 intersection</th>
</tr>
</thead>
<tbody>
<tr>
<td>63.4</td>
<td>Turn right (northwest) onto Rt. 58</td>
</tr>
<tr>
<td>64.4</td>
<td>Stop 7 – Edwards diopsidite. Park on right shoulder of road adjacent to outcrop</td>
</tr>
</tbody>
</table>
**U/Pb titanite (sphene) SE-TF-11**

<table>
<thead>
<tr>
<th>Fractions</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>207Pb/235U ages</td>
<td>1054.0+/-2.5Ma</td>
<td>1034.1+/-3.2Ma</td>
<td>1045.1+/-3.2Ma</td>
</tr>
<tr>
<td>206Pb/238U ages</td>
<td>1053.2+/-2.2Ma</td>
<td>1034.3+/-3.0Ma</td>
<td>1046.6+/-2.9Ma</td>
</tr>
</tbody>
</table>

Figure 17. U-Pb geochronological data on titanite from stop 6.

**Stop 7 – Diopside-calcite skarn near Edwards Village**

*Rt. 58 near Edwards Village* (UTM 18T 4906984N 480873E)

This skarn body marks the contact between a grey granitic gneiss which exhibits a strong foliation and lineation and a marble belt which extends across the adjacent lowland to the northwest. Green diopside with bluish amphibole, sulfides and rare molybdenite form the bulk of the exposure. Large diopside crystals to 20 cm length project into the calcite-filled vein. The cause of the varying coloration of calcite is unknown. It is interesting to note that the skarn does not show a deformational overprint while the rocks immediately surrounding it have strong deformational fabrics.

<table>
<thead>
<tr>
<th>Cum. Mi.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>65.0</td>
<td>Continue of Rt. 58 west for 0.1 mile and turn right onto Maple Avenue. Follow Maple Avenue into the town of Edwards.</td>
</tr>
<tr>
<td>66.0</td>
<td>Turn right (east) on Co. Rt. 24</td>
</tr>
<tr>
<td>69.1</td>
<td>Intersection of Co. Rt. 24 and Hermon Road; continue east on Co. Rt. 24.</td>
</tr>
<tr>
<td>71.3</td>
<td>Stop 8. Dana Hill Metagabbro. Park on right shoulder. Exposures to be visited are in the woods across the road to the north of the parking spot.</td>
</tr>
</tbody>
</table>

**STOP 8 Dana Hill Metagabbro**

*Co. Rt. 24 near Edwards, NY* (UTM 18T)

Park the vans and climb the hill on the north side of the road. On the trail up the hill we will pass several sub-meter width EVENT 4 shear zones.
The Dana Hill Metagabbro preserves multiple deformation and veining events ranging from granulite facies ductile to sub-greenschist facies brittle events (see appendix). In many cases, cross-cutting relationships allow for the determination of a sequence of events. To date, six major deformational/veining events have been identified (Johnson et al. 2004; Streepey et al. 2001). At this stop we will examine the complex deformational events recorded in the body. This outcrop along with the outcrops at the top of the hill across the road, exhibit all 6 deformational events. We will start at the far end of the outcrop and examine the deformational sequence of events recorded. From the oldest to the youngest, this outcrop preserves EVENT 1 mega-shearing, EVENT 3 hornblende veining, EVENT 4 sub-meter shearing, and EVENT 6 folding and brecciation. EVENTS 2 and 4 can be observed at the top of the hill across the road. Events 3 through 5 take place in the presence of a fluid or fluids that drive scapolite replacement of original plagioclase feldspar in the host metagabbro. In the Diana Syenite, cm to dm-wide shear zones (dated to 1052-1034 Ma) also exhibit scapolite replacement of plagioclase feldspar. This scapolitization event is widespread in and around the CCSZ from just north of Harrisville to Colton and is present in both the Highlands and Lowlands terranes, therefore, marks a common event for both terranes.

The goal of this stop is to demonstrate that the Dana Hill Metagabbro body acted as a rigid block during deformation. In some instances, cumulate igneous textures have been completely preserved while in other exposures the gabbro is ultramylonitic in texture. The resistance to deformation in the Dana Hill Metagabbro resulted in an episodic response to the applied stress leading to discrete pulses of deformation. This body preserves individual and distinct events that record the much of deformational history of the region. The earliest shear zones are massive (30m wide) and mylonitic to ultramylonitic. These shear zones record recrystallization temperatures in excess of 700°C. Subsequent shearing events are dramatically
different forming sub-meter wide anastomosing shear zones at recrystallization temperatures at or below 700°C. The last deformation events to affect the Dana Hill Metagabbro transition to brittle failure at low to sub greenschist facies conditions. The deformational history is one of an exhuming footwall with deformation beginning in the granulite facies and eventually passing through the brittle-ductile transition at greenschist to sub greenschist facies conditions. We will examine these events and the available geochronologic data for this complex outcrop.

EVENT 1 shearing accounts for the mylonitic character of the outcrop as a whole. The foliation here dips steeply yet transport lineation orientations plunge shallowly to the north-northwest. Kinematic indicators yield dextral shear sense. These mylonites contain recrystallized clinopyroxene + amphibole + sphene+ plagioclase (An$_{45-51}$) along with accessory minerals (apatite, zircon, +/-quartz). Amphibole compositions for these samples range from Ferroan Pargasite to Magnesian Hastingsite. Chlorine contents are high for all amphiboles studied ranging from 2 to 18% hydroxyl site occupation. Amphibole and plagioclase chemistries are presented in Johnson et al. (2004). All samples exhibit a well-annealed polygonal fabric with perfect 120° triple junctions between grains. Grain sizes show a narrow range of variation for these samples averaging in the range of 100-300 µm for polygonal plagioclase. Re-crystallization temperatures for event 1 samples using the quartz-free geothermometer Holland and Blundy (1994) range from 744 to 770°C (for 6kbar). Scapolite replacement of plagioclase is not present in EVENT 1 shears at this location.

Hornblende veins cut the foliation at high angles in zone a. Hornblende veining belongs to EVENT 3 (we do not see EVENT 2 shear zones in this outcrop.). The hornblende veins are surrounded by reaction halos were scapolite replaces plagioclase feldspar in the host metagabbro. These halos can extend several mm into the surrounding metagabbro. In zone b (see figure 10), the metagabbro is folded and the open to nearly chevron folds are marked by EVENT 3 hornblende veins. What looks like a rotated cleavage fanning across the folds are in fact the old EVENT 1 mylonitic foliation surfaces. This zone transitions into the chaotic breccia zone (EVENT 6; zone c).
Brecciation (EVENT 6) was accompanied by the growth of actinolite, biotite and chlorite after hornblende, and the breakdown of scapolite to a mixture of albite, epidote, and calcite. Breccia sample H-6A preserves rafts and clots of scapolite-rich mylonitic metagabbro with an invasive matrix of fibrous mats of chlorite, epidote, and actinolite. Hornblende (ferroan pargasite) that has not suffered alteration to actinolite is fluorine-rich (average F = .75 wt%; average Cl = .57 wt%).

At the eastern margin of the breccia zone, an EVENT 4 sub-meter scale shear zone is exposed. This shear (sample CR-3-87 Johnson et al. 2004; Streepey et al. 2001) preserves deformation textures (little annealing) and contains the assemblage hornblende + recrystallized clinopyroxene + plagioclase An_{32} + Fe-Ti oxides + scapolite (minor). Plagioclase-amphibole equilibrium pairs where present yield re-crystallization temperatures for event 4 shearing in the range of 730°C to 680°C ±50°C for a pressure of 6 kbar.

**Geochronology of STOP 7**

Figure 20 shows the U/Pb isochron data for shear-zone grown sphene (titantite) for this outcrop. U/Pb data presented represent EVENTS 1, and 4 and yield a tightly constrained age of 1020.7 +/- 3.1 Ma. Since recrystallization temperatures for events 1 through 4 occur at temperatures above the closure temperature for U/Pb in titanite, these dates represent cooling ages for the body. The consistency of U/Pb titanite ages for samples throughout the body indicates that all (Events 1-5) shearing and veining occurred prior to 1020 Ma.

The results of the 39Ar/40Ar for hornblende in these samples is presented in figure 12. These data mark the date at which these samples cooled through the 500-550°C closure temperature for hornblende. The data from this and outcrop A-4 (opposite side of the road) are quite interesting. The results yield two cooling ages: one at ~985-1000 Ma and a second (recorded in two shear zones) at ~935-940 Ma. The latter and younger ages were determined from two samples at this outcrop. The 945 Ma age was used by Streepey et al (2001) to constrain the timing of the last stage of movement along the CCSZ. Only one of these samples (CR-2A2) yields a statistically clear plateau. Both shear zones are overprinted by the later brecciation event and, therefore, may have suffered some Ar loss during this event. Conversely, hornblende overgrowths on undeformed cumulate textured Dana Hill Metagabbro sample from the outcrop across the road also yield a 945 Ma age indicating hornblende growth at this time. Whether or not the 945 Ma age represents renewed deformation remains a point of controversy. The bulk of the shear zones and veins studied in the Dana Hill Metagabbro (and surrounding Diana Syenite body) record 39Ar/40Ar hornblende cooling ages of 985-1010Ma. The generally flat spectra for 39Ar/40Ar data indicate rapid cooling with little to no post-closure disturbance. The Dana Hill Metagabbro outcrops visited today provide an overview of the deformational and thermal history associated with movement along the CCSZ. Since this body is located at the CCSZ detachment, it records the entire deformational history. During exhumation of the footwall (Highlands), the width of the deformation zone narrows with falling temperature and confining pressure and eventually, deformation is confined to regions directly adjacent to the detachment surface. Due to its the resistance to strain, preexisting deformational fabrics in the Dana Hill body were not completely overprinted, leading to the complexly deformed body that we see today. Deformation in the Dana Hill can be broken down into three distinct regimes with falling temperature and pressure: 1. mega-shearing, 2. sub-meter width shearing, 3. brittle failure. Early veining episodes may have been driven by fluid infiltration into the body (driving scapolite-forming reactions). The origin(s) of these fluids (CO_2 and HCl/NaCl rich) is unknown, but a likely source is from exhalation/mobilization of evaporite deposits in the adjacent lowlands hanging wall block. This origin for the metasomatic fluids fits well with the observed and widespread scapolite veining and scapolite replacement of original plagioclase feldspar in the lowlands near Pierrepont (Tyler, 1981; Selleck, pers. comm.).
Today we have examined evidence for significant metasomatism along and across the Carthage-Colton Shear Zone. The evidence for late to post-Ottawan fluid activity comes from:

1. Scapolite replacement of plagioclase which is common in the Diana Syenite Body, Dana Hill Metagabbro, and the Jayville Deposit. Formation of undeformed hornblende and hornblende + tourmaline veins in the Dana Hill metagabbro.

2. Deposition of the magnetite, vonsenite ores at Jayville which are associated with intrusion of the Jayville Granite. The undeformed character of the ore body and portions of the granite indicate late to post deformational intrusive and mineralizing events. The Jayville ore and surrounding country rock record several episodes of fluid-driven recrystallization/mineralization accompanied by significant and incongruent dissolution of phases.


4. Retrograde breakdown of scapolite, diopside and hornblende to form epidote+actinolite+calcite +quartz assemblages in brecciated Dana Hill Metagabbro.

5. Formation of post-deformation wollastonite and late calcite + prehnite veins at the Valentine Mine.

The late Ottawan history along the CCSZ is marked by fluid infiltration. Evidence for multiple fluid infiltration events of both local (magmatic in origin as at Jayville) and regional scales are found throughout the region and mark an active late Ottawan history of ductile to brittle deformation accompanied by granite intrusion and hydrothermal metasomatism. Influx of CO$_2$ and Cl rich fluids that drive widespread replacement of plagioclase by scapolite are more regional
EVENT 1 MEGA-SHEAR CR-12

EVENT 2 SHEAR CR6-A4

EVENT 4 SHEAR CR-2 A2

EVENT 5 HORNBLENDE TOURMALINE

Figure 21. U/Pb and Ar/Ar data for the Dana Hill Metagabbro Body.

in their distribution. These fluid infiltration events drive upper-amphibolite to granulite facies reactions in the Dana Hill Metagabbro with recrystallization temperatures in excess of 680°C, and their effects tend to be concentrated in and along cm- to m-scale shear zones and veins. Boron-rich fluids are associated with high temperature mineralization at Jayville, and the emplacement of lower temperature undeformed hornblende + tourmaline veins found in Dana Hill Metagabbro. The boron and fluorine-rich fluid at Jayville is believed to be of magmatic origin (separation of a low viscosity non-condensed fluid during crystallization of the Jayville Granite). In the Dana Hill Metagabbro, the source of the boron (marked by the late tourmaline + hornblende veins) is unclear, although late Ottawan-aged Lyon Mountain granite gneisses (intrusive into Irish Hill Gneiss) are located less than 1 km to the east of the gabbro body and may have served as a fluid and boron source for these veins. Because of the general lack of tourmaline in the Irish Hill Gneiss and Jayville and Lyon Mountain Granite bodies, the ultimate source for boron is unclear. If the late Ottawan granite intrusives are the boron source, the lack of tourmaline may simply indicate that a boron rich fluid had separated from the magma prior to crystallization. Enough!
Dana Hill
Metagabbro
Sillimanite nodular granite gneiss
(includes the Silver Hill granite)

Irish Hill Gneiss

Hbl Granite

Jayville Granite

Dry Timber Lake Granite
Figure 22. Generalized geologic map showing stops on day 2. Stop 4 is not shown. The map position of the CCSZ is approximate and based on brittle fracture GIS data from the New York State Geological Survey. Uncolored map areas are mixed metasedimentary and metaigneous rocks.

Field guide road log day 2

<table>
<thead>
<tr>
<th>Cum. Mi.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>Road log begins at intersection of Park Street (Co. Rt. 27) and Rt. 11 in the Village of Canton. Turn right (east) at traffic light from Rt. 11 onto Park Street.</td>
</tr>
<tr>
<td>2.2</td>
<td>Intersection of Co. Rt. 27 and Russell Road. Continue southeast on Co. Rt. 27. Intersection of Co. Rt. 27 and Co. Rt. 29 at Waterman Hill. Continue south on Co. Rt. 27.</td>
</tr>
<tr>
<td>5.0</td>
<td>Stop 1, Day 2. Park on right shoulder. Roadcut is on opposite side of road.</td>
</tr>
</tbody>
</table>

Stop 1 – Scapolite+amphibole veins in metagabbro

*Waterman Hill near Canton (UTM 18T 4931136N 492289E)*

The outcrops at this stop consist of interlayered metagabbro (opx+cpx+plag+ilm+hbl) and leucogneiss (qtz+ksp+plag+/-biotite) that are part of a belt of mostly metaigneous lithologies defining a refolded isoclinal fold termed the “Pierrepont Sigmoid”, originally mapped by Martin.
(1916) and thoroughly examined by Tyler (1979). Of particular interest in the exposure on the east side of the road are cm-scale amphibole-scapolite veins developed in the mafic lithology. The veins formed in association with NE-striking, SE-dipping extension fractures within the mafic rock. The vein mineral system consists of a Cl-rich amphibole plus Cl-scapolite vein margin that represents Cl-metasomatism of the vein wallrock, and a vein center consisting of Cl-amphibole+Cl-scapolite plus calcite and quartz. Both amphibole and scapolite form cm-scale radiating crystal aggregates within the carbonate-bearing vein center. Chlorine content in scapolite (~Me50) within the vein fill is commonly 1.5-2.5 wt %; amphibole within veins is ~1.8-3.4 wt. % Cl. We do not yet have precise P, T constraints on the vein mineralization at this locality, but temperatures of greater than 650°C are likely based on the occurrence of orthopyroxene-bearing assemblages in some vein margins in Pierrepont Sigmoid metagabbro (Tyler, 1979). EDS spectral transects and whole rock analyses of veins and wall rock clearly demonstrate that hydrothermal fluids introduced and/or redistributed Cl, K and Na (see below). Trace element data suggest mobility of Ba and Zr. Aqueous fluid inclusions in quartz within the vein centers have halite daughter crystals (Tyler, 1979); hi-density CO₂ inclusions are present in quartz and scapolite within the veins. Mineralized vein orientations (Figure 27) within a 20x10 km area in this vicinity generally indicate NW-SE directed extension, and are consistent with fracture formation as a consequence of extension and brittle failure of metagabbro during regional extension related to detachment along the CCSZ. We interpret these Cl-metasomatic veins as syn-extension features, with associated hydrothermal fluids derived either from spatially associated metasedimentary rocks, e.g. marble, or introduced as magmatic fluids from the belt of ca 1045 Ma leucogranite plutons which lie to the SE of the CCSZ and could underlie this area.

Later mm-scale chlorite+calcite veinlets are often spatially associated with the earlier amphibole-scapolite veins. These later veinlets lack the consistent orientation of the Cl-metasomatic veins and often form minor, low-angle extensional faults with slickenlines. Interlayers of leucogneiss in this unit generally lack brittle fractures suggesting that strong ductile fabrics (protomylonitic to mylonitic at this outcrop) developed to accommodate the strain that caused brittle failure of the metagabbro. Where the leucogneiss is fractured, Cl-biotite may mark the metasomatic fracture halo.

Figure 23a. Fractures with metasomatic wallrock alteration at Stop 1, Day 2. Note central vein fill with calcite/quartz/scapolite/amphibole and marginal amphibole/scapolite alteration halo

Figure 23b. Thin-section view of vein (right center), scapolite+Cl-amphibole alteration halo and less-altered country rock metagabbro. Note scapolite crystals in vein surrounded by calcite and quartz. Scale bar at top in mm.
Figure 24a. Scapolite and amphibole in vein; note calcite matrix. Width of field is ~6 mm

Figure 24b. Partially scapolite-replaced plagioclase at periphery of vein margin alteration zone. Crossed polars. Width of field ~2 mm

Figure 25a. Normalized counts from EDS scan across vein from Stop 1. Central vein fill consists of calcite plus quartz. Vein margin is amphibole+scapolite.

Figure 25b. Whole rock abundance (XRF) of silica in mm-thick slices taken progressively away from vein.

Figure 26a. Whole rock abundance (XRF) of K$_2$O in mm-thick slices taken progressively away from vein.

Figure 26b. Whole rock abundance (XRF) of Na$_2$O in mm-thick slices taken progressively away from vein.
Cum. Mi. | Description
--- | ---
6.7 | Continue south on Co. Rt. 27
10.1 | Intersection of Co. Rt. 27 and Co. Rt. 24 at Stone’s Schoolhouse Corners. Turn left (northeast) onto Co. Rt. 24.
11.3 | Intersection Co. Rt. 24 and Selleck Rd. Turn right (east) onto Selleck Rd.
12.9 | Intersection of Selleck Rd. and Buck Pond Rd. Continue east on Selleck Rd.
15.3 | Intersection of Selleck Rd. and Buck Pond Rd. Turn right (south) onto Buck Pond Rd.
16.3 | Stop 2. Low outcrops on both sides of road. Park on right shoulder beyond driveway. Walk back to east to examine exposures.

**Stop 2, Day 2 – Nodular Leucogranite in the Carthage-Colton Mylonite Zone**

*Buck Pond Road near Selleck’s Corners, New York (UTM 18T, 501304, 4924262)*

Numerous natural outcrops and small road cuts along Buck Pond Road expose quartz-microcline and quartz-mesoperthite leucogranite with common centimeter- to meter-scale quartz-sillimanite segregations, veins, and nodules. The leucogranite is locally gneissic with northwest-dipping banding. Quartz-sillimanite segregations (figure 28, 29) are commonly drawn out into elongate, cm-scale rods surrounded by equigranular quartz-mesoperthite granite. Sillimanite crystals form a mineral lineation in deformed segregations, but these oriented segregations are also crosscut by slightly later granitic veins that contain sillimanite. Sillimanite is often partially replaced by muscovite. The quartz-sillimanite segregations are interpreted as magmatic-hydrothermal in origin, forming via leaching of granite and granitic magma by Cl-rich, acidic fluids during granite pluton emplacement (McLelland, et al 2002). Later ductile strain and continued magmatic intrusion deformed and re-oriented the quartz-sillimanite nodules. Equigranular, coarse, pegmatitic quartz-microperthite granite surrounds some quartz-sillimanite in strain sigmoids that indicate a top-down to the northwest transport. Outcrops of leucogranite south of Buck Pond Road are more massive and contain diffuse pegmatitic zones and quartz veins.
typical of the Lyon Mountain Granite of the Adirondack Highlands. This quartz-sillimanite nodular granite is mappable for ~ 12 km along strike to the southwest as a 1-2 km wide belt immediately southeast of the mapped extent of the CCSZ.

This outcrop was sampled for U-Pb SHRIMP zircon geochronology (Selleck, et al, 2005). Zircons were separated from coarse-textured quartz-microperthite granite that forms a 10-cm-thick band irregularly intrusive into quartz-sillimanite nodule–bearing quartz-microcline gneiss. Nine age determinations on well-developed, oscillatory-zoned rims (Figure 29) give a weighted mean age of 1046 ± 7 Ma. We interpret this result as documenting intrusion of 1046 Ma granite during active extension on the Carthage Colton Shear Zone at this site.
Figure 30. Polished slab of quartz-sillimanite granite from Buck Pond Road locality showing relationships between quartz-sillimanite segregations, equigranular leucogranite, gneissic ‘country rock’ and quartz veins. Note magnetite within quartz-sillimanite nodule at right-center. Slab is approximately 25 cm wide.

<table>
<thead>
<tr>
<th>Cum. Mi.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.3</td>
<td>Return to vehicles; continue west of Buck Pond Road.</td>
</tr>
<tr>
<td>20.7</td>
<td>Intersection of Buck Pond Road and Selleck Road; turn left (west) onto Selleck Rd.</td>
</tr>
<tr>
<td>22.3</td>
<td>Intersection of Selleck Road and Co. Rt. 24. Turn left (southwest) onto Co. Rt. 24.</td>
</tr>
<tr>
<td>23.4</td>
<td>Intersection of Co. Rt. 24 and Co. Rt. 27. Turn left (south) onto Co. Rt. 27</td>
</tr>
<tr>
<td>26.5</td>
<td>Stop 3. Road cut on left (east) side of Co. Rt. 27. Park on right side of road south of intersection.</td>
</tr>
</tbody>
</table>
Stop 3, Day 2

**Pegmatite Intruding Carthage Colton Zone Mylonite**

*Brouses Corners, Clare, New York* (UTM 18T, 495212, 4920802)

![Figure 31](image1.png)

Figure 31. Interlayered pegmatitic leucogranite and mylonite/ultramylonite at Brouses Corners. Note contact relationships between pegmatite and mylonite and possible mylonitic xenoliths in pegmatite. Scale in cm.

Dark mylonitic gneiss and coarse calcisilicate granulite are intruded by coarse, pink leucogranite pegmatite at this locality. Strong fabric in the mylonitic gneiss and local bands of ultramylonite dip northwest and display microstructures that indicate top-down-to-the-northwest transport. The pegmatite contains xenoliths of mylonitized wall rock and pegmatite veins invade and crosscut mylonitic foliation. However, the pegmatite shows mylonitic deformation along portions of its intrusive margins. One m-scale mass of pegmatite forms a large strain sigmoid indicating deformation consistent with other strain markers in the mylonite. Pseudotachylite veins crosscut mylonitic foliation but do not apparently crosscut granite pegmatite. Note the quartz veins within the tabular pegmatite masses; the veins appear to have formed as extension fractures within the pegmatite.

Zircons from sample BC-PEG, a coarse, undeformed pink granite pegmatite, are equant, and faintly zoned in CL and BSE images (figure 32). The age of 1044 ± 7 Ma (Selleck, et al 2005), determined on the basis of nine analyses, overlaps within error the ages of leucogranite at Indian River Road and Selleck’s Corners. This age fixes the timing of active mylonitic strain, as the pegmatite intrudes mylonitic rock but is itself mylonitized along its margins. The pegmatite does not contain pseudotachylite veins, suggesting that these veins developed prior to pegmatite intrusion, although no unequivocal crosscutting relationships have been observed.

The leucogranite pegmatite at this outcrop shows extreme K2O enrichment (figure 35), similar to other late-to-post Ottawan granites along the CCSZ and elsewhere in the Adirondack Highlands (McLelland, et al 2002).
Figure 32a. Concordia diagram of SHRIMP results from Brouses Corners pegmatite

Figure 32b. Typical pegmatite zircon from Brouses Corners pegmatite showing SHRIMP analysis spots. BSE image.

Figure 33a. \( \sigma \)-type grain-tail complex around pyrite spheroid in ultramylonite, Brouses Corners; shear sense indicates top down to the northwest transport. Dark bands are magnetite-rich. Width of field is ~12 mm

Figure 33b. Pseudotachylite in mylonitic gneiss, Brouses Corners. Note crosscutting relationship with mylonitic foliation. Dark, microlitic-textured areas are ksp+qtz+mag. Width of field is ~10 mm
Figure 34a. Ultramylonitic fabric, Brouse’s Corners. Dark bands are magnetite-rich segregations. Porphyroclasts are mainly k-feldspar. Width of field is ~10 mm

Figure 34b. σ−type grain-tail complex in mylonite, Brouses Corners. Dark bands are magnetite-rich segregations. Width of field is ~4 mm

Figure 35. Whole-rock variation diagram illustrating potassium enrichment typical of the Lyon Mountain suite leucgranites at Selleck’s Corners and Brouses Corners localities.
<table>
<thead>
<tr>
<th>Cum. Mi.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.5</td>
<td>Return to vehicles.  Continue south on Co. Rt. 27</td>
</tr>
<tr>
<td>33.3</td>
<td>Hamlet of DeGrasse. During the operation of the Clifton Magnetite Mine, located to the southeast, DeGrasse was the home of miners and managers.</td>
</tr>
<tr>
<td>33.6</td>
<td>Intersection. Turn left (south) to continue on Co. Rt. 27.</td>
</tr>
<tr>
<td>41.5</td>
<td>Intersection of Co. Rt. 27 and 27a. Turn right (west) to continue on Co. Rt. 27</td>
</tr>
<tr>
<td>43.0</td>
<td>Intersection at old Oswegatchie River Bridge. Turn left (south) to cross bridge.</td>
</tr>
<tr>
<td>43.3</td>
<td>Turn left off highway into parking area.</td>
</tr>
<tr>
<td></td>
<td>Stop 4. Late shear zone mineralization in Irish Hill Gneiss</td>
</tr>
<tr>
<td></td>
<td>End of road log. To return to Gouverneur, take Rt. 58 northwest from this location.</td>
</tr>
</tbody>
</table>

**Stop 4 – Fault-related mineralization and deformation in Irish Hill Gneiss**

*Intersection of Rts. 3 and 58 near Fine, NY* (UTM 18T 4898840N 489187E)

Directly north of the parking lot is a small mine audit. We will start by heading north to the old bridge over the Oswegatchie River. Outcrops to the west (down the slope) are of green Irish Hill Gneiss. The outcrops along the road show strong brittle deformation fabrics and a mixture of rock types. Fluorite crystals have been found in vugs and tension gashes in the outcrop. This outcrop lies on the trace of the Kalurah Lineament (Fault) and movements on this lineament are the logical cause for the strong brittle overprint observed in these rocks. 100m west one can find outcrops of Irish Hill Gneiss (Highlands) and to the east (on Route 3) we find pink granite (Highlands lithology?) with a strong brittle overprint.

**Summary of Day 2 and Implications for history of the CCSZ**

The emplacement of granite during extensional collapse of continental collisional orogenic belts is an expected consequence of the temperature and pressure regimes present (Leake, 1990). Intrusion synchronous with extensional collapse and denudation has been documented in numerous ancient orogenic belts, including the late Mesozoic of southeast California (Kula et al., 2002), the Variscan Belt of Spain (Aranguren et al., 1996) and the Proterozoic of Greenland (Hutton et al., 1990). U-Pb zircon studies in the vicinity of the Carthage-Colton Shear Zone suggest that leucogranitic melts intruded at ca. 1045 M after the cessation of the main contractional phase of the Ottawan event but synchronously with extensional deformation (Lamark et al., 2003) that accompanied orogen collapse, perhaps triggered by delamination of overthickened lithosphere.

The emplacement of Lyon Mountain suite granites in the vicinity of the CCSZ and elsewhere in the Adirondack Highlands and the initiation of orogen collapse along the zone may be directly related. The rheologically strong granulite facies rocks of the Adirondack Highlands and correlative rocks of the central granulite terrane of Ontario and Quebec may have maintained a relatively high elevation and resisted collapse until melts were generated and emplaced. Jackson et al. (2004) noted that thickened lithosphere may sustain significant elevation anomalies until the lithosphere is invaded by melts or fluids released during granulite to eclogite transformation. In the Grenville orogen, weakening of formerly strong crust by magma emplacement initiated extensional motion, which gave rise to further melting at lower crustal levels, as suggested for the
1.4 Ga “anorogenic” granites of the Proterozoic Yavapai and Mojave provinces of the Grand Canyon (Seaman et al., 2001). Melt emplacement and crustal weakening may have occurred somewhat earlier along the Tawachiche shear zone in Quebec, where the syntectonic granites described by Corrigan and Van Breeman (1997) occupy similar structural positions, but the intrusions there are somewhat older, ca. 1055 Ma.

The position and age of the leucogranites along the CCSZ indicate that granite melt generation and crustal extension were coeval and related to the initial stages of collapse of the Adirondack portion of the Grenville orogen. The melting was initiated within the hotter granulite-facies Adirondack Highlands that acted as the lower plate along which extension occurred. These melts weakened the formerly strong, dehydrated rocks of the granulite facies Highlands “core” and facilitated rapid crustal extension and unroofing. Further, we assert that the associated CO\textsubscript{2} and HCl hydrothermal activity documented in rocks of the Adirondack Lowlands, which acted as the upper plate of the Carthage Colton Shear Zone, was driven by magmatism from a broad belt of LMG plutons that lie along the SE margin of the Carthage-Colton Shear Zone. These melts also acted to weaken rock and promote more rapid extensional collapse of the orogen, and produced the distinctive low-Ti magnetite ores of the northwest Adirondack Highlands (Foose and McLelland, 1995; McLelland et al., 2002).

Pseudotachylite in association with brittle faults has been described elsewhere in the Grenville Province (e.g., Magloughlin et al., 1999) but its occurrence at the Brousse Corners exposures seen on this trip suggest that the pseudotachylite, ductile high-strain ultramylonite and mylonite, and granite pegmatite developed more or less synchronously. A possible model for earthquake-generating strain rates at depths where deformation would be otherwise ductile and granite melts are emplaced could be deep crustal setting described by Smith et al. (2004) for the westernmost Great Basin near Lake Tahoe, California. Deep (29–33 km) earthquakes within this zone of regional extension are interpreted as originating from high-strain rate events accompanying magma emplacement as dikes are emplaced into extending crust. We suggest that the mylonites, pseudotachylites, and leucogranites of the Carthage Colton Shear Zone were all formed under similar conditions during the collapse of the Grenville Orogen ca. 1045 Ma.

The events and processes described here along the CCSZ are similar in nature and timing to those described by Corrigan and van Breemen (1997) in the Shawinigan Falls, Quebec, sector of the Grenville Province where the Tawachiche Shear Zone juxtaposes an amphibolite facies hanging wall against a granulite facies footwall on the southwestern side of the fault. We interpret these similarities to reflect the late-Ottawan, large-scale tectonic exhumation of the Granulite Terrane of the Grenville Province along major low-angle extensional faults in the Adirondacks (dip NW) and in Quebec (dip NE). Coeval magmatic activity was present in both regions but current information suggests that it was especially pronounced in the Adirondacks (i.e., LMG). It is certain that the Labele Shear zone that marks the western terminus of the Granulite Terrane in Quebec also participated in this unroofing, but details await further investigation.

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42
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