DECIPHERING THE GEOLOGIC EVOLUTION OF THE EASTERN ADIRONDACKS: NEW FIELD, PETROLOGIC AND GEOCHRONOLOGIC DATA

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INTRODUCTION

Models for the tectonic evolution of the Adirondack Mountains have advanced significantly over the past ten to fifteen years. Prior to this, most workers would suggest that the (ca. 1.06 Ga) Ottawan Orogeny was the dominant deformation-metamorphic event in the Adirondacks. Recently published results from geochronological studies based on high resolution, single grain, U-Pb zircon SHRIMP data (McLelland et al., 2001; Hamilton et al., 2004; Heumann et al., 2006; Bickford et al., 2008), along with geochemical and field based studies in the Adirondack Lowlands (Chiarenzelli et al., 2010; Baird and Shrady, 2011), and recognition of an ophiolite suite in the Lowlands (Chiarenzelli et al., 2011) has resulted in significant revision of models of the tectonic evolution of the Adirondacks. These data reveal a major mountain-building event, the Shawinigan Orogeny (~1.2-1.16 Ga) - previously unrecognized in the Adirondack Highlands, resulted in widespread deformation and high grade metamorphism with accompanying partial melting. After the Shawinigan Orogeny, extensive anorthosite-mangerite-charnockite-granite (AMCG) magmatism (1.16. to 1.14 Ga) is interpreted to reflect a period of lithospheric delamination that resulted in asthenospheric upwelling and decompression melting in the mantle (McLelland et al., 2010) that yielded gabbroic magmas parental to the anorthosites. Thermal effects of the gabbroic magmas provided heat to partially melt portions of the lower crust and produce the felsic magmas of the AMCG suite.

In addition, Selleck et al. (2005) proposed that the Lyon Mountain granite was emplaced at the end of the Ottawan Orogeny (ca 1.05 Ga) and that it accompanied extensional collapse following peak-Ottawan compression. Wong et al (2012) support this model with evidence for an extensional shear zone in the eastern Adirondacks and show, using in situ EMP monazite data that the latest, normal-sense motion along the shear zone occurred from approximately 1.05 to 1.0 Ga.

In summary, important developments include: (1) the recognition that the 1200-1160 Ma Shawinigan Orogeny played a major role in a multiphase orogenic history; (2) the extensive AMCG magmatic suite, previously considered to be anorogenic, is now thought to have occurred during post-Shawinigan lithospheric delamination; (3) the 1090-1050 Ma Ottawan Orogeny may overprint but does not obliterate the earlier Shawinigan features; (4) significant shear zones exist on the western and eastern sides of the Adirondack Highlands that record the early stages of collapse and exhumation of the Grenville orogen.

Distinguishing between Shawinigan, AMCG, Ottawan, and extensional stages in the deformation and metamorphic history is essential for P-T-D-t models and for constraining the Adirondack tectonic history in general. Our work in the eastern Adirondacks will delineate the *nature* and *spatial extent* of both the Shawinigan and Ottawan Orogenies. By nature we mean metamorphic grade, style of deformation, composition of igneous rocks, and importantly, age constraints on each of these processes.

The East Adirondack shear zone is an intriguing feature in the Adirondack Highlands, possibly correlative in timing and history with the Carthage-Colton shear zone on the west side of the Adirondacks. However, many questions remain before this late-stage deformation can be wholly integrated into the tectonic history of the Adirondacks. Our on-going research aims to address the following questions:

1) What is the width, length, and intensity of the East Adirondack shear zone?
2) What is the style of the shear zone, is it constructed of many narrow discrete zones (<10 m) or is it distributed more uniformly over a wide zone (> 100m)?
3) Is this an extensional or a compressional shear zone, or does it have a complex, multiphase, diachronous history similar to the Carthage-Colton shear zone?
4) What was the P-T path during shearing, did the latest extensional phase of shearing recorded by these rocks occur at different crustal levels and therefore different metamorphic grades?
5) How does the shear zone link to other high-strain zones in the Eastern Adirondacks and more broadly to the Carthage-Colton shear zone?
6) What is the timing of shearing and is there an inheritance relationship with deformation in the Shawinigan?

Our approach to answering these questions is multifaceted and includes field work, macro- and microscale structural analysis, petrologic analysis and modeling, and geochronology. Field observations are foundational for all the research that follows. Contacts and map scale structures are mapped; kinematic indicators such as deformed porphyroblasts or porphyroclasts and strong lineations are documented. Oriented polished thin sections are used for microscopic kinematic and textural studies. Extensive compositional mapping and elemental analysis provides the data for forward petrologic modeling using Theriak-Domino software (de Capitani and Petrakakis, 2010) in order to determine not only the P-T conditions of metamorphism but also the sequence of metamorphic reactions. In situ electron microprobe dating of monazite is used to constrain the timing of metamorphism and deformation (Williams and Jercinovic, 2012). Application of this technique is discussed elsewhere in the paper.

The stops on this trip are designed to illustrate the wide range of rock types present in the eastern Adirondacks including but not limited to metagabbos, deformed anothositic rocks, charnockites, and garnet-sillimanite gneisses. The geologic context of each stop will be discussed and new data, when available, will be presented. Lively discussion is encouraged. Of course this trip is not the first to visit many of these stops and additional information can be obtained from previous NYSGA and NEIGC field trips including McLelland et al. (2011) and Whitney et al. (2002).

OVERVIEW OF ADIRONDACK GEOLOGY

The Grenville Province of Eastern North America is a Proterozoic orogenic belt that represents the culminating continental collision(s) during assembly of the supercontinent of Rodinia (Rivers, 2008). The Grenville Province extends from northeastern Canada through the eastern and southern portion of the U.S. into Texas with proposed correlations in Australia, Antarctica, Baltica and others (Karlstrom et al. 1999). In eastern Canada, the Grenville Province forms a northeast trending belt approximately 2000 km long and 400-500 km wide. The Adirondack Mountains, located in northeastern New York, are a domical uplift of Mesoproterozoic rocks that are part of the Grenville Province (Fig. 1). The Green Mountain and Berkshire massifs represent outliers of the Grenville Province and lie to the east and southeast of the Adirondacks respectively.

The Adirondack Mountains are underlain by complexly folded, faulted and sheared metasedimentary and metaigneous rocks of wide ranging composition and varying in age from approximately 1.4 to 1.0 Ga (Fig. 1). The Adirondacks are subdivided into the Adirondack Highlands and the Adirondack Lowlands. The Carthage-Colton shear zone defines the boundary between the two (Baird and MacDonald, 2004, Baird, 2008, Johnson et al., 2004, Streepey et al., 2001). While both orthogneiss and paragneiss are found in each region, the Adirondack Highlands are dominated by metaigneous rocks, including several large bodies of anorthosite, and granulite facies metamorphic rocks. The Adirondack Lowlands are underlain by predominantly upper amphibolite facies metasedimentary rocks.

Figure 2 is from McLelland et al. (2013). We will use this model for the tectonic evolution of the Adirondacks throughout the remainder of this field trip guide as a tectonic framework for discussion purposes.

The oldest igneous rocks in the Adirondack Highlands are the tonalitic to granitic rocks of the Royal Mountain suite that outcrop in the southern and eastern Adirondacks (Fig. 1). These ~1.3 Ga gneisses are thought to have formed above a NW-dipping subduction zone along the SE margin of Laurentia. Although we will drive by the ca. 1.3 Ga Blue Goose tonalite, these rocks are currently not part of our research and we are not planning on examining them on this field trip.

In McLelland's model, the Shawinigan Orogeny is initially generated by the subduction of the trans-Adirondack Basin (Chiarenzelli et al., 2010) forming an Andean style margin with the Adirondack Lowlands on the leading edge of the overriding plate (Fig. 2). Upon closure of this basin the Adirondack Highlands-Green Mountain block collided with the Adirondack Lowlands-Central Metasedimentary block resulting in nappe style folds and granulite facies

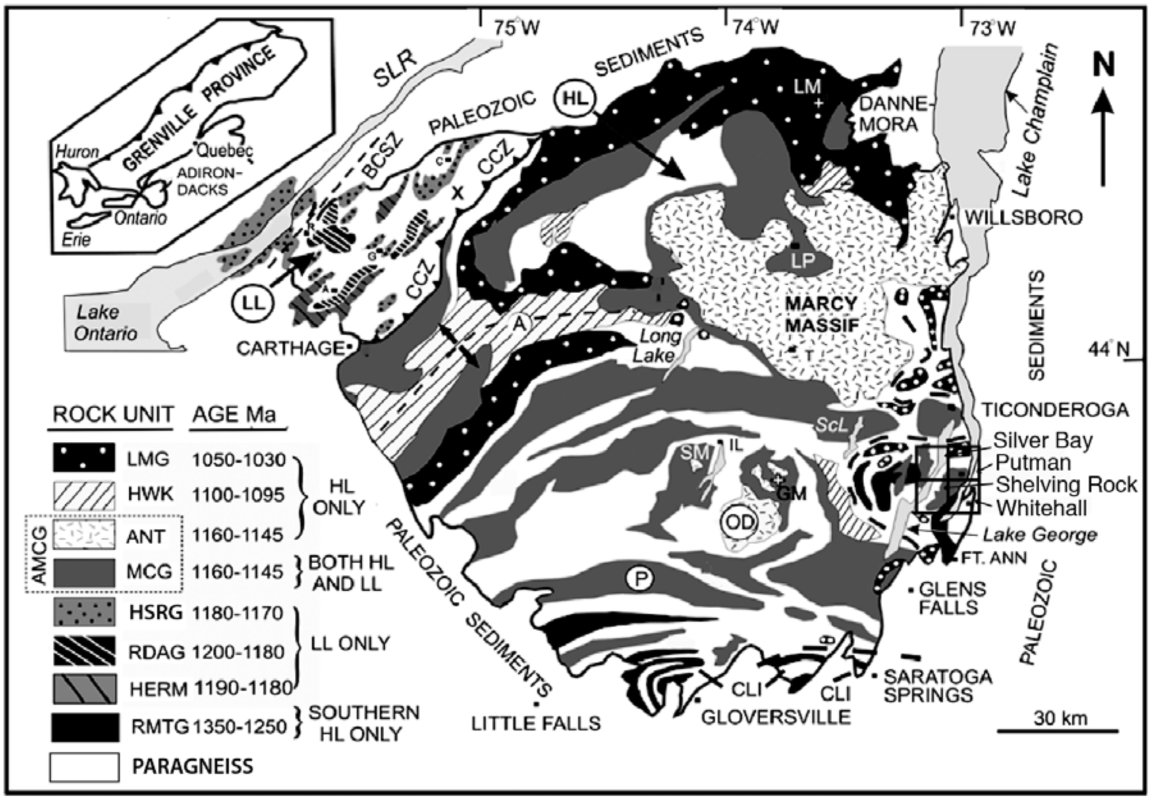

Figure 1. General geologic map of the Adirondacks (after McLelland et al., 2010). Units are as follows: LMG=Lyon Mountain granite, HWK=Hawkeye granite, ANT=anorthosite, MCG=mangerite, charnockite, granite, HSRG=Hyde School – Rockport granite, RDAG=Rossie diorite – Antwerp granodiorite, HERM=Herman granite, RMTG=Royal Mountain tonalite – granite. Silver Bay, Putnam, Shelving Rock, and Whitehall are 1:24,000 quadrangles. CCZ = Carthage Colton Shear Zone, BCSZ = Black Creek Shear Zone, OD = Oregon Dome, A = Arab Mountain Anticline, P = Piseco Anticline, CLI = Canada Lake Isocline, A = Antwerp, C = Canton, G = Gouverneur, SM = Snowy Mountain, IL = Indian Lake, LM = Lyon Mountain, HL = Highlands, LL = Lowlands, LP = Lake Placid.

metamorphism (Heumann et al., 2006; McLelland et al., 2013) (Fig. 2). In this model, this continental lithospheric collision also generated the initial movement along the Carthage-Colton shear zone when the Lowlands block was thrust on top of the Highlands block thus forming an orogenic lid.

McLelland et al. (2010) propose that either towards the waning stages of the compressional deformation associated with the Shawinigan, or shortly after, the overthickened lithosphere began to delaminate. This resulted in upwelling of the asthenosphere and decompression melting in the mantle. Mafic magmas ponded near the base of the crust and begin to fractionate. Plagioclase crystals, being less dense than the parental mafic melt accumulated at the top of the magma. These plagioclase-rich crystal mushes ascended through the crust and crystalized forming the large bodies of anorthosite in the Adirondack Highlands. In addition, heat from the upwelling asthenosphere and ponding magmas generated partial melting in the lower crust. These magmas intruded into the crust and crystalized to form the mangerite-charnockite-granite component of the AMCG suite (McLelland et al., 2010).

The next major compressional event was the Ottawan Orogeny (McLelland et al., 2013), also known as the Ottawan phase of the Grenvillian Orogeny (Rivers, 2008). This orogenic event is proposed to be the result of the collision of Amazonia with the Adirondack Highlands-Lowlands block, which at that time was the eastern edge of Laurentia. Research to date suggests that the Ottawan Orogeny, like the Shawinigan, resulted in nappe-style folding and granulite facies metamorphism (Bickford et al., 2008; McLelland et al., 2013). Ottawan-age deformation and metamorphism has not been recognized in the Adirondack Lowlands (Baird and Shrady, 2011). The Ottawan Orogeny culminated with the assembly of the supercontinent of Rodinia.

A period of orogenic collapse followed the culmination of Ottawan compression. Wong et al. (2012) documented normal-sense, east-directed shear in rocks south Whitehall, NY. In situ EMP monazite data are consistent with this shearing taking place between 1050-1000 Ma. Selleck et al. (2005) suggest that the Lyon Mountain granite was emplaced during extensional collapse. McLelland and Selleck (2011) also suggest that the large, megacrystic garnets are Gore Mountain formed at this time.

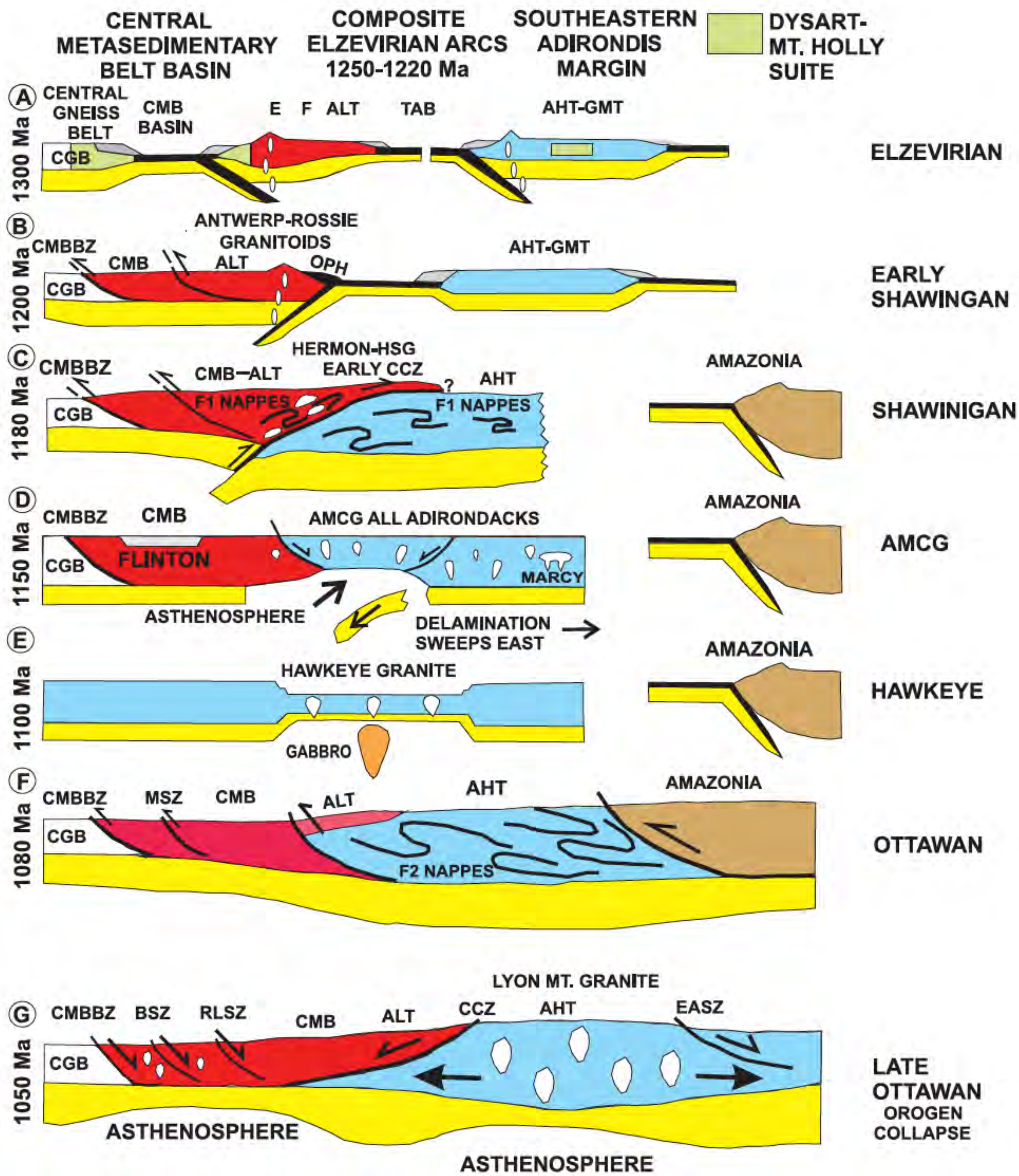

Figure 2. Model of the tectonic evolution of the Adirondack Mountains from McLelland et al. (2013). Abbreviations: AHT =Adirondack Highlands Terrane, AHT-GMT = Adirondack Highlands-Green Mountains Terrane, ALT = Adirondack Lowlands Terrane, AMCG = anorthosite-monzonite-charnockite-granite suite, BSZ = Bancroft shear zone, CCZ = Carthage-Colton Shear Zone, CGB = Central Gneiss Belt, CMB = Central Metasedimentary Belt, E = Elzevir Terrane, EASZ = Eastern Adirondack shear zone, F = Frontenac Terrane, HSG = Hyde School Gneiss , MSZ = Maberly Shear Zone, OPH = Pyrite Ophiolite Complex, RLSZ = Robertson Lake Shear Zone, TAB = Trans-Adirondack basin.

FIELD GUIDE AND ROAD LOG

Meeting Point: Hwy 22 south of Ticonderoga in a parking area on the west side of the road immediately after entering the town of Putnam. If you are driving south from Ticonderoga there is a “Welcome to Putnam” sign just before the entrance to the parking area. The meeting point is about a 90 minute drive from Plattsburgh.

Meeting Point Coordinates: UTM (628044 E, 4851165 N) (See Figure 3)

Meeting Time: 9:00 AM

Distance (miles)		
Cumu- -lative	Point to Point	Route Description
0.0	0.0	Assemble in the parking area on the west side of Hwy 22 south of Ticonderoga in the town of Putnam. Depart parking area heading south.
3.1	3.1	Exposures of the “Great Unconformity” with the Cambrian Potsdam sandstone sitting unconformably on nearly vertically dipping Mesoproterozoic gneisses.
3.6	0.5	Pull over as far to the right as possible and park.

STOP 1. Isoclinal folds, Lyon Mountain granite, and AMCG rocks (60 minutes)

Location Coordinates: UTM Z18 NAD83 (628912 E, 4845232 N)

Examine the granitic gneiss in the northern outcrops on the west side of the road. Note the numerous tight to isoclinal similar folds (Fig. 4). The fold axis trends almost due east and has a gentle eastward plunge. If you look closely at the nose of the fold you can see a new axial planar foliation has developed. If we call the folded foliation S_1 then the new axial planar foliation would be S_2. The foliation on the limbs of the axial planar folds would be a composite S_1/S_2 foliation. Our working hypothesis is that S_1 developed during the Shawinigan Orogeny and S_2 developed during the Ottawan Orogeny. However, this may be problematic if these granitic gneiss are part of the AMCG suite. We have collected oriented samples in this region to see if we can use monazite age data to constrain the timing of foliation development.

Further to the north along this outcrop is a reverse fault that is cut by a pegmatite. Where the pegmatite cuts the granitic gneisses it appears as if fluids from the pegmatite interacted with the gneiss and resulted in potassic alteration of the gneiss.

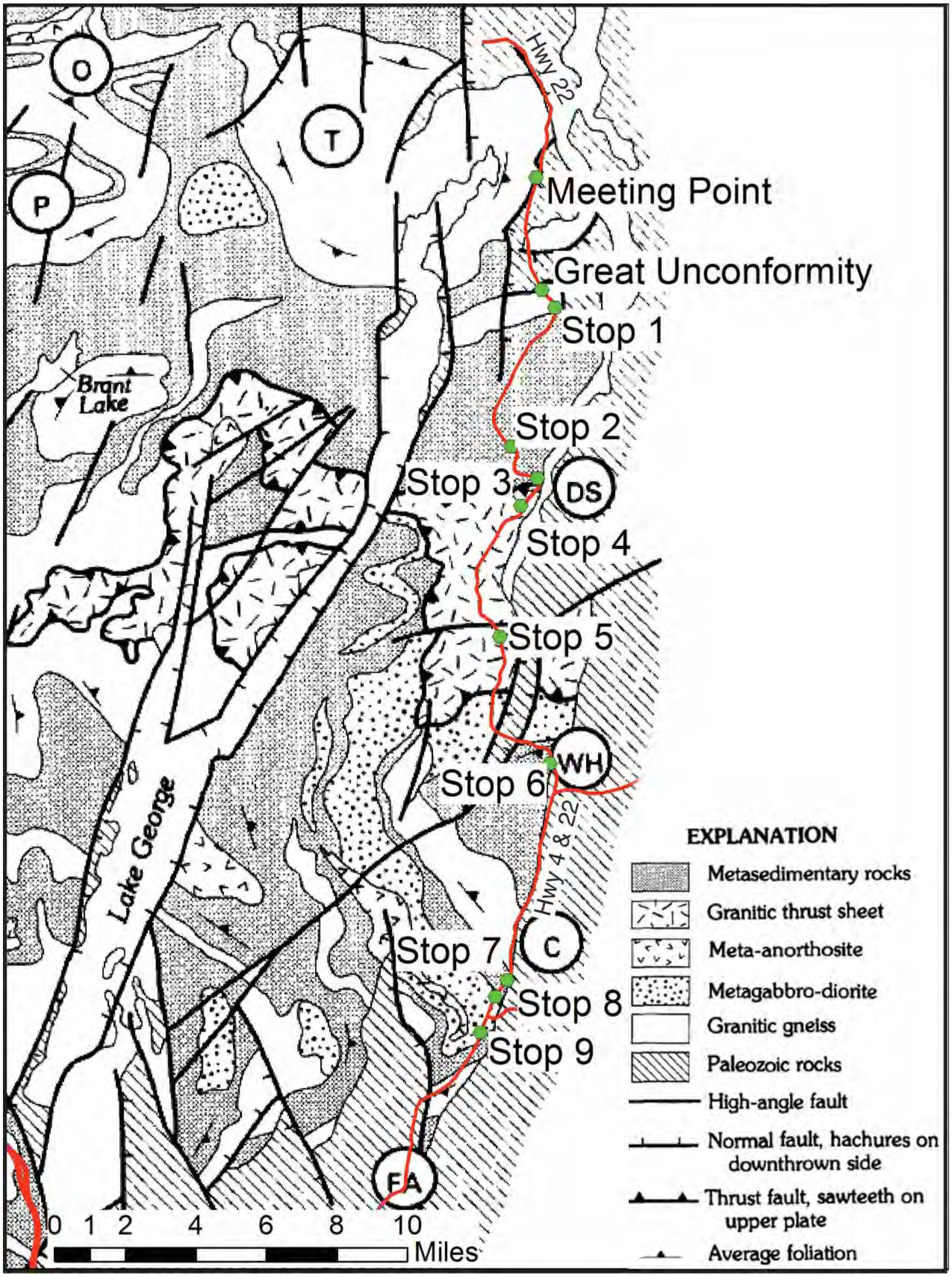

Figure 3. Generalized geologic map of the eastern Adirondacks after McLelland (1990). Also shown are the locations of the stops on this field trip (circles with letters inside): P=Pharoah Mountain, O=Owl's Head Mountain, T=Ticonderoga dome, DS=Dresden Station, WH=Whitehall, C=Comstock, FA=Fort Ann

Proceed south, past a gap in outcrops to the next exposure. Here various phases granites, along with amphibolite that exhibits flow folding are intermixed. The white to gray granitic rock appears locally to be undeformed except for shear zones and is interpreted to be the Lyon Mountain Granite with its typically low (< 0.3 wt.%) MgO composition. The pink granitic rock contains few amphibolite enclaves and is thought to be an AMCG granite. McLelland et al. (2011) refer to this roadcut as an intrusion breccia involving white Lyon Mountain granite that engulfed, disrupted, and flow folded amphibolites. Portions of the Lyon Mountain granite have undergone various phases of alteration by sodic and potassic fluids resulting in elevated concentrations of those elements (Valley et al., 2011).

Figure 4. Tight to isoclinal similar folds in granitic gneiss at Stop 1. Sharpie in fold hinge for scale.

Distance (miles)		
Cumu- -lative	Point to Point	Route Description
4.5	0.9	Return to vehicles and head south, outcrops of Potsdam sandstone.
8.1	3.6	Pull over as far to the right as possible and park.

STOP 2 Lineated K-feldspar megacrystic gneiss and migmatitic paragneiss (30 minutes)

Location Coordinates: UTM Z18 NAD83 (626892 E, 4838882 N)

This rock is a biotite-bearing, K-feldspar megacrystic rock with a pervasive linear fabric. Most of the K-feldspar crystals are strung out and completely recrystallized into finer grained mosaics (Fig. 5), however some large crystals are still present. The dominant lineation is gently plunging to the east.

Graham Baird recently analyzed zircons from this sample using the SHRIMP-RG at Stanford University. Zircon in the unit is euhedral to subhedral, elongate, amber colored, and ranges in length approximately 200-400 µm. Cathodoluminescence of polished grain cross sections reveal that all grains possess oscillatory zoning with no conclusive sign of metamorphic rims or common inherited cores (Fig. 6). Fourteen SHRIMP-RG analyses produce what is interpreted as a unimodal distribution of ages with one

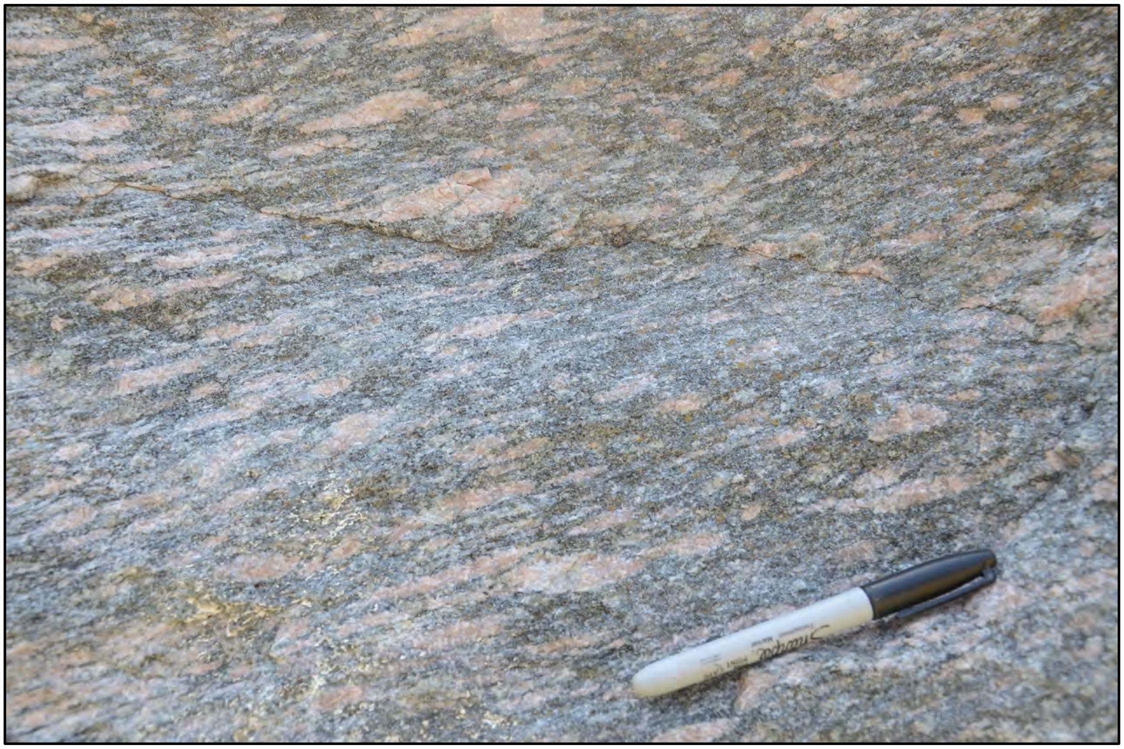

Figure 5. Lineated Bt-bearing, K-feldspar megacrystic gneiss at Stop 2.

inherited core (1497 ± 78 Ma) and 3 anomalously young ages. Seven concordant and near concordant, well clustered analyses produce a 2σ $^{207}Pb/^{206}Pb$ weighted mean age of 1155 ± 15 Ma, interpreted to best represent the age of pluton crystallization (Fig. 6).

The 1155 Ma age is consistent with this granitoid being part of the AMCG suite. The strong, penetrative fabric suggests a phase of deformation after this time.

Further north along the outcrop the K-feldspar megacrystic granitic rocks are intermingled with migmatitic, biotite-bearing gneisses. The contact relationships between these two units are not clear cut. We have sampled both units in order to collect more geochonologic data using EMP analyses of monazite.

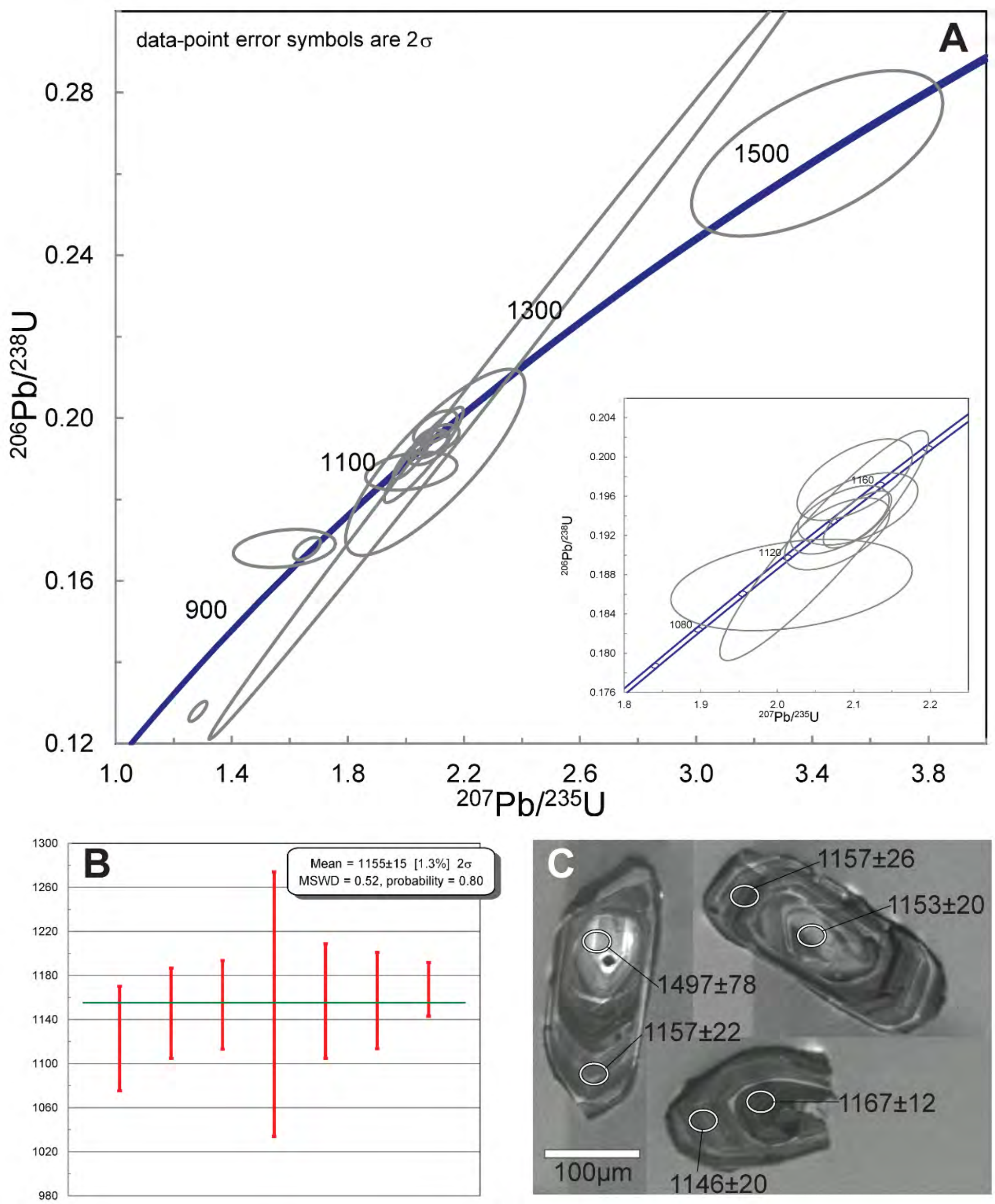

Figure 6. A) Concordia diagram for 14 U/Pb zircon SHRIMP-RG analyses. Inset show the 7 best clustered data used in the $^{206}Pb/^{207}Pb$ weighted mean (B). B) $^{206}Pb/^{207}Pb$ weighted mean of the best data produces an age of 1155 ± 15 Ma (2σ). C) Representative grains and 2σ $^{206}Pb/^{207}Pb$ spot analyses.

Distance (miles)		
Cumu- -lative	Point to Point	Route Description
8.3	0.2	Return to vehicles and head south, mafic boudins in metasedimentary rocks.
8.8	0.5	Pull out with folded granitic rocks near southern end. Also a spring with potable water.
9.4	0.5	Turn left on Belden Road, make a U-turn and park near the intersection of Belden Road and Hwy 22.

STOP 3. Garnet-sillimanite gneisses and coronitic metagabbro (60 minutes)

Location Coordinates: UTM Z18 NAD83 (628107 E, 4837420 N)

Many field trips have stopped at this location over the years. McLelland et al. (1988a) cite evidence from this outcrop to show that there were multiple phases of metamorphism recorded by the rocks in the Adirondacks. A sharp contact between garnet-sillimanite gneiss and a coronitic metagabbro is well-exposed in this outcrop (Fig. 7). The gneiss is a garnet-sillimanite-plagioclase-K-feldspar-quartz gneiss with a small amount of biotite. The garnet-sillimanite gneisses here are often referred to as khondalites. This name originated in India and refers to quartz-garnet-sillimanite gneisses with little to no biotite. Khondalites are often associated with quartzites and calc-silicate rocks and that is the case here. This mineral assemblage is consistent with upper amphibolite to lower granulite facies metamorphic conditions. The garnet-sillimanite gneiss is penetratively deformed with a well-developed foliation and a lineation that plunges gently to the east. Much of the metagabbro is undeformed and a coarsely crystalline texture is preserved throughout much of the unit. There are places within the gabbro however that are deformed and foliated. The gabbro is finely crystalline right at the contact with the gneiss (Fig 7c) and appears to get more coarsely crystalline towards the interior of the body suggesting a chilled margin formed at the contact between the gabbro and the gneiss. The contact between the gneiss and the gabbro is, in places, at a high angle to the foliation in the gneiss. These field relationships suggest that the gneiss was deformed and metamorphosed prior to the intrusion of the gabbro (McLelland et al., 1988).

Coronitic metagabbros are found throughout the Adirondacks (Whitney and McLelland, 1973; Whitney and McLelland, 1983; Regan et al., 2011). Figure 8 illustrates the typical corona texture with an olivine core, surrounded by a rim of orthopyroxene, which in turn is rimmed by symplectic intergrowths of garnet and clinopyroxene. The clouding in the plagioclase is due to numerous microscopic spinel inclusions. Another feature of these rocks that ilmenite is rimmed by Ti-rich hornblende. This mineral assemblage and texture developed via subsolidus recrystallization from a rock that was originally an olivine-clinopyroxene-plagioclase gabbro. Preliminary P-T estimates suggest this mineral assemblage developed at approximately 9 kb and 750 $^{\circ}$C. The growth of amphibole also requires an influx of an H_2O-bearing fluid.

To the south and west of this outcrop of gabbroic rocks, ferrogabbroic rocks and anorthosites, all thought to be associated with the coronitic metagabbro seen here, have a very strong penetrative fabric and in many locations are mylonites. These rocks contain the mineral assemblage garnet-clinopyroxene-plagioclase±orthopyroxene which is similar to the mineral assemblage found in the coronitic metagabbros. Kinematic indicators in these rocks suggest a west-directed thrust sense of motion. These observations suggest this period of deformation and metamorphism must postdate the emplacement of the AMCG rocks.

Figure 7. Contact between garnet-sillimanite gneiss and coronitic metagabbro. Figure 7a shows that locally the foliation in the gneiss is parallel to the contact and locally it is at a high angle to the contact. Figure 7b illustrates the sharp nature of the contact. Figure 7c shows that the metagabbro is finely crystalline in the immediate vicinity of the contact.

McLelland et al. (1988b) report a U-Pb zircon, multigrain age of 1144 ± 7 Ma for the metagabbro. This is interpreted as an igneous crystallization age and is consistent with the gabbro belonging to the AMCG suite. However, Aleinikoff (pers. comm.) has reported a preliminary SHRIMP age of ca. 1107 Ma. We dated monazite from the garnet-sillimanite gneisses following the techniques outlined in Williams et al. (2006), Williams et al. (2007) and applied in Williams and Jercinovic (2012). The technique involves locating all the monazite crystals in the thin section through full section mapping with the microprobe followed by detailed mapping of up to 30 monazite crystals in a thin section to identify different compositional domains within each monazite. Then the microprobe is used for complete spot analyses of different compositional domains in the monazite and ages are calculated from these data. We analyzed monazite from two thin sections of the garnet-sillimanite gneisses. The results are presented in figure 9.

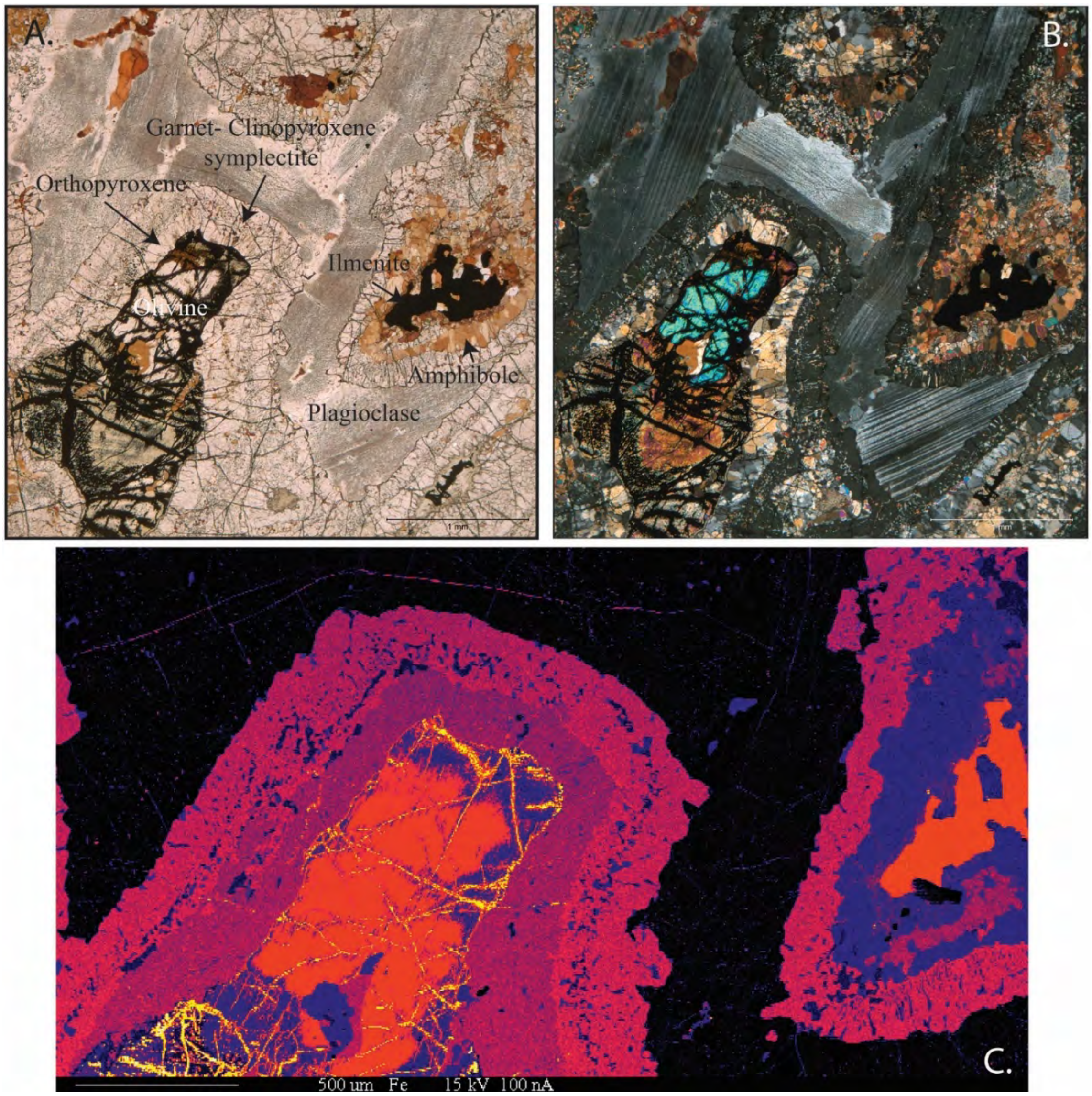

Figure 8. Photomicrographs and Fe-xray map of coronitic metagabbo. Figure 8a and 8b are photomicrographs under plane and cross polarized light respectively. Orthopyroxene surrounds olivine, and is in turn surrounded by garnet-clinopyroxene symplectite. Figure 8c is a Fe-xray map of a portion of the thin section shown in 8a and 8b.

The data broadly suggest three distinct periods of monazite growth. The oldest is set of ages yields a mean age of 1179 $\pm$ 9 Ma. We suggest that this age represents the timing of granulite facies metamorphism and fabric development in the garnet sillimanite gneisses. This age is consistent with metamorphism and deformation occurring during the Shawinigan Orogeny. The next population of analyses yields ages that cluster around 1151 Ma. We hypothesize that this represents a period of monazite growth driven by a thermal perturbation resulting from the intrusion of the gabbroic rocks. This age correlates well with the reported age of the gabbro. With the exception of one analysis yielding an age of approximately 1050 Ma, most of the remaining monazite ages are 1020 Ma or less. These ages are too young to correlate with the proposed timing of the peak of the Ottawan Orogeny (~1090-1050 Ma). One possibility is that monazite grew during the period of post-Ottawan decompression and uplift.

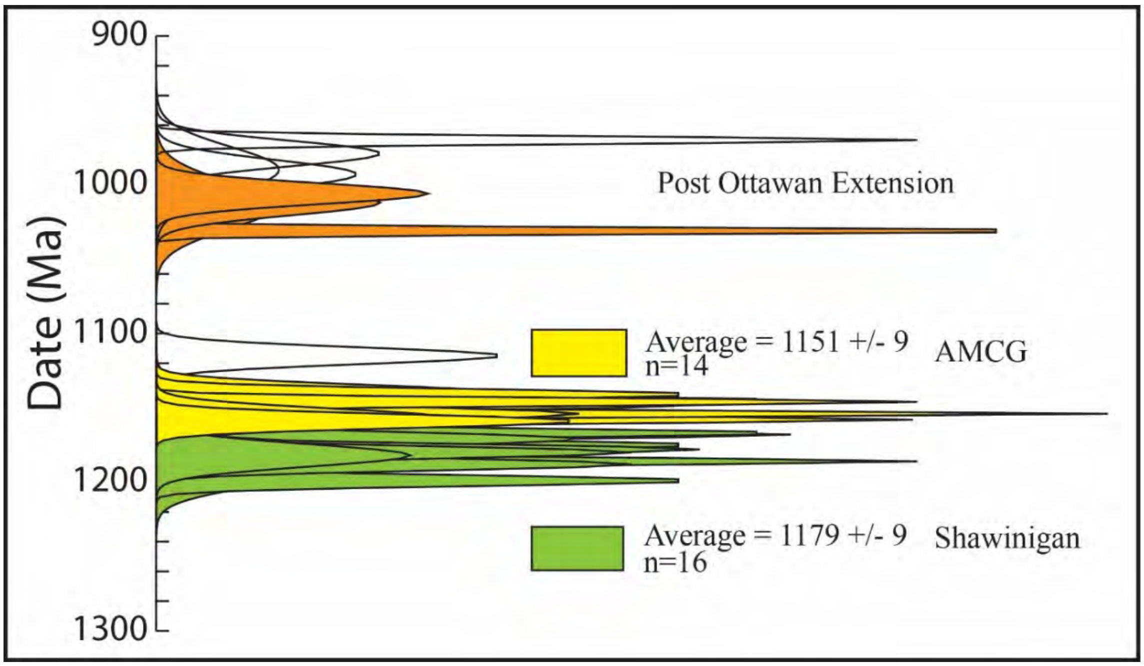

Figure 9. Histogram showing the distribution of ages calculated from spot analyses compositionally and texturally distinct domains in monazite using the Ultrachron at the University of Massachusetts.

The following model is consistent with the field observations and data from this outcrop. The mineral assemblage and the fabric in the garnet-sillimanite gneisses formed during the Shawinigan Orogeny. The gabbro was emplaced at approximately 1150 Ma, after the prominent fabric developed in the gneisses. This time frame is consistent with both the monazite ages from the gneisses and the multigrain age from the gabbro. Following the emplacement of the gabbro there was another period of deformation and metamorphism. This is when the nearby AMCG rocks were deformed and metamorphosed. This is also when the coronitic fabric developed in the metagabbro. This requires in influx of an H_2O–bearing fluid. Unlike the nearby rocks, the coronitic metagabbro was not pervasively deformed at this time nor did any new monazite grow in the garnet-sillimanite gneiss. Perhaps strain was partitioned around this outcrop and the lack of strain resulted in little recrystallization in the largely anhydrous garnet-sillimanite gneisses. The 1020 Ma and younger monazite ages in the garnet-sillimanite gneisses record monazite growth during post Ottawan extensional collapse. We will discuss this further at Stop 8.

Distance (miles)		
Cumu- -lative	Point to Point	Route Description
9.5	0.1	Return to vehicles and turn left heading south on Hwy 22.
10.6	1.1	Turn left on LeClaire Road, make a U-turn and park on the shoulder. The stop is in a quarry on the west side of the highway.

STOP 4 Mylonitic gabbroic anorthosite in a gravel pit (30 minutes)

Location Coordinates UTM Z18 NAD 83: (627320 E, 4836160 N)

Since leaving stop 3, we have been passing through a unit of deformed and metamorphosed mafic rocks ranging in composition from gabbroic to anorthositic. Most of the rocks have a well developed foliation. Many contain porphyroclasts of plagioclase that have been variably deformed (Fig. 10). As mentioned earlier, shear sense indicators in these rocks suggest a west-directed, thrust sense of shear. The mineral assemblage in these rocks is typically garnet-augite-hornblende-plagioclase with little to no orthopyroxene or quartz. The presence of hornblende, a hydrous mineral, requires an H_2O-bearing fluid, possibly introduced during deformation. Although we continue to search we have yet to find any monazite in these rocks.

Distance (miles)		
Cumu- -lative	Point to Point	Route Description
11.4	0.8	Return to vehicles and turn left heading south on Hwy 22. There is a large outcrop of metagabbro with a white marble xenoltth.
12.4	1.0	Good exposures of dark green charnockite.
14.8	2.4	Pull over on the right side of the road and park. The outcrop is on the east side of the highway, please be careful crossing the road.

STOP 5 Pegmatite, charnockite, and mafic gneiss (20 minutes)

Location Coordinates UTM Z18 NAD83: (626394 E, 4830166 N)

This outcrop contains a beautiful exposure of a post-Ottawan pegmatite dike. The hanging wall of the dike is a mafic gneiss. Xenoliths of the mafic gneiss are in the upper third of the dike and show evidence of reacting with the magma (Fig. 11). If you look across the street you can see the continuation of the dike to the north. Most of the outcrop here is granitic gneiss and maroon-brownish charnockite. These rocks are thought to belong to the AMCG suite. If this is correct foliation in these rocks must have developed from a deformational event after ~ 1155 Ma. Towards the south end of the outcrop there are cm-scale pyroxene crystals. This rocks

Figure 10. Porphyroclastic gabbroic anorthosite from Stop 4. Note the asymmetric plagioclase porphyroclasts.

Figure 11. Pegmatite dike cross cutting charnockitic rocks and mafic gneiss. The black spots in the upper part of the dike are xenoliths of the mafic gneiss in the hanging wall. There is a hammer on the right side of the picture for scale.

contains the high grade mineral assemblage garnet-augite-hornblende-plagioclase-quartz±orthopyroxene, indicating that these are upper amphibolite to lower granulite facies metamorphic rocks.

Distance (miles) Cumu--lative	Point to Point	Route Description
16.4-17.0	1.6-2.2	Return to vehicles and continue south on Hwy 22. Outcrops of ca. 1.3 Ga tonalitic rocks (McLelland and Chiarenzelli, 1990).
17.8	0.8	Bridge across Lake Champlain.
19.4	1.6	Pull over on the right side of the road and park. Watch out for poison ivy and unstable rock.

STOP 6. Garnet-sillimanite gneiss (20 minutes)

Location Coordinates UTM Z18 NAD 83: (628669 E, 4824379 N)

The entire road cut consists of well foliated and lineated garnet-sillimanite-K-feldspar-plagioclase-quartz±biotite gneiss. This is another example of khondalite. The sillimanite in this rock forms a prominent lineation of ~10/100. This is similar to all other lineations noted so far on this trip. The mineral assemblage is again consistent with upper amphibolite to lower granulite facies metamorphism.

Distance (miles) Cumu--lative	Point to Point	Route Description
20.3	0.9	Return to vehicles and continue south on Hwy 22. Intersection of Rt. 4 and Hwy 22. Continue straight heading south.
20.9	0.6	McDonalds on west side of the road.
25.5	4.6	Pull over on the right side of the road and park.

STOP 7. Long outcrop of many different lithologies found in the Adirondacks (40 minutes)

Location Coordinates UTM Z18 NAD83: (626719 E, 4832092 N)

The rocks in this outcrop include many of the lithologies found throughout the Adirondack Highlands that have probably been tectonically juxtaposed. The foliation is dominantly NE striking and gently dipping to the southeast. As we move southward we will moving structurally down section. The north end of this outcrop is an impure marble that contains coarsely crystalline graphite, diopside, and quartz. The marble also contains numerous inclusions of a variety of different rock types. Observations such as these led Ebenezer Emmons in his 1842 New York State Monograph "Geology of the State of New York: Survey of the Second Geological District" to state "Of Adirondack rocks we know little of their origin except for the marbles which surely are igneous" (McLelland, pers. comm.). Climb on top of the outcrop for a clear view of a unmetamorphosed, Mesozoic age mafic dike (Fig. 12). There is a millimeter scale chilled margin on the dike. To the south the marble is in contact with a biotite-garnet-quartz-plagioclase±sillimanite gneiss with quartzofeldspathic leucosomes.

As you proceed south from the marble and paragneiss you will encounter a number of different rock types including, garnet-bearing, quartzofeldspathic gneiss, charnockitic gneiss, numerous marbles, calcsilicate rocks with orange grossular garnet and wollastonite, and hornblende-pyroxene plagioclase gneiss.

At the southern end of the outcrop (UTM NAD83: 626522 E, 4832092 N) are biotite-garnet-sillimanite-K-feldspar-plagioclase-quartz gneisses. On some foliation surfaces these rocks contain beautiful matchstick-sized sillimanite. The sillimanite crystals are aligned forming a strong lineation trending approximately 15/135. We are in the process of mapping thin sections from this exposure to look for monazite. We do have monazite data from similar rocks just to the south that we will discuss at the next stop.

Figure 12. Mafic dike intruding marble at Stop 7. Note the rock hammer for scale.

Distance (miles)		
Cumu- -lative	Point to Point	Route Description
26.1	0.6	Return to vehicles and continue south on Rt. 4. Turn left into parking area

STOP 8. Lineated sillimanite gneisses, mylonitic granitic rocks, and the East Adirondack Shear Zone (60 minutes)

Location Coordinates: UTM Z18 NAD83 (626163 E, 4813714 N)

There is an outcrop paragneiss immediately to the south of the parking area on the east side of the road. This outcrop contains interlayered garnet-biotite-sillimanite gneisses with greenish calcsilicate lithologies. The well exposed foliation surfaces of the sillimanite-bearing gneisses commonly have well-lineated, coarsely crystalline sillimanite. The lineation is gently plunging to the southeast, similar to that in the last outcrop.

Follow the outcrop to the south remaining on the east side of Hwy 22 for the time being.

Note the interlayer folds in the upper part of the roadcut on the east. This exposure illustrates an older foliation that was transposed into a new foliation (Fig 13). Perhaps this is an example of a Shawinigan S_1 transposed into a younger S_2.

Figure 13. Interlayer folds in paragneiss along Hwy22 at Stop 8. Red line traces some folds. Note hammer for scale.

Across the highway is an asymmetric mafic boudin (Fig. 14) with a long tail that continues to the south in the upper part of the roadcut. Although it is clear the boudin was involved in a period of ductile deformation, the roadcut is oriented almost at right angles to the lineation direction so it is difficult to use the boudin for kinematic analysis.

Figure 14. Photomosaic of a mafic boudin enveloped by mylonitic, granitic gneiss at stop 8. The mylonitic rocks pictured in figure 15 are located approximately in the center of this picture.

The granitic rocks to the left of the mafic boudin in the picture above are mylonitic, LS-tectonites with megacrystic K-feldspar porphyroclasts (Fig 15). The prominent lineation plunges gently to the southeast. Data from this outcrop was cited by Wong et al. (2012) as evidence for the East Adirondack Shear Zone. They report a U-Pb ziron age obtained using the SHRIMP-RG at Stanford, of the granite in figure 15 of ca. 1140 Ma. This date suggests that it is part of the AMCG suite and was emplaced towards the end or after the Shawinigan Orogeny. Following this reasoning they suggest that most of the strain in the rock is therefore related to Ottawan compression or post

Figure 15. Strongly lineated granitic rock in the East Adirondack Shear zone.

Ottawan extension. They examined the asymmetric K-feldspar porphyroclasts as kinematic indicators to document shear sense motion. Although they found some porphyroclasts that suggested top to the west, thrust sense motion more suggest top to the east, normal-sense motion. From this they concluded that this rock experienced both compressive stresses and extensional stresses but the extension event was younger and overprinted the effects of the compressional event.

Wong et al (2012) also report U-Th-Pb electron microprobe ages from in situ monazite crystals. The data are shown in figure 16. Note the two groupings of peaks in the 1100-1000 Ma age range. The older peaks, shown in blue, cluster between 1080-1050 Ma. These data are from analyses of the outer cores of monazite crystals. They are interpreted to represent monazite growth during Ottawan compression and metamorphism. The younger peaks in red are less than 1050 Ma. These ages come from analyses of the tips of monazite crystals that are elongated in the extensional direction. Wong et al (2012) interpret this as monazite growth during extensional collapse following peak Ottawan compression. This period of extension is synchronous with the extension along the Carthage-Colton shear zone (McLelland et al., 2001; Streepey et al., 2001; Johnson et al., 2004).

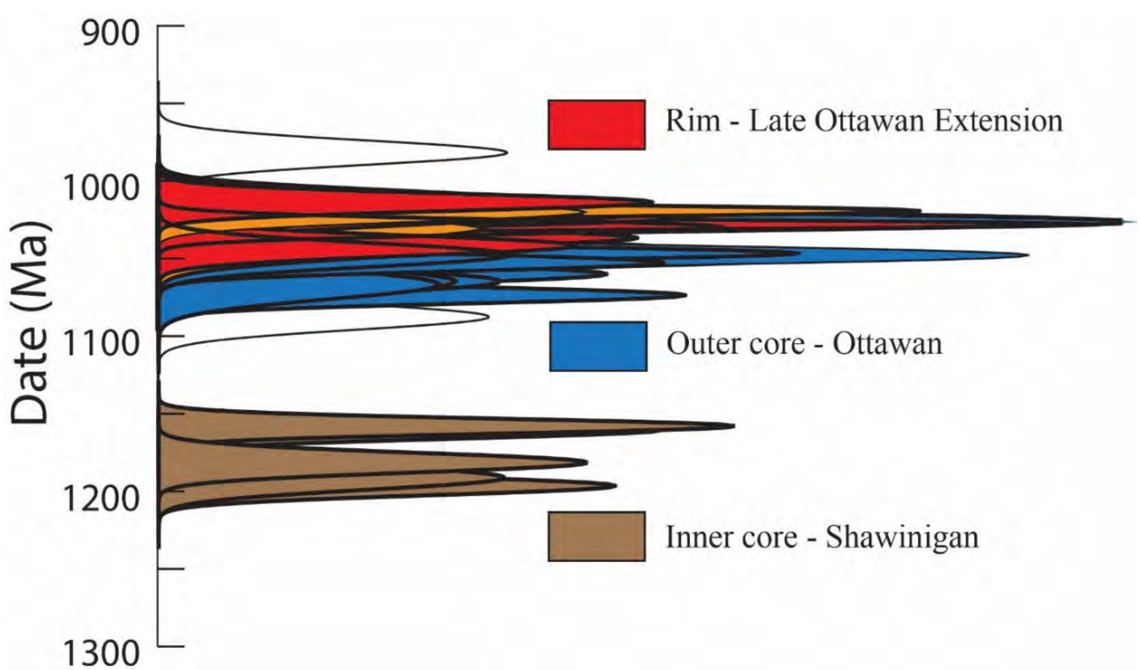

Figure 16. U-Th-Pb electron microprobe ages from in situ monazite from both a mylonitic, K-feldspar megacrystic granite and a garnet-sillimanite paragneiss.

It is interesting to compare this data with that from stop 3. The monazite data from the stop 3 rocks had a strong Shawinigan, AMCG, and post Ottawan signature but virtually no peak Ottawan monazite growth. The monazite data from this outcrop have a strong Shawinigan, peak-Ottawan, and post-Ottawan signature and limited evidence for monazite growth during AMCG times despite AMCG rocks being found in the outcrop.

Distance (miles)		
Cumu- -lative	Point to Point	Route Description
27.1	1.9	Return to vehicles and continue south on Rt.4. Turn right on Kelsdy Pond Road. Park on the side of the road. Carefully corss the highway tot the outcrop on the east side.

STOP 9. Mylonitic, migmatitic gneiss

Location Coordinates UTM Z18 NAD83: (625497 E, 4812086 N)

This is a beautiful exposure of a garnet-biotite-plagioclase-K-feldspar-quartz ± sillimanite gneiss (Fig 17). Most of the white layers are interpreted as leucosomes that formed during anatectic melting via a biotite dehydration reaction such as:

Biotite + plagioclase + sillimanite + quartz ⟶ K-feldspar + garnet + melt.

Much of garnet in the leucosomes was probably produced via this reaction.

Figure 17. Photograph of a portion of the outcrop at stop 9. Garnet is visible in the white leucosome, particularly to the right of the hammer. A softball sized feldspar crystal, which is part of a dismembered pegmatite, is in the lower left portion of the picture.

The strongly attenuated nature of the leucosomes, along with also remnants of pegmatite dikes that are now sheared out in the foliation plane (Fig. 17) attest to the significant strain recorded by these rocks. The rocks have the same strong southeast-trending, gently plunging lineation that we have seen in the last two stops. We suggest that some of the strain in these rocks may be the result of post-Ottawan extension collapse in the EASZ.

This outcrop was part of a study by Bickford et al. (2008). They concluded that these rocks underwent partial melting at approximately 1050 Ma at the tail end of the Ottawan Orogeny. They suggest anatexis was facilitated by an influx of H_2O-bearing fluids and decompression as a result of extensional collapse.

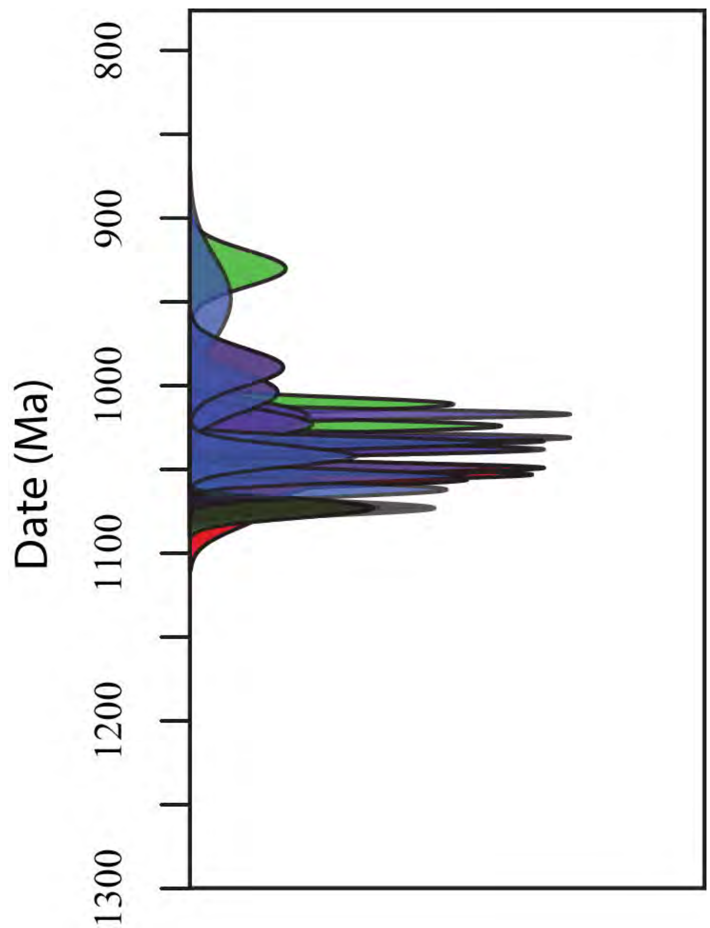

Figure 18. Histogram showing monazite ages from 9 monazite crystals from a single thin section from Stop 9.

Figure 18 shows our preliminary U-Th-Pb electron microprobe monazite data from this outcrop. The data shown in figure 18 are from 9 monazite crystals in a single thin section. Our data show monazite growth from approximately 1080 Ma through 1000 Ma. The data are consistent with recrystallization during the Ottawan and post Ottawan extension and in good agreement with the results of Bickford et al. (2008). It is interesting to note the lack of any Shawinigan or AMCG ages when the rocks approximately one mile to the north have a strong Shawinigan signature. We are in the process of collecting more data in order to further explore the effects of the Shawinigan and Ottawan Orogenies and post Ottawan orogenic collapse on these rocks.

End of Trip.

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