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GEOLOGY AND GEOCHRONOLOGY OF THE EASTERN ADIRONDACKS

by

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INTRODUCTION

The eastern Adirondacks contain a wide variety of rock types, and this trip will visit representatives of the major lithologies. Stops include units recently dated by U-Pb geochronology including multi- and single-grain TIMS and SHRIMP II analyses as well as in-situ dating of monazites.

The Adirondack Mountains represent a southwestern extension of the Grenville Province via the Thousand Islands – Frontenac Arch across the St. Lawrence River (Fig. 1). The region is topographically divided into the Adirondack Highlands and Lowlands separated by the Carthage-Colton Mylonite Zone (CCMZ, Fig. 2). The former is underlain largely by orthogneiss metamorphosed to granulite facies and the latter by upper-amphibolite grade metasediments, notably marbles. Both sectors have experienced multiple deformations resulting in refolded major isoclines. The tectonic history consists of a tripartite division, as summarized below and in Fig. 3. Broadly, the various lithologies fall into the following groups: 1350-1300 tonalites rifted from Laurentia at ca. 1300 Ma, 1250 Ma granodiorites; 1160-1150 Ma anorthosites, mangerites, charnockites, and granites (AMCG suite); 1100-1090 Hawkeye granite; and 1055-1040 Ma Lyon Mountain Granite (LMG). The four major orogenic events associated with these are: an Andean arc along southeast Laurentia, the Elzevirian (ca1250-1220), the Shawinigan (1210-1140 Ma) and the Grenvillian (1090-1045 Ma) orogenies (Fig. 3). The Elzevirian involved a back-arc rift basin with protracted outboard arc magmatism and accretion and was followed by the collisional Shawinigan Orogeny between Laurentia and the Adirondack Highlands – Green Mountain Terrane. The Ottawan was a Himalayan-type collision of Laurentia with Amazonia (?). Most of the metamorphic and structural effects present in the Adirondacks are the result of the Ottawan Orogeny, but Shawinigan and Elzevirian features can be recognized locally. Both the AMCG suite and the LMG are thought to be late- to post-tectonic manifestations of delamination of over-thickened orogens undergoing terminal extensional collapse.

Structurally, the eastern Adirondacks are dominated by the same large, recumbent fold-nappe structures (F_2) as found in the southern Adirondacks (Fig. 2), and with fold axes oriented dominantly ~E-W parallel to stretching lineation. As in the southern Adirondacks, these Ottawan fold-nappes are thought to posses sheared-out lower limbs, but this has yet to be demonstrated at map scale. F1 folds of Shawinigan age occur as minor folds within the much larger F2 recumbent isoclines. At least two distinguishable upright fold events are superimposed on the nappes: F3 with shallow plunging ~E-W axes and F4 with shallow-plunging NNE axes. Both of these can be shown to be of late Ottawan (ca, 1050-1040 Ma) origin. All of three fold sets affect Hawkeye and older units, and thus must be of Ottawan age. This is also the case with the strongly penetrative rock fabric, including strong ribbon lineations that are present in these rocks and are largely associated with the large fold-nappes. Intense fabric and nappe structure are largely absent from the ca. 1050 Ma Lyon Mountain Granite; however, this unit is folded by F3 and F4, and this is interpreted to reflect its intrusion in late, post-nappe stages of the Ottawan orogenic phase of the Grenvillian orogeny. In the northern portion of the eastern Adirondacks the NNE, F4, folds become quite tight and have a strong lineation associated with them. This may be the result of rock sequences being squeezed between large, domical prongs of anorthosite during terminal Ottawan exhumation.

Most of the region likely experienced peak Ottawan temperatures of ~750-800° C and pressures of ~8 Kbar (Spear and Markussen, 1997; Storm and Spear, 2005 and references therein). Evidence exists that similar P, T conditions were attained in the Shawinigan orogeny (Heumann et al., 2006). Based upon extensive oxygen isotopic work by John Valley and his students, it appears most likely that Ottawan metamorphism proceeded under fluid-absent conditions (Valley *et al.*, 1982, 1992). Note, however, that this does not exclude the presence of late, post-peak fluids associated with the emplacement of Lyon Mountain Granite.

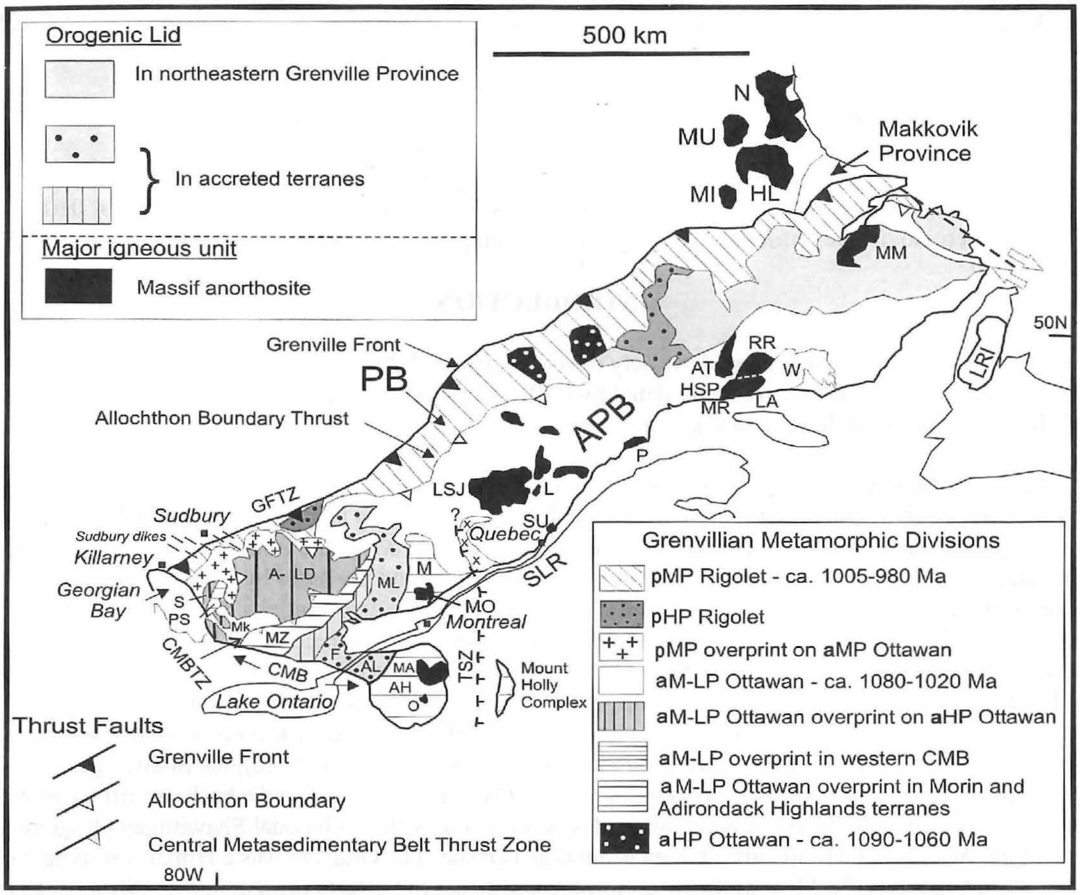

Figure 1. Generalized map shows the Grenville Province whose three major tectonic divisions (Rivers, 1997) are indicated. The Orogenic Lid of Rivers (2008) is shown in light gray. The accreted ca. 1.3-1.4 Ga Montauban-La Bostonnais arc is shown by X- pattern. **Abbreviations**: A-LD- Algonquin- Lac Dumoine domain; AL-Adirondack Lowlands; AH- Adirondack Highlands; APB- Allochthonous Polycyclic Belt; CMB- Central Metasedimentary Belt; CMBTZ, Central Metasedimentary Belt thrust zone; F, Frontenac terrane; GFTZ- Grenville Front Tectonic Zone; LRI- Long Range inlier; M- Morin terrane; MK- Muskoka domain; ML- Mont Laurier domain; MZ- Mazinaw terrane; O- Oregon dome; PS- Parry Sound domain; RR- Romaine River, S- Shawanaga domain; SLR- St. Lawrence River, TSZ – Tawachiche Shear Zone with its southern projection, W- Wakeham terrane. **Abbreviations for metamorphic divisions**: p-MP- parautochthonous medium pressure belt; aM-LP- allochthonous medium to low-pressure belt; aHP- allochthonous high-pressure belt; pHP- parautochthonous high-pressure belt. **Major anorthosite massifs with ages**: AT- Atikonak (ca 1130 Ma); HL- Harp Lake (ca. 1450 Ma; HSP- Havre-St-Pierre, (ca. 1126 Ma, dashed white line is the Abbe-Huard lineament; L- Labrieville (1060 Ma); LA- Lac Allard HL) (ca. 1060 Ma); LSJ- Lac-St.-Jean (ca. 1155 Ma); MA- Marcy Massif (ca. 1155 Ma), MO- Morin (ca. 1153 Ma), MI- Mistastin (ca. 1420 Ma); MU- Michikamau (ca. 1460 Ma); MR- Magpie River (ca. 1060 Ma); N- Nain-(ca 1383- 1269 Ma); P- Pentecôte (ca 1350 Ma); S- St. Urbain (ca. 1060 Ma). *Modified after Rivers (2008 and McLelland et al. (2010a).*

The most recognizable fold patterns in the Adirondack Highlands are those of the ~E-W F3 and ~NNE F4 folds that span the entire region, e.g., Fig. 2, P (Piseco dome). These upright , relatively open folds exhibit E-W stretching lineations coaxial with the F3 folds. Because these folds both affect the ca. 1050 Lyon Mt. Granite and are crosscut by it, they are most likely synchronous with the terminal, extensional phase of the Ottawan orogeny. We interpret them as "a" and "b" domical folds that have been identified in large scale extensional orogens such as the Aegean core complex (Jolivet et al., 2004) and are due to the extension itself. Axes of the "a" folds form parallel to the principle extension due to constriction, whereas the "b" folds form approximately perpendicular to extension and slightly postdate the "a" folds. The axes of F2 folds are approximately parallel to extension and may have formed in this orientation and/or were rotated into it by extensional strain.

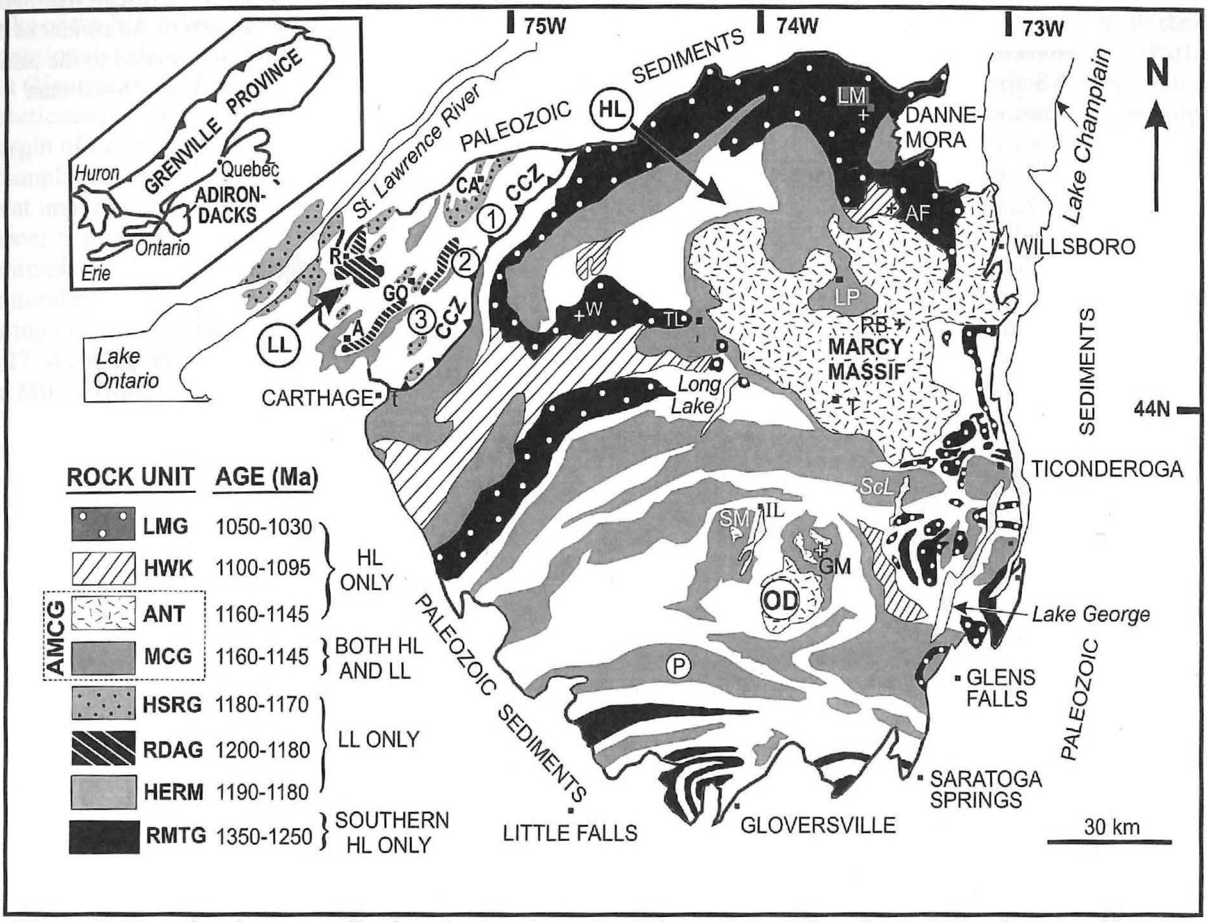

Figure 2. Map showing generalized geology and geochronology of the Adirondacks. Units designated by patterns and initials consist of igneous rocks dated by U-Pb zircon geochronology with ages indicated in the legend. Units present only in the Highlands (HL) are: RMTG – Royal Mountain tonalite and granodiorite (southern and eastern HL only), HWK -Hawkeye granite, LMG – Lyon Mountain granite, and ANT – anorthosite. Units present in the Lowlands (LL) only are HSRG – Hyde School and Rock port granites (Hyde School also contains tonalite), RDAG – Rossie diorite and Antwerp granodiorite. Granitoid members of the anorthosite-mangerite-charnockite-granite (AMCG) are present in both the Highlands and Lowlands. Unpatterned areas consist of metasediments, glacial cover, or undivided units. Other abbreviations: CCZ-Carthage-Colton Shear Zone, CL- Cranberry Lake, LL-Lowlands, OD Oregon dome anorthosite, SM – Snowy Mountain anorthosite, LM- Lyon Mountain SLR- St. Lawrence River. *Modified after McLelland et al, 2010a*.

Recent investigations in the Grenville Province demonstrate that the Ottawan orogen (Rivers, 2008) and its Adirondack outlier (McLelland et al., 2010a) underwent terminal extensional collapse that, in the latter case, was accompanied by emplacement of Lyon Mountain Granite. The most complete local study of this sort is that of Selleck et al. (2005) that utilized zircon geochronology to document that down-to-the-west displacement along the northwest dipping Carthage-Colton Shear Zone (CCZ, Fig. 2) was coeval with intrusion of Lyon Mt. Granite (Fig. 2) into the fault complex at ca 1050-1045 Ma. It is thought that, at peak Ottawan contraction, the over-thickened lithosphere experienced delamination by foundering, convective thermal erosion, or both. Following delamination of the dense lithospheric keel, the orogen rebounded and hot asthenosphere moved to the crust-mantle interface where it underwent depressurization melting to yield aluminous gabbro that differentiated into anorthositic crystal mushes that ascended, along with crustal granitic melts, to yield the AMCG suite (McLelland, 2010b). The asthenospheric diapir likely underwent degassing, and caused fertilization and melting of deep crust to yield Lyon Mountain Granite. As the granite ascended into the crust, it both lubricated and enhanced low-angle normal faults formed in response to increased topographic elevation, fluids, and anatexis; all leading to orogen collapse. In such situations, it is not uncommon to find that collapse is quasi-symmetrical around the orogen core thus giving rise to a mega-gneiss dome or double-sided core complex such as the Shuswap complex. Given this, we have undertaken research aimed at establishing whether, or not, low-angle down-to-the-east normal faulting took place in the eastern Adirondacks at ca 1050-1040 Ma. Geological evidence is consistent with this proposal, and kinematic indicators related to the issue are described in Stop 7 of the Road Log where the authors present evidence supporting topside down-to-the-east displacement. Some of the more regional geological evidence is discussed below.

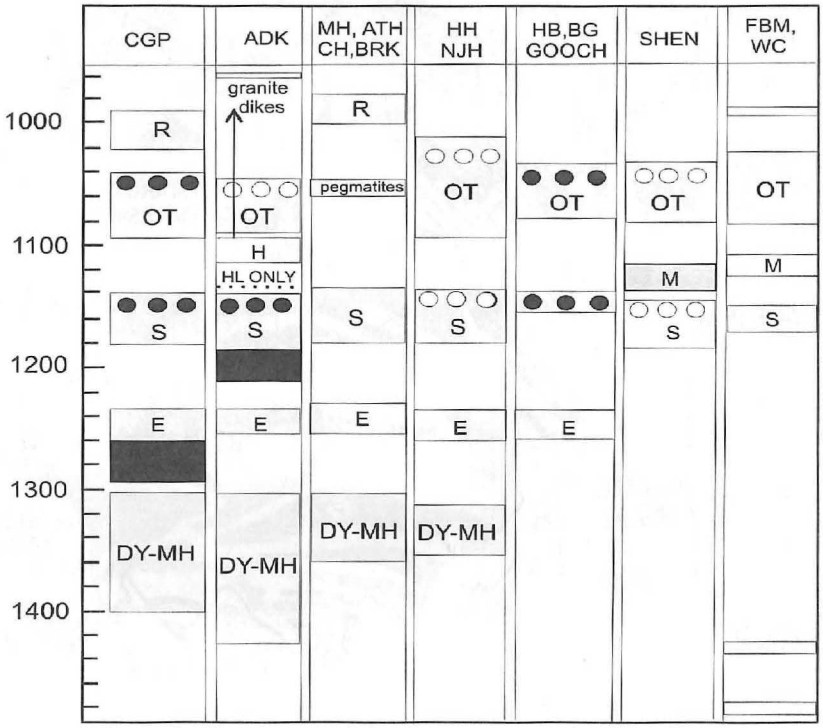

Figure 3. Chart summarizing Mesoproterozoic orogenic events in eastern North America during the interval 1.5-0.9 Ga. The gray blocks labeled R and OT represent the ca 1.09-1.03 Ga Ottawan orogenic phase and the ca. 1000-980 Ma Rigolet phase of the Grenvillian orogeny, respectively (Rivers, 2008). The black circles represent late- to post-tectonic AMCG suites, whereas the smaller, white circles represent MCG magmatism only. The black blocks in the Elzeverian (E) and Shawinigan (S) orogenies represent pre-orogenic arc magmatism. The events labeled DY-MH in the lower gray blocks represent ca.1.45-1.3 Ga continental arc magmatism along the southeastern margin of Laurentia. Portions of the arc rifted during the formation of the Central Metasedimentary Belt (ca. 1.3-1.22 Ga) and are now situated in the Adirondacks and the Mesoproterozoic inliers of the northeast Appalachians where they are known as the Dysart-Mt. Holly suite. Geographic abbreviations from left to right: CGP – Canadian Grenville Province, ADK – Adirondack Mountains, MH – Mount Holly, ATH – Athens dome, CH – Chester dome, BRK – Berkshire Mountains, HH – Hudson Highlands, NJH - New Jersey Highlands, HB – Honey Brook uplands, BG – Baltimore Gneiss domes, GOOCH – Goochland Terrane, WC– Wolf Creek, SHEN– Shenandoah Blue Ridge, FBM– French Broad Massif. *Modified after McLelland, 2010a.*

Figs. 1 and 4 show the trace and southward projection of the Tawachiche Shear Zone (TSZ) that outcrops to the west of Quebec City. The TSZ is an eastward dipping (~30-45°) normal fault of Ottawan (ca. 1050-1070 Ma) age that drops the medium grade, ca. 1.35 Ga Montauban- La Bostonnais island arc down against the granulite facies rocks of the Morin and Mekinac Terranes (Fig. 6). It follows that the TSZ represents an important structure in the extensional collapse of the Grenville Province. The direction of offset appears to be to the northeast at the northern end (Hanmer et al., 2000) to more easterly to the south (L. Nadeau, pers. comm.). There is evidence that the TSZ experienced an earlier phase of reverse fault motion that resulted in the thrusting of the island arc over the eastern margin of Laurentia. The southern projection of the TSZ extends down the through Paleozoic cover of the Champlain Valley, but there is no current seismic or magnetic evidence to support the projection. The issue is of great importance, because, if the TSZ does project southward as shown, then it suggests that it may have been the master fault of the eastern Adirondack shear zone that played a central role in the extensional collapse of the Adirondacks similar to that played by the Carthage-Colton Shear Zone to the west. These issues also imply that the Adirondacks and Morin Terrane belong to a larger, Shuswap-scale, symmetrical gneiss dome that was exhumed during the extensional collapse of the Ottawan orogen. Related to this, is the report of a hornblende Ar/Ar age of 1127 Ma in the Mtount Holly complex (Sutter et al., 1975). Although this is only a single data point, it suggests that the Mount Holly complex did not experience Ottawan temperatures >500°C. Clearly more work is necessary.

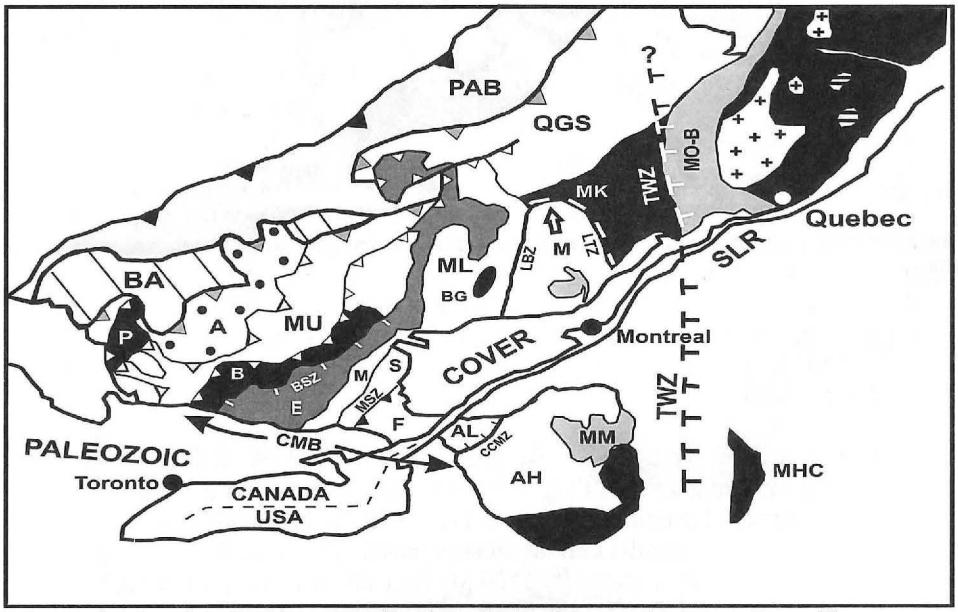

Figure 4. Map showing the generalized geology of the southwestern Grenville Province showing the location of the Tawachiche shear zone (TSZ) and its southern projection. Abbreviations: A– Algonquin Terrane, AH- Adirondack Highlands, AL- Adirondack Lowlands, B– Bancroft Terrane, BA -Barillia Terrane, BG– Bondy gneiss, BSZ– Bancroft Shear Zone. CCMZ- Carthage-Colton Mylonite Zone, CMB – Central Metasedimentary Belt, E– Elzevir Terrane, F – Frontenac Terrane, LBZ- Labelle shear zone, M– Morin Terrane, M– Mazinaw Terrane, MHC- Holly Complex, MK– Mekinac Terrane, MM– Marcy massif, MO-B– Montauban-La Bostonnais arc, MSZ- Maberly shear zone, PB- Parry Sound domain, PAB– Parautochthonous Belt, QGS – Quebec Gneiss segment. *Modified after Hanmer et al., 2000.*

The Canada Lake recumbent isocline is a prominent feature of the southwestern Adirondacks (Figs. 2, 5). It is an Ottawan (based on monazite dating of axial plane foliation) nappe-type structure that extends from Saratoga Springs (SS, Fig. 5) to the southwestern Adirondacks west of Gloversville-Johnstown (GJ, Fig. 2,5) – a total distance of over 125 miles along its axial trace. Throughout this tract, the axis trends ~N60W, 10-20S. The lithologies comprising the western segment of the isocline are repeated to the east of Great Sacandaga Reservoir in the southeastern Adirondacks. Given the pattern of strikes and dips in Fig. 5, there appear to be only two ways of achieving the repetition: either by thrust faulting or normal faulting. Although there is remaining uncertainty, kinematic indicators tend to support the normal fault alternative. The fault trace consists of a distinctive shear belt hosting pegmatites and quartz veins that are locally mylonitic and stained by hydrothermal fluids. We propose that this belt represents the trace of a low angle (~45°) normal fault whose projection is shown on Fig 5. Coarse, synkinematic pegmatites are common in, and near, the belt, and secondary muscovite occurs locally. The projection of the shear belt beyond the map boundaries is uncertain. These issues are discussed in greater detail at stop 7.

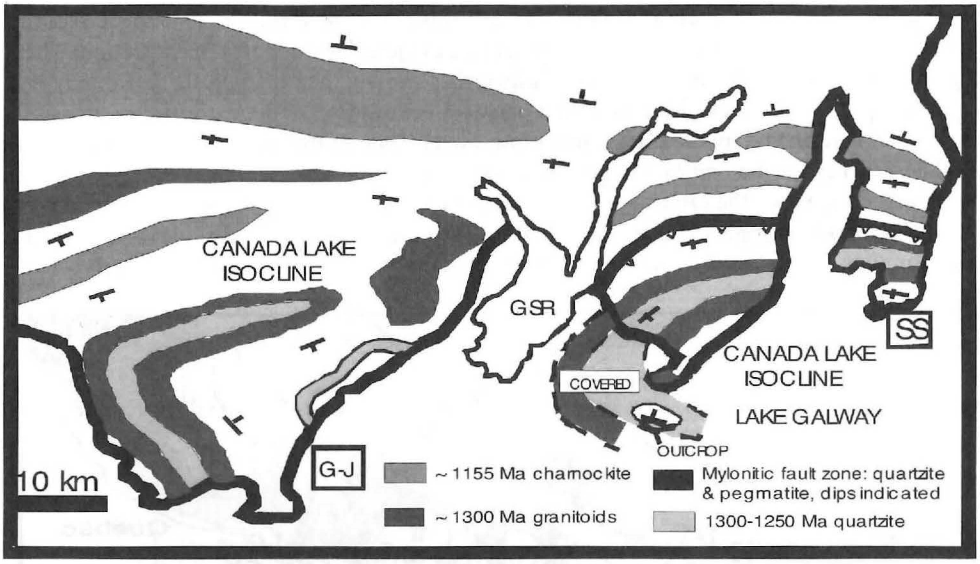

Figure 5. Geologic map showing the southeastern Adirondacks. The heavy hachured line denotes the location of a high-shear zone containing minimally deformed pegmatite, down-dip lineation and repeating the Canada Lake isocline. G-J – Gloversville-Johnstown, SS-Saratoga Springs, GSR – Great Sacandaga Reservoir. *Modified from Bickford et al., 2008.*

Our current interpretations of the plate tectonic evolution of the Adirondacks and adjacent portions of the Central Metasedimentary Belt are summarized in Fig. 6. The sequence begins with the rifting of the ca. 1.45-1.3 Ga continental margin arc along eastern Laurentia corresponding approximately with the current Central Gneiss Belt. The top panel shows the situation just after the Central Metasedimentary back arc basin had begun to close via subduction at the onset of the Elzevirian orogeny. By 1200 Ma the Composite Elzevirian Arc had closed against Laurentia and northwestward subduction beneath the future Adirondack Lowlands had begun. Calcalkaline magmatism related to the subducting plate gave rise to ca 1200-1170 Ma calcalkaline plutons rocks in the Lowlands. By 1170 Ma the basin had completely closed as the Highlands collided with Laurentia to initiate the Shawinigan orogeny. In the process the Lowlands were thrust over the Highlands along approximately the same fault zone as the current Carthage-Colton Shear Zone. By 1160 Ma delamination led to the rise of asthenosphere and the formation of the ca.1155 Ma AMCG suite. The collision with Amazonia began at ca 1090 Ma and was preceded by a little understood period of extension and intrusion of the Hawkeye granite. The onset of the Ottawan phase of the Grenvillian orogeny began at ca. 1090Ma and involved ~40 my of deformation and mountain building that produced the great recumbent isoclinal folds of the Adirondack Highlands together with their intense ductile fabrics. This was followed by delamination, extensional collapse along the Carthage-Colton Zone and the eastern Adirondack shear zone and was accompanied by melting of the deep crust to produce the Lyon Mountain Granite. Details can be found in McLelland et al., 2010a.

The geology of the Adirondack Highlands is far more complex than can be shown on a small map such as Fig. 2. In contrast to this, Fig. 7 details the geology of the southern and central Adirondacks, and Fig. 8 depicts even more detailed geology in the field trip area of the eastern Adirondacks.

ACKNOWLEDGEMENTS

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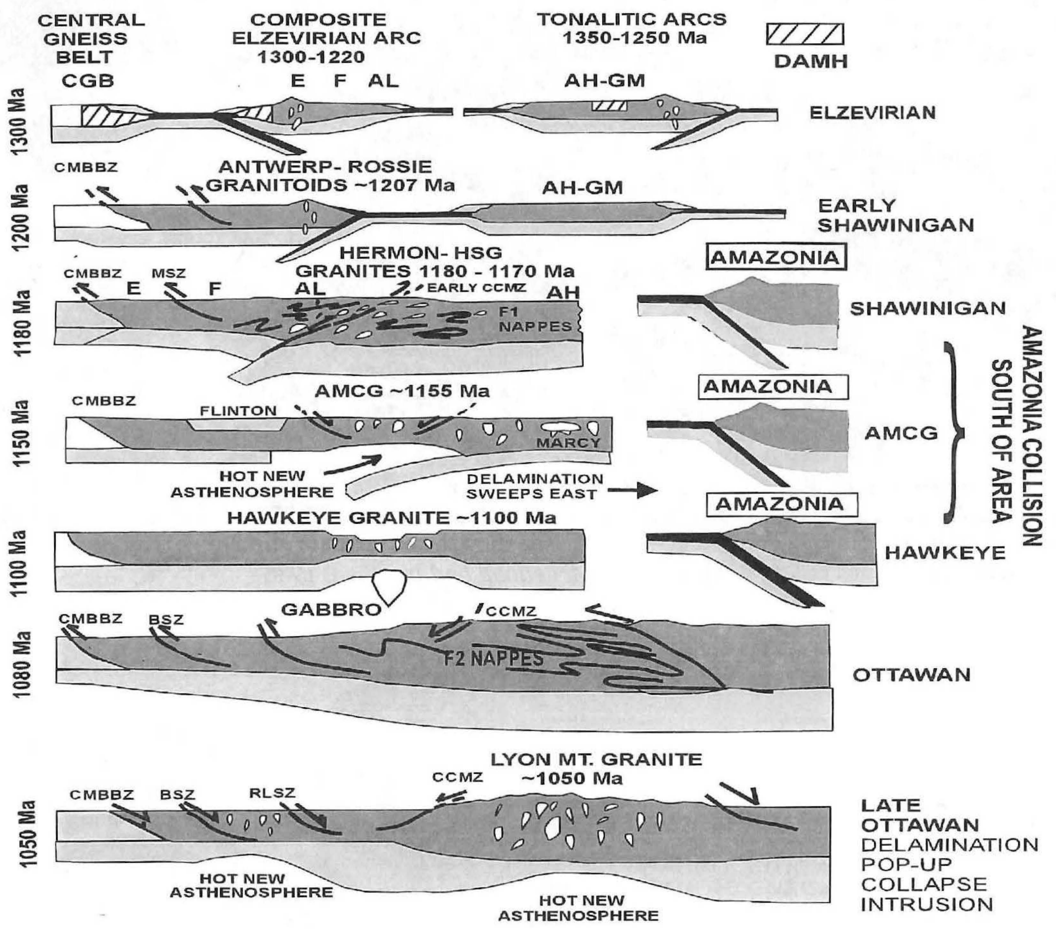

Figure 6. Figure shows plate tectonic models along a line from the Adirondack Mountains to the Central Metasedimentary Belt Boundary Zone (CMBBZ). The ruled areas schematically represent the Dysart-Adirondack-Mt. Holly suite (DAMH). **Abbreviations**: AH–Adirondack Highlands, AHGM–Adirondack Highlands-Green Mountains Terrane, AL–Adirondack Lowlands, BSZ–Bancroft Shear Zone, CCMZ– Carthage-Colton Shear Zone, E- Elzevir Terrane, F–Frontenac Terrane, HSG –Hyde School Gneiss, RLSZ–Robertson Lake Shear Zone. The eastern Adirondack extensional shear zone is shown by the heavy fault line and arrow in the bottom (1050 Ma) panel. *Modified after McLelland et* al., 2010b.

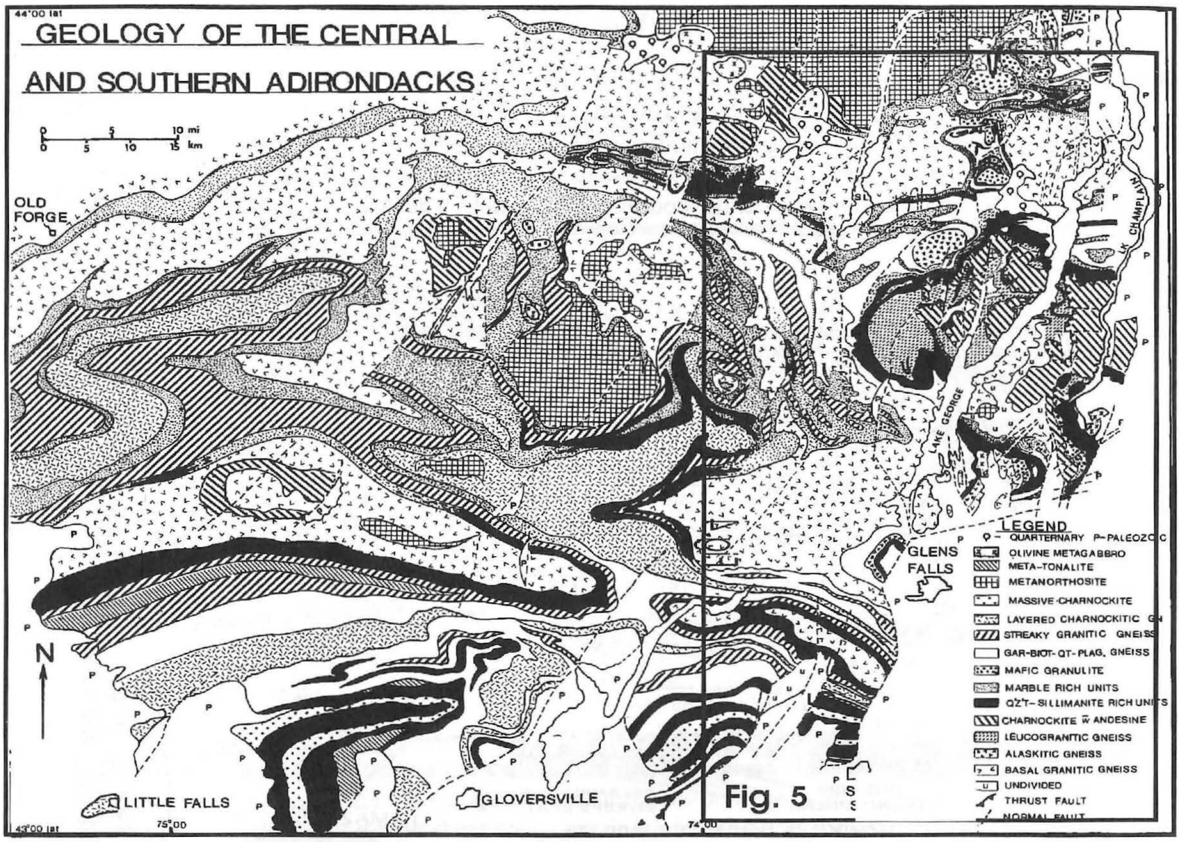

Figure 7. Map showing the generalized geology of the southern and central Adirondack Highlands. The inscribed rectangle locates Fig. 8. *Modified after McLelland and Isachsen, 1986.*

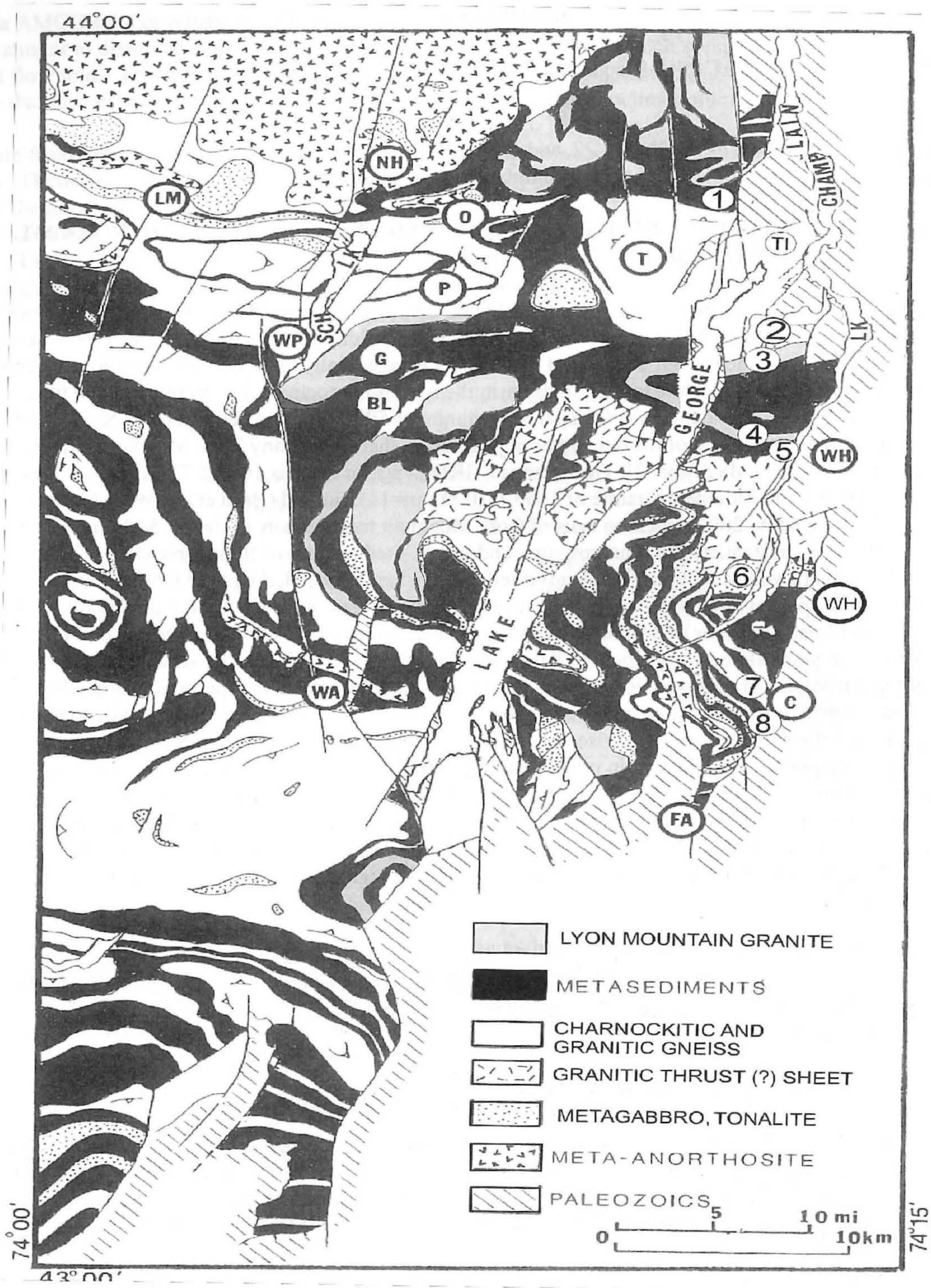

Figure 8. Showing field trip stops 1-8 on a detailed map of the geology of the southeastern Adirondack Highlands. **Abbreviations:** BL- Brant Lake, C- Comstock, FA- Fort Ann, LM- Loch Muller, NH- North Hudson, O- Owl's Head, P- Pharaoh Mt., T- Ticonderoga, Ti- Ticonderoga dome, WA- Warrensburg, WH- Whitehall, WH- Whitney Pond. *Modified after Thompson e t al., 1990.*

ROAD LOG

Meeting Point: 8:00AM at McCardell Bicentennial Hall, Middlebury College

Mileage

0.0 Traffic light at junction of Rt. 9N, Rt. 22, and Rt. 74. Turn west on Rt. 74.

0.3 Park on north side of Rt. 74 as it begins to climb uphill at first roadcut.

STOP 1. ~1050 Ma PAGIOCLASE-RICH PEGMATITE, AND AMPHIBOLITE WITH GORE MT. -TYPE MEGACRYSTIC GARNETS. (20 MINUTES)

The roadcut consists of various metasediments including quartzite, calcsilicate, and marble. A nearly vertical, very coarse pegmatite and amphibolite occurs near the south end. Within the pegmatite are large (~6-8") gray to light green crystals of andesine (An39, Tan, 1966) that display exceptionally good twinning striations when viewed in good sunlight. The untwinned white to pink feldspar in the rock is microcline. Both muscovite and titaniferous biotite are present. Tan (1966) calculated a feldspar temperature of 590°C for this body. The importance of this pegmatite is that it is characteristic of the late Ottawan pegmatites that accompany Lyon Mountain Granite and have been dated at ca. 1030-1055 Ma (Table 2). The average SHRIMP age of these is 1044 ± 7 Ma (n=8). This compares to and average age of Lyon Mountain Granite of 1050 ± 10 Ma (n=11). Sm-Nd (Basu et al., 1991, Mezger et al., 1991,) and Lu-Hf (Connelly, 2007) isochron ages of Gore Mountain megagarnets is 1049 ± 5 Ma (n=3). Clearly these ages overlap and substantiate the synchronous – and interrelated - nature of these three events. The interrelationship is that Lyon Mountain Granite advected fluids when it ascended into the Ottawan mid-crust, and these fluids were transported into country rock by late pegmatitic phases. Release of the fluids (mainly H2O) then affected dry rocks already at upper amphibolite facies grade. The hydrous fluids transformed dry ca 1155 Ma AMCG gabbros into garnetiferous amphibolites. The anomalous presence of fluid at these temperatures provided a medium for rapid transport of chemical constituents; hence garnet growth greatly outpaced garnet nucleation. The growth of giant garnets proceeded along with that of coarse hornblende that got "shouldered" aside to form black rims (shells) around the garnets. Continued rise in temperature led to the reaction of hornblende and garnet to plagioclase and orthopyroxene as the terrain moved into the granulite facies. At essentially the same time, weakening of the mid- and lower-crust by fluids and Lyon Mountain Granite resulted in extensional collapse of the orogen and termination of the Ottawan orogeny. These issues are thoroughly discussed by McLelland and Selleck (2011). To see the local example of large garnet rimmed by black hornblende, proceed east to the adjacent amphibolite where fluids from the pegmatite facilitated transport at high temperatures under conditions where fluid is not generally present.

0.3 Traffic light at junction of Rt. 9N, Rt. 22, and 74. Continue straight ahead (south, Rt. 22).

3.0 Ticonderoga railroad station and Ft. View Inn. High cliffs on west side of highway consist of marble and amphibolite, and ca. plagioclase-rich pegmatites

8.0 Park along southbound shoulder of Rt. 22

STOP 2. THE GREAT UNCONFORMITY (20 MINUTES)

This famous locality provides a classical view of an unconformity spanning ~500 my. Above the unconformity, the horizontal layers of the Lower Cambrian Potsdam sandstone can be seen. Note the abundance of quartz pebbles in the lower conglomerate. Below are vertical gneissic layers of Mesoproterozoic units. The altered contact between the Potsdam and the gneiss is not an ancient soil horizon but is due to "recent" groundwater alteration at the contact.

8.6 Turn left into parking area.

STOP 3. LYON MOUNTAIN GRANITE INTRUSION BRECCIA (40 MINUTES)

Roadcuts on the west side of the highway expose excellent examples of Adirondack isoclinal similar folds developed in granitic gneiss. The fold axes are oriented almost E-W and plunge gently around the horizontal, which is common in the Adirondacks. However, the axial planes are vertical which is very unusual for Adirondack isoclinal folds, which are commonly recumbent. In places the folded units appear to be crosscut by other pegmatitic and granitic material. The age of the isoclinally folded granite gneiss remains uncertain. It may belong to the ca.

1155 Ma AMCG suite or it may be a phase of Lyon Mountain Granite. The dark, discontinuous amphibolite layers in it are similar to disrupted amphibolites farther south along on this stop, which seem in places to form vertical isoclinal flow folds. Towards the north end of the roadcut a deformed pegmatite fills a small reverse fault. It is possible that this records compression that caused vertical flowage and isoclinal folding.

South from the outcrop of vertical folds, large roadcuts expose a series of intrusion breccias in which Lyon Mountain Granite has disrupted amphibolites and other rocks. A number of crosscutting relationships can be seen. Many of the granitic rocks display minimal deformational fabric as would be expected for Lyon Mountain Granite. Chemical analyses of the pink/red and white/gray facies are given in Table 1 along with the ranges of compositions found for Lyon Mountain Granite. It is clear that the granites at this stop fall comfortably into the Lyon Mountain Granite clan. Note that, in addition to granite, several different facies of Lyon Mountain lithologies exist and include a quartz-albite rock, a mafic granite group, plagioclase-rich variety, a potassic, microcline type, and contaminated varieties.

Table 1. Analyses of LMG at Stops 3 and 7

SAMPLE	LMG Average	LMG PINK	LMG WHITE	PINK	LMG GRAY
STOP	N/A	3	3	7	7
OXIDE					
SiO2	69 - 75	75.29	74.49	60.04	74.16
TiO2	0.28 - 1.04	0.070	0.06	0.73	0.23
Al2O3	12 - 14	13.25	13.42	19.34	12.38
Fe2O3T	3 - 7	1.11	1	4	1.86
MnO	0.04 – 0.13	0.01	0.01	0.05	0.01
MgO	0.01 – 0.32	0.03	0.01	1.2	0.28
CaO	1.0 – 1.86	0.45	0.76	3.33	1.31
Na2O	2.5 – 5.4	3.28	2.22	4.75	2.89
K2O	2.8 – 5.7	5.77	7.45	4.97	5.2
P2O5	0.03 – 0.09	0.08	0.1	0.175	0.03
LOI		0.45	0.5	0	0
TOTAL		99.79	99.80	98.29	98.35

Relations seen in this long roadcut should leave little doubt that the ca. 1050 Ma Lyon Mountain Granite is an igneous intrusive rock and locally, at least, was ascending rapidly and rather violently during the late extensional collapse of the Grenville orogen. The abundance and possible low ductility of the amphibolites are suggestive a bimodal relationship between the two igneous rocks. Outcrops similar to this can be found along Rt. 9N from Ticonderoga to Crown Point.

15.7 Turn right (west) onto old Rt. 22. Park along shoulder of road.

STOP 4. BOUDINS, METSEDIMENTS, LYON MOUNTAIN GRANITE (30 MINUTES)

Mapping shows that the units in these roadcuts continue westward where they cross Lake George and then pass through a fold nose before heading back to the east where they connect with the Lyon Mt. Granite exposures at stop 3 (Figs. 2, 8) . The fold is a west plunging F3 antiform with a vertical northern lib and a south limb that dips ~30°S. It is uncertain whether the folding was prior to, later than, or broadly synchronous with the intrusion of Lyon Mountain Granite, although we prefer the third alternative because of the ca. 1050 Ma ages of F3, F4 and Lyon Mountain Granite. Within the roadcut both gray and pink facies of granite can be seen. Chemical analyses of these two facies are given in Table 1 where it can be seen that the gray facies fits easily into the Lyon Mountain Granite range, but the pink facies does not. Thin sections of the gray member exhibit minimal fabric but those of the pink facies are foliated. This suggests that the pink facies may be AMCG granite; however, there are local instances where such compositions are present in Lyon Mountain granite due to contamination or bad sampling. Accordingly assignment of an age for the pink facies must await U/Pb zircon dating.

In addition to the granitic rocks, the roadcut provides excellent examples of mafic boudins, pegmatites, calcsilicate, and garnetiferous metasediments. Some of the latter are rich in small garnets.

15.8 Parking area with potable spring water
16.8 Park along right side of road.

STOP 5. DRESDEN STATION ROADCUT; MULTIPLE LITHOLOGIES (30 MIN)

Large roadcuts on either side of the highway contain some of the best exposures seen anywhere in the Adirondacks. Lithologies include strongly foliated ferrodiorite at the south end of the western roadcut and an olivine metagabbro at the south end of the eastern roadcut. Also present are marbles, calcsilicates, garnet-sillimanite metasediments, and graphitic schist. Dips are everywhere steep to the south, and a strong subhorizontal E-W lineation is widely developed. Well-exposed isoclinal folds are present at several localities in the roadcuts. These features are described below.

a) Tectonized ferrodiorite at the southwest end of the roadcut is part of a much larger mass of this rock that can be seen immediately to the south. This unit forms the lower portion of a small anorthositic complex that underlies hills to the west. Commonly the ferrodiorite contains plagioclase incorporated from the anorthosite into which it grades. The age of this small plutonic complex remains uncertain, but it has experienced Ottawan deformation. The contact of the ferrodiorite with quartzite at the south end of the main roadcut is highly foliated and may represent detachment surface.

b) A few tens of feet to the north an isoclinal fold is visible and is cored by marbles.

c) The southern end of the eastern roadcut passes through a dark metagabbro with a U-Pb zircon age of 1146 $\pm$ 7 Ma indicative of AMCG suite affinities (McLelland and Chiarenzelli, 1989) or 1106 $\pm$ 6 Ma (Aleinikoff, 2006 pers. comm.). The rock contains olivine and two pyroxenes with clinopyroxene exceeding orthopyroxene. The olivines are rimmed by orthopyroxene-clinopyroxene-garnet coronas and small grains of spinel clouded plagioclase. Whitney and McLelland (1973) and McLelland and Whitney (1980) have extensively described coronas of this type, and relevant reactions are given in their publications. The coronas are thought to have formed during granulite facies conditions during the Ottawa orogeny. The northern contact of the metagabbro exhibits a good chill margin and the adjacent garnet-sillimanite metapelite has undergone microscopically visible anatexis along the contact. Small amounts of restite from this anatexis contain spinel and corundum. Within the metagabbro good ophitic texture is well preserved and randomly oriented plagioclase laths are undeformed despite the fact that these rocks experienced the Ottawan Orogeny (1090-1030 Ma). Preservation of original, delicate igneous textures in the metagabbros is thought to be the result of their strength, low ductility, and anhydrous nature. The pristine nature of the chilled contact margin may reflect the fact that the local country rock had already been dehydrated. This possibility is manifested by relationships plainly displayed on the top surface of the roadcut where the metagabbro truncates strong linear (~N-S) and planar fabrics in a garnet-sillimanite xenolith (?). It follows that the fabric is older than ca 1146/1106 Ma and most likely represents Shawinigan (ca 1210-1160 Ma) penetrative deformation. This is one of the few examples of unequivocal pre-Ottawan fabrics in the Adirondack Highlands. Within the metagabbro, and exposed near the truncated contact, are planar surfaces that exhibit strong E-W lineation defined by elongate mineral grains. This lineation parallels Ottawan fabrics and is interpreted as due that that event. Across the highway, the metagabbro thins and is exposed at the top of the roadcut at its northern end as a narrow (~0.5 m) body of hydrothermally altered mylonite surrounded by metasediments. This exposure may represent a fold nose or a boudin neck resulting from attenuation. Whatever structure is involved is somewhat immaterial compared to the fact that at this locality the metagabbro exhibits mylonitic foliation and lineation parallel to regional and local Ottawan trends thus substantiating that the Ottawan Orogeny was strongly felt in the eastern Adirondack Highlands.

d) As one proceeds north at road level from the metagabbro contact, a series of metasediments are encountered. The first of these is the garnet-sillimanite (+ feldspar, quartz, and graphite) with a fabric orientation that now parallels E-W regional Ottawan structures. Presumably the fabric was originally formed in the Shawinigan but was rotated into parallelism by intense Ottawan tectonism. Note the manner in which the marbles have torn through other lithologies that now sit within them as tectonic "fish". Beyond the marble unit, a schistose unit shows a sulfidic stain. Close inspection shows that these rocks represent highly fractured equivalents of the garnet-sillimanite unit with which it is commonly associated. It is also the horizon that was mined for graphite in the late 1800's and into the 20th century. The unit is known as the Dixon Schist; hence Dixon-Ticonderoga pencils. Presumably the fracturing provided pathways for fluids that deposited sulfides and graphite. Given the ductile nature of the Ottawan Orogeny, this fracturing must have been a late event associated with orogen collapse.

e) At the northern end of the roadcut there are excellent exposures of the garnet-sillimanite unit (khondalite) with its distinctive, pea-size garnets. Although these garnets exhibit the pale-lavender color commonly associated with spessartine, there is very little of this molecule present, and the garnets are dominantly almandine. Many garnets have spiral arms and almost all are zoned with clear rims and ilmenite-rich cores. This difference between these and many other garnets may be the result of Shawinigan vs. Ottawan growth.

23.5 Park along right of highway near intersection with Blue Goose Road

STOP 6. Ca 1350 Ma TONALITIC GNEISS (20 MINUTES)

Within the Adirondacks, the ca 1350-1250 Ma suite of tonalitic to granodioritic rocks McLelland and Chiarenzelli (1990) is restricted to the southern and easternmost regions (Figs. 2, 7, and 8). Identical lithologies and ages are present in the Green Mts., Vermont (Ratcliffe et al., 1991) and in the western Central Metasedimentary Belt (Hanmer et al., 2000). Together this group is known as the Dysart-Green Mt suite. Its strongly calcalkaline signatures attest to its origin within an arc. Hanmer et al., 2000 have argued cogently that the arc lay along the southeastern margin of Laurentia, and fragments were rifted to the east during the formation of the Central Metasedimentary Belt backarc basin. The ca. 1250 Ma granodiorites were formed in outboard island arcs at the onset of the Elzevirian orogeny. The tonalites themselves tend to be compositionally homogeneous and consist of approximately 25% quartz, 80% intermediate plagioclase ($\sim AN_{35}$), and 10% mafics. They are characterized by their gray color and the presence of disrupted amphibolite layers thought to represent synemplacement gabbroic dikes. These are present on the top of the roadcut on the east side of the highway.

26.8 Junction Rts. 4 & 22 in Whitehall
33.9 Turn left into parking area

STOP 7. KINEMATIC INDICATORS, MONAZITES, MYLONITES (40 MINS)

This long outcrop, described and analyzed by Wong et al., (2011), provides some of the best exposures of mylonitic rocks and kinematic indicators in the Adirondacks. At its north end it exposes mylonitic metapelitic migmatites that are folded around E-W recumbent isoclinal axes that are visible only in minor folds. Upright, relatively open folds that are approximately coaxial with the E-W isoclines and refold them. Extensional down-dip ribbon lineations are readily apparent on foliation surfaces and trend ~E-W. SHRIMP dating of zoned zircons shows that the migmatization is mostly of Shawinigan origin, but a substantial portion yield Ottawan ages of ca. 1050 Ma (Bickford et al., 2008). This differs from zircons in otherwise identical metapelites in the southcentral and southwest Highlands where Ottawan rims are small or absent. The difference is attributed to the presence of fluids in the eastern Highlands in contrast to a fluid-poor terrane to the west. The presence of secondary muscovite, wollastonite, and commercial graphite deposits in the eastern Adirondacks are consistent with the fluid hypothesis.

Towards the south end of the roadcut the mylonitic migmatites are intruded by pink megacrystic, L>S granitic tectonite of AMCG (1140-1150 Ma, zircon) age (Wong et al. 2011). The coarse megacrysts have been elongated in the E-W direction and have developed asymmetric tails (Fig. 9) that result in spectacular down-dip ribbon lineations on southeasterly dipping foliation surfaces. On the east side of the highway, there are several excellent ~E-W joint surfaces that afford good opportunities for examining the feldspar tails sub-parallel to lineation. Most (75%) of these tails, as well as S-C fabrics, indicate a displacement of topside down and to the southeast. Spectacular boudins on both sides of the highway provide strong evidence for intense ductile extension. Two cross-cutting pegmatites yield zircon emplacement ages of 1030 ±10 Ma (Wong et al., 2011).

DEXTRAL, TOP SIDE DOWN TO EAST, PLUNGE 15°, S40°E

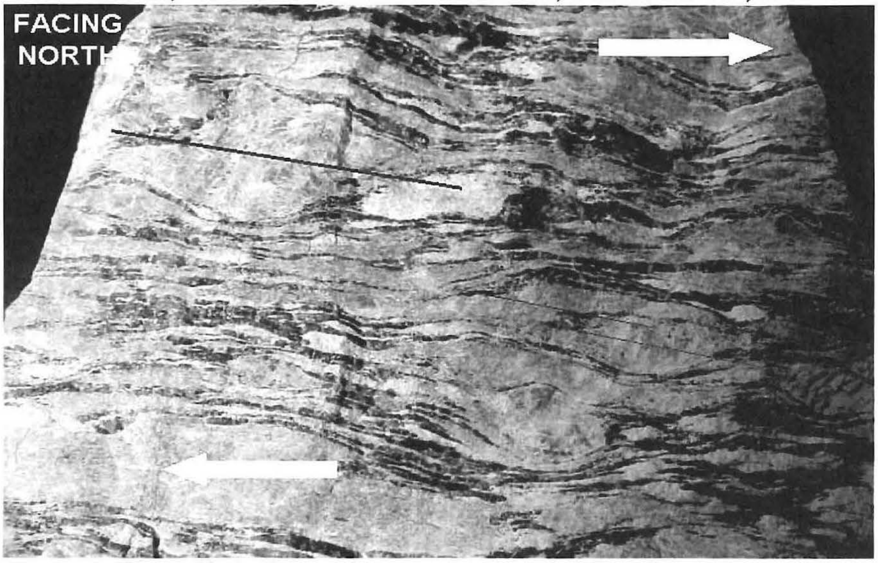

Figure 9. Kinematic indicators from granite tectonite, Stop 7.

This supports the contention that the last intense ductile deformation was along a SE-dipping, normal detachment fault system, and we suggest that this was coeval with the NW-dipping ca 1045 Ma Carthage-Colton Zone that dropped the Lowlands down to the northwest and into juxtaposition with the Highlands.

The age of the down-to-the-east extension registered by the kinematic indicators has been established by in-situ monazite dating provided by the University of Massachusetts Ultrachron. The results are shown in the age spectra of Fig. 10a and representative analyzed monazite grains in Fig. 10b. The cores of the grains yield an average age of 1176 ± 17 Ma and reflect Shawinigan growth similar to results in the south-central Adirondacks (Heumann, et al., 2006). The outer cores, or mantles, yield an Ottawan age of 1051 ± 5 Ma, and the rims are dated at a late Ottawan age of 1026 ± 5 Ma. In Fig 10b the monazite grains are shown with their original orientation preserved and indicate that late growth took place in the region of pressure shadows relative to the down-to-the-east shear strain. These results provide strong support for a late Ottawan extensional shear zone in the eastern Adirondacks.

We also suggest that the eastern detachment fault may be an along-strike continuation of the Tawachiche Shear Zone in Quebec (Fig. 4) that dropped the Montauban-La Bostonnais arc down to the east and into juxtaposition with the Morin Terrane (Nadeau et al, 1992, Corrigan and van Breemen, 1997, Bickford et al, 2008, McLelland et al., 2010a). The picture that emerges is one of late-stage orogen collapse affecting the Adirondack-Morin Terranes at the end of the Ottawan orogeny.The collapse, was accompanied by emplacement of Lyon Mt Granite and gave rise to a symmetrical core complex or gneiss dome on the scale and style of the Shuswap Complex in the northwestern Rocky Mountains of British Columbia.

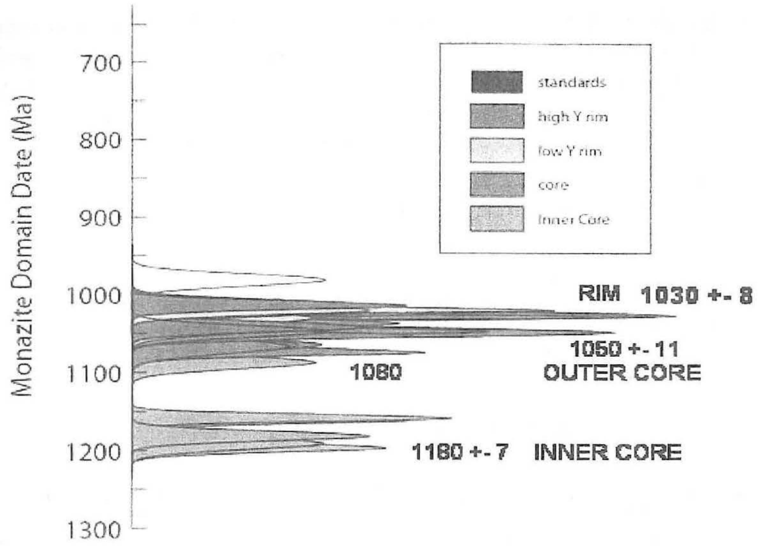

Figure 10a. Plot showing monazite age spectra for grains in ca. 1155 Ma megacrystic granite tectonite along Rt. 22 at Comstock, NY. *Modified from Wong et al, 2011.*

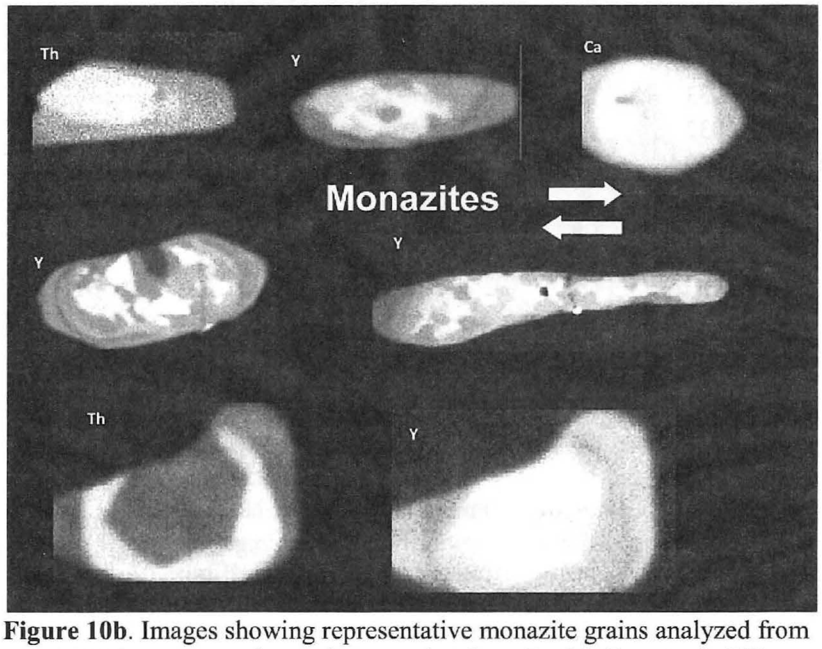

Figure 10b. Images showing representative monazite grains analyzed from ca. 1155 Ma megacrystic granite tectonite along Rt. 22, Comstock, NY. *Modified after Wong et al., 2011.*

34.3 Stop light at junction of Rts. 4 & 22 at Comstock
34.8 Park along right shoulder of road

STOP 8. STRAIGHT GNEISS, ANORTHOSITE, ULTRAMAFICS (20 MINUTES)

This roadcut contains excellent straight gneiss of several lithologies as well as some unusual rock types. At the northeastern end two large boudins of garnet-rich metagabbro are enclosed by foliated amphibolite with a narrow transition zone between parent and product. Near its SE end are superb mylonitic straight gneisses of sillimanitic migmatitic metapelites. Pegmatites are in various stages of disruption. To the north these become interlayered with garnetiferous gabbroic anorthosite that closely resembles the metapelite leoucosomes except for the presence of hornblende and coarser and more abundant garnets. Gabbroic layers are also present as well as a peculiar aluminous ultramafic that contains actinolite-phlogopite-serpentine-talc-chlorite- diaspore. The diaspore occurs as rounded lavender spots that might be mistaken for garnet. A whole rock analysis yields SiO_2 = 33%, Al_2O_3 = 17.5 %, Fe_2O_3 = 85, MgO = 24.32%, and CaO = 3%. The protolith is uncertain. Calcsilicates are found on both sides of the highway, but on the west side contain pods and layers of orange grossularite-diopside-wollastonite skarn. Nearby these is a discontinuous layer consisting of ~80% red garnet. These types of lithologies are indicative the presence of fluids at high temperature.

At the southern end of the eastern roadcut exceptionally good straight gneiss is developed from a migmatitic metapelitic protolith. A number of disrupted pegmatites result in aligned pods cored by larger, more strain resistant microcline.

Table 2. (From McLelland and Selleck, 2011)

AGES OF LATE PEGMATITE DIKES (Ma), ADIRONDACK HIGHLANDS

METHOD/LOCALITY	AGE	ERROR 2 SIGMA	MINERALOGY	REFERENCES
SHRIMP				
Gore Mountain	1045	7.5	mic, olig, qt, hbd, biot, zirc	McLelland and Selleck, 2011
Cranberry Lake	1055	7.4	mic, olig, qt, hbd, biot, zirc	McLelland and Selleck, 2011
Comstock a	1033	11	mic, qt	Wong et al.,2011
Comstock b	1032	13	mic, qt	Wong et al.,2011
Chateaugay Mine	1040	9	mic, olig, qt, hbd, mgt, zirc	Valley et al., 2010
Lyonsdale	1038	8	mic, pgf, qt, mgt, tour, sill	McLelland et al 2002
Dannemora	1030.4	1.8	mic, pgf, qt	Valley et al., 2010
Brouses' Corners	1047	4	mic, qt, hbd-biot	Selleck et al., 2005
Selleck Road	1047.5	7	mic, qt, hbd-biot	Selleck et al., 2005
LA-MC-ICP-MS				
Roe Spar Bed Hill	1042	21	mic, olig., ab, qt, biot, all, zir, tour.	Lupulescu et al., 2011
Scott's Farm	1063	9	mic, olig., ab, qt, biot,.hbd,	" " "
Mineville, Old Bed	1040	9	mic, qt, all, mgt, scap	" " "
Crown Point	1025	3	mic, and, ab qt, biot, hbd, all, zirc	Tan, 1966
Sugar Hill	1052	17	mic, ab, qt, mgt	Lupulescu et al., 2011

Table 3. (From McLelland and Selleck, 2011, a is from Valley et al. 2011)

ANALYSES OF QUARTZ-OLIGOCLASE DIKES

	QUARTZ-OLIGOCLASE CHATEAUGAY MINE		TICONDEROGA	WARRENSBURG DIKE DARK	WARRENSBURG DIKE LIGHT
OXIDE	a	b	n=2		
SiO2	64.29	63.77	74.41	74.30	72.58
TiO2	0.26	0.26	0.380	0.78	0.07
Al2O3	16.67	17.02	13.45	12.53	17.15
Fe2O3	5.88	6.72	1.54	4.0	1.0
MnO	0.02	0.02	0.02	0.01	0.01
MgO	0.1	.01	0.5	0.89	0.09
CaO	2.99	2.88	1.5	2.97	4.0
Na2O	6.43	6.21	5.11	3.4	5.06
K2O	1.75	2.22	1.92	1.75	0.71
P2O5	0.12	0.12	0.145	0.141	0.044
Total	98.82	98.21	98.98	100.77	100.71
NORMS					
Q	12.48	12.78	30.9	39.23	29.11
or	10.19	13.09	11.62	10.02	4.17
ab	58.08	56.15	46.57	29.53	44.55
an	11.75	12.13	6.49	15.15	20.93
AN%	16.8	17.9	12.2	31.71	30.12

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