TRIP A-5
GEOLOGY AND GEOCHRONOLOGY OF THE SOUTHERN ADIRONDACKS

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INTRODUCTION

The location of the Adirondacks within the larger Grenville Province is shown in Fig. 1.Topographically, the Adirondacks are divided into Highland (H, Fig 2) and Lowland (L, Fig. 2) sectors. The former is underlain principally by orthogneiss, the latter by paragneiss rich in marble, and the Carthage-Colton Mylonite Zone separates the two regions (Fig 2a,b). The region has experienced multiple metamorphic and intrusive events and large-scale ductile structures are common (McLelland, 1984;McLelland *et al,* 1996). U-Pb zircon geochronology (Table 2, Fig. 3) indicates that the oldest igneous rocks exposed are ca 1350-1300 Ma tonalitic, arc-related plutons (Fig.2a) intrusive into older Highland paragneisses of uncertain age (McLelland *et al.*, 1996). The oldest igneous rocks in the Lowlands consist are ca. 1200 Ma granodiorites (Fig.2a) intrusive into older paragneisses of uncertain age (Wasteneys *et al,* 1999). In both the Highlands and Lowlands metapelitic migmatites >1200-1300 Ma contain anatectic material of ~1170 Ma age. Following intrusion ca. 1207 Ma granodiorites in the Lowlands, leucogranitic and tonalitic rocks were emplaced at ca 1172 Ma (Fig.2a,b) and were accompanied by deformation and metamorphism (Wasteneys *et al,* 1999) assigned to the latest, culminating phase (ca. 1220-1160 Ma) of the Elzevirian Orogeny of Moore and Thompson (1980).

From ca 1160-1150 Ma the entire Adirondack-Frontenac region was intruded by anorthosite-charnockite-mangerite-granite (AMCG, 1155 Ma, Fig. 2b) magmas that are associated with four anorthosite massifs (Marcy, Oregon, Snowy, Carthage) recently dated *directly* at 1155 $\pm$ 10 Ma by SHRIMP II zircon techniques. Early age determinations of the anorthosite (McLelland and Chiarenzelli, 1990; Silver, 1969) were based on multigrain dating of MCG granitoids that exhibit mutually crosscutting relationships with the Marcy Anorthosite Massif (MM, Fig. 2b) and are interpreted as coeval with it. The absence of direct dating of the anorthosite was due to the sparse igneous zircon populations in rocks of this composition, a condition that posed a serious obstacle to the study of anorthosites prior to the advent of single grain TIMS and SHRIMP II methods. Current SHRIMP II direct dating of the Adirondack anorthosite massifs demonstrates that both they and their associated ferrodiorites and granitoids were emplaced at 1155 $\pm$ 10 Ma and that the entire complex represents a classic AMCG suite.

The final major events of Adirondack evolution comprise: 1) the emplacement of the Hawkeye granite suite at ca 1095 Ma (Fig 2b) followed almost immediately by 2) high-grade metamorphism (Storm and Spear, Appendix to this article; Spear and Markussen, 1997; Bohlen *et al* 1985; Valley *et al.,* 1990) resulting in vapor-absent, peak granulite facies conditions in the Highlands (T ~ 750°-800° C, P ~ 6-8 kbar) and associated with widespread recumbent, isoclinal folding and the development of intense penetrative fabrics. This granulite facies metamorphism and deformation are assigned to the collisional Ottawan Orogeny of Moore and Thompson (1980), evidence of which occurs throughout the Grenville Province (cf. Rivers, 1997; McLelland *et al.*, 2001b). Toward the end of this major orogenic event much of the Adirondack region was intruded by late- to post-tectonic leucogranites (ca. 1055 Ma, Fig 2a) belonging to the Lyon Mt. Granite (LMG) and thought to be related to delamination and extensional collapse of the orogen (McLelland *et al,* 2001b). The Elzevirian and Ottawan Orogenies, taken together, comprise the Grenville Orogenic Cycle (ca. 1350-950 Ma) of Moore and Thompson (1980).

GENERAL GEOLOGY

The southern Adirondacks are underlain by a package of older rocks that is only sparsely represented north of the Piseco anticline. These same lithologies are present in the eastern Adirondacks east of the Northway (Rt 87). The package is characterized by a significant thickness of migmatitic metapelites (Stop 1), some very thick orthoquartzites (Stop 2), tonalitic and granodioritic plutons (Stops 3and 4), and various members of the AMCG suite (Stops 5 and 8). Marbles are present (Stop 7) and deformation is profound (Stops 6 and 9). Taken as a whole, the southern and eastern Adirondacks appear to have been derived from one or more magmatic arcs (Fig. 4) similar to those elsewhere in the Central Metasedimentary Belt (cf., Rivers, 1997; Carr *et al.*, 2000). The growth and amalgamation of these arcs spans the time interval ca 1400-1170 Ma and is referred to as the Elzevirian

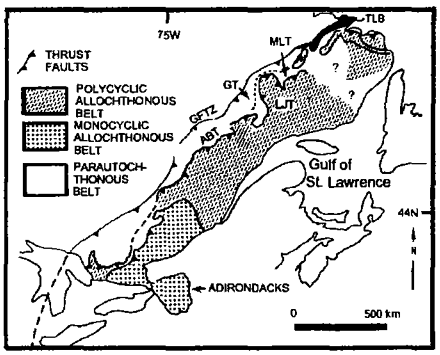


Fig. 1. Location of the Adirondack Mts. within the greater Grenville Province. Tectonic subdivisions after Rivers (1997). GFTZ - Grenville Front Tectonic Zone; ABT- Allochthon Boundary Thrust; GT-Gagnon Terrane; LJT-Lac Jeune Terrane; MLT-Melville Lake Terrane; TLB - Trans-Labrador Batholith

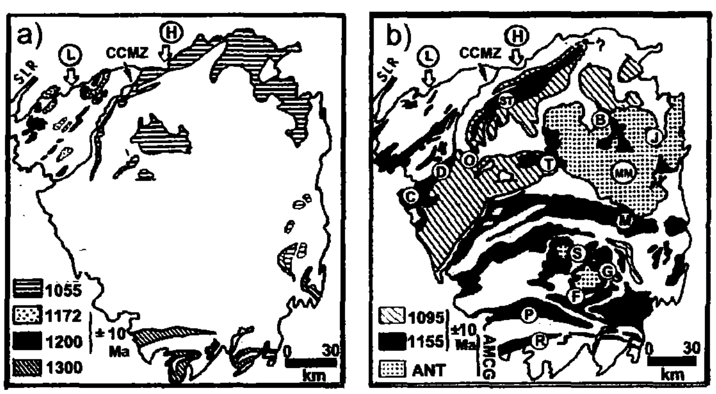


Fig. 2- Generalized geologic-chronologic maps of the Adirondacks broken into two panels for ease of viewing. The major metaigneous units are shown by patterns and their ages are given in the legend. C-Carthage, D-Diana, B-Bloomingdale; J-Jay;F- Oregon Dome Ferrodiorite; G-Gore Mt; O-Oswegatchie; P-Piseco; R-Rooster Hill; T-Tupper Lake; ST-Stark; MM-Marcy Massif, CCMZ- Carthage Colton Mylonite Zone;H-Highlands; L-Lowlands; SLR-St. Lawrence River.

Orogeny. The culminating Elzevirian Orogeny is thought to have occurred during the interval ca 1210-1170 Ma and resulted from the collision of the Adirondack-Green Mt block with the southeastern margin of Laurentia, which at that time was represented by a magmatic arc of northwest polarity developed on the present day Adirondack Lowlands. This culminating collision resulted in deformation and metamorphism that can be recognized in the southern and central Adirondack Highlands. The tonalites and granodiorites manifest the arc(s) and the migmatitic metapelites represent its apron of flysch. The thick orthoquartzites and thin marbles may represent shelf sequences developed on the passive margin of the Adirondack Highlands-Green Mt block prior to the culminating collision. These events are summarized in Fig. 4.

Following the culminating Elzevirian collision, the overthickened orogen began to delaminate and rebound as buoyancy forces dominated those of contraction. As the orogen rebounded, it underwent structural collapse and exhumation, and regional extensional basins formed and accumulated sediments, e.g., the Flinton Basin and Flinton Group (Fig. 4). At the base of the orogen hot new athenosphere moved in to replace delaminated lithosphere $\pm$ lower crust, and depressurization led to the production of gabbroic melts that ponded at the crust-mantle interface in response to density inversion. Due to the dominance of buoyancy forces, the crust-mantle environment was relatively stable, and the gabbroic melts were able to undergo quiescent crystallization. Under these conditions olivine and pyroxene sank to the floor of the chambers while plagioclase crystals floated and accumulated into crystal-rich mushes along the chamber roof. Simultaneously, the latent heat of crystallization from this process provided enough thermal energy to cause significant partial melting of the overlying continental crust. The resultant melts were largely anhydrous and ranged from syenitic, to monzonitic, to granitic and, with the crystallization of orthopyroxene, yielded mangerites and charnockites. Ultimately the crust grew weak enough, and the plagioclase mushes (ie gabbroic anorthosite) of sufficiently low density that they began to ascend and were emplaced at upper crustal levels (<10 km, Valley, 1985; Spear and Markussen, 1997) where they crystallized into AMCG complexes. Continued low-pressure fractionation of the anorthositic magmas led to further growth of plagioclase and the consequent evolution of increasingly mafic interstitial, residual liquid. Many of these were filter-pressed into fractures to form dikes and sheets of ferrodiorite; others pooled into plutonic ferrodioritic masses. We speculate that ultimately the evolving liquids became so mafic that they underwent immiscibility to produce magnetite-ilmenite concentrations such as those at Tahawus (Fig. 2) and comb-textured clinopyroxene-plagioclase dikes similar to those seen at Jay on trip C-1. Representative whole rock compositions of the AMCG suite are given in Table 1. U-Pb dating of all of these rock-types documents that the Adirondack AMCG suite was emplaced at ca 1155 $\pm$ 10 Ma (Table 2). Recent attempts to assign an age of ~1040-1050 Ma to the emplacement of the Marcy Massif are inconsistent with this hard evidence and are quite simply wrong.

Table 1. Representative whole Rock Analyses of AMCG suite Rocks

	1*	2*	3*	4*	5*	6*	7*	8*
SiO_2	42.8	55.88	56.89	53.65	62.12	51.63	54.54	53.54
TiO_2	6.04	1.6	0.47	0.52	0.87	3.1	0.67	0.72
Al_2O_3	10.53	23.18	23.82	24.90	16.48	14.23	25.61	22.50
Fe_2O_3	21.6	2.4	1.21	0.41	1.49	2.1	1.00	1.26
Fe0	na	6.57	1.3	0.70	3.96	13.5	1.26	4.14
MnO	0.02	0.09	0.02	0.02	0.09	0.16	0.02	0.07
MgO	5.68	2.08	0.65	1.45	1.06	2.63	1.03	2.21
Ca0	8.77	4.87	8.19	12.21	. 3.27	6.5	9.92	10.12
Na_2O	2.17	4.26	5.38	3.92	4.81	2.67	4.53	3.70
K_2O	0.84	2.76	1.13	1.20	5.13	2.41	1.01	1.19
P_2O_5	0.66	0.48	0.09	0.09	0.30	0.57	0.09	0.13
Total	99.34	101.47	99.57	99.9	99.9	99.5	100.1	100.00

1*- Oregon Dome Ferrodiorite; 2*- Gabbroic Anorthosite, Green Mt; 3*- Anorthosite, Green Mt; 4*- Anorthosite, Owl's Head; 5*- Mangerite, Tupper Lake; 6*- Keene Gneiss, Hull's Falls; 7*- Marcy Facies Anorthosite; 8* - Whiteface Facies Anorthosite.

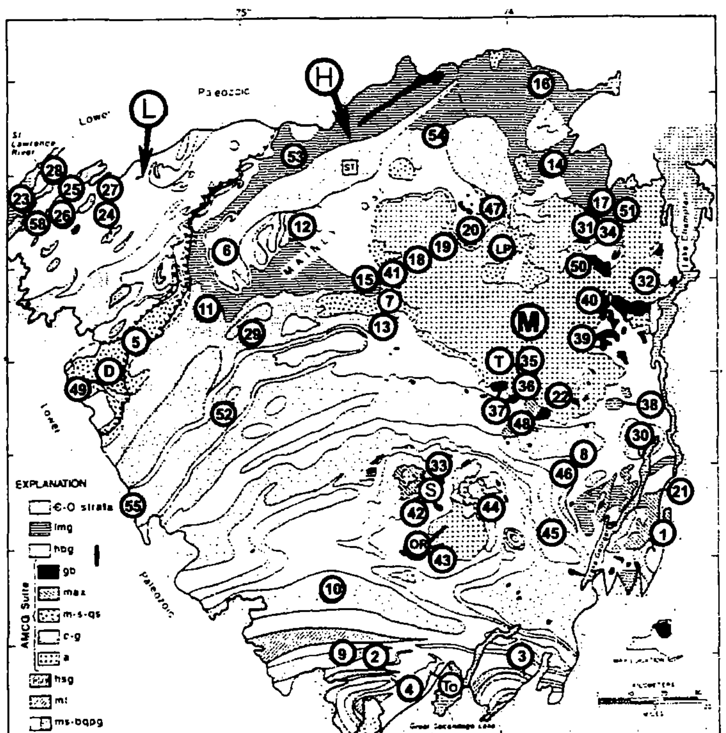


Fig 3. Generalized geologic map of the Adirondack Mtns. Showing locations of samples dated by U-Pb techniques and keyed to Table 2. H-Highlands, L-lowlands, CCMZ-Carthage Colton Mylonite Zone, D-Diana, LP-Lake Placid, OR-Oregon Dome, M-Marcy Massif, T-Tahawus, To-Tomantown pluton, ST-Stark Anticline,lmg-Lyon Mountain Granite, hbg-hornblende granite, ga-gabbro, max- mangerite with andesine xenocrysts, m-s-qs- mangerite, syenite, c-g- charnokite,granite, a-anorthosite, hsg-Hyde School Gneiss, mt- metatonalite, ms-bqpq- metasediments. Biotite-quartz-plagiolcase.

Table 2. Summary of U-Pb Zircon Geochronology For Adirondack Metaigneous Rocks

Map Number	Sample Number	Location	Multigrain TIMS AGE (Ma)	ERR	Singlegrain TIMS AGE (Ma)	ERR	SHRIMP II Analysis AGE (Ma)	ERR	TDM
HIGHLANDS									
Tonalite and Granodiorite									
1	AM87-12	South Bay	1329	37					1403
2	AM86-12	Canada Lake	1302	6					1366
3	LDT	Lake Desolation	>1336						1380
4	AM87-13	Canada Lake	1253	41					
Mangerite and Charnockite									
5	AM86-2	Diana Complex	1155	4			1154	17	1430
6	AM86-15	Stark Complex	1147	10					1495
7	AM85-6	Tupper Lake	1134	4			1169	11	1345
8	9-23-85-7	Schroon Lake	1125	10			ca 1155		
9	AM86-17	Rooster Hill	1156	8					1436
10	AM86-9	Piseco Dome	1150	5					1346
11	AC85-2	Oswegatchie	1146	5					
30	Silver,'69	Ticonderoga	1113	16			ca 1155		
42	AM86-8	Snowy Mt	>1095				1177	22	
44	AM87-3	Gore Mt	>1088				1155	6	
47	AC85-10	Bloomingdale	1133	51			1160	14	
48	AM87-10	Minerva	>1082				1159	12	
49	AM86-1	Croghan	1155	13					
41	Granitedike	Wabeek Quarry					ca 1155		
50	AC85-11	Yard Hill	1143	33					
Anorthosite and Olivine Gabbro									
18	AC85-8	Rt 3, Saranac Lk, ANT	>1113, 1054	22			1149	35	
19	AC857	Rt 3, Saranac Lk, ANT	>1087, 1052	20			1161	12	
20	AC85-9	Forest Home Rd, ILM	996	6					
21	AM87-11	Dresden Station Gab.	1147	7					1331
22	CGAB	North Hudson Gabbro	>1109, 1057	conc			1150	14	
31	BMH01-4	Jay, ANT Pegmatite					1160	15	
34	BMH-01-3	Jay, Cpx-Pgf Dike					1140	18	
35	BMH01-1	Tahawus ANT					ca 1155		
36	BMH01-2	Blue Ridge ANT					1153	11	
37	BMH01-1	Blue Ridge Gabbro					ca 1155		
39	BMH01-19	Exit 29 NWY, ANT					ca 1155		
40a		Woolen Mill Gabbro					1154	9	
40b		Woolen Mill ANT2					1151	6	
43	AM87-8	Oregon Dome Fer'd'rt					1155	6	
Hawkeye Granite Suite									
12	AM86-3	Carry Falls	1100	12					
13	AM86-6	Tupper Lake	1098	4					1314
14	AM86-13	Hawkeye	1093	11					
45	Moon Mt.	Moon Mt	1103	15					
52	NOFO-1	Stillwater Reservoir	1095	5					
53	AM87-6	St. Law/Fran. Co. Line	1090	6					
54	AM87-7	Santa Clara	1080	4					
Lyon Mt Granite									
15	AM86-4	Piercefield	1075	17			1058	18	1576
16	AM86-10	Dannemora	1073	6			1052	11	
17	AM86-14	Ausable Forks, Qt-Ab	1057	10			1041	16	1350
29	CLFG	Wanakena	1113	10	1069	10	1047	10	
38	9-23-85-6	Grasshopper Hill	>1065		1049	3			
51	AM86-11	Ausable Fks., Fay GRT	1089	26	1047	2			
55	PL-3	Port Leyden			1035	4			
LOWLANDS									
Hyde School Gneiss									
23	AM86-16	Wellesley Island	1416		1172	5			1440
24	AC85-4	Gouverneur	1284						1525
25	AC87-4	Fish Creek	1236		1172	5			1210
26	AC85-5	Hyde School	1230		1172	5			1360
27	AC85-1	Reservoir Hill	ca 1172						
Antwerp Granitoid									
58	ANTG	Antwerp-Rossie	1183	7			1207	20	

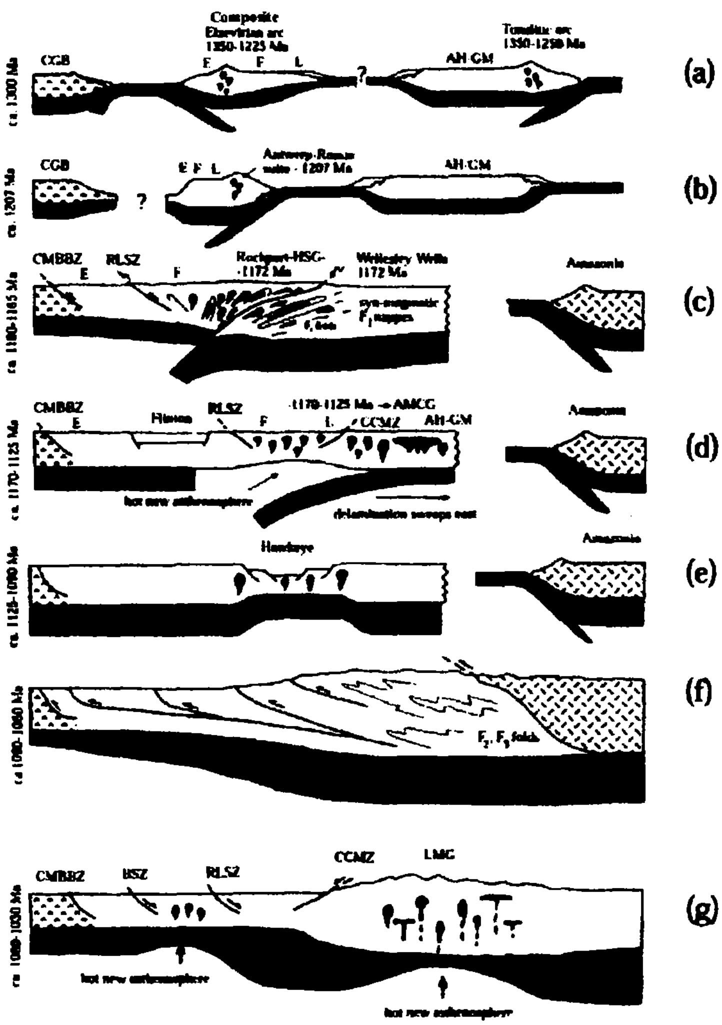


Fig. 4. Tectonic cartoon showing the evolution of the Grenville Province. See text for discussion. Modified after McLelland et al. (1996) and Wasteneys et al. (1999). Abbreviations as follows: AH-GM, Adirondack Highlands-Green Mountains; BSZ, Bancroft shear zone; CGB, Central Granulite Belt; CCMZ, Carthage Colton mylonite zone. CMBBZ- Central Metasedimentary Belt Boundary Zone; RLSZ, Robertson Lake Shear Zone; E, Elzevir terrane, F. Frontenac terrane; HSG, Hyde School gneiss; L, Adirondack Lowlands; LMG, Lyon Mountain granite.

As pointed out by Buddington (1939), there exist several facies and types of anorthosite and related rocks. Examples are given in Table 1. The coarse Marcy facies appears to be a cumulate, and in its purest form is found in rafts of 10-20cm quasi-euhedral grains with ~10% subophitic pyroxene. These are interpreted as rafts formed by plagioclase flotation at the base of the crust and subsequently transported upward by other, less coarse and commonly more mafic facies of anorthosite. The composition of these large plagioclases ranges from An_{45}-AN_{52}. Fram and Longhi (1994) showed that pressure decreases the An content of plagioclase crystallizing from gabbroic magma at the rate of ~ 1%An/kbar. Since the rafts are thought to have crystallized from gabbro at ~10-12 Kbar, this would explain their relatively sodic compositions. The presence of giant (10-25cm) aluminous orthopyroxene in the rafts is also consistent with this model. It is common for rafts to be disrupted by the transporting magma and numerous large, blue-gray andesine crystals in finer grained anorthositic rocks are of this origin. The various plagioclase mushes that were emplaced within the crust are thought to have been broadly similar to the Whiteface facies (Buddington, 1939) and evolved towards more pure anorthosite (generally less coarse than rafts) by low-pressure fractionation of plagioclase. During this process ferrodioritic residual magmas were produced and were commonly filter-pressed into dikes and sheets (McLelland et al, 1990). Ultimately, the residual magmas became so mafic that they split into immiscible silicate and Fe, Ti-oxide phases to yield magnetite-ilmenite deposits such as those at Tahawus.

Emplacement of the AMCG suite was followed by ~50 Ma of relative quiescence terminated by emplacement of the Hawkeye granitic suite at 1103-1095 Ma. This interval corresponds almost exactly with the major magmatism in the plume-related Mid-continent Rift, and we attribute Hawkeye magmatism to far-field echoes from the Mid-continent plume (Cannon, 1994). This far-field effect is interpreted to have thinned the crust and lithosphere and led to significant crustal melting to produce the mildly A-type Hawkeye suite. At the same time, the crust underwent heating that continued to be present when the culminating collision with Amazonia (?) took place thus initiating the Ottawan Orogeny at ca 1090 Ma. Note that magmatism in the Mid-continent Rift was shut off at this time by westward-directed thrust faults. Within the Adirondacks, the already heated crust was loaded by thrusting and contraction along ~NW-SE lines of tectonic vergence. This heating followed by loading led to a counterclockwise P,T,t path (see Fig. 12). From ~1090-1060 Ma contraction dominated the region and great nappe structures formed (Figs. 5,6). These are represented today by extremely large isoclinal, recumbent folds such as the Canada Lake isocline and the Little Moose Mt syncline, both of which have ~E-W axial trends and plunge gently about the horizontal (Fig. 6). It is uncertain, but possible, that these structures were initiated as thrusts and then toed-over to form a greatly thinned and attenuated lower limb. Associated with the nappes are pervasive penetrative fabrics imposed upon Hawkeye and older rocks and attesting to the extraordinarily high temperature ductile strains imposed on these rocks (McLelland, 1984).

As discussed by Spear and Markussen, garnet coronas in mafic rocks appear to have formed during late-Ottawan isobaric cooling from ~800-600°C. Associated with these coronitic rocks are small, equant zircons interpreted as metamorphic in origin and yielding ages of ~1050 Ma. As discussed in the text for Stop 8, these are thought to date the corona-forming reaction. This is consistent with the Sm-Nd age of ca 1050 Ma for the large Gore Mt garnets (Mezger et al, 1992). Following isobaric cooling the Ottawan orogen is thought to have undergone delamination and rebound. This was accompanied by emplacement of the distinctive Lyon Mt Granite suite that hosts the great Kiruna-type low-Ti magnetite deposits of the Adirondacks and is exposed across wide tracts of the Highlands. Zircon dating of the Lyon Mt Granite by both single grain TIMS and SHRIMP II methods (McLelland et al, 2002) documents that the thick, and oscillatory zoned, mantles of its zircons grew from melts at 1050 ± 10 Ma. The cores of these zircons are of AMCG and Elzevirian age and whole rock Nd-model ages are consistent with the production of Lyon Mt Granite from melting of these earlier lithologies. An especially interesting member of the Lyon Mt Granite is a quartz-albite (Ab_{98}) that is associated with the iron-oxide deposits and is interpreted to be the result of sodic hydrothermal alteration (McLelland et al., 2002).

Further relevant details accompany the descriptions presented in at individual stops.

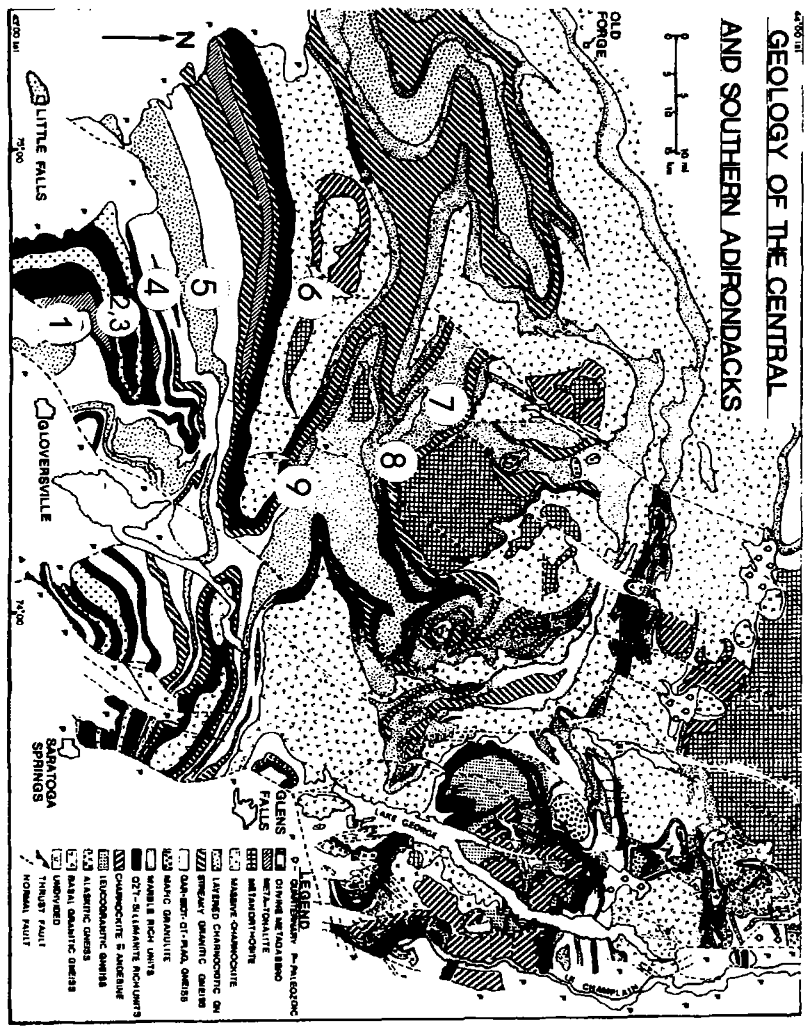


Fig. 5 Generalized geologic map of the southern and central Adirondacks showing field trip stops 1-9.

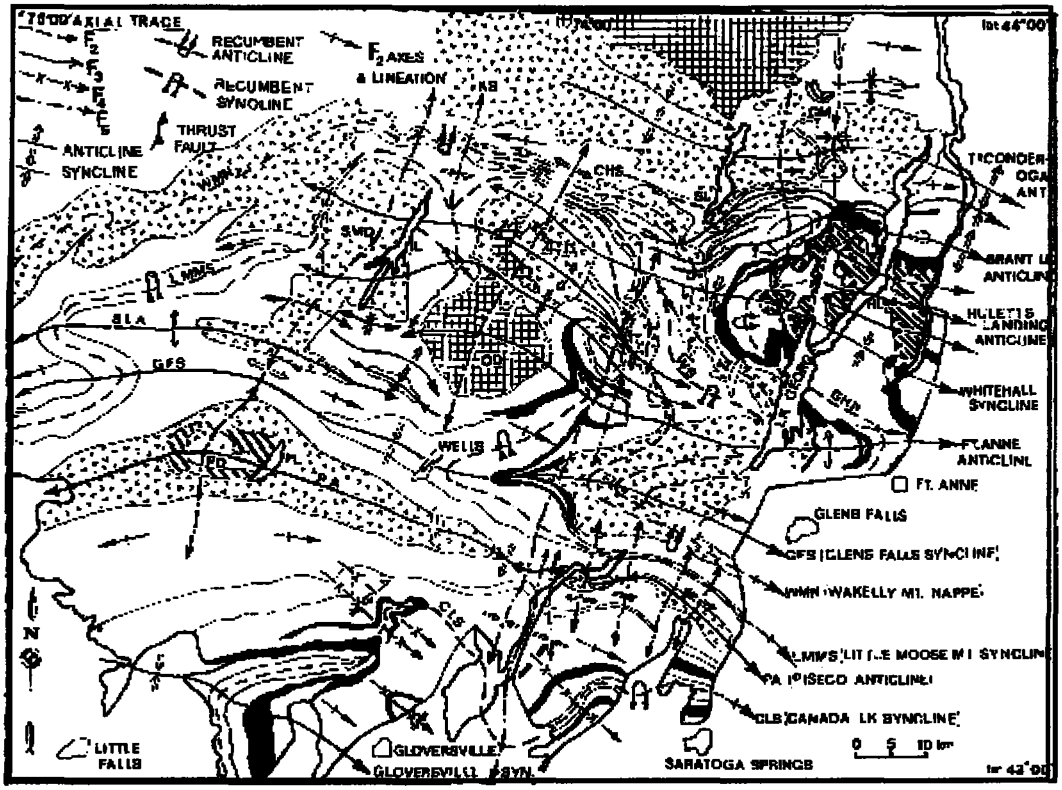


Fig. 6 Fold structures of the southern and central Adirondacks

ROAD LOG
MILEAGE
0.0 Caroga Lake Post Office in Caroga Lake, NY.
2.8 Roadcuts of migmatitic metapelite. Park on right (west) shoulder of Rt 29A.

STOP 1. PECK LAKE MIGMATITIC METAPELITE. (30 MINUTES). This exposure along Rt 29A just north of Peck Lake is the type locality of the Peck Lake migmatitic metapelites that consist of restitic sillimanite-garnet-biotite-quartz-oligoclase melanosome and quartz and two-feldspar leucosome of approximately minimum melt composition (McLelland and Husain 1986). Small red garnets are common in the leucosome and, in most cases, grow across foliation. The leucosomes occur as irregular, elongate bodies generally parallel to foliation but quite commonly exhibiting crosscutting relationships with respect to the restite and to one another. Based upon these compositional and crosscutting relations, the leucosomes are interpreted as anatectites and a reasonable metapelitic source rock can be prescribed by reintegrating their composition with that of the restite (Table 3) to yield a greywacke-slate precursor. The restriction of these partial melts to within the migmatite is thought to be the result of near-solidus, hydrous melting that would cause ascending melts to intersect the solidus as they began to rise. Close inspection of the leucosomes reveals that, in their most pristine configuration, they consist of coarse granite and pegmatite. In low strain zones elsewhere in the Adirondacks it is manifestly clear that the leucosomes originally formed an anastamosing arrays of veins, dikes, sheets, and pods. Subsequent high strain resulted in rotation into psuedoparallelism and commonly produced disruption that caused separate grains of white feldspar some of which show elongate tails – ie, the rock was on its way to becoming a mylonitic "straight gneiss". At the last stop (Stop 9) of this trip we shall see the end result of this process in a series of platy, stretched, and highly grain size reduced and mylonitic equivalents of the rocks seen here. The anatectic origin of these units is further suggested by the uncommon, but not rare, occurrence of plagioclase- and/or garnet-rimmed hercynitic spinel in the restite. Recently, Bickford and McLelland have run a U/Pb zircon pilot study on the age of the anatectites and have found that they contain 1220-1250 Ma cores, 1020-1050 Ma metamorphic rims, and relatively thick, nicely zoned mantles that fall into the interval 1190-1170 Ma. Some of the rims show zoning, but this is minor compared to the mantling zircon. These results demonstrate that majority of the anatectites were produced by partial melting during the culminating Elzevirian Orogeny dated at ca 1210-1170 Ma (Wasteneys and McLelland, 1999) and are not of Ottawan origin. Currently, we are continuing this research by utilizing both zircon and monazite geochronology.

TABLE 3. COMPOSITIONS OF AVERAGE LEUCOSOME ,HOST,AND SELECTED CLASTICS

	Average Leucosome (N = 31)	Average Host (N = 12)	Average Host + 15% Average Leucosome	Average Greywacke (N = 23)	Average PC Slate (N = 33)	Average Slate (N = 36)
SiO2	74.39	61.75	63.12	64.70	56.30	60.64
Al203,	13.85	17.83	17.18	14.80	17.24	17.32
TiO2	.05	1.32	1.15	.50	.77	.73
Fc2O3	.89	8.70	7.55	4.10	7.22	4.81
MgO	.27	2.07	1.83	2.20	2.54	2.60
CaO	1.25	2.60	2.40	3.10	1.00	1.20
Na20	2.77	2.44	2.76	3.10	1.23	1.20
K2O	5.83	3.20	3.44	1.90	3.79	3.69
MnO	.02	.07	.06	.10	.10	
P205	.08	.15	.12	.20	.14	
LOI	.30	.42	.40	2.40	3.70	4.10
TOTAL	99.70	100.55	100.00	101.00	98.70	98.00

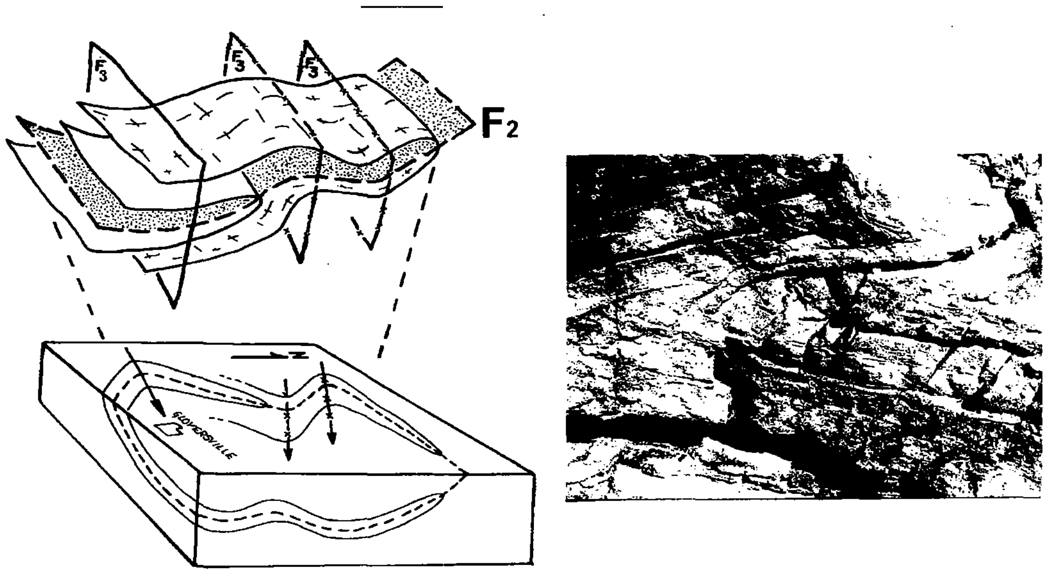


Fig.7 (a) Three dimensional cartoon showing geometry of interference of isoclinal and upright folds in the Canada Lake Isocline (F_2) and the resultant outcrop pattern. (b) F_2 minor fold recently blasted from roadcuts at stop 2.

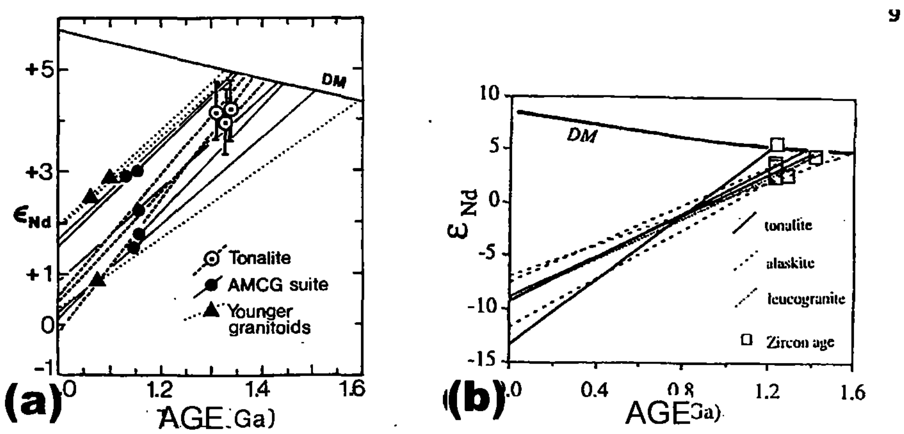


Fig . 8 Epsilon Nd plots for the Adirondack Highlands (a) and Lowlands (b)

This outcrop provides an excellent mesoscale example of Adirondack structure (Fig. 7). The overall strike of foliation is N60-70W and dips vary from north to south and pass through the vertical demonstrating that the roadcut defines a large minor isoclinal, recumbent fold. Smaller, meter-scale isoclinal folds are also well exposed and are aligned parallel to the roadcut-scale fold. All of these are similar in style, and parallel to, the very large, regional Canada Lake isocline or nappe. It is clear that the Canada Lake nappe stage of deformation rotates an earlier foliation and has a moderately dipping axial planar foliation that intersects the earlier foliation at a high angle. The time interval between these foliations remains unspecified, but it is clearly post-anatexis and probably all Ottawan (Ca 1090-1030 Ma). It appears that the Ottawan has successfully obliterated most Elzevirian fabrics. Note that some of the smaller minor folds contain apparently terminated compositional layers that could very well represent Elzevirian isoclinal noses. If so we are looking at isoclinally refolded isoclines.

Migmatitic metapelites of this sort occur throughout the southern and western Adirondacks as well as in the Adirondack Lowlands. We interpret them as flysch sequences of shale and greywacke that were being shed from the Elzevirian magmatic arcs that dominated the region from ca 1400-1300 Ma. Tonalites and granodiorites of the arcs locally crosscut the metapelites and provide a minimum age for them. In a broad sense, they are thought to be coeval. The metapelites of the Adirondack Lowlands are compositionally similar, but are thought to represent a different, younger, and uncorrelative arc environment.

3.5 Turn around at Peck Lake and head back north on Rt 29A.
5.9 Junction NY Rt. 29A and NY Rt. 10.
7.3 Nick Stoner Inn on west side and Nick Stoner Golf Course on east side of Rt 29A-10.
7.8 Town of Caroga sand and gravel depository on east (right) side of Rt 29A-10. Pull in and park.

STOP 2. IRVING POND QUARTZITE. (20 Minutes). The Irving Pond quartzite unit cores the Canada Lake isocline and is folded back on itself. At map scale it is exposed across strike for over 3000m but its "true?" thickness is on the order of 1000m. Notwithstanding, it represents an enormous volume of orthoquartzites with minor pelitic intercalations. Its minimum age is unknown but is being investigated by zircon geochronology. Similar quartzites along the St Lawrence River contain zircons as young as 1300 Ma, and the same may prove to be true for the Irving Pond. It is suggested that these quartzites may have been deposited along the present eastern margin of the Adirondack-Green Mt block between ca 1250 and 1200 Ma (see Fig. 4). During that interval, this margin was passive as the block moved westward towards the Elzevirian subduction zone that dipped westward beneath Laurentia and its leading margin, ie, the Adirondack Lowlands (Fig. 4b,c). Upon collision, (ca 1200-1170 Ma), the accumulated sandstones were deformed and metamorphosed. Although this scheme is speculative, it is consistent with the little that is known about Elzevirian events.

Within the clearing there are three small, but informative outcrops. The first consists of 30-40cm-scale layers of pure quartzite together with 2-3cm-scale metapelitic layers of. These dip gently to the southeast. The bulk of the Irving Pond quartzite consists of layer upon layer of the pure quartzite with little, if any, intervening metapelite. The second exposure is located a few tens of feet to the west where the rocks form a low ledge running uphill. The southern termination of the ledge that faces the clearing shows steeply dipping layers that are discordant with underlying layers. The discordance is due to some sort of ductile shearing in the outcrop but does not affect the following interpretation. Looking back to the first outcrop, it is clear that the gently dipping layers seen there can be projected up above the ground surface so that they must have been situated overhead at this locality; however, they must also have suddenly dipped steeply and rotated through the vertical in order to have their present configuration, ie, they form recumbent isoclinal folds. The trend of this recumbent, isoclinal fold axis is ~N70W and the plunge is ~15 deg. southwest, ie, it is a minor fold of the Canada Lake isocline family and of Ottawan age. At the base of the southernmost outcropping, and below a small ledge, there is preserved a foot-scale isoclinal nose. Inspection of the geometry makes it clear that the outcrop preserves an isoclinally refolded isocline-perhaps of Elzevirian age.

Farther down the clearing towards the highway a clean outcrop consists of pure, glassy quartzite dip slopes exposed together with dark layer-like bodies of fine-grained pyroxene-plagioclase granulite. Elsewhere, the chemistry of the granulites approximates that of diabase, is unlike calcsilicate, and locally exhibits microscopic diabasic texture (McLelland and Husain, 1986). The igneous nature of the granulites is further manifested by the xenoliths of quartzite present in them. Elsewhere the metadiabases are isoclinally folded and the limbs of these folds clearly truncate 10-15 cm-scale intrafolial isoclinal folds that are rotated by the isocline. We interpret this older set of isoclinal minor folds to be Elzevirian in age. The metadiabases have not been dated, but they are similar to some mafic rocks of the ~1150 Ma AMCG suite and are tentatively assigned an AMCG age.

8.0 Large roadcuts of charnockite on both sides of Rt. 29A-10. Park on right hand (east) side just past guardrails at crest of hill.

STOP 3. CANADA LAKE CHARNOCKITE. (20 MINUTES). Large roadcuts expose the type outcrops of the Canada Lake charnockite (Figs. 8-11). This highly deformed orthogneiss has a granodioritic composition, and consists of 20-30% quartz, 40-50% mesoperthite, 20-30% oligoclase, and 5-10% mafics including small, sporadic grains of orthopyroxene. The exposures exhibit the drab olive color typical of charnockites around the world. In the woods these rocks tend to weather pink and exhibit a maple sugar brown weathering rind. The unit is ~500m thick and consists throughout of relatively homogeneous granitoid with pegmatites and minor amphibolitic layers. A multigrain U-Pb zircon age 0f 1251 $\pm$ 33 Ma (McLelland and Chiarenzelli, 1990) indicating that this unit belongs with other calcalkaline rocks of broadly Elzevirian age. Mapping along its contact for a total distance of ~300 km, has not revealed any crosscutting features, but xenoliths of country rock have been recognized and substantiate an intrusive origin. The apparent conformity is attributed primarily to extreme and ductile tectonism. In addition, an original conformable, sheet-like form is quite possible. Rocks of similar age and composition are found in the Green Mts. of Vermont (Ratcliffe and Aleinikoff, 19xx).

9.2 Canada Lake Store on the left (south side) of Rt. 29A-10. Turn in to parking lot and park diagonally.

STOP 4. ROYAL MT. TONALITE (30 MINUTES). Steep roadcuts exposed across from the Canada Lake Store expose typical tonalitic rocks that are relatively common within the southern and eastern Adirondacks, the Green Mts of Vermont, and the Elzevir terrain of the Central Metasedimentary Belt of the Canadian Grenville. In all of these occurrences, the tonalites manifest the presence of magmatic arcs that existed along the southeastern margin of Laurentia during the interval ca 1400-1200 Ma diagnostic of the Elzevirian. Within the Adirondacks, multi- and single-grain TIMS U-Pb zircon geochronology indicate emplacement of the tonalitic magmas at ca 1350-1300 Ma. The present outcrop has been dated by both TIMS methods and the single grain age is constrained at 1307 $\pm$ 2 Ma (Aleinikoff, pers comm., 1991). Well-documented examples of these arc terrains extend to the Llano uplift and Van Horn areas of Texas (Mosher, 1999; Patchett and Ruiz, 1990; Roback, 1996) and attest to a global-scale system that may have been an ancient analogue of the present day East Indies arc. During the Elzevirian, various arcs must have collided and amalgamated, and continental arcs may have come into existence as well. These details remain to be unraveled, but in the meantime we note that the Elzevirian came to a close at ~1210-1170 Ma with the collision of the Adirondack Highlands-Green Mt block with the Andean-style arc then existent along the southeastern edge of Laurentia (Fig 4c). McLelland et al (1991), refer to this collisional event as the "culminating Elzevirian Orogeny" that closed out the Elzevirian interval of arc magmatism and amalgamation in the area.

The whole rock chemistry of the Adirondack calcalkaline rocks are shown in Figs (9,10,11) where their calcalkaline affinities are clearly visible. In addition, ε_{Nd} characteristics are presented in Fig. 8 and demonstrate that the tonalites represent juvenile additions to the crust from the mantle, and partial melting of the older rocks can produce younger Adirondack granitoids. Neither the Sm-Nd data, nor any other isotopic data, give any hint of pre-1350 Ma crust in the Adirondacks and suggest that the original arc must have been of ensimatic origin.

Numerous disrupted amphibolitic sheets are present within this outcrop and within Adirondack tonalites in general. The origin of these is enigmatic but they do not appear to have been derived from local country rocks. Their elongate, sheet-like character suggests that they may represent coeval mafic dikes of the sort commonly observed in tonalites. It is also possible that they represent enclaves incorporated from an amphibolitic source region. This interesting problem needs some isotopic investigations to be applied to it.

In a few places the tonalite crosscuts the migmatitic metapelites seen at Stop 1. This fixes a minimum age for the latter at ca 1300 Ma. As indicated in the discussion at Stop 1, the tonalites and metapelitic rocks may represent an original, essentially coeval, magmatic arc-flysch system.

11.0 Pine Lake. Junction of Rts 29A and 10. Turn right (north) on Rt 10 towards Speculator.
16.7 North end of East Stoner Lake. Pull off into parking area just north of Town of Arietta sign.

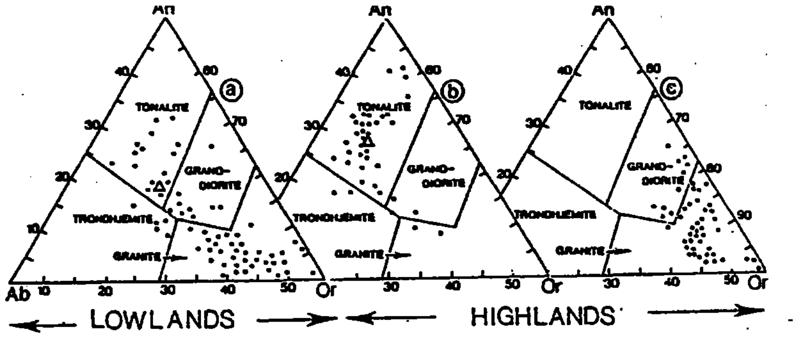


Fig. 9. Plots of normative Ab-An-Or for (a) Hyde School Gneiss, 9b) Highlands tonalites and © Tomantown pluton.Open symbols gives average value for tonalites. Fields after Barker(1979).

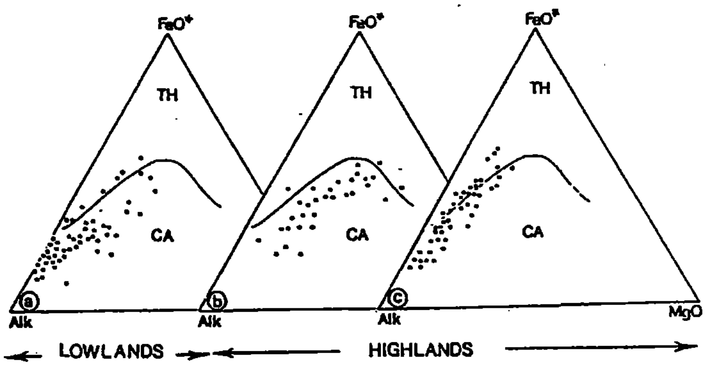


Fig. 10. AFM plots for (a) yde School Gneiss, (b)Highland tonalites, and © Tomantown pluton.

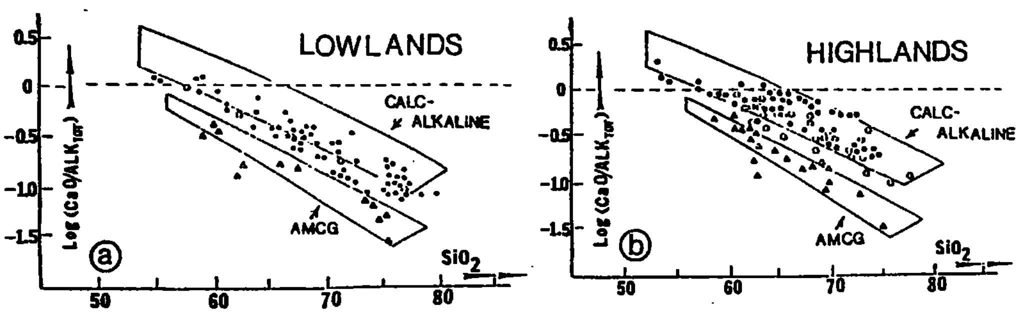


Fig. 11. Calcalkali ratio versus SiO2 for (a) the Adirondack Lowlands and (b) the Adirondack Highlands. In (a) open circles are average values for 1172 Ma Hyde School Gneiss, closed circles for typical Hyde School, and open triangles for ca 1155 Ma AMCG rocks. In (b) open circles are for the ca 1250 Ma Tomantown pluton, closed circles for the older (ca 1300 Ma) calcalkaline rocks, and open triangles for AMCG rocks.
rocks, and open triangles for for AMCG suite rocks. (After Brown, 1982)

STOP 5. ROOSTER HILL MEGACRYSTIC CHARNOCKITE. (20 MINUTES). This deformed charnockite is characterized by the presence of 20-40% megacrysts (2-4cm) of alkali feldspar set in a groundmass of quartz, oligoclase, biotite, hornblende, garnet, and sporadic orthopyroxene. In general, these have undergone dynamic recrystallization during high temperature shear strain and have developed asymmetrical tails, although flattening reduces the degree of asymmetry in most cases. In cases where tail asymmetry permits, a southeast side up and to the northwest (N70W, 10-15SE) is clearly the dominant displacement sense. As the degree of shear strain intensifies, both feldspars and quartz become elongated in the direction of tectonic transport and ribbon or pencil gneisses result. The orientation of these fabric-forming elements is parallel to the regional isoclinal fold axes. In Fig. 8 the ε_{Nd} growth curve for Rooster Hill charnockite lies on one of the AMCG suite growth lines that pass through the tonalite region indicating that this suite can be derived by partial melting of the ca 1300 Ma arc rocks.

19.2 Low roadcut in migmatitic metapelites.
20.6 Avery's Hotel on left (west) side of Rt 10.
21.7 Roadcut through granite, gabbro, and tonalite.
23.2 Pink AMCG granitic rocks, gabbro, and small exposure of fine-grained anorthosite. A large inclusion of calcsilicate in pink granite is exposed and interpreted as a xenolith.
23.5 Roadcut of metasedimentary quartzites and pelitic rocks together with anatectites.
29.2 Fault breccias in charnockite.
29.7 Junction of Rt 10 (ends) and Rt 8. Turn right (east) on Rt 8.
30.2 Long roadcut of mylonitic ribbon gneiss in pink granitic rocks of the Piseco anticline. Ribbons trend N70W and plunge 10-15 SE parallel to both recumbent F_1 isoclines and upright $F_{2\ such}$ as the Piseco anticline. A multigrain U-Pb zircon date from this outcrop gives an age of 1155 $\pm$ 10 that is interpreted as the age of magmatic emplacement.
32.5 Pull off and park on LEFT (NW) shoulder of Rt 8.

STOP 6. RIBBON GNEISS IN THE CORE OF THE PISECO ANTICLINE. (30 MINUTES).

A long, low roadcut on the left (northwest) side of Rt 8 exposes outstanding examples of ribbongneiss developed in a megacrystic facies of the Piseco core rocks. The overall composition here is similar to that of the Rooster Hill megacrystic charnockite examined at Stop 5, but here the original feldspars and quartz have been extended into ribbons on the order of 60cmx.25mmx.05mm (McLelland, 1984). Assuming interstitial quartz aggregates of ~1cm diameter, the current dimensions indicate an extension of 6000%, ie, if this strain were to be equally distributed throughout a 1km thick block of crust that block would be 60km long.25 km wide, and .005 km thick. Of course, such high ductile strain cannot be integrated through the entire crust, but the numbers provide some flavor for the strain involved.

The ribbon gneisses exposed here are folded into a minor anticline that rotates the foliation of these L>>S tectonites. The axis of this minor fold trends N70W and plunges 10-15SE. This orientation is parallel to the axis of the F_3 Piseco anticline, to the F_2 recumbent isoclines of the Adirondacks (Figs. 6,7), and to the axis-parallel elongation lineations associated with these isoclines. The fact that all of these structural elements are parallel to one another indicates that they all shared some common kinematic experience during their tectonic evolution. In order to identify the common experience, we first note that all of the deformation in these ca 1150 Ma rocks must be of Ottawan age. Next we note that minor isoclinal folds in the outcrop lie with their axial planes in the foliation and their axes defining rod-like structures parallel to the N70W extension lineation. The low dip of the lineation suggests that the mechanism responsible for it was likely to have been thrust faulting out of the southeast and towards the northwest. This would have resulted in the stretching that elongated the quartz and feldspar. The thrusting could also have rotated earlier fold axes into the thrust plane and parallel to the direction of tectonic vergence. However, rather than rigid rotation of the axes, it is proposed that the early folds became too ductile to buckle and their axes began to "flow" as passive markers in the direction of tectonic transport, i.e., the recumbent fold axes began to undergo increasing curvature in response to the velocity gradients in the ductile flow field. The ultimate result of this process is sheath folds, and it is suggested that the isoclinal folds with axes parallel to the ribbon lineation represent parts of sheath folds. It is further suggested that the Canada Lake isocline may itself be a large sheath fold whose southern closure is obscured by Paleozoic overburden. The large F_3 folds such as the Piseco anticline and the

Gloversville syncline are interpreted as structures formed by NS constrictional forces that arose in response to the EW elongation associated with the large scale, ductile thrusting of the Ottawan Orogeny. Later NNE upright folds of the F_4 set were superimposed on the F_2 sheath folds and the F_3 corrugations by continued, but waning, NW-SE contraction associated with the NNE suture situated somewhere beneath, or beyond, the present day Coastal Plain. Finally, it should be remarked that the ribbon lineations and upright lineation-parallel corrugations described above are similar to those encountered in core complexes. The problem with this alternative is that the late- to post-tectonic Lyon Mt Granite emplaced at ca 1050 Ma is unaffected by these fabrics. Accordingly, we associate the fabrics with ductile Ottawan thrusting. Orogen collapse similar to core complex kinematics is thought to have taken place at ca 1050-1030 Ma.

43.2 Junction of Rt 8 and Rt 30 in Speculator. Turn right (south) on Rt 30.
46.7 Roadcuts of Marble. Park on right (south) shoulder.

STOP 7. MARBLE AND CALCSILICATE. (30 Minutes). Exposed in roadcuts on both sides of the highway are examples of typical Adirondack marbles and their associated lithologies, ie, garnetiferous amphibolite, calcsilicates, and various disrupted blocks of both internal and external members. The disruption and boudinage attests to the extremely ductile behavior of the marbles. Also exposed are vertical, crosscutting, and undeformed veins of tourmaline-quartz symplectite. Besides calcite, the marbles contain diopside, tourmaline, sulfides, and graphite. The graphite has a biogenic carbon signature, and the marbles are thought to have formed inorganically via stromatolite accretion in an evaporitic environment. Some calcsilicate layers consist of almost monomineralic white, Mg-rich diopside crystals up to 10 cm in length. These are probably the result of metasomatism by fluid phases. The presence of the approximately Mg-pure assemblage

$$\textit{tremolite} \Rightarrow \textit{enstatite} + \textit{diopside} + \textit{quartz} + H_2O$$

allowed Valley *et al* (1983) to calculate a fluid with $X(H_2O) = .11-.14$ for the reaction. Elsewhere in the outcrop localized occurrences of wollastonite reflect the presence of H_2O as an agent lowering CO_2 activity. In both cases, the metamorphic conditions were T=710°C and P = 7 kbar. These cases provide excellent examples of how the dilution of a fluid phase by a second constituent lowers activities and allows reactions to run to the right at P,T conditions below that for the pure fluid.

In the High Peaks region there exist many well-exposed examples of places where marble and calcsilicate xenoliths occur within anorthosite. This relationship documents that the marbles are older than ca 1150 Ma. It is likely that they formed during the same shelf sequence event that was posited for the Irving Pond quartzite precursor sands, ie, ca 1220-1200 Ma.

47.2.1 Roadcuts of steeply dipping metasediments.
47.6.1 Long roadcuts in ping granitic gneiss interlayered with calcsilicates. The layering here is interpreted as tectonic and the granite as intrusive.
48.7.1 Small, high roadcut on right (southwest) side of Rt 30. Park on right shoulder.

STOP 8. MASSIF ANORTHOSITE AND FERRODIORITE OF THE OREGON DOME. (30 MINUTES). This small, but instructive roadcut has outstanding examples of two important facies of anorthosite as well as a typical ferrodiorite dike associated with massif anorthosite. The best vantage point for examining the anorthosite and ferrodiorite is on top of the roadcut. Whole rock analyses of these rocks are given in Table 1.

On climbing to the top of the outcrop at its south end, one immediately sees a distinctive dark dike of ferrdiorite filled with plagioclase grains (white, $\sim An_{43}$) and andesine xenocrysts (blue-gray, $\sim An_{52}$); note reaction rims on the blue-gray andesine. The dike exhibits somewhat soft contacts and irregular veinlets shoot off in a fashion suggesting that the anorthosite was not yet wholly solidified when the dike intruded. Farther up the outcrop two ~30cm-scale xenoliths occur in a ~5-10m-scale ferrodiorite; one of these is fine grained and the other coarse. The eastern contact of the ferrodiorite is situated just to the highway-side of the coarse xenolith. Calcsilicate xenoliths also occur in the ferrodiorite and are characterized by sulfidic staining near road level.

Farther up the outcrop the exposed rock consists entirely of anorthosite. A fine-grained, leucocratic facies forms a matrix to large (5-20cm long) crystals of blue-gray, iridescent andesine that is typical of massif anorthosite. In places these crystals appear broken as if disrupted from a larger mass. An example of a still intact mass is found at the far end of the outcrop where a raft of very coarse grained Marcy-type anorthosite with ophitic to sub-ophitic orthopyroxene sits in a matrix of fine-grained leucoanorthosite that clearly disrupts the raft at its edges. Close inspection of the matrix reveals that its small pyroxenes exhibit subophitic texture; hence the finer grained facies must be magmatic. Workers in Adirondack anorthosite have always noted that grain size reduction produces leucanorthosite similar to this this fine-grained facies, and examples of this may be seen at this stop. However, it is possible to distinguish between the grain size reduced and the fine-grained igneous varieties by noting that plagioclase in the former has the same composition as the coarse plagioclase, whereas the igneous variety is invariably 5-10% less anorthitic than the coarse plagioclase; in this case 52% versus 44% (Boone et al, 1969). Genetic interpretations and further details of the anorthositic suite are given in the main text.

The smooth, upper surface of the outcrop affords excellent opportunities to examine the garnet coronas or "necklaces" that are found throughout the Adirondack anorthosites. These are accounted for by the reaction

$$\textit{Orthopyroxene} + \textit{Plagioclase} + \textit{Fe,Ti-Oxide} \Rightarrow \textit{Garnet} + \textit{Clinopyroxene} \pm SiO_2.$$

Spear and Markussen (1997) have studied this, and other garnet-producing reactions, and determined that they took place during isobaric cooling (P~6-7 kbar) from ~700°-~630°C during waning stages of the Ottawan Orogeny (1090-1030 Ma). McLelland et al (2001) have suggested that this reaction took place at ca 1050 Ma, which is the age of small, equant metamorphic zircons associated with the coronites. The zirconium was provided by Fe-Ti oxide, which accepts significant Zr into the Ti lattice site.

Recent SHRIMP II U-Pb dating of zircons from the ferrodiorite documents its age as 1155 $\pm$ 9 Ma, and this sets a minimum age for the anorthosite. Thirty kilometers to the northeast at Gore Mt, charnockite enveloping, and showing mutually crosscutting relationships with the Oregon Dome anorthosite (Lettney, 1969), yields a SHRIMP II age of 1155 + 6 Ma. These results document that the anorthosite series of the Oregon Dome was emplaced at ca 1150 Ma. This age is indistinguishable from emplacement ages of the Marcy massif and marks the time of emplacement of the Adirondack AMCG suite.

50.7 Minor marble, calcsilicate, amphibolite together with meter-scale layers of white quartz-feldspar leucosomes containing sporadic sillimanite and garnet. SHRIMP II ages of zircons from these outcrops indicate that the leucosomes crystallized from melt at 1180-1170 Ma. This interval is interpreted as the time of anatexis associated with the migmatitic metapelites of the region, and falls into the culminating Elzevirian Orogeny.

51.7 Junction of Rt 8 and Rt 30. Continue south on Rt 30.

52.2 Charnockite on the north limb of the Glens Falls syncline.

54.5 Entering the town of Wells that sits on a Paleozoic inlier dropped down at least 700m by a NNE trending graben structure.

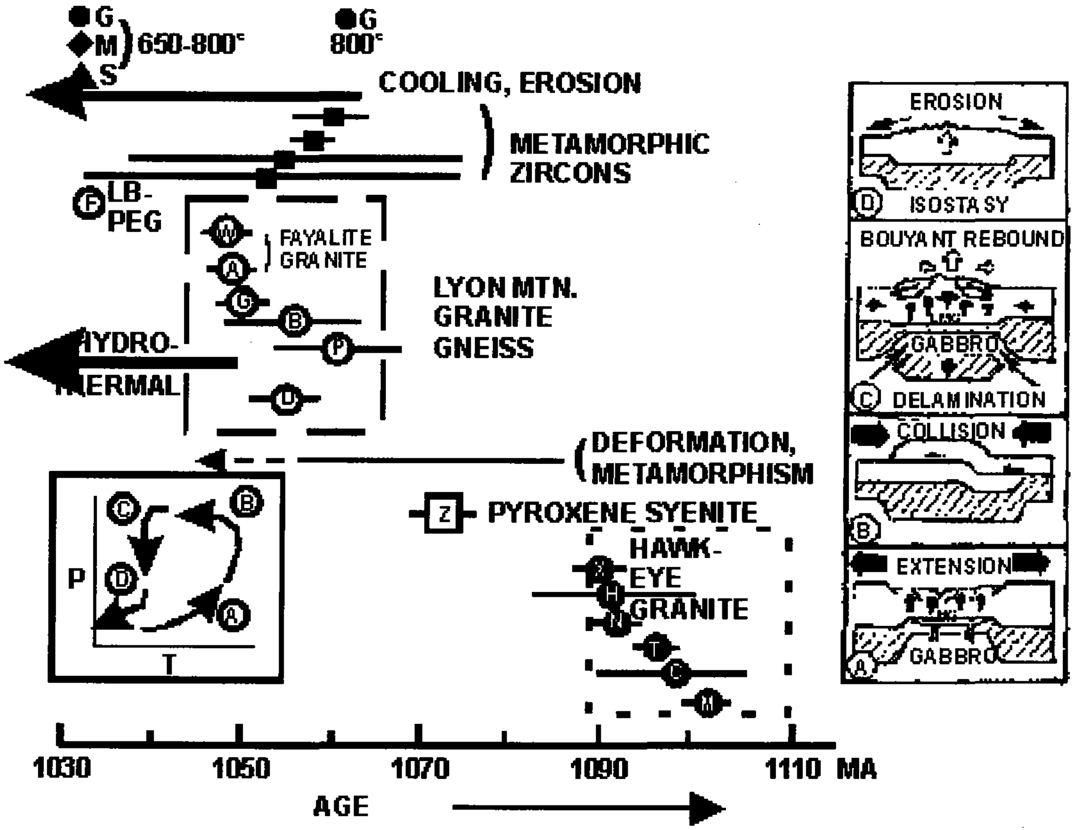
55.0 Leaving town of Wells.

58.7 Pumpkin Hollow. As you round the big bend next to the river look for a large parking area on the right (west) side of Rt 30. Pull into it and park.

STOP 9. MYLONITIC STRAIGHT GNEISS OF MIGMATITIC METAPELITE. (30 MINUTES). Large roadcuts on the east side of Rt 30 expose excellent examples of migmatitic metapelite identical to that seen at Stop 1, but now at a high grade of strain that has resulted in extreme ductile grain size reduction that has produced long tails on the feldspars and remarkable long ribbons of quartz now consisting of annealed subgrains in the process of annealing further into smaller grain size. The high strain has produced a platy mylonite that is a "par-excellence" example of straight gneiss. The alternating light and dark layers represent porcellaneous leucosome together with restitic biotite-garnet-quartz-feldspar ± sillimanite. Numerous intrafolial isoclinal minor folds can be seen, especially in the leucosome. All of these observations make it clear that the "layering" seen in the outcrop has nothing to do with any primary or "stratigraphic" features, although some observers still try to make this assertion. The layering is strictly tectonic in origin and provides a fine learning opportunity with which to make the case with students (and others). Note the strong N70W lineation on foliation surfaces. A strong component of flattening has also affected these rocks making it difficult to interpret kinematic indicators.

At the south end of the outcrop the mylonitic migmatite is in contact with homogeneous, strongly foliated granitoids of the Piseco anticline. These granitoids have been dated at ca 1155 Ma, while the structurally overlying migmatites must be at least 1300 Ma of age since they are crosscut by the tonalites. The absence of any crosscutting contact emphasizes how ductile high strain can wipe out angular discordances.

The northerly dip of the mylonitic migmatite sequence is due to the fact that we are located on the southern limb of the Glens Falls syncline or the northern limb of the Piseco anticline. These dipping layers are locally broken across by ductile normal faults with brecciated pegmatite fillings. These features have not been dated, but a ca 1050 Ma age is expected.



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M
S
650-800°
G
800°
COOLING, EROSION
METAMORPHIC ZIRCONS
LB-PEG
FAYALITE GRANITE
LYON MTN. GRANITE GNEISS
HYDRO-THERMAL
DEFORMATION, METAMORPHISM
PYROXENE SYENITE
HAWK-EYE GRANITE
P
T
1030
1050
1070
1090
1110 MA
AGE
EROSION
ISOSTASY
BOUYANT REBOUND
GABBRO
DELAMINATION
COLLISION
EXTENSION
GABBRO