NEW YORK STATE GEOLOGICAL ASSOCIATION

FIELD TRIP TO EASTERN NEW YORK:

BARROVIAN METAMORPHISM IN DUTCHESS COUNTY

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INTRODUCTION

In the late 1800's, the notion of metamorphism was beginning to occupy a distinct place in geological thinking. The first studies linking metamorphic phenomena to distinctive mineralogical assemblages were of contact metamorphic aureoles around shallow igneous bodies. In the English speaking world, the notion of regional metamorphism, with "depth zones" marked by distinctive mineral assemblages is at attributed to George Barrow , who described such zones in 1893 in a Proterozoic meta-sedimentary sequence in the Scottish Highlands. We call these zones "Barrovian Zones" in his honor.

Dutchess County, New York, was mapped by Robert Balk of Mt. Holyoke College during a nine year period in the 1920's and 30's. Balk's paper (1936) is a classic study of the structural geology and stratigraphy of a highly deformed area. Balk's attractive sketch map has been included as Figure 1. His paper was accompanied by a mineralogical - petrological paper by his friend and colleague Tom Barth (1936) of the Mineralogical Institute, Oslo. Although this area has been recognized as perhaps America's pre-eminent Barrovian terrane, these authors interpret the metamorphism as due to igneous activity, including "emanations".

This area remains one of the clearest Barrovian sequences in the world. Unfortunately, possibly because of the eminence of these two papers, later geologists seem to have been somewhat intimidated, and relatively few studies have been undertaken here in subsequent years. Garlick and Epstein (1967) attempted to determine maximum temperatures of metamorphism using oxygen isotopes of metamorphic mineral assemblages. Vidale (1973, 1974) investigated the vein mineralogy and showed that vein-mineral assemblages were a good indication of metamorphic grade. Hames et al (1991) used $^{40}Ar/^{39}Ar$ dating of micas to determine an age of about 445 m.y. for the Taconian metamorphism.; they also found an eastern zone overprinted with younger (390-400 m.y.; interpreted as Acadian) metamorphic modification. Two papers by Whitney et al(1996a and 1996b) have investigated detailed mineralogy, concentrating on the garnets.

Figure 1. Sketch geologic map of Balk (1936). The stops for the trip are shown as numbered black dots.

GEOLOGICAL BACKGROUND

The county is underlain mainly by Cambrian and Ordovician wackes deposited during the geosyncline-filling stage of the Appalachian geosyncline. It is the metamorphism of these sedimentary rocks during the Taconian Revolution (end of Ordovician) that we will be examining on this field trip.

Following is a brief outline history of the geological evolution of the northeastern Appalachian chain, taken from Bird and Dewey (1970). Figure 2 outlines their scheme.

1) Early Stage (550 to 450 m.y.; Cambrian and early Ordovician)

At the beginning of this stage the emergent North American continent subsided in its eastern portion. A vast shallow sea covered the eastern half of North America and left a deposit of quartz-rich beach deposits on top of deeply eroded pre-Cambrian metamorphic and igneous rocks. In this area we see this sequence as the Poughquag quartzites (which we will not see on this trip).

A carbonate platform developed on the eastern margin of this rifted continent. We will see some of the marbles which originated as this platform (Stockbridge marbles).

2) Middle Stage (450 to 534 m.y.; late Ordovician)

During this stage thick wackes accumulated in a "geosyncline" which at this time was adjacent to a passive margin of the Atlantic Ocean ("IAPETUS Ocean"). We now refer to this deposit as a continental margin prism. Bird and Dewey (1970) call it an "exogeosyncline" Subduction beneath a volcanic ridge in western New England (to the east) elevated a tectonic welt, whose erosion shed sediments to the west, in a depression adjacent to the carbonate platform on the eastern edge of the continent. This sequence was deposited initially on the downwarped carbonate platform. These wackes have been known as the "Hudson River Shales" or "Normanskill Shales", and they were the focus of studies a century and a half ago by James Hall that led to the initial concept of geosynclines.

In the later stages of their deposition these fine-grained wackes were tectonically interlayered with blocks of older sedimentary sequences that slid into the depression from the rising welt to the east. The dominantly Cambrian and early Ordovician sediments are sandier than the late Ordovician shales, and the entire sequence is a tectonically interlayered on a scale of a mile or so. Mapping these tectonic units and deciphering their stratigraphy, even in higher metamorphic grades, has been a major accomplishment of many field geologists, mainly from Columbia and Harvard Universities, during this century.

During this trip we will see metamorphosed equivalents of both the younger (mainly autochthonous and finer grained) and older (mainly allochthonous and coarser grained) sediments. Thus, the rocks seen here are not all of the same original composition.

At the final, climactic stage of the Taconian Revolution, paleo-Europe collided with the North American platform and subduction ceased. further tectonic thickening occurred, and granitic melts were generated, mainly slightly to the east of the area visited on this trip.

3) Third and later stages. (437 - 345 m.y.; Silurian to late Devonian)

In the early part of this stage the emergent, tectonically thickened terrane was rapidly eroded to sea level, with debris carried as far west as western New York ("Queenstown Delta"). A vast inland sea became the locus of evaporite deposits, and the quartz-rich sand beneath and around this deposit is represented locally by the Shawangunk sandstone. Renewed convergence to the east resulted in a renewed uplift, and the shed sediments formed the Devonian "Catskill Delta". This second convergence largely of western and southern Europe and western Africa, was completed in latest Devonian and created the super-continent called "Laurasia". This continent remained welded until the rifting at about 200 m.y. which produced the present-day Atlantic Ocean, which formed more or less along the earlier suture line.

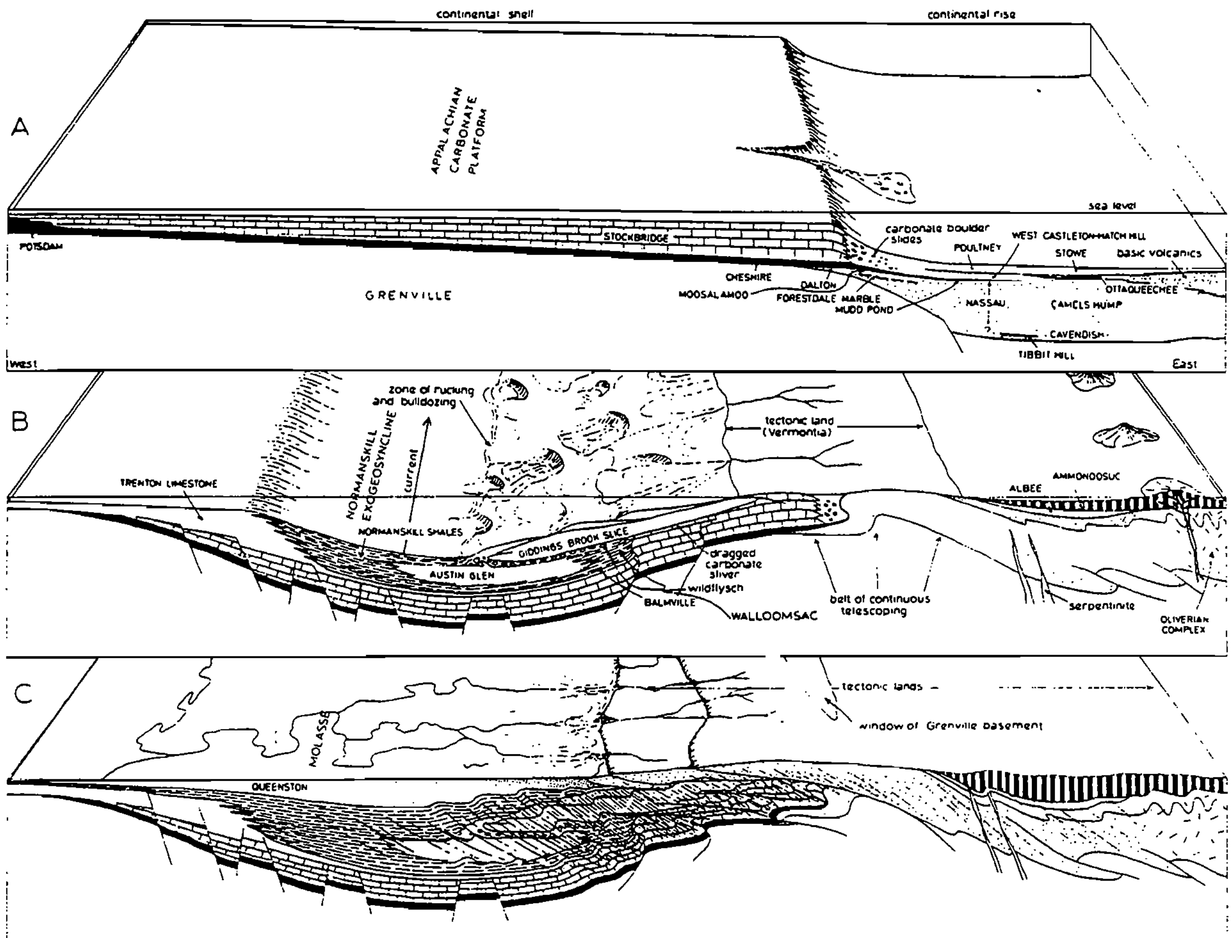

Figure 2. Bird and Dewey's (1970) tectonic evolution scheme, as a series of block diagrams. The continental platform is on the left and the IAPETUS ocean on the right. Note the platform carbonates (Stockbridge), autochthonous continental rise sediments (Austin Glen) and allochthonous slices (Giddings Brook). In the top diagram (A), our area is on the right side. In the second and third diagrams (B and C), our area is approximately in the middle.

Caption for Figure 1. (Explanation of the map)
The short-lined pattern (denser lines to the east) is the clastic Cambrian and Ordovician sedimentary package that is the main focus of the trip. Underlying pre-Cambrian is the random-orientation dash pattern, and overlying it is a narrow belt of densely stippled basal Cambrian Poughquag quartzite. The platform carbonates are unpatterned. Isograds, marking the first appearance of distinctive metamorphic minerals, are shown for the biotite, garnet, and sillimanite grades. There are numerous small plutons scattered especially on the eastern side of the trip; these are shown by a variety of random-orientation patterns.
The stops for the field trip are shown as numbered black dots.

According to the excellent tectonic map of Williams (1978) the rock units seen here are divided into continental shelf carbonate deposits, and continental rise prism clastics. Rock units corresponding to the island-arc welt, the remnants of mid-ocean volcanics and associated sediments, and "exotic" parts of the European continent are all found to the west of the present area.

METAMORPHISM OF THE EARLY PALEOZOIC WACKES AND ASSOCIATED ROCKS

Most of the trop will be devoted to the prograde metamorphism of the "package" of Cambrian and Ordovician tectonic slices during the first major event (end-Ordovician). We see these rocks presently displayed with higher grades of metamorphism to the east, because the later Devonian event raised the rocks more to the east. Subsequent erosion exposed levels that were originally deeper in this direction.

Although they are exposed in this area, time limitations prevent us from examining the pre-Cambrian basement beneath the Paleozoic stratigraphic sequence, and the basal Cambrian quartz-rich shallow water sandy deposits. We will see mainly the wacke sequence, and we will examine one exposure of the marble sequence.

STOPS:

The first two exposures we will be unable to examine, both because of time limitations and the difficulties of handling groups along busy highways. However, these exposures can be profitably examined from the vans. The first is a prominent klippe of dolomite which occurs just west of Newburgh, just before we turn on to highway 9. This dolomite represents the originally platform limestone which was later dolomitized. These dolomites (indeed, many dolomites elsewhere) have abundant silica, either representing original sedimentation or introduced along with the magnesium of dolomitization.

The second exposures to be examined from the van are the layered wackes exposed magnificently along the entrance to the Mid-Hudson Bridge. These are classic Austin Glen (='Hudson River Shales") with beautifully displayed graded bedding. Although the rocks seem to be entirely argillaceous in gross inspection, under the microscope there are revealed abundant tiny dolomitic fragments from the platform. These are the protolith of many of the metamorphic rocks seen later.

First stop [Unmetamorphosed],
Grand Ave and Main Street, Poughkeepsie. We will stop in the small parking lot on this corner. (The large rectangular block is a fine example of a New England two-mica granite). The rocks exposed along Grand Avenue (beware of cars!) are highly tectonized versions of the wacke seen just on the other side of the river. They have not developed a metamorphic mineralogy, and we refer to these as highly tectonized, unmetamorphosed sedimentary rocks. The fine-scale graded bedding is still visible in crumpled fragments. Original sedimentary sulfide has recrystallized as larger pyrite crystals, which weathering has created brown streaks on the outcrops. There is a slight wash of gypsum also present. Some original resistant sandy beds are visible as detached blocks within this melange. These blocks are dark brown because of the weathering of iron-rich dolomite crystals.

Second stop [Biotite Grade],
Wingdale Road, just east of the junction with Highway 55. This stop is our first glimpse of metamorphism. The fine-grained biotite visible in thin section (and in hand specimen if you have good eyes and imagination!) gives the rock a shiny luster. The evidence for metamorphism is mainly the quartz veins, which are themselves deformed by physical deformation as they developed. The ubiquity of these veins in metamorphosed terranes results from the fact that most metamorphic reactions of sedimentary protoliths commonly produce water and SiO_2. Vidale (1974) has studied these vein assemblages in Dutchess County and found that, at increasing higher metamorphic grades to the east, the vein mineralogy includes mica and feldspar, in addition to quartz. Stratigraphic layering is not visible here.

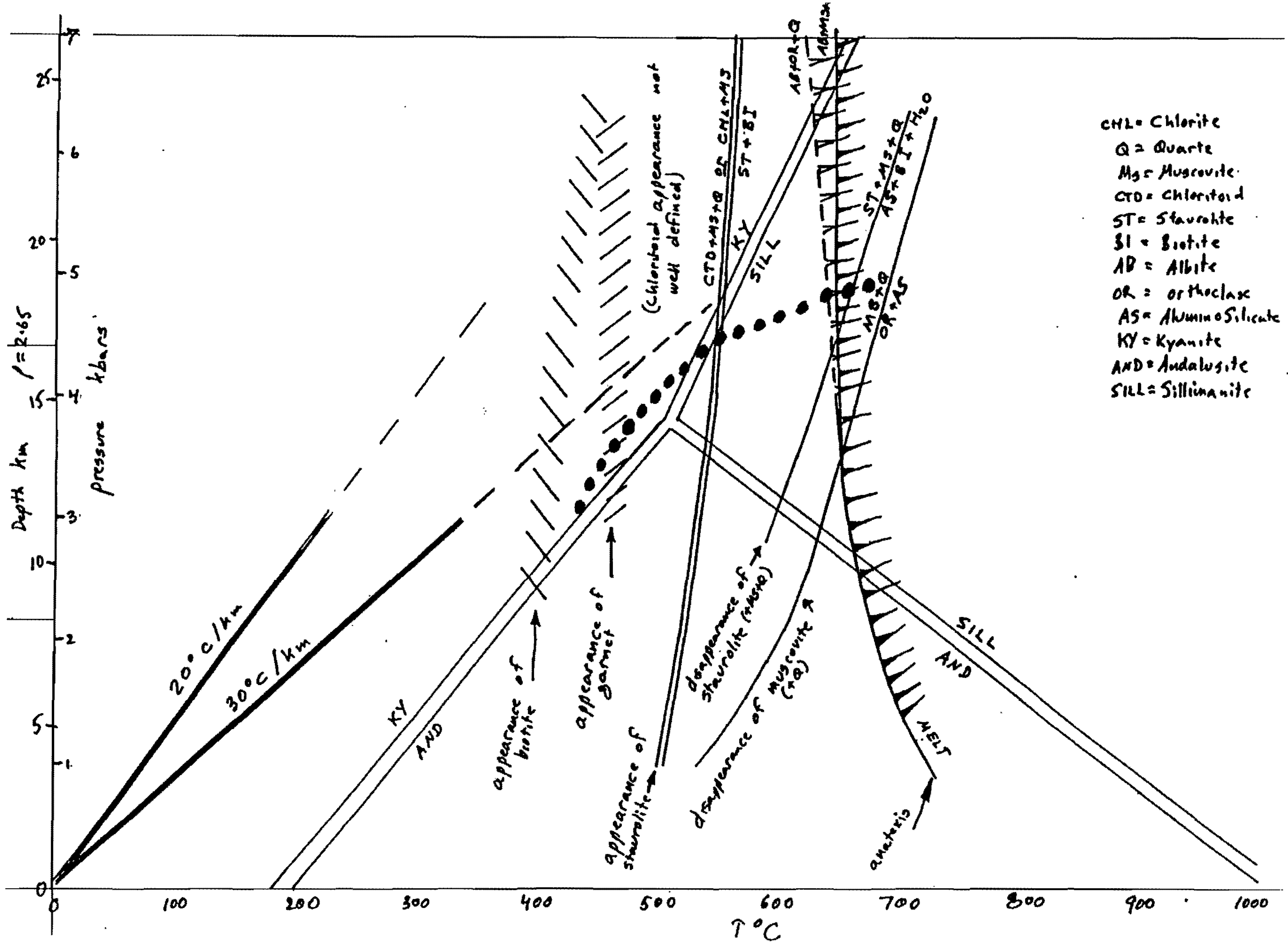

Figure 3. P - T diagram, showing the alumino-silicate triple point and reaction lines of the ALS system; lower (20°C/km) and higher (30°C/km) thermal gradients, a few important metamorphic mineral reactions, and the beginning of melting (anatexis). Approximate P - T path during metamorphism (estimated, less certain at higher T) shown as black dots (from Whitney et al 1996).

Third stop [Garnet Grade],
Wingdale Road, just beyond intersection to Clove and Clove Valley. Here the rock represents metamorphism of a fine sandy sediment. Both chloritoid and garnet are visible in rocks seen along the highway in outcrop. Chloritoid is an aluminous mineral which is stable apparently within a fairly narrow range of T and P, passing to staurolite at slightly higher grades. There is abundant tourmaline in thin section. Evidently this is detrital, because xenotime, apatite, and thorianite have also been found.

Fourth stop [Staurolite grade],
Wingdale road, vicinity of Bald Mountain, beyond Pheasant Ridge. Here the protolith was more quartz rich and less aluminous. It is evidently one of the sandy Cambrian units. Garnet and Staurolite are both visible in this quartzose, micaceous schist. There are abundant quartz veins.

Fifth Stop [Kyanite grade],
Highway 55, west of Pawling. The protolith is very aluminous. Here kyanite crystals and pale pink garnets are visible. Beware of black spots on this outcrop which are bits of tar spattered during road paving!

Sixth stop [Sillimanite grade, pegmatite],
Quaker Hill Road, east of Pawling. The protolith of this rock is evidently very similar to that seen at the Fifth stop. The rock is very garnet rich, with staurolite visible in thin section. There are many patches of pegmatite here, suggesting that the grade of metamorphism is approaching the beginnings of development of a hydrous silicate melt. Larger pegmatite bodies occur within a few miles of this locality. Tourmaline is sometimes visible in outcrop; it is conspicuous in thin section. Large crystals of staurolite are also visible in thin section. The sillimanite is seen only as fibrolite in mica-rich parts of the thin section.

Seventh stop [Sillimanite Orthoclase grade; gneiss],
Western Connecticut, west of Mizzentop. Here the meta-sediment has become a gneiss, which means extensive recrystallization of a highly weakened rock close to its melting point. There is abundant evidence of venitic separation of a granitic melt. In thin section sillimanite is visible as fibrolitic patches in mica-rich parts of the rock. Both plagioclase and K-feldspar reflect the high grade and partial melting of this rock. Although the rock resembles a granite, the chemical composition is clearly sedimentary.

Eighth stop [marble],
West Patterson. We have passed, without stopping, many seemingly excellent marble outcrops already. However, most of these marbles have been extensively hydrothermally altered , and the calc-silicate minerals are in a very poor state of preservation. This recently exposed outcrop at West Patterson has largely escaped this overprint, and there is excellent diopside, tremolite, and phlogopite in these rocks.

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Williams, H., 1978, Tectonic lithofacies map of the Appalachian orogen (map; scale 1:1,000,000). Memorial University of Newfoundland, Map 1

	Miles
The route from Binghamton to the start of the trip is as follows: East on 17 to junction with 17K, 2.7 miles east of contact between Silurian and Ordovician. East on 17K to Interstate 84, just west of Newburgh. North on 9W at Newburgh to Mid Hudson Bridge. The road log starts here.	
Turnoff to Mid Hudson Bridge	0.0
jct. Highway 9, east side of Hudson River	1.3
proceed on highway 55 to Church Street; follow Church St. (straight); 55 veers right	2.6
Church St. feeds on to Main St.; continue E. to Raymond St., STOP 1 is parking lot on NE corner The rocks examined at STOP 1 are the outcrops on Raymond St. adjacent to the parking lot. The rocks are highly deformed but not metamorphosed (no quartz veins, no indisputably metamorphic minerals). There are some traces of stratification and there are coarse blocks of more resistant sandstone.	3.3
Lunch can be obtained at one of several fast-food or sub shops a few blocks back; then proceed E to rejoin highway 55; continue E on highway 55 to jct. of County Road 21; turn left on 21	14.0
The next three stops are on county road 21. Be very careful with traffic. Cars tend to drive fast here and sight lines are limited. The road is narrow and parking along the sides is crowded.	
STOP 2 (parking has to be on left side. Careful!) is just before summit of rise on road. Note: Be extremely careful with traffic on this road! The outcrop is very overgrown (Also watch out for abundant poison ivy.). Here the rock is shiny and coarser grained than at STOP 1. There are no traces of stratification. There are many quartz veins.	14.8
Proceed east on 21; at jct. with highway 9 (16.9 miles) continue on 21 up the hill. STOP 3 (park on right side) is just before guard rail on right. Rocks examined are a few hundred feet up the road on the left side. Again be careful with traffic. There is visible garnet (mainly fairly small) and some chloritoid (black, shiny diamond-shaped crystals).	17.7
Proceed eastward on 21. STOP 4 (park on left. Careful!). We will walk back up the hill to examine a good outcrop on the north side of the road. Here there is abundant garnet, common staurolite prisms, and coarse muscovite. There are several quartz veins, some of which are deformed.	21.0
Proceed eastward to Wingdale. There is a good marble here, but we will not examine it on this trip. At mile 23.9 turn right on to combined state highways 22 and 55. Continue south to the village of Pawling. Just at the far edge of Pawling turn right on 55, heading west.	30.8
Continue west on 55, past vivid (but altered) marble outcrops along road. You will pass Harmony Hill Road at mile 32.9. Continue up hill to where outcrops of schist appear on the right side of the road. The exact spot is somewhat difficult to locate, but there is a concrete drain next to the highway at the best place to see kyanite. This is STOP 5 Here there is good kyanite (some with faint blue color) and abundant, small, very pale garnets	34.5

Proceed a few hundred feet further west and turn around by backing into blacktopped driveway. Backtrack to the east; highway 55 turns back to the north at a 270° cloverleaf (mile 38.6). Continue north to Quaker Hill Road. Turn right (east) on Quaker Hill Road.	38.9
Continue on Quaker Hill Road. Just after the junction with Reservoir Road, Quaker Hill Road takes a sharp hairpin turn to the right. Stop on the right side of the road just beyond the turn. STOP 6 The rocks here are coarse grained schist with abundant, coarse garnet. Staurolite is unidentifiable in outcrop but present in many sections. The sillimanite is very fine grained fibrolite. There are several pods of pegmatite, and tourmaline can be found in places.	
Continue up the road. Turn right on Church Rd. at mile 41.8 Observe the magnificent woodwork on the barn here. Proceed southward, swinging eastward to the center of the tiny hamlet of Mizzentop, with its beautiful church and handsome stone public library. At mile 42.3 there is a stop sign. Proceed east from here (same road). Cross into Connecticut (road quality deteriorates noticeably! Note that you have just passed through a narrow strip of real estate that New York got from Connecticut in 1685 when Connecticut said it wanted to keep the bit around Stamford. You do remember your history, don't you? Proceed east into Connecticut (now Wakeman Road). Turn right at stop sign at mile 44.9 on highway 37. Our next stop is a pulloff on the left (again!) at the telephone pole. STOP 7. There is no good outcrop here but there are several large fragments provided by the telephone company. The rock here is a gneiss, with good migmatitic veins.	45.1
Continue south a short distance and turn right at mile 45.3 This is Chapel Hill Rd., but I didn't see a sign. Continue on this road. The crossing into New York is where the road deteriorates. Continue right for several miles, with road gradually swinging left (south) and descending a long hill. At mile 50.8 the road intersects highway 22, heading south. Join 22 here and IMMEDIATELY turn right on to highway 311. Proceed through Patterson to the junction of highway 292. Park on 292 on the left just beyond the junction. STOP 8. This is a fresh marble outcrop, with very good diopside prisms visible in outcrop. There is good tremolite and phlogopite also, but these cannot be seen in outcrop.	52.2
Continue west on 292, going straight at the intersection at mile 55.5 (292 goes right). You are on Mooney Hill Rd., but I didn't see a sign. This road winds for several miles and joins interstate 84. Turn right (west) on 84)	56.0
A few miles along, there is a rest stop on 84. If time permits, walk back up the hill (be careful). Just at the entrance of the rest stop there are magnificent exposures of pre-Cambrian gneisses that are startlingly similar the gneisses seen at STOP 7.	59.4
The trip is now over. Return to Binghamton via 84, 17K, and 17.	

Dutchess Co. Analyses of rocks

	B-2	202-72	13-71	B-4	15-71	95-69	B-5	21A-71	19-71	20B-71	106A-72	136-69	25-71	142A-69	23A-71	24-71
grade	chl	chl	chl	bi	bi	gar	gar	sill	sill	sill	sill	sill	sill	sill-or	sill-or	sill-or
SiO2	65.0	72.9	70.3	66.9	77.4	62.5	62.6	64.5	66.5	66.2	61.1	60.8	64.9	66.1	62.3	62.4
TiO2	0.89	0.49	0.69	0.65	0.48	0.91	0.83	0.73	0.69	0.69	0.81	0.86	0.98	1.06	1.07	0.81
Al2O3	16.2	8.7	13.2	14.3	9.9	16.3	16.5	14.6	15.8	14.8	17.6	17.9	18.4	16.8	18.1	17.0
Fe2O3	1.13	0.48	2.32	1.06	1.31	2.45	0.54	1.61	1.92	1.18	1.39	0.86	2.43	1.52	2.03	2.24
FeO	5.80	2.19	4.04	5.16	2.48	4.36	5.45	4.84	4.44	5.48	6.77	6.45	4.88	5.17	5.60	5.28
MnO	0.04	0.30	0.09	0.10	0.20	0.10	0.12	0.82	0.74	0.16	0.64	0.73	0.07	0.22	0.12	0.26
MgO	1.74	1.65	3.04	3.45	2.09	3.34	3.47	5.00	5.06	4.48	4.53	4.09	2.00	1.88	2.06	2.38
CaO	0.02	4.96	0.18	0.28	0.04	0.91	1.98	1.15	0.55	0.77	0.89	1.08	0.29	0.32	0.79	2.06
Na2O	2.63	0.94	0.04	0.90	0.12	0.99	1.35	1.51	0.98	1.41	0.93	3.23	0.18	0.28	1.11	2.34
K2O	2.80	1.89	2.76	3.09	2.79	5.05	4.56	3.41	2.67	3.79	4.20	3.23	3.77	4.35	3.46	3.33
P2O5	0.12	0.18	0.10	0.20	0.08	0.16	0.14	0.15	0.10	0.12	0.13	0.13	0.15	0.16	0.14	0.16
H2O+	3.23	1.39	2.13	3.32	1.51	2.29	1.61	0.92	0.69	0.87	1.45	1.24	1.66	3.23	2.71	1.12
CO2			0.00		0.00		0.15	0.00	0.00	0.00						0.00

	212-72	B-19	17A-71	B-6	127-72	B-7	137-72	155-72	22A-71	22B-71	138-69	DC94-7	DC-94-1	DC-942	DC94-3	DC93-4
grade	bi	gar	gar	gar	gar	staur	staur	staur	sill	sill	sill	bi	bi	gar	staur	staur
SiO2	51.8	52.9	58.3	55.4	44.2	56.5	55.2	58.8	57.8	56.9	57.8	65.0	61.8	63.4	59.6	62.5
TiO2	1.20	1.20	0.98	0.99	1.51	0.99	1.27	0.87	1.16	1.23	1.23	0.80	0.84	0.80	1.01	0.65
Al2O3	24.2	25.3	22.2	22.3	28.3	22.5	22.9	20.4	22.7	22.0	21.0	16.3	18.1	16.4	23.5	14.8
Fe2O3	1.80	1.22	3.16	1.30	2.29	1.11	1.73	1.29	3.86	5.24	2.28	7.08	8.14	7.33	8.91	6.63
FeO	7.70	7.83	4.76	6.82	8.02	7.26	5.95	7.59	3.64	3.78	6.48					
MnO	0.14	0.13	0.07	0.14	0.16	0.19	0.25	0.35	0.07	0.15	0.27	0.11	0.15	0.14	0.15	0.75
MgO	2.30	1.67	1.41	2.35	2.60	1.97	2.28	2.38	1.44	2.07	2.28	3.73	4.71	3.87	1.89	8.00
CaO	0.10	0.25	0.20	0.38	0.69	0.49	1.05	1.45	0.81	0.58	0.90	1.54	0.14	1.87	0.23	1.07
Na2O	1.52	2.25	1.31	1.02	1.33	1.66	2.64	3.05	1.38	1.77	2.40	0.59	1.40	1.21	1.10	1.61
K2O	4.35	3.62	3.34	5.45	5.73	5.00	4.49	2.06	5.37	4.72	4.58	3.99	3.76	4.13	3.67	3.92
P2O5	0.12	0.17	0.17	0.20	0.12	0.12	0.15	0.04	0.23	0.15	0.08					
H2O+	4.74	3.94	2.43	3.55	3.89	2.80	2.74	2.24	1.33	2.35	1.82	4.89	4.70	3.53	3.81	1.46
CO2			0.00	0.00		0.00			0.00							

	DC94-8	DC94-9	DC94-1	YD94-1	YD94-2	YD94-3	YD94-4	YD94-5	stop 2	stop 3	stop 4	stop 5	stop 6	stop 7
grade	staur	staur	sill	unmm	unmm	unmm	unmm	unmm	bi	gar	staur	kyan	sill	sill or
SiO2	60.9	54.2	60.1	66.1	63.2	72.9	65.6	58.4	51.7	52.1	56.4	58.6	54.1	80.2
TiO2	0.91	1.29	1.18	0.83	0.78	0.72	0.80	0.94	1.06	1.26	1.28	0.7	1.12	0.6
Al2O3	21.3	24.8	23.1	13.2	13.7	12.2	12.8	15.4	22.8	28.9	23.5	17.8	29.6	9.27
Fe2O3	8.99	10.23	7.36	4.71	5.39	4.53	4.79	6.14	12.11	8.76	8.74	10.1	8.4	3.7
FeO														
MnO	0.16	0.29	0.16	0.05	0.08	0.04	0.08	0.10	0.67	0.13	0.29	1.57	0.04	0.05
MgO	2.11	2.47	1.90	1.85	2.10	1.62	1.60	2.00	4.92	1.58	2.27	7.2	2.07	0.96
CaO	0.29	0.43	0.95	5.80	6.77	2.45	6.88	8.12	0.62	0.72	1.02	0.89	1.01	1.65
Na2O	0.75	1.21	1.18	1.56	1.77	1.38	1.80	1.62	1.52	1.05	1.25	0.24	1.26	1.7
K2O	3.93	4.71	3.33	2.30	2.35	2.24	2.15	2.85	4.43	4.75	4.82	4.14	4.53	1.83
P2O5				0.15	0.14	0.15	0.14	0.16	0.05	0.27	0.3	0.46	0.21	0.16
H2O+	2.31	2.52	1.80											
CO2														

Analyses "B-x" are from Barth, 1936; analyses "DC94-x" and "YD94-x" are from Whitney et al, 1996;
(row labeled "H2O+" for YD94 and DC94 samples records the LOI)
Analyses "stop x" are our analyses from stops on this trip; remaining analyses from Vidale, 1973