# TRIP B-1

# STRUCTURE, PETROLOGY AND GEOCHRONOLOGY OF THE PRECAMBRIAN ROCKS IN THE CENTRAL HUDSON HIGHLANDS

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## INTRODUCTION

Recent studies in the New York portion of the Reading Prong indicate that the Hudson Highlands may consist of two terranes of Precambrian rock (Harwood and Zietz, 1974; Hall et al., 1975). A western terrane consists of charnockitic gneisses and paragneiss intruded by syntectonic granitoid plutons. An eastern terrane consists of quartzofeldspathic gneisses having lithic and structural similarities with the Fordham gneiss immediately to the south in Westchester County (Hall et al.,1975). Fundamental differences in lithology, structure, geochronology and magnetic signature have been summarized by Harwood and Zietz (1974) and Hall et al. (1975). Although the position and nature of the contact separating the two terranes remains problematical, an approximate boundary may be placed in the vicinity of the Ramapo-Canopus fault system in the Hudson Highlands. Detailed study is needed to establish the relationship between the two suites of rock. The purpose of this field trip is to examine the structure, petrology and geochronology of Precambrian rocks at select sites in both terranes. The Lake Carmel area in the eastern Highlands (stops 1 and 2) and the West Point area in the western Highlands (stops 3, 4, 5, 6, 7, 8) have been chosen for this purpose (Fig. 1).

## ACKNOWLEDGEMENTS

We wish to express our appreciation to the personnel of the Mill Pond Garden Center, the Tri-County Land Management Corporation, the Harriman State Park and the United States Military Academy at West Point for the cooperation they extended us in planning this field trip and to Mr. and Mrs. August Michel for allowing us to examine rock exposures on their property.

## LAKE CARMEL AREA

The following bedrock map units are found in the Lake Carmel area (Fig. 4):

pЄbg. Gray, migmatitic biotite-hornblende-quartz-feldspar gneiss with sparse thin layers of amphibolite (estimated minimum thickness, 1000 feet).

pЄam. Heterogeneous group of rocks consisting of three members: (1) garnetiferous amphiboloite, (2) biotite-quartz-plagioclase gneiss with sparse amphibolite, and (3) predominantly biotite-quartz-plagioclase gneiss, biotite-hornblende-quartz-plagioclase gneiss, hornblende gneiss and amphibolite with subordinate leucocratic granitic gneiss and sparse pyroxenite (estimated thickness, 600 feet).

pЄga. Weakly foliated leucocratic granitic gneiss with subordinate biotite-hornblende-quartz-plagioclase gneiss and hornblende gneiss containing

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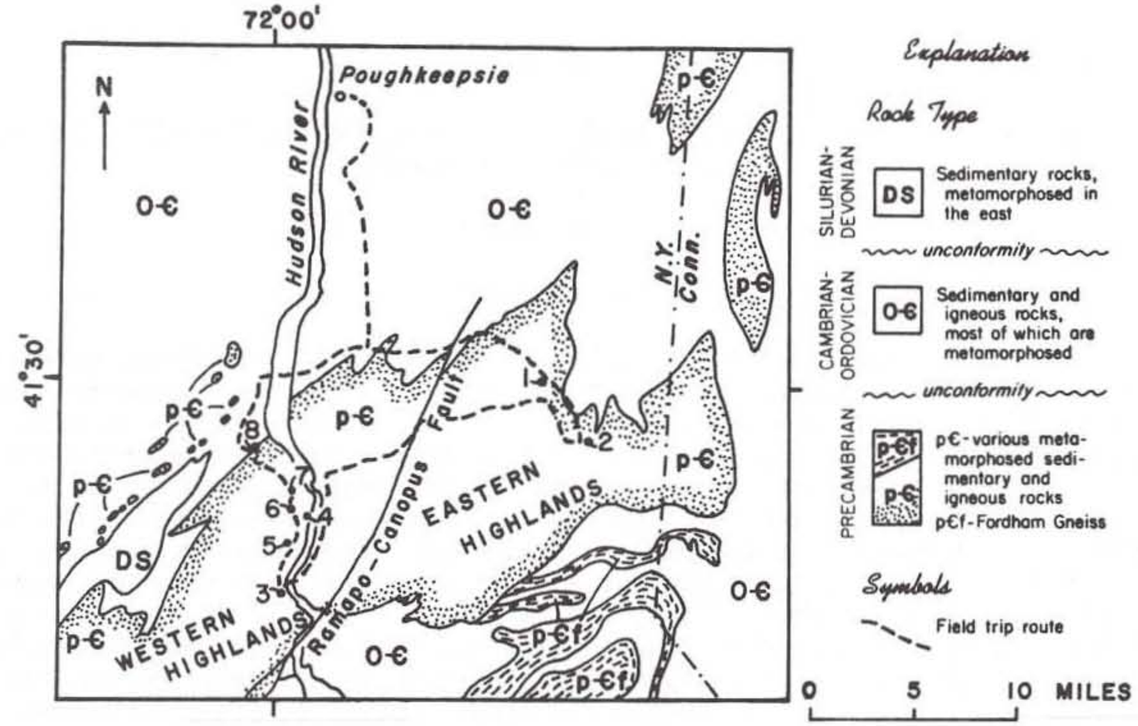

Figure 1. Index map and route for field trip B-1.

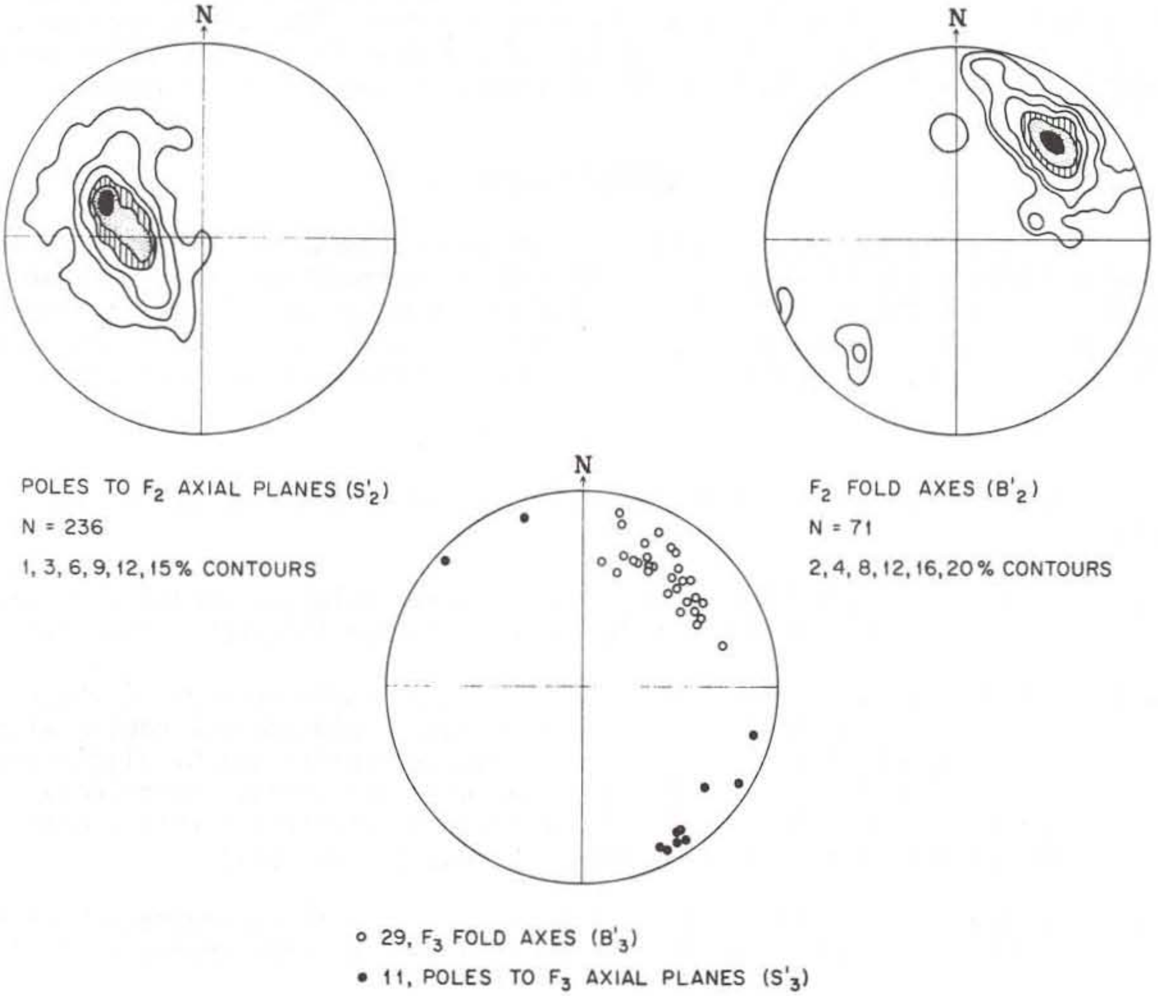

Figure 2. Equal-area diagrams of structural data for the Lake Carmel area.

amphibolite, quartz-feldspar gneiss, pyroxene-hornblende-quartz-plagioclase gneiss, pyroxenite and calc-silicate (estimated thickness, 1800 feet).

pꞒlg. Layered biotite-hornblende-quartz-plagioclase gneiss with subordinate amphibolite and biotite-quartz-feldspar gneiss (estimated thickness, 1800 feet).

pꞒq. Biotitic amphibolite and feldspathic quartzite (estimated minimum thickness, 800 feet).

Mineral assemblages indicate upper amphibolite facies conditions of metamorphism (Hall et al., 1975).

A preliminary summary of deformational and metamorphic events is as follows:

F0. Tightly appressed rootless intrafolial folds; orientation variable; formation of penetrative axial plane foliation ($S_0$) parallel to compositional layering; existence of these folds requires more thorough study to be proven; age, uncertain.

F1. Tightly appressed isoclinal folds; orientation variable; no axial plane foliation developed; age, uncertain.

F2. Reclined, recumbent and inclined similar folds; orientation of axial surfaces ($S_2^1$) and fold axes ($B_2^1$) are shown in figure 2; folding accompanied by intrusion of granite and injection of granitic seams parallel to axial surfaces of $F_2$-folds; transposition of $S_0$ into axial planar foliation ($S_2^1$) along thrust faults; recrystallization of high-grade mineral assemblages to upper amphibolite facies assemblages (Hall et al., 1975); age of folding and recrystallization, Taconic(?).

F3. Open, upright folds; poles to axial planes of $F_2$-folds lie on a girdle defining an axis oriented N55°E at 28° which coincides with $F_3$-fold axes (Fig. 2); retrograding of upper amphibolite mineral assemblages (?); intrusion of pegmatite (?); development of quartz-filled extension fractures (?); age, Paleozoic.

F4. Open, upright folds; warping of $F_0$-$F_3$ fabric elements about a horizontal axis trending about N20°W; folding results in reversal in plunge of $F_2$- and $F_3$-folds and is responsible for the dome-and-basin interference pattern; age, Paleozoic (?).

The significance of a prominent mineral lineation throughout the area is not clearly understood.

We are tentatively assigning a Taconic age to the $F_2$-deformation and recrystallization for the following reasons:

(1) textural studies of mineral assemblages indicate that recrystallization of Precambrian gneisses to amphibolite facies conditions accompanied the $F_2$-folding ( Hall et al., 1975).

(2) $^{40}Ar/^{39}Ar$ studies indicate that a single Paleozoic recrystallization of these gneisses occurred about 480 m.y. ago during a Taconic event (Dallmeyer and Sutter, 1976).

Radiometric studies are being carried out in areas adjacent to the Lake Carmel area. Rb/Sr whole rock work on samples of a major biotite-muscovite-quartz-plagioclase gneiss to the north and west of Lake Carmel has shown that this rock has an age of 1296 ± 77 m.y. and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7032 ± 0.0003 (all errors given at the 95% confidence level). Another sample set from a similar rock immediately north of Peekskill yielded an age of 1256 ± 16 m.y. and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7021 ± 0.0005. A granite gneiss southeast of Croton Falls Reservoir (Prucha et al., 1968) has yielded an age of 1308 ± 41 m.y. and an initial ratio of 0.7029 ± 0.0005 (Mose, unpub. data). No U/Pb age determinations have been made on rocks of the eastern Hudson Highlands.

K/Ar and Rb/Sr age determinations on single mineral separates (usually biotite) from rocks in this area range from about 300 m.y. to 800 m.y. (Long and Kulp, 1962; Clark and Kulp, 1968). The younger mineral ages (300-450 m.y.) were obtained over most of the eastern Hudson Highlands where the Paleozoic metamorphic overprint reached garnet grade or higher. The older mineral ages (700-800 m.y.) are from the western edge of the eastern Hudson Highlands (along the eastern side of the Ramapo-Canopus fault zone), where the Paleozoic metamorphic overprint reached biotite grade or lower.

## THE WEST POINT AREA

The following bedrock map units are found in the West Point area (Fig. 3):

### Metasedimentary and metavolcanic rock

pЄqp. Various charnockitic quartz-plagioclase gneisses with subordinate amphibolite, quartz-plagioclase leucogneiss, calc-silicate and minor additional metasediments.

pЄpg. Migmatitic paragneiss with subordinate amphibolite and rusty weathering pyroxenic gneisses (pЄpga), quartz-plagioclase gneisses (pЄpgg) and minor calcareous, ferruginous and quartzitic metasediments.

### Early tectonic and syntectonic intrusive rocks

pЄsk. Hornblende granitic and quartz monzonitic gneisses with subordinate hornblende granite (all derived from lower crustal or mantle sources); intrudes pЄqp and pЄpg.

### Syntectonic and late tectonic intrusive mobilizates

pЄch. Coarse-grained, garnet and biotite-bearing leucocratic granite (Canada Hill granite); derived by anatexis of paragneiss (pЄpg); intrudes pЄpg and pЄsk.

pЄpd. Coarse-grained diorite (Pochuck diorite); derived by partial anatexis of intermediate rocks as charnockitic quartz-plagioclase gneisses; intrudes pЄqp; forms local pockets too small to be indicated on map.

### Late to post-tectonic intrusive rocks

pЄal. Coarse-grained magnetite alaskite; intrudes pЄqp, pЄpg and pЄsk.

Mineral assemblages indicate lower granulite facies conditions of metamorphism (Dallmeyer and Dodd, 1971; Hall et al., 1975).

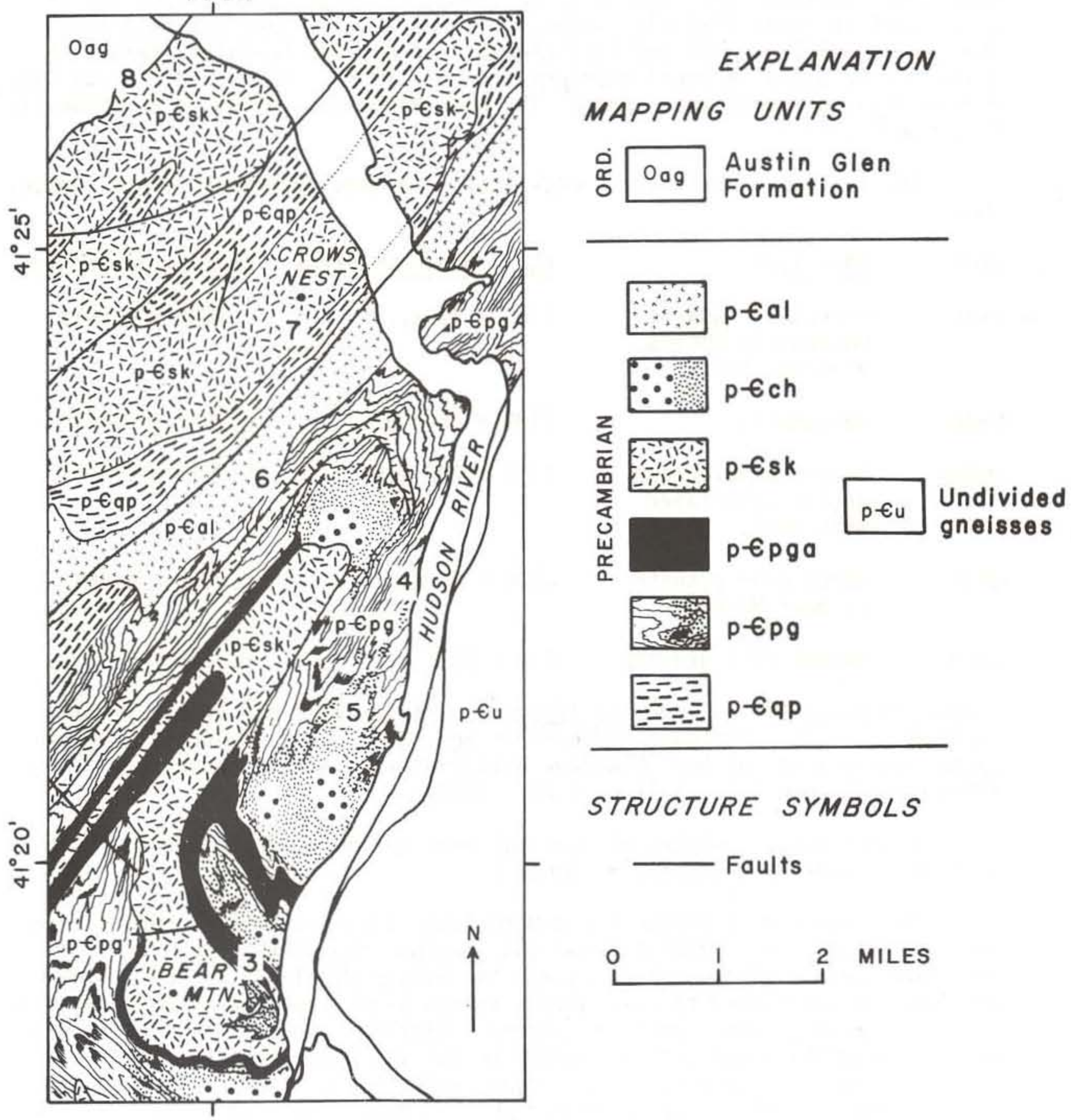

Figure 3. Generalized geologic map of the West Point area. Numbers indicate field trip stops.

At least three periods of folding have deformed rocks in the West Point area. The earliest fold generation ($F_1$) resulted in regional isoclinal folds. The prominent regional foliation is axial planar to $F_1$-folds. The second generation of folds ($F_2$) developed as plane, cylindrical, isoclinal folds with southeast dipping axial planes and fold axes that plunge approximately N35°E at 10° parallel to the regional mineral lineation ($L_2$). The Crows Nest antiform, West Point antiform, Hessian Lake synform and Ft. Montgomery antiform are regionally developed $F_2$-folds. A localized set of open, upright folds ($F_3$) with nearly vertical axial planes and fold axes that plunge N45°E at 35° refolded elements of $F_1$- and $F_2$-folds. Refolding during $F_3$ resulted in local reorientation of minor $F_2$-folds and mineral lineation ($L_2$) to a southwest plunge. The Bear Mountain synform is a regionally developed $F_3$-fold.

The following Rb/Sr whole rock ages have been determined (Mose, unpub. data):

| Unit | Rock Type | Age ± 95% C.L. error | Initial $^{87}Sr/^{86}Sr$ |
|---|---|---|---|
| pЄsk | Hornblende quartz monzonitic gneiss at Crows Nest | 1169 ± 44 m.y. | 0.7055 ± 0.0019 |
| pЄpg | Paragneiss | 1139 ± 26 m.y. | 0.7067 ± 0.0010 |
| pЄpgg | Quartz-plagioclase gneiss associated with pЄpg | 1115 ± 208 m.y. | 0.7033 ± 0.0017 |
| pЄsk | Hornblende granite at Bear Mountain | 1086 ± 34 m.y. | 0.7020 ± 0.0021 |
| pЄch | Canada Hill granite | 914 ± 31 m.y. | 0.7193 ± 0.0013 |

Zircons from Canada Hill gneiss (pЄpgg, quartz-plagioclase gneiss,?) have yielded a nearly concordant $^{207}Pb/^{206}Pb$ age of 1170 m.y.; zircons from the hornblende granite at Bear Mountain have yielded a nearly concordant $^{207}Pb/^{206}Pb$ age of 1060 m.y. (Tilton et al., 1960).

A preliminary summary of deformational and metamorphic events for the West Point area is presented in Table 1.

The scheme of petrogenetic and tectonic events presented here differs in several important respects from that proposed by Berkey and Rice (1919) and Lowe (1950). Both workers viewed the Hudson Highlands as consisting of a series of metasediments selectively intruded and reworked by an early dioritic phase of plutonic activity (Pochuck diorite, pЄpd) to form rocks characteristic of the pЄqp unit. A second pervasive, highly active phase of plutonism (Canada Hill granite, pЄch) again selectively granitized original metasediments to form migmatitic paragneiss (pЄpg). The final phase of plutonism resulted in the syntectonic emplacement of hornblende granite (Storm King granite, pЄsk) with its more fluid phase, the alaskite (pЄal).

We consider the following observations critical in supporting our proposed sequence of events:

(1) pЄpd is restricted to rocks of basic and intermediate composition (pЄqp) and pЄch to migmatitic paragneiss (pЄpg). Rather than a model

| Deformational Event | Fold System | Type of Folds | Important Tectonic Features | Metamorphic Event | Important Crystalloblastic and Other Features | Igneous Intrusions | Age of Events |
|---|---|---|---|---|---|---|---|
| | | Post-Grenville uplift of the Hudson Highlands | | | | | |
| | | | | | Retrogression of high grade mineral assemblages with cooling<br>Deuteric mineralization in the Canada Hill granite | Intrusion and crystallization of alaskite | |
| $D_3$ | $F_3$ | Local, open, upright, isoclinal folds; vertical axial planes; fold axis almost coaxial with $F_2$-fold axis; refolding causes local reversal in plunge of $F_2$-folds | Local fracture cleavage subparallel to axial surface of $F_3$-folds | $M_{p\epsilon}$ | | Final emplacement and crystallization of Canada Hill granite in axial regions of $F_3$-folds | Crystallization of Canada Hill granite, 914 m.y.<br>Formation of uraninite in hornblende pegmatite (Phillips mine), 920 m.y. |
| $D_2$ | $F_2$ | Regionally developed isoclinal folds plunging about N35°E at 10°; refolding of $F_1$-folds | Development of penetrative mineral lineation ($L_2$): prominent regionally developed mineral lineation. Local development of axial plane foliation ($S_2$): prominent $F_1$ foliation is preserved | | | Large-scale mobility of Canada Hill granite; emplacement in axial regions of $F_2$-folds | |
| | | | | Thermal maximum, 1100-1150 m.y.<br>T = 700°-750°C; P = 3-6 kb. | Continued recrystallization and rotation of prismatic and platy minerals parallel to $F_2$-fold axes | Final crystallization of melt in the core of the Bear Mtn. pluton<br>Initiation of anatexis of paragneiss and incipient mobilization of partial melt Canada Hill granite; partial anatexis in the quartz-plagioclase gneisses | Final crystallization of the Bear Mtn. pluton, 1086 m.y. |
| $D_1$ | $F_1$ | Tightly appressed, isoclinal folds oriented NW-SE with axial surfaces moderately to steeply inclined with variable orientation | Development of penetrative axial plane foliation ($S_1$) subparallel to primary compositional layering; prominent regionally developed foliation in Precambrian rocks | | Recrystallization of minerals to granulite facies | Recrystallization of the Crows Nest pluton and crystallized portions of the Bear Mtn. pluton; core of the Bear Mtn. pluton remains melt<br>Intrusion and partial crystallization of the Bear Mtn. pluton | Recrystallization of quartz-plagioclase gneiss (1115 m.y.) and paragneiss (1139 m.y.) |
| | | | | $M_{p\epsilon}$ | | Intrusion and crystallization of the Crows Nest pluton | Crystallization of the Crows Nest pluton, 1169 m.y. |
| Sequence of sedimentary and volcanic rock; deposition prior to 1170 m.y. | | | | | | | |

Table 1. Preliminary summary of Grenville petrogenetic, tectonic and metamorphic events in the West Point area of the Hudson Highlands, New York.

of selective intrusion, we believe that anatexis of gneisses of differing initial bulk compositions followed by a period of limited movement for the mobilizate best explain the distribution and composition of these rocks. An anatectic origin for Canada Hill granite from paragneiss is supported by isotopic studies (Mose and Helenek, 1976).

(2) hornblende quartz monzonitic gneiss from the Crows Nest pluton yields an Rb/Sr whole rock age of 1169 ± 44 m.y. while hornblende granite from the Bear Mountain pluton yields an age of 1086 ± 34 m.y. Both plutons are deformed to varying degrees, the older pluton being structurally more complex than the younger pluton. This indicates a rather long period of early tectonic and syntectonic intrusion for these granitoid rocks. Initial $^{87}$Sr/$^{86}$Sr ratios indicate a lower crustal or mantle source for these rocks.

(3) Canada Hill granite cross-cuts structures in and contains inclusions of pꞒpg and pꞒsk. A Rb/Sr whole rock age of 914 ± 31 m.y. and a high initial $^{87}$Sr/$^{86}$Sr ratio support the contention that Canada Hill granite is a syntectonic to late tectonic, palingenetic intrusive rock post-dating intrusion of Storm King granite plutons.

(4) alaskite cross-cuts structures in and contains inclusions of pꞒqp, pꞒpg and pꞒsk. It differs petrographically from the hornblende granitic rocks. Its relationship to the Canada Hill granite is uncertain.

## APPENDIX I. INTERPRETATION OF RADIOMETRIC DATA FOR THE HUDSON HIGHLANDS

### WESTERN HIGHLANDS TERRANE

The interpretation of Rb/Sr and U/Pb ages from regionally metamorphosed terranes has been a subject much discussed among Appalachian geologists. The ages reported here for the metasedimentary (paragneiss, pꞒpg) and metavolcanic (quartz-plagioclase gneisses, pꞒqp) units in the western terrane are most reasonably interpreted to be the time of regional metamorphism. Strontium isotopic homoginization presumably occurs during metamorphism of these rocks because of their relatively porous, water-rich and fine-grained nature. On the other hand, the ages reported for the plutonic rocks (hornblende granitic rocks, pꞒsk, and Canada Hill granite, pꞒch) are most reasonably interpreted to be the time of rock crystallization. The hornblende granites (containing zircon populations characteristic of plutonic rocks, Eckelmann and Helenek, 1975) are interpreted by us to be part of a series of syntectonic sills and phacolithic plutons. Their low $^{87}$Sr/$^{86}$Sr initial ratios suggest that they were formed in the lower crust or upper mantle and were emplaced with little or no contamination by crustal strontium. Taken together with the ages from the metasediments and metavolcanics, the data reveal that the western Hudson Highlands were metamorphosed about 1100 m.y. to 1150 m.y. ago during what is commonly known as the Grenville dynamothermal event.

The Canada Hill granite is a late tectonic body which formed about 914 m.y. ago. Field relations, rock chemistry and initial strontium isotopic compositions of the granite and its enclosing paragneiss show that this granite formed by partial melting of the paragneiss. The 914 m.y. age places a lower limit on the interval on Grenville metamorphic activity.

K/Ar biotite age determinations from Grenville rocks in the western Hudson Highlands average 829 ± 34 m.y. (1 , 12 ages; data from Tilton et al., 1960, and Long and Kulp, 1962). One interpretation of the K/Ar data is that the rocks experienced a metamorphic event at this time. In the absence of any dated plutonic rocks produced at this time, this interpretation seems doubtful. Another interpretation is that the biotite in these rocks was kept at a temperature greater than its argon retention temperature until about 830 m.y. ago. Dallmeyer et al. (1975) have used biotite (retention temperature estimated to be $300^{\circ}$ to $350^{\circ}$ C) and hornblende (average age about 900 m.y.; retention temperature estimated to be $500^{\circ}$-$550^{\circ}$ C) to determine a Late Precambrian uplift rate for this area of about $10^{-5}$ meters per year.

## EASTERN HIGHLANDS TERRANE

Although not conclusive, evidence suggests that the granite gneiss and biotite-muscovite-quartz-plagioclase gneiss dated by the Rb/Sr technique may be metamorphosed plutonic rock. We interpret these data to indicate that the eastern Hudson Highlands were formed during a major dynamothermal metamorphism about 1250-1300 m.y. ago. These are among the oldest rocks in the Appalachian system. A similar age has beem determined for layered gneisses in the Blue Ridge of North Carolina (Fullagar and Odom, 1973; Rankin et al., 1969).

Recent work in the Manhattan Prong by Grauert and Hall (1973) has shown that syntectonic zircon formed in the Fordham gneiss 980 m.y. ago. Since similar gneisses are found in the eastern Hudson Highlands, it is likely that the Highlands were again metamorphosed at this time.

Rb/Sr whole rock work on granitic gneisses in the Manhattan Prong (Yonkers gneiss, Long, 1969; Pound Ridge gneiss, Mose and Hayes, 1975) has shown that the Fordham gneiss was partially melted and formed the granitic gneisses about 600 m.y. ago. Hall (pers. comm.) has observed other similar rocks associated with Grenville terranes in New England. It is not unreasonable to think that this 600 m.y. event (Avalonian orogeny, ?) was felt in the eastern Hudson Highlands.

The K/Ar and Rb/Sr single mineral ages from the eastern Hudson Highlands and from the adjacent Manhattan Prong have been interpreted in different ways. Long and Kulp (1962) and Clark and Kulp (1968) interpreted the data to indicate that the area experienced a metamorphic event at about 460-480 m.y. ago (the oldest K/Ar ages from the Fordham gneiss in the Manhattan Prong) and another metamorphic event at about 360 m.y. ago (the average K/Ar age from micas in the zone of Paleozoic sillimanite grade metamorphic overprint in the Highlands and in the Manhattan Prong).

We prefer to interpret the data using the model proposed by Butler (1972) for K/Ar biotite ages on the Blue Ridge rocks. In this model, the metamorphic isograds and K/Ar age pattern are inferred to be the result of a single metamorphic event. K/Ar mica ages from crystalline rocks which existed before the Paleozoic metamorphism (e.g. Grenville gneisses) are not regarded as useful chronometers for the Paleozoic event. These micas may or may not have lost all their pre-Paleozoic metamorphism radiogenic argon, or they may have continued to lose argon after the Paleozoic metamorphic event if they were not rapidly uplifted after the metamorphic event. K/Ar ages from high grade metasedimentary rocks first metamorphosed during the Paleozoic are also not regarded as useful. These rocks, which have yielded biotite K/Ar ages of 300-350 m.y., are thought to have remained continually at high temperatures in excess of the biotite argon retention temperature until 300-350 m.y. ago. The only useful K/Ar data (for determining the time of metamorphism) are biotite K/Ar ages from rocks which were first progressively metamorphosed (and formed biotite) during the Paleozoic, and which were uplifted soon after metamorphism. The best area (for biotite formation followed by earliest uplift and cooling) would be in the zone of biotite grade regional metamorphism.

In the Blue Ridge, K/Ar data from the zone of biotite grade metamorphism reveals that the Paleozoic event occurred at least 435 m.y. ago. In the Manhattan Prong, the only useful K/Ar data come from the Manhattan schist, a mid-Ordovician metasediment. There are no K/Ar data from biotite grade schist, but K/Ar data from garnet grade schist (Long and Kulp, 1962) shows that the Paleozoic metamorphism occurred at least 410 m.y. ago.

Dallmeyer (1975) has suggested that the Cortlandt complex, situated between the Rosetown complex and the Peekskill pluton, is coeval with part of the Rosetown complex. The Rosetown complex exhibits no metamorphic textures and is known to be a series of Cambro-Ordovician intrusions (Mose et al., 1975; Dallmeyer, 1975). Since the Cortlandt was emplaced after the Paleozoic metamorphic event (it intruded rocks in the zone of garnet through sillimanite grade), the metamorphic event which produced the Paleozoic metamorphic isograds occurred after the deposition of the youngest sedimentary rock (Manhattan schist- Unit A; about 460 m.y. old) and before the intrusion of the Cortlandt complex, which Dallmeyer interprets to be about 440 m.y. old.

It now appears that the metamorphic activity which affected the Manhattan Prong and the eastern Hudson Highlands was a single mid-Ordovician event (440-460 m.y. ago), commonly called the Taconic orogeny. It is, however, not clear to what extent the Devonian age Acadian orogeny (which is recorded in the rocks of New England and in the Piedmont of the central and southern Appalachians) was felt in the Manhattan Prong and eastern Hudson Highlands. The Peekskill pluton (Mose et al., 1976), the Bedford, New York, pegmatite and the Branchville, Connecticut, pegmatite (Clark and Kulp, 1968) all formed in Devonian time, indicating that the Manhattan Prong and probably the eastern Hudson Highlands were at high enough temperatures to generate igneous intrusions. Chase and Brock (1976) have shown that the Paleozoic sillimanite isograd in the Croton Falls area (north-central Manhattan Prong) appears folded, indicating that structural deformation occurred after the Taconic orogeny. Granitoid to gneissic granitic rocks in the Croton Falls complex have yielded a Rb/Sr whole rock age of 407 ± 25 m.y. (95% C.L.), indicating that they were formed in post-Taconic time (i.e., after 440-460 m.y.), but were subsequently recrystallized (Mose, unpub. data).

Post-Taconic deformation and igneous activity has clearly occurred in the Manhattan Prong and probably also in the eastern Hudson Highlands. However, it is not yet possible to decide if this activity represents a distinct Acadian orogenic event, preceded by a post-Taconic cooling, or if the activity merely represents adjustments which occurred during a long mid-Paleozoic interval of slow post-Taconic uplift and cooling. Most workers today favor the second interpretation, relating the uplift to the folding of Silurian-Devonian rocks west of the Hudson Highlands and not to the metamorphism of Silurian-Devonian rocks east of Cameron's line in New England.

|  |  |  |
|---|---|---|
| 15.4 | 0.8 | Carey Rd. overpass. Exposures of lower members of the Wappinger Group on both sides of I-84. |
| 16.9 | 1.5 | Gently folded syncline in the Wappinger Group on the left (north) side of I-84. The Hudson Highlands are seen to the right (south). |
| 17.8 | 0.9 | Exposures of lower members of the Wappinger Group. |
| 19.2 | 1.4 | The prominent valley to the right (south) is an extension of the Ramapo fault through the Hudson Highlands. |
| 19.4 | 0.2 | Intersection of I-84 and the Taconic State Parkway. Continue east along I-84. |
| 20.1 | 0.7 | Large exposures of Precambrian gneiss. Biotite granitic gneiss predominates with subordinate amphibolite and hornblende biotite granite gneiss. Rocks have varying degrees of cataclastic deformation. Minerals are partially altered. Toward the eastern end of the exposure is infolded Poughquag quartzite. |
| 20.7 | 0.6 | Large exposures of Precambrian gneiss. Predominant rocks are biotite-quartz-plagioclase gneiss and quartz-plagioclase leucogneiss with subordinate amphibolite, biotite-hornblende-quartz-plagioclase gneiss and pyroxenite. All minerals are partially altered and replacement textures common. |
| 21.3 | 0.6 | Large exposures of Precambrian gneiss. Entering the Poughquag 7½' quadrangle. |
| 21.7 | 0.4 | Rest area on I-84. |
| 22.2 | 0.5 | Toward the left (northwest) is a spectacular view of the Hudson Valley. |
| 22.3 | 0.1 | Large exposure of Precambrian gneiss. Precambrian rocks from this point to stop 1 consist of biotite-quartz-plagioclase gneiss, biotite-hornblende-quartz-plagioclase gneiss, amphibolite and biotite-muscovite-quartz-plagioclase gneiss. |
| 24.4 | 2.1 | Large roadcut of Precambrian amphibolite. |
| 25.1 | 0.7 | Large exposure of light gray, biotite-muscovite-quartz-plagioclase gneiss. Sampling locality for Rb/Sr whole rock dating (1296 ± 77 m.y.). |
| 25.2 | 0.1 | Turn off I-84 at Exit 17 (Ludingtonville Rd.). |
| 25.6 | 0.4 | Turn right at stop sign onto Ludingtonville Rd. |
| 25.7 | 0.1 | Intersection of Ludingtonville Rd. and Route 52. Turn right (north) onto Route 52. |
| 25.9 | 0.2 | Turn right into the parking area at the Mill Pond Garden Center. |

STOP 1. Mill Pond Garden Center. (No hammers, please!)

Exposure of light gray, biotite-muscovite-quartz-plagioclase gneiss. This foliated gneiss is one of the most important lithologies in the eastern Hudson Highlands. The exposure seen here is on strike with the large roadcut of light gray gneiss on I-84. In the I-84 outcrop, the biotite-muscovite-quartz-plagioclase gneiss contains bands consisting of biotite-actinolite-plagioclase gneiss. Foliation trends about N40°E and is almost vertical. The light gray, biotite-muscovite gneiss is among the oldest rocks found in the Hudson Highlands and yielded a Rb/Sr whole rock age of 1296 ± 77 m.y. with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7032 ± 0.0005.

Exit parking lot and turn left onto Route 52. Return to I-84 East.

| | | |
|---|---|---|
| 26.2 | 0.3 | Turn right onto entrance ramp of I-84 East and proceed on I-84. |
| 26.8 | 0.6 | Entering the Lake Carmel 7½' quadrangle. Exposures of Precambrian rock. |
| 28.1 | 1.3 | Exposures of metamorphosed Middle Ordovician clastic rocks (Walloomsac formation). |
| 28.9 | 0.8 | Turn off I-84 at Exit 18 (N.Y. Route 311, Lake Carmel-Patterson). |
| 29.2 | 0.3 | Turn right at stop sign onto Route 311. |
| 29.6 | 0.4 | Entering the Village of Lake Carmel. |
| 29.9 | 0.3 | Intersection of Route 311 and Terry Hill Rd. (street marker on the right). Turn left onto Terry Hill Rd. |
| 30.8 | 0.9 | Intersection of Terry Hill Rd. and Fair St. Continue straight and proceed south on Fair St. |
| 31.6 | 0.8 | Intersection of Fair St. and Bullet Hole Rd. Turn left onto Bullet Hole Rd. |
| 32.0 | 0.4 | Pass beneath I-84 overpass. |
| 32.3 | 0.3 | Turn left into Forest Haven Apartments. |

STOP 2. Forest Haven Apartments.

A short traverse will be made through the upper pꞒga unit and the lower pꞒlg unit (Fig. 4). No hammers, please!

Station A. pꞒlg unit. Exposures of layered, medium-grained, mesocratic biotite-hornblende-quartz-plagioclase gneiss. Prominent $F_2$-folds have axial planes trending about N40°E, 60°S. Fold axes plunge about S70°E at 60° but marked variability from this direction is noted. Abundant crenulation folds are related to $F_2$-folds.

Station B. pꞒga unit. Leucocratic granitic gneiss forms large domical exposures. Amphibolite with calc-silicate nodules defines a large $F_2$-fold.

Station C. pꞒlg unit. Exposures of layered biotite-hornblende-quartz-plagioclase gneiss. Prominent $F_2$-folds have axial planes oriented N-S, 55°E; folds plunge N58°E at 34°. The change in orientation of $F_2$-axial planes from station A is a result of $F_3$-folding.

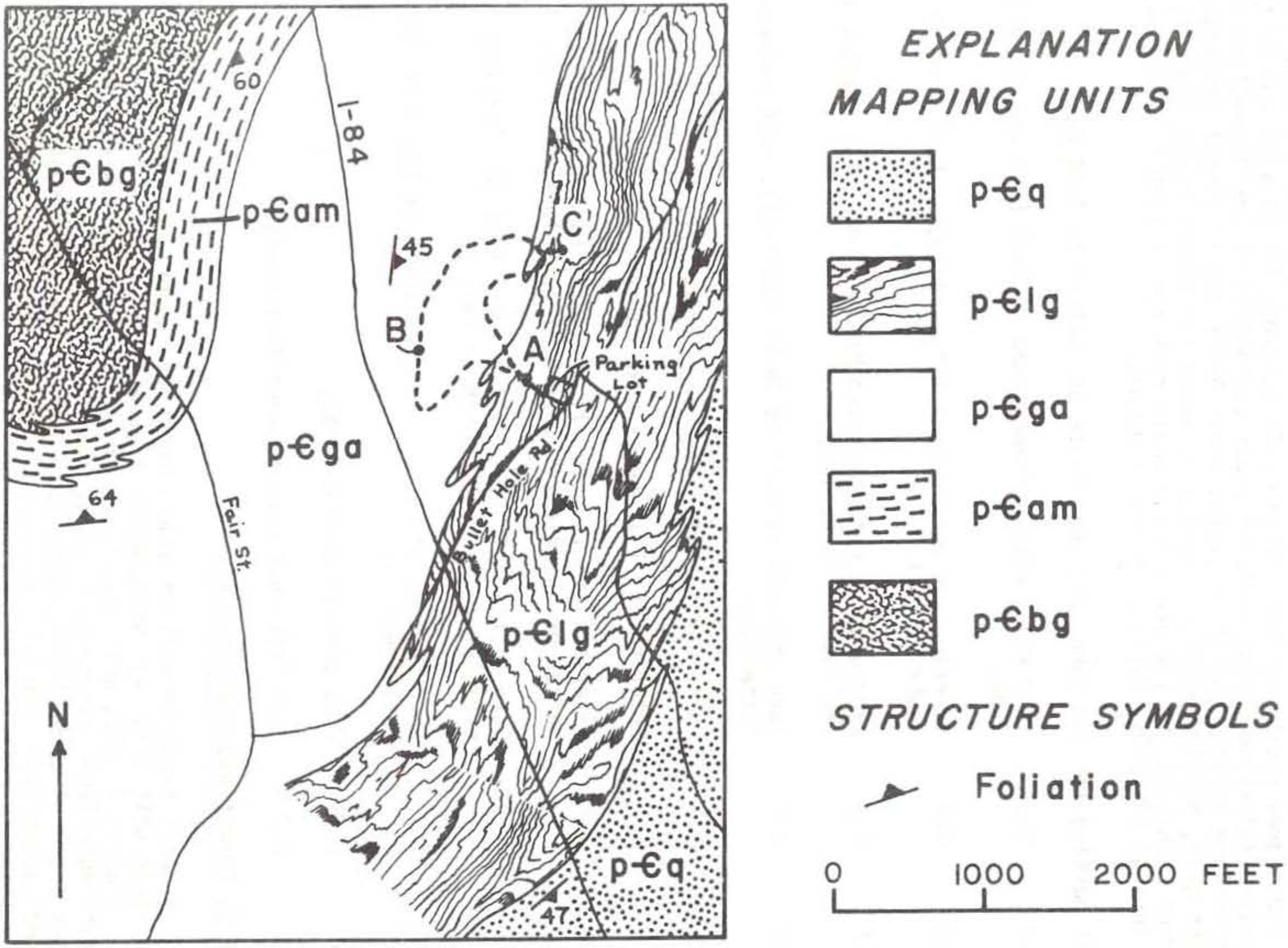

Figure 4. Geologic map of the region in the vicinity of stop 2.

Turn right and proceed west along Bullet Hole Rd.

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| 32.6 | 0.3 | Pass beneath I-84 overpass and continue on Bullet Hole Rd. |
| 33.0 | 0.4 | Intersection of Bullet Hole Rd. and Fair St. Turn left and proceed along Fair St. |
| 33.6 | 0.6 | To the right is George Fischer Middle School. |
| 34.1 | 0.5 | Intersection of Fair St. and Tilly Foster Rd. Turn left (south) onto Tilly Foster Rd. |
| 35.5 | 1.4 | Intersection of Tilly Foster Rd. and Route 6. Turn left (east)and proceed on Route 6. About one mile to the south, samples of a granite gneiss yielded a Rb/Sr whole rock age of 1308 ± 41 m.y. |
| 35.8 | 0.3 | Intersection of Route 6 and Route 312. Turn left at traffic signal and proceed along Route 312. To the right (south) is the Tilly Foster Mine. |
| 36.9 | 1.1 | Intersection of Route 312 and I-84. Geology of the large roadcut to the right described by Fenster and Brock, 1975. |
| 37.1 | 0.2 | Turn left onto entrance ramp of I-84 West and proceed on I-84. |
| 38.5 | 1.4 | Large exposures of the pЄq unit and the pЄlg unit. |
| 39.2 | 0.7 | Large exposure of the pЄga unit. This roadcut is described in detail in Hall et al. (1975). |
| 39.8 | 0.6 | Exposures of the contact between the pЄga unit and the pЄam unit. |
| 40.1 | 0.3 | To the left in the eastbound lane of I-84 are exposures of the pЄbg unit. |
| 40.5 | 0.4 | Turn off Exit 18 (N.Y. Route 311, Lake Carmel-Patterson). |
| 40.7 | 0.2 | Turn left at stop sign onto Route 311. Proceed beneath I-84 overpass and continue west on Route 311 South. |
| 41.2 | 0.5 | Entering Lake Carmel. |
| 41.8 | 0.6 | Intersection of Route 311 and Route 52. Turn right and proceed north on Route 52. |
| 43.6 | 1.8 | Kent Primary School to the left. |
| 43.8 | 0.2 | Turn left onto North Kent Rd. immediately beyond the Kent Primary School. |
| 44.7 | 0.9 | Intersection of North Kent Rd. and Whangtown Rd. Bear right and continue on North Kent Rd. |
| 44.8 | 0.1 | Exposure on the left is a sampling locality for Rb/Sr |

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| | | whole rock dating (1296 ± 77 m.y.) of the biotite-muscovite-quartz-plagioclase gneiss. |
| 45.1 | 0.3 | Intersection of North Kent Rd. and Church Hill. Proceed along North Kent Rd. |
| 45.4 | 0.3 | Exposure on the left is a sampling locality for Rb/Sr whole rock dating (1296 ± 77 m.y.) of the biotite-muscovite-quartz-plagioclase gneiss. |
| 45.7 | 0.3 | Intersection of North Kent Rd. and Ressique Rd. Continue along North Kent Rd. |
| 46.8 | 1.1 | Three-way intersection between North Kent Rd., Farmers Mills Rd. and Gypsy Trail Rd. (North Kent Rd. becomes Farmers Mills Rd.). Continue along Farmers Mills Rd. |
| 47.5 | 0.7 | Intersection of Farmers Mills Rd. and Milltown Rd. Proceed along Farmers Mills Rd. |
| 47.9 | 0.4 | Intersection of Farmers Mills Rd. and Ninham Rd. Continue along Farmers Mills Rd. |
| 48.6 | 0.7 | Entering the Oscawana Lake 7½' quadrangle. |
| 49.8 | 1.2 | Intersection between Farmers Mills Rd. and Route 301. Bear right and proceed west on Route 301. |
| 52.0 | 2.2 | Entering Clarence Fahnstock State Park. |
| 52.3 | 0.3 | Exposures of paragneiss on the right side of Route 301. |
| 52.9 | 0.6 | Intersection of Route 301 with the Taconic State Parkway. Continue straight on Route 301. |
| 53.1 | 0.2 | Entering the Ramapo-Canopus fault zone. Note sheared rock on both sides of road. |
| 53.9 | 0.8 | Canopus Lake. The Ramapo-Canopus fault roughly trends along the axis of the lake. |
| 55.0 | 1.1 | Exposure on the right is a sampling locality for Rb/Sr whole rock dating (914 ± 31 m.y.) of the Canada Hill granite. |
| 56.8 | 1.8 | Entering the West Point 7½' quadrangle. Exposure to the right of the road is sampling locality for Rb/Sr whole rock dating (914 ± 31 m.y.) of the Canada Hill granite. |
| 59.1 | 2.3 | Intersection of Route 301 and Route 9. Jog right and left and continue on Route 301. |
| 60.6 | 1.5 | Intersection of Route 301 and Fishkill Rd. (from the right). Continue straight on Route 301. |
| 61.0 | 0.4 | Turn left onto Peekskill Rd. and proceed south. This allows us to bypass the town of Cold Spring. |

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| 61.5 | 0.5 | Intersection between Peekskill Rd. and Route 9D. Turn left and proceed south on Route 9D. |
| 64.0 | 2.5 | Entering the Village of Garrison. |
| 64.9 | 0.9 | Intersection of Route 9D and Route 403. Continue south on Route 9D. |
| 65.0 | 0.1 | Entering the Peekskill 7½' quadrangle. |
| 65.7 | 0.7 | Site of the Robinson House on the left. Benedict Arnold secretly offered the British the surrender of West Point and settled the particulars in a midnight meeting with Major John Andre in the Robinson House on Sept. 21, 1780. Andre was captured two days later and hanged at Tappan, Oct. 2, 1780. Arnold made his escape to the British sloop, Vulture. |
| 66.0 | 0.3 | Prominent landform to the left is Sugarloaf Mountain. |
| 68.1 | 2.1 | Eastern anchor for the chain across the Hudson River which failed to prevent British ships from sailing up the Hudson River during the War of Independence. |
| 69.5 | 1.4 | Turn right onto the Bear Mountain Bridge at the intersection of Route 9D and Route 6W/202W. The large mountain straight ahead and to the left is Bear Mountain. The prominent knob straight ahead and to the right is the Torne. Proceed across the bridge to the traffic circle. |
| 70.0 | 0.5 | Bear right into the traffic circle. Proceed 3/4 the way around the traffic circle and turn right onto Route 9W to the Bear Mountain Inn. |
| 70.3 | 0.3 | Entering Rockland County. Proceed on Route 9W South. |
| 70.6 | 0.3 | Turn right onto service road and proceed to Bear Mountain Inn parking area. |

STOP 3. Bear Mountain.

Stop 3 is a short walk north of Bear Mountain Inn to the roadway north of Hessian Lake (Fig. 3). The exposures that will be studied at this locality are in Harriman State Park and regulations prohibit destruction of the environment in any way. NO HAMMERING, PLEASE!

Several lithologies typical of the western Highlands terrane are seen in these exposures. These include the paragneiss (pЄpg) with its associated amphibolite and rusty pyroxenic gneiss (pЄpga) and foliated hornblende granite (pЄsk). Canada Hill granite (pЄch) cross-cuts structures in all three lithologies. These units form the lower limb of a reclined isoclinal $F_2$-antiform (Ft. Montgomery antiform).

pЄpg, pЄga and pЄsk are folded into isoclinal digitations and compositional layering is completely transposed into an $F_1$ axial planar foliation. $F_2$-folds are locally similar in style and are usually more open than $F_1$-isoclinal folds. Several minor $F_2$-folds occur in the hornblende granite at this locality. A hornblende lineation best seen in the amphibolite (pꞒpga) trends about N37°E at 37° and is parallel to fold axes of $F_2$-folds. The broad curvature to the units in the Bear Mountain area seen on the map (Fig.3), is due to $F_3$-folding. Fold axes of $F_3$-folds plunge N50°E at 36° in this area.

The deformation seen in the hornblende granite at this locality is absent in the main mass (core) of hornblende granite at Bear Mountain. However, a strong hornblende lineation in the core granite parallels the hornblende lineation in the amphibolite (pꞒpga) of the paragneiss unit (pꞒpg). Since marginal gneissic facies of the hornblende granite locally possess secondary foliation related both to $D_1$ and $D_2$, the Bear Mountain pluton has been involved in all phases of deformation. The Rb/Sr whole rock age of 1086 m.y. and the U/Pb age of 1060 m.y. obtained from the lineated core facies of the pluton probably indicate the time of crystallization of residual melt in the Bear Mountain pluton. This would suggest that final crystallization of the hornblende granite was coeval with the termination of $F_2$-folding in the West Point area.

The coarse-grained, leucocratic Canada Hill granite cross-cuts linear and planar structures in the granite-gneiss sequence and contains inclusions of pꞒsk and pꞒpga (the latter not seen in these exposures). In other localities where the hornblende granite and Canada Hill granite are in close proximity, the relationship between the two granites is at best equivocal. Field relationships seen at these exposures clearly demonstrate the cross-cutting nature of the Canada Hill granite. This, combined with a Rb/Sr whole rock age of 914 m.y., supports the assignment of a post-Storm King age to the Canada Hill granite. The crystallization of Canada Hill granite represents the termination of Grenville activity in the Hudson Highlands.

Leave the Bear Mountain Inn parking lot and turn left onto the service road. Proceed approximately two hundred yards and turn left onto Routes 9W and 202.

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| 71.1 | 0.5 | Enter the traffic circle and proceed halfway around. Bear right onto Route 9W north toward West Point-Newburgh. |
| 71.4 | 0.3 | Bridge over Popolopen Brook (also known as Hell Hole). |
| 71.6 | 0.2 | To the right of the road is the site of Fort Montgomery, prominent in the American Revolution. |
| 72.0 | 0.4 | Entering the town of Ft. Montgomery. |
| 73.1 | 1.1 | Exposures of Canada Hill granite in the core of the Crystal Lake pluton. |
| 73.8 | 0.7 | To the left side of Route 9W is a large exposure of Canada Hill granite. |
| 75.3 | 1.5 | Large exposure on the left side of Route 9W is hornblende granitic gneiss. This is an extension of the Bear Mountain pluton and forms the core of the West Point antiform. |
| 75.6 | 0.3 | Bear right off Route 9W and proceed to stop sign. Turn right onto Route 218 South. |
| 75.8 | 0.2 | On the left side of the road are exposures of paragneiss in contact with hornblende granitic gneiss in the core of |

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| | | the West Point antiform. |
| 76.2 | 0.4 | Entering the Village of Highland Falls. Proceed on Route 218 (Mountain Rd.). |
| 76.6 | 0.4 | To the left is Highland Falls Junior High School. Continue down Mountain Rd. |
| 76.8 | 0.2 | Turn right at stop sign onto Main Street and immediately left onto Mill Street along small triangular park. Proceed to stop sign and turn left onto two lane concrete highway (Route 970). Route 970 parallels Main St. and allows us to bypass the town of Highland Falls. |
| 77.3 | 0.5 | Turn right at Station Hill and park in cleared area. |

STOP 4. Northern margin of the Crystal Lake pluton.

The next two stops will illustrate field relationships between the paragneiss unit (pЄpg) and the Canada Hill granite (pЄch) by taking a cross-sectional traverse through the Crystal Lake pluton (Fig. 3). Canada Hill granite is found in several zoned plutons restricted to the paragneiss unit, the largest of which is the Crystal Lake pluton. Stop 4 is located at the northern margin of the pluton; stop 5 is located in the core of the pluton. In traversing the Crystal Lake pluton from margin to core, we will proceed from non-migmatitic paragneiss, through a marginal zone of migmatite (metatexite of Mehnert, 1968) into a core of diatexite (a rock characterized by "complete or nearly complete melting, when molten and unmolten portions can no longer be distinguished", Mehnert, 1968, p. 253). The following lithologies make up the Crystal Lake pluton and its enclosing rocks:

Non-migmatitic paragneiss is an equigranular rock with a metamorphic fabric containing quartz, plagioclase feldspar, microcline, biotite and garnet. Quartz, microcline and plagioclase feldspar are present in about equal amounts.

Migmatite consists of leucosome and melanosome. Leucosome is a coarse-grained, inequigranular rock containing quartz, microcline, plagioclase feldspar and biotite with or without garnet. In mineralogy, leucosome is similar to diatexite. Melanosome is finer and more even grained than leucosome and consists of varying proportions of quartz, plagioclase feldspar, biotite, garnet and occasionally sillimanite. Alkali-feldspar is minor or absent.

Diatexite is a coarse-grained, inequigranular rock consisting of quartz, slightly perthitic microcline, plagioclase feldspar (calcic oligoclase) and varying amounts of garnet and biotite. Sphene and zircon are ubiquitous accessory minerals; sillimanite, graphite and tourmaline are rare. Two facies of diatexite occur in the Crystal Lake pluton: homophanous diatexite (a homogeneous granite) and schlieric diatexite (homogeneous granite with schlieren of restite). Alteration related to crystallization of diatexite resulted in the formation of secondary muscovite and epidote and the alteration of biotite.

The Q:Ab/Pl:Or and mineralogical ratios for these rocks are plotted in figure 5. The normative Q:Ab:Or ratio of diatexite lies in the field of igneous plutonic rocks containing 80% or more normative quartz-albite-orthoclase (Fig. 5A). These data support a magmatic origin for the

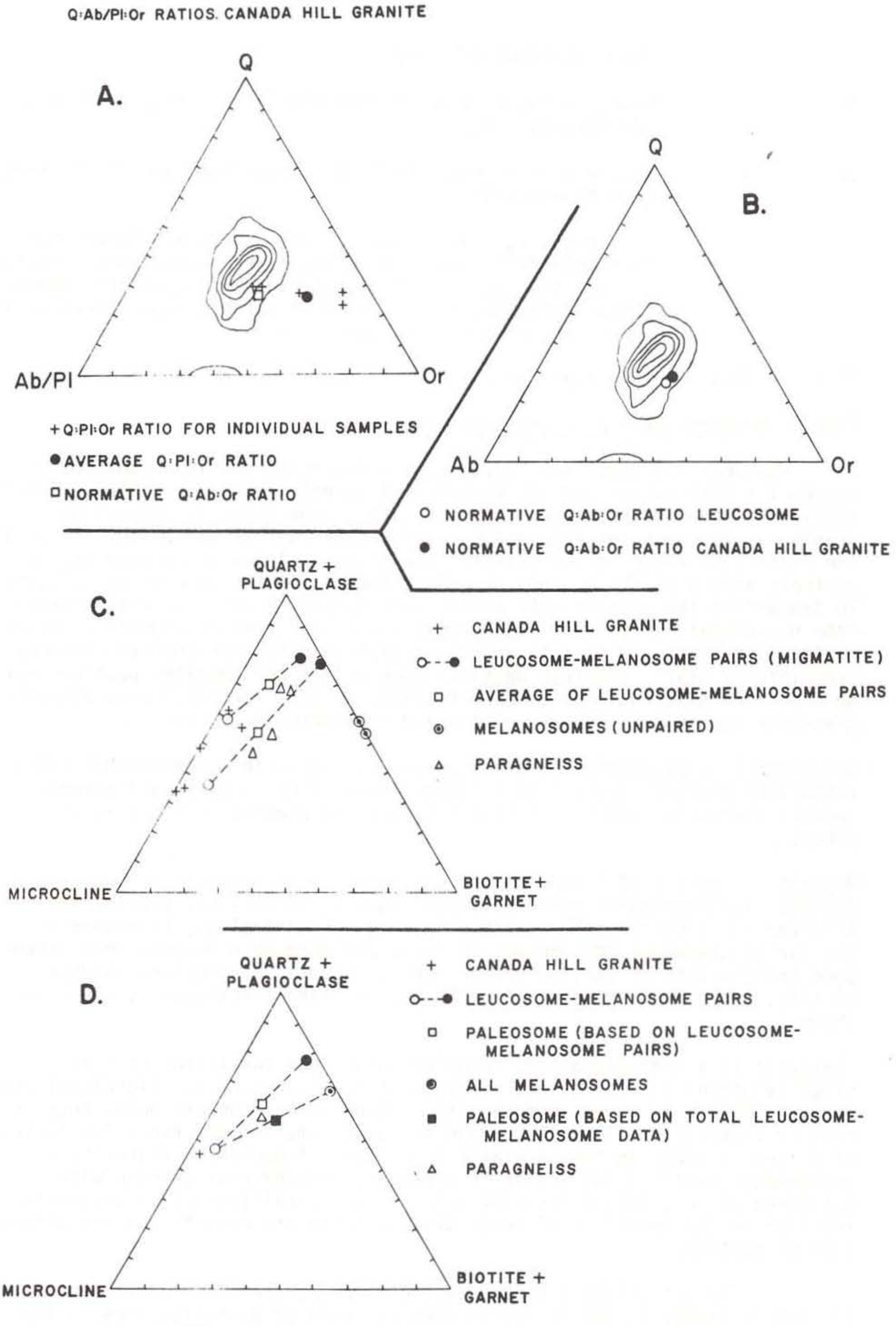

Figure 5. Q:Ab/Pl:Or and mineralogical data for Canada Hill granite, migmatite and non-migmatitic paragneiss.

diatexite facies of the Canada Hill granite. The normative Q:Ab:Or ratio of leucosome in migmatite likewise lies in the field of magmatic rock (Fig. 5B). Mineralogical data for Canada Hill granite (diatexite), migmatite and non-migmatitic paragneiss are plotted in figures 5C and 5D. The composition of Canada Hill granite and leucosome is virtually identical. The homogenized composition of leucosome-melanosome pairs approximates the mineralogical composition of non-migmatitic paragneiss. These data indicate that non-migmatitic paragneiss represents paleosome from which migmatite and Canada Hill granite formed by anatexis.

Isotopic studies also support an anatectic origin for the Canada Hill granite. Paragneiss yielded a Rb/Sr whole rock age of 1139 m.y. with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7067. The Canada Hill granite (diatexite) yielded an age of 914 m.y. and an initial ratio of 0.7193. The data also show that the average $^{87}Rb/^{86}Sr$ ratio of the paragneiss is 3.8. If the paragneiss remained a closed chemical system between 1139 m.y. and 914 m.y. ago, **its average $^{87}Sr/^{86}Sr$ ratio would have changed from 0.7067 to about 0.718.** A calculated ratio of about 0.718 is essentially the same (given the error) as 0.7193, the initial $^{87}Sr/^{86}Sr$ ratio of the 914 m.y. old Canada Hill granite. This indicates that the paragneiss anatectically yielded a granitic melt in an isotopically non-fractionating manner which crystallized at about 914 m.y. ago to form Canada Hill granite.

Station A. Leave the parking area and proceed to Route 970/Main St. Turn right onto Route 970/Main St. and walk to large outcrop of the non-migmatitic paragneiss on the east side of the road.

Proceed down Route 970/Main St. in the direction of the parking area. Continue south past Station Hill several hundred feet to Michel's Gift Shop. Bear left off Route 970/Main St. and proceed down gravel road passing through the nursery (this gravel road is known as Wood Lane). Proceed to the end of Wood Lane past three private houses to the large exposure overlooking the Hudson River.

Station B. Large exposure of migmatite and Canada Hill granite. No hammers, please!

Return to the parking area at Station Hill. Turn left onto Route 970.

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| 77.8 | 0.5 | Intersection of Route 970 and Main St./Route 218. Bear left and proceed south on Route 218. |
| 78.9 | 1.1 | Proceed over the overpass of Route 218 and Route 9W and park in the large area immediately beyond the overpass. |

STOP 5. Canada Hill granite (diatexite)

Large roadcut exposing the schlieric facies of Canada Hill diatexite.

Turn around and drive back over the overpass (Route 218 over Route 9W).

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| 79.1 | 0.2 | Take a sharp right at stop sign and turn onto the entrance ramp of Route 9W. Bear right onto Route 9W. Proceed north on Route 9W. |
| 80.5 | 1.4 | Hornblende granitic gneiss in the core of the West Point antiform is seen to the left. |

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| 80.8 | 0.3 | Entering the West Point 7½' quadrangle. |
| 80.9 | 0.1 | Large roadcut to the left is paragneiss (pЄpg). |
| 81.3 | 0.4 | To the right is an exposure of a thin sheet of honrblende quartz monzonitic gneiss (pЄsk). |
| 81.7 | 0.4 | Pull off to the right into small parking area south of the West Point Golf Course. |

STOP 6. Magnetite alaskite.

Magnetite alaskite (pЄal) is a late to post-tectonic plutonic rock occupying a narrow fault-controlled valley between the Crows Nest antiform and West Point synform (Fig. 3). Alaskite is a medium- to coarse-grained, massive rock consisting of quartz (21%), white plagioclase feldspar (41%), pink microcline (35%) and magnetite (3%). Secondary minerals include muscovite, sericite and opaque oxides. Inclusions of country rock and xenocrysts derived from the country rock are common in the marginal facies of the alaskite. Recrystallized biotite inherited from the adjacent paragneiss is seen in this exposure of alaskite. A fracture cleavage is commonly developed in alaskite.

The relationship of alaskite to other Highlands lithologies remains uncertain. While it intrudes pЄqp, pЄpg and pЄsk, its relationship to Canada Hill granite is not at all clear. The fracture cleavage in the alaskite may be related either to $D_3$ or to some post-$D_3$ deformational event. The lack of any penetrative structures related to $D_1$ and $D_2$, however, indicates the alaskite was intruded late in the deformational history.

Carefully pull back onto Route 9W.

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| 82.0 | 0.3 | Route 9W overpass over Route 218. Continue straight on Route 9W. |
| 82.3 | 0.3 | To the left are large exposures of charnockitic quartz-plagioclase gneisses (pЄqp). Coarser grained, massive rock is the alaskite which intrudes the quartz-plagioclase gneisses. |
| 83.4 | 1.1 | Pull off the road into the parking area at the overlook. |

STOP 7. Crows Nest Lookout.

View of the Hudson River, Constitution Island and the United States Military Academy at West Point. The ridge southwest (to the right) of the Military Academy is held up by a thin sheet of hornblende quartz monzonitic gneiss. The hornblende granitic gneisses are the most resistant of the Highlands lithologies to weathering and are the major ridge formers in the Hudson Highlands. The quartz monzonitic gneiss at West Point forms a prominent ridge which outlines the structure of the West Point antiform. The fold axis of this antiform plunges N36°E at 22°; the axial plane is oriented N30°E, 74°S. The valley at the base of the Crows Nest is underlain by magnetite alaskite.

The Crows Nest lookout is situated along the southeasterm limb of the Crows Nest antiform. Exposures of hornblende quartz monzonitic gneiss surround the lookout. The foliation in the gneiss is an $F_2$ axial planar foliation oriented N45°E, 70°N. This foliation is continuous with a secondary foliation described by Murray (1965) in the crest of the Crows Nest antiform at Bull Hill. The hornblende quartz monzonitic gneiss forms the core of the Crows Nest structure and yielded an Rb/Sr whole rock age of 1169 m.y. The Crows Nest antiform plunges N43°E at 18°; the axial plane is oriented N60°E, 45°N. A prominent mineral lineation trends N40°E at 22°.

On the far side of Route 9W across from the lookout, a basic dike (orientation, N75°W, 62°S), about 90 feet thick, cuts the trend of the Crows Nest fold. Undeformed basic dikes are plentiful in the Highlands and parallel the dominant joint directions in the Highland gneisses. The majority of dikes are lamprophyric or diabasic; dioritic and andesitic as well as dikes consisting of syenite and quartz porphyry are less common. The age of these dikes is uncertain.

Carefully leave the parking area and proceed north on Route 9W.

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| 83.6 | 0.2 | Exposures of hornblende quartz monzonitic gneiss in the core of the Crows Nest antiform. |
| 84.6 | 1.0 | Entering the Cornwall 7½' quadrangle. To the left is a shear zone separating the Crows Nest block from the Storm King block. |
| 84.9 | 0.3 | Large hill of bedrock to the right is the crest of Storm King Mountain (Butter Hill, elevation 1380 feet) underlain by hornblende granitic gneiss. |
| 85.5 | 0.6 | Turn right onto Mountain Rd. and proceed up hill past Storm King School to the left. |
| 86.0 | 0.5 | Intersection of Mountain Rd. and Maple Rd. (from the left). Continue along Mountain Rd. |
| 86.9 | 0.9 | Three-way intersection between Mountain Rd. and the Boulevard (roadway not marked). Turn left and proceed along the Boulevard. |
| 87.2 | 0.3 | Park along the road at Edward Payson Roe Memorial Park. |

STOP 8. Northern border fault of the Hudson Highlands.

Hornblende granite thrust adjacent to Ordovician clastic rocks. The trace of the fault on the map trends about N35°E. Berkey (1910), however, reported an orientation of N70°E, 45°S for the fault plane based on subsurface data obtained from the Catskill aqueduct project. The question arises as to whether the northern border fault is a high angle thrust fault or a low angle overthrust. A short distance southeast of this locality, Lowe (1958) reported overthrusting of Storm King granite over intensely crumpled Ordovician slaty shales. Further to the southeast (1400 feet southeast of this stop), Berkey (1910) noted that sheared hornblende granite was penetrated to a depth of 412 feet in a series of drill holes in Pagenstechers Gorge (ravine along Mountain Rd.). A tunnel bored across the Hudson River in 1912 from Storm King Mountain to Breakneck Ridge at a depth of 1100 feet and two inclined drill holes across the Hudson in the same area intersecting at a depth of about 1500 feet, both penetrated hornblende granite beneath the Hudson River (Kemp, 1912). These data would appear to suggest that the northern border fault of the Hudson Highlands is a high angle thrust fault with local overthrusting.

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| 87.3 | 0.1 | To the left is the Museum of the Hudson Highlands. |
| 87.5 | 0.2 | Exposures of hornblende granite gneiss are seen on both sides of the road. |
| 88.0 | 0.5 | Intersection of the Boulevard and Maple Rd. (from the left). Continue along the Boulevard. |
| 88.2 | 0.2 | Intersection of the Boulevard and Hasbrouck Rd. Bear left along the Boulevard. |
| 88.6 | 0.4 | Turn right onto the service road for Route 9W. |
| 88.7 | 0.1 | Turn right onto Route 9W and proceed northwest along Route 9W. |
| 91.8 | 3.1 | Bridge over Moodna Creek. |
| 93.3 | 1.5 | Hills off to the right are the Hudson Highlands. |
| 93.7 | 0.4 | Entering New Windsor. Continue along Route 9W. |
| 94.4 | 0.7 | Entering Newburgh. Continue along Route 9W. |
| 94.8 | 0.4 | To the right is a road leading to Washington's headquarters in Newburgh (1782-83). Continue north acorss Main St. on Route 9W. |
| 94.9 | 0.1 | Entering the Newburgh 7½' quadrangle. |
| 96.1 | 1.2 | Intersection of Route 9W and Route 52. Bear left onto Route 52. |
| 96.2 | 0.1 | Turn right onto I-84 East. |
| 96.7 | 0.5 | Cross the Beacon-Newburgh Bridge. To the right (south) is a spectacular view of the northern passage of the Hudson Highlands. On the right is Storm King Mountain. On the left is Beacon Hill-Breakneck Ridge. The small island in the Hudson River is Pollepel Island. Entering the Wappingers Falls 7½' quadrangle. |
| 98.4 | 1.7 | Toll booths. Proceed through the toll booths east on I-84. |
| 101.3 | 2.9 | Hornblende granite in the Glenham gneiss belt. |
| 101.6 | 0.3 | Exposure of the upper members of the Wappinger Group with conglomeratic Middle Ordovician Balmville limestone. |
| 103.2 | 1.6 | Turn off I-84 at Exit 13 (Route 9 to Poughkeepsie). |
| 103.4 | 0.2 | Turn left (north) at stop sign onto Route 9 and proceed north on Route 9 to the Village of Wappingers Falls |
| 108.5 | 5.1 | Entering the Village of Wappingers Falls. |

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| 109.6 | 1.1 | Bridge over Wappingers Lake. |
| 110.2 | 0.6 | Intersection of Route 9 and Vassar Rd. Turn right onto Vassar Rd. |
| 113.9 | 3.7 | Five-way intersection at traffic signal in Red Oaks Mill (Route 376, Spackenkill Rd., Vassar Rd.). Proceed straight through the intersection (north) onto Route 376. |
| 116.2 | 2.3 | Intersection of Route 376 and Raymond Ave. (road sign reads "to 44 and 55"). Bear right onto Raymond Ave. |
| 116.3 | 0.1 | Turn right into south parking lot on the Vassar College Campus. |

## REFERENCES CITED

Berkey, C.P., 1910, Geology of the New York City (Catskill) aqueduct: New York State Mus. Bull., no. 146, 277 pp.

Berkey, C.P. and Rice, M., 1919, Geology of the West Point quadrangle, New York: New York State Mus. Bull., no. 225-226.

Butler, J.R., 1972, Age of Paleozoic regional metamorphism in the Carolinas, Georgia, and Tennessee, southern Appalachians: Amer. Jour. Sci., v. 272, p. 319-333.

Chase, P.J. and Brock, P.W.G., 1976, Sillimanite and sillimanite-orthoclase isograds in the Croton Falls quadrangle, southeast New York (abstr.): Geol. Soc. America Abstr., v. 8, no. 2, p. 149-150.

Clark, G.S. and Kulp, J.L., 1968, Isotopic age study of metamorphism and intrusion in western Connecticut and southeastern New York: Amer. Jour. Sci., v. 266, p. 865-894.

Dallmeyer, R.D., 1975, $^{40}$Ar/$^{39}$Ar release spectra of biotite and hornblende from the Cortlandt and Rosetown plutons, New York and their regional implications: Jour. Geol., v. 83, p. 629-643.

Dallmeyer, R.D. and Dodd, R.T., 1971, Distribution and significance of cordierite in paragneisses of the Hudson Highlands, southeastern New York: Contr. Mineral. Petrol., v. 33, p. 289-308.

Dallmeyer, R.D. and Sutter J.F., 1976, $^{40}$Ar/$^{39}$Ar incremental-release ages of biotite and hornblende from variably retrograded basement gneisses of the northeasternmost Reading Prong, New York: their bearing on Early Paleozoic metamorphic history: Amer. Jour. Sci., v. 276, p. 731-747.

Dallmeyer, R.D., Sutter J.F. and Baker, D.J., 1975, Incremental $^{40}$Ar/$^{39}$Ar ages of biotite and hornblende from the northeastern Reading Prong: their bearing on late Proterozoic thermal and tectonic history: Geol. Soc. America Bull., v. 86, p. 1435-1443.

Eckelmann, F.D. and Helenek, H.L., 1975, A petrologic study of zircon populations from the Storm King granite, Hudson Highlands, New York (abstr.): Geol. Soc. America Abstr., v. 7, no. 1, p. 52.

Fenster, D.F. and Brock, P.W.G., 1975, Structure and petrology of the Hudson Highlands near Brewster, New York (abstr.): Geol. Soc. America Abstr., v. 7, no. 1, p. 56.

Fullagar, P.D. and Odom, A.L., 1973, Geochronology of Precambrian gneisses in the Blue Ridge province of northwestern North Carolina and adjacent parts of Virginia and Tennessee: Geol. Soc. America Bull., v. 84, p. 3065-3080.

Grauert, B. and Hall, L.M., 1973, Age and origin of zircons from metamorphic rocks in the Manhattan Prong, White Plains area, southeastern New York: Carnegie Inst. of Washington, Ann. Rpt. of the Director, Dept. Terrestrial Magnetism (1972-73), p. 293-297.

Hall, L.M., Helenek, H.L., Jackson, R., Caldwell, C., Mose, D.G. and Murray, D.P., 1975, Some basement rocks from Bear Mountain to the Housatonic Highlands: New England Intercollegiate Geological Conference, Guidebook, New York, Trip A-1, p. 1-29.

Harwood, D.S. and Zietz, I., 1974, Configuration of Precambrian rocks in southeastern New York and adjacent New England from aeromagnetic data: Geol. Soc. America Bull., v. 85, p. 181-188.

Kemp, J.F., 1912, The Storm King crossing of the Hudson River, by the new Catskill aqueduct of New York City: Amer. Jour. Sci., v. 34, p. 1-11.

Klemic, H., Eric, J.H., McNitt, J.R. and McKeown, F.A., 1959, Uranium in Phillips Mine-Camp Smith area, Putnam and Westchester Counties, New York: U.S. Geol. Survey Bull. 1074-E, p. 165-199.

Long, L.E., 1969, Whole-rock Rb-Sr age of the Yonkers gneiss, Manhattan Prong: Geol. Soc. America Bull., v. 80, p. 2087-2090.

Long, L.E. and Kulp, J.L., 1962, Isotopic age study of the metamorphic history of the Manhattan and Reading Prongs: Geol. Soc. America Bull., v. 73, p. 969-996.

Lowe, K.E., 1950, Storm King granite at Bear Mountain, New York: Geol. Soc. America Bull., v. 61, p. 137-190

__________, 1958, Pre-Cambrian and Paleozoic geology of the Hudson Highlands: New York State Geological Association, Guidebook, Peekskill, Trip D, p. 41-52.

Mehnert, K. R., 1968, Migmatites and the origin of granitic rocks: Elsevier Publishing Co., New York, 393 p.

Mose, D.G. and Hayes, J., 1975, Avalonian igneous activity in the Manhattan Prong, southeastern New York: Geol. Soc. America Bull., v. 86, p. 929-932.

Mose, D.G. and Helenek, H.L., 1976, Origin, age and mode of emplacement of Canada Hill granite, Hudson Highlands, New York (abstr.): Geol. Soc. America Abstr., v. 8, no. 2, p. 233-234.

Mose, D.G., Baiamonte, M., Hayes, J. and Lo Bello, L., 1975, Rb/Sr age determination of a multiple intrusion in the Ramapo fault zone, southeastern New York (abstr.): Geol. Soc. America Abstr., v.7, no. 1, p. 97.

Mose, D.G., Ratcliffe, N.M., Odom, A.L. and Hayes, J., 1976, Rb-Sr geochronology and tectonic setting of the Peekskill pluton, southeastern New York: Geol. Soc. America Bull., v. 87, p. 361-365.

Murray, D.P., 1968, An investigation of origin, structure, and metamorphic evolution of the Precambrian rocks of the West Point quadrangle, New York: unpub. M.Sc. thesis, Brown University, Providence, R.I., 69 p.

Prucha, J.J., Scotford, D.M. and Sneider, R.M., 1968, Bedrock geology of parts of Putnam and Westchester Counties, New York, and Fairfield County, Connecticut: New York State Mus. and Sci. Service Map and Chart Ser., no. 11, 26 p.

Rankin, D.W., Stern, T.W., Reed, J.C. and Newell, M.F., 1969, Zircon ages of felsic volcanic rocks in the upper Precambrian of the Blue Ridge, Appalachian Mountains: Science, v. 166, p. 741-744.

Tilton, G.R., Wetherill, G.W., Davis, G.L. and Bass, M.N., 1960, 1000-million-year-old minerals from the eastern United States and Canada: Jour. Geophys. Research, v. 65, p. 4173-4179.