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ORDOVICIAN DUCTILE DEFORMATION ZONES IN THE HUDSON HIGHLANDS AND THEIR RELATIONSHIP TO METAMORPHIC ZONATION IN COVER ROCKS OF DUTCHESS COUNTY, NEW YORK

Nicholas M. Ratcliffe[1], Rosemary Vidale Buden[2], and William C. Burton[1]

Introduction

The results reported here stem from a program of detailed mapping of fault zones within the Ramapo seismic zone in New York, New Jersey and Pennsylvania funded by the USGS Reacter Hazards, and Earthquake Hazards Programs and by the Nuclear Regulatory Commission. The objective of these studies is to establish the relationship between geologic structure and low level seismicity that has been well located in this area. The rocks traversed on this trip are dominated by Paleozoic age semiductile shear zones in Proterozoic basement gneiss that forms the seismogenic source rock in the Ramapo seismic zone. Knowledge of the structure and mineralogy of these shear zones should provide important clues to the understanding of deeper parts (depths greater than 10 km) of present day seismogenic structures. On a regional scale these structures localized brittle failure in Early Mesozoic time to create the Triassic-Jurassic Newark basin (Ratcliffe, 1980).

Recent 1:24,000 mapping of the Middle Proterozoic basement rocks and the Cambrian through Ordovician cover sequence of the northern Hudson Highlands by Ratcliffe and Burton has defined a complex system of semiductile deformation zones (Fig. 1) that are largely responsible for deformation of the basement rocks in the Taconic orogeny. We have traced these narrow 0.5 to 100 meter thick zones of intense deformation and determined that the mineral assemblages contained in them record a prograde sequence from chlorite to sillimanite plus muscovite grade that is colinear with the Barrow zonation in Dutchess County described by Balk (1936) and Barth (1936) and most recently studied by Vidale (1974, a, b), Bence (Bence and McLelland, 1976) and McLelland and Fisher (1976) (Fig. 2).

$^{40}Ar/^{39}Ar$ mineral dates from muscovite, biotite and hornblende from basement rocks and Paleozoic cover rocks in this zonation suggest that the metamorphic zonation is Taconian, perhaps as old as 465 Ma., and not Acadian. (Bence and Rajamani, 1972, Dallmeyer and Sutter, 1976, Sutter and others, 1985).

The shear zones and Middle Proterozoic basement gneiss near shear zones contain new metamorphic assemblages that are consistent with Taconian remetamorphism. Biotite from the California Hill shear zone at staurolite grade gives an $^{40}Ar/^{39}Ar$ plateau age of 436 ±3 Ma. (John Sutter, personal communication, 1982).

When traced northward these ductile deformation zones pass upwards, as strong S_2 deformation zones, into the Paleozoic cover rocks that contain the classical garnet through sillimanite grade assemblages of Dutchess County. Locally these zones of S_2 deformation are retrogressive and tectonic foreshortening of the isograds in the cover rocks is indicated from structural studies.

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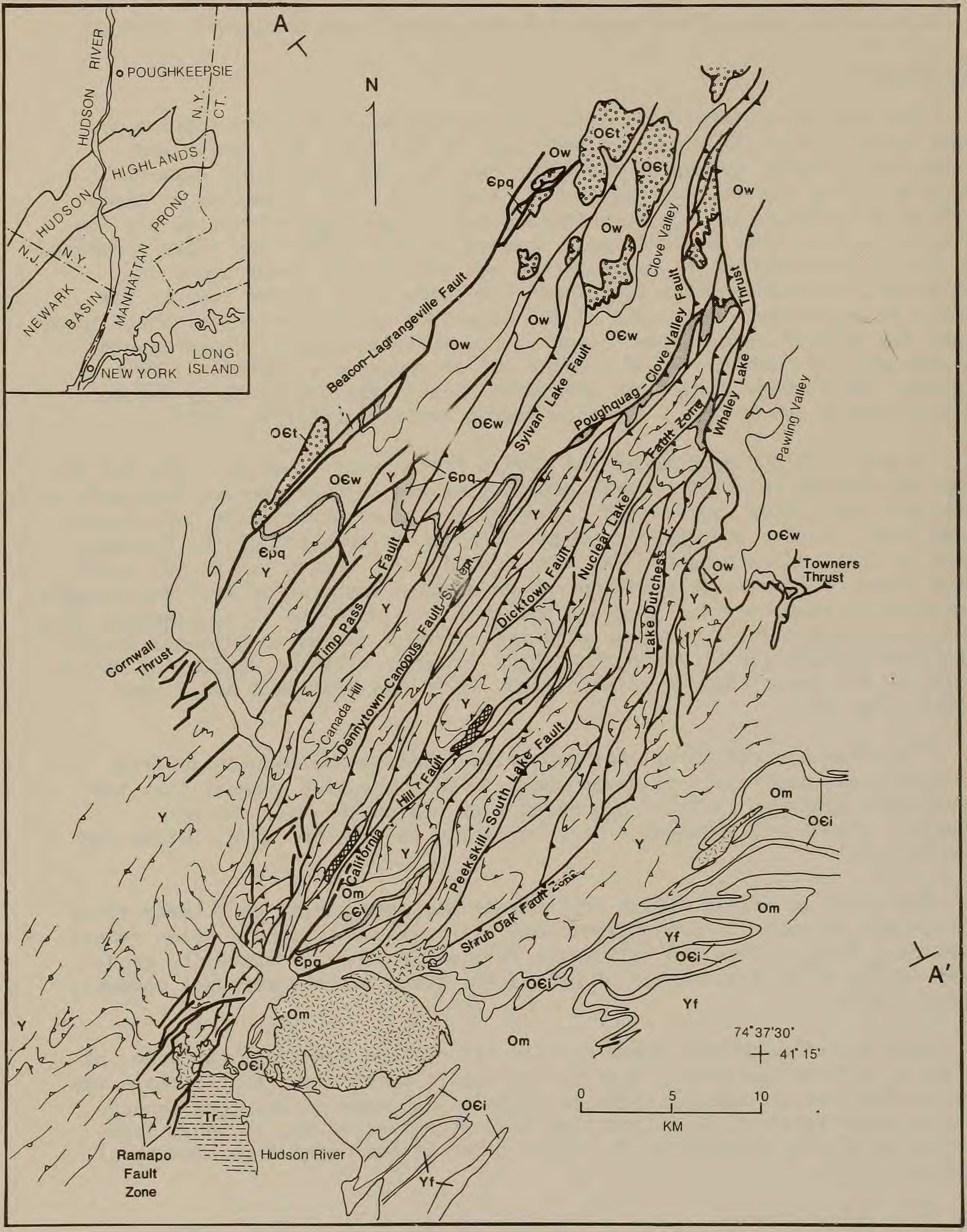

HUDSON RIVER
POUGHKEEPSIE
N.Y.
CT.
HUDSON HIGHLANDS
PRONG
N.J.
N.Y.
NEWARK BASIN
MANHATTAN
LONG ISLAND
NEW YORK
A
N
A'
OЄt
Ow
Єpq
OЄw
Clove Valley
Beacon-Lagrangeville Fault
Sylvan Lake Fault
Poughquag-Clove Valley Fault
Whaley Lake Thrust
Fault Zone
Pawling Valley
Y
Timp Pass Fault
Denmytown-Canopus Fault System
Canada Hill
Dicktown Fault
Nuclear Lake
Lake Dutchess
Towners Thrust
Cornwall Thrust
California Hill Fault
Peekskill-South Lake Fault
Stirub Oak Fault Zone
Om
OЄi
Yf
Tr
Ramapo Fault Zone
Hudson River
74°37'30"
41°15'
0
5
10
KM

EXPLANATION FOR FIGURE 1

Tr TRIASSIC AND LOWER JURASSIC ROCKS OF THE NEWARK BASIN — UPPER TRIASSIC - LOWER JURASSIC — MESOZOIC

— UNCONFORMITY —

ROCKS OF THE HUDSON HIGHLANDS

- **Ow** WALLOOMSAC FM.
- **OЄw** WAPPINGER GRP.
- **Єpq** POUGHQUAG QUARTZITE

— UNCONFORMITY —

- **Y** UNDIFFERENTIATED GNEISSES, SHOWING STRUCTURAL FORMLINES (Y FOLIATION)

ROCKS OF THE MANHATTAN PRONG

- **Om** MANHATTAN SCHIST (INCLUDES Є? ROCKS)
- **OЄi** INWOOD MARBLE & LOWERRE QUARTZITE
- **Yf** FORDHAM GNEISS

ROCKS OF THE TACONIC ALLOCHTHON (UNDIFFERENTIATED)

- **OЄt**

LOWER PALEOZOIC INTRUSIVE ROCKS

- PEEKSKILL GRANITE — DEVONIAN
- CORTLANDT, ROSETOWN, PEACH LAKE, CROTON FALLS INTRUSIVE COMPLEXES — UPPER ORDOVICIAN; MIDDLE ORDOVICIAN

DEVONIAN, UPPER ORDOVICIAN, MIDDLE ORDOVICIAN, CAMBRIAN AND LOWER ORDOVICIAN — PALEOZOIC

PROTEROZOIC INTRUSIVE ROCKS

- CANOPUS AND WICCOPEE PLUTONS — MIDDLE PROTEROZOIC

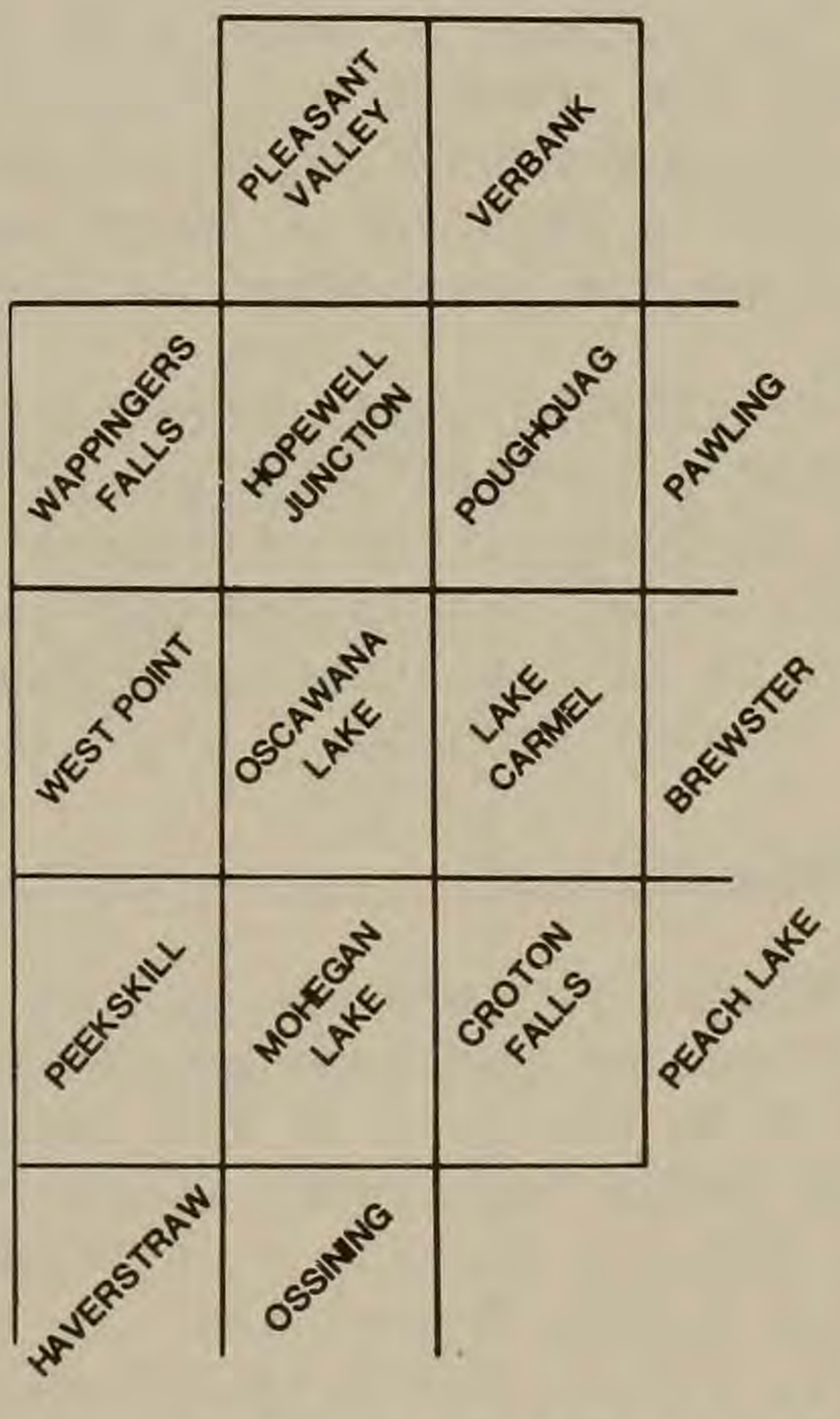
———— MESOZOIC FAULT

▼▼▼ DUCTILE SHEAR ZONE

▽▽▽ TACONIC ALLOCHTHON THRUST FAULT

———— CONTACT

LOCATION OF FIGS. 1,2,3



QUADRANGLE INDEX MAP FOR FIGS. 1,2,3

Figure 1 Simplified regional geologic map of the northern end of the Hudson Highlands showing semiductile deformation zones. Formlines show prominent regional F_2 foliation of Proterozoic age in basement rocks, barbs show dip.

At the time Vidale published her paper on vein assemblages (Vidale, 1974, a, b), she recognized that the occurrence of index minerals and critical assemblages was quite irregular and probably affected by structural and or retrogressive complications. She therefore did not publish her mineral assemblage data.

We have reexamined all of Rosemary Vidale's unpublished mineral assemblage data and her extensive thin section collection from this area as well as our own oriented sections from shear zones in the cover rocks in an attempt to relate the distribution of isograds to structural evolution of the area. We believe the data indicate that the pattern of metamorphic isograds in Dutchess County was strongly affected by faulting and deformation resulting from accumulation of strain in the quartzofeldspathic basement rocks arising from failure along semiductile shear zones. We relate strain softening of the basement rocks, oversteepening of the isograds and final tectonic emplacement of the isograd-containing rocks to a single but dynamically changing dynamothermal regime of Taconian age (Ratcliffe, 1983).

We have mapped basement and cover rock in detail in order to delimit zones of faulting; however, the lithic successions and details of the mineralogy of protoliths and their relationships will not be stressed on this trip. Those interested in the regional distribution of shear zones of this system exposed to the south in New Jersey may find a discussion and maps in Ratcliffe (1980). Comparable features from the Berkshire massif in Massachusetts have been described by Ratcliffe and Harwood (1975).

The purpose of this trip is to examine the structural details of the semiductile shear zones, associated folding, and mineralogy of the shear zones at various grades from chlorite through sillimanite grade and to relate these features to structures found in the cover rocks in Dutchess County. The route and stops are identified in Figure 3.

Finally we would like to thank John Rodgers who first introduced us in the 1960's to the "chicken and egg argument" regarding the role of metamorphism in controlling of styles of deformation in basement rocks. We are not certain which one is the egg in this case, but it seems clear that the form and style of the structures and the metamorphic patterns are interrelated in a very complex fashion.

Regional geology

Middle Proterozoic gneiss that was strongly deformed and metamorphosed to hornblende or pyroxene granulite grade during the 1,000 Ma. "Grenville event" constitute the core of the Hudson Highlands and the basement (Fordham Gneiss) of the Manhattan Prong. Late Proterozoic, largely undeformed metadiabase dikes locally provide good strain markers within the basement. Lower Cambrian through Middle Ordovician cover sequence rocks locally are preserved as infolds within the Hudson Highlands, providing additional information for estimation of Paleozoic folding and metamorphic grade of remetamorphism of the basement rocks. The cover sequence in ascending order consists of: Lower Cambrian Poughquag Quartzite, Lower Cambrian through Lower Ordovician Wappinger Group (dolostone and limestone), Middle Ordovician Walloomsac Formation, (carbonaceous schist, quartzite and aluminous schist) and rocks of the Taconic allochthons (aluminous schist and phyllite) ranging from Late

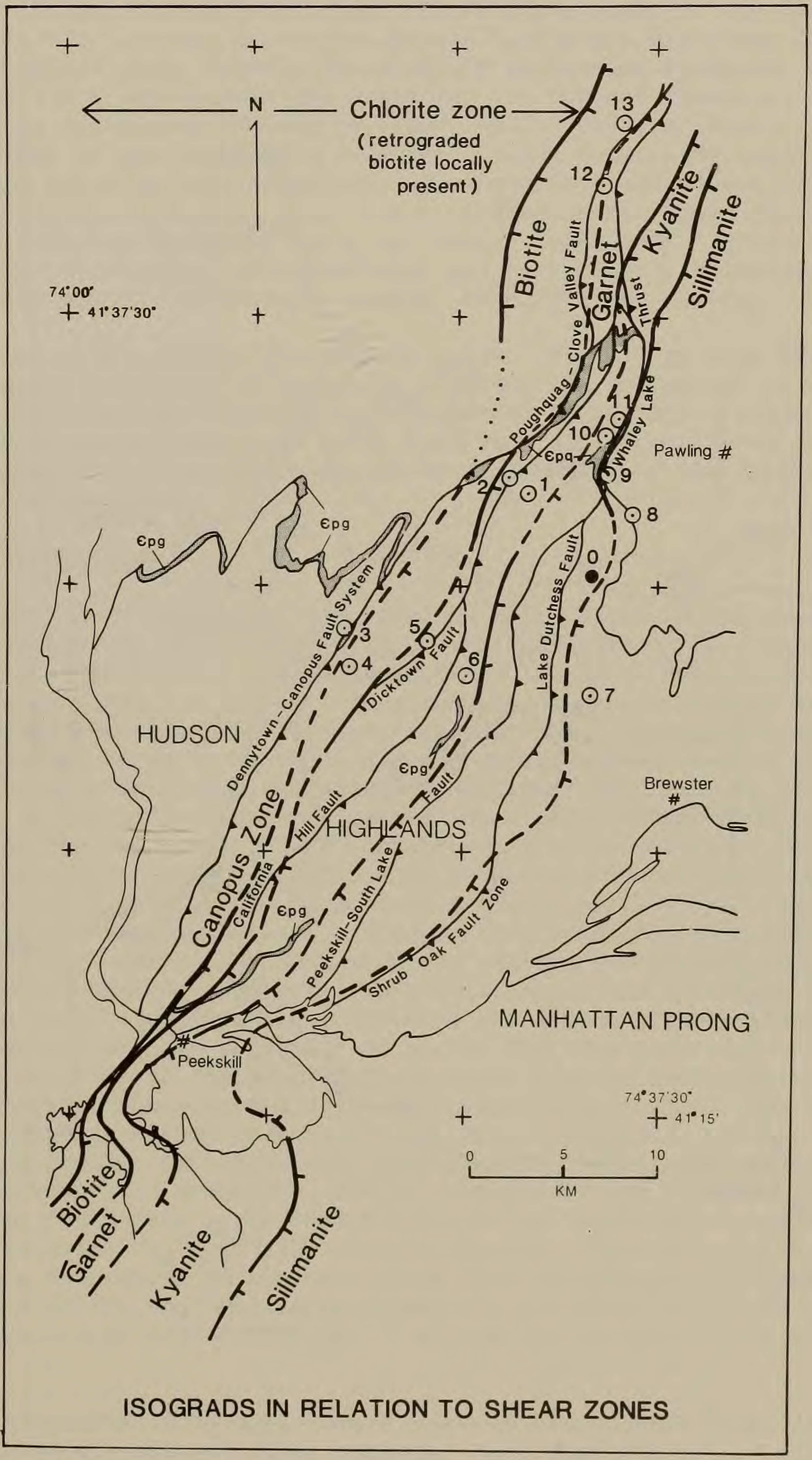


Figure 2 Simplified regional map showing isograds of Taconic age in relationship to shear zones in basement and cover rocks.

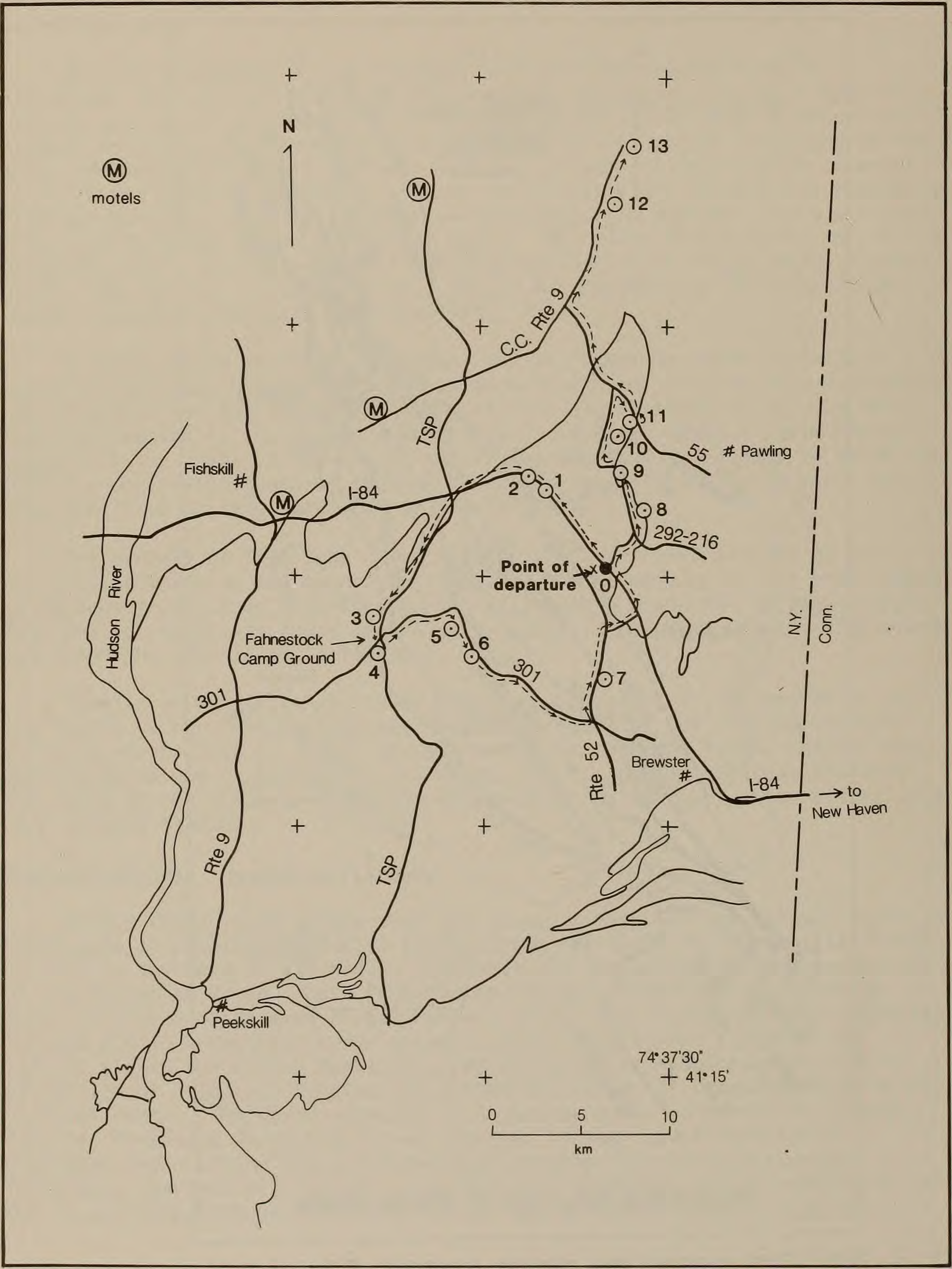


Figure 3 Route of field trip and stops.

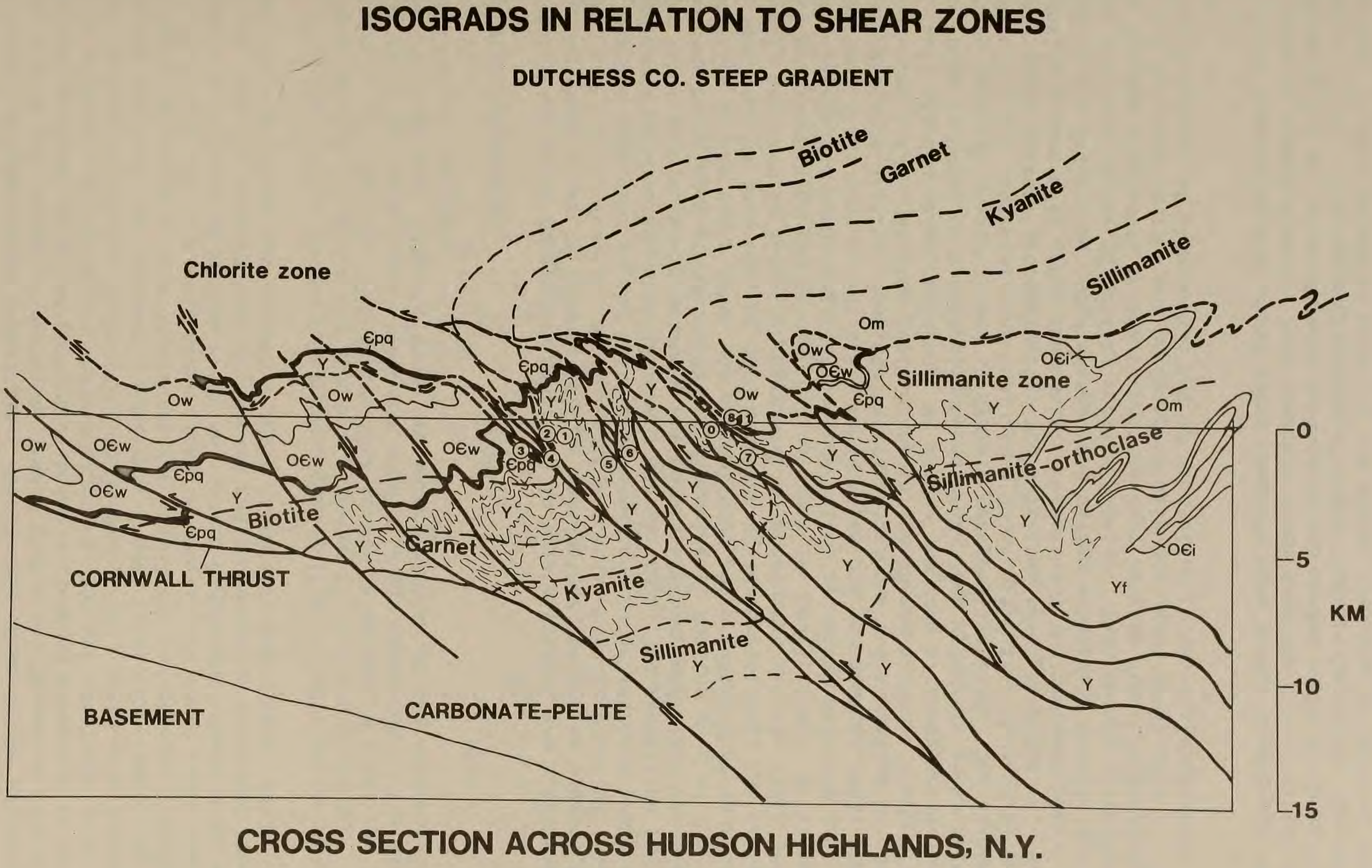
Proterozoic through Middle Ordovician. Correlative rocks of the Manhattan Prong consist of: Lowerre Quartzite, Inwood Marble and Manhattan Schist. The Manhattan contains units correlative with the Walloomsac Formation as well as several possibly allochthonous units similar to, but not identical with rocks of the Taconic allochthon (Ratcliffe, 1968, Hall, 1968). Plutonic igneous rocks and dikes of the Cortlandt, Rosetown, Croton Falls, and Peach Lake intrusives of probable Late Ordovician age (Ratcliffe and others, 1983) crosscut schistosity and Paleozoic shear zones in metamorphic cover rocks and basement in both the Manhattan Prong and Hudson Highlands. These rocks were intruded into the already highly deformed and tectonically thickened basement rocks near the end of the Taconic orogeny (Ratcliffe and others, 1983).

Formlines within Middle Proterozoic gneiss (Fig. 1) outline the attitude of the prominent foliation and gneissic layering (F_2 foliation) of the Proterozoic deformation. Discontinuities marked by mylonitic rocks are identified as solid heavy lines with teeth that show dip direction of the shear zones. Section A-A' (Fig. 4) shows our interpretation of the relationship of shear zones to isograds.

Structural Terminology

Fault and fault zone rocks described in this guidebook are classified using the terminology of Sibson (1977). Semiductile faults, as opposed to brittle and ductile faults, are faults in which discrete dislocation is discernible and both ductile and brittle deformation characteristics are present as expressed by minerals with different ductilities. The protoliths for all of the fault-zone rocks in basement are moderately coarse-grained gneisses, containing hornblende-granulite-facies assemblages, but the bulk of the deformation in the shear zones was accomplished under metamorphic conditions much less intense than that of the formation of the protoliths. At low grades (chlorite and biotite zone) retrogression is pronounced and the final products are fine-grained diaphthoritic mylonites, that is, phyllonites. At higher grades, (garnet to kyanite grade) protomylonite, mylonite, mylonite gneiss and ultramylonite are common. At sillimanite grade coarser-grained fault rocks marked by coarse biotite, complete recrystallization and annealing of quartz ribbons, and triple-junction grain contacts are common although the unmistakable fault structures are present. We prefer the term blastomylonite for these rocks in order to distinguish these rocks from mylonitic rocks that preserve subgrain shapes formed by dynamic recrystallization. The sequence of fault-zone rocks described here thus range from phyllonite, through mylonitic gneiss, augen gneiss, protomylonite, and mylonite, to blastomylonite. With increasing metamorphic grade the ductile response of the basement rocks increases and fault-zone rocks change from having relatively brittle deformation characteristics to totally ductile fabrics. This change in structural style becomes pronounced in the transition zone between staurolite-kyanite zone and sillimanite zone and corresponds with the onset of dynamic recrystallization of plagioclase and of microcline in quartzofeldspathic rocks.

Folds associated with shear zones commonly have curved hingelines, and are purse-or sheath-shaped. They commonly pitch down the dip of either the schistosity "s" or "c" surfaces. Such folds are termed reclined folds (Rickard, 1971). The reclined nature of these folds is important because the hingelines in many exposures parallel the strong lineation or mullion struc-



ISOGRADS IN RELATION TO SHEAR ZONES

DUTCHESS CO. STEEP GRADIENT

CROSS SECTION ACROSS HUDSON HIGHLANDS, N.Y.

Figure 4 Generalized cross section along approximate line of section A-A' in Figure 1, showing regional shear zones in relationship to isograds. Cross section was prepared from an earlier version of the map (Fig. 1), and contacts do not all agree precisely. Approximate locations of field trip stops are shown.

ture in the mylonite zones interpreted as the elongation lineation.

Textures seen in outcrop and in thin section are: "s", a schistosity axial planar to folds in the protolith near shear zones; "c", shear or mylonitic foliation parallel to the mylonite zones; and "sb", shear bands expressed as spaced dislocations in the mylonitic "c" fabric. Larger augen or porphyroclasts, principally of K feldspar, commonly show excellent retort structure in which tails of recrystallized materials or metamorphic products of the augen define the sense of displacement. Plagioclase crystals in some exposures exhibit brittle fracture, and "card deck" displacements, in which microdisplacements have a sense reversed to that of the bounding shear zone. These textures and structures and their kinematic significance are neatly described by Simpson and Schmid (1983). Photomicrographs are given in Plates 1-5.

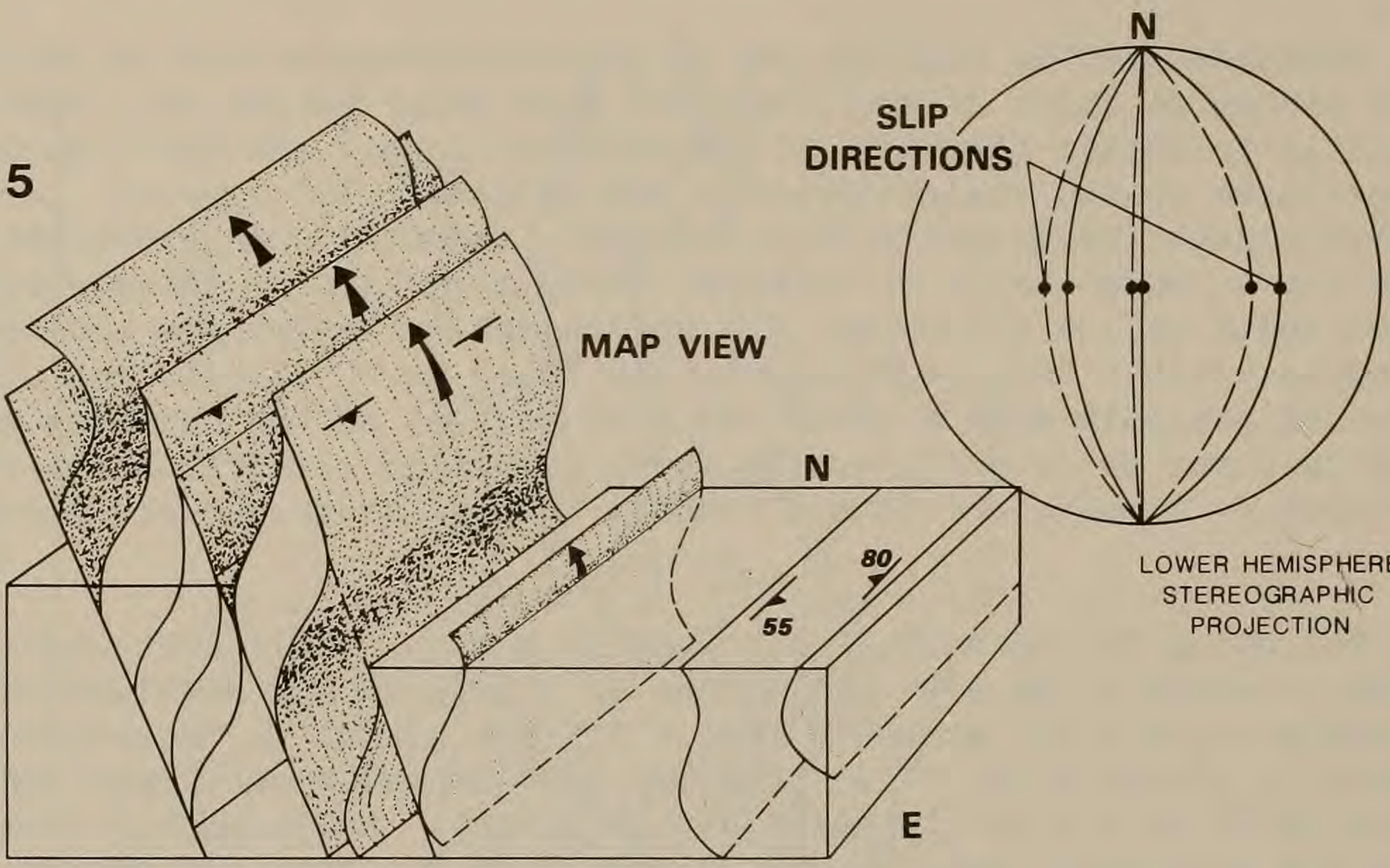
Following the techniques outlined by Hansen (1971) the rotation sense and plunge of minor folds with amplitudes of 1 to 2 cm and wavelengths less than a centimeter within the mylonite fabric "c" are useful in determining tectonic transport. These minor folds commonly have curved hinge lines and are minor sheath folds as originally described by Hansen. Measurements from narrow zones are consistent and repeatable resulting in unusually narrow separation angles. Treatment of larger amplitude folds across an outcrop is less useful. The strong lineation on the mylonite surfaces, i.e. within the "c" surfaces, are rods or mullion-like structures related to the intersection of "c" and "s" or "sb" and are substantially parallel to the slipline as determined from the separation-angle technique.

Throughout the area samples of phyllonite and mylonite from shear zones were collected and sectioned in a direction normal to "c" and parallel to the strong elongation lineation, and in a section normal to the lineation. The growth fabrics of fault minerals and protolithic minerals were noted. The results indicate that $2M_1$ muscovite, chlorite and epidote grew in low grade rocks, followed by biotite, garnet, hornblende, staurolite-kyanite and finally by sillimanite, with microcline, and muscovite. The minerals are progressively stable within the shear zones (in rocks of suitable composition) in a zone approximately colinear with the mineral zonation in Paleozoic cover rocks of Dutchess County (Vidale, 1974a, b) Bence (in Bence and McLelland, 1975), and in the Manhattan Prong (Ratcliffe and others, 1983).

Description of the shear zones

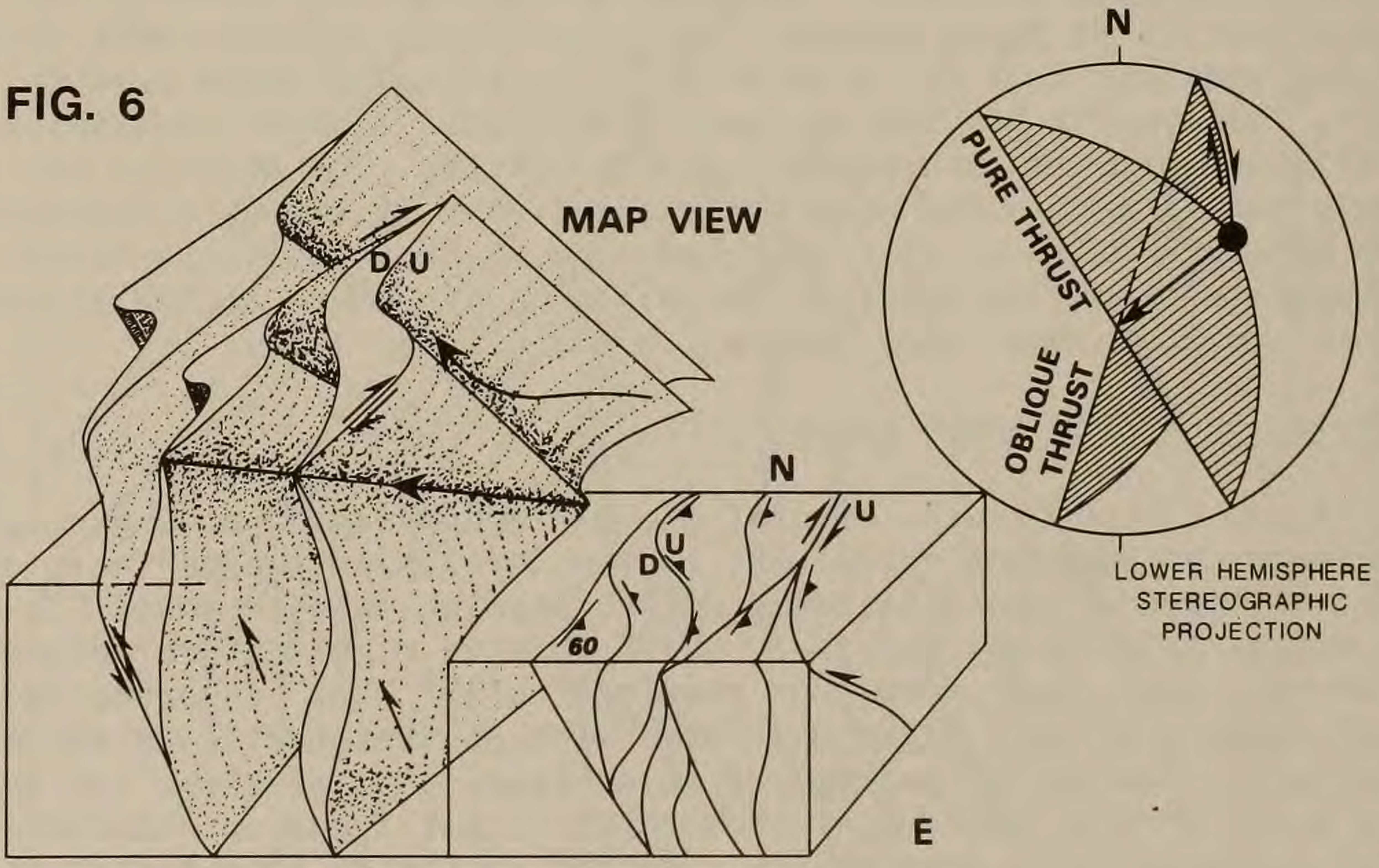
A ten-kilometer-wide zone of closely spaced anastomosing shear zones transects the basement rocks east of the Dennytown-Canopus fault system (Fig. 1) based on our detailed 1:24,000 mapping. Shear zones 0.5 meter to 100 meters thick trend N-S to N. 40° E forming right-lateral sigmoidal patterns. Dips range from near vertical to 45° S.E. In cross section the shear zones also have sigmoidal forms with southeast-side-up sense of displacement. The entire package of shear zones is limited at its upper surface by a major thrust, the Whaley Lake thrust, that transports inverted Paleozoic cover-sequence rocks over gneiss. To the southeast this thrust is traceable to the area of the Towners thrust (Fig. 1). The floor of the package is the Canopus-Dennytown fault system that can be traced northward into the Poughquag-Clove Valley fault that places cover sequence rocks at garnet and higher grade over carbonate rocks of the Wappinger Group. The assemblage of

FIG. 5



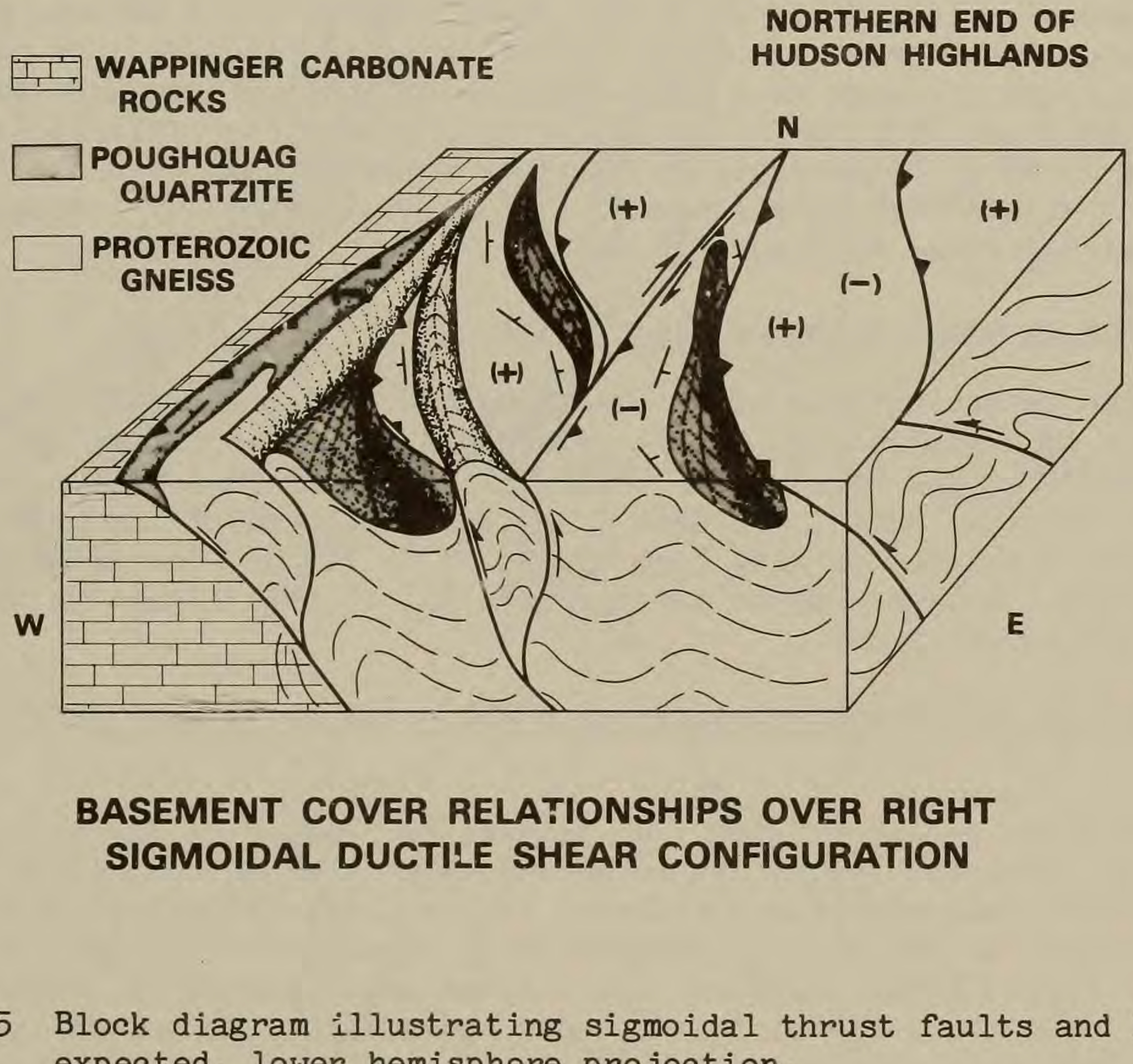
SIGMOIDAL THRUST FAULT CONFIGURATION OF DUCTILE SHEARS (SLIP DIRECTION UP-DIP)

FIG. 6



OBLIQUE THRUST FAULT CONFIGURATION OF DUCTILE SHEARS (SLIP DIRECTION, OBLIQUE RIGHT-SLIP)

FIG. 7



BASEMENT COVER RELATIONSHIPS OVER RIGHT SIGMOIDAL DUCTILE SHEAR CONFIGURATION

Figure 5 Block diagram illustrating sigmoidal thrust faults and lineations expected, lower hemisphere projection.

Figure 6 Block diagram illustrating oblique-thrust faulting and lineations expected on pure thrusts and oblique-thrust fault segments of sigmoidal faults, lower hemisphere projection.

Figure 7 Relationship of folds in cover sequence and basement within blocks between shear zones.

shear zones can be viewed as floor and roof of a complex duplex system with intense internal deformation. The Poughquag Quartzite at the base of the cover sequence is preserved in a series of fault-bounded synforms that record the passive style of the thrust-related folding.

The block diagrams in Figures 5, 6, and 7 portray conceptually the relationship of the semiductile shear zones to the folds in the cover sequence. In Figure 5 the map and cross section of normal thrust ramps are portrayed anc the elongation lineations (mullions and sliplines) expected illustrated. In Figure 6 shear zones having sigmoidal plan views as well as cross-section forn are illustrated. Slip directions for such faults are illustrated. This pattern is thought to represent the Hudson Highlands shear zones. Folding of the cover sequence into synforms formed over basement rocks deforming by such a sigmoidal oblique-thrust pattern is illustrated in Figure 7. Of particular note is the trend of folds in a more northwesterly direction than the trace of the master shears. The complex series of mylonite-related foliations and folds might normally be ascribed to multiple deformational episodes F_1, F_2 etc. but we believe that they are more logically explained by a single fold-thrust model described by Figures 6 and 7.

Sliplines and movement sense of shear zones

Slipline determinations after the technique of Hansen (1971) show a slip direction of approximately N. 77° E. regardless of the strike of the shear zone, showing that the curvilinear traces of the shear zones are primary rather than folded. Additional data from west and south of the area shown in Figure 8 show sliplines ranging from due E. to N. 70° E. The lineations mapped by Balk (1936) are approximately parallel to this lineation and date from the fold-thrust event.

Relationship of fold-thrust structures to folds and foliations in the cover rocks

The fold and thrust fabrics, and lineations related to the shear zones, represent at least the second dynamothermal event seen in the Paleozoic rocks (Fig. 9). Cover-sequence rocks attached to the basement gneiss contain a strong foliation or schistosity substantially parallel to bedding and contain beds highly folded about recumbent to inclined axial surfaces. These first generation folds are deformed in the shear zones into tight second generation S_2 folds. Similarly, cover rocks above the Whaley Lake thrust contain folds and schistosity older than the thrust fabric. Near thrust faults the structural overprinting by the S_2 (thrust-related) fabric is strong. This post-schistosity fabric continues northward into the cover-sequence rocks east and west of Clove Valley, where it is expressed locally by zones of phyllonite.

Metamorphic assemblages in shear zones and regional isograds

Previous workers do not all agree on the location of metamorphic isograds. Vidale (1974a, b) moved Barth's (1936) isograds further west than previously shown but Bence's isograds (in Bence and McLelland, 1976) differ markedly from Vidale's results. Additional data and reexamination of all of Vidale's thin sections has resulted in a minor modification (Fig. 9). Biotite first occurs west of Clove Mt. in the Pleasant Valley quadrangle as sporadically developed small crystals growing across a foliation but almost always

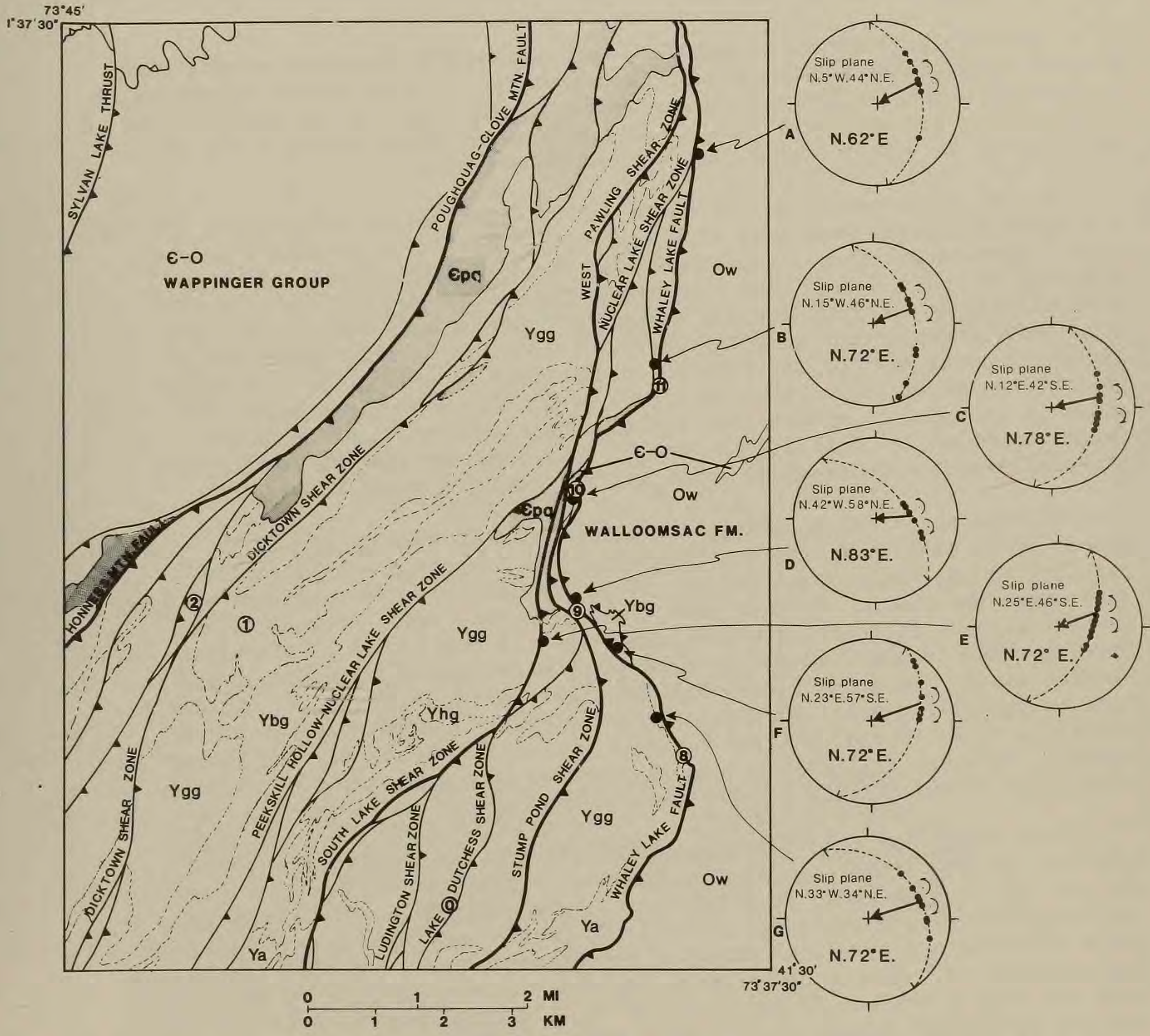


Figure 8 Generalized geologic map of the Poughquag Quadrangle showing slipline determinations from shear zones, outlines of marker units in Middle Proterozoic basement rocks, and field trip stops. Key to symbols: Ya, amphibolite, Ygg, granitic biotite gneiss, Ybg, biotite feldspar gneiss and paragneiss, Єpq, Poughquag Quartzite, Є-O, Wappinger Group, Ow Walloomsac Formation.

partially retrograded by a later foliation (Vidale, 1974a). East of Clove Valley two generations of biotite are widely developed: (1) as large post-schistosity (S_1) non-oriented porphyroblasts that include schistosity and (2) as small, fine-grained crystals intergrown with muscovite and/or chlorite or as small isolated flakes in a second- generation foliation associated with S_2 shear zones.

Chloritoid is strongly dependent upon the highly aluminous composition present only in the Taconic allochthonous rocks. It also occurs sporadically as post-S_1 crystals that are retrograded in S_2 in rocks at the northern end of Clove Valley and along the foot of East Mountain. Above garnet grade chloritoid occurs as robust post-S_1 and as post-S_2 crystals.

Garnet first occurs at the north end of Clove Valley in isolated outcrops and again along the west foot of East Mountain east of a prominent S_2 shear zone. Garnets are compositionally zoned (Bence and McLelland, 1976) and euhedral in rocks west of the Pleasant Ridge shear zone, but east of this, in staurolite-zone and higher grade rocks, have deeply corroded cloudy cores and clear but irregular overgrowths. Garnet is post-S_1 in most exposures but is syn-S_2 in rocks east of the Pleasant Ridge shear zone (Fig. 9). Although the staurolite isograd appears to be offset by the Pleasant Ridge shear zone, tiny euhedral staurolite, garnet and biotite appear as syntectonic minerals in S_2 fabric in mylonite of this shear zone. This suggests that synmetamorphic recrystallization accompanied rapid uplift along the shear zone.

Sillimanite first occurs as fibrolite tails on kyanite kinked in S_2 shear zones, or on biotite in the same fashion. The isograd for sillimanite, parallel to the Whaley Lake thrust, is controlled by these reactions in S_2 just above the fault. Further east, away from the fault, staurolite and kyanite without fibrolite are widely present. A small area of fibrolite-bearing rocks is also present in strongly sheared kyanite-staurolite and kyanite schist along the Pleasant Ridge shear zone. On Figure 9, the deflection in the sillimanite isograd is produced by the preferential growth of fibrolite in Walloomsac schists having a strong S_2 fabric near the Whaley Lake thrust. Here the sillimanite isograd may have been controlled kinetically by conditions in the dynamically recrystallizing rock.

From west to east in the basement rocks muscovite, epidote, chlorite, biotite, garnet, tremolite-talc, hornblende, staurolite, kyanite, sillimanite and microcline have grown in shear zones. Clear growth in the elongation direction indicate syntectonic crystallization in many specimens. Based on these observations re-metamorphism of the basement rocks and shearing were contemporaneous. In the cover rocks the observations differ. S_2 shear zones with the same prominent N. 70° to N. 80° E. lineation are retrogressive and destroy previously formed biotite in areas west of Clove Valley and along the base of East Mountain (Stops 12, 13, Fig. 9). Rocks in the highlands on East Mountain and cover rocks south along the Whaley thrust contain clear indications of syntectonic thrusting and crystallization of sillimanite, kyanite, staurolite and biotite and garnet.

Mineral assemblages within the cover rocks affected by the shear zones indicate that the isograds for staurolite, kyanite and sillimanite trend more northeasterly than the shear zones (Fig. 9). However, mineral assemblages and growth fabrics indicate peak temperature assemblages are shared between foot-

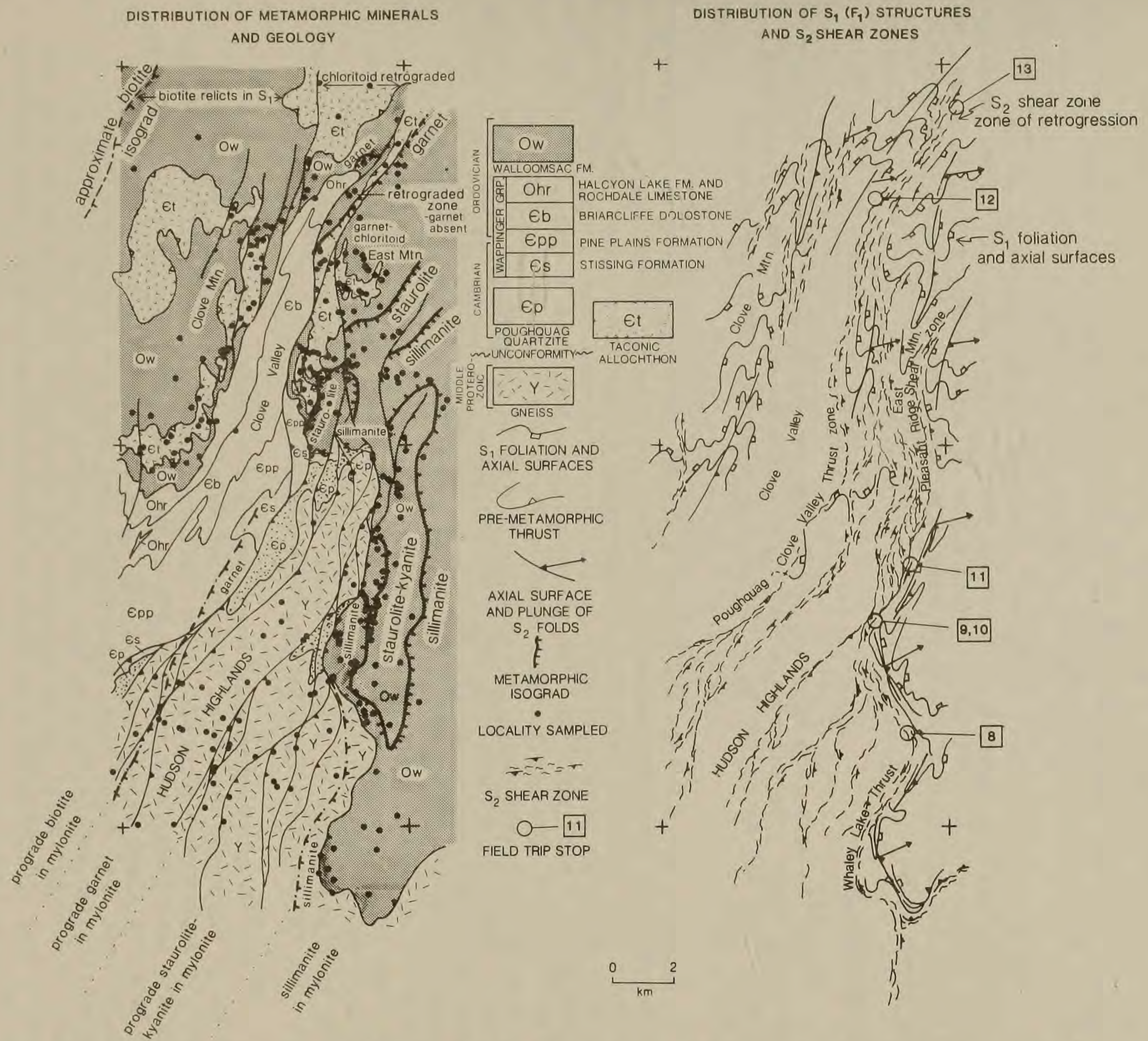


Figure 9 Generalized geologic map of the Verbank and Poughquag Quadrangles showing S_2 shear zones in cover rocks, metamorphic isograds, and pockets of relict (pre-S_2) minerals. Isograds have tick marks on higher temperature side.

wall and hanging wall blocks of the shear zones at high grades. The mineral data therefore suggest that the peak metamorphic conditions in the high grade rocks formed synchronous with the semiductile faulting but that similar-style S_2 faulting postdated peak conditions in the lower- temperature cover rocks, along the Poughquag-Clove Valley fault (Fig. 9) and to the west. Examination of the cross section along line A-A' (Fig. 4) shows that the metamorphic zonation from biotite to sillimanite is too narrow, less than 5 km wide (Fig. 9), to be accounted for by shallow-dipping regional isothermal surfaces, and steeply inclined isograds are required. The close correspondence between index minerals in the cover rocks and the shear zones in the basement rocks suggests that the isogradic surfaces were deformed by the same episode of ductile deformation that produced the shear zones in the basement.

The model we propose, therefore, involves thermal weakening of the quartzofeldspathic basement rock during the M_1 event, uplift by formation of shear zones, strain softening, acceleration of this uplift, and final upward and westward movement of the core rocks and Barrovian assemblages contained in the cover rocks.

Geochronology

^{40}Ar/^{39}Ar data from biotite, muscovite, and hornblende from the basement and cover rocks affected by the Barrovian gradient described here yield ages ranging from 465 Ma to 370 Ma. (Bence and Rajamani, 1972; Dallmeyer and Sutter, 1976).

Basement rocks across the Hudson Highlands have been unevenly retrograded in the Taconic dynamothermal events to form new mineral assemblages. Petrographic data indicate that this retrogression is most pronounced near shear zones. Enclaves of non- or only partially-retrograded rocks exist between the shear zones. K-Ar and ^{40}Ar/^{39}Ar geochronologic data from biotite, hornblende ^{40}Ar/^{39}Ar ages from the northern Reading Prong and areas within the overprinted areas to the north are shown on Figure 10 (reproduced from Sutter and others, 1985). Included are data from Dallmeyer and Sutter (1976), Bence and McLelland (1976) and a new biotite plateau age of 436 ±3 Ma from the California Hill shear zone near Stop 6. Sample 11HP was taken near stop 2, 512 BP at stop 11; and 179 BP from cover rocks on East Mountain near stop 12. The biotite sample in the California Hill shear zone was collected from an area where protoliths adjacent to the shear zone yield hornblende and biotite plateau ages of 913 and 710 Ma, and conventional K-Ar ages on biotite are 800 Ma (Dallmeyer and Sutter, 1976 Figure 1).

^{40}Ar/^{39}Ar plateau ages of hornblende and biotite between 470 and 377 shown in Figure 10 have been interpreted as cooling ages from a 460-470 Ma, Taconic metamorphic plutonic event (Dallmeyer and Sutter, 1976). The biotite plateau ages from cover rocks at 444 ±3 Ma (staurolite-kyanite grade), of 418 ±5 Ma at sillimanite grade, and a 436 ±3 Ma at staurolite-kyanite grade (California Hill shear zone) support the idea that the remetamorphism and mylonitization are of Taconic age. The regular increase in grade eastward found within the shear zones reported here reinforces the conclusion that the shear zones and deformation related to them are Taconic rather than Acadian or younger.

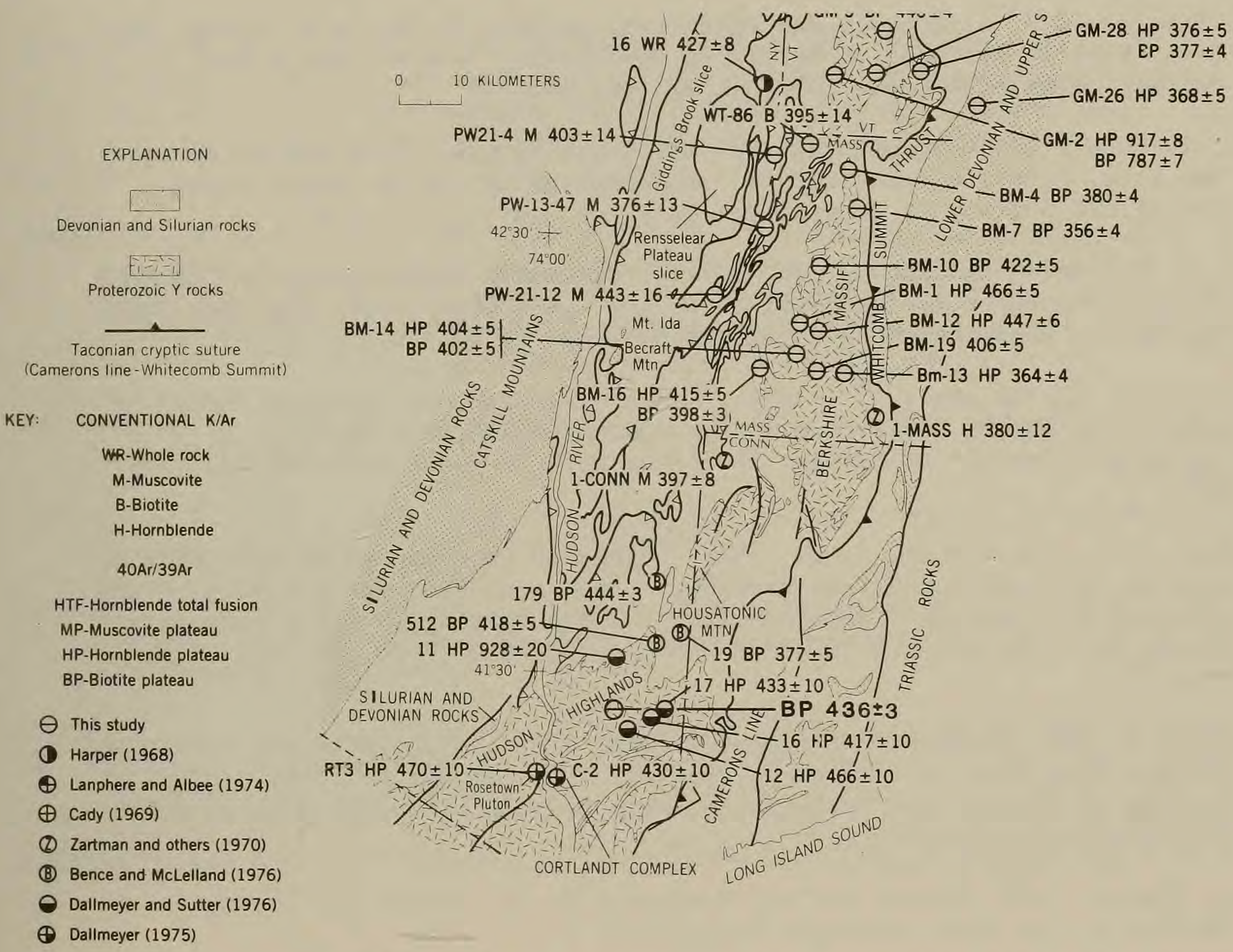


Figure 10 Selected $^{40}Ar/^{39}Ar$ data from northern end Hudson Highlands and western New England, reproduced from Sutter and others (1985), where references not referred to in this paper may be found.

Summary and tectonic setting

The structural evolution of this area is intimately related to the thermal history that accompanied dynamothermal metamorphism in the closing stages of the Taconic orogeny. Previous studies to the south, near the Cortlandt complex, and to the north in the Berkshires of Massachusetts have shown that an episode of ductile faulting on imbricate thrust slices was coincident with peak dynamothermal metamorphism about 460-470 Ma (Sutter and others, 1985, Ratcliffe and others, 1983). Stanley and Ratcliffe (1985) have related this event to tectonic thickening of sialic crust beneath an east dipping collisional margin. The remetamorphism of the basement rocks, formation of the shear zones and ductile remobilization formed during this Late Ordovician event.

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Plates - Photomicrographs of shear zone rocks

The following plates contain photomicrographs of thin sections of shear-zone rocks arranged in order of increasing metamorphic grade. Each is approximately 1 cm across, taken in plane polarized light except where crossed nicols noted. References to Plates indicated in margin of road log as: Pl. 1A to read see Plate 1A.

Plate 1. Chlorite and biotite zone phyllonites from Dennytown-Canopus fault system, Stops 3 and 4.

A. Phyllonite from Proterozoic quartz plagioclase gneiss, Stop 3, section parallel to strike, N.E. at top, S.E. at right, matrix fine grained muscovite, epidote, chlorite, quartz and albite, biotite is shredded and replaced by muscovite, chlorite and opaques, clear sigmoidal flamboids of strained quartz, crossed nicols.

B. Mylonitic Poughquag Quartzite, Stop 3, section parallel to strike, N.E. at top, S.E. to right, strained quartz pebbles show right sigmoidal shapes, matrix fine-grained muscovite, chlorite and quartz, crossed nicols.

C. Phyllonite, Stop 4, Canopus shear zone near T.S.P., down dip section, top up, S.E. top right, clear areas folded quartz ribbons consisting of dynamically recrystallized subgrains in a matrix of muscovite, epidote, quartz and new biotite, relict Proterozoic biotite (dark spots) is shredded.

D. Biotite-rich mylonite in Dicktown fault near Stop 5, horizontal section N. at top, E. at right, mylonitic foliation "c" consists of fine biotite, epidote, albite and muscovite, largely from breakdown of original plagioclase in gneiss, garnet in quartz ribbons are fractured, pulled apart and retrograded to chlorite. N. 50° E. shear bands show right-lateral component.

Plate 2. Biotite and garnet grade mylonite of the Dicktown and California Hill fault zones.

A. Horizontal section of biotite-oligoclase-rich mylonite of California Hill fault showing right-lateral quartz, oligoclase tails on a large oligoclase porphyroblast, sigmoidal mylonitic "c". N.E. at top, S.E. at right. Biotite from this rock yielded 436 ± 3 ^{39}Ar/^{40}Ar plateau age (Sutter, personal communication, 1982).

B. Vertical section parallel to rods in muscovite mylonite, Stop 2, S.E. to right, showing brittle fracture of plagioclase and microcline in a matrix of ductile quartz, muscovite, biotite, epidote; ribbon of quartz are polygonized. Euhedral garnet present in some samples from this outcrop, garnet isograd.

C. Vertical section parallel to rods of vertically dipping mylonite in South Lake shear zone near Stop 0, vertical mylonitic foliation top left to lower right corner. Sigmoidal mylonitic foliation shows up from the west sense of motion, matrix, muscovite, biotite and dynamically recrystallized quartz, plagioclase, microcline, and tiny euhedral garnet. (Upper garnet to staurolite-kyanite zone.)

D. Horizontal section of augen gneiss in Nuclear Lake shear zone near Stop 11, showing right-sigmoidal "c" foliation, crosscutting shear bands "sb", N.E. at top, S.E. at right, matrix muscovite, biotite, and dynamically recrystallized plagioclase, microcline and quartz staurolite-kyanite zone.

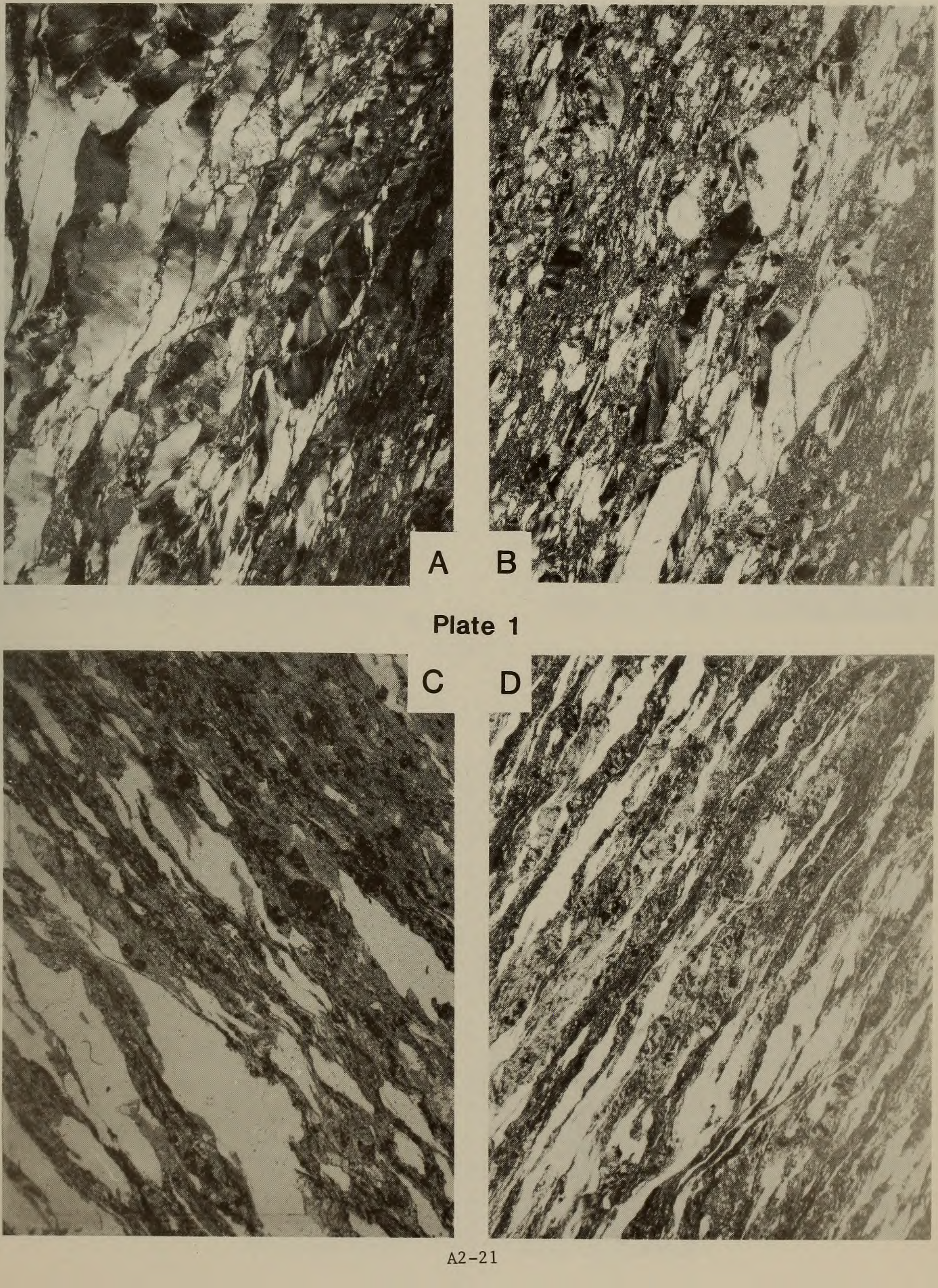

Plate 1

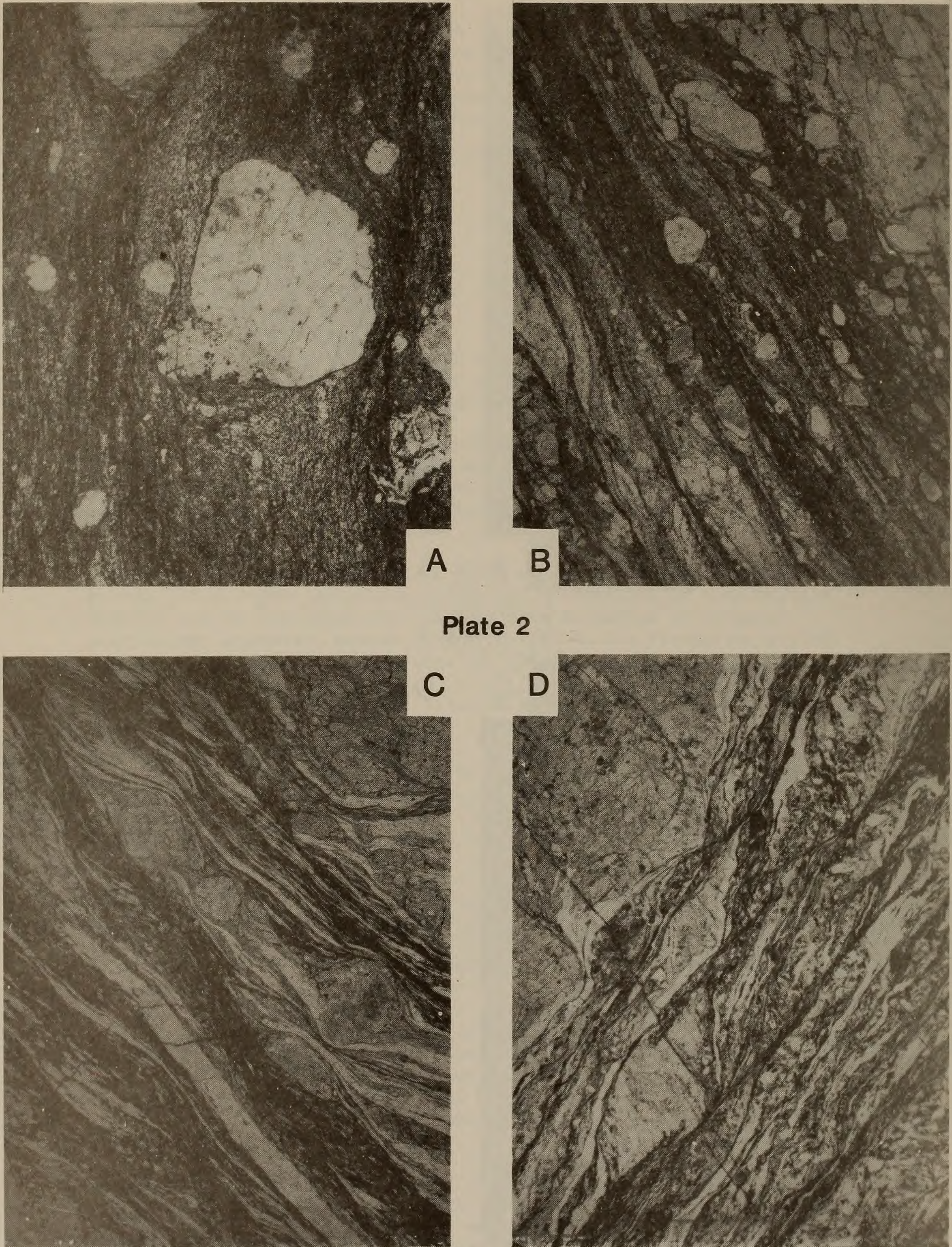

Plate 2

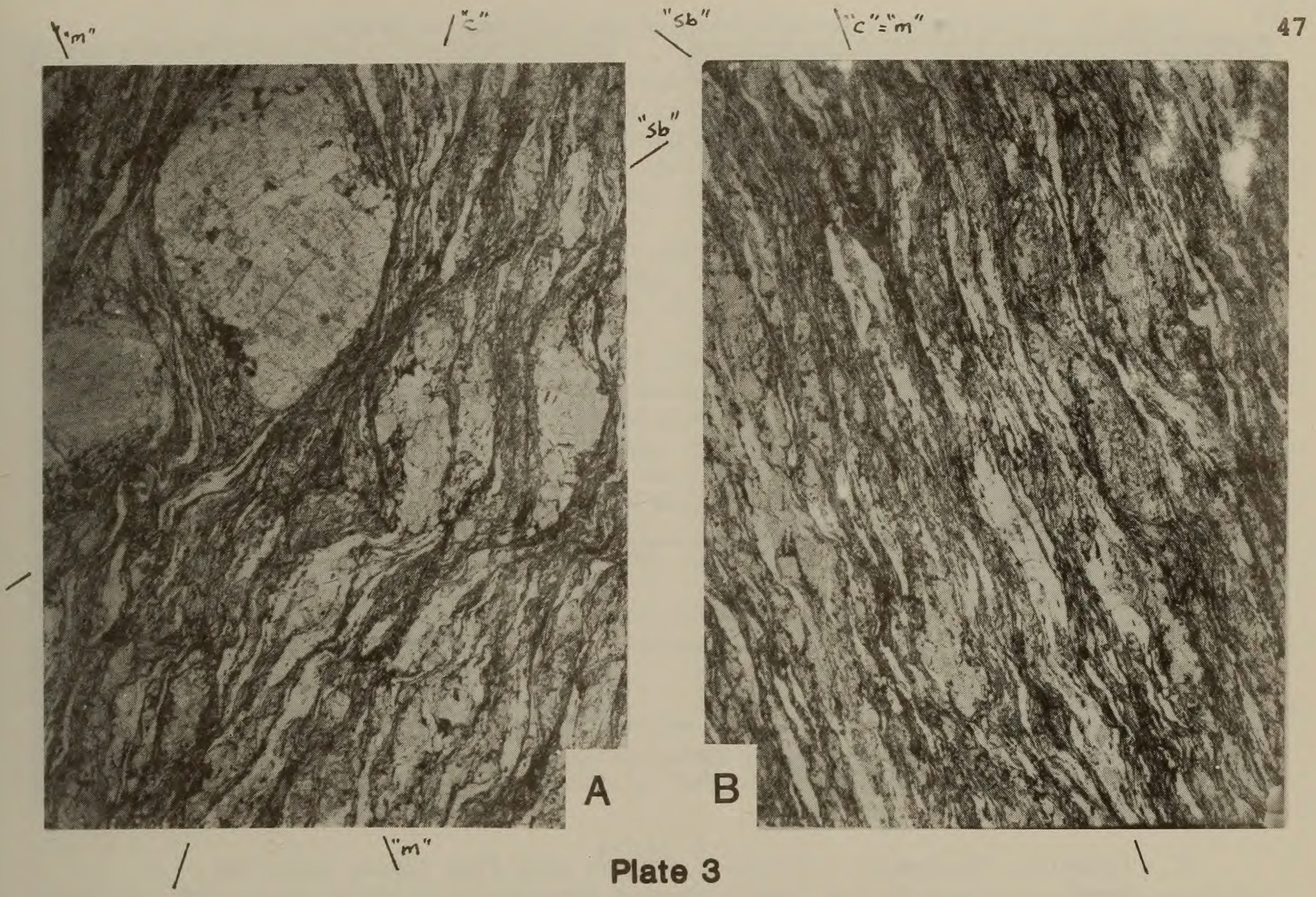

Plate 3

Plate 3. Mylonites (staurolite-kyanite and sillimanite grade).

A. Augen gneiss, Stop 10, cut parallel to strike, N.W. at top, N.E. to right. Mylonite matrix muscovite, biotite, plagioclase, microcline surrounding augen of microcline-perthite, ductile flamboids of quartz have annealed texture. Small plications suggest shortening perpendicular to "s", right-lateral sigmoidal "c", and shear bands "sb".

B. Vertical section parallel to rods, in same rock as A, clear area polygonal quartz in flamboids, microcline light grey, plagioclase clear, biotite and muscovite define "c" and "s", N.E. to right.

C. Vertical section parallel to rods, blastomylonite at Stop 7, E. to right, ramp structures defined by dynamically recrystallized quartz microcline (grey), and plagioclase with annealed polygonal quartz, muscovite and biotite define schistosity. The loss of all brittle deformation characteristics marks the change to completely ductile, penetrative deformation of the basement gneiss at the kyanite- sillimanite transition.

Plate 4. Structures in cover rocks. Whaley Lake thrust.

A. Biotite, garnet, plagioclase, fibrolite, quartz Walloomsac schist with strong S_2 folds and fibrolite growing in S_2 subparallel to thrust. E. to right. Stop 11.

B. Mylonite in Walloomsac, 6 cm above contact with mylonite gneiss Stop 11, vertical section parallel to rods, and S_2 hinges, polygonal quartz in ribbons, ramp faults, and "augen" of coarse M_1 biotite with syntectonic tails of fine biotite in S_2.

C. Mylonitic Walloomsac 1 cm above contact with Pine Plains Formation, Poughquag-Clove Valley fault, showing shredded M_1 biotite and muscovite-rich mylonite, thrust direction from right (N.E.) to left (S.W.).

D. Mylonite in Walloomsac at staurolite grade along Pleasant Ridge fault, section perpendicular to hingelines of S_2 folds, matrix contains tiny euhedral staurolite, garnet, biotite and muscovite; synmetamorphic thrust fabric.

Plate 5. S_2 fabrics in cover rocks, Stops 12-13.

A. Mylonitic Walloomsac at north end of Clove Valley near Stop 12, showing shredded M_1 biotite in retrogressive matrix of muscovite, chlorite and calcite, horizontal section.

B. Phyllonitic Taconic rocks at Stop 13, horizontal section showing low angle intersecting shears. Biotite and muscovite in S_2, parent rock may have had small garnets--like C below.

C. Euhedral small garnet, ilmenite, biotite, plagioclase, muscovite, chlorite quartz schist, Stop 12, showing ilmenite oriented in S_2, and locally bent where passing from garnet into S_2 matrix, where S_2 shearing is strong, near top, matrix is chlorite-rich and resembles D below.

D. Mylonitic muscovite, chlorite quartz S_2 phyllonite from same outcrop as C; matrix is rich in chlorite and iron-stained chlorite or stilpnomelane, no garnet or coarse grained muscovite present in C remains. Interpreted as a rock retrograded from C along S_2 fabric.

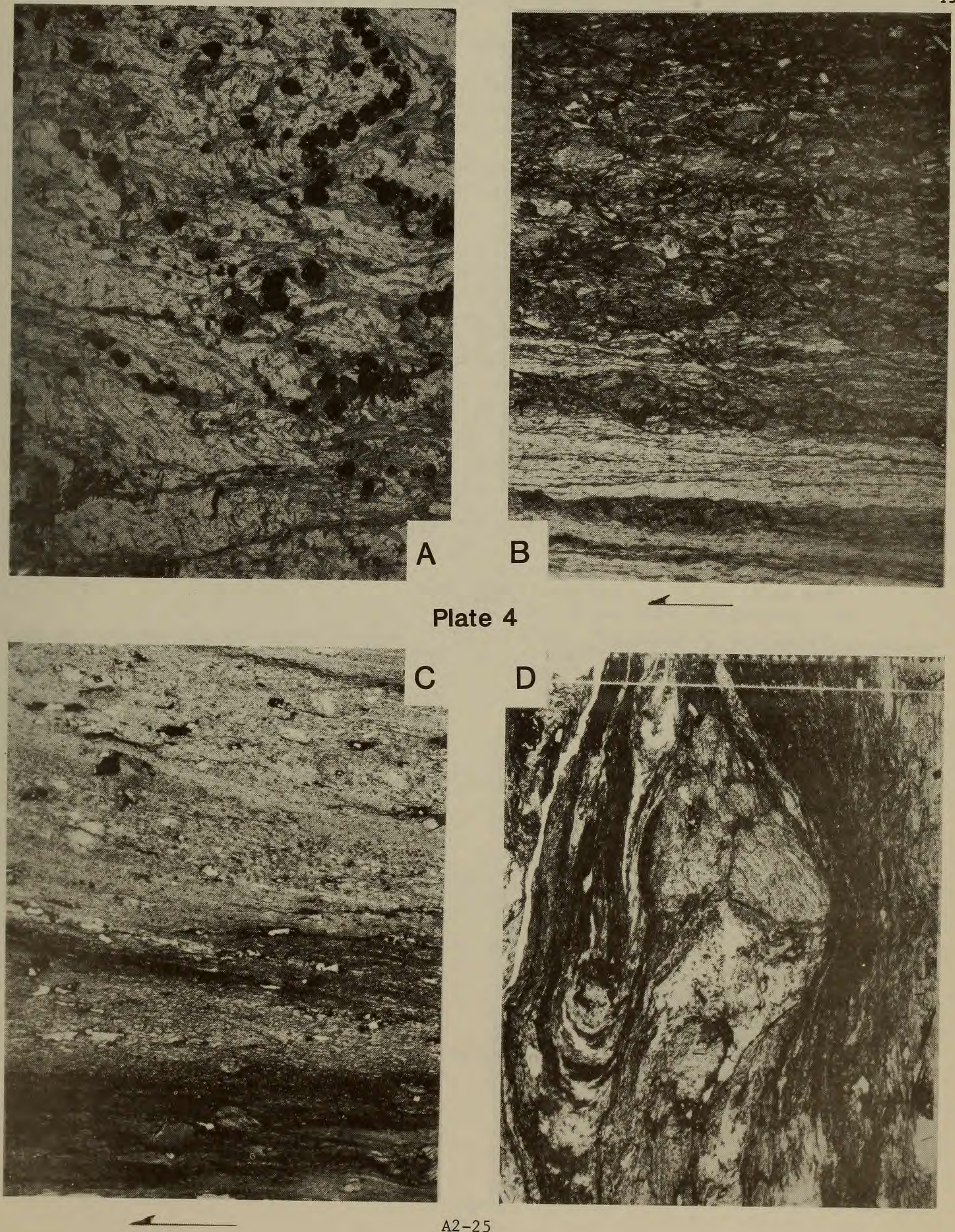

Plate 4

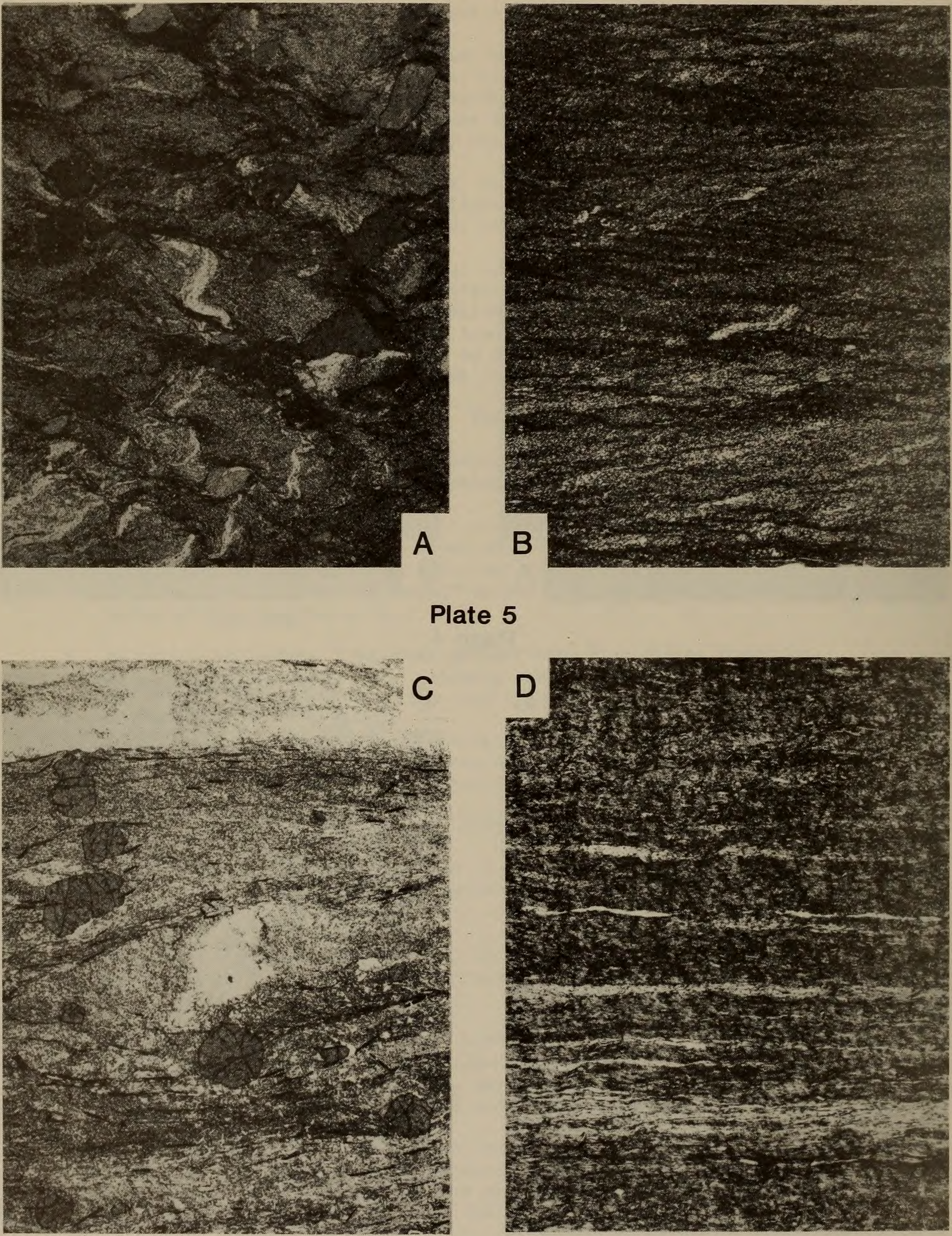

Plate 5

Road log (see Plates for photomicrographs)

(For route and stop locations refer to Figure 3.)

Starting point: entrance ramp to westbound lane of I-84 (Exit 17) at Route 52, Ludingtonville, N.Y. in the Poughquag quadrangle. Introduction 8:00, leave 8:30. References to plates pertinent to Stops given in margin.

Stop 0: Introduction at first outcrops in westbound lane to I-84 at Ludingtonville, staurolite-kyanite zone, Poughquag quadrangle (Figs. 2,8) (30 min).

The trip begins within the interior of the basement massif in rocks strongly affected by Paleozoic remetamorphism. A small but well-developed shear zone in granitic gneiss and amphibolite can be seen in the north side of the entrance ramp. Strongly developed folds in gneiss and amphibolite have axial surfaces expressed by a (Pl. 3A,B) moderately strong schistosity "s" striking N-S to N.15 W. Biotite lineations plunge southeast parallel to the hinge lines of these folds. In the vicinity of the shear zone the schistosity swings into parallelism with the N. 35° E. trend of the strong "c" or shear foliation, in a right- lateral configuration. Locally shear bands trend N. 60° E. and produce microoffsets in a right- lateral sense. In vertical section, ramps indicate motion up from the southeast or east. A strong lineation plunges N. 75-80° E. in the plane of the schistosity "s" as an intersection lineation, or down the "c" surfaces, producing a mullion structure common to all mylonites in the Hudson Highlands. The structural elements seen in this small exposure are common throughout the shear zones and basement rocks in the northern end of the Hudson Highlands. At garnet grade or lower (Stops 1 and 2) the zones of strain are spaced and penetrative internal deformation by "s" is rare except within shear zones. Outcrops at this stop exhibit the type of structures illustrated by Figure 6.

Cumulative mileage

00 - head west on I-84 (Poughquag quadrangle)

1.5 - outcrops of amphibolite, rusty calc-silicate gneiss with near-vertical foliation

2.6 - well foliated grey biotite-feldspar gneiss (Ybg), minor amphibolite (Ya) intruded by biotite granite gneiss (Ygg)

3.5 - large outcrop of Ygg and Ybg -- park on entrance ramp near west end of roadcut

3.8 Stop 1:

(20 min) Middle Proterozoic granitic gneiss, biotitic feldspar

gneiss intruded by Middle Proterozoic granite, Poughquag quadrangle. This stop and the previous two large outcrops illustrate well the nature of the basement rock that is largely unaffected by Paleozoic faulting or mylonitization. This material was the protolith for almost all of the shear zones we will visit. Note the coarse grain size, the coarse gneissosity and style of the Proterozoic folds.

The roadcut exposes a suite of gneisses which are a product of partial assimilation of mafic country rock by intrusive granitic material. The darker-colored gneiss represents the relict parent material and was originally hornblende or hornblende-biotite gneiss. It contains blue-green hornblende altered to biotite, primary biotite, plagioclase and quartz. Small felsic "sweatouts" in the mafic gneiss contain equal proportions of microcline, plagioclase, and quartz.

The lighter-colored gneisses are more clearly intrusive in character and contain abundant microcline, plagioclase, and quartz. Country-rock contamination is evidenced by scattered grains of hornblende altered to biotite and badly corroded garnets. Primary biotite defines the Proterozoic gneissic foliation. A coarse-grained pegmatite appears to cross-cut the other granitic gneisses and may represent a later intrusive event.

With the possible exception of the pegmatite, strongly aligned biotite flakes in the gneisses indicate that intrusion and crystallization took place during or before formation of the dominant mid-Proterozoic gneissic fabric (F_2). This fabric is the structure outlined in Figure 1 within Proterozoic rocks. Strained quartz is common in all the rocks, and partial but widespread alteration of plagioclase and breakdown of biotite to epidote and muscovite are indications of Paleozoic retrogression. (Reboard cars and drive to extreme west end of parking lot.)

An hornblende $^{40}Ar/^{39}Ar$ incremental release age of 928 ±20 Ma (Fig. 10) has been determined from outcrops to the west on I-84.

4.1 Stop 2:

(15 min) Muscovite-rich mylonite zone in biotite-quartz-feldspar-gneiss near Dicktown shear zone (garnet zone).

(Pl. 2-B)

A 3-meter-thick muscovite-rich mylonite is exposed near the contact between biotite granitic gneiss and more plagioclase-rich biotite gneiss. This outcrop is situated within a zone of highly mylonitized and retrograded gneiss within the garnet zone of Paleozoic metamorphism. Tiny euhedral garnets, biotite, epidote and abundant muscovite characterize mylonite in this area. A short distance west mylonite zones contain Proterozoic garnets retrograded to biotite. The mylonite strikes N.30° E. and dips 74° SE., and contains a strong east-plunging rodding. Exposures of minor shear zones at the west end of the cut show shear bands striking N 55° E. with a right-lateral sense of motion. Retort structures and card-deck displacements of fractured plagioclase crystals might be seen in vertical sections. Tracing of Middle Proterozoic units shows Paleozoic folds were limited to the ductile deformation zone and penetrative Paleozoic foliation is absent from the areas between shear zones.

West on I-84

4.5 Crops of rusty quartz-pyroxene and hornblende- plagioclase gneiss, amphibolite and other paragneisses.

6.5 Exit I-84 onto Taconic State Parkway headed south toward N.Y.

10.6 Hortontown Hill Road, mylonitic biotitic paragneiss and calc-silicate rock in Canopus shear zone.

12.7 Exit Rt. 301 west.

13.1 Entrance to Canopus Beach (log ends)

Stop 3: Dennytown fault zone and the town of Poughquag (20 min.). Quartzite and chlorite-grade phyllonitic rocks.

(Pl. 1A,B)

This exposure marks the westernmost and lowest- grade phyllonite zone that we have mapped. It essentially marks the start of the Paleozoic structural front in which mylonite-phyllonite retrogression becomes important. From this point south for about 2 km a series of small inliers of fault-bounded exposures of Poughquag Quartzite can be found. From this point chloritic, muscovitic phyllonite can be traced southwestward to near Peekskill, New York (Figs. 1 and 2). Phyllonite zones are exposed both east and west of the small syncline in the Poughquag. The unconformity with biotite-quartz-plagioclase gneiss is nearly exposed near the southwest end of the syncline. Muscovite, chlorite, epidote and locally actinolite are retrograde minerals in the shear zones where Proterozoic biotite, garnet, plagioclase and hornblende show complete retrogression to a fine-grained phyllonitic matrix. Plagioclase, microcline, pyroxene, and hornblende are microfaulted, and quartz forms excellent nonannealed ribbon structure.

13.1 Log resumes - turn west on Rt. 301.

13.4 Turn right onto T.S.P. southbound ramp, park at maintenance shed before parkway.

Stop 4: (15 min.) Chlorite-biotite zone shear zone in Canopus fault.

Small outcrops by the Taconic Parkway and in the woods to the south
illustrate well the type of mylonite and phyllonite developed along
the Ramapo-Canopus fault system. Garnet and biotite are altered to
chlorite, K feldspar and plagioclase are altered to epidote and
(Pl. 1-C) muscovite, and quartz is present in ribbon structure. Locally
calc-silicate rocks form spectacular fine-grained calcite-rich
mylonite in which chunks of diopside-hornblende calc-silicate rocks
float. Actinolite is the common alteration mineral along borders
of calc-silicate blocks and is present as fine needles in the
ductilely deformed calcite matrix. Green muscovite-rich phyllonite
like this is easily traced in mapping, forming resistant small
ridges in lowlands or distinctive notches on hillsides. This zone
extends southwestward to near Annsville, New York where evidence of
Proterozoic sillimanite-grade ductile shearing as well as Mesozoic
reactivation is present.

(turn around and return to Rt. 301)

13.5 Eastbound (right turn on 301)

16.2 Turn right on Sagamore Drive

16.4 Turn left onto unnamed dirt road.

16.6 Stop by small grey garage on left.

Stop 5: Garnet to biotite-grade mylonite in Dicktown fault, (Oscawana Lake quadrangle) (10 min.).

(Pl. 1-D)

This small outcrop is the only one easily accessible to a group so
we will have to settle for this. The Dicktown fault is traceable
as a continuous fault zone expressed by a thickness of up to 100
meters of medium-grained biotite-rich mylonite, protomylonite and
ultramylonite along the northwestern side of a large block of
internally undeformed Proterozoic gneiss (Figs. 1 and 2). The
(Pl. 2-A) southeastern boundary of the block is the California Hill shear
zone from which the 436 ±3 Ma ^{40}Ar/^{39}Ar age was obtained. The
Dicktown fault rocks dip vertically or steeply to the northwest.
To the south garnet within this zone is retrograded to biotite.
Locally, spears of biotite formed from garnet have aspect ratios of
15:1 in the mylonitic foliation. Microtextures support an up-from-
the-northwest and right-lateral sense of motion consistent with the
steep northwest-dipping planes shown in Figure 6. To the north
tiny euhedral garnets have grown within mylonites of the Dicktown
fault.

In this outcrop bands of ultramylonite 1-2 cm thick bound layers of mylonite containing complex intrafolial folds. Exposures to the northwest are of biotite granitic gneiss which is the protolith for this rock.

17.1 Stop sign, turn right on Route 301.

18.6 at Kent Cliffs

19.0 Park on left side of road opposite large roadcut.

Stop 6: Mylonitic fabric, shear zones and reactivation structures at ESERCO drill site (Fig. 11). (20 min).

At this roadcut, in Ygg biotite granitic gneiss, strongly developed mylonitic structures occur in spaced shear zones identified as M1 to M4. Near mylonite zones the K-feldspar becomes pinkish and muscovite more abundant. Augen gneiss is common. A 1 km deep drill hole was completed near the site (Fig. 11) in Nov. 1984 by ESERCO for in-situ stress determinations. The hole started in amphibolite gneiss and penetrated down into granitic gneiss. The log of the drill hole and core taken at spaced intervals reveal mylonitic structures similar to those seen in the roadcut. At 1680 feet a biotite-rich mylonite zone was cored that shows structures similar to zones M1-M3 (Fig. 11). Brittle fractures are spaced throughout the core and the mylonite at 1680 feet shows clear evidence of reactivation as a normal fault. Examination of the mylonites at M-3 and M-4 also reveal gouge and evidence of normal faulting. Triassic reactivation of Paleozoic and older mylonites is common in the Hudson Highlands, and the exposures here illustrate this well. Biotite from the California Hill fault zone resembling zones M_1 - M_4 yielded an $^{40}Ar/^{39}Ar$ plateau age of 436 ±3 Ma. Zoback and others (1985) determined from hydrofracturing and bore-hole-breakouts that the principal horizontal compressive stress is located in the northeast quadrant.

21.4 Turn right on 301, cross viaduct, turn left and follow 301 to Carmel.

23.6 At light turn left on Rt. 52, follow 52 North.

24.2 Pull into shopping center and park behind buildings.

Stop 7: High grade mylonitic gneiss and blastomylonite in granitic gneiss in sillimanite and kyanite grade at Carmel, New York (Lake Carmel quadrangle).

(P1.3-C)

Between the last stop and this point we have crossed into a zone in which redeformation of the Proterozoic basement is intense. Mylonite zones up to Stop 6 are clearly defined zones of intense deformation that bound relatively undeformed areas of gneiss. In the area between Stop 6 and 7 shear zones contain biotite, garnet

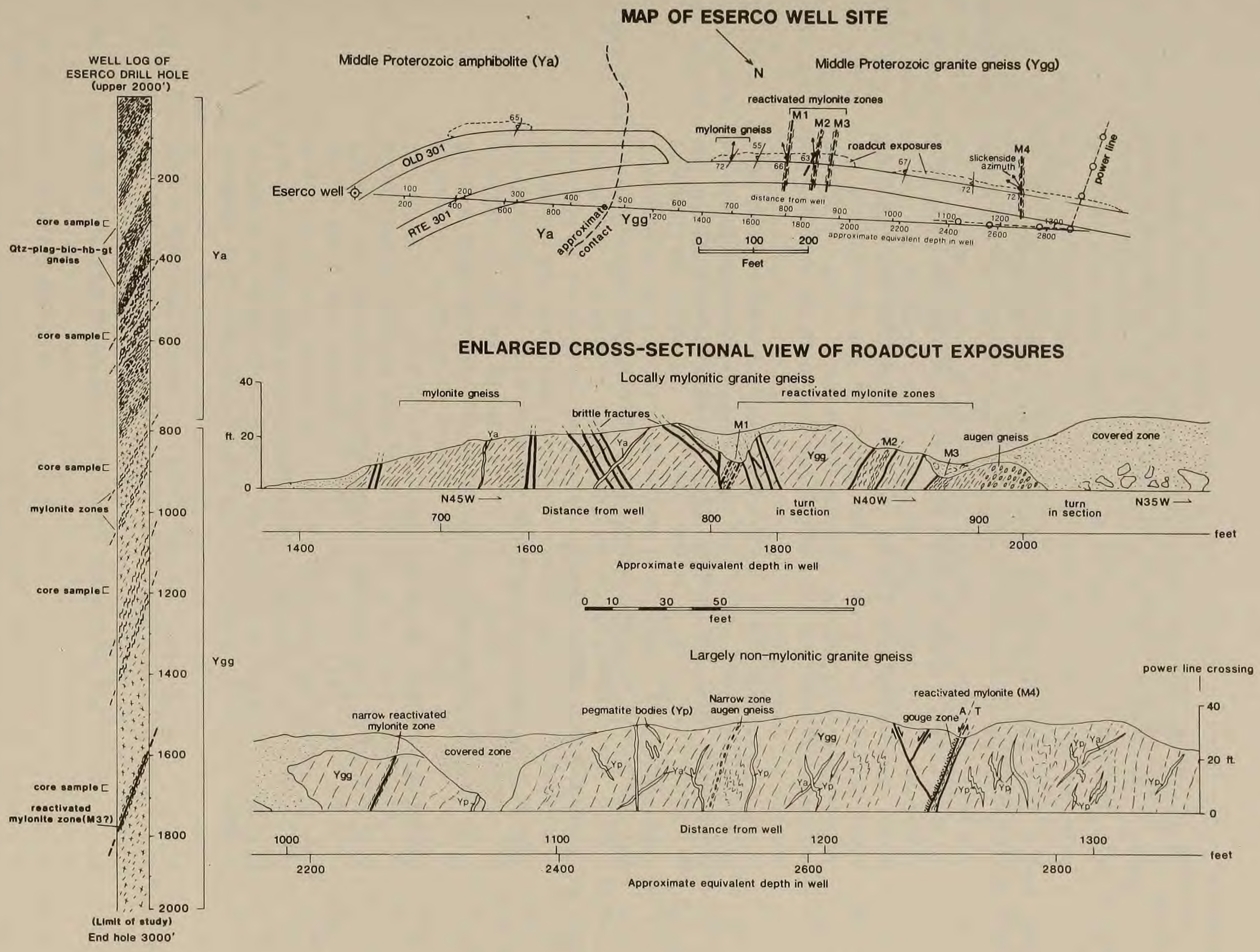

Figure 11 Cross section of roadcut in mylonitic granite gneiss at Stop 6 and partial log of ESERCO drillhole showing mylonite zones M_1 - M_3 sampled in core.

and kyanite and locally staurolite and kyanite, and deformation zones are still discrete features. At the stop and to the east shear zones become less continuous and internal deformation in the gneiss more fully developed, with complete refolding of Proterozoic structures.

The augen gneiss and blastomylonite seen in this outcrop can be traced northward to Stop 9. At this locality, coarse biotite-rich zones and anatectic (?) granitic material define the mylonitic fabric. A strong downdip rodding, retort-shaped augen, and microramp structures define fold-thrust fabrics similar to those seen at lower grades. Muscovite, biotite, microcline and plagioclase all show ductile deformation and evidence of dynamic recrystallization. No sillimanite has been found at this site but we are close to if not within the sillimanite zone.

From the parking lot walk up the slope to outcrops of well-rodded mylonitic gneiss, blastomylonite showing reclined folds with axes plunging N. 75° E., and excellent ramp structure showing an up-from-the-northeast sense of motion. Stringers of aplite and pegmatite appear in segregrations in the mylonitic fabric.

24.2 Resume log: exit parking lot and turn right on Rt. 52.

26.8 Turn right on Rt. 311 S.

30.5 I-84--turn onto westbound lane.

31.1 Excellent outcrops of sillimanite schist of Walloomsac Formation near contact with gneiss. Sillimanite rods plunge down the dip of S_2 (fault-related structure).

31.6 Contact with mylonite gneiss.

33.3 Exit 17--turn right at Ludingtonville exit.

33.4 Immediately turn left on unmarked road (Carey Rd.)

34.5 Stop sign--right onto Holmes Rd.

36.0 Rt. 292--turn left at Holmes Rd.

36.1 Entrance to Camp Henry Kaufman (log ends).

Stop 8: Contact of mylonitic gneiss with Walloomsac Formation at Whaley Lake thrust (sillimanite grade). (Optional Stop)

Park by superintendent's house in excellent mylonitic gneiss with strong NE-plunging fold-thrust lineation. Walk east 600 feet to small cliff exposure of Walloomsac exhibiting excellent slabby S_2

fabric and biotite spears that plunge northeast parallel to the strong lineation in the underlying and highly folded gneiss. Intensely developed mylonite and fold-thrust fabric is present immediately beneath the Whaley Lake thrust in a zone up to 0.25 km thick.

The Walloomsac Formation and the underlying mylonite derived from gneiss contain fibrolite, garnet, biotite and locally hornblende growing within the thrust (S_2) fabric.

From camp turn right (north) on 292.

37.9 Pear Tree Rd.--park on side street.

Stop 9: Augen gneiss at sole of Whaley Lake thrust.

(Pl. 3A-B) Outcrops in the railroad cut under the bridge exhibit excellent augen gneiss with N. 35° W. 50° NE mylonitic foliation. Augen of microcline show retort structure indicating up from the northeast side parallel to the northeast-plunging strong lineation. Outcrops to the north belong to Walloomsac Formation above the Whaley Lake thrust, and contain a strongly developed S_2 fabric with spears of biotite that plunge downdip. From here follow leader into development to N. and park at circle- Note: You must have owner's permission to park here to get to RR tracks. When revisiting this outcrop utilize the RR access road from Rt. 292 at north end of Whaley Lake, not this entrance.

Stop 10: Whaley Lake thrust, carbonate sliver, fold-thrust folds and gneiss sliver.

Outcrops by the lake shore are Poughquag Quartzite with stacked isoclinal reclined folds that plunge N. 86° E. On the east side of the railroad tracks are exposures showing white dolostone (Wappinger) which are also folded into reclined folds. Near the top of the cut steeply-dipping beds on the limb of a recumbent synform are truncated by dark gray, mylonitic Poughquag Quartzite. The fault contact can be traced in the top of the outcrop where recumbent, reclined folds involving both rocks plunge due south to N. 60° E. down the dip of the axial surface of the S_2 folds.

Walk east into the woods following the quartzite to its contact with mylonitic augen gneiss similar to rocks at Stop 9. The upper contact of the gneiss sliver with overlying mylonitic Walloomsac Formation is exposed at the break in slope to the east. This entire sequence is interpreted as slivers of quartzite, dolostone and gneiss interleaved in the Whaley Lake thrust. Near this locality syntectonic (S_2) garnet, biotite, and sillimanite are present in the Walloomsac.

Log resumes at Pear Tree Rd. and Rt. 292, at Stop 9--turn left on 292 and follow north to Rt. 55 east.

41.3 Stop sign--take 292 to right.

42.3 Stop by large outcrop at west end of Walloomsac Formation.

Stop 11: Contact Walloomsac Formation and gneiss.

These excellent exposures show the nearly exposed contact between mylonitic granitic gneiss and the Walloomsac at sillimanite (Pl. 4A-B) grade. "C" and "s" fabrics show up-from-the-east and right-lateral sense of motion. The strong platy structure and isoclinal folds in the Walloomsac are S_2-generation structures that postdate the crystallization of coarse biotite, garnet and staurolite and locally kyanite. In exposures to the east biotite and kyanite are (Pl. 2D) kinked and form retort structures with syntectonic fibrolite forming the tails, indicating up from the northeast parallel to the elongation lineation. Thrusting and the S_2 event were accomplished under sillimanite-grade conditions.

Biotite from this outcrop yield an $^{40}Ar/^{39}Ar$ plateau age of 418 ±5 (Figure 10, Bence and McLelland, 1976). Turn around and follow 55 west through town of Poughquag, to Columbia County Rt. 9 and turn right.

45.0 Turn right onto Columbia County Rt. 9.

47.2 Intersection Columbia County Rt. 21.Continue north on Columbia 9 through Clove to small bog or pond on east side of road 800 feet south of Sweezy Creek. Get owner's permission and park by pond.

Stop 12: S_2 fabric in Walloomsac Formation, aluminous Taconic rocks, and structures of Clove Valley in relation to isograds (30 min).

Park by pond and walk south and east through pasture to low cliffs 1000 feet southeast of pond.

These exposures of muscovite-chloritoid-quartz schist contain (Pl. 4C,D) excellent quartzite beds that outline intense reclined S_2 folds with northeast-plunging axes. Locally, minute garnet is present. S_2 structures like these dominate the fabric in the Walloomsac and Taconic rocks on East Mountain, above the (S_2) Poughquag-Clove Valley fault. Locally zones of retrogression are intense and phyllonites contain muscovite and chlorite. In the Walloomsac a second generation of fine biotite and muscovite defines the S_2 structure.

(Pl. 5 A, B,C,D) To the north along the slopes can be seen sheared Walloomsac with S_2 structures and finally a large and spectacular outcrop of brecciated limestone conglomerate belonging to the Balmville Limestone, which forms the basal conglomerate at the base of the Walloomsac Formation.

In Figure 9 we have related the mineral data and the shear zone structures to the isograds. It is important to note that the garnet and higher grade rocks lie for the most part east of and above the Poughquag-Clove Valley fault that is expressed by retrogressive phyllonite. One locality containing garnet is present west of the fault zone, but a garnet-absent retrograded zone intervenes.

In our interpretation the metamorphic isograds have been folded and faulted during late-stage events so that the metamorphic mineral assemblages have been juxtaposed.

Turn right on 9 and follow leader north.

48.0 North Clove Rd.

49.0 Brush Hill Rd.

49.5 Outcrop of Walloomsac with strong S_2 structure and no garnet, sharp turn to left.

50.0 Right-angle turn to left

50.5 Cross Beaver Creek and park by white barn-house on right side of road.

Stop 13: Green phyllonite in S_2 shear zone.

Pl. 5 A,B) Well displayed small exposures of phyllonite derived from Taconic rocks that normally contain garnet and chloritoid, exposed by the owner's swimming pool and in small ledges to the east. Examination of Rosemary's thin sections from the Dover Plains and Amenia quadrangles to the northeast, on strike with this zone, all exhibit extensive S_2 shearing and retrogression.

In the area west of Clove Valley, on Clove Mountain, chloritoid and biotite both exist sporadically as relict minerals of the M_1 event and are commonly retrograded in the strong penetrative S_2 foliation.

Our conclusion therefore is that the classical prograde metamorphic zonation in eastern Dutchess County is really a structurally complicated and partially retrograded sequence and not an intact package of prograde assemblages.

-End Trip-

Return on Rt. 9 via Rt. 55, to Ludingtonville exit. From here take I-84 east to Danbury and Hartford.