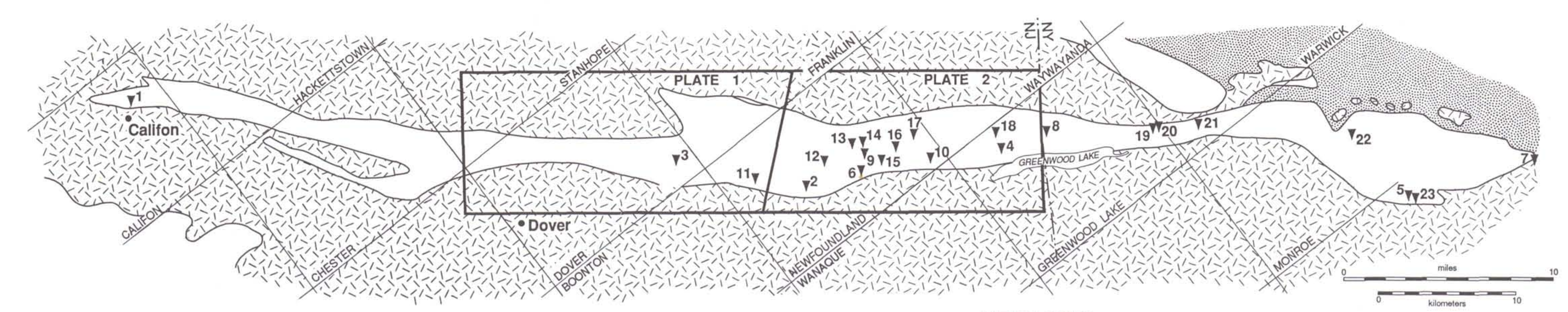
DEPARTMENT OF ENVIRONMENTAL PROTECTION
DIVISION OF WATER RESOURCES
NEW JERSEY GEOLOGICAL SURVEY

BEDROCK GEOLOGIC MAP OF THE GREEN POND MOUNTAIN REGION
FROM DOVER TO GREENWOOD LAKE, NEW JERSEY
GEOLOGIC MAP SERIES 91-2
PLATE 1 of 3



2▼ Stratigraphic Section (number corresponds to that in table)

CHESTER – USGS 7.5' topographic quadrangle name

LITHOLOGIES

▨ Ordovician Martinsburg Formation

▨ Proterozoic undivided

☐ Paleozoic undivided

No.	Stratigraphic units	Thickness	Reference
1	Hardyston Quartzite-Leithsville Formations, undivided	>117 ft	Markewicz and Dalton (1977)
2	Green Pond Conglomerate	1000-1260 ft	Barnett (1970)
3	Longwood Shale Berkshire Valley Formation Poxono Island Formation	300-350 ft 126 ft 350 ft	Barnett (1970)
4	Dkec group Cornwall Shale Bellvale Sandstone Skunnemunk Conglomerate	405 ft 600 ft 2000 ft 3000 ft	Barnett (1970)
5	Connelly Conglomerate	38 ft	Barnett (1970)
6	Hardyston Quartzite-Leithsville Formations, undivided	135 ft est.	Barnett (1970)
7	New Scotland through Decker Formations (NY)	167-198 ft	Johnson (NJGS Permanent notes)

No.	Stratigraphic unit	Thickness	Reference
8	Bellvale Sandstone	1630 ft est.	Johnson (NJGS permanent notes)
9	Bellvale Sandstone	1840 ft est.	Johnson (NJGS permanent notes)
10	Green Pond Conglomerate Cornwall Shale Bellvale Sandstone	1000 ft est. 900 ft est. 2000 ft est.	Johnson (NJGS permanent notes)
11	Green Pond Conglomerate	1160 ft	Johnson (NJGS permanent notes)
12-21	Bellvale Sandstone Skunnemunk Conglomerate	1510-3018 ft 3280 ft	Kirby (1981)
22	Bellvale Sandstone	2040 ft	Finks (1968)
23	Green Pond Conglomerate Longwood Shale Decker Ferry Formation	>305 ft 168 ft >55 ft	Finks (1968)

Figure 1. Location of measured stratigraphic sections in the Green Pond Mountain and Belvale Mountain-Schunemunk Mountain regions

CORRELATION OF MAP UNITS

Rocks of the Green Pond Mountain Region

Unit	Age	Period	Era
Dsk Dbv Dcw	Middle Devonian	Devonian	Paleozoic
Dkec	Lower Devonian		
Spbv	Upper Silurian	Silurian	
Sl	Middle and Upper Silurian		
Sg	Lower and Middle Silurian		

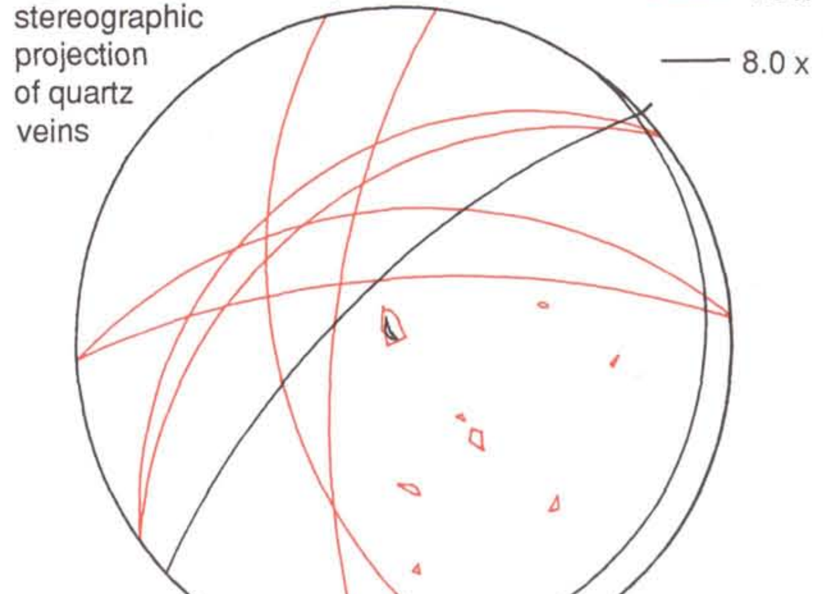
Rocks of the Lehigh Valley Sequence

Unit	Age	Period	Era
Om	Middle and Upper Ordovician	Ordovician	Paleozoic
Ꞓlh	Middle and Lower Cambrian	Cambrian	

Rocks of the Reading Prong

Unit	Age	Period	Era
Z(?)u	Upper(?) Proterozoic	Proterozoic	Precambrian
Yu	Middle Proterozoic		

Figure 3. Lower hemisphere equal angle stereographic projection of quartz veins



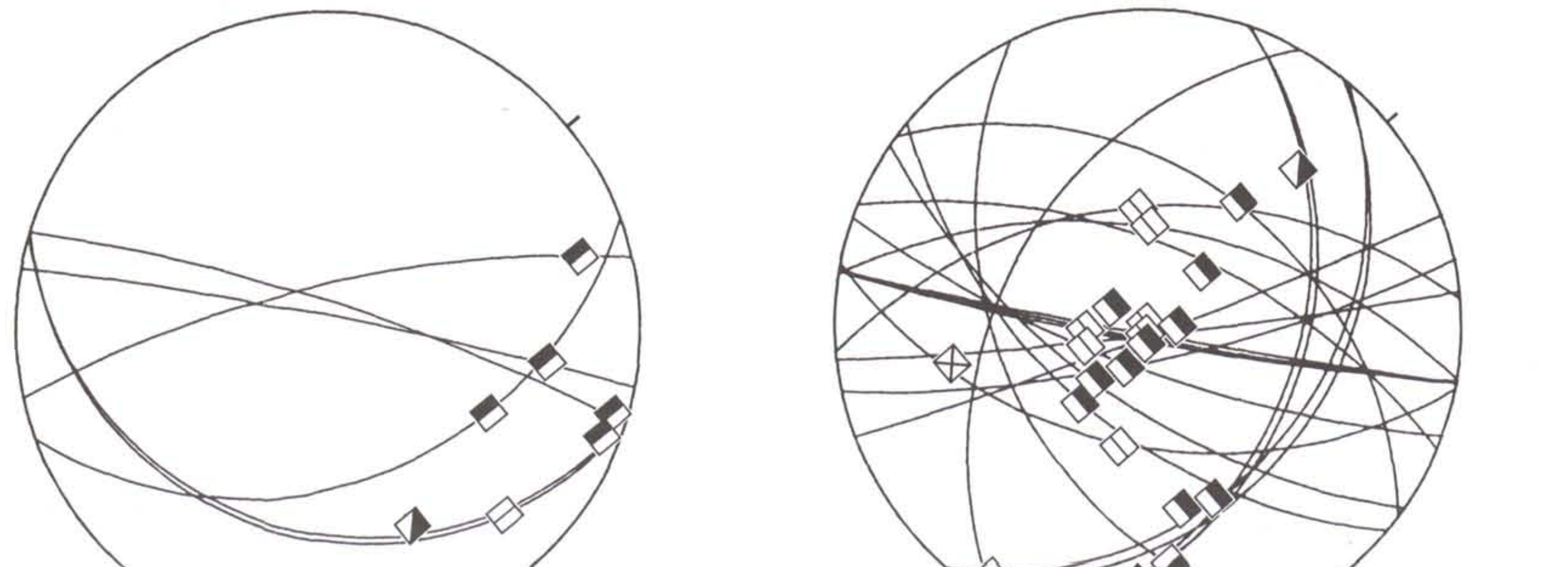


Figure 4.(left) **Figure 5.**(right)
Small fault population analyses. Explanation on Plate 2.

CONTOUR INTERVAL 20 FEET
SCALE 1:24,000

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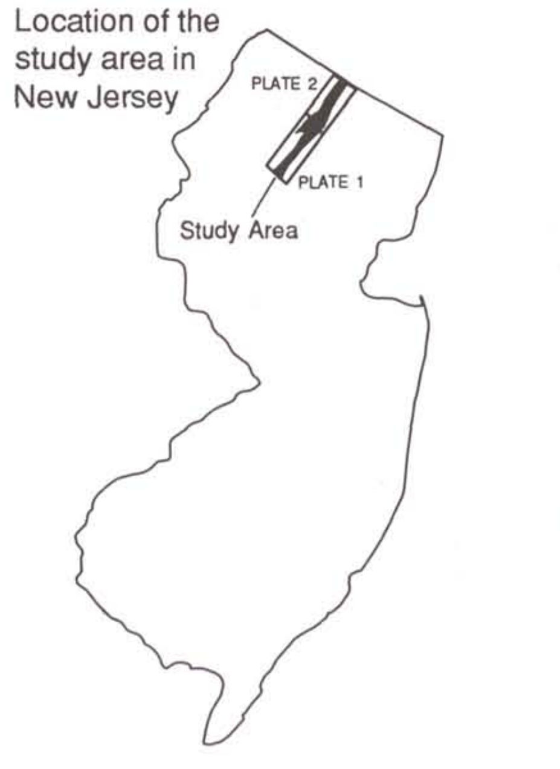
Plate 1. Southern Map and Description of Map Units

Location of the study area in New Jersey



DESCRIPTON OF MAP UNITS

Dsk **Skunnemunk Conglomerate** - Grayish-purple to grayish-red, thin- to very thick-bedded, cross-bedded, polymictic conglomerate and sandstone; interbedded with thin-bedded, medium-gray sandstone, and greenish-gray and grayish-red shale with mud cracks. Conglomerate is more abundant than sandstone and contains clasts of white vein quartz, red and green quartzite, sandstone, red and gray chert, and red shale. Conglomerate and sandstone matrix consists primarily of hematite and microcrystalline quartz. Conglomerate cobbles range from 2.5 to 6.5 in. across and average cobble size increases upward. The lower contact with the underlying Bellvale Sandstone is conformable and gradational. The unit is about 3000 ft. thick.

Dbv **Bellvale Sandstone** - Medium-gray to medium-bluish-gray siltstone and sandstone, weathering light-olive gray to yellowish gray and greenish black, interbedded with black to dark-gray shale, locally fossiliferous. Very thin- to very thick-bedded, commonly cross-bedded and graded, generally coarsens upward. Upper beds are grayish-red to grayish-purple sandstone with quartz pebbles as large as 1.2 in. The lower contact with the underlying Cornwall Shale is conformable and is placed where bed thickness of shale and siltstone is about equal. The unit is 1750 to 2000 ft. thick.

Dcw **Cornwall Shale** - Black to dark-gray, fissile shale, very thin- to thick-bedded, fossiliferous, interbedded with laminated to very thin-bedded, medium-gray and light-olive-gray to yellowish-gray siltstone which increases upward in the unit. Lower contact with the Kanouse Sandstone unobserved but assumed to be conformable. The unit is about 950 ft. thick.

Dkec **Kanouse Sandstone, Esopus Formation, and Connelly Conglomerate, undivided**

Kanouse Sandstone - Medium-gray, light-brown, and grayish-red, sparsely fossiliferous, fine- to coarse-grained sandstone and pebble conglomerate, ranging from thin- to thick-bedded. Basal conglomerate beds are interbedded with siltstone similar to that in the upper part of the Esopus Formation and contain well-sorted, subangular to subround, gray and white quartz pebbles up to 0.4 in. across. The unit is about 45 ft. thick.

Esopus Formation - Laminated to thin-bedded, light-gray to dark-gray siltstone, interbedded with dark-gray to black mudstone, dusky-blue sandstone and siltstone, black siltstone, and yellowish-gray siltstone and sandstone. Fossiliferous. Upper contact appears transitional with the Kanouse Sandstone and lower contact appears conformable with the Connelly Conglomerate. The unit is about 325 ft. thick at Greenwood Lake and is estimated to be 185 ft. thick in Longwood Valley.

Connelly Conglomerate - Thin-bedded, very light-gray to yellowish-gray quartz-pebble conglomerate weathering grayish-orange. The quartz pebbles average 0.4 to 0.8 in., are subround to well rounded, and well sorted. The unit unconformably overlies the Berkshire Valley Formation and is about 35 ft. thick.

Spbv **Berkshire Valley and Poxono Island Formations, undivided**

Berkshire Valley Formation - Very thin- to thin-bedded, medium-gray to pinkish-gray, fossiliferous limestone, interbedded with gray to greenish-gray calcareous siltstone and silty dolomite, medium-gray to light-gray dolomite conglomerate, and thinly laminated grayish-black shale. Yellowish-gray weathering common. Lower contact is conformable with the Poxono Island Formation.

Poxono Island Formation - Very thin- to medium-bedded sequence of medium-gray, greenish-gray, or yellowish-gray, mud-cracked dolomite, light-green, pitted, medium-grained calcareous sandstone, siltstone, and edgewise conglomerate with gray dolomite, and quartz-pebble conglomerate with angular to subangular pebbles as much as 0.8 in. across. Grayish-green shales at the lower contact are interbedded and transitional with the underlying dark-reddish-brown Longwood Shale. The combined thickness of the Berkshire Valley and Poxono Island Formations ranges from an estimated 250 ft. at Greenwood Lake to 400 ft. in Longwood Valley.

Sl **Longwood Shale** - Thin- to very thick-bedded, dark-reddish-brown shale interbedded with very thin- to thin-bedded, cross-bedded, very dark-red sandstone and siltstone close to the conformable, basal contact with the Green Pond Conglomerate. About 325 ft. thick.

Sg **Green Pond Conglomerate** - Basal, thin- to very thick-bedded, very dark-red to grayish-purple and gray, pebble-to-cobble conglomerate containing clasts of red shale, siltstone, and chert, yellowish-gray sandstone and chert, dark-gray shale and chert, and predominantly grayish-white and pinkish-white milky quartz pebbles. Quartz cobbles are as much as 4 in. across. One red shale clast measured 18 in. Basal conglomerate fines upsection into thin- to thick-bedded, medium- to coarse-grained quartz-pebble conglomerate, quartzitic arkose and orthoquartzite, then reddish-brown siltstone. The quartzite increases upward in the unit. Milky quartz pebbles commonly average 0.8 to 1.2 in. across. Red arkosic quartz-pebble conglomerate and quartzite dominate over subordinate gray and grayish-green interbeds. Lower contact not observed, but assumed to be unconformable. About 1000 ft. thick.

Om **Martinsburg Formation** - Phyllonitic, light-olive-gray to dark-gray shale with thin, discontinuous silty lenses weathering yellowish gray. Contacts unobserved, thickness unknown.

Ꞓlh **Leithsville Formation and Hardyston Quartzite, undivided**

Leithsville Formation - Very finely crystalline, thin- to medium-bedded, light- to dark-gray and light-olive-gray dolomite weathering medium-gray, dark brownish-gray, and dark yellowish-brown. Contains occasional fine to medium crystalline patches. Interbedded clastic rocks include very thin-bedded, grayish-yellow to pinkish-gray sandstone and shale, and red shale with minor green- and yellowish-brown-weathering laminations. The lower contact with the Hardyston Quartzite is gradational. The unit ranges from 0 to an estimated thickness of 185 ft.

Hardyston Quartzite - Thin- to medium-bedded, light- to medium-gray and bluish-gray conglomeratic sandstone. Varies from pebble conglomerate to fine-grained, well-cemented sandstone. Conglomerate contains subangular to subround white quartz pebbles ranging from 0.4 to 1.0 in. Unit at many places has a gray- to grayish-brown-weathering rind and sulfide mineralization in its matrix. The unit ranges in thickness from 0 to about 30 ft.

Zu(?) **Late Proterozoic (?), undivided** - Thin-bedded, cross-bedded, and graded, fine- to coarse-grained, moderate-yellowish-brown to yellowish-gray, very low-grade metaquartzite. Dark-greenish-gray to dark-reddish-brown, phyllonitic, arkosic metaquartzite locally along the trace of the Reservoir fault. Contacts unobserved. Thickness unknown.

Yu **Middle Proterozoic, undivided** - Mixed gneisses and granitoid rocks of the New Jersey Highlands.

Base from U.S. Geological Survey 7.5' quadrangles, Boonton, 1981, Franklin, 1971, Greenwood Lake, 1954, Newfoundland, 1971, Wanaque, 1971, Waywayanda, 1954

Geology mapped by G.C. Herman and J.P. Mitchell, 1985-89
Field assisted by D.H. Monteverde and M.E. Kaeding
Reviewed by A.A. Drake, Jr. and A.E. Gates
Edited by I.G. Grossman
Cartography by M. Fiorentino and W.P. Graff

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PLATE 2 of 3

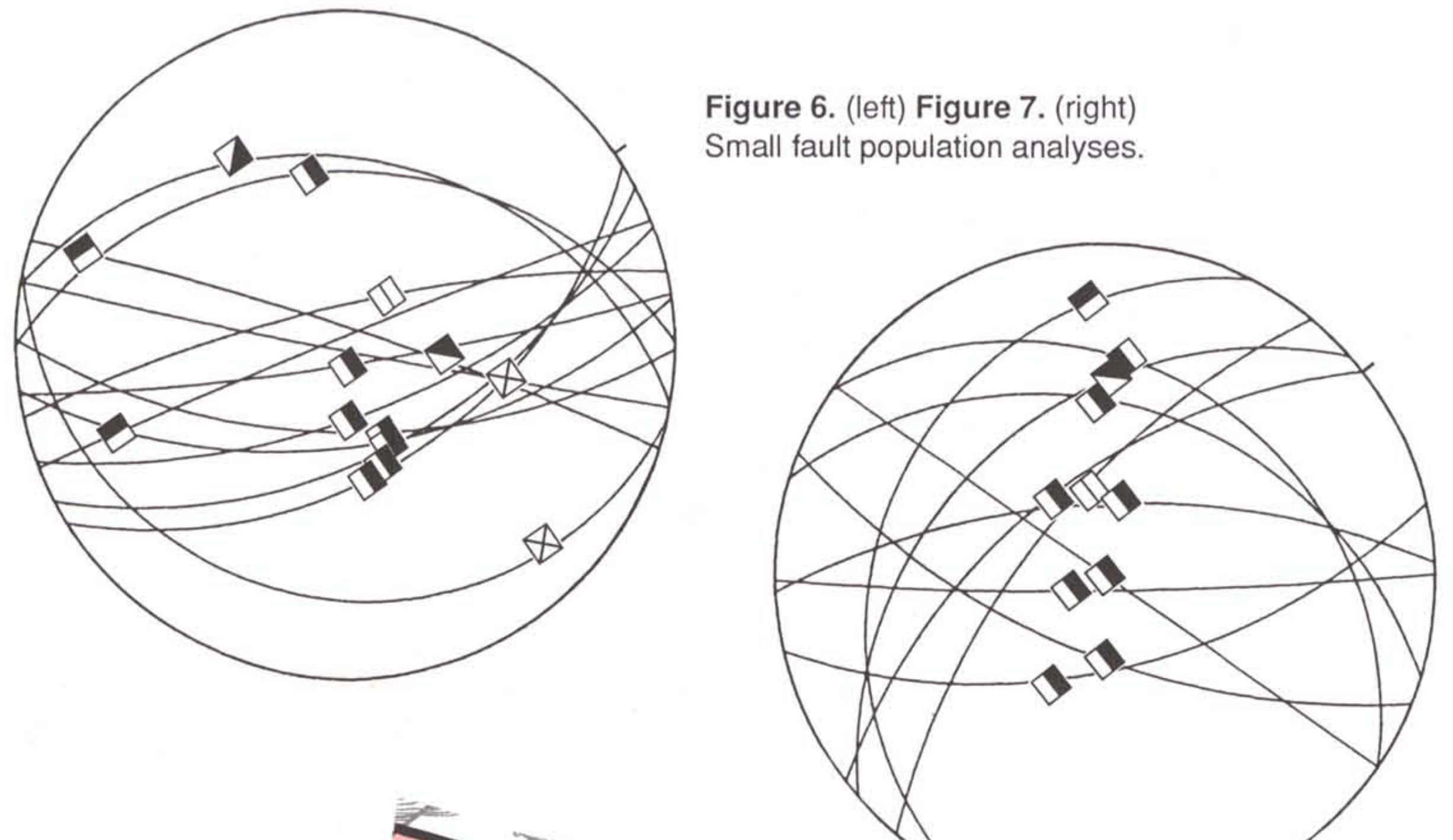

Figure 6. (left) **Figure 7.** (right)
Small fault population analyses.

EXPLANATION OF FIGURES 4-7. STEREOGRAPHIC PROJECTION DIAGRAMS FOR SMALL FAULT ANALYSIS.
Lower-hemisphere equal-angle diagrams relating to stations on map as shown. Great circles correspond to shear planes.

Slickenside Lineations

Dip-slip (pitching > 60° on shear plane)

- ⬒ Reverse
- ⬓ Normal
- ⊟ Undetermined sense of dip-slip offset

Oblique-slip (pitching > 30° and < 60° on shear plane)

- ◩ Reverse/right lateral
- ◪ Reverse/left lateral
- ◪ Normal/right lateral
- ◩ Normal/left lateral
- ⊠ Undetermined sense of oblique-slip offset

Strike-slip (pitching < 30° on shear plane)

- ◨ Right lateral
- ◧ Left lateral
- ◫ Undetermined sense of strike-slip offset

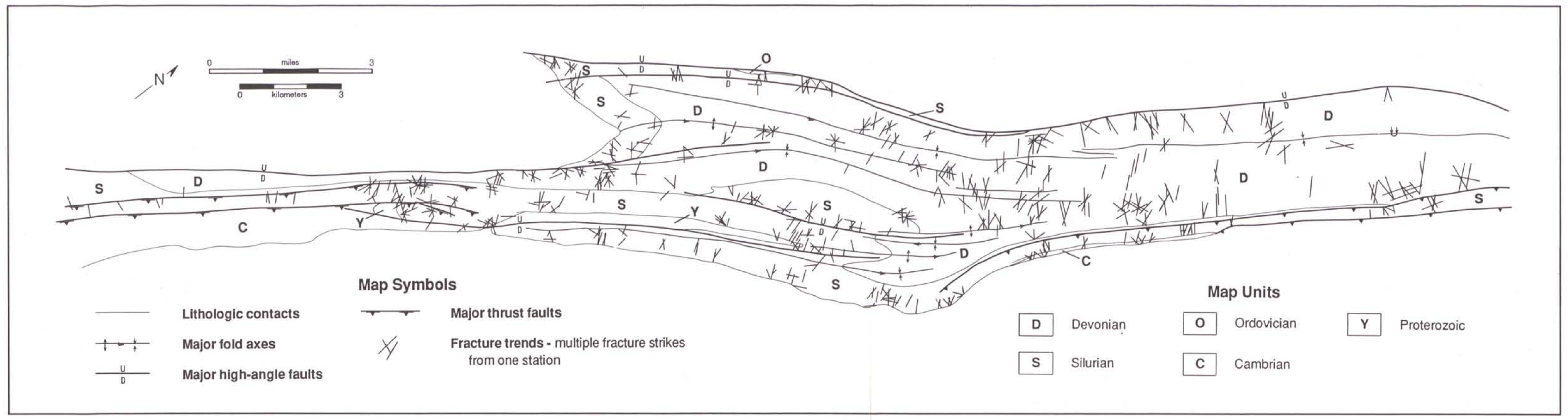

Figure 2. Extrapolated fracture analysis and generalized geology for the study area.

CONTOUR INTERVAL 20 FEET
SCALE 1:24,000

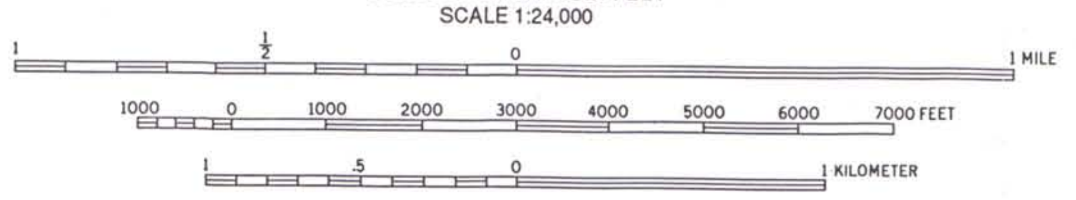

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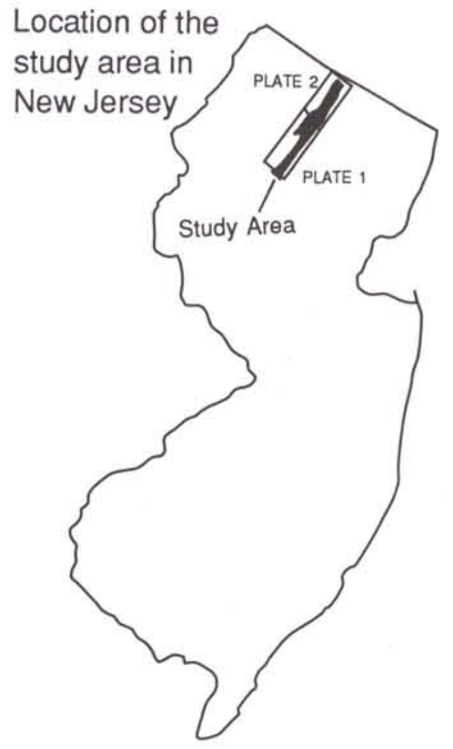
Plate 2. Northern Map and Explanation of Map Symbols



EXPLANATION OF MAP SYMBOLS

Where multiple measurements were taken, the station location is shown preferentially by bedding, small faults, cleavage, lineation, then jointing. Other symbols are fitted as closely as possible.

Contact - Dotted where concealed

FAULTS

High Angle - U, Upthrown side; **D**, downthrown side. Arrows indicate relative strike-slip component. Dotted where concealed.

Thrust fault - Sawteeth on upper plate. Dotted where concealed.

Brittle-ductile shear zone

Brittle shear zone

Small fault - showing dip

FOLDS

Anticline - Showing crest line and direction of plunge. Dotted where concealed.

Syncline - Showing trough line and direction of plunge. Dotted where concealed.

Overturned anticline - Showing trace of axial surface and direction of dip of limbs. Dotted where concealed.

Overturned syncline - Showing trace of axial surface and direction of dip of limbs. Dotted where concealed.

Gently-inclined to recumbent anticline - Showing trace of axial surface and direction of dip of limbs. Arrow tail indicates dip direction of upper limb. Dotted where concealed.

Gently-inclined to recumbent syncline - Showing trace of axial surface and direction of dip of limbs. Arrow tail indicates dip direction of upper limb. Dotted where concealed.

MINOR FOLDS

Minor anticline or antiform - Showing bearing and plunge

Minor syncline or synform - Showing bearing and plunge

Minor fold - Showing bearing and plunge

Minor assymmetric fold - Showing bearing and plunge and rotation sense

Minor kink fold - Showing bearing and plunge

PLANAR FEATURES

Strike and dip of beds

- Horizontal
- Inclined
- Vertical
- Overturned
- Undulatory (average strike and dip)

Strike and dip of cleavage

Spaced cleavage

- Inclined
- Vertical

Crenulation or spaced cross cleavage

- Inclined
- Vertical

Strike and dip of joints

- Horizontal
- Inclined
- Vertical
- Multiple joint readings

Strike and dip of Proterozoic foliation

- Inclined
- Vertical
- Mylonitic

LINEAR FEATURES

Bearing and plunge of intersection of bedding and cleavage

Bearing and plunge of intersection of disjunctive cleavages

Mineral lineation in Middle Proterozoic rocks

OTHER SYMBOLS

Figure 7. **Location of small-fault measurements** - used in population analysis illustrated by corresponding figure.

Base from U.S. Geological Survey 7.5' quadrangles, Boonton, 1981, Franklin, 1971, Greenwood Lake, 1954, Newfoundland, 1971, Wanaque, 1971, Waywayanda, 1954

Geology mapped by G.C. Herman and J.P. Mitchell, 1985-89
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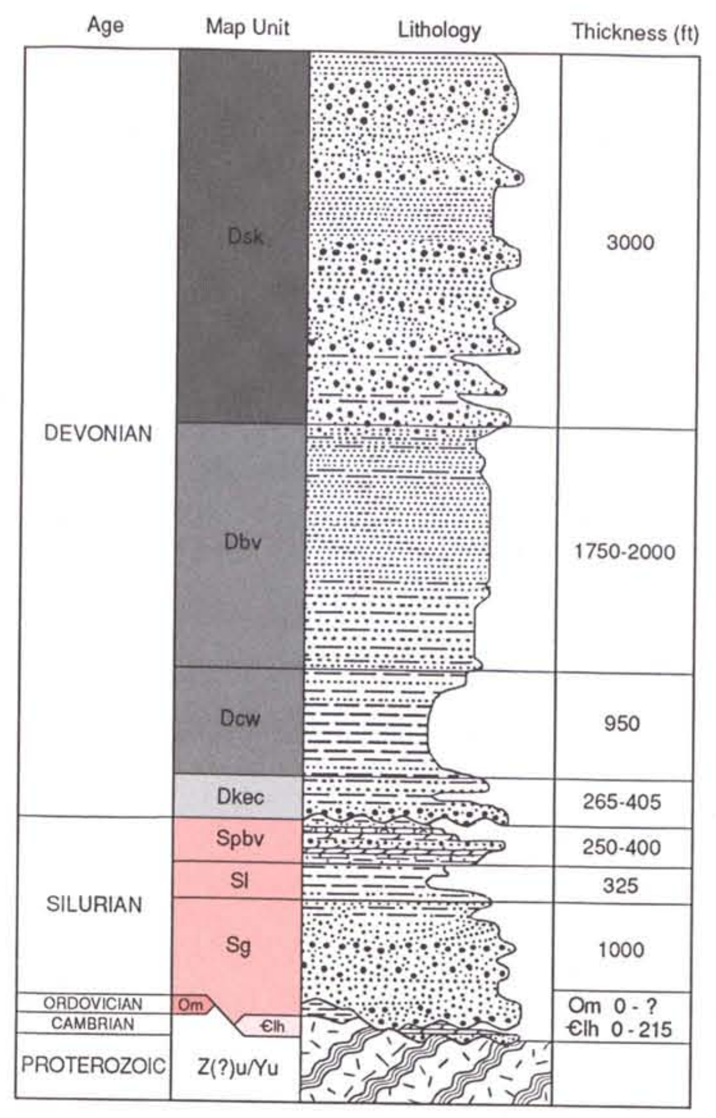

Figure 9. Generalized stratigraphic column for the Green Pond Mountain region.

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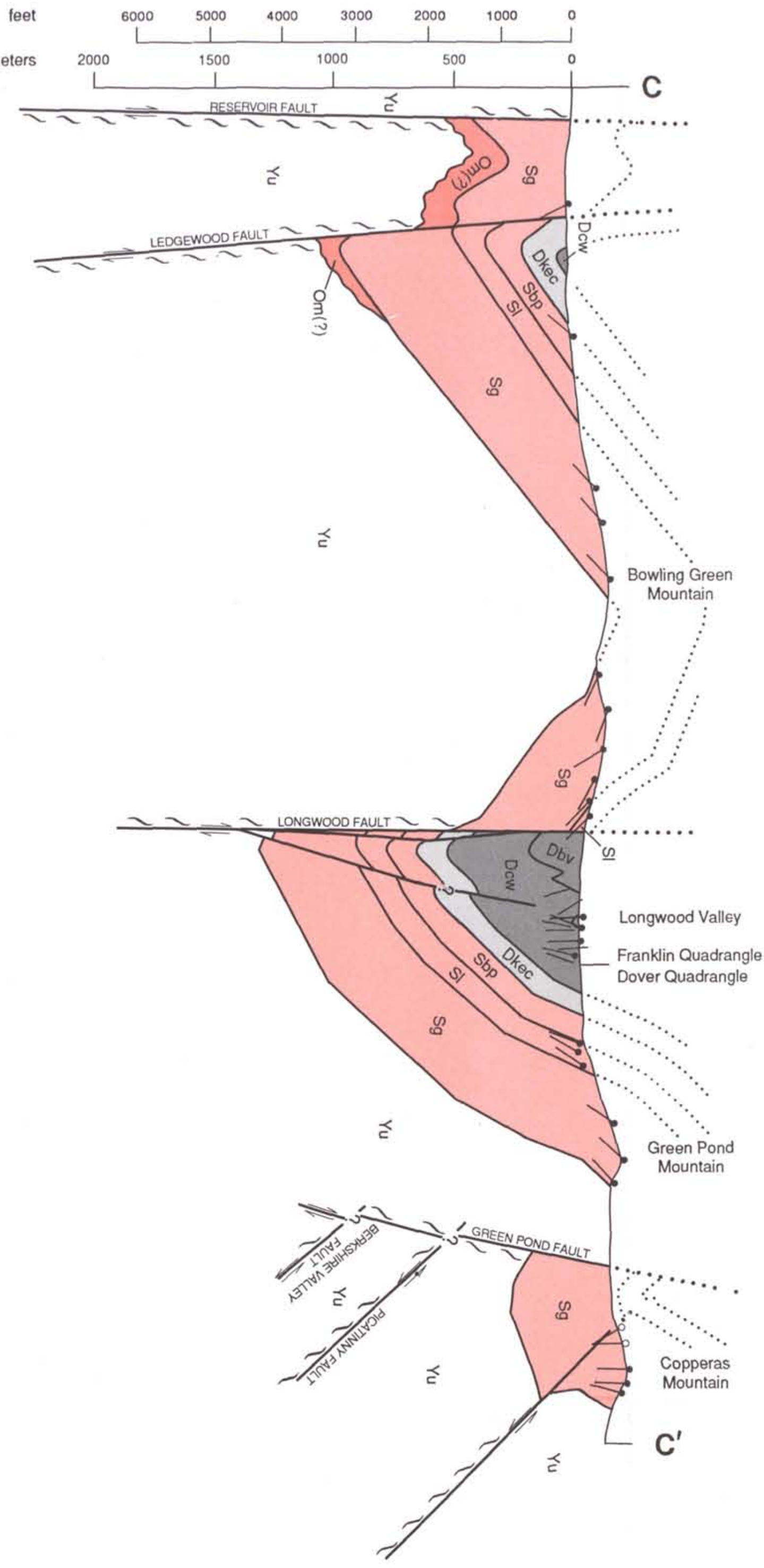
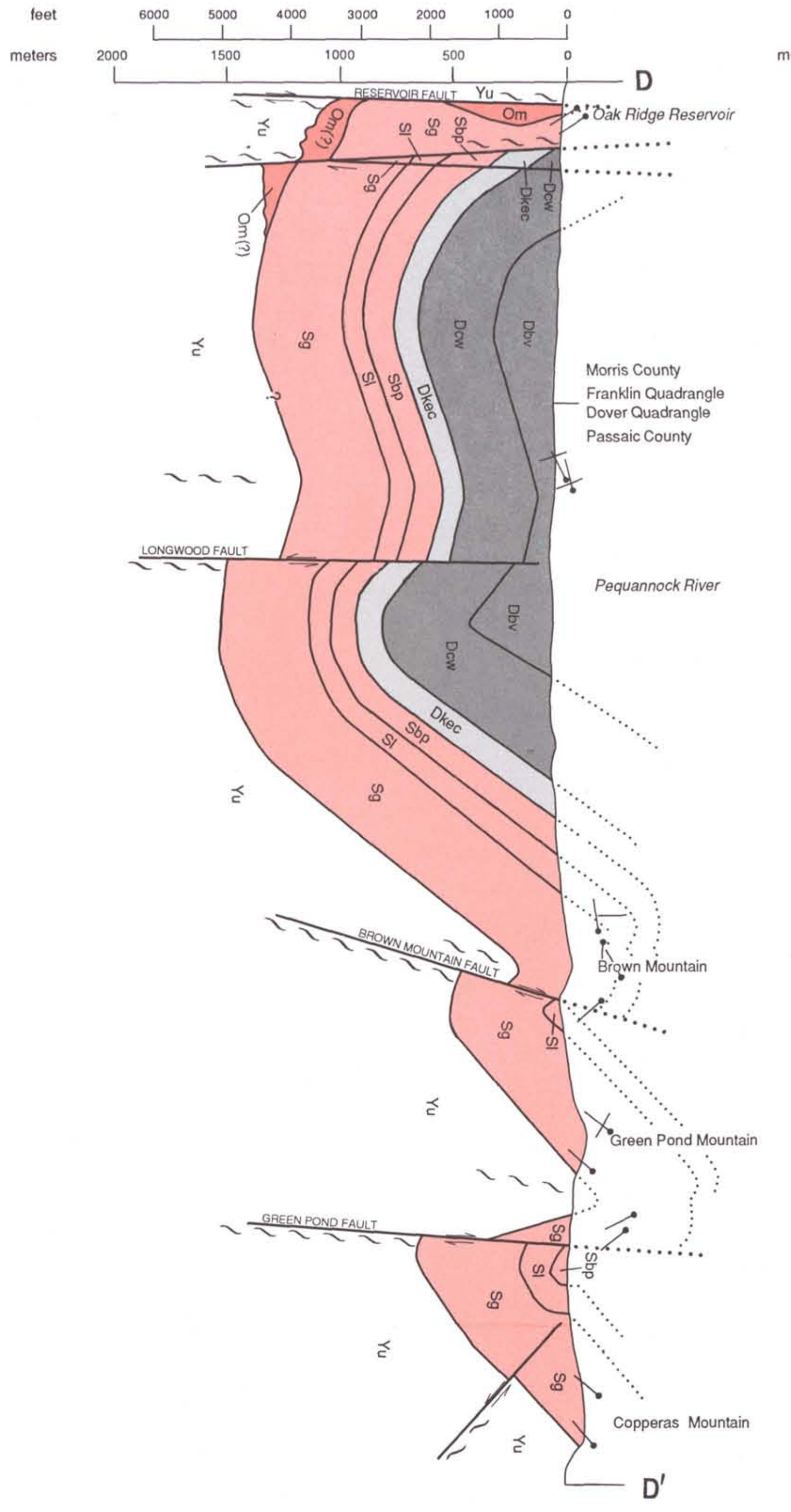
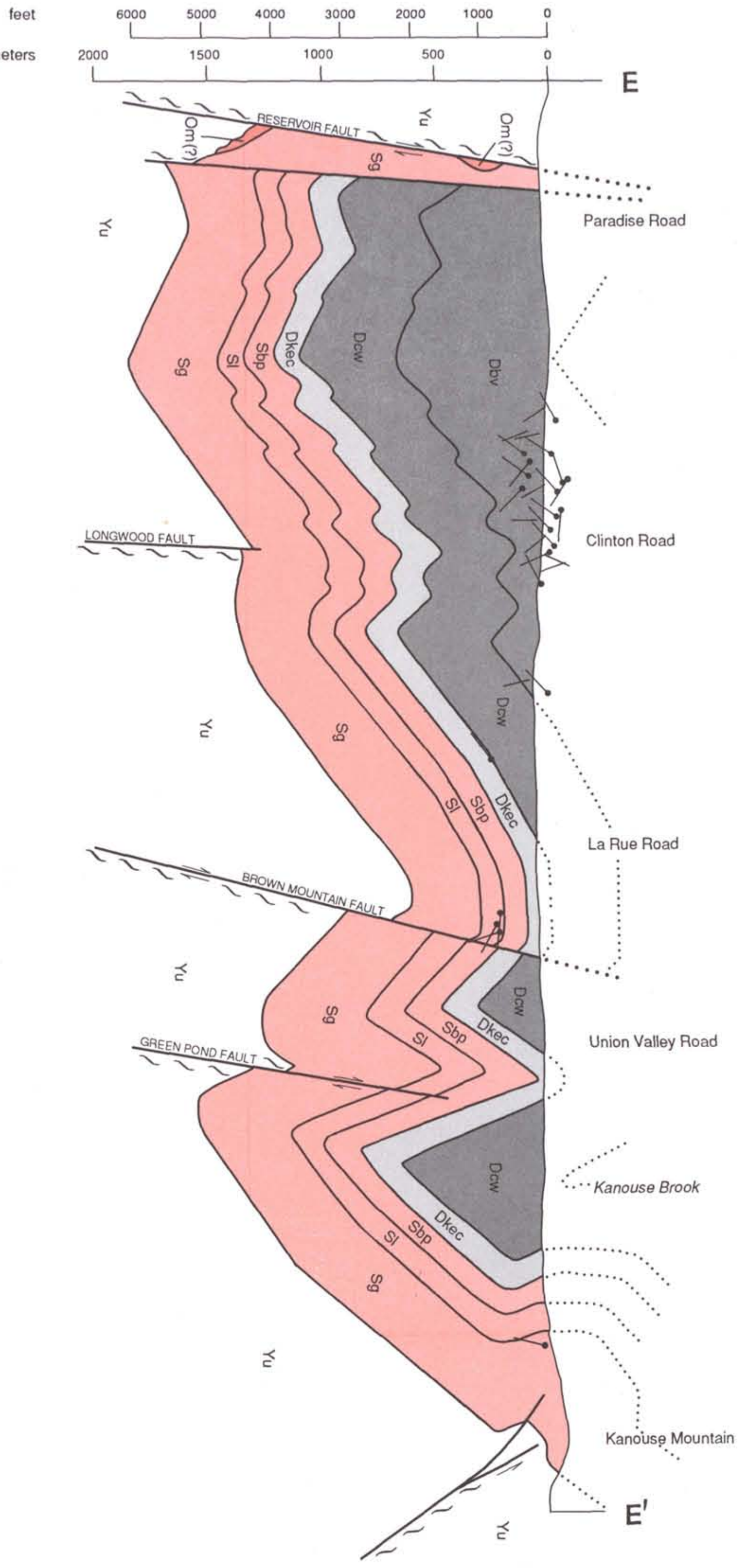
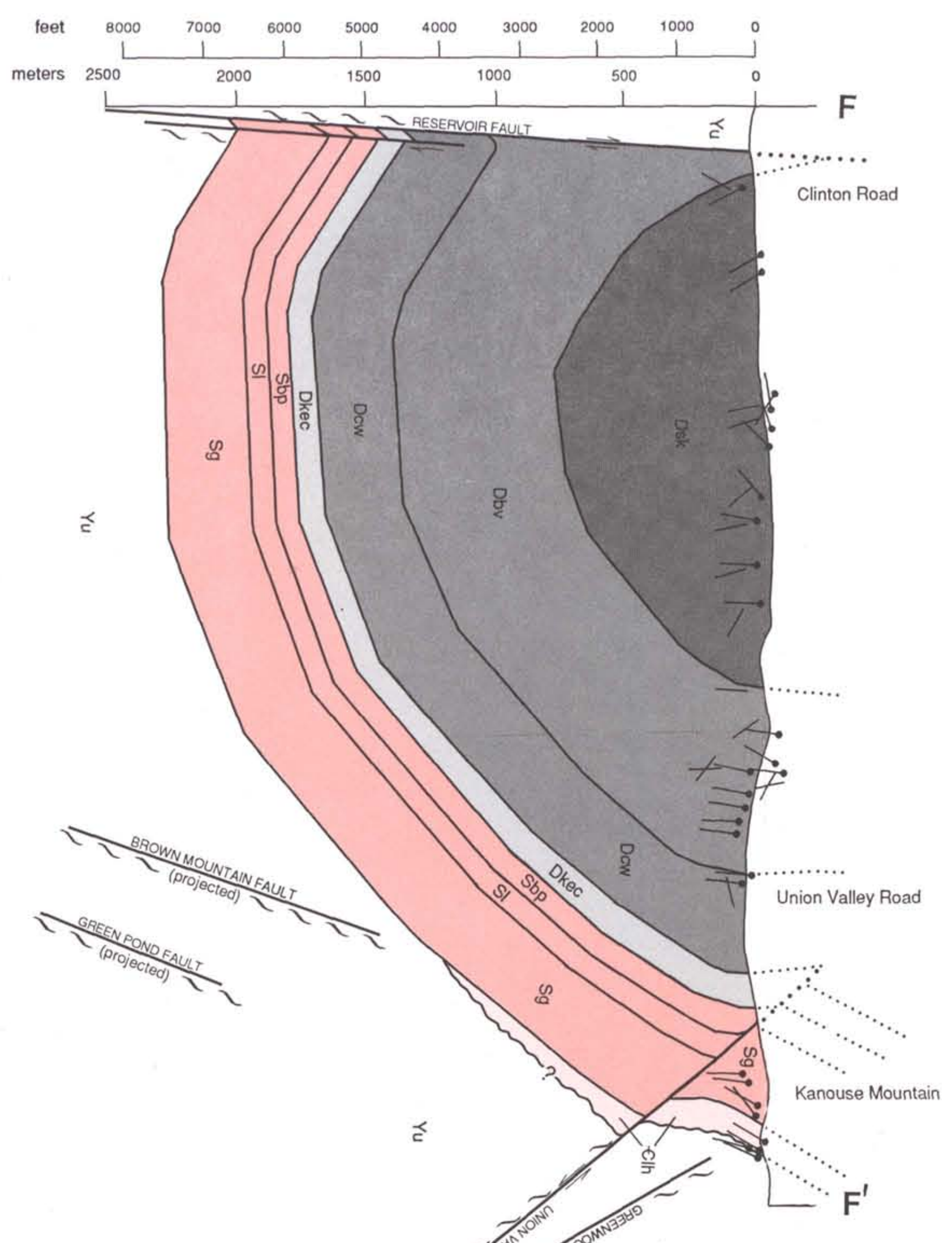
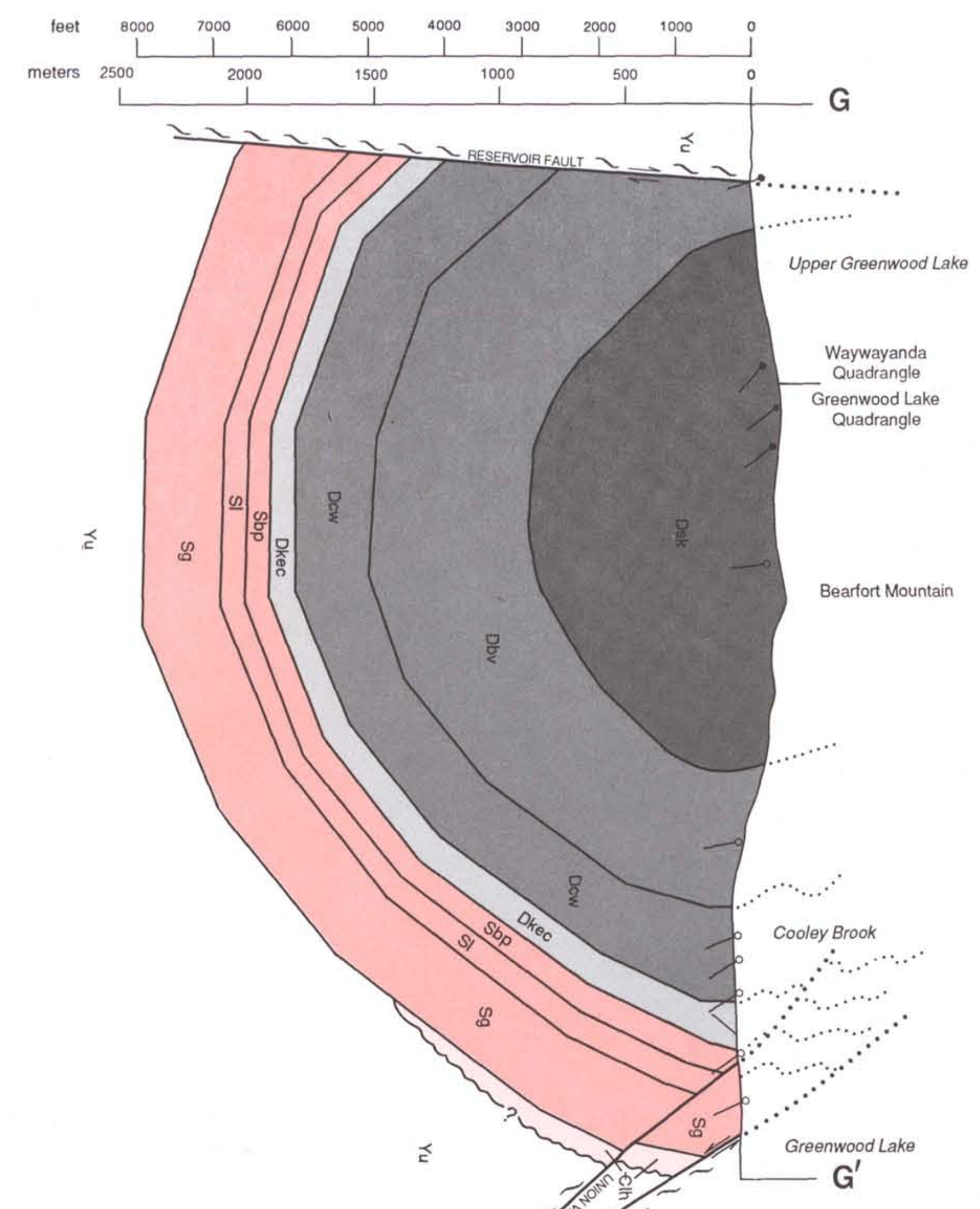
Plate 3. Cross Sections and Discussion

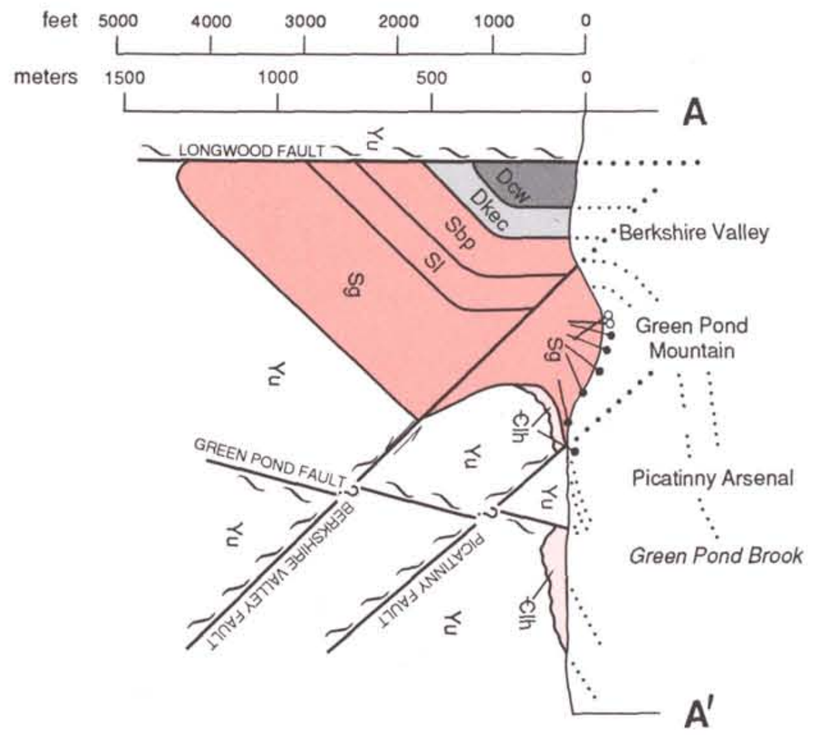


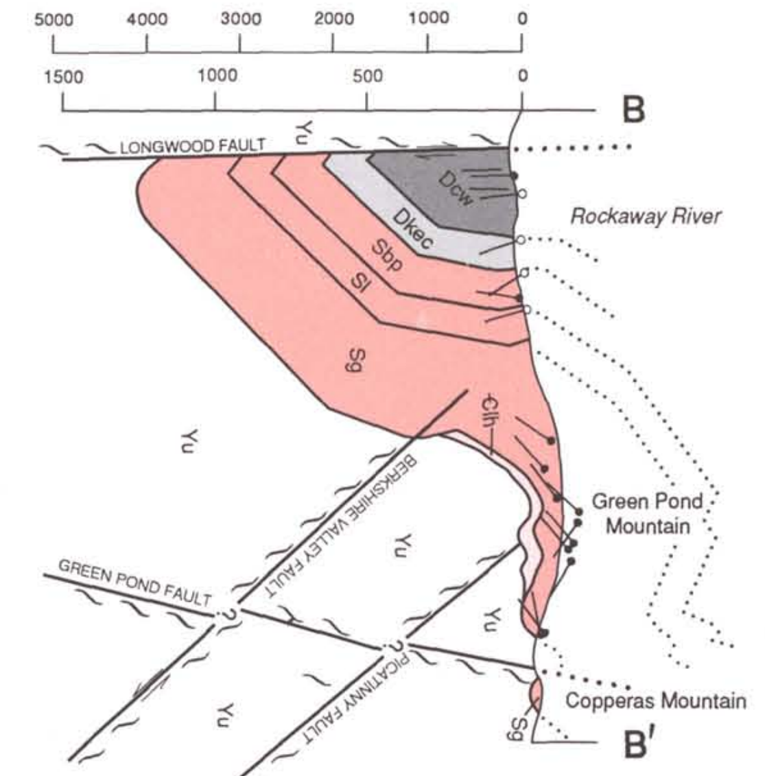












Explanation of Cross-section Symbols

Projected apparent dip

Upright bedding

Overturned bedding

Spaced cleavage

Basement shear zone

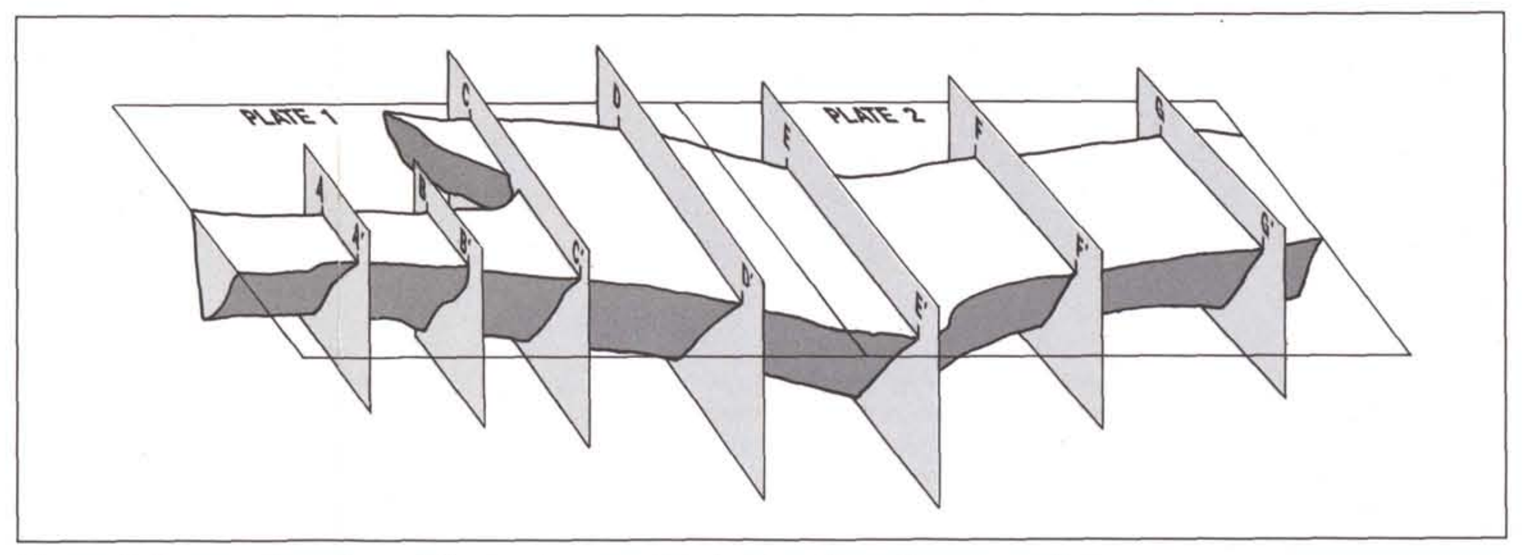


Figure 8. Perspective view of the study area showing location of cross sections.

INTRODUCTION

The Green Pond Mountain region, a narrow belt of Paleozoic sedimentary rocks, lies within the New Jersey Highlands. This report deals with that part of the region extending from near Dover, New Jersey to the New York State line (pl.1, fig. 1), a distance of about 26 miles. Beyond the study area, the rock belt extends about 20 miles southwest to Califon, New Jersey, and 22 miles into New York, where it is known as the Belvale Mountain-Schunemunk Mountain region. The study area is marked by northeast-trending ridges underlain by resistant formations and intervening valleys developed primarily along belts of more easily eroded rock. The valleys are largely blanketed with glacial deposits which obscure the bedrock geology, especially southwest of Dover where the Wisconsinan terminal moraine crosses the region.

Work in this area began as early as 1835 (Rogers, 1836, p. 129-130). Studies at the turn of the century by Darton (1894) and Kummel and Weller (1902) established the geologic framework. A more recent geologic map and stratigraphic correlation was prepared by Barnett (1976). This study adds many stratigraphic and structural details and a new interpretation of the structural geology.

STRATIGRAPHY

The Paleozoic rocks of the Green Pond Mountain region range in age from Early Cambrian to Middle Devonian. The events shaping the stratigraphy were, from older to younger, a Cambrian-Ordovician marine transgression and Early Silurian regression; then a Middle- to Upper-Silurian transgression and Middle-Devonian regression.

Quartzite and conglomerate of the Hardyston Quartzite unconformably overlie the Middle and Late Proterozoic gneissic and granitoid basement rocks of the New Jersey Highlands. The lower part of the Hardyston has been interpreted as rift facies alluvium. In the upper part of the formation the alluvium has been reworked and augmented by orthoquartzitic marine deposits of an advancing Early Cambrian sea (Aaron, 1969).

The Hardyston Quartzite interfingers with drift-facies dolomite and interbedded clastic rocks in the lower parts of the overlying Leithsville Formation. Passive-margin carbonate-bank deposition from Early Cambrian into the Early Ordovician resulted in the Leithsville Formation and the superjacent Allentown Dolomite. Though the Allentown Dolomite has not been mapped in the study area, within the Green Pond Mountain region it has been recognized in well cuttings in the German Valley to the southwest (Volkert and others, 1990); its equivalent, the Pine Plains Formation, is mapped in the New York part of the rock belt (Offield, 1967).

The Martinsburg Formation is a series of shales and graywacke turbidites deposited in a flysch basin following uplift, then submergence of the carbonate platform. In the Green Pond Mountain region, the Martinsburg Formation crops out at two locations close to the Reservoir fault in the vicinity of Oak Ridge Reservoir. Both outcrops are bounded on the southeast by down-dropped fault slices of Green Pond Conglomerate. The identification as the Martinsburg, rather than the lithologically similar but younger Cornwall Shale, is based on its juxtaposition to the conglomerate and reports of Ordovician brachiopods by Barnett (1976).

The Martinsburg Formation is also reported along the Reservoir fault (Worthington, 1953) where the Green Pond Conglomerate pinches out between Holland and Bowling Green Mountains (pl. 1). However, this tectonized sedimentary rock is a dark-greenish-gray to dark-reddish-brown phyllonite containing stretched, sand-sized, quartz grains and does not resemble the tectonized shales near Oak Ridge Reservoir. This phyllonite, and other anomolous rocks of uncertain affinity it occurs with, are shown here as of probable Late Proterozoic (Proterozoic Z) age. Immediately to the southwest, and southeast across the trace of a subsidiary fault, the Green Pond Conglomerate unconformably overlies a patchy strip of very low-grade metamorphic arkose and quartzite unlike any of the Paleozoic or Middle Proterozoic basement rocks in the region. Other Late Proterozoic rocks of low metamorphic grade (Chestnut Hill Formation of Drake, 1984) occur in the southwest part of the Highlands of New Jersey.

In the Valley and Ridge and the southwest part of the Highlands of New Jersey, a widespread unconformity separates rocks of the Beekmantown Group from superjacent rocks of Trenton age nearly everywhere west of the Green Pond Mountain region. To the north, in the area of Warwick, New York, Offield (1967) shows that rocks of Trenton age are sparse and occur as small patches unconformably overlying rocks of the Beekmantown Group and conformably underlying the Mount Marino Shale (equivalent to the Martinsburg Formation). Northeast of Warwick, the Mount Marino Shale may unconformably overlie rocks as old as the Upper Cambrian Pine Plains Formation. Within the Green Pond Mountain region, the Early Silurian Green Pond Conglomerate unconformably overlies Cambrian and Early Ordovician carbonates everywhere except at Bowling Green, Brown, and Green Pond Mountains, where it unconformably overlies basement. Trenton-age rocks are nowhere present. The actual contact between the conglomerate and basement is not exposed, but both formations crop out in places within a few feet of it. The lack of pervasive fault-related tectonite fabrics close to the contact rules out a major structural displacement, although minor shear strain associated with cover-layer folding is probable. These relationships, together with the occurrence of the Martinsburg Formation along the Reservoir fault near Bowling Green Mountain, where the entire Cambrian-Ordovician carbonate sequence is missing, strongly suggest that erosion of the Cambrian-Ordovician carbonates in the Green Pond Mountain region continued during deposition of the Trenton rocks elsewhere, and that the Cambrian-Ordovician rocks were completely eroded during a broad regional uplift extending from pre-Trenton emergence to at least the time of deposition of the Martinsburg Formation. As a result, the Martinsburg Formation may have been locally deposited directly on basement rocks; a unique occurrence in the Appalachians (A. A. Drake, Jr., U.S. Geological Survey, written communication, March 1989). The absence of the Martinsburg Formation elsewhere in the area suggests that the formation was either locally deposited in the Green Pond Mountain region, or completely eroded prior to deposition of the Green Pond Conglomerate, except where locally preserved by faulting.

The lower part of the Green Pond Conglomerate is thought to be consolidated piedmont alluvium derived from a rising source area to the east, which consisted of Proterozoic crystalline and lower Paleozoic sedimentary rocks. It consists of a basal cobble- to pebble-conglomerate that fines upward into interbedded pebble-conglomerate, quartzitic arkose, orthoquartzite, and siltstone. The basal conglomerate is coarser to the east at Green Pond, Brown, and Kanouse Mountains where angular cobbles of shale and quartz are common. To the west, at Bowling Green Mountain, the basal conglomerate contains mostly subangular to subround quartz pebbles and is interbedded with quartzitic arkose and orthoquartzite. The common occurrence of varicolored cherts in the conglomerate led Emery (1952) to include sedimentary rocks of Normanskill and Deepkill age as source rocks. The angularity and mixed composition of the conglomerate clasts led Finks (1968) to include a eugeosynclinal Taconic sequence as an eastern source. A Taconic sequence proposed by A. A. Drake, Jr., (U.S. Geological Survey, written communication, March 1989) includes rift facies, pre-margin material and slope-and-rise rocks of Laurentia.

The middle-to-upper parts of the Green Pond Conglomerate (quartzitic arkose, orthoquartzite, and siltstone) and the lower parts of the Longwood Shale represent piedmont alluvium or marine sand from a westward-receding shoreline (Finks, 1968). The upper part of the Longwood Shale marks the definite onset of a second marine transgression. Hartnagel (1907) reported marine fossils in these deposits in New York, and Finks (1968) noted intertidal sedimentary features. The interbedded shale, siltstone, and dolomite of the overlying Poxono Island Formation marks a Late Silurian return to shallow-marine continental-shelf conditions that continued with deposition of the calcareous sandstone, dolomite, and fossiliferous limestone of the overlying Berkshire Valley Formation.

Above the Berkshire Valley Formation, the Lower Devonian sedimentary sequence records a fluctuating shoreline prior to return of prolonged marine conditions in Middle Devonian time. The Connelly Conglomerate, correlated with the Oriskany Sandstone of the Valley and Ridge Province of New York (Finks, 1968; Boucot and others, 1970), unconformably overlies the Berkshire Valley Formation. Deposition of this pebbly, beach-type sand records a regression of the sea prior to renewed marine submergence and deposition of the overlying Esopus Formation (Finks, 1968). The cyclical siltstone, fine sandstone, and mudstone of the Esopus suggest a littoral, sublittoral, and bathyal marine environment which is corroborated by indicator fossil horizons (Finks, 1968). The Kanouse Sandstone, correlated with the Onondaga and Schoharie Formations of the Valley and Ridge Province of New York (Finks, 1968; Boucot and others, 1970), is similar to the Connelly Conglomerate and is thought to be a nearshore sandy beach deposit.

Shale above the Kanouse Sandstone was called Monroe Shale (Darton, 1894), Cornwall Shale (Bayley and others, 1914), and Marcellus Formation (Barnett, 1976). The term Cornwall Shale is reinstated here because it has priority and because this formation is restricted in its distribution to the Green Pond Mountain and Belvale Mountain-Schunemunk Mountain regions. The Cornwall Shale conformably overlies the Kanouse Sandstone and marks a return to deep shelf conditions.

The Bellvale Sandstone records delta progradation in response to marine regression caused by the Middle Devonian Acadian orogeny. The lower Bellvale contains roughly equal proportions of siltstone (subgraywacke) and shale, and coarsens upward into sandstone (sublithic arenite) and quartz-pebble sandstone. The Bellvale Sandstone has been interpreted as primarily a delta-front sheet and consisting of four recognizable facies: distal bar, distributary mouth bar, distributary channel, and subaerial delta plain (Kirby, 1981). The lower Bellvale Sandstone is transitional with the upper Cornwall Shale and represents a fifth facies, progradational, distal turbidite.

The youngest Paleozoic rocks are the alluvial fan deposits of the Middle Devonian Skunnemunk Conglomerate. The conglomerate forms a continuous outcrop belt in the northeastern part of the study area. Its well-cemented cobble-to-pebble conglomerate and quartzite underlie the several northeast-southwest trending ridges atop Bearfort Mountain whereas the less resistant siltstones and shales within the formation underlie linear swales parallel to these ridges. The Skunnemunk Conglomerate has been interpreted as a southeastern outlier of the Catskill delta of New York and Pennsylvania (Barrell, 1913, 1914a, 1914b). Consistent with this, Kirby (1981) interpreted the various lithologies as alluvial-plain facies representing distributary-channel, subaerial-delta, fluvial-channel and overbank-silt sediments. A coarsening upward trend and an upward increase in the proportion of metamorphic rock fragments compared to sedimentary rock fragments within the Bellvale-to-Skunnemunk transition reflect an advancing metamorphic and sedimentary source area from the east (Kirby, 1981) or the unroofing of a metamorphic source area (A. A. Drake, U.S. Geological Survey, written communication, March 1989). Paleocurrent studies show general westerly sediment transport during deposition of both the Bellvale and Skunnemunk Conglomerate (Kirby, 1981).

MACROSTRUCTURAL GEOLOGY

The Green Pond Mountain region is a block-faulted and downwarped basin segmented by northeast-southwest striking faults. It is fault bounded to the northwest along its entire length, and on the southeast side from Pinecliff Lake northward. The fault structures internal to the region are moderate- to high-angle reverse faults dipping both northwest and southeast. Folding within the region is an expression of the strain resulting from fault movement. Folds involving Silurian and younger rocks are of kink-fold type and have straight limbs, narrow hinge zones, and open to tight interlimb angles (Rowlands, 1983).

The region includes several doubly-plunging, northeast-trending folds. At the New Jersey - New York border, the structure is a tight syncline, overturned to the northwest. Between Clinton Reservoir and Lake Denmark, three major anticline-syncline pairs are segmented by faults located southeast of the anticline crests. These faults juxtapose older rocks to the northwest with younger rocks to the east. South of Lake Denmark, a single major anticline-syncline fold pair is segmented by many faults parallel to regional strike.

The Reservoir fault forms the northwest boundary of the rock belt from Bowling Green Mountain to the New York State line. It is generally viewed as a fault contact between basement and cover rocks, but in actuality consists of many anastomosing faults that extend away from this contact on both sides. It is a major deformation zone with a complex movement history. Ductile and brittle-ductile shear zones containing retrograde mineral assemblages dip steeply southeast within the Middle Proterozoic rocks of the Reservoir fault system (Bizub and Hull, 1986; Hull and others, 1986; R. A. Volkert, N.J. Geological Survey, written communication, 1988). Drilling records from northeast of Clinton Reservoir (Williams, 1981) and northwest-dipping overturned strata between the Reservoir and Russia faults suggest localized, steep, northwest dips.

A Phanerozoic compressive movement history along the fault system is recorded in the Paleozoic rocks by small fault populations (pls. 1 and 2) that show both dip-slip and strike-slip shear. A pronounced left-lateral strike-slip component is evident from stratigraphic displacement along the small faults and is corroborated by foliation drag in the bordering Middle Proterozoic rocks (R.A. Volkert, New Jersey Geological Survey, written communication, 1988). Significant normal dip-slip displacement has not been observed; such evidence can be very localized and easily missed (Hull and others, 1986).

The Longwood Valley fault borders the region south of Green Pond. Its subsurface attitude and movement history are uncertain. A rejoining splay fault southwest of Woodstock (Dover quadrangle) preserves a brittly deformed fault slice of Kanouse Sandstone in which quartz vein arrays indicate compressive dip-slip movement.

Southeast-dipping reverse faults locally occur along the eastern margin of the region north of Echo Lake. The Greenwood Lake fault, bounding the region from Pinecliff Lake northward, was recognized by Offield (1967) and Rowlands (1983). The Union Valley fault is interpreted from the overturned beds of Green Pond Conglomerate and Esopus Formation along and to the south of Union Valley Road, on drilling reports (R.E. Wright Associates, 1987), and from missing stratigraphic units west of Greenwood Lake. Its nature and continuity are unclear. Both faults involve dip-slip components of less than 1640 feet based on stratigraphic separation. The en echelon arrangement of the faults suggests slip transfer between them along strike.

The Bowling Green Mountain anticline is the westernmost of three anticlines in the area south of Clinton Reservoir. It is flanked on the northwest by the Reservoir fault system and on the southeast by the Longwood Valley fault. The relationship between faults here and cover folding is unclear. Little deformation is evident in the Proterozoic rocks near the fold-hinge area, and the most common strain features in the cover rocks are in the southeast fold limb, where elongate, en echelon quartz veins strike subparallel to regional strike and dip steeply to moderately northwest within the bedding plane. Associated minor bedding flexures trend subparallel to regional strike and plunge moderately northeast. These relationships suggest that the anticline is a cover fold related to movement on the Longwood Valley fault, and perhaps a blind splay fault to the north, rather than to movement on a basement fault in the Middle Proterozoic core of Bowling Green Mountain.

To the east of Bowling Green Mountain, the Brown Mountain anticline is bounded on the southeast by the Brown Mountain fault. This doubly-plunging anticline and the Brown Mountain fault are in en echelon alignment with the Green Pond Mountain anticline and Green Pond fault respectively. The Brown Mountain fault is interpreted as a moderate- to high-angle, northwest-dipping reverse fault because the southeast limb of the anticline is locally overturned to the southeast along the fault trace.

Green Pond Mountain is underlain by the southeasternmost anticline in the area. The Green Pond fault borders the Green Pond Mountain anticline on the southeast and is interpreted as a near-vertical to northwest-dipping reverse fault. This interpretation is based on vertical strata near the Proterozoic core of the anticline and on the en echelon alignment with the Brown Mountain fault. Both faults probably originated deep within the Middle Proterozoic basement, and may share in displacement slip transfer with the Longwood valley fault.

The area immediately south of Green Pond Mountain is interpreted as containing conjugate shears involving moderate- to high-angle reverse faults dipping both northwest and southeast. Ramsay and Huber (1987, fig. 26.29) illustrate how such shear zones can develop large bulk strain resulting in lateral shortening and vertical elongation, as interpreted for this area. The southeast-dipping reverse faults continue southward from Picatinny Lake. The Picatinny fault crops out at Picatinny Arsenal in Dover, New Jersey. The fault loses displacement to the northeast within the arsenal and becomes a system of isolated splay faults and related fault-tip folds. The Berkshire Valley fault is inferred from missing stratigraphic units between southeast-dipping, overturned beds of Green Pond Conglomerate and rocks resembling the Esopus Formation and the Cornwall Shale in Berkshire Valley (Ebasco Services, 1958; Canace and others, 1983).

MESOSTRUCTURAL GEOLOGY

Cleavage, Joints and Veins

Cleavage allows a rock to split along secondary, aligned fractures or other spaced, planar structures or textures produced by deformation or metamorphism. The two primary types of cleavage are slaty and spaced. Spaced cleavage includes fracture, strain-slip, and crenulation varieties (Suppe, 1985). A joint is a surface of parting or fracture without differential displacement. Parting joints subparallel to bedding are most common in the study area; these are excluded from the data shown here to emphasize the distribution and orientation of the subordinate joint sets. A vein is a tabular or sheetlike epigenic mineral filling of a fracture in a host rock. Mineralized, slickensided shear planes are not considered to be veins. Various types of vein arrays have been recognized by Ramsay and Huber (1987). The present study excludes small (less than 3 feet long) veins in en echelon alignment.

Two noncoaxial, spaced cleavage sets (pls. 1 and 2) affect the rock sequence. The older set is regional in extent, formed during the initiation of folding, and strikes subparallel to the folds (Rowlands, 1983). The second set postdates folding, strikes roughly east-west, is restricted in distribution, and locally crenulates the first cleavage (Herman, 1987; Mitchell and Forsythe, 1988).

The dominant joint sets, aside from bedding partings, are cross-strike, subvertical fractures, and cross-strike hybrid shear fractures (conjugate fractures having an acute dihedral angle of less than 60°). Subordinate joint sets generally occur near fold axes or faults, strike both subparallel and oblique to the fold axes and vary from vertical to gentle in dip. These subordinate joint sets include the longitudinal (vertical) set and related hybrid shear fractures.

Figure 2 (pl. 2) relates the joint data to the major fold axes and faults. This extrapolated- fracture analysis involved locating subparallel-striking joints (less than 5° strike divergence) from adjacent field stations and drawing a line parallel to the strike of the joints through each of the stations. The length of the lines is proportional to the number of joints of similar strike. The compilation should be used in conjuction with fracture-trace and lineament analyses.

Vein data are from all rock types but have a sampling bias favoring the more competent units: Green Pond Conglomerate, Bellvale Sandstone, and Skunnemeunk Conglomerate. Figure 3 (pl. 2) shows the most common veins and pole maximums of 196 quartz-filled veins from 100 stations. The polygons in the middle right hemisphere are maximums of the poles-to-veins for the composite vein distribution. The maximums represent 4 and 8 times the average relative pole density for the composite vein set. The maximums are derived from the spherical area associated with each data pole relative to the average pole area determined from the composite vein set, rather than the more usual poles-per-1° counting circle (Gray and others, 1987).

The most common vein orientations are north-south, with dips ranging from 68° W to 6° E. Six subordinate maximums appear in three conjugate acute sets varying about the north-south strike and dipping at moderate angles to the west. One interpretation of the data, based on the assumptions that the veins result from mineralization in a dilatant fracture, and that dilatant fractures are oriented at low angles to regional compressive stresses, is that the orientations of the veins reflect a single north-south compressional event. The subordinate veins in this interpretation may have filled fractures that had a suitable component of resolved compressive stress to attain dilatation. Another interpretation is that the veins reflect a sequence of regional compressive forces that vary slightly in azimuth from north-south. Mitchell (1985) and Mitchell and Forsythe (1988) interpret vein arrays as recording three compression directions at successively clockwise positions from the northwest (NW, NNW to N, and NE). The vein data of this study corroborates their interpretation.

Minor Faults within the Reservoir Fault System

The minor faults shown on plates 1 and 2 are slickensided surfaces of minor displacements. Most are characterized by overlapping quartz fibers oriented at low angles to slip surfaces (slickenfibers of Wise and others, 1984). These were used to determine the sense of fault displacement as described by Durney and Ramsay (1973).

Lower hemisphere, equal-angle stereographic projections (figs. 4, 5, 6, and 7) of minor-fault attitudes (great-circle tracings) and accompanying slickenside lineations (squares) are shown for four locations near the northeast-trending Reservoir fault system. Minor faults strike dominantly subparallel to the fault traces and, to a lesser extent, at oblique angles to them. Dip-slip motion on minor faults is dominantly reverse. Strike-slip motion of minor faults striking subparallel to the trace of the fault system is dominantly left-lateral (figs. 4 and 7); however, both reverse and left-lateral motions are recorded at the site shown in figure 7. The abundant display of two different motions on subparallel minor faults near the Reservoir fault suggests that movement occurred on the fault at least twice in the Phanerozoic.

Discussion

Two phases of post-Taconic compressive deformation are recorded in the region by two noncoaxial cleavage sets (pls. 1and 2). These phases resulted from compressive stress directed northwest-southeast and north-south, and substantiate progressive clockwise rotation of the compressive stress field described by Mitchell and Forsythe (1988). This interpretation is also compatible with the movements recorded in the Paleozoic components of the Reservoir fault system; the dip-slip motions result from the regional compressive event oriented nothwest-southeast. The strike-slip motion could result from reactivation due to a changing stress field oriented at a suitable angle to contribute significant shear stress and oblique-fault motion. Analogous movement may have occurred on other faults within the region, but these relations have not been studied in comparable detail. Normal faults resulting from extensional rifting during the Mesozoic may be present but were not observed.

TIME OF DEFORMATION

A minimum of three phases of Paleozoic deformation are recorded within the study area. The first was a broad uplift during the Ordovician Taconic orogeny, resulting in the differential removal of pre-Silurian sedimentary rocks throughout the region. This uplift may have involved block faulting which initially segmented the Martinsburg Formation, now exposed along the Reservoir fault. The second and third phases were noncoaxial compressive events during the Late Paleozoic Alleghanian orogeny. The second phase, resulting from the development of deep-seated moderate- to high-angle brittle and brittle-ductile shear zones, involved block faulting, kink folding, and cleavage development along a regional northeast trend. The third phase, probably related to the restricted cross-cleavage development and reactivated strike-slip motion within the Reservoir fault system, resulted in north-south shortening strain. Mesostructures associated with both later phases include the joints, veins, slickensided shear planes, and en echelon vein arrays in the post-Ordovican rocks.

The last two deformation phases are thought to result from the Alleghanian orogeny because they involve rocks of Middle Devonian age, and because the progressive clockwise rotation of the recorded finite-strain azimuths (Mitchell, 1985; Mitchell and Forsythe, 1988) correlates with those reported for both the Allegheny Plateau in Pennsylvania and New York (Geiser and Engelder, 1983), and the Kittatinny Valley of New Jersey (Drake and Lyttle, 1985). Most of the faults are probably Alleghanian, based on their relation to rocks of Devonian age. However, their relative timing is uncertain, and they may be coeval with each other. Pre-Alleghanian deformation within the region is suggested by ductile deformation fabrics and cross-cutting mesostructures in the Proterozoic rocks of the Reservoir fault system.

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