LATE PALEOZOIC DEFORMATION IN THE RESERVOIR FAULT ZONE AND GREEN POND OUTLIER, NEW JERSEY HIGHLANDS

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INTRODUCTION

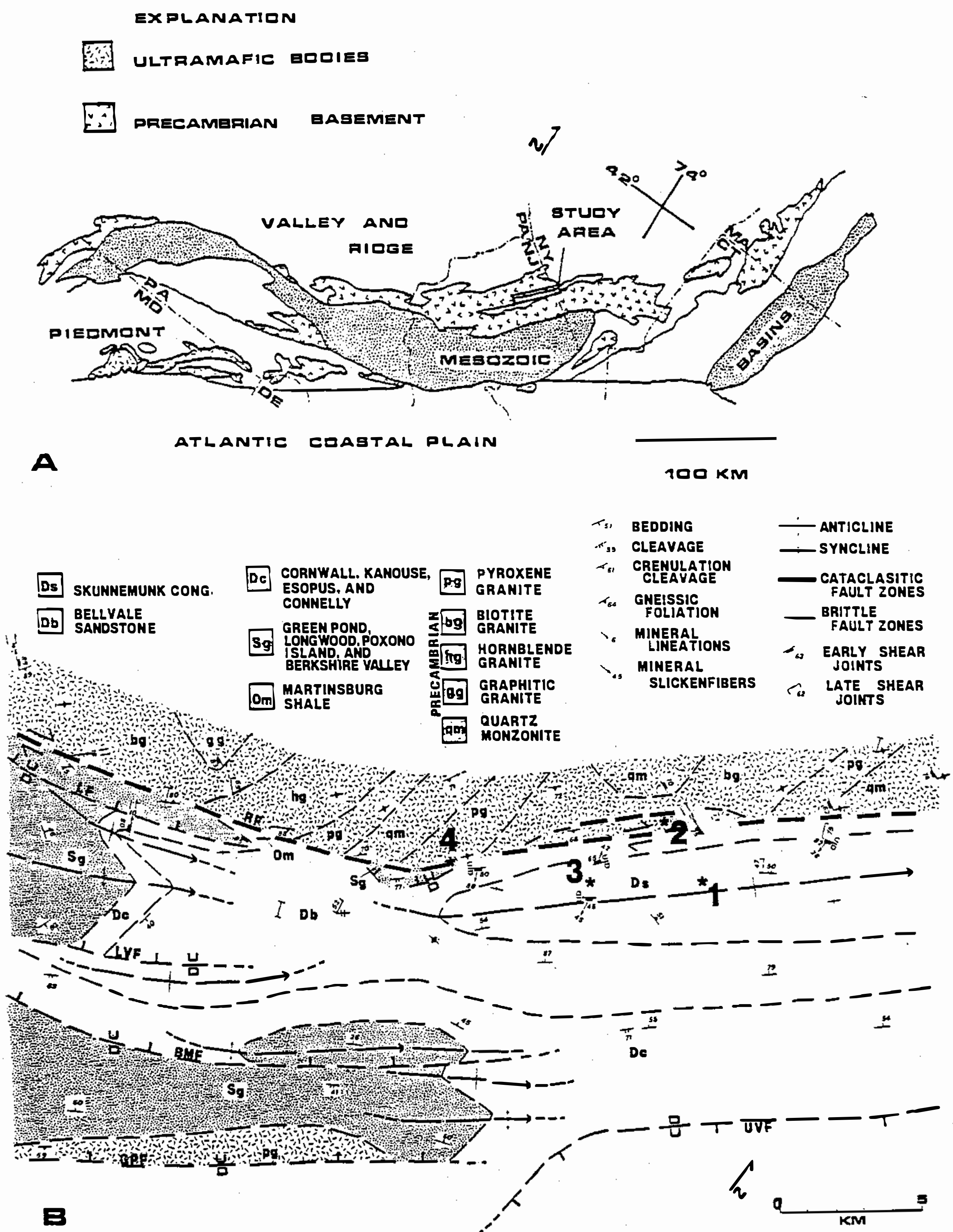
The New Jersey Highlands are part of the Precambrian Reading Prong which extends from Massachusetts to Pennsylvania (Fig. 1a). The field study area is in north-central New Jersey and contains the Reservoir Fault zone and Green Pond outlier.

The Reservoir Fault zone forms the boundary between the western side of the Paleozoic sedimentary rocks of the Green Pond outlier and Grenville gneisses of the New Jersey Highlands (Fig. 1b). The Paleozoic Green Pond outlier locally contains northwest-dipping reverse faults (Herman, 1987; Herman and Mitchell, 1989) and southeast-verging folds. These structures indicate southeast directed transport which is enigmatic with respect to the rest of the Appalachian foreland fold and thrust belt.

The major structure in the area is the northeast-striking Reservoir Fault zone. The fault zone is a high angle 100 m wide cataclasite and semi-brittle mylonite zone, which is composed predominantly of Grenville gneisses. Numerous theories have been presented for the deformational history of the Reservoir Fault zone including Mesozoic normal faulting (Lewis and Kummel, 1912; Ratcliffe, 1980), Proterozoic wrench faulting (Helenek, 1987), Alleghanian sinistral strike-slip faulting (Mitchell and Forsythe, 1988), and Alleghanian reverse faulting (Herman and Mitchell, 1989). Recent work by Malizzi and Gates (1989) indicates that the Reservoir Fault zone and Green Pond outlier form the east side of a positive flower structure that formed through Late Paleozoic dextral transpression with later sinistral strike-slip reactivation.

STRATIGRAPHY

The bedrock stratigraphy in northern New Jersey includes a sequence of Grenville gneisses (locally known as the Byram and Losee gneisses) and Middle Paleozoic clastics and carbonates. The Middle Proterozoic gneisses in the New Jersey Highlands are the oldest units in the study area (Fig. 1b) and have been dated at 913 ma by Rb/Sr whole rock analysis of the Canada Hill granite in New York (correlative of the Byram gneiss of New Jersey) (Helenek and Mose, 1984). The Precambrian units consist of well foliated, medium-grained hornblende, pyroxene, and biotite quartz monzonite gneisses and well foliated, medium-grained hornblende, pyroxene, graphite, and biotite granite to alkali-feldspar granite gneisses. The gneisses contain accessory apatite, magnetite, garnet, zircon, sphene, and ilmenite with secondary and joint-filling epidote, chlorite, quartz, and hematite. The granite gneisses contain zones of locally abundant scapolite, apatite, diopside, potassium feldspar, plagioclase, titanite, and tremolite indicating a possible calc-silicate protolith.



EXPLANATION
ULTRAMAFIC BODIES
PRECAMBRIAN BASEMENT
N
42°
74°
STUDY AREA
VALLEY AND RIDGE
NY
PA NJ
CT
MA
PA
MD
PIEDMONT
MESOZOIC
BASINS
DE
ATLANTIC COASTAL PLAIN
A
100 KM
BEDDING
CLEAVAGE
CRENULATION CLEAVAGE
GNEISSIC FOLIATION
MINERAL LINEATIONS
MINERAL SLICKENFIBERS
ANTICLINE
SYNCLINE
CATACLASITIC FAULT ZONES
BRITTLE FAULT ZONES
EARLY SHEAR JOINTS
LATE SHEAR JOINTS
Ds SKUNNEMUNK CONG.
Db BELLVALE SANDSTONE
Dc CORNWALL, KANOUSE, ESOPUS, AND CONNELLY
Sg GREEN POND, LONGWOOD, POXONO ISLAND, AND BERKSHIRE VALLEY
Om MARTINSBURG SHALE
PRECAMBRIAN
pg PYROXENE GRANITE
bg BIOTITE GRANITE
hg HORNBLENDE GRANITE
gg GRAPHITIC GRANITE
qm QUARTZ MONZONITE
LF
RRF
LYF
BMF
UVF
GPF
B
KM

Localized cataclasite zones occur in the quartz monzonite gneiss, biotite granite gneiss, hornblende granite gneiss, and pyroxene granite gneiss. Age relations between the gneisses are unknown but all are cut by zircon, biotite, and monazite bearing granitic pegmatites.

The Paleozoic sedimentary rocks of the Green Pond outlier (Table 1) overlie the Middle Proterozoic rocks. The Green Pond outlier consists of Ordovician-Devonian sedimentary units, typical of the Valley and Ridge Province to the west (Kummel and Weller, 1902). The Ordovician Martinsburg Formation is the oldest unit in the study area. The Martinsburg Formation is overlain by the Middle Silurian Green Pond conglomerate (correlative of the Shawangunk Formation) and Longwood shale (correlative of the Bloomsburg Formation) (Wolfe, 1977). Upper Silurian units include the Poxono Island Formation and Berkshire Valley Formation. The lower Devonian units include the Connelly conglomerate (correlative of the Oriskany Formation), the Esopus Formation, and the Kanouse Formation which are overlain by the Cornwall shale. The Bellvale sandstone and Skunnemunk conglomerate (correlative of the Catskill formation) are the Middle Devonian units. All of the sedimentary units contain en-echelon quartz vein arrays.

The Precambrian gneisses of the New Jersey Highlands were formed from unknown protoliths by a Grenvillian tectonothermal event (Helenek, 1987). The gneisses are overlain by the Ordovician shale which represents sediment that filled a west-facing starved basin (Pollack, 1975). Fluvial molasse deposits shed from a highlands to the southeast, subsequent to the Taconic orogeny, produced the Middle Silurian clastic units. A Late Silurian and Early Devonian marine transgression occurred forming a shallow sea (Wolfe, 1977). Marine carbonates and sandstones were deposited at the margin of the sea. Uplift caused by the Acadian orogeny produced a Middle Devonian marine regression. During the marine regression deltaic clastic units were deposited, and are the youngest units in the Green Pond outlier.

PRE-EXISTING STRUCTURE

A pervasive gneissic foliation and isoclinal folds are the earliest recognizeable structures in the Grenville gneisses. The foliation is nearly vertical and north- to northeast-striking. The foliation is defined by aligned pyroxene, biotite, hornblende, and graphite along with quartz and feldspar ribbons depending upon lithology. It has been proposed that the gneissic foliation represents a medium to high-grade Proterozoic mylonite zone in the granitic units (Hull et al., 1986) but a thorough investigation of Grenville deformation is beyond the scope of this study. The gneisses also contain isoclinal folds in the foliation with northeast-striking, vertical axial planes. The Grenville gneisses are cut by northeast-striking, nearly vertical granitic pegmatites along the Reservoir Fault.

Fig. 1. (A) Regional map of the Central Appalachians indicating the study area. (B) Geologic map of the Reservoir Fault and Green Pond outlier (modified after Herman and Mitchell, 1989). RF-Reservoir Fault, LF-Longwood Fault, LVF-Long Valley Fault, BMF-Brown Mountain Fault, GPF-Green Pond Fault, and UVF-Union Valley Fault. Fault movement sense indicators as indicated.

TABLE 1. Stratigraphy (Barnett, 1976; Herman and Mitchell, 1989; this study).

DEVONIAN	Skunnemunk Conglomerate- Thin to very thick bedded, medium-grained quartz pebble conglomerate with a red-purple medium-grained sandstone matrix with medium-grained red sandstone interbeds. Conglomerate is locally crossbedded. 915 m thick. Bellvale Sandstone- Thin to very thick interbedded gray, medium-grained sandstone and gray shale. Locally fossiliferous and crossbedded. 600 m thick. Cornwall Shale- Thin to thick bedded, fine-grained fissile black shale interlayered with laminated gray siltstone. Moderately fossiliferous. 300 m thick. Kanouse Sandstone- Medium to thick bedded, gray to tan conglomerate and coarse to fine-grained graded sandstone. 15 m thick. Esopus Formation- Thin interlayers of gray mudstone and medium-grained sandstone. Fossiliferous. 60 to 100 m thick. Connelly Conglomerate- White, medium-grained quartz pebble conglomerate with a tan, medium-grained sandstone matrix. 12 m thick.
SILURIAN	Berkshire Valley Formation- Thin-bedded limestone with interlayers of gray, intraformational dolomitic breccia. Thickness unknown. Poxono Island Formation- Medium-bedded gray dolomite interlayered with thin bedded medium-grained calcareous sandstone. 80 to 130 m thick. Longwood Shale- Medium-bedded purple shale with interlayers of red crossbedded medium-grained sandstone. 100 m thick. Green Pond Conglomerate- Medium-grained quartz pebble conglomerate with a medium-grained sandy matrix and silica cement. The conglomerate contains thin bedded interlayers of crossbedded sandstone. 300 m thick.
ORD.	Martinsburg Shale- Black, slaty fine-grained shale with thin beds of medium-grained sandstone. Moderately fossiliferous and crossbedded. Thickness unknown.
PRECAMBRIAN	Granite Pegmatites- Very coarse-grained quartz, plagioclase, and microcline pegmatites dikes with minor biotite. Accessory zircon and apatite. Secondary epidote, hematite, and monazite. 1 to 10 m thick. Quartz Monzonite Gneisses- Medium-grained hornblende, pyroxene, and biotite, quartz monzonite gneisses with quartz, plagioclase (An-37%), and microcline. Accessory magnetite, apatite, garnet, sphene, and zircon with secondary chlorite. Granite Gneisses- medium-grained hornblende, pyroxene, graphite, and biotite granite to alkali-feldspar granite gneisses with microcline and plagioclase (An-38%). Accessory sphene, apatite, zircon, and magnetite with secondary epidote, chlorite, monazite, and hematite. Locally contains abundant scapolite, tremolite, and titanite.

LATE PALEOZOIC STRUCTURES

Late Paleozoic structures in both the Green Pond outlier and Reservoir Fault zone consist of dextral strike-slip shear zones and coeval folds, cleavage, and reverse faults. Northeast-striking dextral strike-slip kinematic indicators are present in both the Paleozoic and Precambrian units within the Reservoir Fault zone. The Silurian Green Pond conglomerate contains semi-ductile Type II S-C mylonites (Lister and Snoke, 1984) within the Reservoir fault zone. Exposures exhibit a well defined C-surface and a poorly defined S-surface typical of a Type II S-C mylonites (Fig. 2a). The Green Pond conglomerate also exhibits northwest-striking dextral shear bands that cut the C-planes (Fig. 2a). S-planes are defined by the quartz grains of the rock matrix and C-planes are defined by quartz ribbons.

The sheared Green Pond conglomerate also contains microstructural northeast-striking dextral strike-slip kinematic indicators. Recrystallized σ-Type porphyroclasts (Simpson and Schimd, 1983; Simpson, 1986; Passchier and Simpson, 1986) in quartz ribbons with rotated tails and dragged deformation bands in quartz ribbons (Fig. 2b) indicate dextral movement. The fabric in the quartzite contains a foliation and shear bands aligned subparallel to bedding that indicate movement sense. Similar structures were described in the Moine thrust zone of northwest Scotland by Bowler (1989). Northwest- and northeast-striking conjugate deformation bands and deformation lamellae in quartz grains (Heard and Carter, 1968) occur in the Type II S-C mylonites and indicate a dextral shear sense. Deformation bands and lamellae develop when the rate of dynamic recrystallization of the mineral is low with respect to the shear strain rate (Passchier and Simpson, 1986; Simpson, 1986). The maximum compression direction is indicated by the acute angle between the deformation bands. A west-northwest to east-southeast maximum compression direction is indicated by the conjugate deformation bands.

Sheared Bellvale sandstone within the Reservoir Fault zone consists of a 5 m wide zone of semi-ductile cataclasite and thin minor faults filled with hematite and chlorite. Northeast-striking dextral movement is indicated by offset quartz veins and sandy laminations. Fine-grained kinked chlorite indicates an east-southeast to west-northwest maximum compression. Drill core samples from along the Reservoir Fault in the Cornwall shale contain northeast-striking dextral strike-slip and reverse shear indicators. The shear indicators from the drill core samples include dragged and offset quartz veins and slickenfibers.

The Grenville gneisses within the Reservoir Fault zone also exhibit northeast-striking dextral strike-slip indicators. The Reservoir Fault zone consists of cataclasite with epidote, hematite, and chlorite in the shear planes. The cataclasite contains microcline, quartz, and plagioclase grains with pull-apart textures (Fig. 3a). The cataclasite also contains thin minor faults filled with calcite, epidote, and chlorite that offset quartz and plagioclase grains. The gneisses also contain coarse-grained chlorite fish and fine-grained recrystallized muscovite fish.

The Grenville gneisses contain horizontal mineral lineations indicating northeast-striking strike-slip movement. Dominant northeast-striking and minor northwest-striking conjugate shear joints (Fig. 4a) with horizontal slickenfibers indicate dextral and sinistral movement, respectively (Fig. 3b). The shear joints were analyzed using a technique developed by Hardcastle

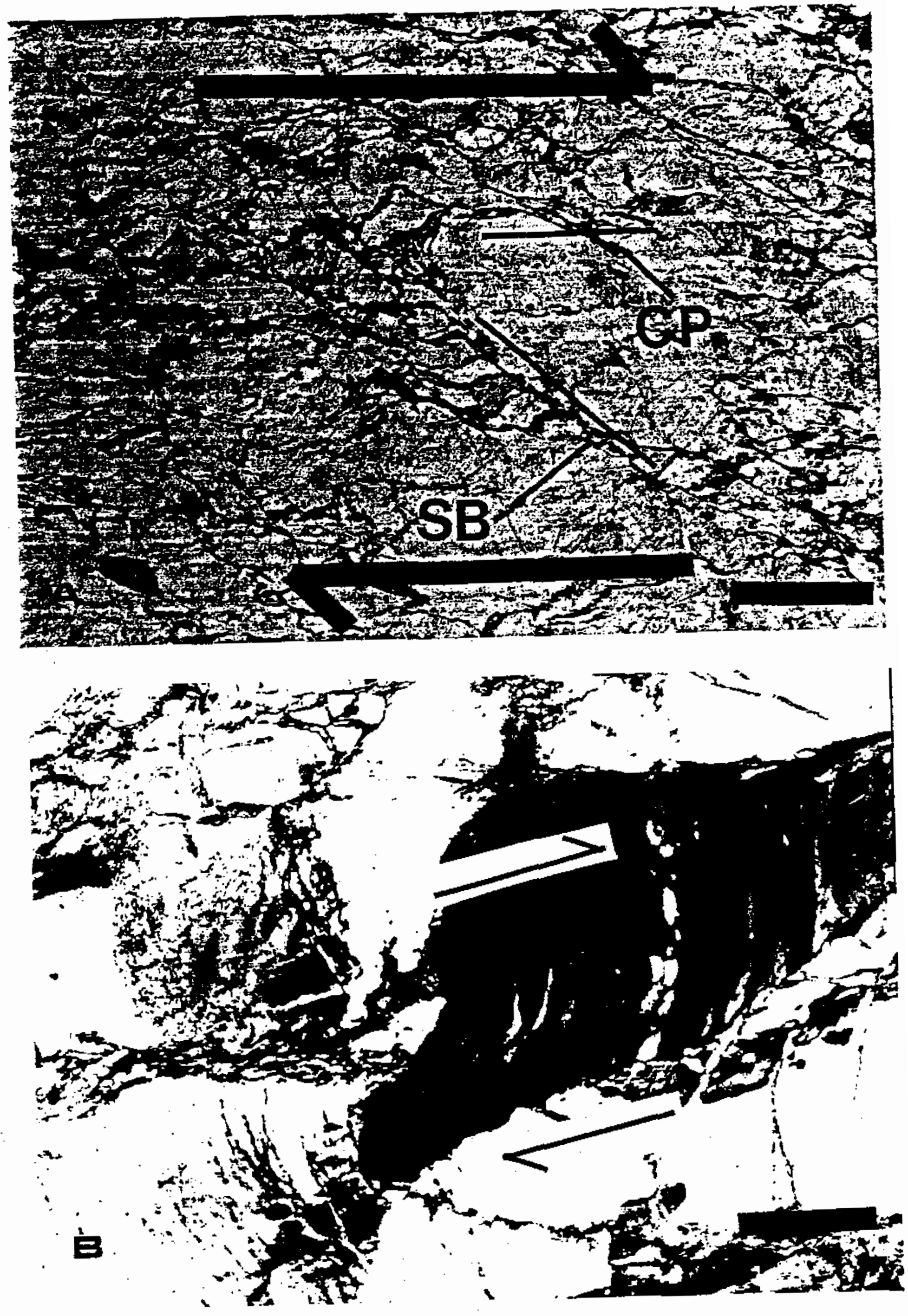
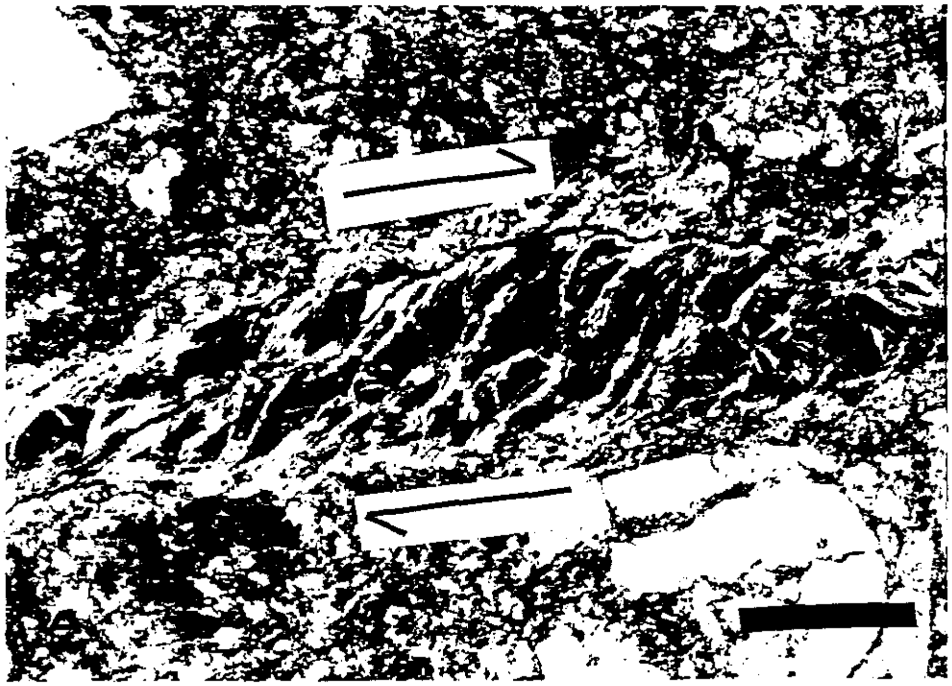


Figure 2. (A) Northeast-striking C-plane (CP) and northwest-striking shear band (SB) in a Type II S-C mylonite from the Silurian Green Pond conglomerate from within the Reservoir fault zone, both indicating dextral drag. Bar scale 10 mm. (B) Deformation bands in a Type II S-C mylonite from the Silurian Green Pond conglomerate in the Reservoir fault zone indicating northeast-striking dextral shearing. Bar scale 1 mm.



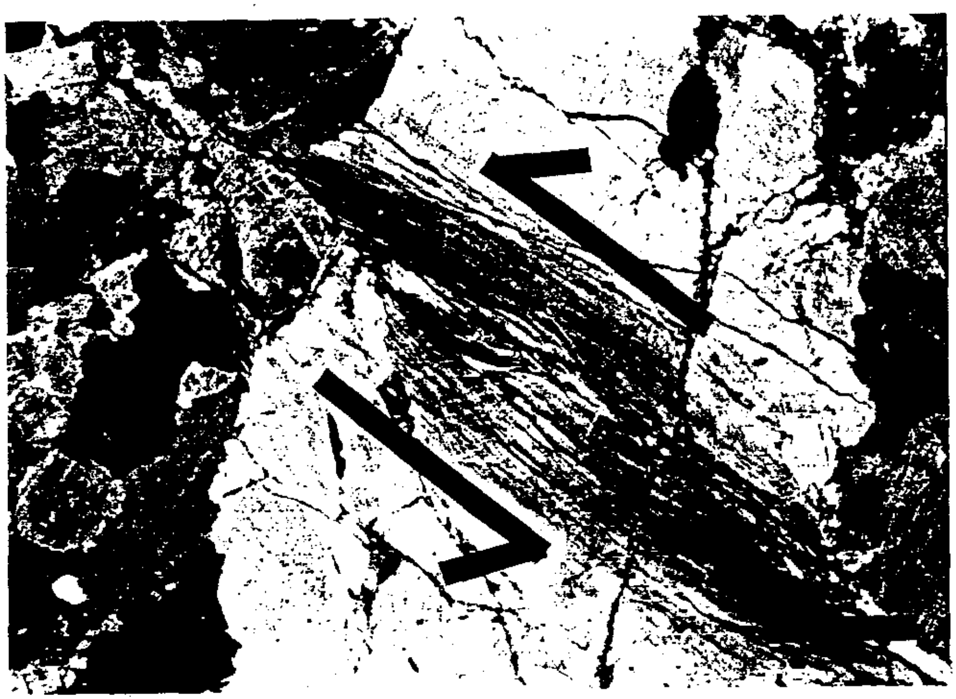


Figure 3. (A) Dextral chlorite fish in Grenville granite gneiss from within the Reservoir fault zone. Bar scale 1 mm. (B) Offset quartz ribbon indicating northwest-striking sinistral faulting. Bar scale 5 mm.

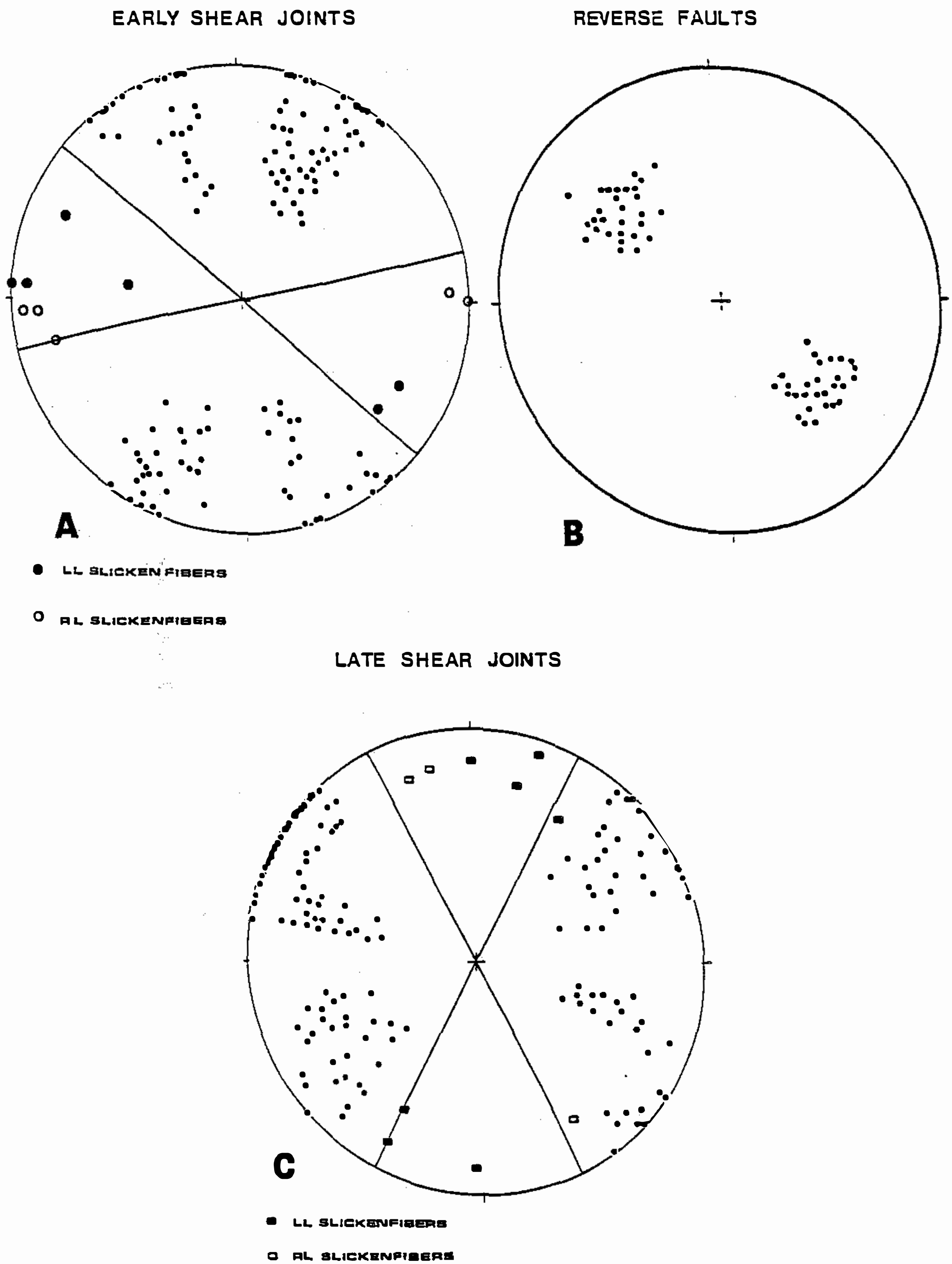
(1989) from methods of Reches (1987), where tensor configurations for fault populations are derived using a least squares regression solution. Only well exposed faults containing slickenfibers with well developed steps were used. A total of 19 minor faults were analyzed using this method and yielded N80W as the average maximum stress direction. In addition, plagioclase kink geometry (Gay and Weiss, 1974) indicates an almost east-west maximum compressive stress. The microstructures and tensor analysis yield very similar stress directions.

The adjacent Green Pond outlier locally contains northwest-dipping reverse faults (Herman, 1987; Herman and Mitchell, 1987; Mitchell and Forsythe, 1988) and southeast-verging folds (Fig. 1b). The reverse faults exhibit top to the southeast movement indicated by fibrous, stepped quartz and chlorite slickenfibers. Detailed mapping indicates apparent steepening of reverse faults with depth. West-side up near vertical reverse movement also occurred on the Reservoir Fault. Southeast-verging folds are indicated by axial plane orientations and bedding-cleavage relations. The mesoscopic folds are assymmetric with northwest-dipping axial planes (Bizub and Hull, 1986; Mitchell and Forsythe, 1988). The sandstones and conglomerates in the outlier contain pervasive solution cleavage sub-parallel to bedding, but the shales exhibit slaty cleavage.

Northeast-striking and northwest-dipping reverse movement indicators are evident in drill core samples of Devonian Cornwall shale from along the Reservoir Fault zone. Mesoscopic conjugate reverse faults, referred to here as small scale keystone structures, consist of northeast-striking, northeast- and northwest-dipping reverse faults (Fig. 4b). The small scale keystone structures range from 0.2 to 10 m wide but apparently reflect large scale structures as well. The sedimentary rocks of the Green Pond outlier contain the majority of the keystones in the study area. Slickenfibers indicate reverse movement sense. In addition, offset quartz veins and quartz pebbles indicate reverse movement in the Skunnemunk conglomerate. The Grenville gneisses also contain small scale keystone structures. Reverse movement sense is indicated by offset gneissic foliation and stepped slickenfibers.

LATEST STRUCTURES

This latest deformation overprints the earlier structures. The Reservoir Fault was reactivated as a sinistral strike-slip brittle fault. Horizontal slickenfibers on northeast-striking faults indicate this latest strike-slip movement. Kinked brittle plagioclase grains and northeast-striking sinistral offset grains are evident in thin sections of the gneisses. En-echelon vein arrays in the Green Pond outlier also indicate northeast-striking sinistral strike-slip movement (Mitchell and Forsythe, 1988). Minor northeast- and northwest-striking conjugate shear joints with horizontal slickenfibers indicate sinistral and dextral strike-slip movement, respectively (Fig. 4c). The Late Paleozoic shear joints are offset by the latest shear joints on the meso- and microscopic scale. The latest shear joints were also analyzed using the Hardcastle (1989) method. A maximum compression of N00E was derived from a total of 30 minor faults. Kinked plagioclase geometry (Gay and Weiss, 1974) and east-west crenulation cleavage also support the late north-south maximum compression.


EARLY SHEAR JOINTS
REVERSE FAULTS
A
B
LL SLICKEN FIBERS
RL SLICKENFIBERS
LATE SHEAR JOINTS
C
LL SLICKENFIBERS
RL SLICKENFIBERS