Deformation in the Striped Rock Pluton, Southwest Virginia

by

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(ABSTRACT)

The Striped Rock pluton of the late-Proterozoic Crossnore Plutonic-Volcanic suite is located beneath the Fries Thrust zone in the Blue Ridge province of southwest Virginia. The multiphase granite pluton has been affected by episodes of brittle and crystal plastic deformation at both the microscopic and mesoscopic scales. Brittle deformation preceded and postdated crystal plastic deformation.

The pluton is cut by pervasive centimeter-scale cataclasite zones and ductile shear zones that vary in width from a few millimeters to several hundred meters. The majority of mylonite zones in the pluton strike east and northeast and are inclined moderately southeast. Cataclasite zones strike northeast and northwest. Deformation is most intense along the southern contact with the Cranberry gneiss where both pluton and country rock are deformed into a northeast-striking zone of mylonitic augen gneiss. The intensity of deformation decreases northwestward. Southeast-directed normal fault displacement is common to east and northeast-trending shear zones. A minor group of northwest-oriented shear zones dip moderately southwest and northeast and show sinistral, strike-slip displacement. Quartz-, chlorite- and stilpnomelane-filled cracks and veins with northeast and northwest trend uniformly overprint mylonite and cataclasite zones of all scales.

Microstructure changes progressively with increasing strain. Feldspar grains are cut by at least two generations of mineralized, dilatant microcracks. Minerals precipitated in the early set of microcracks have undergone extensive crystal plastic deformation. Late-stage microcracks are filled with completely undeformed minerals.

The spatial distribution of normal fault mylonite zones is geometrically consistent with generation during 1) late-Proterozoic extension, 2) Mesozoic extension, 3) rigid-body rotation during Paleozoic thrusting, or 4)"gravitational collapse" during Paleozoic thrusting. Field and microstructural evidence favor (4). The exact timing of deformation is not, however, well-constrained.

Acknowledgements

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I would like to thank for her support, advice and critical review of this manuscript. Additionally, support and advice given by and are gratefully acknowledged.

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Introduction

The Southern Appalachians are characterized by numerous northeast-trending imbricate thrust fault systems and westward vergent fold belts generated in compressional tectonic regimes (e.g., Bryant and Reed, 1970; Cook et al., 1979; Bartholomew and Lewis, 1984). The Blue Ridge structural province comprises a northeast-trending anticlinorium extending from southern Maryland through Alabama (Rankin et al., 1973). Exposed in the core are crystalline rocks of early-Precambrian age, flanked by younger late-Precambrian and Cambrian metasedimentary and metavolcanic sequences. Crystalline rocks contained in the Blue Ridge thrust sheet in southwest Virginia have undergone a complex history of deformation and metamorphism associated with Precambrian (Grenville) and Paleozoic (Taconic, Acadian and Alleghanian) orogenic events (e.g., Bryant and Reed, 1970; Rankin et al., 1973; Glover et al., 1983).

Crystalline rocks deform very heterogeneously. Most of the deformation is restricted to narrow, planar zones of predominantly simple shear deformation (Ramsay and Graham, 1970). Shear zones are commonly localized by planar anisotropies in an otherwise homogeneous rock mass (e.g., Knipe and White, 1979;

White et al., 1980; Segall and Simpson, 1986). They may form by brittle processes (e.g., Chester et al., 1985), crystal plastic processes (e.g., White, 1976) or a combination of both (e.g., Tullis and Yund, 1977). Both brittle and ductile shear zones are characterized by very large strain accumulations relative to the adjacent rock mass and form when the hardening capacity of the rock has been exceeded (White et al., 1980).

The brittle-plastic transition (terminology of Rutter, 1986) is defined by a gradual change from predominantly brittle to predominantly crystal plastic deformation mechanisms. The transition is thought to occur at crustal levels where a change from seismic faulting to aseismic creep takes place (Sibson, 1983). The change in flow regimes from predominantly cataclastic to predominantly crystal plastic may be correlated with variations in physical conditions such as stress, strain rate (e.g., White, 1976), the presence of fluids (e.g., Blacic and Christie, 1984), metamorphic reactions (e.g., White and Knipe, 1978), confining pressure and temperature (e.g., Tullis and Yund, 1980). The responses of deformation mechanisms to changes in these parameters are reflected in the microstructure of the rock and are well illustrated in rocks deformed under conditions corresponding to the brittle-plastic transition in the earth's crust. This paper documents the progressive change from predominantly cataclastic to predominantly crystal plastic deformation mechanisms in the Striped Rock pluton, a heterogeneously deformed composite granite pluton located in southwest Virginia (Fig. 1). The pluton was chosen for detailed study because it is crosscut by numerous mylonitic shear zones and cataclasite zones ranging in width from a few millimeters to several hundred meters. Several models for the structural evolution of the pluton are presented.

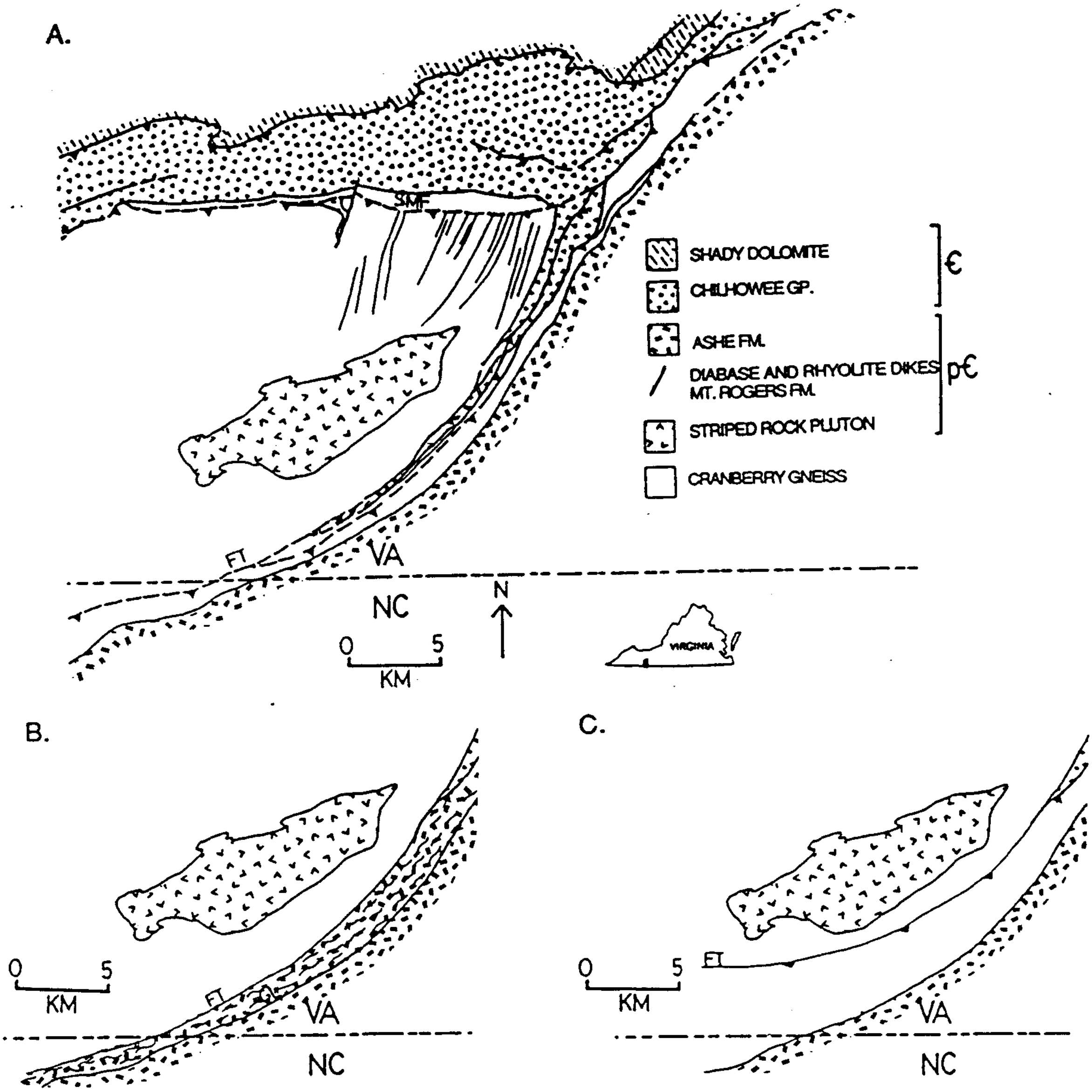


Figure 1. Regional geology of the study area. Stone Mt. Fault (SMF), Fries Thrust (FT), Gossan Lead Thrust (GL). a) Rankin et al. (1972), diabase and rhyolite dikes from Stose and Stose (1957). b) Stose and Stose (1957). c) Bartholomew and Lewis (1984). See text for explanation.

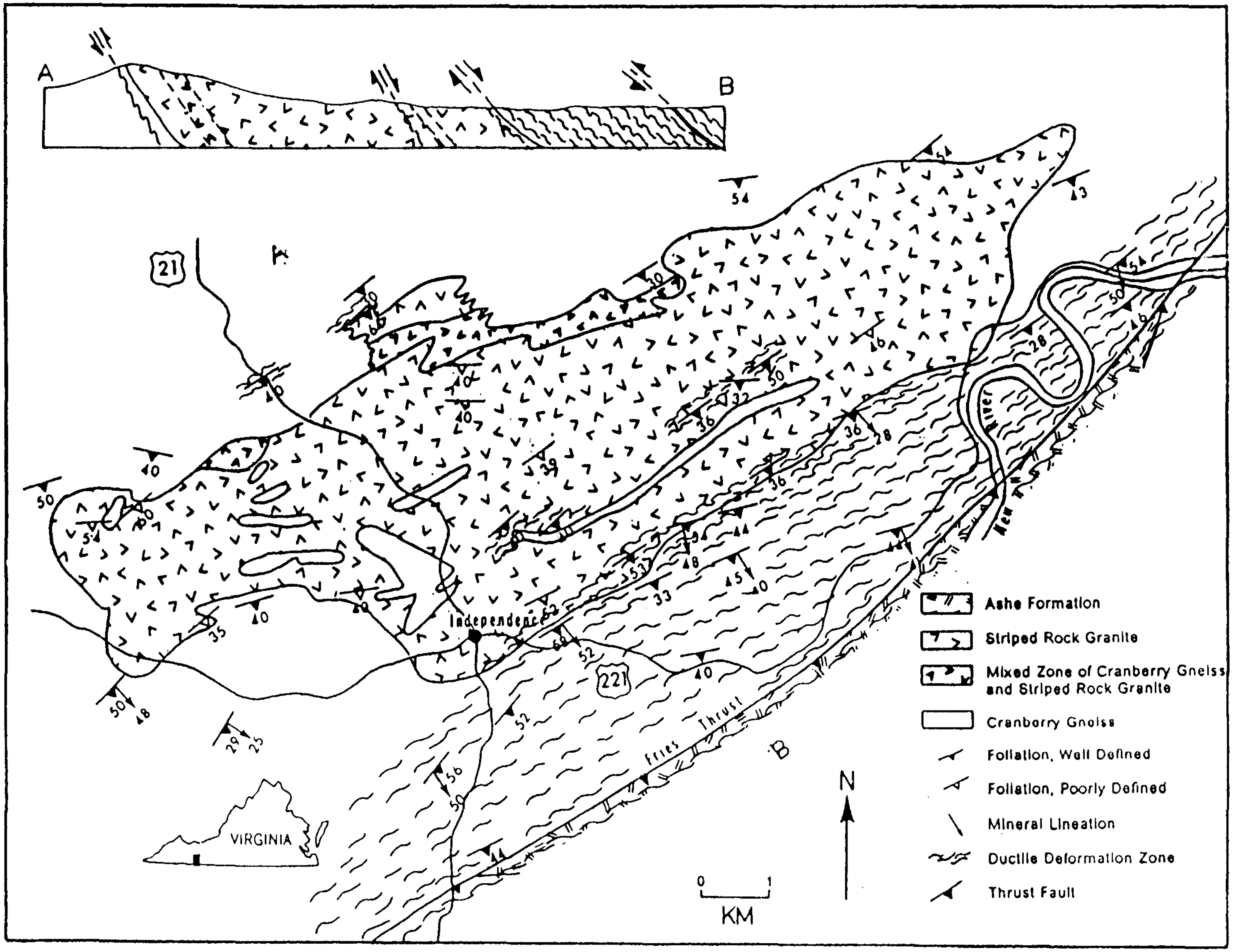
Regional Geology

The Striped Rock pluton (Stose and Stose, 1957; Riecken, 1966), a member of the Crossnore Plutonic-Volcanic Group (Rankin, 1970, 1972; Rankin et al., 1983), is located in the Blue Ridge Thrust Sheet in the vicinity of Independence, Virginia. The pluton is contained in a structural block bounded to the north by the Stone Mountain fault and to the south by the Fries Thrust zone (Figs. 1, 2).

The Crossnore Plutonic-Volcanic Group is comprised of a suite of anorogenic peralkaline granitoids and bimodal volcanics of late-Proterozoic age (ca. 690-710 Ma., Rb-Sr whole rock data, Odom and Fullagar, 1984). The Striped Rock pluton is 681 $\pm$ 10 Ma. (Rb-Sr whole rock data, Odom and Fullagar, 1984) and consists of four phases with compositions in the range of granite to quartz syenite (Riecken, 1966). It is intrusive into variably deformed schists and gneisses originally mapped as the Grayson Gneiss, Saddle Gneiss, Shoal Gneiss and Beaverdam Creek Augen Gneiss (Stose and Stose, 1957; Riecken, 1966) herein referred to collectively as the Cranberry Gneiss (Bryant and Reed, 1970; Rankin, 1970; Rankin et al., 1972). Rb-Sr whole rock data yield ages in the range of of 1.0-1.2 Ga. for gneisses in the study area (Fullagar and Odom, 1973; Fullagar et al., 1979; Odom and Fullagar, 1984). The pluton and surrounding rocks were subjected to greenschist facies metamorphism during the late Paleozoic (Rankin et al., 1973). Relict upper amphibolite to granulite assemblages that are normally characteristic of Grenville-age metamorphism are reported from a few localities (Stose and Stose, 1957; Bartholomew and Lewis, 1984).

The pluton is situated along the northwest margin of the Fries Thrust zone, structurally below the Fries Thrust sheet (Fig. 2). The Fries Thrust zone comprises a zone of ductile deformation 2-km wide in the vicinity of Independence, Virginia, and

Figure 2. Generalized geologic map of the Striped Rock pluton and vicinity (after Stose and Stose, 1957; Riecken, 1966).


A
B
21
221
Independence
New River
Fries Thrust
VIRGINIA
N
0
1
KM
Ashe Formation
Striped Rock Granite
Mixed Zone of Cranberry Gneiss and Striped Rock Granite
Cranberry Gneiss
Foliation, Well Defined
Foliation, Poorly Defined
Mineral Lineation
Ductile Deformation Zone
Thrust Fault

is believed to be part of a continuous northeast-trending fault system that extends from northern Virginia through western North Carolina (Bartholomew and Lewis, 1977, 1984; Kaygi, 1979). Offset of metamorphic isograds indicates that the last major movement along the Fries Thrust system post-dated the late-Paleozoic peak of regional metamorphism (Rankin et al., 1973). Minimum displacement is estimated at approximately 50 km along the Fork Ridge segment in North Carolina (Bartholomew and Lewis, 1984) and 65 km in the vicinity of Grandfather Mountain Window, North Carolina (Rankin et al., 1973). Metasedimentary rocks of the late-Precambrian Ashe Formation (Rankin, 1971; Rankin et al., 1973) and the Cranberry Gneiss are juxtaposed across the Fries Thrust zone 2 km south of Independence (Stose and Stose, 1957; Rankin et al., 1972).

Some disagreement exists as to the exact location of the leading edge of the Fries Thrust sheet in the vicinity of the study area (Fig. 1). The Fries Thrust was originally mapped by Stose and Stose (1957) as a zone of ductile deformation across which the Cranberry gneiss and Ashe Formation were juxtaposed. Rankin et al. (1972) mapped the Fries Thrust as a family of faults cutting the Cranberry Gneiss in the same location as originally mapped by Stose and Stose (1957). Bartholomew and Lewis (1984) remapped the Fries Thrust cutting the Cranberry Gneiss north of the location of Rankin et al. (1972) and Stose and Stose (1957).

Deformation

Mesoscopic Structure

A variably-developed, discontinuous foliation, defined by aligned phyllosilicates and flattened quartz aggregates, is present throughout the Striped Rock pluton. Foliations strike 040°-100°, are inclined moderately to the south (Figs. 2, 3a), and often contain mineral elongation lineations that plunge moderately south-east (Fig. 4a). Deformation in the Striped Rock pluton is most intense along the southern contact zone where it abuts the northwest margin of the Fries Thrust zone and decreases northwestward (Fig. 2). The deformation gradient is not, however, uniform; narrow mylonite zones and cataclasite zones occur throughout the pluton. Foliations in the surrounding Cranberry Gneiss strike 030°-130°, dip moderately south and contain mineral elongation lineations almost identical to those in the pluton (Figs. 3b-c, 4b). Mineral lineations in both the pluton and country rock are defined by aligned phyllosilicate fibers and/or prismatic minerals.

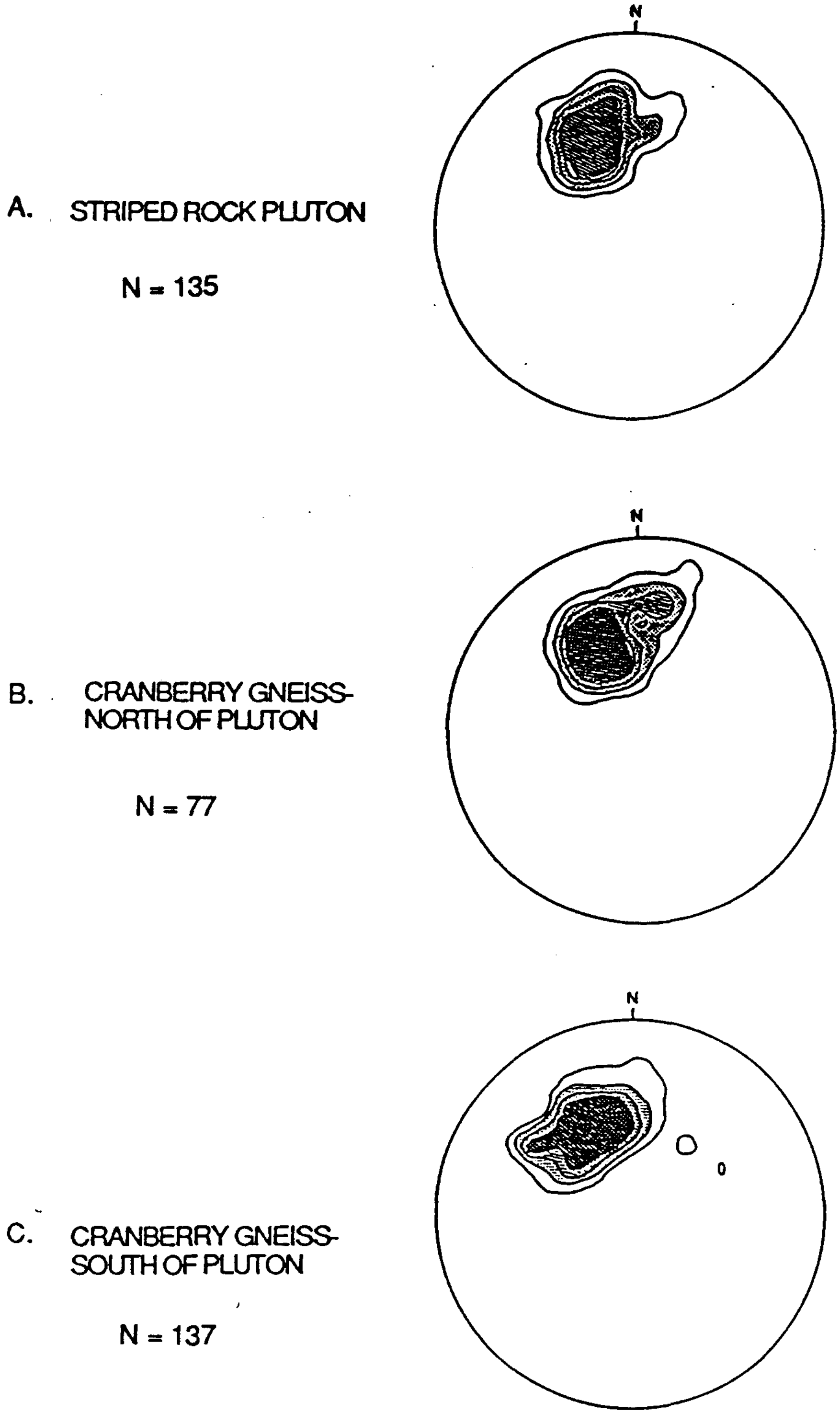


Figure 3. Poles to foliation contoured at 2, 4, 6 and 8 points per (100/n)% area. a) Striped Rock pluton, b) Cranberry Gneiss north of the pluton, c) Cranberry Gneiss south of pluton.

A.

B.

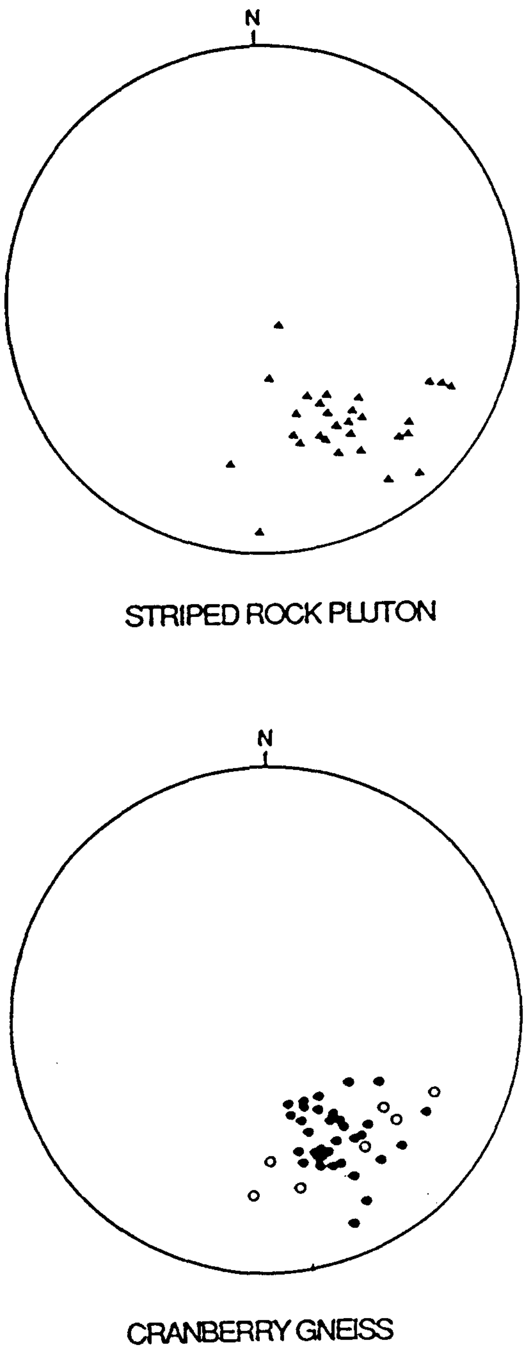


Figure 4. Mineral elongation lineations. a) Striped Rock pluton b) Cranberry gneiss, north of pluton-open circles, south of pluton-closed circles.

Mylonitic Shear Zones

The pluton is transected by mylonitic shear zones of variable width that are separated by zones of weakly- to moderately-deformed granite or quartz syenite. The largest scale ductile shear zone occurs along the southern contact where both pluton and country rock are deformed into a northeast-trending zone of mylonitic augen gneiss several hundred meters wide (Fig. 2). Shear bands enclosing asymmetric feldspar porphyroclasts (5 mm-1 cm) are well-developed in the augen gneiss; the angle between the C (cisaillement) and S (schistosite) planes (Berthe et al., 1979) decreases with increasing strain. Mylonitic foliations within this shear zone strike 040°-065°, dip moderately southeast and contain mineral elongation lineations that plunge 40°-60° toward 140°-160°. The mylonitic foliation varies in strike by approximately 35°, anastomosing around weakly deformed lenticular blocks of granite (cf. Coward, 1976; Mitra, 1978, 1979; Simpson, 1983). Foliations and mineral elongation lineations in this ductile deformation zone are subparallel to planar and linear fabrics contained in the Cranberry Gneiss in the adjacent Fries Thrust zone (Figs. 2, 3b, 4a-b).

Narrow, discontinuous mylonite zones, ranging in width from a few millimeters to 1 meter, occur throughout the pluton and are commonly observed in subparallel arrays separated by 20 cm to 10 m. The majority of ductile deformation zones trend 030°-090°, dip moderately southeast and are spaced a few centimeters to tens of meters apart (Figs. 5a, 6). A minor group of ductile shear zones, up to a few centimeters wide, trend 320°-340°, dip moderately southwest and northeast and exhibit a gently plunging mineral elongation lineation. This group of shear zones is associated with northeast-trending shear zones in outcrop and occurs in groups of 1 to 3 spaced

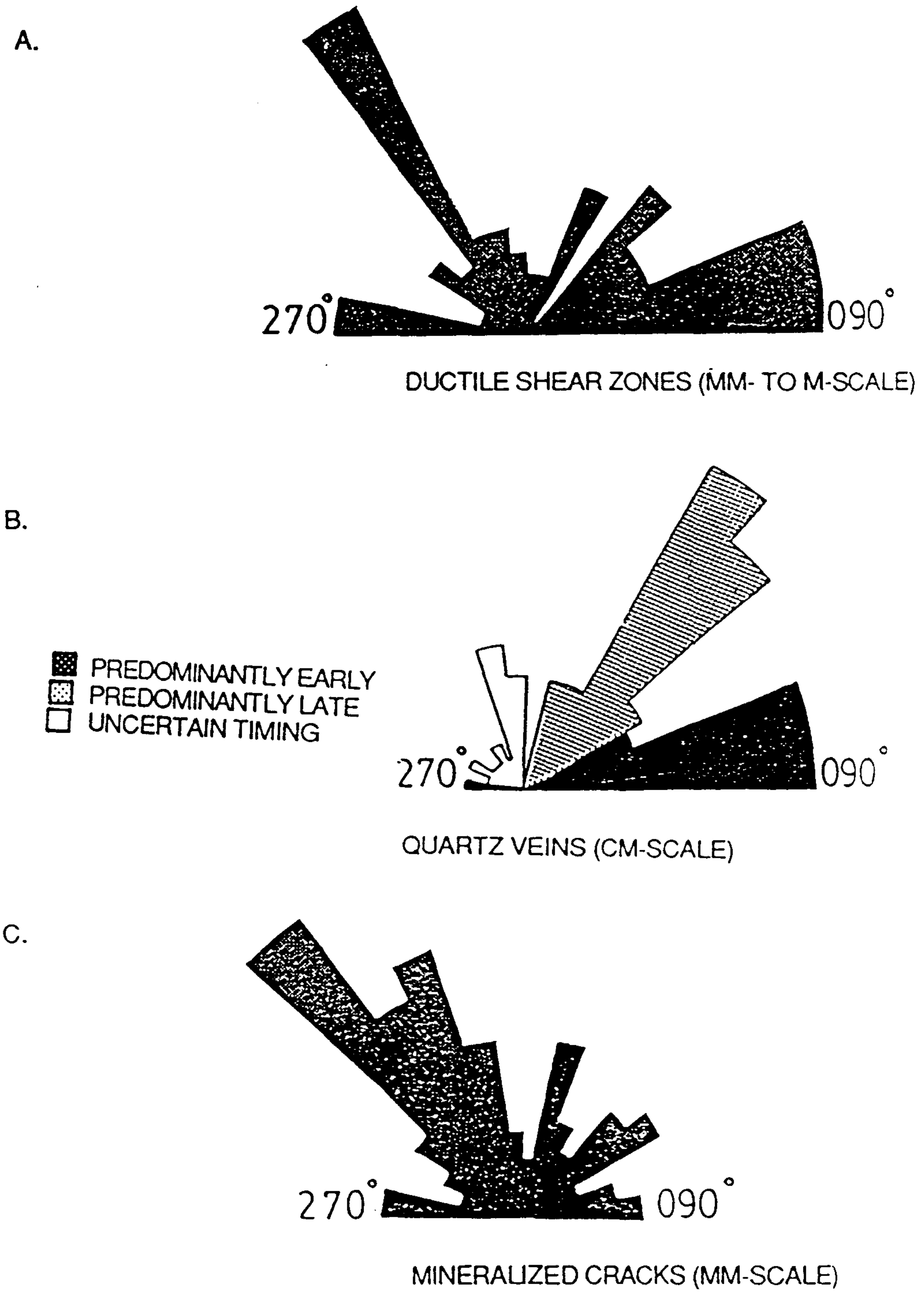


Figure 5. Rose diagrams showing strikes of a) ductile shear zones, b) quartz veins, c) millimeter-scale quartz-, chlorite- and stilpnomelane-filled cracks.

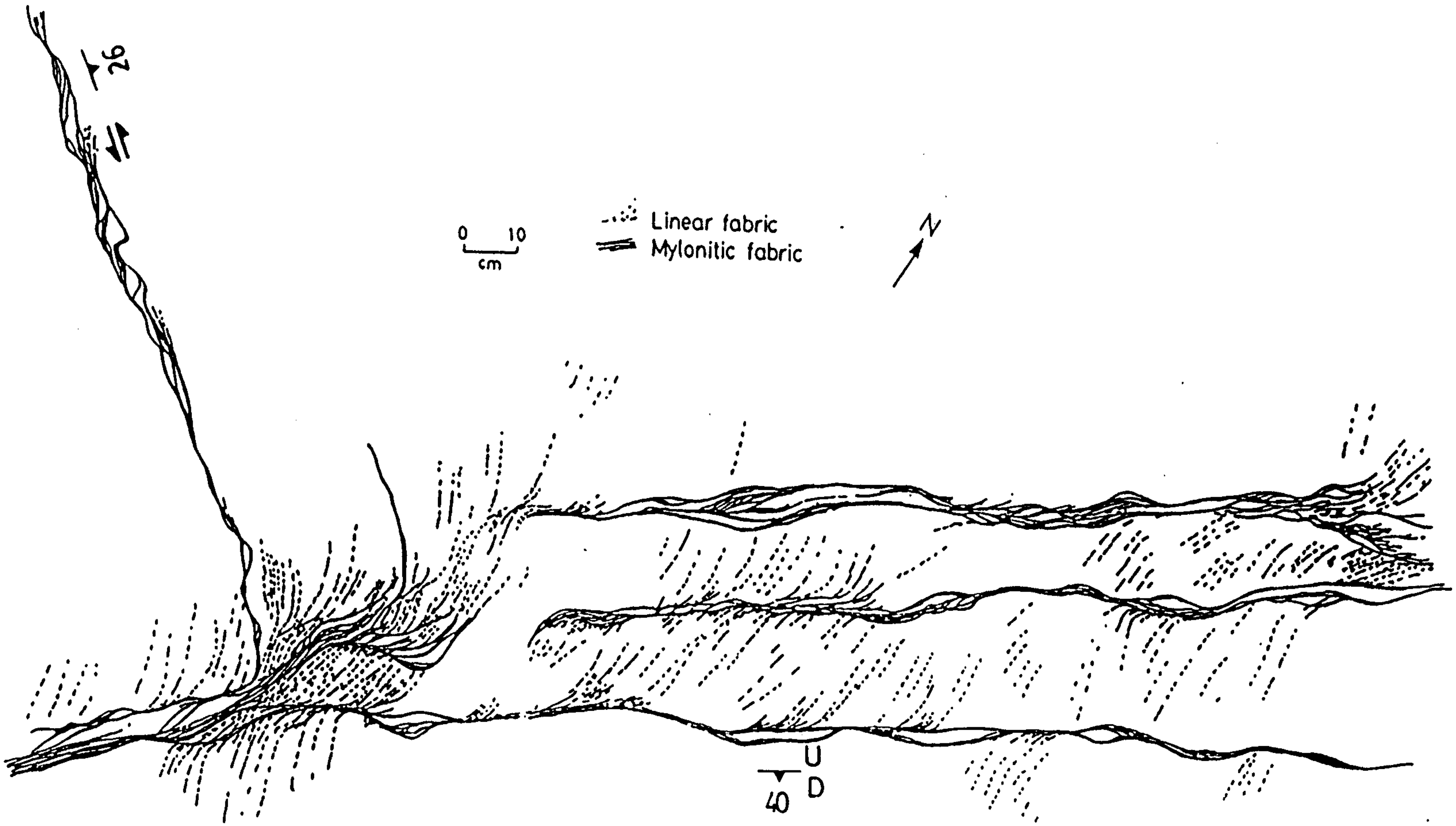


Figure 6. Map view of outcrop showing cm-scale mylonite zones with northeast and northwest strike. Note the deflection of a linear fabric defined by aligned biotites and K-feldspar grains into the shear zones and the anastomosing geometry.

40-50 cm apart. Locally, mylonitic shear zones striking 320°-340° splay off of shear zones striking 030°-060° (Fig. 6).

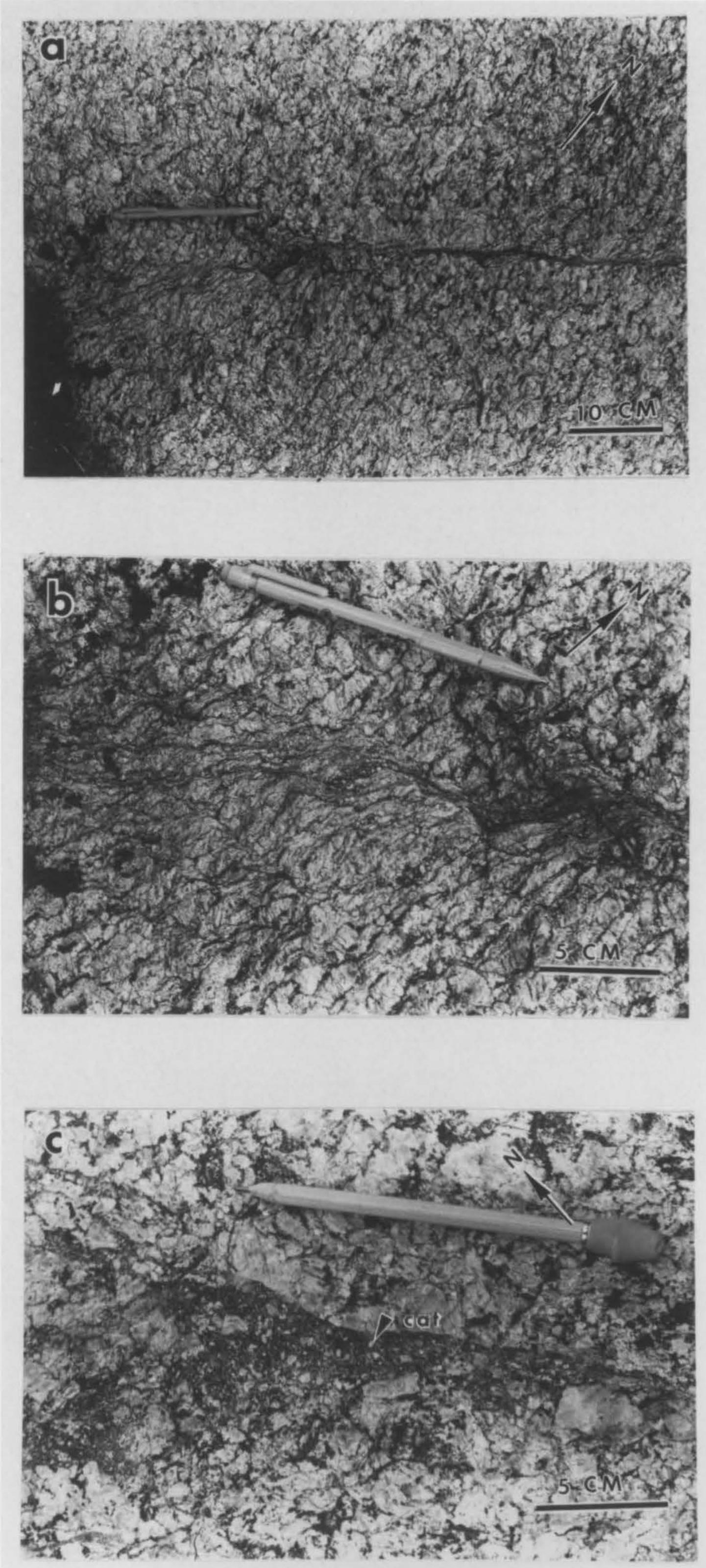
Mylonitic shear zones are characterized by sharp boundaries and a marked reduction in grain size of all constituent minerals (Figs. 6, 7a-b). The transition from weakly- to intensely-deformed rock takes place over distances of less than 1 cm and the average grain size becomes progressively more uniform and smaller (< 20 um) toward the middle of the shear zones. Planar and linear fabrics contained within the intervening zones of less deformed rock are deflected into ductile shear zones. Figures 7a-b show a linear fabric defined by aligned potassium feldspars and clots of biotite deflected into a centimeter-scale shear zone. At the shear zone boundary, the feldspar grains are rotated into the plane of the mylonitic foliation by slip on cleavage planes. Strain is dissipated over a wider area at the tips of shear zones and gradually dies out altogether.

Mylonitic foliations in discrete ductile shear zones are defined by elongate feldspar aggregates, aligned phyllosilicates and ribbon quartz. A well-developed mineral elongation lineation defined by aligned mineral fibers is contained in the foliation plane. Mylonitic foliation anastomoses around lenticular blocks of weakly-deformed rock (Fig. 6).

Cataclasite Zones

Cataclasite zones trend 030°-040° and 320°-340°, range in width from a few millimeters to several centimeters and are usually moderately to steeply inclined to the south or north. Spacing of brittle shear zones is very variable and their occurrence is restricted to coarse-grained granite (feldspars up to 3 cm in length) and

Figure 7. Cm-scale ductile and brittle shear zones. a) ductile shear zone in coarse-grained biotite granite. b) close up of shear zone shown in (a). Strain is distributed over a progressively wider area toward the termination of the shear zone. Note the deflection of a linear fabric defined by aligned biotite clots and feldspars into the shear zone. c) cataclasite zone in coarse-grained biotite granite. Note the sharp boundaries and randomly oriented angular fragments in a finer grained matrix.


a
N
10 CM
b
N
5 CM
c
N
cat
5 CM

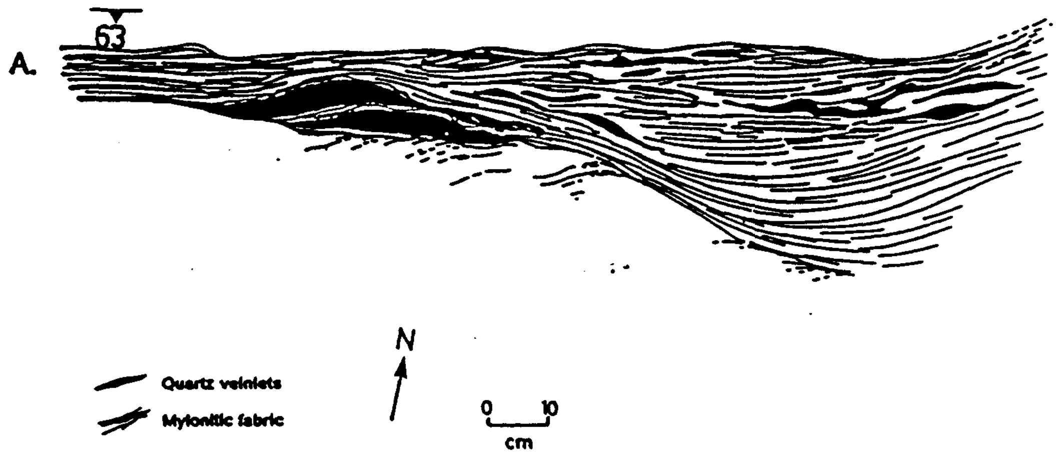
quartz syenite phases of the pluton. Cataclasite zones are characterized by a marked reduction in grain size, however, unlike mylonite zones, the grain size does not become uniform with increasing strain. Large angular fragments (up to a few mm in longest dimension) showing no preferred grain shape oriention are surrounded by a finer-grained matrix (Fig. 7c).

Vein quartz is commonly associated with cataclasite zones in outcrop. Cataclastically deformed rock occurs along the walls of quartz veins and fragments of cataclasite are observed within the veins suggesting that the quartz was precipitated within brittle deformation zones after their formation.

Mineralized Fractures

At least two generations of mineralized fractures are present in the Striped Rock pluton, preceding and postdating ductile shear zone formation. The early generation comprises a set of steeply inclined fractures filled predominantly with quartz precipitate and minor green biotite striking 070°-090° (Fig. 5b). They range in width from a few millimeters to 3 cm and are spaced several centimeters to tens of meters apart. Veinlets up to a few centimeters wide occur within and parallel to ductile shear zones with east and northeast trend and are locally deflected into them (Figs. 8a-b). Where contained in ductile shear zones, the quartz veinlets exhibit mineral elongation lineations that plunge 40°-70° toward 140°-180°, parallel to mineral lineations contained in the mylonitic foliation plane.

A later set of steeply inclined, millimeter- to centimeter-scale cracks filled with quartz, chlorite, epidote and stilpnomelane strike 030°-060° and 320°- 340° and uniformly overprint mylonite zones and cataclasite zones of all scales (Figs. 5c, 9a-d).



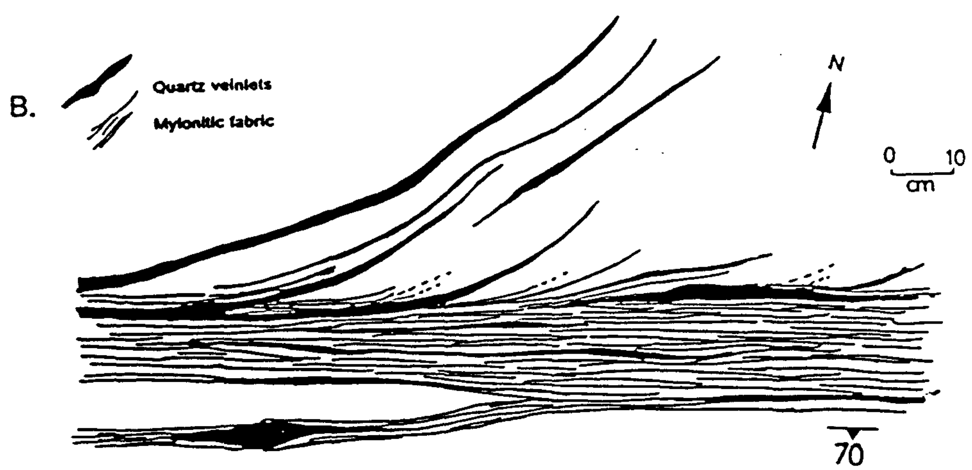
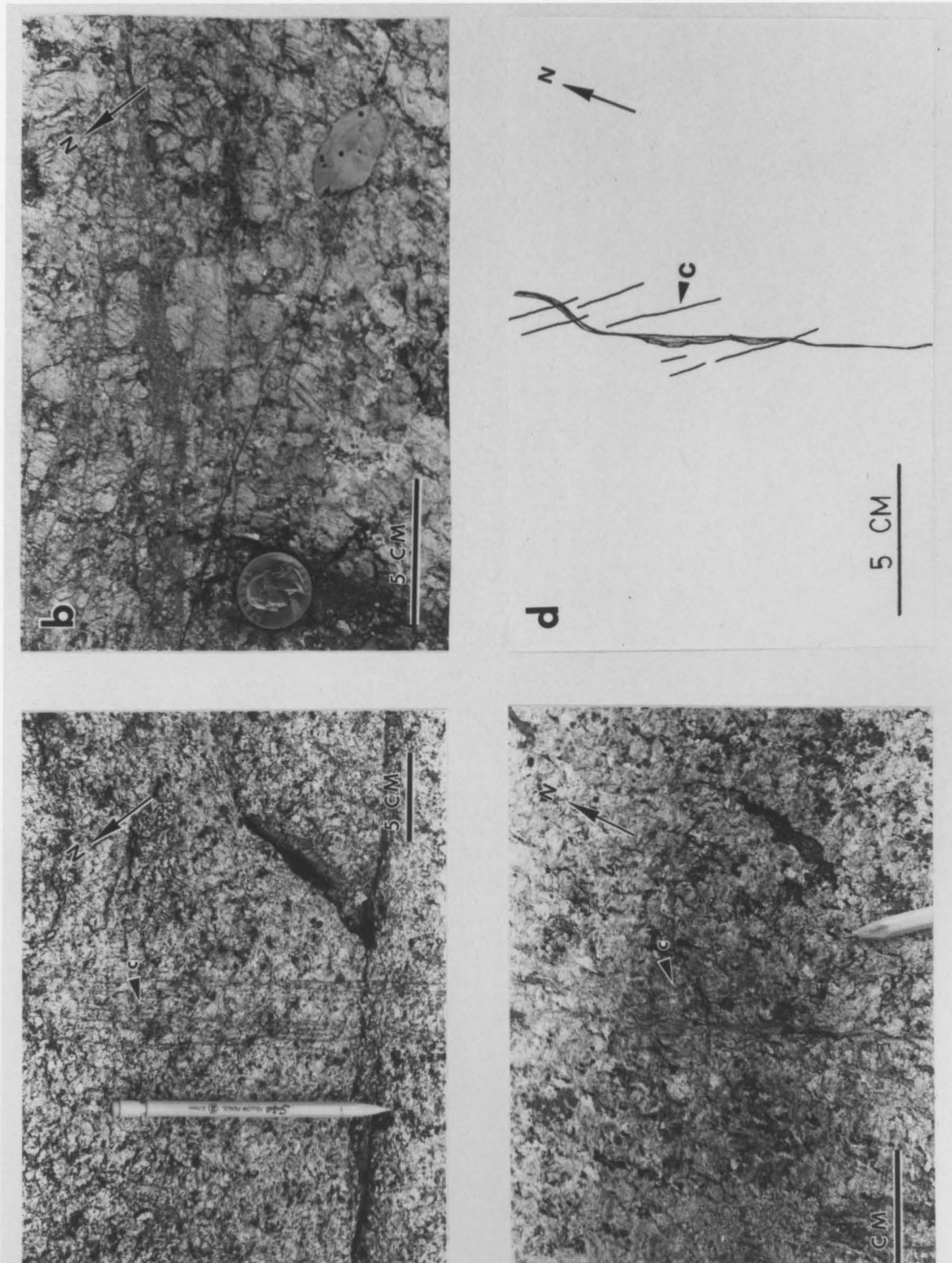


Figure 8. Map view of mylonitic shear zones in medium-grained biotite granite. a) quartz veinlets deformed in mylonitic shear zone b) quartz veinlets deflected into and deformed in shear zone. Mineral elongation lineation plunges into the plane of the outcrop and movement sense is south side down in (a) and (b).

Figure 9. Late-stage mineralized cracks. a) parallel array of mineralized cracks cross cutting medium-grained biotite granite. b) mineralized cracks in en-echelon array crosscut cataclastic zone in quartz syenite. c) mineralized cracks in en-echelon array cross cut ductile shear zone in medium-grained biotite granite. d) sketch of (c).


a
b
c
d
N
c
5 CM

Minor groups of mineralized cracks of unknown relative timing trend east-west. Spacing is variable and ranges from a few millimeters to several meters. Mineralized extension cracks with northwest trend typically occur in en echelon-arrays a few centimeters to several meters in length and crosscut quartz veins with trend 030°-060°. Most of the late, mineralized cracks are dilational, however, some show limited displacement of a few millimeters to a few centimeters (Fig. 10).

Microstructure

In its least deformed state, the Striped Rock pluton is a medium- to coarse-grained, fluorite-bearing, biotite granite comprised of 12-29% plagioclase (An 9-12), 41-60% potassium feldspar (microcline microperthite), 15-32% quartz and 5-10% biotite (Riecken, 1966). Coarse-grained quartz syenite occurs in a few localities. Accessory minerals include white mica (as an alteration product of feldspar), apatite, allanite, epidote, titanite and hornblende. Igneous textures are preserved in only a few relatively undeformed regions of the pluton; completely undeformed granite or quartz syenite has not been observed. Primary flow textures defined by aligned potassium feldspar grains up to 3 cm long or clots of biotite are observed in a few localities (Figs. 7a-b).

Microstructure changes progressively with increasing strain and the original igneous character of the rock is completely lost within cataclasite zones and ductile shear zones. A marked reduction in grain size occurs by microcracking, dynamic recrystallization and reaction with increasing strain (Fig. 11a). The grain size of all constituent minerals becomes more uniform with progression from undeformed rock

Figure 10. Map view of outcrop in coarse-grained quartz syenite showing the relative timing of cataclasite zone, quartz vein, late-stage quartz- chlorite- and stilpnomelane-filled cracks. Note the small offset of both the quartz vein and cataclasite zone.

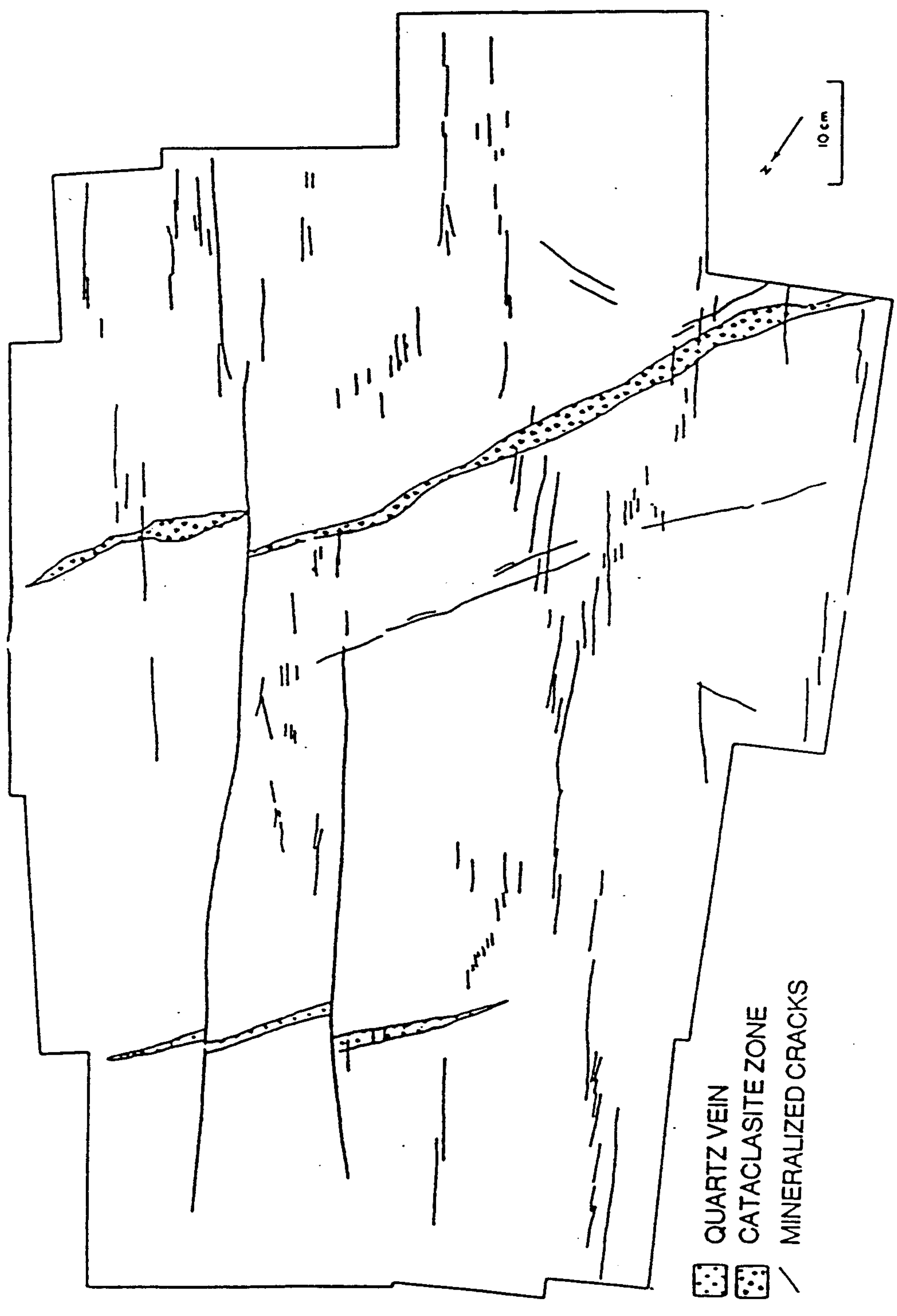
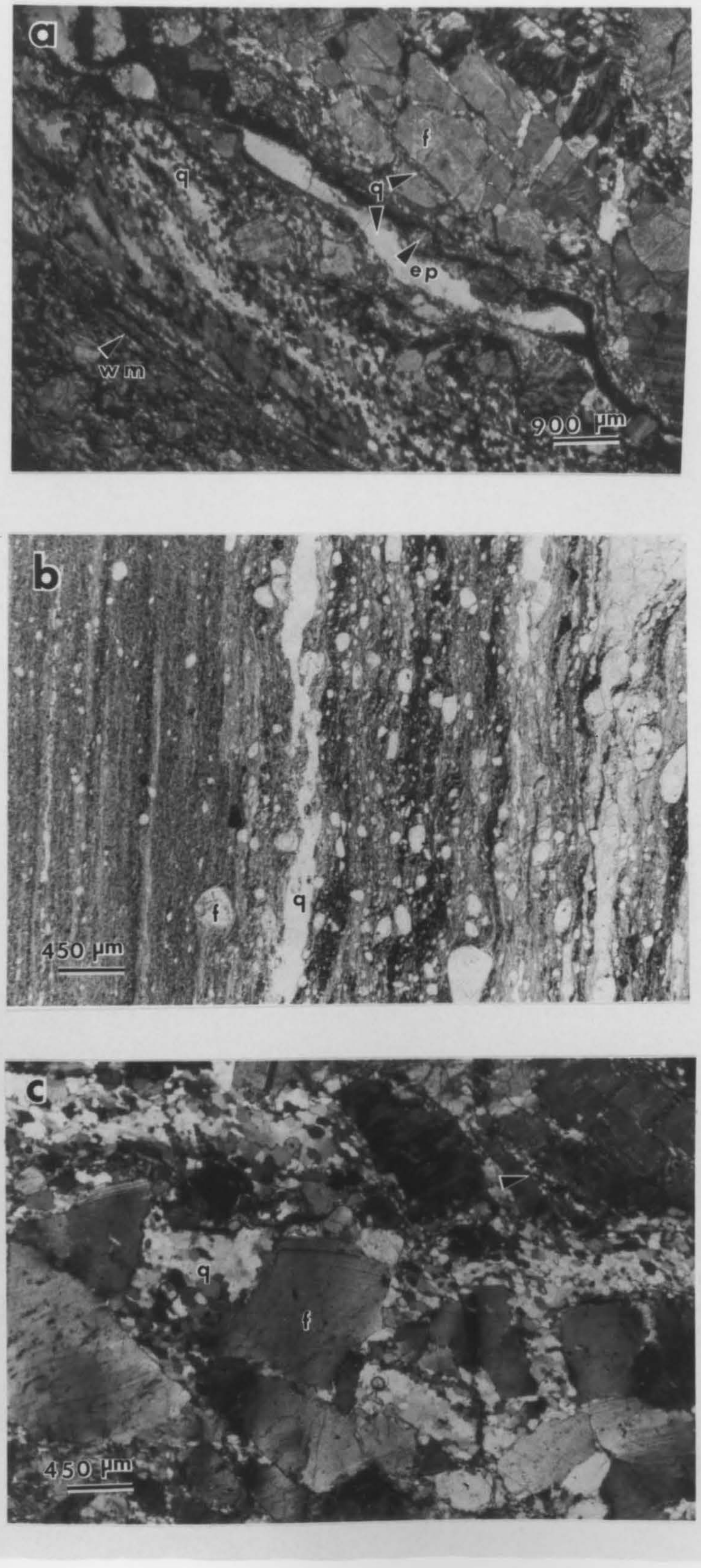

10 cm
N
QUARTZ VEIN
CATACLASITE ZONE
MINERALIZED CRACKS

Figure 11. Photomicrographs of shear zones. a) progressive grain-size reduction in a ductile shear zone. Note the large, fractured, K- feldspar grain at the shear boundary. Quartz filling the fractures is deformed. b) progressive grain-size reduction in an ultramylonite zone, the protolith is medium- grained biotite granite. Note the very small grain size. c) cataclasite zone of (7c) showing the microscopically crystal plastic deformation of quartz.


a
f
q
q
ep
wm
900 µm
b
f
q
450 µm
c
q
f
450 µm

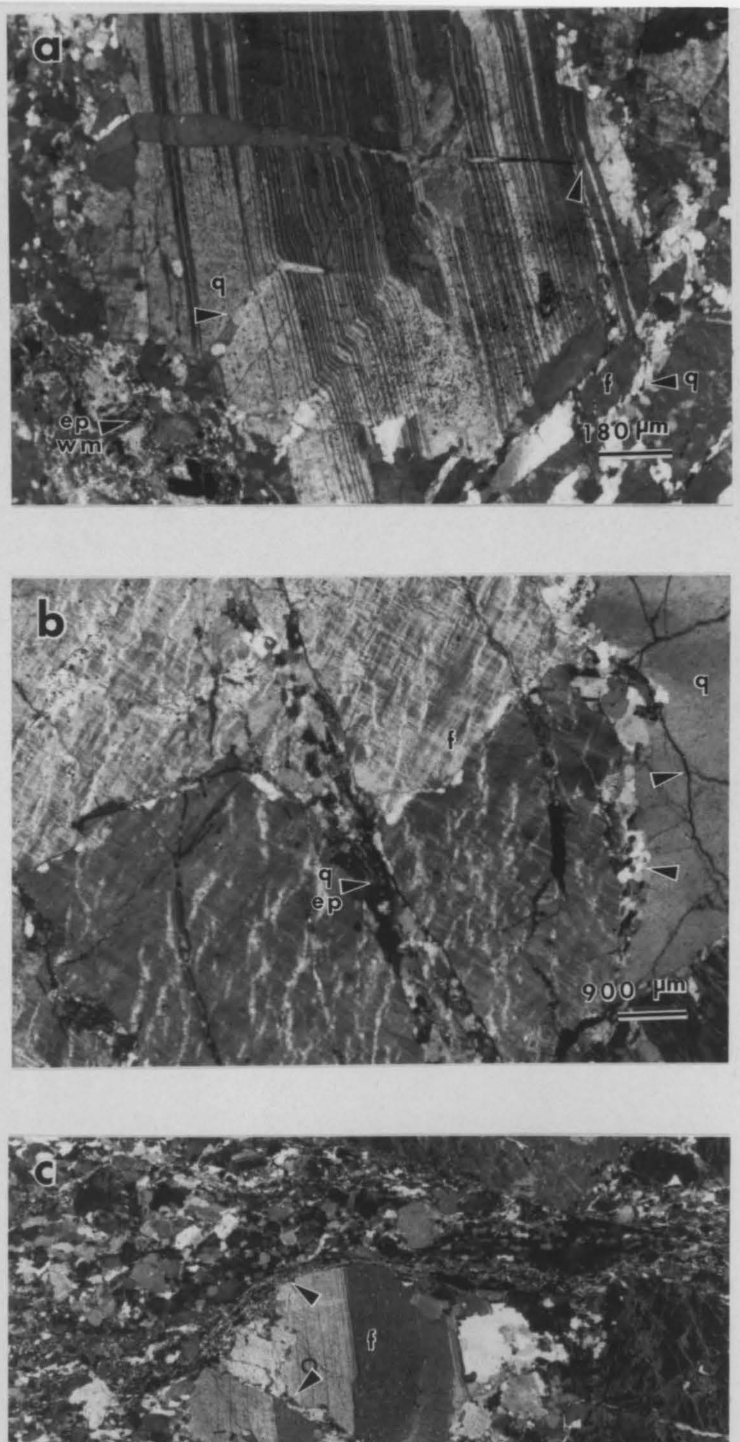
into ductile shear zones (Fig. 11b). There is a concomitant change in bulk mineralogy to a more micaceous and quartz-rich rock with reduction in grain size. Narrow quartz ribbons, 100 um to 3 mm in width, alternating with fine-grained aggregates of white mica, epidote and feldspar define the mylonitic foliation.

Mesoscopic cataclasite zones are common in coarse-grained areas of the pluton. Although these zones appear to be cataclasites in outcrop (Fig. 7c), quartz microstructure shows markedly crystal plastic behavior (Fig. 11c). Feldspar grains are pulled apart following fracturing resulting in distinctly angular fragments (20 um - 3 mm) randomly oriented in a finer-grained matrix of polygonal quartz grains.

Feldspar

Plagioclase and potassium feldspar have undergone alteration to quartz, white mica and epidote. The extent of reaction varies from very minor to almost complete. Feldspar grains are transected by intra- and intercrystalline microfractures often along (001) and (010) cleavages. Intracrystalline cracks occur entirely within a grain; intercrystalline cracks extend from a grain boundary through one or more grains (Simmons and Richter, 1976). Two types of intra- and intergranular cracks are recognized: 1) dilatant cracks, 20-100 um wide, along which no appreciable displacement has taken place prior to mineralization and 2) shear fractures, some of which are mineralized. Mineralized dilatant cracks are the most abundant and are either wedge shaped (Fig. 12a) or have subparallel planar walls (Fig. 12b). Wedge-shaped microcracks extend from grain boundary toward the interior of the grain where they terminate. Very narrow cracks are often observed in the process zone at the crack

Figure 12. Photmicrographs of feldspar grains. a) wedge shaped, quartz-filled microcracks in a plagioclase grain. Note the kinked twins and intracrystalline shear fracture. b) planar quartz- and epidote-filled microcracks in an alkali feldspar grain Note the closed intracrystalline cracks in the adjacent quartz grain and incipient recrystallization along the grain boundary. c) plagioclase grain cut by a mineralized shear fracture. Note the grain shape fabric in quartz fillina the crack and the preferred alignment of white mica grains along the grain boundary.


a
q
f
q
ep
wm
180 µm
b
q
f
q
ep
900 µm
c
f
q
450 µm

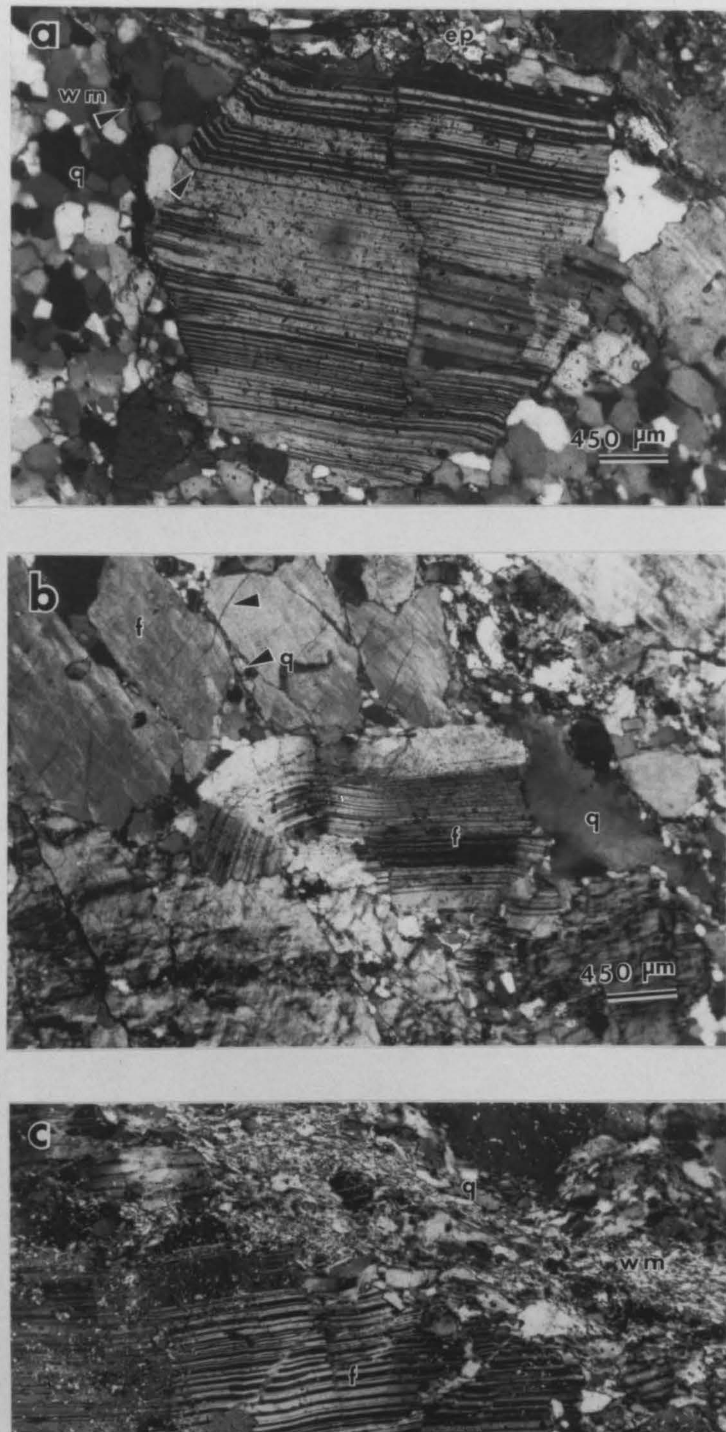
tip. Planar microcracks are either intra- or intergranular, the latter of which extend as much as two grain diameters into adjacent grains.

Intracrystalline shear fractures, which frequently offset growth twins and cleavage planes, terminate either within the crystal or at the grain boundary (Figs. 12c, 13a). Displacements of up to 50 um at grain boundaries decrease toward grain centers suggesting Mode 3 failure (Lawn and Wilshaw, 1975). The relative motion of intragranular shear fractures that completely cross cut grains are related to the bulk rotation of the grain.

Feldspar grains almost always exhibit some degree of irregular, patchy undulose extinction (Figs. 13b-c) unlike the sweeping extinction characteristic of deformation at higher metamorphic grades (e.g. Hanmer, 1982; White and Mawer, 1986). Plagioclase grains are commonly bent, locally as much as 50°, and display sharp kinks in growth twins (Figs. 12a, 13a-c). Very narrow shear fractures and mineralized wedge shaped cracks are common where grains are bent to more extreme angles.

Thermally activated deformation mechanisms (dislocation glide and climb) become important at temperatures in the range of 450°-500° (Tullis, 1983) and are unlikely to be operative at the relatively low temperatures of greenschist grade metamorphism. Feldspars are, however, very prone to microcracking which is known to produce optical microstructures similiar to those resulting from deformation by dislocation glide and climb (Tullis and Yund, 1977, 1987; Tullis, 1983). Recent experimental evidence has demonstrated the importance of cataclastic flow over a wide range of temperature and pressure conditions (Tullis and Yund, 1987). The extensive cataclasis and lack of subgrains and strain-free new grains indicative of dynamic recrystallization of feldspars strongly suggest that cataclastic flow is an important mechanism of deformation in feldspar.

Figure 13. Photomicrographs of feldspar grains. a) intracrystalline shear fracture and kinked twins in plagioclase grain. b) bent plagioclase grain with patchy undulose extinction. Note the parallel dilatant mineralized cracks in the adjacent alkali feldspar grain cross cut by intergranular cracks. c) bent twins and patchy undulose extinction. Note the extensive alteration of the large plagioclase grain and alignment of white micas at the bottom left.


a
ep
wm
q
450 µm
b
f
q
f
q
450 µm
c
q
wm
f
wm
450 µm

Quartz

Primary quartz exhibits abundant evidence of moderate to intense intracrystalline deformation. Undulose extinction and deformation bands are common, even where the rock appears undeformed in hand sample. Multiple healed intracrystalline cracks, defined by fluid inclusion trails, occur in conjugate sets and subparallel arrays in slightly-strained grains (Fig. 14a; cf. Simmons and Richter, 1976; Knipe and White, 1979; Simpson, 1986). Dynamic recrystallization of primary quartz is demonstrated by the presence of polygonal grains (20-50 um) which commonly surround larger grains (3-4 mm) containing subgrains in core and mantle structures (Fig. 14b; White, 1976). Rotational recrystallization is the predominant mechanism of recrystallization. This interpretation is supported by the gradual progression from subgrains to new grains toward the margins of partially recrystallized grains. Grain boundary migration, indicated by bulging grain margins, is also operative to a lesser extent. Elongate domains containing quartz that is not yet completely recrystallized display undulose extinction, deformation bands and small (< 20 um) polygonal subgrains. The major operative process in these zones is dynamic recovery which is demonstrated by ubiquitous subgrains but no new grains (White, 1976). At higher states of strain, mosaics of completely recrystallized polygonal grains replace these domains. The size and shape of recrystallized quartz grains varies where growth is inhibited by adjacent micas (Fig. 14c).

Type 2 polycrystalline quartz ribbons (Boullier and Bouchez, 1978), 50 um-4 mm wide and oriented parallel to mylonitic foliations, are ubiquitous to ductile deformation zones of all scales. Quartz within the ribbons is almost completely recrystallized into polygonal mosaics of elongate to equant grains that exhibit somewhat

Figure 14. Photomicrographs of quartz. a) healed intracrystalline microcracks in primary quartz grain defined by fluid inclusion arrays. Note the undulatory extinction. b) primary quartz grain with well-developed core and mantle structure. Note the alignment of white mica aggregates and quartz grain-shape fabric. c) a polycrystalline quartz ribbon within a mylonite zone. Aligned micas in the lower part of the photograph inhibit the growth of quartz.


a
180 µm
b
f
q
wm
ep
450 µm
c
q
wm
f
450 µm

undulose extinction (Fig. 14c). Shape ratios vary from 3:1 to 4:1. Very narrow (300 um wide), less deformed elongate domains containing undulose extinction and deformation bands persist in some shear zones and show a strong dimensional orientation subparallel to the mylonitic foliation. Well-developed quartz grain shape fabrics are oblique to ribbon boundaries and indicate a component of rotational strain (Eisbacher, 1970; Burg and Laurent, 1978; Lister and Snoke, 1984).

Quartz and to a lesser extent green or brown biotite, epidote, albite, white mica or a combination of these minerals are deposited in dilatant microcracks in feldspar grains (Figs. 12a-c, 13a-c). Quartz is often almost completely recrystallized into mosaics of equant or elongate polygonal grains (20-50 um) where it occurs in cracks in feldspar grains contained in moderate- to high-strain zones (Fig. 11a). A preferred grain shape fabric is present in some microcracks indicating shearing subsequent to mineralization. Secondary quartz precipitated in microcracks lacks the planar fluid inclusion arrays that are ubiquitous to primary quartz (cf. Simpson, 1986). Deformed biotite and white mica grains in cracks are typically kinked and display undulose extinction. The high interference colors of epidote and the small grain size of albite (< 20 um) precluded determination of the degree of deformation of these constituents.

The presence of plastically-deformed minerals sealing cracks in feldspar grains in moderately- to highly- strained areas indicates that dilatant cracking preceded the onset of crystal plastic deformation. Microcracks containing completely undeformed stilpnomelane, quartz and biotite cross cut earlier formed fractures sealed with deformed minerals in high strain zones (Fig 13b). In weakly-deformed samples, several generations of mineralized cracks are observed. Minerals sealing the cracks show only slight evidence of crystal plastic deformation or are completely undeformed.

Quartz crystallographic fabrics

Quartz C-axes were measured using a universal stage. The samples were cut parallel to the mineral elongation lineation and perpendicular to the foliation plane (XZ plane). The size of quartz grains in the samples is variable and ranges from 20 um to 100 um. The C-axes define broad girdles oblique to the mylonitic foliation (Fig. 15a-c). The asymmetry of girdles with respect to the foliation indicates a component of rotational strain (Bouchez, 1977; Burg and Laurent, 1978; Schmid and Casey, 1986). Shear sense determined from the obliquity of the girdles is consistent with that deduced from other microstructural movement sense indicators such as asymmetric porphyroclasts, shear bands and oblique quartz grain shape fabrics.

Micas

Original igneous biotite is present in clots ranging in size from 2 to 5 mm. Relict grains (100 um-3 mm) that persist in mylonitic shear zones show a preferred orientation of (001) subparallel to the foliation. Undulose extinction, kinks and slip on (001) demonstrate crystal plastic deformation of primary micas. Relict biotite grains are distinguished from secondary crack-sealing biotite by their larger grain size and abundant inclusions.

White mica aggregates show a strong length preferred grain shape orientation in moderately- to highly-strained areas of the pluton. Where the bulk strain is low the degree of preferred orientation decreases. White mica aggregates occur in pressure shadows adjacent to feldspar grains, parallel to feldspar grain boundaries (Fig. 12c, 13c) and subparallel to mylonitic foliations in ductile shear zones (Fig. 14c).

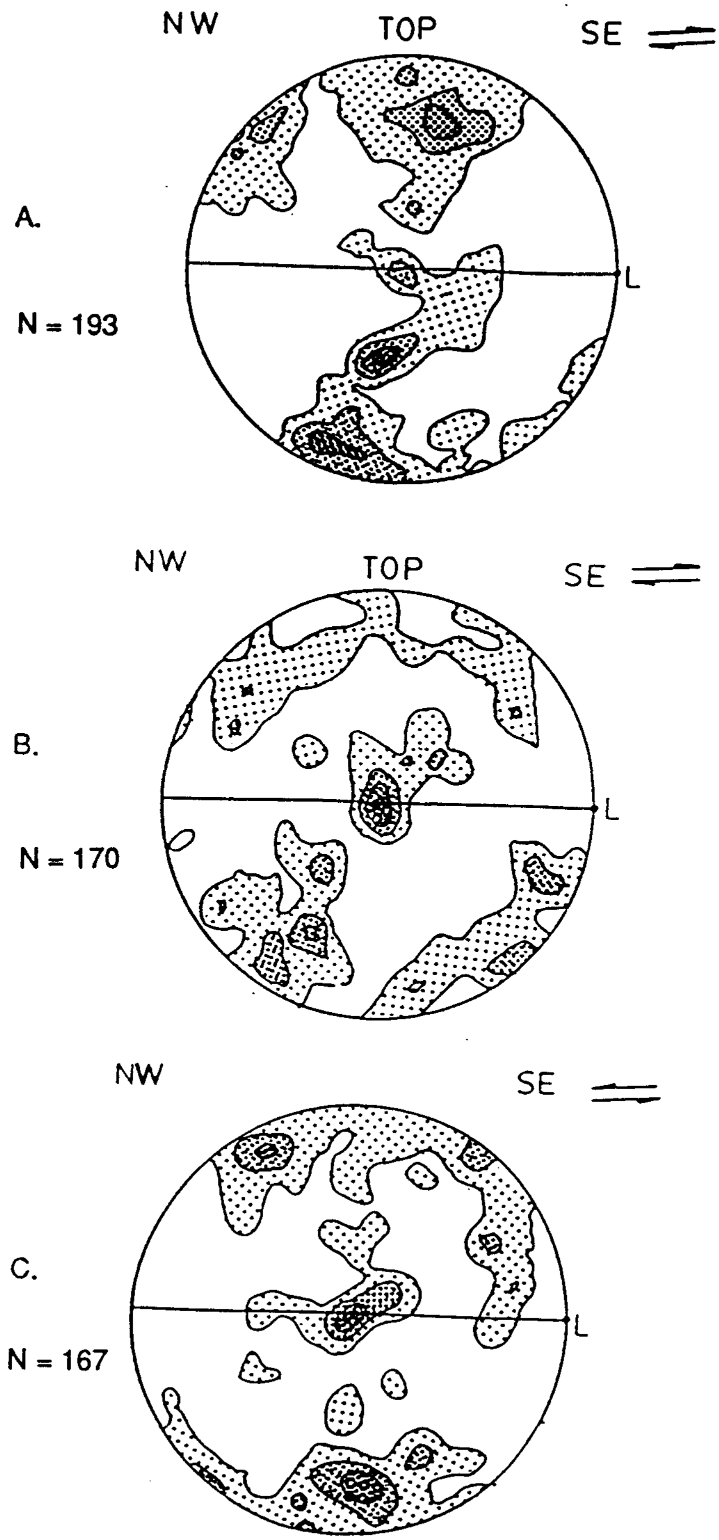


Figure 15. Quartz C-axes contoured at 1, 3, 5, and 7 points per (100/n)% area showing sense of shear. a) 050, 40S, top to the SE. b) 085, 70S, top to the SE. c) 330, 60N, sinsitral strike-slip.

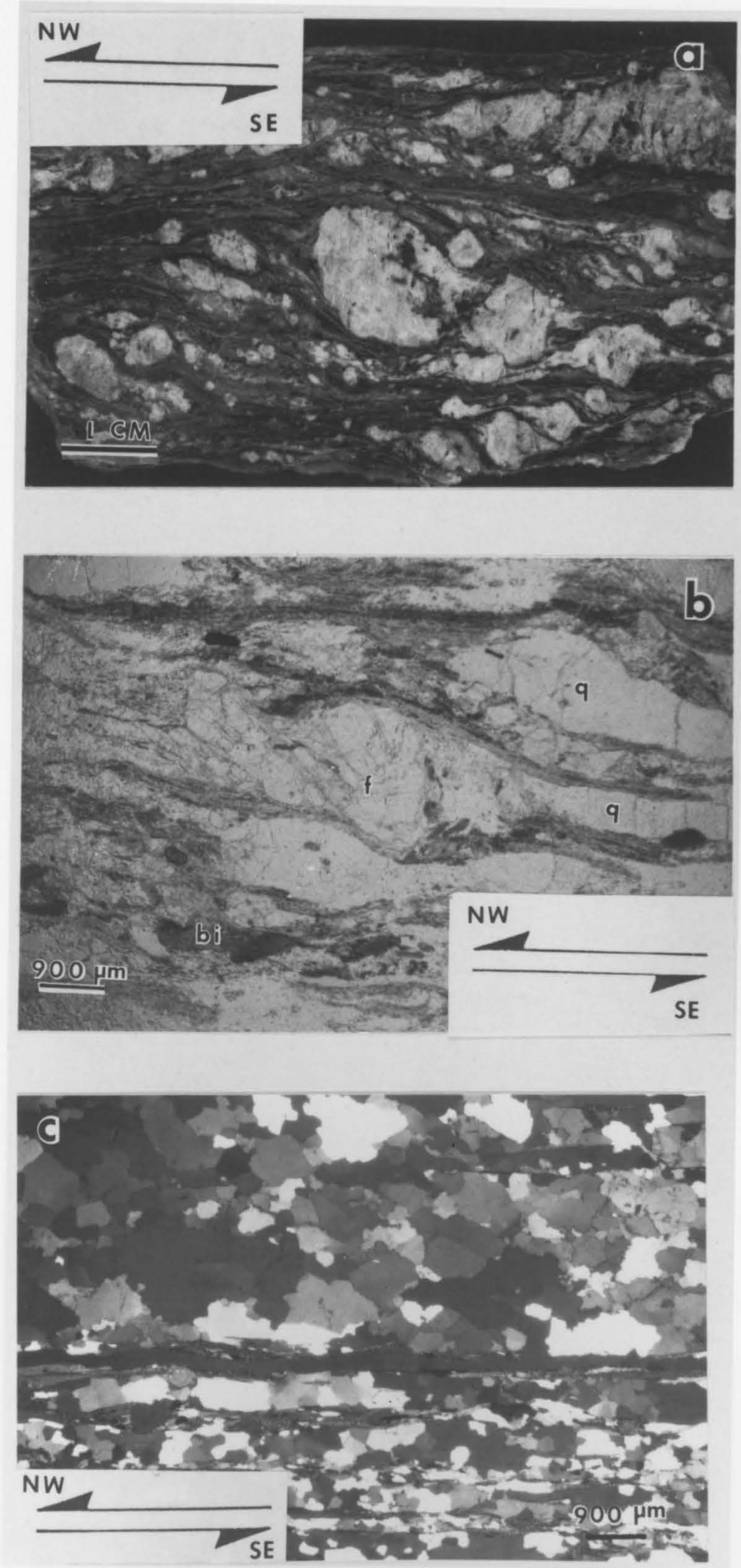
Cranberry Gneiss microstructure

The Cranberry Gneiss is comprised of blue quartz-bearing schists and gneisses with widely varying texture and composition (Stose and Stose, 1957; Riecken, 1966). Very coarse-grained augen gneisses containing large potassium feldspar porphyroclasts (3 cm) in a matrix of predominantly quartz, chlorite and green biotite are located to the north of the pluton. Quartz-mica schists, equigranular medium- to fine-grained biotite gneiss and quartzite occur within the Fries Thrust zone south of the pluton. Schistosity is parallel to compositional layering.

Feldspar porphyroclasts in coarse-grained augen gneisses show abundant evidence of intragranular cracking (Figs. 16a-b). Microcracks are sealed primarily with quartz and to a lesser extent white mica, epidote and biotite. Quartz precipitated in microcracks occurs as polygonal grains (20-50 um) which show slightly undulose extinction. Core and mantle structures are often observed in interstitial quartz indicating recrystallization by subgrain rotation (White, 1976). Interstitial quartz also occurs as irregularly shaped grains with lobate margins which suggests grain boundary migration.

Quartz aggregates in equigranular biotite gneisses are recrystallized into mosaics of equant polygonal or irregulary shaped grains with lobate margins. The degree of recovery, indicated by flat extinction, increases southward (Fig. 16c).

Figure 16. Movement sense indicators in the Cranberry gneiss. a) slab showing shear bands in coarse-grained augen gneiss located to the north of the pluton. b) photomicrographs showing shear bands and fractured feldspar porphyroclasts in augen gneiss located to the northwest of the pluton. c) photomicrograph showing quartz grain-shape fabric in equigranular gneiss located south of the pluton.


NW
SE
a
1 CM
b
q
f
q
bi
900 µm
NW
SE
c
NW
SE
900 µm

Movement sense indicators

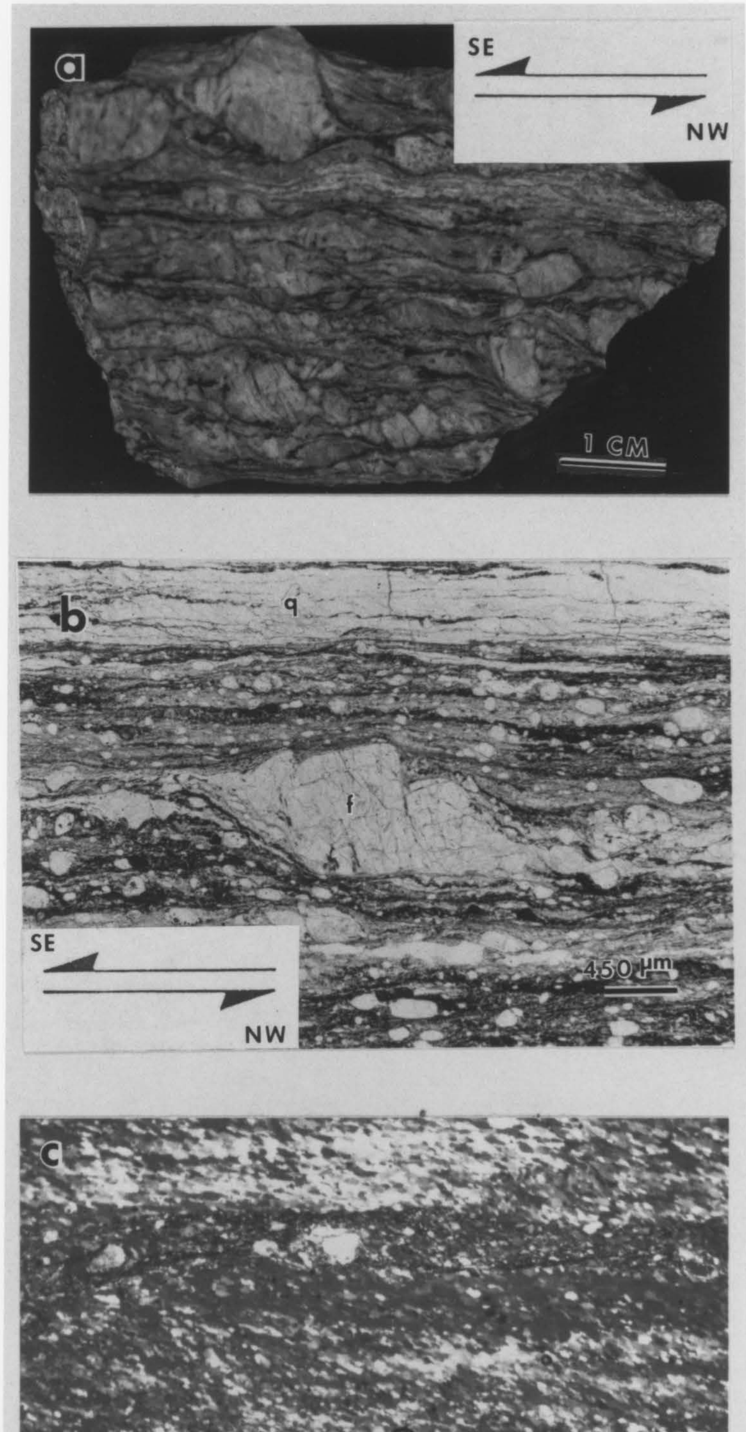
The majority of ductile shear zones of all scales with east and northeast trend show very consistent southeast-directed normal fault displacement with a minor component of oblique slip. Shear zones trending northwest show predominantly sinistral strike-slip displacement. Shear sense in cataclasite zones is unknown.

Movement sense was deduced in outcrop by fabric asymmetry within and at shear zone boundaries (Ramsay and Graham, 1970) as well as by offset of passive markers such as large potassium feldspar grains and mineralized fractures that could be traced across the deformation zones. Care was taken to make observations in the plane parallel to the mineral elongation lineation and perpendicular to the mylonitic foliation (XZ plane). Fabric asymmetry and relative offset of markers viewed in other planes show incorrect movement sense (Figs. 6, 8b).

The following microstructural movement sense indicators are all consistent with southeast-directed displacement along shear zones with east and northeast trend and sinistral strike-slip displacement along shear zones with northwest trend (Figs. 15a-c, 17a-c): 1) asymmetric porphyroclasts (e.g., Passchier and Simpson, 1986), 2) shear bands (e.g., Berthe et al., 1979; Lister and Snoke, 1984), 3) oblique quartz grain shape fabrics (e.g., Eisbacher, 1970; Lister and Snoke, 1984) and 4) quartz crystallographic fabrics (e.g., Bouchez, 1977; Burg and Laurent, 1978; Schmid and Casey, 1986).

Shear sense in the Cranberry Gneiss was deduced by asymmetric porphyroclasts, shear bands, and oblique quartz grain shape fabrics (Figs. 16a-c). Penetrative rotational fabrics show top to the northwest movement sense except along the southern contact with the pluton. In this region, both pluton and country

Figure 17. Movement sense indicators in east- and northeast- trending shear zones in the Striped Rock pluton. a) slab showing shear bands in northeast-trending zone of mylonitic augen gneiss located along the southern contact b) photomicrograph showing asymmetric alkali-feldspar porphyroclast in a meter-scale ultamylonite zone with east trend c) Quartz grain-shape fabric in centimeter-scale ultramylonite zone with east trend.


a
SE
NW
1 CM
b
q
f
SE
NW
450 µm
c
SE
NW
900 µm

rock are deformed into a zone of mylonitic augen gneiss several hundred meters wide that shows southeast-directed normal fault displacement (Fig. 2).

Discussion

Deformation History

The Striped Rock pluton was affected by episodes of cataclastic and crystal plastic deformation. Brittle deformation preceded and postdated crystal plastic deformation (Fig. 18).

Early Brittle Deformation

Deformation of the pluton commenced with widespread dilatant microcracking. Distributed stable cracking is characteristic of deformation close to the brittle-plastic transition (Paterson, 1978). Mechanically induced cracks are produced when the local stress exceeds the local strength and stable cracking will continue as long as rigid grains form the stress supporting framework (Simmons and Richter, 1976). Microcracks either terminate within a grain or at the grain boundary, in which case,

	Mesoscopic	Microscopic
D_1	Cm-scale quartz veins	Microcracks in feldspar and primary quartz
D_2	Mylonitic shear zones, cataclasite zones	Crystal plastic deformation of minerals in D_1 microcracks; grain-size reduction of feldspar by microcracking; recrystallization of primary and secondary quartz
D_3	Mm- to cm-scale quartz-, chlorite- , and stilpnomelane-filled cracks	Undeformed minerals precipitated in microcracks cutting D_1 microcracks

Figure 18. Deformation history.

crystal plastic deformation in neighboring grains takes up the stress at the crack tip (e.g., Mitra, 1984). Macroscopic ductile flow results from a combination of micro-cracking and dislocation motion (Tullis and Yund, 1977).

An external stress applied to granitic areas of the pluton resulted in distributed, stable cracking. This interpretation is supported by pervasive, mineralized microcracks and shear fractures in almost all feldspar grains and healed microcracks in primary quartz grains defined by planar arrays of fluid inclusions (Figs. 12b, 14a). Quartz microstructure clearly shows that interstitial quartz accomodated the imposed stress by crystal plastic deformation and small amounts of microfracturing (Fig. 12b). The amount of matrix that deformed by crystal plastic processes is observed to increase with increasing strain (Fig. 11a). Quartz syenite responded to the applied stress by forming cataclasite zones. Syenitic regions of the pluton lacked sufficient quartz (matrix) to accomodate the stress by crystal plastic deformation. Failure took place along cataclasite zones when feldspar grains could no longer support the applied stress.

At the mesoscopic scale, millimeter- to centimeter-scale fractures filled predominantly with quartz and minor amounts of biotite striking 070°-090° occur throughout the pluton (Fig. 5b). Quartz precipitated in this set of fractures contains abundant evidence of crystal plastic deformation demonstrating the existence of the veins prior to the onset of crystal deformation. The relative timing of mesoscopic and microscopic cracking is uncertain.

Crystal Plastic Deformation

Mesoscopic ductile shear zones with east and northeast trend are interpreted to have nucleated on mineralized fracture zones in an otherwise homogeneous rock (cf. Mitra, 1984; Segall and Simpson, 1986). Field evidence strongly supports the existence of an early set of millimeter- to centimeter-scale quartz veins. Quartz veinlets are deflected into and deformed within the ductile shear zones (Figs. 8a-b). Mineral elongation lineations are well-developed in vein quartz in ductile shear zones. The lineations in the quartz are parallel to lineations contained in the foliation planes of shear zones in which the quartz is deformed. The parallel orientation of the mineral lineations in vein quartz and the mylonitic foliation implies coeval generation of the lineations.

The southern pluton-country rock contact, which is contained in the Fries Thrust zone, provided a larger scale zone of mechanical weakness. Both the pluton and country rock are deformed into a zone of mylonitic augen gneiss that shows southeast-directed normal fault displacement. This zone is interpreted to mark the northern limit of the Fries Thrust zone based on the similiarity in orientation of planar and linear fabrics in the Striped Rock pluton and the Cranberry Gneiss south of the pluton (Figs. 2, 3a-c, 4a-b).

Feldspar grains are cut by several generations of mineralized dilatant microcracks. Minerals (principally quartz) precipitated in many of the cracks have undergone extensive crystal plastic deformation (Fig. 11a). Quartz is completely recrystallized and occurs in polygonal mosaics of equant to elongate grains (20 um). Biotite and white mica grains are kinked. The presence of plastically deformed minerals sealing cracks in feldspar grains demonstrates that microcracking preceded the onset of crystal plastic deformation.

Completely recrystallized quartz ribbons are ubiquitous to mylonitic shear zones of all scales and constitute a significant portion of the total mineral constituents (Fig. 11a). Quartz grain shape fabrics that are oblique to ribbon boundaries indicate a component of rotational strain (Eisbacher, 1970; Burg and Laurent, 1978; Lister and Snoke, 1984). Shear sense deduced from oblique grain-shape fabrics is consistent with that of other microstructural movement sense indicators implying synchronous generation of fabrics in the quartz ribbons and the shear zones. Crystal plastic deformation therefore followed precipitation of quartz.

The presence of aqueous fluid is an important factor influencing both deformation and compositional changes. The extensive reaction of feldspar (feldspar + water = quartz + white mica + epidote) indicates the presence of fluid during deformation because reactions involving hydration proceed only with the introduction of water. This reaction has, in fact, gone nearly to completion in the more extensively deformed areas of the pluton, most notably at the southern contact with the Cranberry Gneiss (Fig. 13c). The small size of new quartz and white mica grains facilitates grain boundary sliding and enhances diffusion controlled processes (White, 1976). Fine-grained quartz- and mica-rich zones produced by reaction should, therefore, be weaker than their coarser-grained hosts. The very strong preferred grain shape orientation of white mica aggregates, parallel to mylonitic foliation, parallel to feldspar grain boundaries, and in pressure shadows adjacent to feldspar grains clearly, indicates syndeformational growth (Figs. 12c, 13c). Metamorphic reactions taking place during deformation of the pluton may have provided a mechanism for strain softening in zones of high fluid-rock interaction (e.g., Mitra, 1978; White and Knipe, 1978; Beach, 1980).

Late-stage Brittle Deformation

Millimeter-scale quartz-, chlorite- and stilpnomelane-filled cracks and centimeter-scale quartz veins striking 030°-060° and 320°- 340° overprint cataclasite zones and mylonitic shear zones of all scales (Figs. 9a-d). The mineral assemblage contained in this set of fractures (chlorite and stilpnomelane) is dissimiliar to that of the earlier set of fractures suggesting that they are temporally unrelated. The orientations of the cracks are consistent with northwest-directed compression (Fig. 5c).

Microcracks filled predominantly with undeformed quartz, stilpnomelane, green biotite and epidote crosscut earlier generations of microcracks containing crystal plastically deformed filling material. The mineral assemblage contained in the late-stage microcracks is distinct from the earlier generation of cracks. Stilpnomelane is not present in early microcracks.

Tectonic Models

Movement sense indicators show very consistent southeast-directed normal fault displacement along shear zones with east and northeast trend (Figs. 17a-c). The spatial distribution of normal fault mylonite zones is geometrically consistent with: 1) Late-Proterozoic extension, 2) Mesozoic extension, 3) rigid rotation of the pluton during Paleozoic thrusting, or 4) "gravitational collapse" during Paleozoic thrusting.

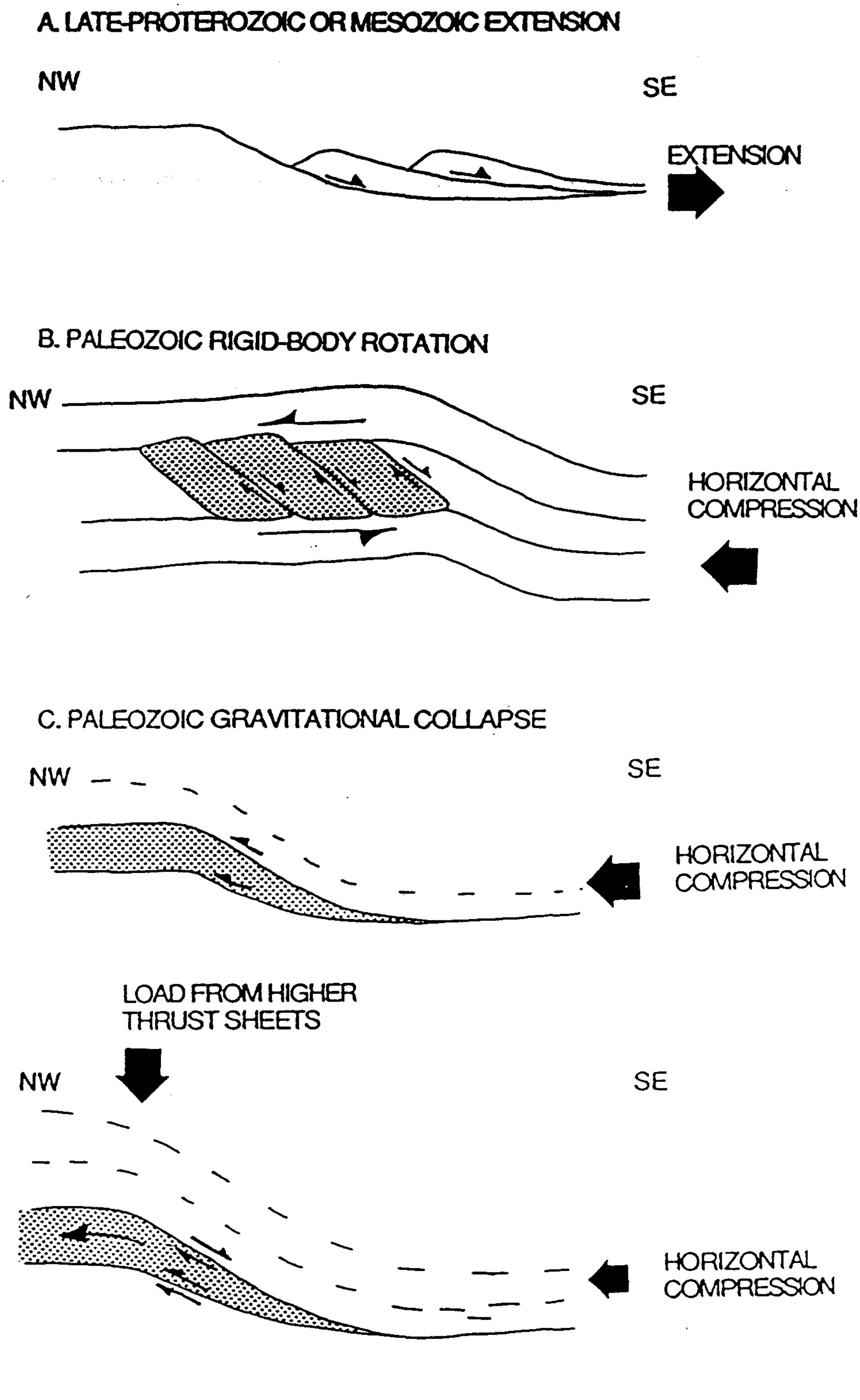


Figure 19. Tectonic models.

Late-Proterozioc Extension

Numerous diabase and rhyolite dikes with northeast trend intrude the Cranberry gneiss north of the study area (Fig. 1; Stose and Stose, 1957; Rankin, 1970). The dikes are believed to have been generated during late-Proterzoic crustal extension and are included in the Crossnore Plutonic-Volcanic Group (Rankin, 1970). The similiar orientation of the dikes to some of the extensional shear zones present in the Striped Rock pluton suggests a common origin during late-Proterozoic crustal extension (Fig. 19a). This model requires quartz fabrics generated during late-Proterozioc extension to have remained intact through Paleozoic metamorphism and compressional deformation. Preservation is very unlikely because thermally activated recovery processes and syntectonic recrystallization in quartz are initiated at relatively low temperatures (250°- 300°, Tullis and Yund, 1977) and quartz fabrics would have been reset. No such resetting of extensional fabrics has been observed. Additionally, the syntectonic retrograde mineral assemblage is inconsistent with late-Proterozioc deformation and by similiar reasoning would not have survived Paleozoic prograde metamorphism.

Fractures along which ductile shear zones are interpreted to have localized could have been generated at this time. Crustal extension is believed to have taken place from 700 Ma. to 570 Ma. (Odom and Fullagar, 1984) and could have produced strong anisotropies in the pluton. Approximately 100 m.y. were available following crystallization (681 $\pm$ 10 Ma.) for the pluton to have been brought up to near surface crustal levels where fracturing may have taken place. Local variation in the extension direction resulting from an irregularly shaped margin could have produced a set of east-northeast trending fractures. The actual geometry of the continental margin, however, is poorly constrained at this time.

Mesozoic Extension

Ductile deformation zone geometry is also consistent with Mesozoic extension (Fig. 19a). Many Triassic basins are, in fact, bounded by reactivated northeast-trending mylonite zones. The reactivation of temporally unrelated mylonites was, however, generally cataclastic, producing a fault breccia (e.g., Bobyarchick and Glover, 1979). This model implies that rocks of the Blue Ridge were at a lower crustal level than those of the Piedmont during the Mesozoic in order for the deformation in the pluton to have been predominantly crystal plastic. No regional geologic evidence exists to support this.

Late-stage, northeast- and northwest-striking cracks and veins filled with quartz, chlorite and stilpnomelane overprint the mylonite zones and cataclasite zones. The orientation of these brittle structures are consistent with northwest-directed compression. There is no regional evidence to support compressional deformation following Mesozoic extension.

Paleozoic Rigid-Body Rotation

Northwest-directed thrusting may have resulted in rigid-body rotation of the pluton (Fig. 19b). The micaceous schists and gneisses of the Cranberry Gneiss are rheologically different from the pluton and are likely to have deformed by crystal plastic processes more readily. Rotation of the pluton may have initiated southeast-directed normal fault mylonites on pre-existing fractures. The main problem with this model are the dips of the shear zones. The inclination of the mylonite zones would be expected to be initially steep, becoming shallower with increasing rotation. No rotation of normal fault mylonite zones has been observed; foliations and lineations within rocks of the Fries Thrust zone are inclined almost identically to those in the pluton (Fig. 3).

Paleozoic Gravitational Collapse

A modified "gravitational collapse" model (e.g., Burchfiel and Royden, 1985; Burg et al., 1984) would allow a rigid wedge of basement rock, bounded by shear zones with opposite movement sense, to be squeezed northwestward during Paleozoic overthrusting (Fig. 19c). Shear zones on the upper side of the basement block would display a movement sense opposite to that of regional shear sense. Continued loading of thrust sheets could cause a reorientation of the stress field resulting in a downward-directed maximum compressive stress which could produce normal-fault mylonites. Mineral elongation lineations indicating transport direction in the pluton are almost identical to those contained in rocks within the Fries Thrust zone which, in turn, have a strong rotational fabric that is consistent with generation during northwest-directed thrusting (Figs. 3, 4). The strong similiarity in orientation of stretching lineations and foliations suggests that the fabrics in the pluton were generated during the same deformational event as the fabrics in the rocks of the Fries Thrust zone. The similiarity may, however, be entirely coincidental.

The conditions of deformation during generation of northwest- directed rotational fabrics and southeast-directed rotational fabrics do not appear to have been appreciably different. In both cases, feldspar grains are cut by fractures sealed with deformed minerals and are altered to quartz + epidote + white mica, the latter of which shows a strong preferred grain shape orientation. Quartz is highly recrystallized and grain shape fabrics are commonly well-developed. The degree of recovery in quartz in equigranular gneisses in the Fries Thrust zone, indicated by a decreasing degree of undulatory extinction and an increase in regularity of recrystallized grain boundaries, increases southward (Fig. 16c). Similiar textures reported by Lister and Price (1978) were attributed to high grain boundary energy and resultant grain boundary migration. Increased strain energy may be associated with more intense deformation within the Fries Thrust zone.

The close proximity of the pluton to the Fries Thrust zone suggests that a correlation may exist between the observed transition from cataclastic to crystal plastic process and tectonic loading. Dilational cracking is well known to occur during stress buildup in fault zones. The region around the fault zone dilates in response to increasing stress which induces the migration of fluids from the surrounding area into the fault zone (seismic pumping, Sibson et al., 1978). Similar processes are thought to be operative in the formation of ductile shear zones in the Striped Rock pluton. Reactions (e.g., feldspar reacting to quartz + white mica) taking place in zones of fluid buildup, could result in significant reaction-enhanced ductility during early stages of shear zone formation (e.g., White and Knipe, 1979). It is suggested that the pluton initially responded to increased stress and perhaps increased strain rate by stable microcracking. Fluids migrating ahead of the advancing thrust sheet are likely to have invaded the pluton via networks of microcracks. The change in deformation mechanisms from predominantly cataclastic to predominantly crystal plastic is interpreted to be a result of increased confining pressure due to tectonic loading of the Fries Thrust Sheet (Fig. 2). The increased confining pressure would cause cracks oriented at a high angle to the direction of compression to close; cracks oriented at a low angle to the direction of compression would remain open. Healed intracrystalline cracks defined by planar arrays of fluid inclusions are very common to the Striped Rock pluton and are interpreted as early dilational cracks that closed upon increase in confining pressure; mineralized cracks are those cracks that remained open.

Mitra (1979) extrapolated Von Mises criterion for the deformation of single crystals to the deformation of a homogeneous body of rock. The Von Mises criterion states that at least five independent slip systems must be active simultaneously at any time in order for deformation of a body to take place without creating voids. The following sets of shear zones have been identified in the Striped Rock pluton (Fig. 5b): 1) 090°-070° inclined southeast, 2) 030°- 050° inclined southeast, 3) 010°-350° steeply inclined, 4) 320°-340° inclined northeast and 5) 320°-340° inclined southwest. Internal shape change of the pluton could therefore, have been accomodated by coeval slip along shear zones with east, northeast, north and northwest trend. This hypothesis is further supported by the association of shear zones with northwest and northeast trend in outcrop (Fig. 6). Northwest-trending shear zones splay off of northeast-trending shear zones in a manner similiar to secondary shears observed in brittle fault systems (Chinnery, 1966).

K-Ar data yield ages in the 400 Ma. range for the Striped Rock pluton (Riecken, 1966) and the Cranberry Gneiss (Carr and Kulp, 1957) in the vicinity of Independence (Fig. 20). The significance of these ages is uncertain because sample locations and analytical procedures are unknown. If the dates record cooling ages, they suggest that the area was subjected to a thermal event prior to 402-438 Ma.. This implies that

STRIPED ROCK PLUTON		
681 ± 10 Ma.	Rb/Sr whole rock	Odom and Fullagar, 1984
438 ± 12 Ma.	K/Ar biotite	Riecken, 1966
CRANBERRY GNEISS FROM MIXED ZONE		
513 + 20 Ma.	K/Ar biotite	Riecken, 1966
CRANBERRY GNEISS		
1320 Ma.	Rb/Sr whole rock	Dietrich et al., 1969
790 Ma.	Rb/Sr mineral	Dietrich et al., 1969
667 ± 18 Ma.	K/Ar biotite	Riecken, 1966
406 ± 20 Ma.	K/Ar whole rock	Carr and Kulp, 1957

Figure 20. K/Ar and Rb/Sr data for the Striped Rock pluton and Cranberry Gneiss.

the deformation in the pluton may have taken place during the Taconic orogeny. Late-stage cracks are filled with a mineral assemblage dissimiliar to that of earlier microcracks and veins suggesting that they are temporally unrelated. The orientation of these mineralized cracks is consistent with later compression (Acadian or Alleghanian).

Conclusion

The orientations of southeast-directed normal fault mylonite zones in the Striped Rock pluton are consistent with generation during Paleozoic thrusting. Microstructures in the plutonic rocks are almost identical to microstructures in the surrounding gneisses suggesting that strain rate, confining pressure and temperature were similiar during the generation of northwest- and southeast-directed rotational fabrics. Mineralized fractures overprint all ductile structures. The orientations of these fractures are consistent with northwest-directed compresson during a later event.

The possibility does exist that the bulk of the pluton was not affected by the regionally significant Paleozoic thrusting event. Every shear zone in the pluton has not been analyzed and the lack of mylonite zones that show northwest-directed displacement may be an artifact of sampling or exposure. The actual timing of the deformation is presently not well constrained but is consistent with either Taconic or Acadian thrusting and brittle overprinting during a later compressional event.

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Appendix A. Microprobe Data

Feldspar Analyses Sample 3A

	1A	1B	1C*	1D*	2
SiO_2	63.87	64.90	69.32	68.61	64.09
Al_2O_3	19.17	18.98	18.98	20.18	18.75
TiO_2	00.02	00.01	00.00	-0.01	00.02
FeO	00.04	00.05	-0.01	00.01	00.05
MnO	00.00	00.01	-0.01	-0.01	00.00
MgO	00.01	00.00	-0.03	00.00	00.00
CaO	00.04	00.02	00.11	00.13	00.04
Na_2O	00.23	00.25	11.12	10.93	00.36
BaO	00.00	00.00	00.00	00.00	00.00
K_2O	16.17	16.21	00.13	00.92	16.16
SUM	99.55	100.43	99.61	100.76	99.47
An	0.20	0.10	0.54	0.62	0.20
Ab	2.11	2.29	98.70	94.17	3.27
Or	97.68	97.61	0.76	5.21	96.53
Si	2.966	2.983	3.028	2.980	2.979
Al	1.049	1.028	0.977	1.033	1.027
Ti	0.001	0.000	0.000	0.000	0.001
Fe	0.002	0.002	0.000	0.000	0.002
Mn	0.000	0.000	0.000	0.000	0.000
Mg	0.001	0.000	0.002	0.000	0.000
Ca	0.002	0.001	0.005	0.006	0.002
Ba	0.000	0.000	0.000	0.000	0.000
Na	0.021	0.022	0.942	0.920	0.032
K	0.958	0.950	0.007	0.051	0.958
O	8.000	8.000	8.000	8.000	8.000

*Fills cracks in grain analyzed

Feldspar Analyses Sample 3A

	7A	7B*	7C*	8	9
SiO_2	64.57	68.53	68.22	94.98	67.05
Al_2O_3	19.09	20.20	20.06	0.42	19.65
TiO_2	0.00	-0.01	-0.02	-0.01	0.00
FeO	0.15	0.01	0.02	0.00	0.08
MnO	-0.01	-0.01	0.00	0.01	-0.02
MgO	0.00	-0.01	0.00	-0.01	0.00
CaO	0.06	0.05	0.03	0.01	0.12
Na_2O	1.68	11.91	11.93	0.02	10.15
BaO	0.00	0.00	0.00	0.00	0.00
K_2O	14.35	0.06	0.06	0.24	2.21
SUM	99.89	100.73	100.30	95.66	99.24
An	0.30	0.23	0.14	3.01	0.57
Ab	15.06	99.44	99.53	10.90	86.97
Or	84.64	0.33	0.33	86.08	12.46
Si	2.971	2.973	2.974	3.981	2.975
Al	1.035	1.033	1.030	0.021	1.028
Ti	0.00	0.00	-0.001	0.00	0.00
Fe	0.006	0.00	0.001	0.000	0.003
Mn	0.00	0.00	0.00	0.00	-0.001
Mg	0.00	-0.001	0.00	-0.001	0.00
Ca	0.003	0.002	0.001	0.00	0.006
Ba	0.00	0.00	0.00	0.00	0.00
Na	0.150	1.002	1.008	0.002	0.873
K	0.842	0.003	0.003	0.013	0.125
O	8.00	8.00	8.00	8.00	8.00

*Fills cracks in grain analyzed

Feldspar Analyses Sample 3A

	3	4	5	6	6A*
SiO_2	64.04	64.57	67.32	67.88	63.87
Al_2O_3	18.80	18.72	20.26	19.68	19.10
TiO_2	00.11	00.09	00.01	00.00	00.00
FeO	00.02	00.02	00.01	00.07	00.06
MnO	00.05	00.01	00.36	00.00	00.01
MgO	00.05	00.01	00.02	-0.01	00.00
CaO	00.03	00.01	00.36	00.13	00.04
Na_2O	00.29	00.24	11.11	11.94	00.21
BaO	00.00	00.00	00.00	00.00	00.00
K_2O	16.09	16.34	00.37	00.06	16.47
SUM	99.47	100.01	99.65	99.75	99.76
An	0.15	0.05	1.72	0.60	0.20
Ab	2.66	2.18	96.17	99.08	1.90
Or	97.19	97.77	2.11	0.33	97.90
Si	2.976	2.985	2.958	2.978	2.965
Al	1.030	1.020	1.049	1.017	1.045
Ti	0.001	0.000	0.000	0.000	0.000
Fe	0.004	0.003	0.008	0.003	0.002
Mn	0.001	0.001	0.000	0.000	0.000
Mg	0.003	0.001	0.001	0.001	0.000
Ca	0.001	0.000	0.017	0.006	0.002
Ba	0.000	0.000	0.000	0.000	0.000
Na	0.026	0.022	0.947	1.016	0.019
K	0.954	0.964	0.021	0.003	0.975
O	8.000	8.000	8.000	8.000	8.000

*Fills cracks in grain analyzed

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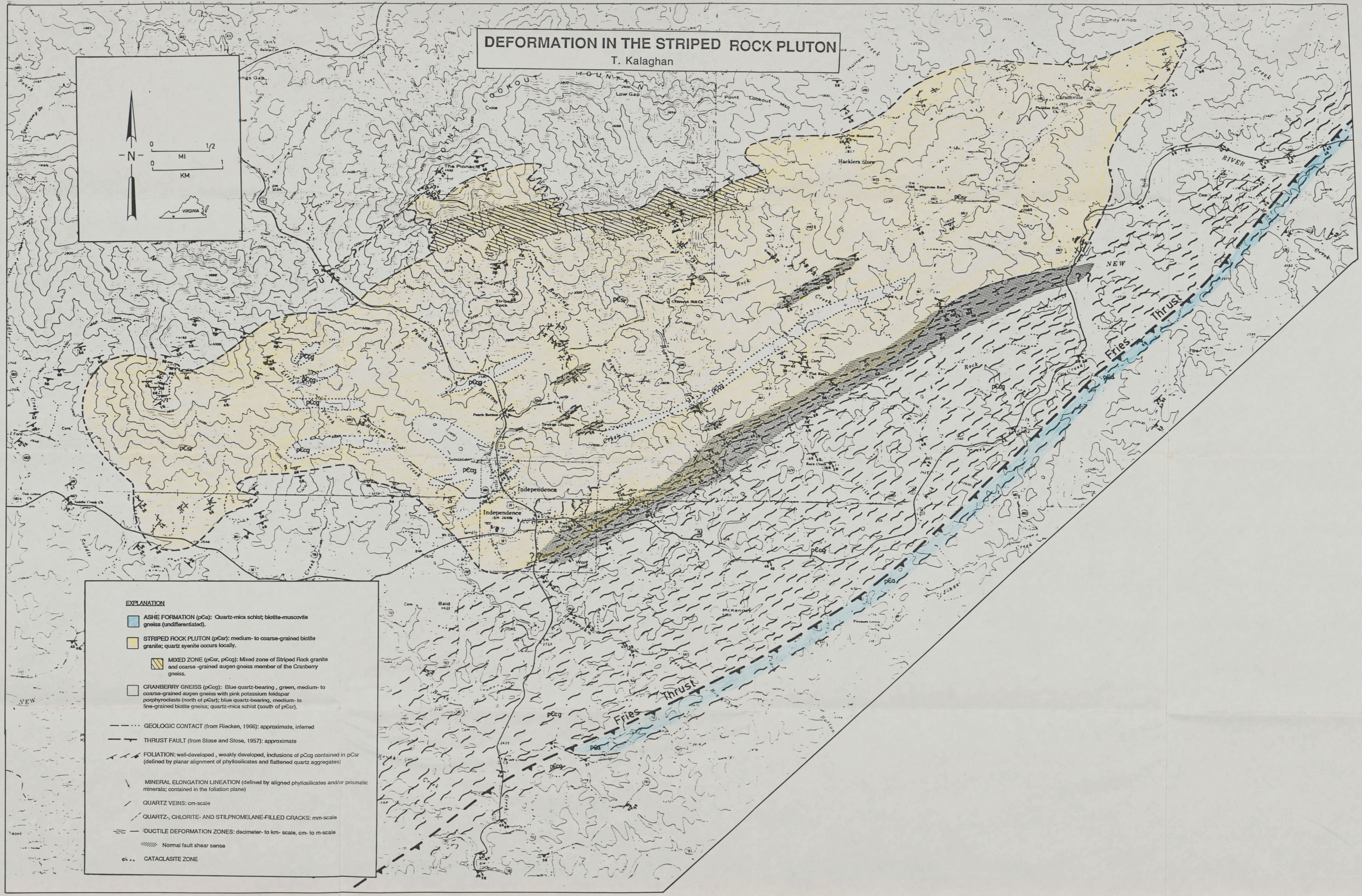
DEFORMATION IN THE STRIPED ROCK PLUTON
T. Kalaghan
N
0 1/2 MI
0 1 KM
VIRGINIA
EXPLANATION
ASHE FORMATION (p€a): Quartz-mica schist; biotite-muscovite gneiss (undifferentiated).
STRIPED ROCK PLUTON (p€sr): medium- to coarse-grained biotite granite; quartz syenite occurs locally.
MIXED ZONE (p€sr, p€cg): Mixed zone of Striped Rock granite and coarse -grained augen gneiss member of the Cranberry gneiss.
CRANBERRY GNEISS (p€cg): Blue quartz-bearing , green, medium- to coarse-grained augen gneiss with pink potassium feldspar porphyroclasts (north of p€sr); blue quartz-bearing, medium- to fine-grained biotite gneiss; quartz-mica schist (south of p€sr).
GEOLOGIC CONTACT (from Riecken, 1966): approximate, inferred
THRUST FAULT (from Stose and Stose, 1957): approximate
FOLIATION: well-developed , weakly developed, inclusions of pCcg contained in pCsr (defined by planar alignment of phyllosilicates and flattened quartz aggregates)
MINERAL ELONGATION LINEATION (defined by aligned phyllosilicates and/or prismatic minerals; contained in the foliation plane)
QUARTZ VEINS: cm-scale
QUARTZ-, CHLORITE- AND STILPNOMELANE-FILLED CRACKS: mm-scale
DUCTILE DEFORMATION ZONES: decimeter- to km- scale, cm- to m-scale
Normal fault shear sense
CATACLASITE ZONE
Fries Thrust
Fries Thrust
NEW RIVER
Independence
Hacklers Store
Carsonville
Lundy Knob
Low Gap
Bald Hill
p€sr
p€cg
p€a