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GEOMETRY AND DEFORMATION HISTORY OF MYLONITIC ROCKS AND SILICIFIED ZONES ALONG THE MESOZOIC CONNECTICUT VALLEY BORDER FAULT, WESTERN MASSACHUSETTS

A Thesis Presented

by

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ABSTRACT

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MAY, 1988

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The Connecticut Valley border fault is a major, probably listric, west-dipping normal fault, that uplifted Precambrian to Devonian schists and gneisses of the Pelham Dome on the east, and formed a lowland to the west where Triassic and Jurassic sediments accumulated. It extends from northwestern New Hampshire south to Long Island Sound. Five kilometers of vertical displacement, and dips of 20 to 40 degrees have been estimated for central Massachusetts.

Mylonitic and silicified rocks were examined from the Village of Millers Falls, in north-central Massachusetts, south to Belchertown, in central Massachusetts. Silicified rocks occur on the footwall of the fault in seven locations, and mylonitic rocks were studied in one location.

Mylonitic rocks involve protomylonite with small areas of rock that have characteristics of orthomylonite and ultramylonite. This indicates that some rocks were affected

by the faulting process at depth in a ductile environment with heterogeneous strain rates. S - C fabrics (schistosite-cisaillement) within the mylonites indicate a west-side-down motion direction, supporting the usual observation that the border fault is a normal fault. The mylonites were cut by a cataclastic intrusion breccia which was subsequently mylonitized, developing an S-C fabric similar to that in the host mylonite rock. Mylonites are indicative of low strain rates in a ductile regime, while cataclasites indicate higher strain rates. This suggests that the fault surface was not a smooth plane, but had irregularities that temporarily changed the strain rates imposed on the rocks.

Conditions nearer to the surfaces involved a brittle extensional environment where volumes of rock borderin the fault in the footwall were brecciated. The mylonites also were uplifted into the brittle regime. Joints, veins and minor normal faults were developed within the mylonites, cutting previous ductile features. Silicification occurred in the brecciated rock masses where hydrothermal fluids circulated through the fractured volumes of rock replacing primary metamorphic and igneous minerals with new minerals, primarily quartz.

Several groups of joints and veins within the silicified

rocks have north-south strikes similar to the trend of the border fault in many areas. One style of joint strikes northeast to northwest, dips west, has a platy character, and appears to mimic the local fault plane orientation. Fluids that initially silicified the breccia masses also produced the quartz, and later, hematite veins in at least two subsequent hydrothermal pulses. Combined joint data show no conclusive evidence as to whether joint development and orientation was controlled by the geometry of the border fault, or by regional stresses. Combined vein data, however, show strong evidence that vein orientation was controlled by a regional stress field and not directly by border fault geometry. A mean strike for the veins of N15E suggests an extensional stress of N75W-S75E for the region at the time of vein formation. Extensional stresses of N60W-S60E and N68W-S68E have been estimated in previous studies for the Northfield basin and Amherst areas during the early Mesozoic. Vein formation was later and suggests that the regional stress field rotated counterclockwise over time.

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CHAPTER 1

INTRODUCTION

Statement of the Problem

Several studies of the Mesozoic Connecticut Valley basins, and specifically the border fault, have been previously performed, but no detailed work has yet been done on the silicified zones along the fault trace. This study concentrated on six silicified areas, and one area containing mylonites and fault surfaces. Silicification resulted where hydrothermal fluids circulated through fractured volumes of rock near fault surfaces and replaced primary metamorphic and igneous minerals with new minerals, primarily quartz. The purpose of this study is to find what the structural features of the silicified zones can show about the geometry of the border fault, and, through investigation and classification of silicified rock types, to provide further information on the deformational history of the fault zone.

Regional Setting

The Connecticut Valley border fault is traceable from New Haven Connecticut, northward through central Connecticut, western Massachusetts, and into New Hampshire and Vermont. The Connecticut Valley Mesozoic basins lie immediately west of the border fault, and are thought to be

a half-graben (Wheeler, 1937; Sanders, 1960, 1963; Jasaitis, 1983), and possibly an early abortive attempt to open an Atlantic Ocean. Divided by the Amherst inliers, that are structural highs of Paleozoic crystalline rocks on the hanging wall of the fault, the basin is sectioned off into the large Hartford basin to the south, and the much smaller Deerfield and Northfield basins to the north. Robinson (1967a, 1979), Onasch (1973), and Laird (1974) worked in the areas to the east of the fault, and have developed an understanding of the structural history. Six periods of deformation have been recognized, the first five being mostly ductile in nature, with the development and backfolding of regional nappes, the rising of gneiss domes, and late metamorphic faulting and folding. The sixth phase involved brittle Mesozoic faulting and dike emplacement. It was during this phase that the Connecticut Valley basins and the border fault developed. The border fault downdropped Cambrian to Devonian gneisses and schists mantling the west side of the Pelham dome, and progressively formed a lowland which was filled with Mesozoic volcanics and sediments derived from the east.

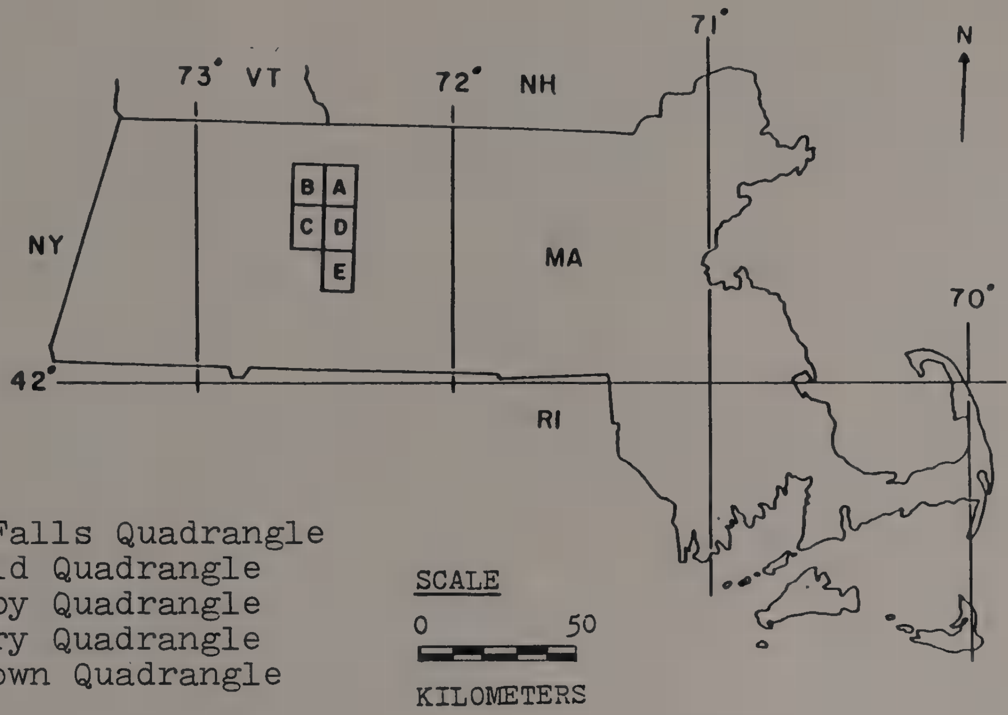
Nature of the Border Fault

The fault is considered to be a large, west-dipping, listric, Late Triassic to Early Jurassic, normal fault

(Emerson, 1898, 1917; Wheeler, 1939; Robinson, 1967a; Laird, 1974; Jasaitis, 1983). Vertical displacement has been estimated at the Massachusetts - New Hampshire border to be 5 km (Robinson, 1979). Estimates around Springfield, Massachusetts suggest a vertical displacement of 8 to 12 km (Jasaitis, 1983). In map view the fault is not linear. Three fault splays are found near French King Bridge location, three are found at East Mineral Hill, and two at Lake Arcadia, suggest that the border fault is a series of faults at some localities, forming zones probably 30 to 180 meters wide (Ashenden, 1973).

Nature and Location of the Silicified Zones

The silicified zones occur along the fault trace, and represent brecciated areas affected by massive silica replacement during hydrothermal alteration. These zones are cut by several small faults, and are moderately to extensively jointed. The joints and minor faults are younger than the Mesozoic border fault. Other features of the rock include late-stage quartz and specular hematite veins, and a locally pervasive foliation. The study area included five quadrangles in western Massachusetts (Figure 1). It extended from the village of Millers Falls, 35 km south to Lake Arcadia in Belchertown (Figure 2), and was divided into seven subareas (Figures 3 through 7). From



A. Millers Falls Quadrangle
B. Greenfield Quadrangle
C. Mount Toby Quadrangle
D. Shutesbury Quadrangle
E. Belchertown Quadrangle

Figure 1. Map of Massachusetts showing quadrangles involved in study.

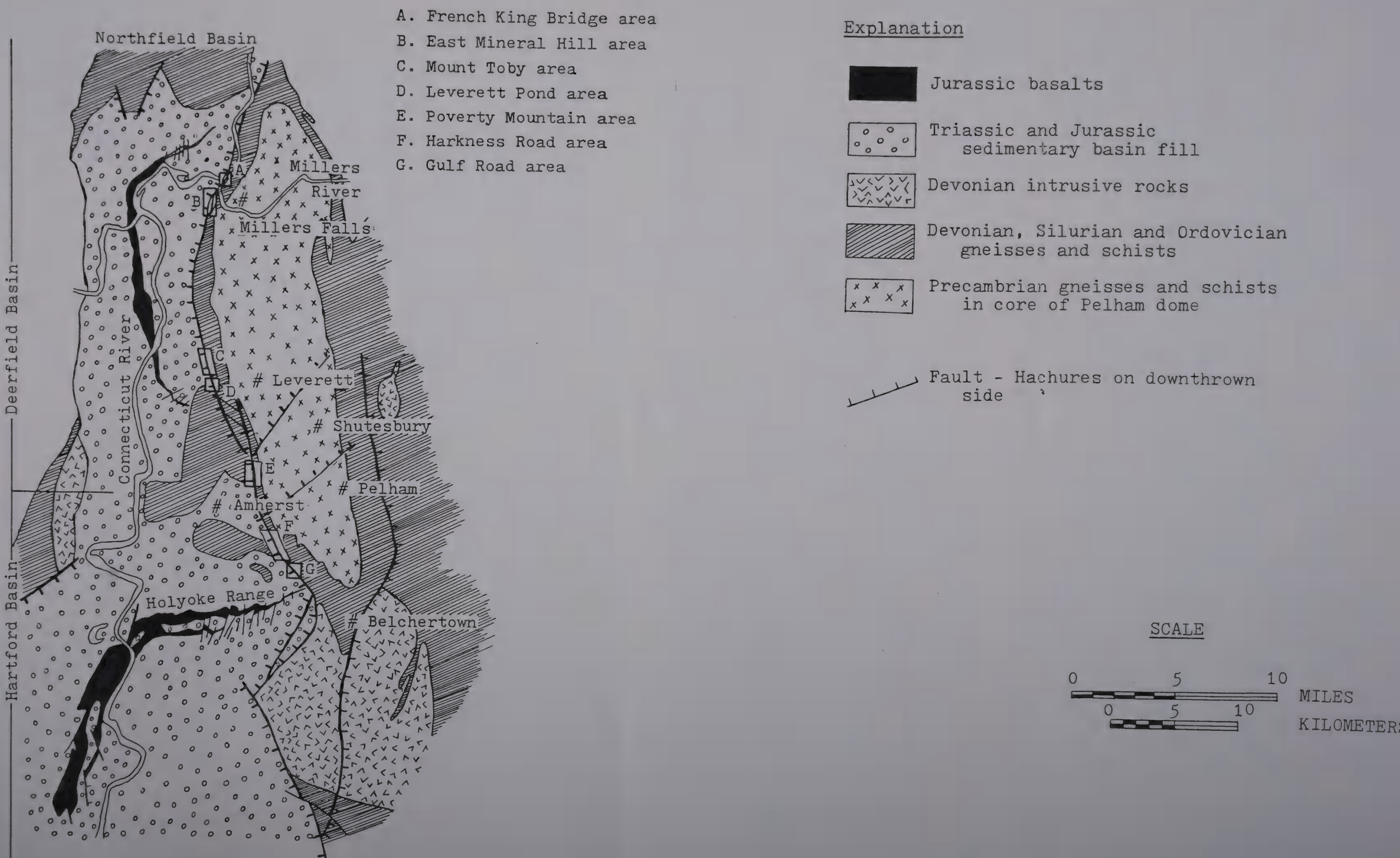


Figure 2. Simplified excerpt of Bedrock Geologic Map of Massachusetts showing seven detailed map areas.

north to south they are as follows:

1. The French King Bridge area (A in Figure 2 and Figure 3) is located immediately north of French King Bridge, near the confluence of the Connecticut and Millers Rivers, in the Millers Falls 7 1/2-minute quadrangle. Mylonite outcrops 90 meters north of the bridge are dark gray, moderately foliated, and have coarse-grained clasts in a finer-grained matrix. Several slickensided surfaces are also exposed in this area. Ashenden (1973) studied the area in 1969 when the Turners Falls dam was under repair and the water level was low enough that data could be collected from rocks that would normally be under water.

2. The East Mineral Hill area (B in Figure 2 and Figure 4) is a large silicified zone forming two long resistant ribs. It is located 1.5 km northwest of the village of Millers Falls, on East Mineral Hill, in the Greenfield 7 1/2-minute quadrangle. This rock represents a breccia zone where mineral constituents were replaced by massive silica and cemented by later quartz and specular hematite veins. Quartz constitutes most of the rock mass, giving it a blotchy white, pink, and gray color. It is distinguished from the neighboring silicified pegmatite by its lack of muscovite and feldspar, and its blocky appearance, which is the result of a moderately well developed joint system.

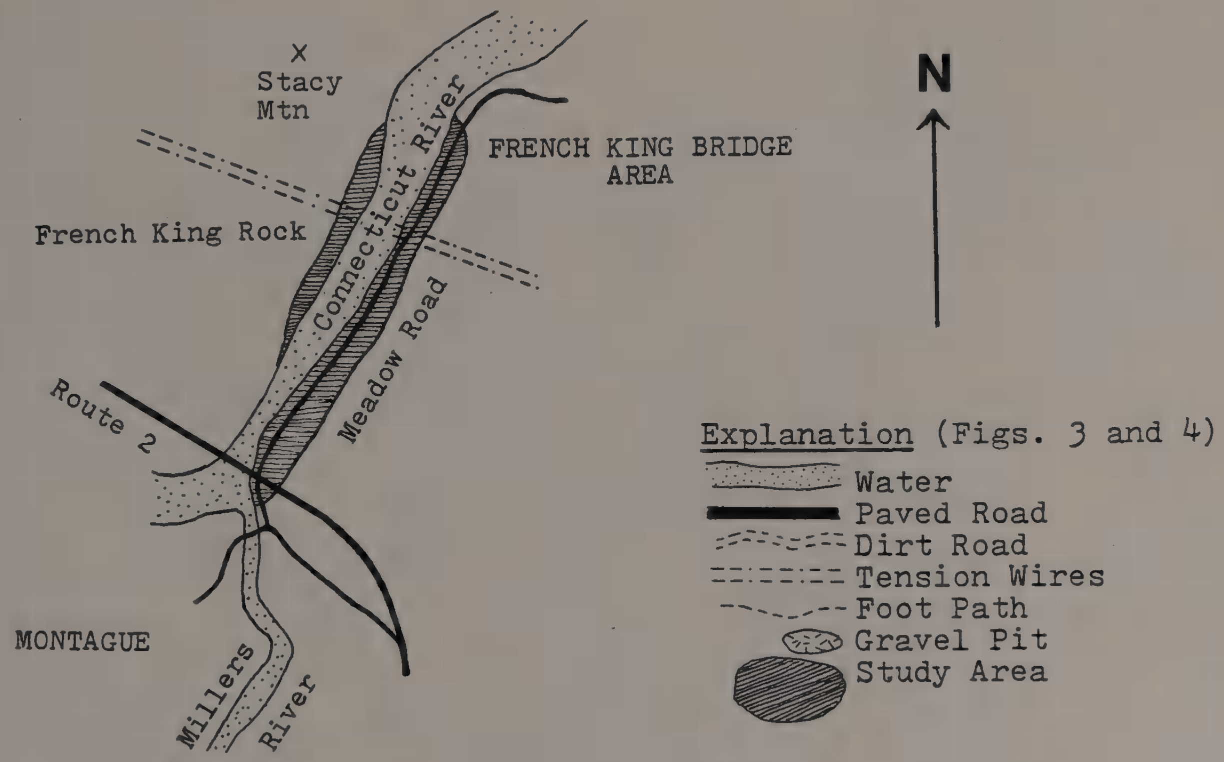


Figure 3. Index map for French King Bridge area.

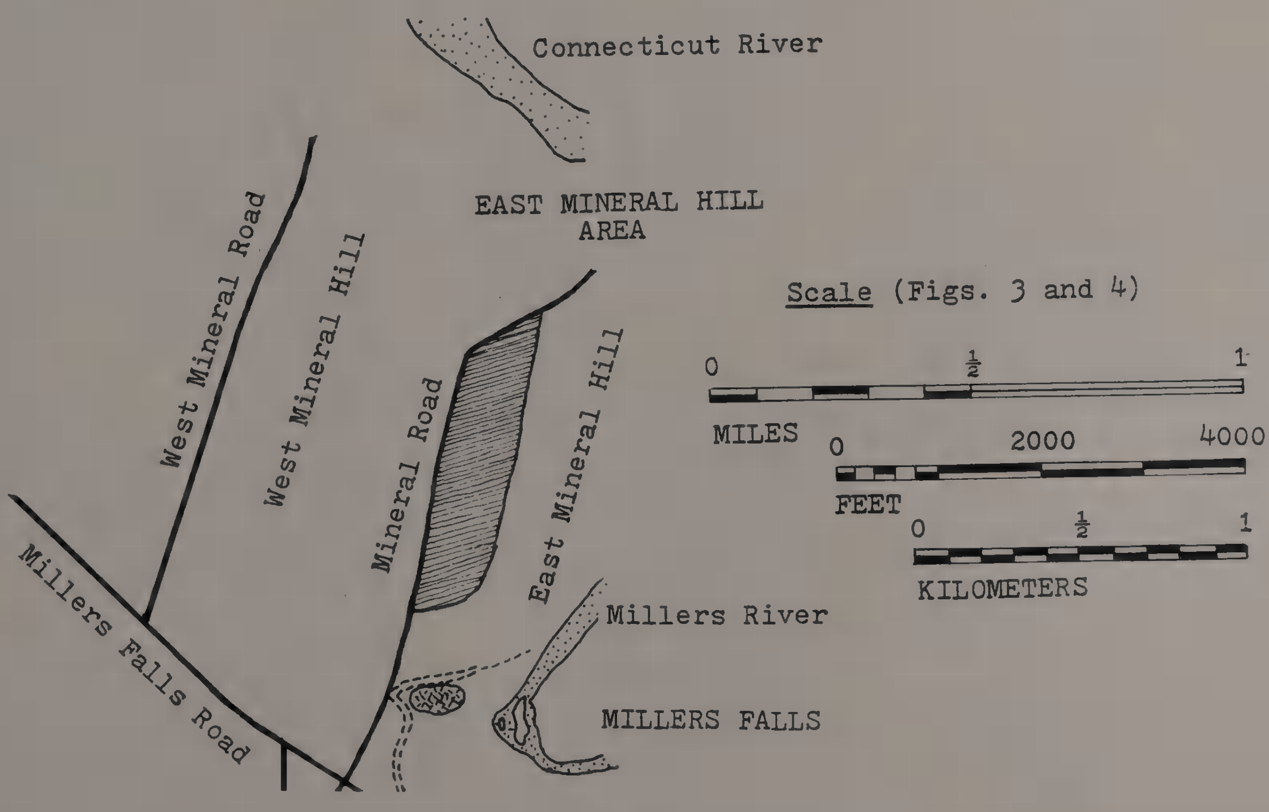


Figure 4. Index map for East Mineral Hill area.

Later veins of white quartz are locally abundant. Minor faults do not appear to cut this zone.

3. The Mount Toby silicified zone (C in Figure 2 and Figure 5) is located in the Mount Toby 7 1/2-minute quadrangle, 1.5 km due north of the Long Hill Road - Route 63 intersection in Leverett, and extends northward for 460 meters. The majority of outcrop is a gray- to rusty-red-weathering, dark-gray rock with locally abundant late quartz veins and an extensive, well developed joint system that makes collection of fresh samples very difficult. A long rib of more silica-rich rock is found in a swampy area at the north end of the zone that resembles the rock found at the East Mineral Hill area. Both outcrops are moderately jointed, have vuggy quartz, and are cut by late white quartz veins.

4. The Leverett Pond Zone (D in Figure 2 and Figure 5), less than 155 meters long, is also located in the Mount Toby quadrangle. The rock is gray in color, but local areas of silica-richer rock have the characteristic white color. This zone has a moderately developed joint system but lacks the rusty-red weathering characteristic of the previous zone.

5. The Poverty Mountain area (E in Figure 2 and Figure 6) is the largest silicified zone and is located 460 meters

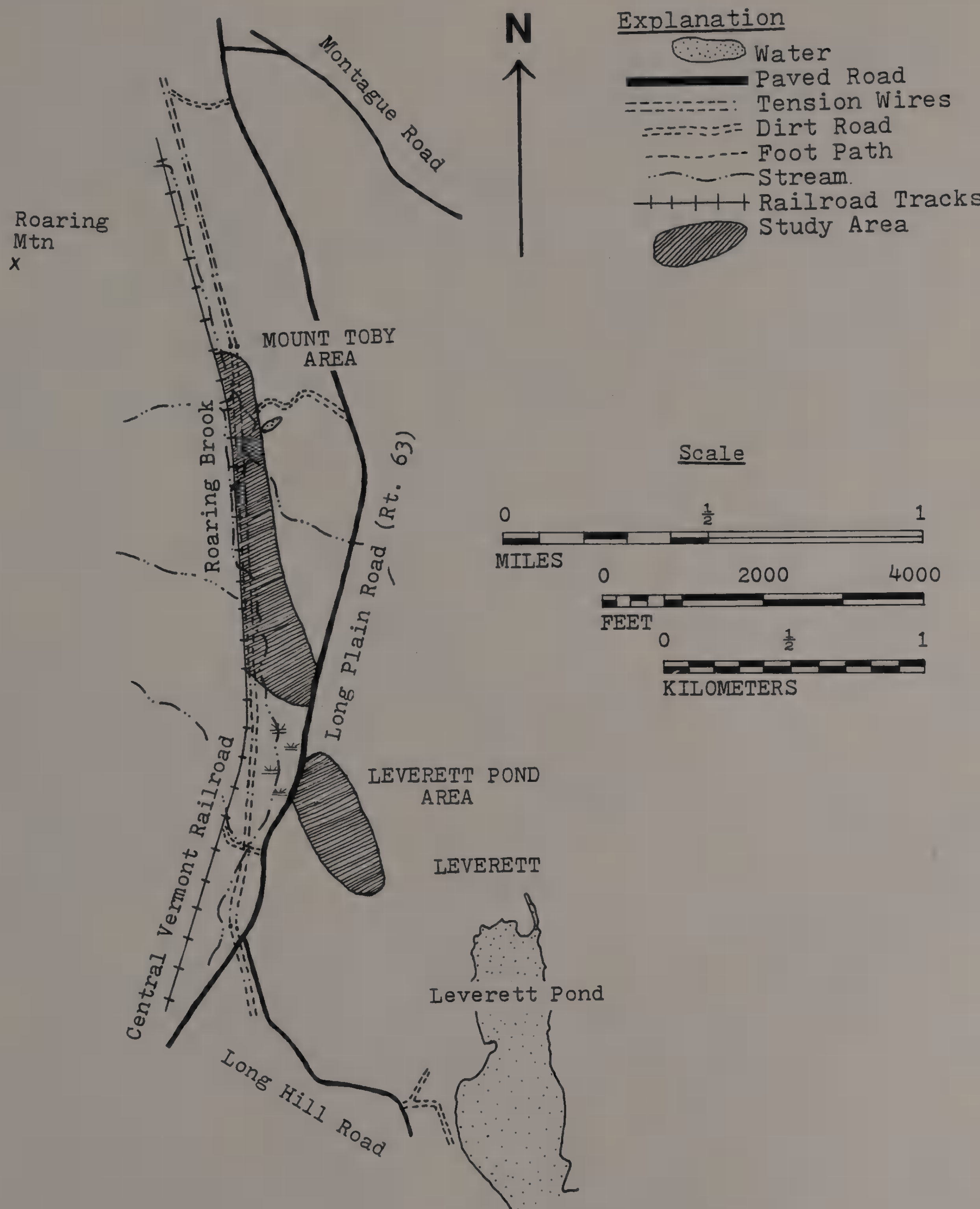


Figure 5. Index map for Mount Toby and Leverett Pond areas.

southeast of the common juction among the towns of Shutesbury, Pelham and Amherst (374 feet) in the Shutesbury 7 1/2-minute quadrangle. It extends southward for 915 meters. The rock is greenish-gray, heavily jointed and has locally abundant quartz veins, vuggy quartz and specular hematite veins. This zone is cut by minor normal faults which are the youngest feature in the silicified zone.

6. The Harkness Road area (F in Figure 2 and Figure 7) is located in the Belchertown 7 1/2-minute quadrangle. This zone starts 610 meters northeast of the Harkness Road - Route 9 intersection as small remnant pieces of brecciated pegmatite with coarse-grained white quartz, orthoclase and plagioclase. Small silicified knobs are found 305 and 915 meters south of the pegmatite in a S25E direction. These knobs consist of greenish-gray, very fine-grained silicified rock.

Another 610 meters along this same line, in a gravel pit behind Mike's Speed Shop on Route 9, are three fault-related rocks. Silicified rock is in contact with metamorphic rock, and the metamorphic rock is cut by pseudotachylite veins. This outcrop is found along the east side of the fault trace. The silicified rock is poorly jointed, and appears as a thin coating, up to several centimeters thick, on the metamorphic rock. Hydrothermal pyrite deposits are also

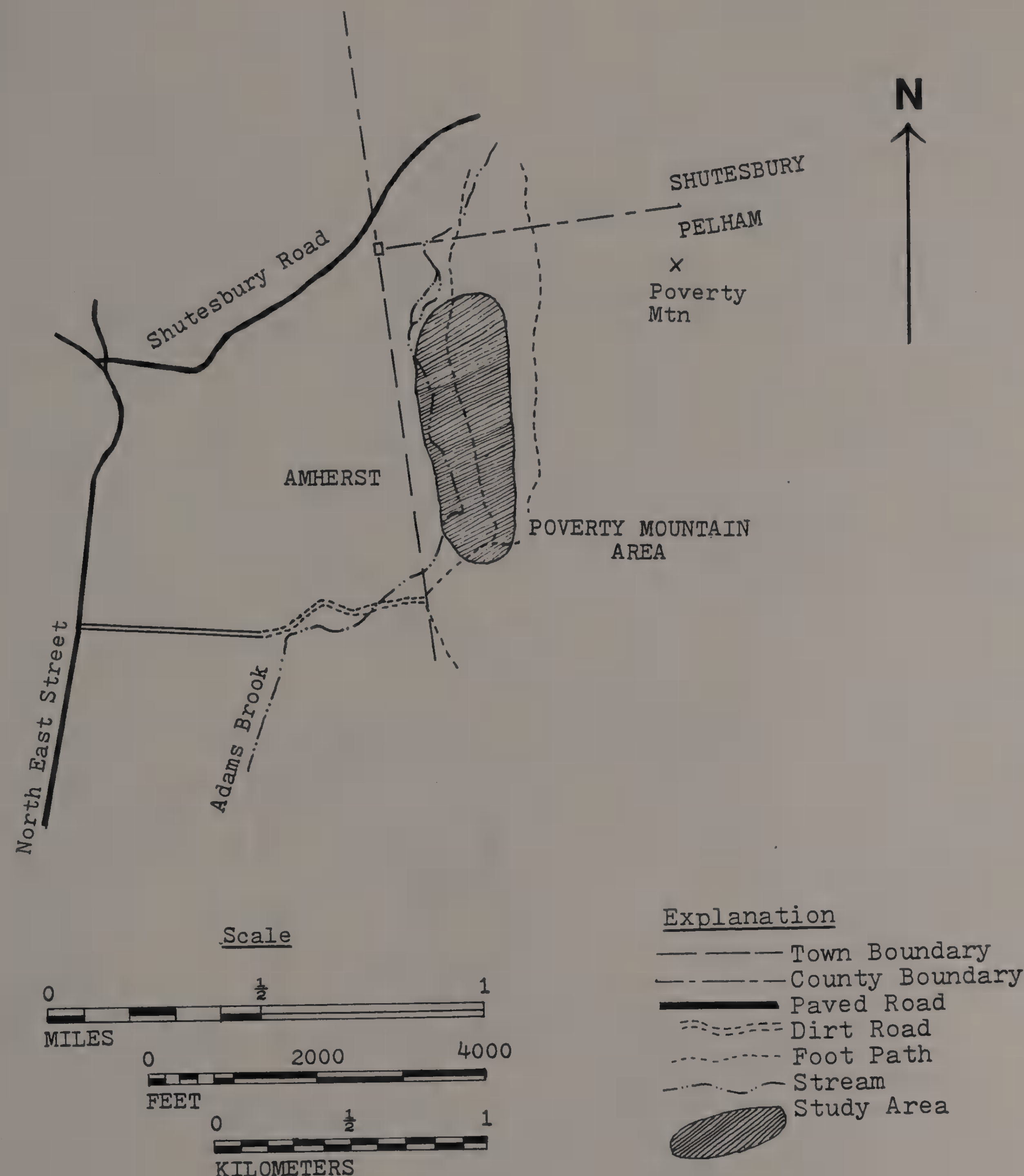


Figure 6. Index map for Poverty Mountain area.

present in an outcrop along the east side of the fault trace in this area. Late quartz veins are less important in this area.

7. The Gulf Road silicified zone (G in Figure 2 and Figure 7), also in the Belchertown quadrangle, is located 150 meters north of the Route 9 and Gulf Road intersection. The rock is greenish-gray, moderately jointed, and has late-stage quartz veins.

Topography and Vegetation

Topography of the field area from Millers Falls to Belchertown is a series of low lying and swampy areas with silicified rock providing relief such as raised ribs and ledges. Minimum elevation is 200 feet in the French King Bridge area at the shore of the Connecticut River. The other six areas start at a minimum elevation of 350 feet and have a maximum elevation at the tops of the ribs or ledges of 450 to 530 feet. Mixed deciduous and coniferous trees characterize the overstory. Understory growth is most significant in the mainly deciduous stands, and is typically woody shrubs such as mountain laurel.

Previous Work

No detailed work had been performed on the silicified zones in the field area until this project, but three of the

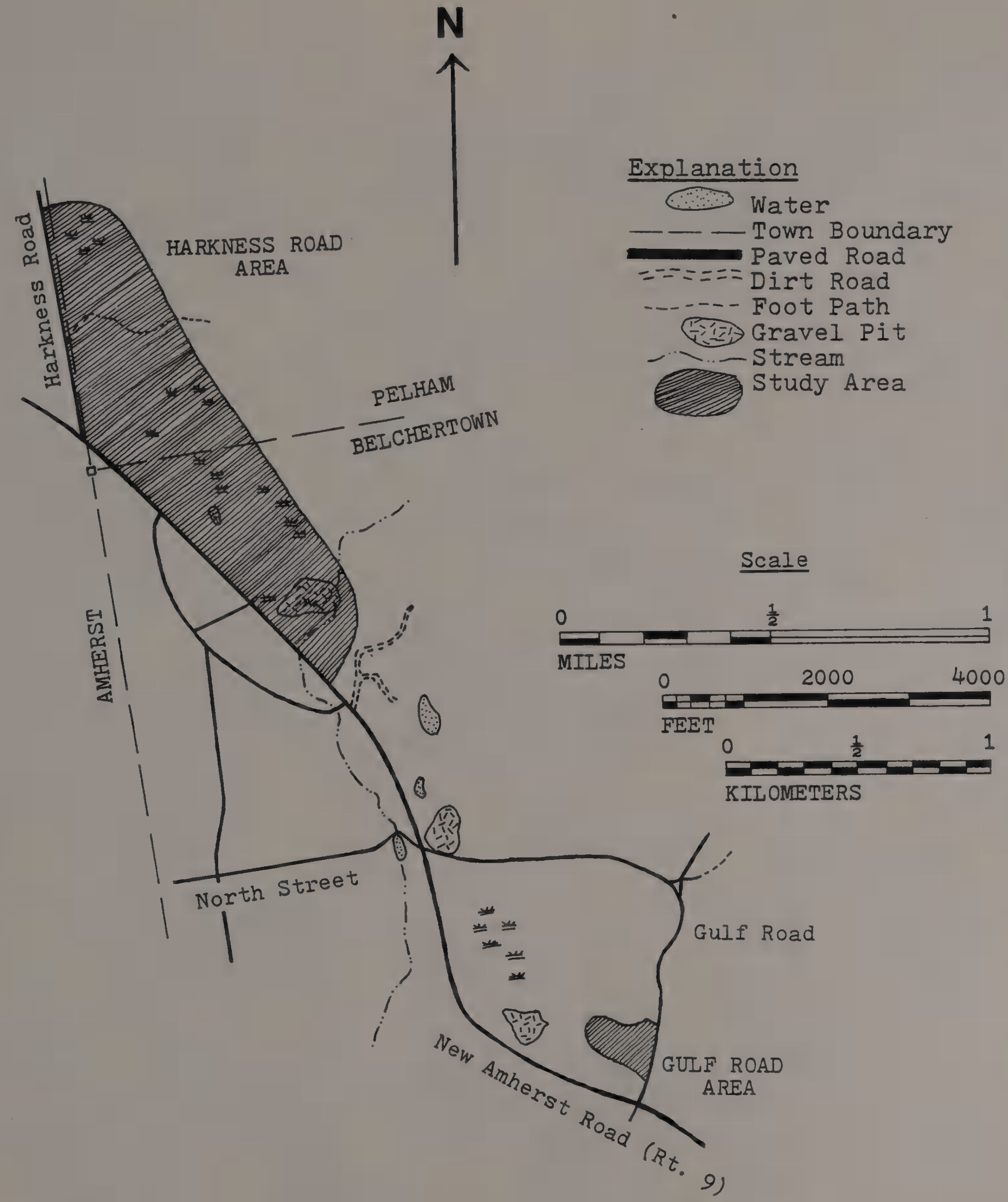


Figure 7. Index map for Harkness Road and Gulf Road areas.

zones were labelled on previous maps. The East Mineral Hill area was included on Ashenden's 1973 map, the Leverett Pond area was included on Jasatis's 1983 map, and the Poverty Mountain area was included on the recent Bedrock Geologic Map of Massachusetts (Zen, et al., 1983).

On a more general scale, many studies of the Mesozoic Connecticut Valley basins, and the border fault have been performed. Edward Hitchcock (1841, 1917) described the geology of the area for the first geologic map of the State of Massachusetts, and the geology of Rhode Island. B.K. Emerson (1898) studied the area in more detail and defined the border fault as a west-dipping, normal fault. Bain (1932, 1941, 1957) provided models for the origin and structure of the Connecticut Valley basin. In his 1932 paper the border fault was described as a high-angle, reverse, thrust fault with east to west displacement. His later works defined the fault as a right-lateral, strike-slip fault. Wheeler (1937) worked on the western boundary of the Connecticut Valley and determined it to be locally an east-dipping normal fault so that parts of the valley represent a graben structure. Wheeler (1939) studied irregularities in the eastern border fault and determined that they resulted in differential movement of the basin fill along the fault plane to produce warping of the fill.

Salients in the fault plane, areas where the fault plane projects westward, represent places where subsidence of the fill was least. Reentrants, parts of the fault plane that project eastward, represent places along the fault where subsidence was greatest.

More recent work includes that of Sanders (1960, 1963) who defined a history for the Connecticut Valley basin starting with a period of initial graben subsidence, and igneous activity. This was followed by longitudinal crustal arching in the graben with no associated faulting or igneous activity. Then came a second period of graben subsidence, followed by a late system of faulting including both dip-slip and strike-slip faults. Ashenden (1973) studied the French King Bridge area in detail and measured five fault surfaces, three sets of slickensides, one mylonite foliation, and one quartz lineation in the mylonite. Robinson (1967a, 1979), Onasch (1973), and Laird (1974) all worked in areas east of the fault to develop a structural history for west-central Massachusetts. Piepul (1975) studied jointing and faulting at the southern end of the border fault in Connecticut. Chandler (1978) studied graben mechanics at the junction of the Hartford and Deerfield basins near Amherst. And finally, Jasaitis (1983) worked on the Amherst inliers including the area of the border fault

that runs through the east side of his field area. He described the valley as a half graben structure.

Field Methods

The area was subdivided into seven zones. Measurements of structural features, including joints, minor faults, mineral lineations, veins, and foliations were taken using a Brunton compass. Two types of data collection techniques were used in the field for the quantitative study of planar and linear features in the seven areas; a general survey of structural features, and the construction of six detailed outcrop maps, two in each of the larger silicified zones. Detailed outcrop maps are made using a wood frame 5 feet square. The frame is sectioned off by strings at one foot intervals. All features were measured and mapped for each square and then compiled for plotting purposes. This technique is useful for (1) observing data trends and clustering patterns using maps and associated equal area diagrams, and (2) measuring minor structural features that may not be evident using the general sampling techniques where a much larger area is covered. One disadvantage of this system of small map areas is that changes in trends over larger areas may not be recorded. This problem might possibly be avoided by constructing several maps, putting the grid at positions far enough apart on the outcrop that

any changes could be recorded.

Petrographic work was performed on rock samples taken from traverses across the strike of the larger silicified zones, and other texturally significant samples. These were used to help explain and compare fault-related rocks and silicification textures. Sampling was started in the unaltered rock on one side of the zone, through the zone, to unaltered rock on the opposing side. Thus the variable effects of silicification could be observed through the entire zone.

CHAPTER 2

MYLONITIC ROCKS - FRENCH KING BRIDGE AREA

Introduction

The French King Bridge area is important to this study because it contains several fault-related rock types including cataclastic, mylonitic, and silicified rocks. One outcrop with mylonites is present in this area and was studied in detail. Most of this chapter is devoted to the physical appearance and structural characteristics of the mylonites based on field work and thin section observations.

Higgins (1971) and Wise et al. (1984) gave definitions for mylonites as well as cataclasites. Mylonites can be divided into three categories; protomylonites, orthomylonites, and ultramylonites. Protomylonites have a matrix produced by syntectonic crystal-plastic processes and have a minor mylonitic foliation. A minor amount of recovery and annealing is exhibited, and surviving porphyroclasts make more than 50 percent of the rock mass. Orthomylonites have a similar matrix but show a strong foliation or fluxion structure. Some recovery and annealing has occurred, and porphyroclasts range from 10 to 50 percent of the rock mass. Ultramylonites show a large amount of recovery and annealing. Porphyroclasts comprise less than 10 percent of the rock mass and matrix grain size is less

than 0.5 mm in diameter. Protomylonites are developed in a stick-slip faulting environment but with slightly higher confining pressures and temperatures, and slightly lower strain rates than cataclasite rocks. A transition to an aseismic stable sliding environment of ductile faults occurs to produce orthomylonites. Going from cataclasites to protomylonites, orthomylonites, and finally to ultramylonites, there is an increase in confining pressure and temperature, and a decrease in strain rates. The rocks involved in this study include protomylonites, orthomylonites, and an ultramylonite. Cataclasites are involved as intrusions into the mylonites.

Character and Distribution of Rock Types

Rock Types Outside Mylonitic Zones

Figure 8 is a geologic map of the French King Bridge area. The border fault in this area is split into three splays. The overall trend for the fault trace is N24E, and a dip of 40 degrees has been estimated (Ashenden, 1973). Rocks located to the east of the easternmost splay include a west-dipping layer of Fourmile Gneiss and a west-dipping, isoclinal syncline of Partridge schist that has been infolded into the Gneiss. Partridge schist in the vicinity of the French King Bridge is traceable from underneath the French King Bridge, northward along the east bank of the

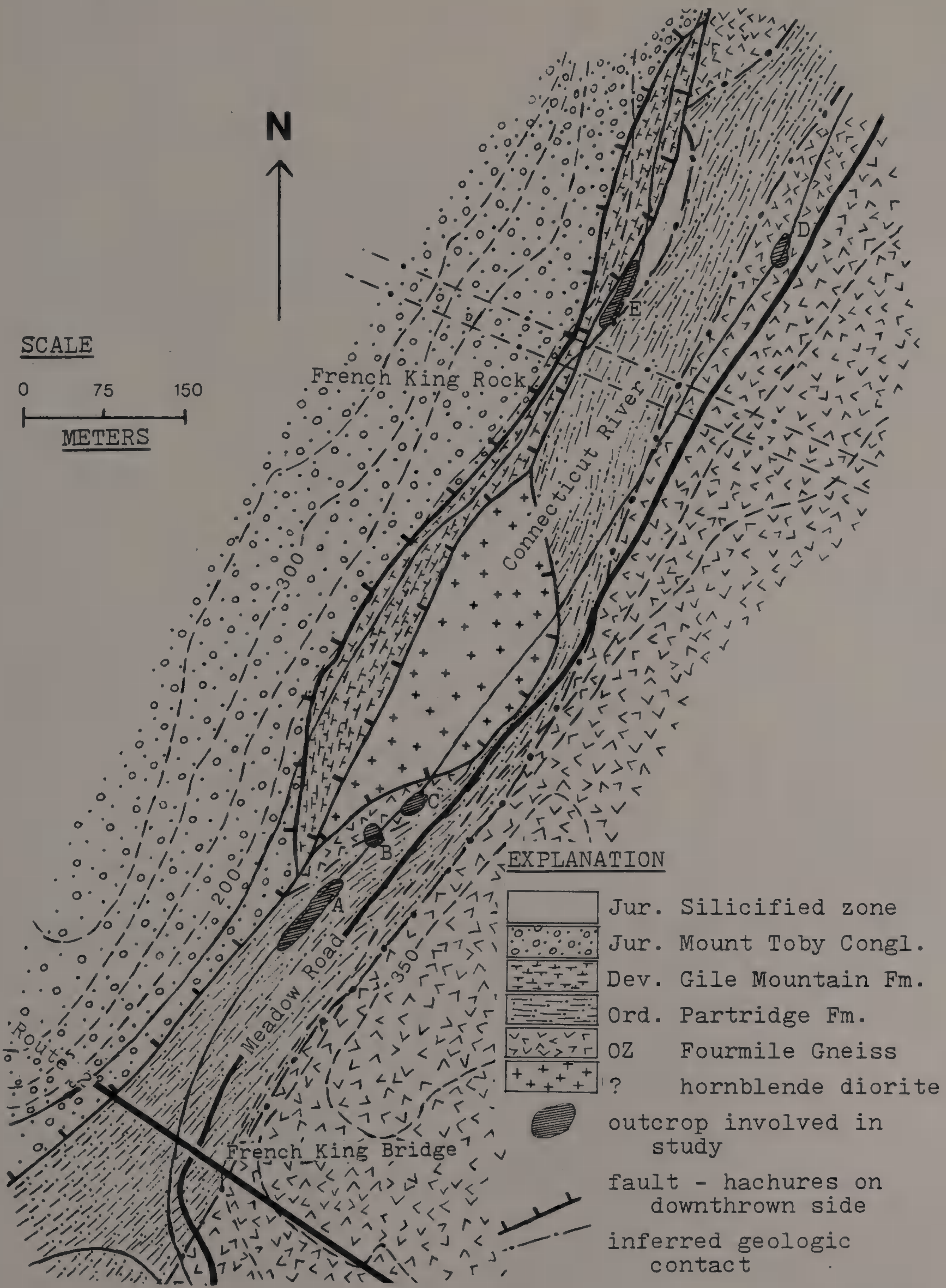


Figure 8. General geologic map of French King Bridge area.

Connecticut River for about 380 meters. Rocks caught up between the fault splays include a hornblende diorite of uncertain age in the eastern slice, and Gile Mountain Formation in the western slice. Mount Toby Conglomerate is located west of the westernmost fault splay.

Mylonitic and Silicified Rocks

Fault-affected rocks occur along the west and east bank of the Connecticut River. Stations A through E (Figure 8) were the outcrops studied. The most northern exposures include a silicified zone located along the west bank, at E. This is a brecciated zone of gray-weathering, pinkish-gray, fine-grained rock of the Gile Mountain Formation. The rock has a strong north-trending, west-dipping platy character which has been partially obliterated by brecciation. Brecciation of the outcrop makes joint and fracture patterns present in the area difficult to distinguish. Across the river on the east bank is a small outcrop of silicified cataclastic Fourmile Gneiss, referred to as station D. This rock is gray-weathering, pinkish- to greenish-gray, and very fine-grained, with a west-dipping cataclastic foliation and a west-plunging quartz lineation. The same strong north-trending, west-dipping platy character is found in this outcrop and is the result of joint surfaces that break up the rock into 5 to 10 centimeter plates. Large grains seen

with the aid of a hand lens appear brittlely fractured with sharp offsets through the grains.

Approximately 610 meters south of station D is station C which is a silicified cataclased gneiss of the Fourmile. A glassy black silicified rock is present as small lenses throughout the rock. A mylonitic fabric is dominant in this outcrop. South of station C, and 305 meters north of the French King Bridge is station B which is a large outcrop containing a series of mylonites jutting out into the river. Station A is an outcrop of Partridge Schist along the east bank of the river.

Station B has been studied in the most detail. Six units are recognized based on tectonic and physical characteristics (Figure 9). The rock units are derived from Fourmile Gneiss and pegmatites and all are heavily jointed. Total measurable thickness is 2.6 meters. The layer which is structurally the lowest is a sheared biotite gneiss of the Fourmile. This rock has an obvious foliation and quartz lineation. It lies directly to the west of the Partridge Formation. The next unit is 137.2 cm. of mylonitic vein quartz containing highly deformed gneiss blocks. One such block is located in the middle of the unit and is 12.7 cm. wide; another, located toward the base of the unit, is 25.4 cm wide. The unit has a strong mylonitic foliation and

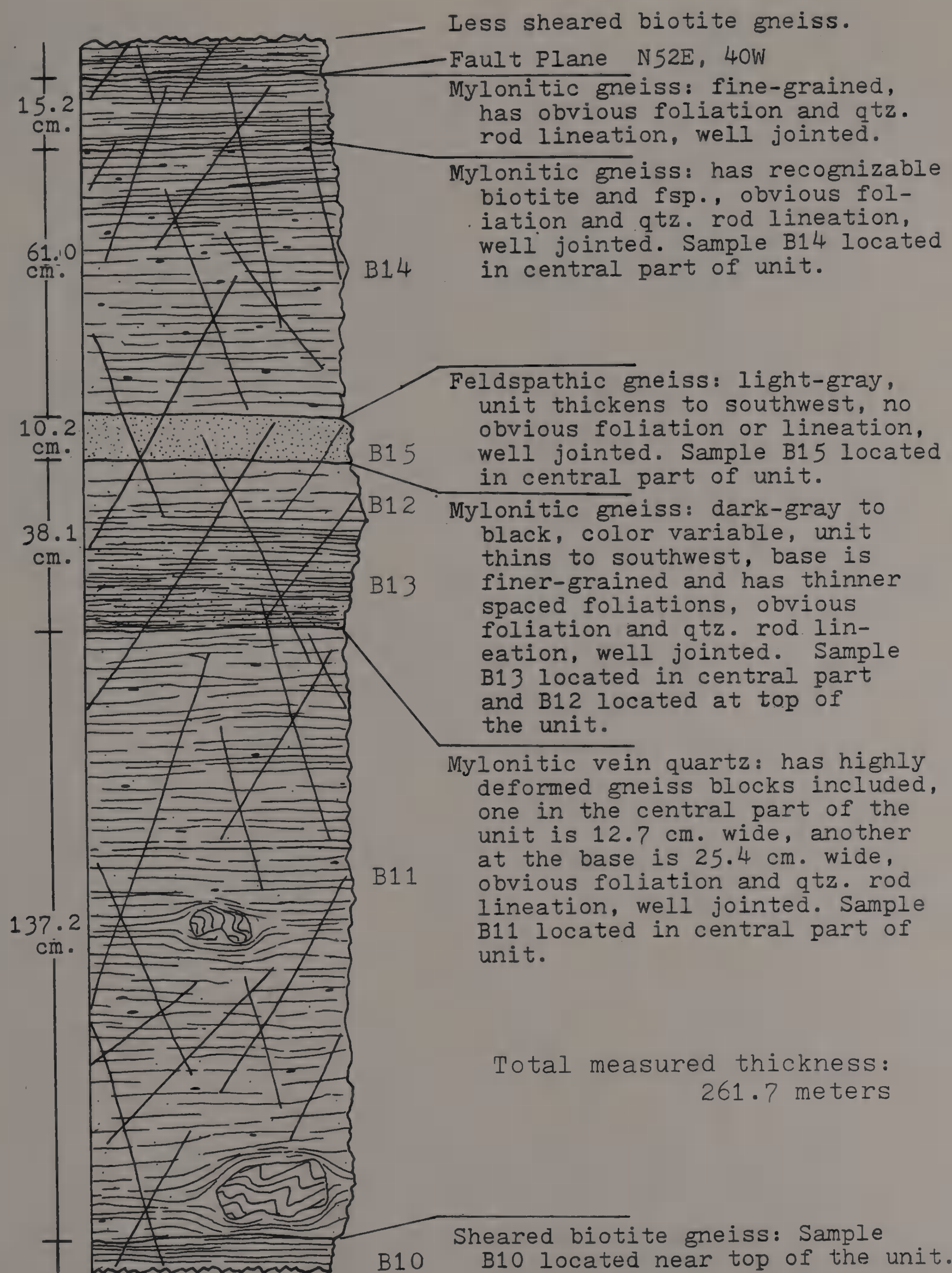


Figure 9. Tectonic units at station B: French King Bridge area.

quartz lineation; it may have been derived from a pegmatite within the Fourmile Gneiss. Above this is 38.1 cm. of dark-gray to black mylonitic gneiss. The dark color of the rock varies within the unit and becomes a lighter gray towards the top. This unit has an obvious mylonitic foliation and quartz lineation, and thins to the southwest. The base is finer-grained, and has thinner platy spacings than the top. Next is 10.2 cm of light-gray mylonitic feldspathic gneiss. No obvious foliation or lineation can be seen in this rock. This unit thickens to the southwest. Above the feldspathic gneiss is 61.0 cm of mylonitic gneiss with obvious biotite and feldspar grains. A mylonitic foliation and a quartz lineation are obvious. The uppermost unit is 15.2 cm of fine-grained cataclastic rock. Again, this unit has an obvious foliation and quartz lineation. This is in fault contact with less mylonitized biotite gneiss out toward the river.

Thin Section Observations

Six samples, B10 - B15, collected from station B were sectioned to determine rock types and fault-related textures. Two thin sections apiece were cut from B10 through B14. An "A" series was cut perpendicular to the dominant mineral lineation, and a "B" series was cut parallel to this lineation. In each case the section was

perpendicular to the foliation. Thin section numbers read B10A, B10B, etc. B15 had no obvious lineation so only one section was cut. Note that the sample numbers at station B as indicated in Figure 9 are not in order from bottom to top. One other section, B13B1, was cut from sample B13 but was mistakenly not cut parallel to the quartz lineation. Therefore any features within the section that involve angular relationships give apparent values, which as less than the true maximum. Ordinarily, this section would not be used, however, there is a significant structural feature found within section that was not found in any of the other sections. This feature will be discussed, but otherwise section B13B1 was not used to develop rock descriptions or presentation of the majority of structural details.

Thin sections cut perpendicular to the lineation have a blocky appearance and generally show no linear arrangements of features. Those sections cut parallel to the lineation were the most useful in developing rock descriptions, studying planar features, and understanding the movement history of the border fault. Samples B14 and B15 represent protomylonites with little recovery and annealing, and a weaker foliation. Samples B10 and B11 have characteristics of orthomylonites with a moderate to strong linear fabric represented by C-slip surfaces, elongated quartz rods, and

other attenuated grains. Some recovery and annealing has taken place with the formation of subgrain clusters. Sample B12 has characteristics of an ultramylonite with a large amount of recovery, some relect porphyroclasts in a very fine-grained foliated groundmass, with grain sizes less than 0.5 mm in diameter. Table 1 gives an account of the detailed thin section observations.

Quartz is abundant throughout the outcrop. In sections cut parallel to the mineral lineation, quartz grains have been deformed into elongate, rod-like features that constitute the mineral lineation, and very small, recrystallized subgrains. The subgrains are unstrained, exhibiting complete extinction, and are indicative of a higher degree of deformation relative to the elongate quartz rods which are moderately to highly strained with sweeping and undulatory extinction. Average long axis lengths for elongate quartz rods is 3.0 to 4.0 mm; however, some rods have lengths from 8.0 to 30.0 mm. Subgrains are spherical, and they form as trains subparallel to the mineral lineation, or clustered as groups with a "mortar texture". Average size for subgrains is from 0.1 mm or smaller to 2.0 mm.

Undulose extinction in quartz is typically indicative of low strain rates and temperatures, and represents numerous

microscopic fractures. These microfractures form dislocations and will begin to collect to form deformation lamellae. With an increase in temperature and deformation these lamellae collect to form deformation bands within the host grain, which are observed as an extinction difference between material within the band and the host grain. Unstrained, recrystallized quartz will start to form trains of small spherical subgrains along the boundaries of the bands. The subgrains represent areas of low strain and the boundaries of the deformation bands represent areas of high strain. With further deformation, the strain encroaches into the interior of the bands causing more quartz to recrystallize into subgrains. Trains of subgrains form parallel to each other and pile up into clusters. This progression represents an increase in recovery mechanisms.

In sections cut perpendicular to the lineation, quartz mostly appears as anhedral grains that are not elongate, representing cross sections of rods. These grains range in size from 2.0 to 3.0 mm. Locally, some quartz appears as super fine-grained masses. The quartz content for the entire outcrop is variable and ranges from 25% to 40%.

Feldspar is identified as rounded and elongate relict grains, and as very small rounded grains in the groundmass. Percentages will be given for the larger rounded and

Table 1. Thin section observations: French King Bridge samples B10 - B15.

Sample #	B10A	B10B
Oriented Sample	YES	YES
Quartz	anhedral, coarse-grained, strained, cut by late fractures// subgrains 35% (15% is subgrains)	strained, anhedral, coarse-grained//some angular//subgrains 30% (15% is subgrains)
Feldspar	relict grains//evidence of twinning 5%	relict grains 3%
Other	groundmass 39% slip surface mat. 5% fsp. alteration 5% chlorite tr, hematite tr, muscovite tr — 1%	groundmass 39% slip surface mat. 20% fsp. alteration 5% chlorite 2% muscovite tr, hematite tr — 1%
Mylonitic textures	subgrain dev. in qtz. w/ mortar texture	elongate grains//subgrain dev.//recrystallized tails//S-C fabrics
Cataclastic textures	cracked qtz. and fsp. fluid inclusions	cracked qtz. and fsp. angular grains// fluid inclusions
Overall rock textures	angular, blocky appearance of larger grains supported by fine- to v. fine-grained matrix	linear arrangement of larger grains between slip surfaces, supported by v. fine- to fine-grained matrix
Foliation	NONE	mylonite fol. defined by slip surfaces N63E, 28NW
Lineation	NONE	strong qtz. rodding N57W, 24
Color (hand sample)	med. gray	med. gray
Grain size	subgrains: 0.1 mm qtz.+fsp.: 2.0-3.0 mm matrix: v. fine-grained	subgrains: 0.1 mm qtz.+fsp.: 2.0-3.0 mm matrix: v. fine-grained
Quartz veins	NONE	YES-late stage, cuts qtz. grains and shear zones
Hematite veins	YES- few, random, small	YES- few, small, random
Mineral overgrowths	NONE	NONE
Notes		motion indicator west-side-down

cont. next page

Table 1. continued

B11A	B11B
YES	YES
anhedral, strained, coarse-grained, some w/ angular boundaries, others rounded//subgrains: v. fine-grained 40% (10% is subgrains)	strained, elongate, coarse-grained qtz. rods// subgrains - v. fine-grained 40% (10% is subgrains)
relict grains 10%	plag. w/ multiple twins relict grains 10%
groundmass 34% fsp. alteration 10% slip surface mat. 5% chlorite tr ┐ hematite tr ├ 1% muscovite tr ┘ apatite tr	groundmass 34% fsp. alteration 10% slip surface mat. 5% chlorite tr ┐ hematite tr ├ 1% muscovite tr ┘
subgrain development in qtz. w/ mortar texture	subgrain dev.//elongate grains//S-C fabrics//re-crystallized tails
cracked qtz. and fsp. fluid inclusions// angular grains	cracked qtz. and fsp. angular grains//fluid inclusions
angular, blocky appearance of larger grains supported by v. fine- to fine-grained matrix	linear arrangement of larger grains between slip surfaces, supported by v. fine- to fine-grained matrix
NONE	mylonite foliation N71E, 34NW
NONE	moderate qtz. rodding N62W, 09
med. gray	med. gray
subgrains: 0.1 mm qtz: 2.0 mm average matrix: v. fine-grained	subgrains: 0.1-0.2 mm qtz: 1.0-2.0 mm average but up to 8.0 mm matrix: v. fine-grained
YES- small up to 0.1 mm wide	YES- late stage
YES- small up to 0.1 mm wide	no veins but reddish staining evident
NONE	NONE
	motion indicator west-side-down

cont. next page

Table 1. continued

Sample #	B12A	B12B
Oriented sample	YES	YES
Quartz	v. fine-grained most in groundmass//some larger porphyoclasts 40%	v. fine-grained most in groundmass//some larger porphroclasts 34%
Feldspar	same as qtz. 15%	same as qtz. 23%
Other	groundmass 40% slip surface mat. 2% fsp. alteration tr hematite 2% chlorite (worms) 1%	groundmass 35% slip surface mat. 5% fsp. alteration tr hematite 3%
Mylonitic textures	subgrain development in qtz.	S-C fabrics// extreme grain size reduction// subgrain dev.
Cataclastic textures	late brittle fractures	breccia sections that break up parts of the groundmass
Overall rock	v. fine-grained matrix supporting larger porphyroclasts	v. fine-grained matrix supporting larger porphyroclasts
Foliation	NONE	mylonite fol. defined by by slip surfaces N82E, 43NW
Lineation	NONE	Faint-relect qtz. rods more obivious in hand sample N75W, 25
Color (hand sample)	med. blue-gray	light blue-gray w/ local tan areas
Grain size	v. fine-grained	subgrains: 0.1 mm largest grains are 0.5 mm rest is v. fine-grained
Quartz veins	YES- small, random cut by fractures	YES- small random up to 0.1 mm wide//anhedral grains
Hematite veins	YES- small, random	YES- small branching some cut by qtz. veins
Mineral overgrowths	NONE	NONE
Notes		motion indicator west-side-down

cont. next page

Table 1. continued

B13A	B13B
YES strained, anhedral, fine-grained, angular //subgrains 25-30%	YES strained, anhedral, elongate, coarse-grained//subgrains 25%
fsp. 35-40%	plag.-untwinned// microcline//altered & brecciated 30%
groundmass 23-33 % slip surface mat. 5% fsp. alteration tr muscovite 1% hematite tr	groundmass 27% slip surface mat. 10% fsp. alteration 5% muscovite 3% hematite tr
subgrains	subgrain dev//elongate grains//S-C fabrics
brecciated qtz. and fsp.	brecciated qtz. and fsp.//cut by late brittle fractures// cataclastic intrusion breccia
amorphous collection of v. fine- to fine-grained fragments v. fine- to fine-grained	linear arrangement of larger grains between slip surfaces, supported by v. fine- to fine-grained matrix
very faint foliation	strong mylonite foliation// N82E, 43NW
possible very faint qtz. rodding	strong quartz rodding N75W, 25
med. blue-gray w/tan areas	med. blue-gray w/tan areas
largest is up to 0.1-0.2 mm for qtz.//fsp. is larger up to 8.0 mm// most is v. fine-grained	qtz. rods: 2.0-3.0 mm elongate fsp.: up to 30 mm// rest: 0.1 mm
YES- late stage	YES- small random and are cut up by breccia sections
YES- small random	YES- small random
NONE	NONE
	spectacular breccia intrusion-see text for details

cont. next page

Table 1. continued

Sample #	B14A	B14B
Oriented sample	YES	YES
Quartz	small angular fragments //few larger angular fragments 40%	strained, elongate grains, anhedral// subgrains 30%
Feldspar	untwinned plag. heavily altered & brecciated// relict grains 15%	untwinned plag.//large brecciated grains// elongate & relict 50%
Other	groundmass 29% slip surface mat. 5% muscovite 1%	groundmass 13% slip surface mat. 5% hematite 2% muscovite tr
Mylonitic textures	subgrains	subgrain dev.//elongate grains//S-C fabrics
Cataclastic textures	brecciated qtz. and fsp.//angular grains	brecciated qtz. and fsp.//angular grains
Overall rock	angular, blocky appearance of larger grains supported by fine- to v. fine-grained matrix	linear arrangement of larger grains between slip surfaces supported by v. fine to fine-grained matrix
Foliation	NONE	weak mylonite fol. defined by slip surfaces N75E, 37NW
Lineation		rough qtz. rod lineation N85W, 22
Color (hand sample)	med. gray	med. gray
Grain size	qtz: average 0.1-0.4 mm larger up to 3.0 mm// same for fsp.	qtz. rods: 1.0-2.0 mm fsp: 1.0-2.0 mm average but up to 15 mm//other grains 0.1-0.2 mm
Quartz veins	NONE	NONE
Hematite veins	YES- few, small, random	YES- few, small, random
Mineral overgrowths	hematite as small black spots on qtz.	NONE
Notes		motion indicator west-side-down

cont. next page

Table 1. continued

B15
NO
brecciated, strained, anhedral, not elongated much//subgrains 30%
brecciated, angular, untwinned plag. 47%
groundmass 15% slip surface mat. 3% calcite 3% hematite 2%
subgrain dev.//weak S-C fabrics.
brecciated qtz. and fsp.
mostly angular larger grains supported by a very fine-grained matrix
very faint
possible very faint qtz. rods
med. gray
qtz. rods: up to 1.0 mm// average grain size 0.1-0.4 mm
YES- earlier veins have been broken up by later events
YES- few, small random
NONE

elongate grains, but feldspar which is part of the groundmass will be included with groundmass percentages. Feldspar percentages increase from 3% at the bottom of the outcrop to 50% at the top. Sizes for grains average 2.0 to 3.0 mm, except in sample B12 where the average grain size is 0.2 to 0.3 mm. However, in thin sections cut parallel to the mineral lineation, and viewed under plain light, the long axes for some elongate grains can reach 8.0 mm, and a few up to 30.0 mm. When viewed under crossed polars, these elongate grains appear to be made of numerous small rounded grains up to 1.5 mm in diameter.

Feldspar is also found in the groundmass. The amount of groundmass present appears to be inversely related to the amount of relict feldspar grains (Table 1). Percentages for groundmass material range from 39% at the base of the outcrop, to 40% in the center, down to 13% at the top of the unit.

The groundmass appears to consist of ground up feldspar and quartz, as well as secondary sericite, which is a hydrothermal alteration product of feldspar (Figure 10). Hydrothermal alteration of feldspar occurred during the later brittle stage of the fault, post-dating the ductile shearing. In the lower samples, B10 and B11, the groundmass consists chiefly of very fine-grained sericite, at least

one-half of the total. The other half consists of small rounded feldspar and quartz grains and a very fine-grained material resembling sericite, but having 1st order gray and yellow interference colors. Sizes for the small grains are 0.1 to 0.4 mm, and they make up 3% to 5% of the groundmass. In the central (B13 and B12) and upper parts of the outcrop (B15 and B14) sericite still makes up one-half of the groundmass, but the other half is chiefly recognizable small, less than 0.5 mm, rounded grains of feldspar and quartz.

Some feldspar grains have altered to a brownish-gray, fibrous material with a branching or radiating internal structure (Figure 10). This material has a mottled extinction and 1st order gray birefringence. In many cases, evidence of multiple twinning is still detectable. This material is commonly associated with relict feldspar grains. Small greenish, rod-like grains are contained within this alteration material, and could possibly be pumpellyite, which would also be an alteration of feldspar. Percentages for this material ranges from 10% at the bottom of the outcrop, to trace amounts in the central portion. It is not found in samples B15 or B14.

An important constituent of these mylonitic rocks is the material which makes up the slip surface zones. They

consist of thin layers of dark, reddish-brown to black, mostly opaque, multimineralic aggregates with a greatly reduced grain size, commonly with a flow texture (Figure 10). These zones are possibly made of ground-up biotite and muscovite, associated with sericite which has acquired a reddish tint in the vicinity of the darker material. In the outcrop these zones are subparallel planes that make up the mylonitic foliation, but in thin section, they are represented in cross sections so appear as long, branching, thin, sublinear features.

Accessory minerals include chlorite, hematite, muscovite, and calcite. Chlorite is associated with the slip surface zones, and is an alteration product of biotite. Cleavage planes for the chlorite are aligned parallel to these zones. In sample B12A chlorite appears as wormy structures (Figure 11). Chlorite is also observed in section B10B to have formed at the points of higher strain on a sigmoidal-shaped grain (Figure 12). Subgrain development occurred in the opposing pressure shadows. Percentages range inconsistently from trace amounts up to 2%. Hematite is present as late stage brittle-fracture and joint fillings from trace amounts up to 2%. Muscovite is associated with the slip surface zones as trace amounts up to 2%, and has in most cases been ground up, but not so

Figure 10. Sketch from section B11B showing groundmass, slip surfaces and feldspar alteration product.

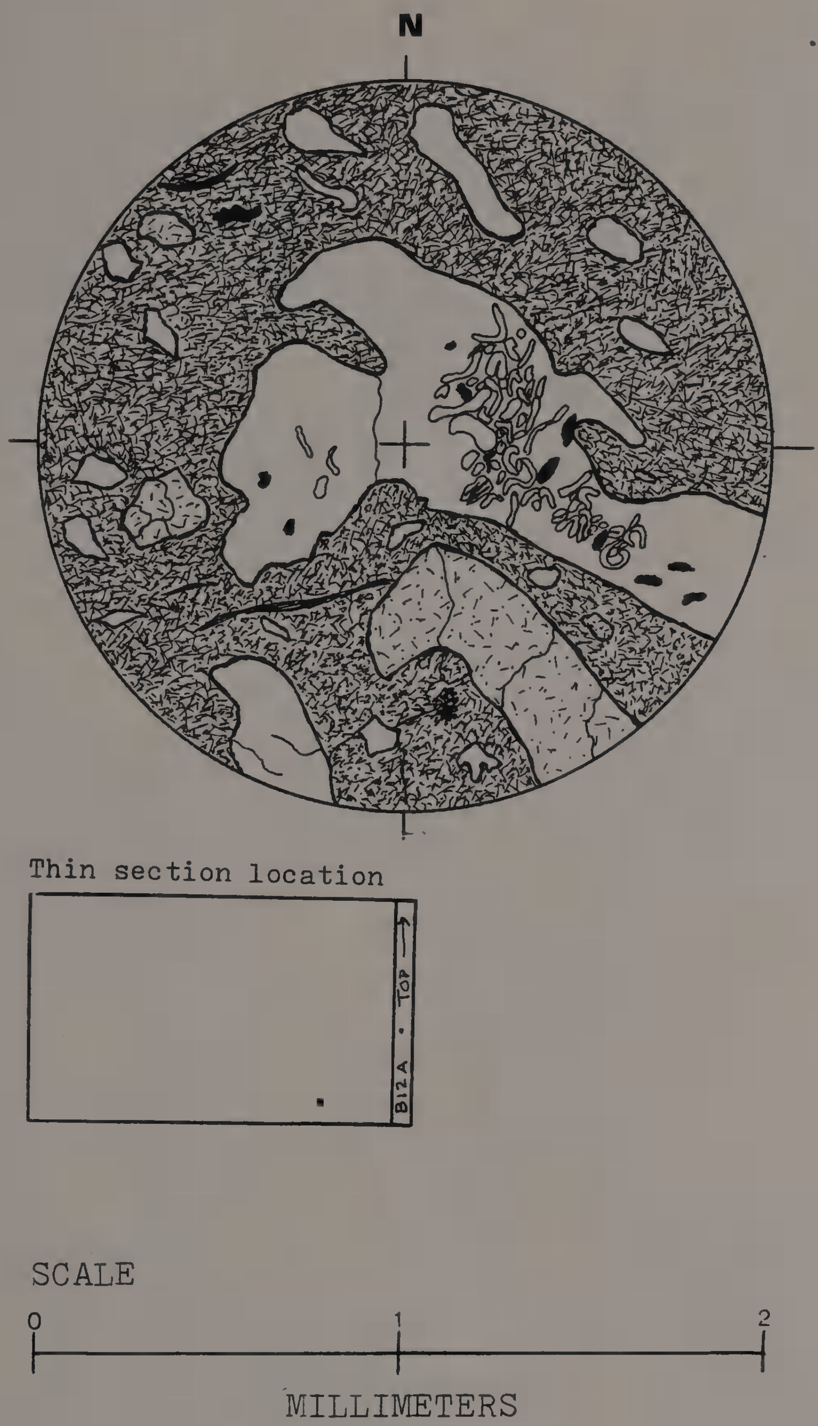


Figure 11. Sketch from section B12A showing chlorite as wormy structures.

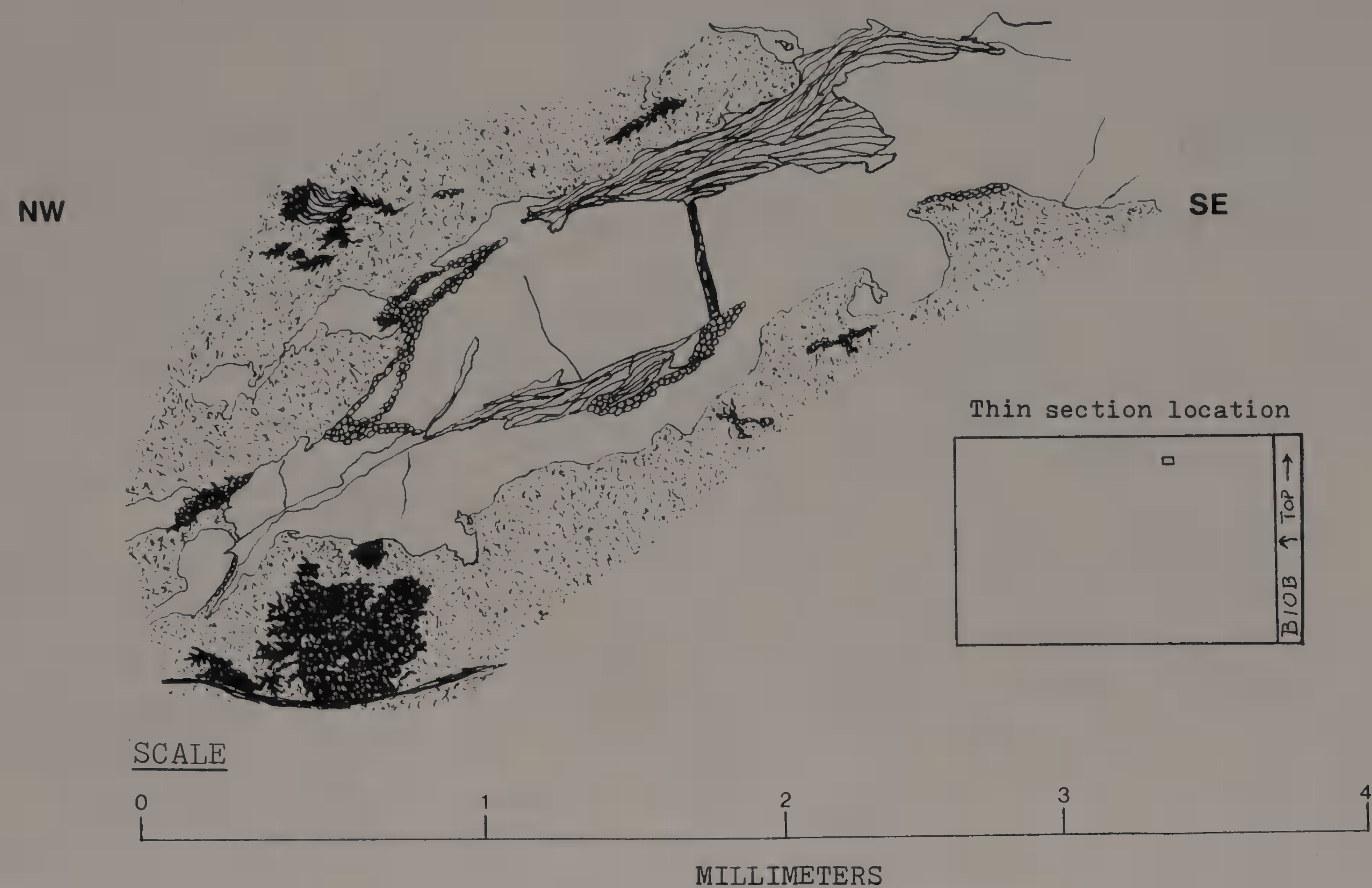


Figure 12. Sketch from section B10B showing elongate quartz grain with chlorite and subgrain development.

fine-grained as sericite. Cleavage planes for muscovite are also aligned parallel to the zones. Calcite is found in sample B15 as 3% of the section, and accessory apatite is found in B11A. Calcite and apatite commonly crystallize in the later stages of hydrothermal deposition, occurring in veins and cavities (Deer, et al., 1982). Calcite in this case is associated with quartz and sulfides. These minerals post-date shearing, being formed during the brittle stage of faulting.

Structural Data

Field Data

Structural features at the French King Bridge area were measured and categorized to try to determine any relationship of the fault-affected rocks to the geometry of the border fault. Features that were considered were joints, veins and fault surfaces, some with associated slickensides. Sources of information came from the field as well as from thin sections of the mylonites at station B. Data collected directly from the outcrop gave information about the brittle deformation phase of the border fault and data from thin sections gave information about both the brittle and earlier ductile deformation phases.

Observations of the outcrop at station B, suggest that there are three sets of joints. One is a northeast-

striking, platy, west-dipping set; the second is a northeast-striking set, dipping moderately to the east; and a third is a northeast-striking set, dipping steeply to the east and west. Measurements were taken and plotted as poles to planes on an equal area diagram, and then contoured to try to isolate these groups (Figure 13). The data is fairly scattered but the contour diagram shows three concentrations of points. A strong northeast-southwest trend is demonstrated by two of the three concentrations one west-dipping; another moderately east-dipping. The third concentration is northwest-striking and dips steeply to the northeast and southwest. The strike of the west-dipping set is close to the N40E strike of the foliation in the Partridge Schist at station A.

Quartz vein data for stations D and E were plotted (Figure 14). Although not many data points are represented, a mean trend for these veins was calculated to be N24E with steep dips to the northwest and southeast. The veins were formed by an extensional stress oriented N66W - S66E. Locally, the same extensional stress would have been present at the time of border fault formation.

Ashenden and Robinson studied the French King Bridge area in 1969 when the water level in the river was low due to dam repairs at Turners Falls. Outcrops were exposed that

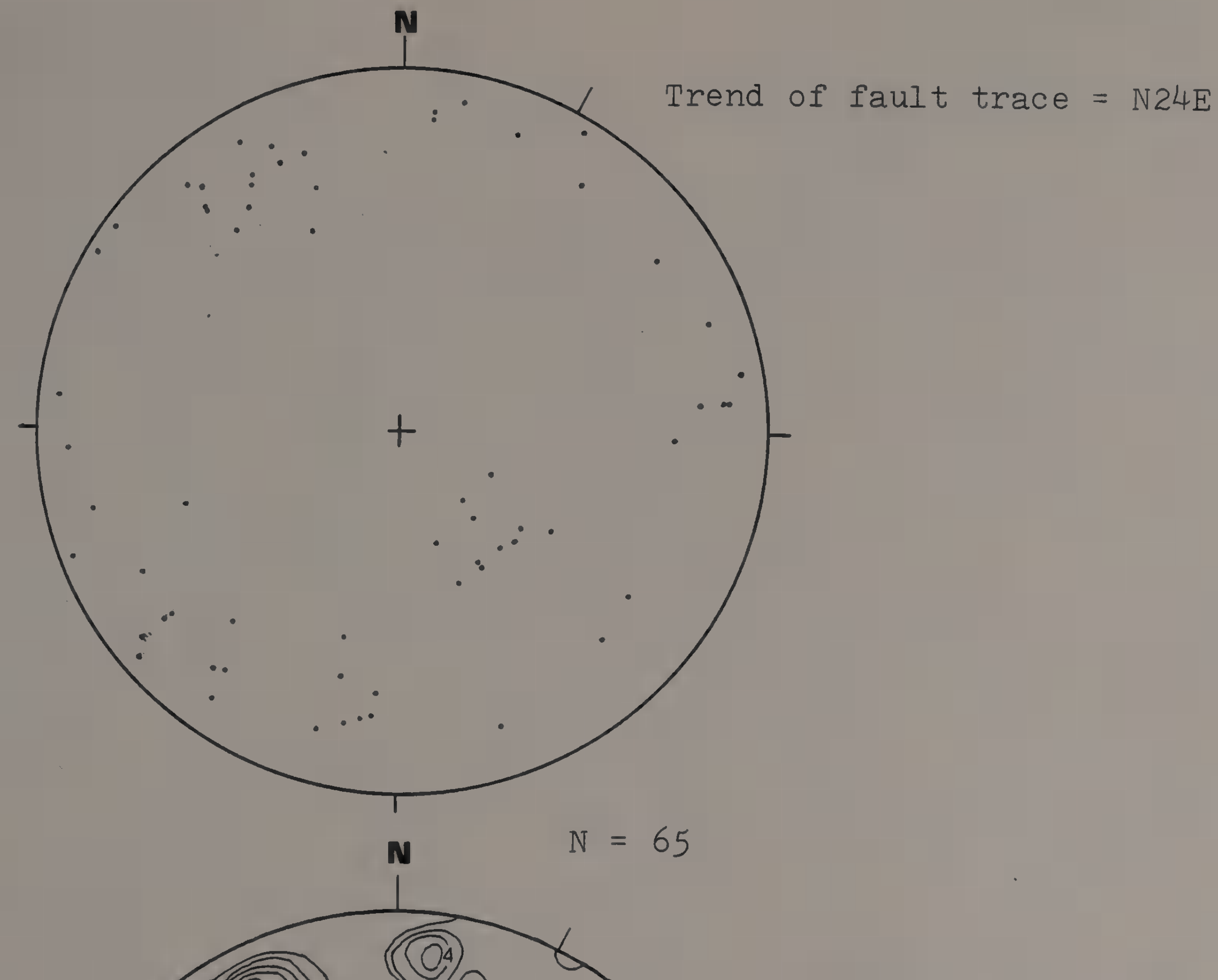
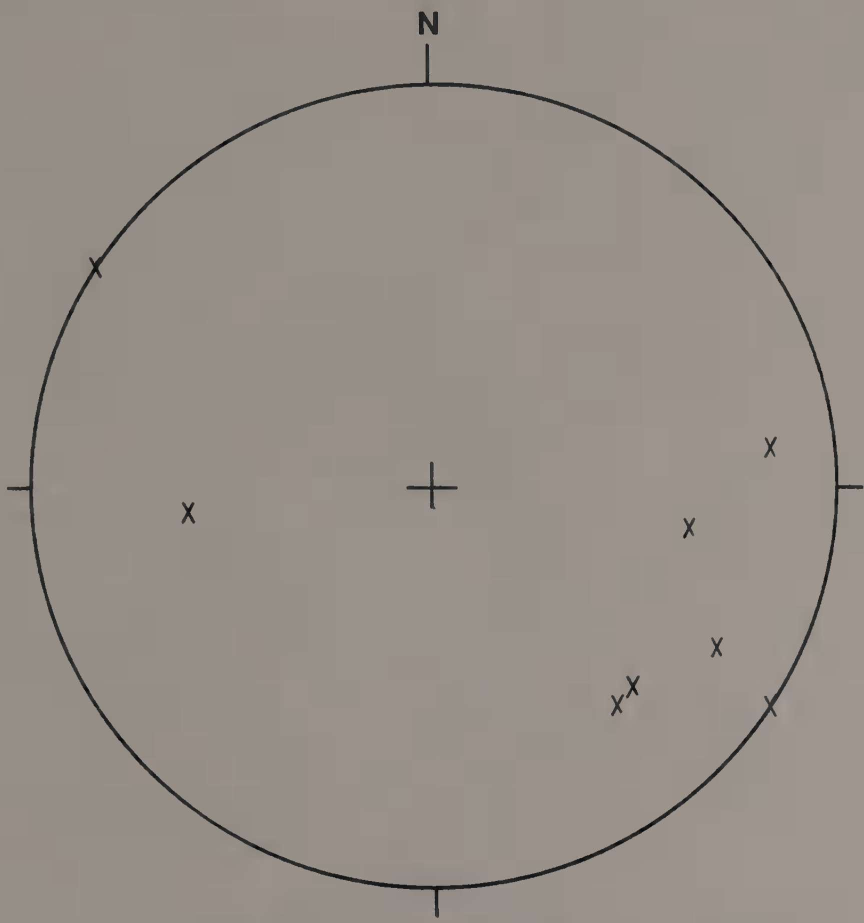


Figure 13. Joint data from station B, French King Bridge area.



Quartz Veins

Figure 14. Vein data from stations D and E, French King Bridge area.

are normally under water. A total of five fault surfaces and three sets of slickensides were measured. One mylonite foliation and one quartz lineation in the mylonite were also measured (Figure 15, upper left). The faults strike from N05E to N80E. The N24E trend of the border fault falls well within this range. Slickensides trend from N37W to N85W and plunge from 22 to 39 degrees to the northwest. Ashenden and Robinson's data are compatible with a major fault trending northeast and dipping to the west about 40 degrees, which is the dip of the fault estimated for this area.

Similar data were collected by the author during the summers of 1985 and 1986 (Figure 15, center). Nine northeast-southwest striking, west-dipping fault surfaces were measured for the area, three of which had associated slickensides. The average trend for these surfaces is N26E which agrees with the N24E trend for the border fault. Slickensides plunge between 42 and 59 degrees west, however the dip of the fault planes with the slickensides is between 70 and 85 degrees. The motion on these faults has a larger strike-slip component of motion compared to Ashenden and Robinson's data. The shallower dipping planes correspond well but no slickensides were present on these planes.

Ten mylonite foliations and six quartz lineations were also measured and an average orientation calculated for each

(Figure 16). An average orientation for the foliation is N78E, 44NW, and for the quartz lineation, N68W, 22. These two orientations are also plotted on Figure 15 (center) and compare well with Ashenden and Robinson's data which is not unreasonable since foliation and lineation measurements from both studies came from the same outcrop.

Foliation measurements were also taken from the Partridge Schist outcrop at station A to compare with the mylonitic foliations from station B (Figure 17). The object of this comparison was to see if the west-dipping structural grain inherent in the west flank of the Pelham dome, and controlled the geometry of the border fault, had any relationship to the west-dipping mylonitic foliation. Both trend northeast and dip moderately to the west, but only three of the seven metamorphic foliation poles closely correspond to the mylonitic foliation poles. It appears that there may be a controlling relationship but more data points would be needed in order to reach any firm conclusions.

Thin Section Data

Evidence for both ductile shearing and brittle fracturing is recognized in the rocks. Ductile deformation is characterized by S-C fabrics, attenuated micas, quartz subgrain development, mylonitization of quartz, some

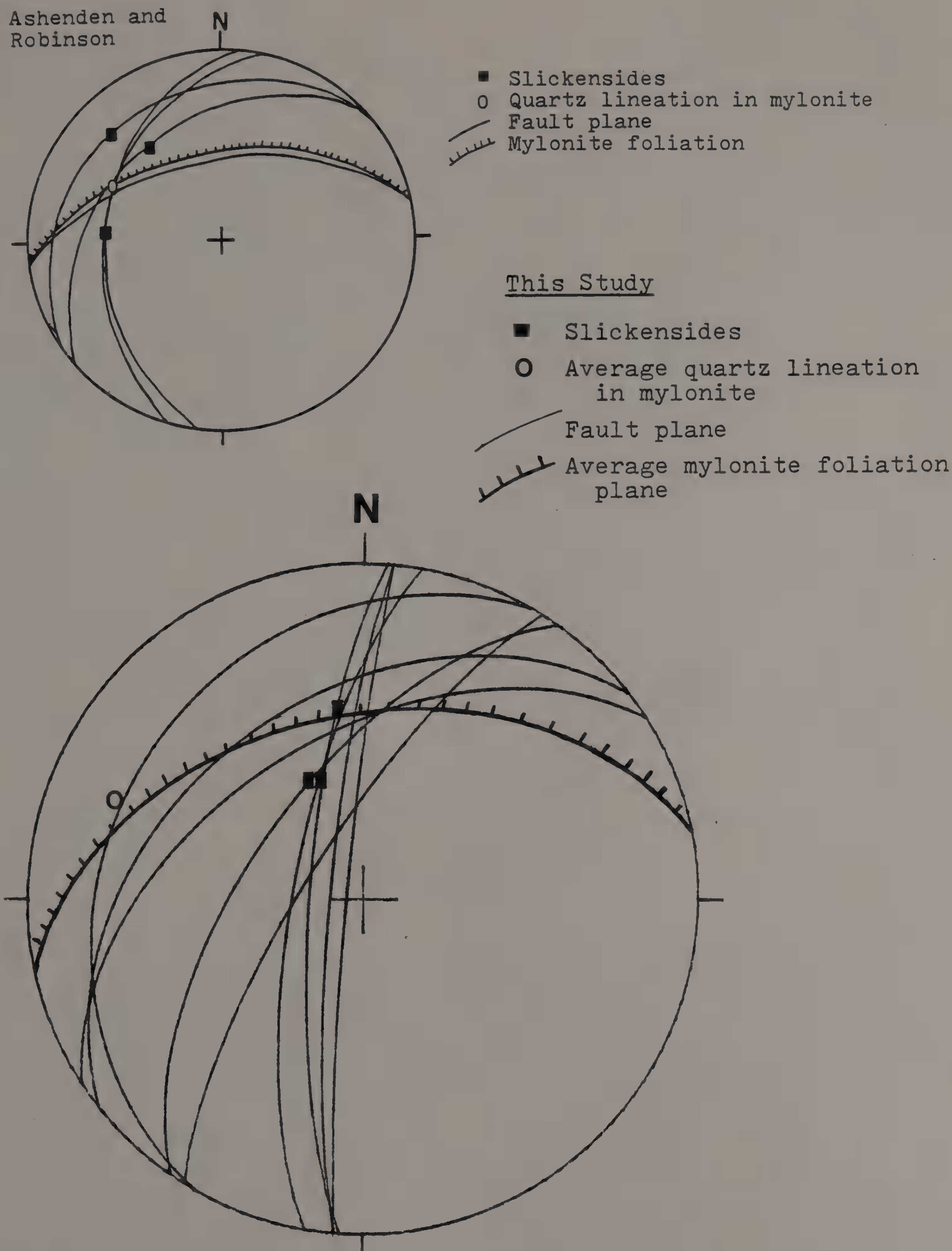
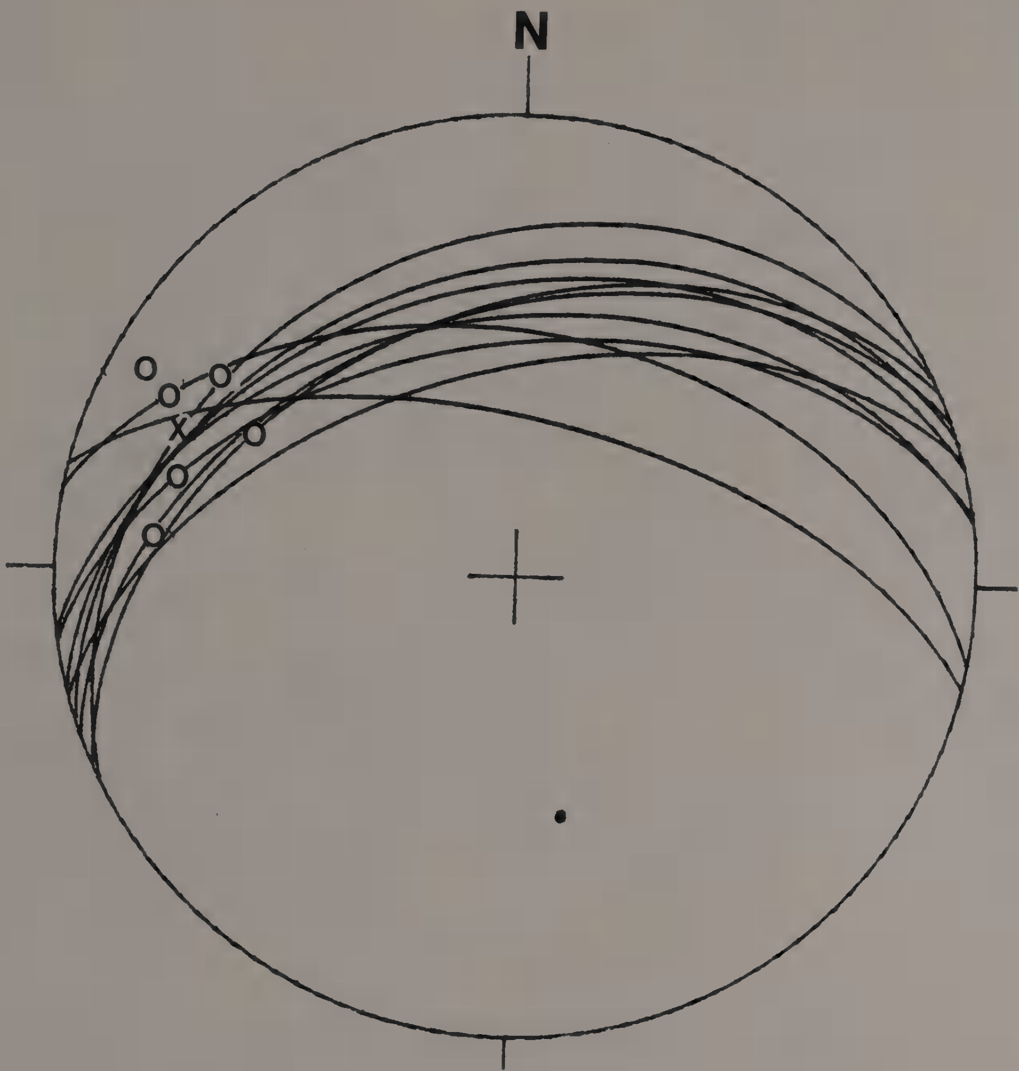


Figure 15. Comparison of Ashenden and Robinson's data (Fall 1969) with data from this study, station B - French King Bridge area.



EXPLANATION

Mylonite foliation

O Quartz lineation

• Pole to average mylonite foliation plane

X Average quartz lineation

Figure 16. Total mylonite foliation and quartz lineation measurements, station B - French King Bridge area.

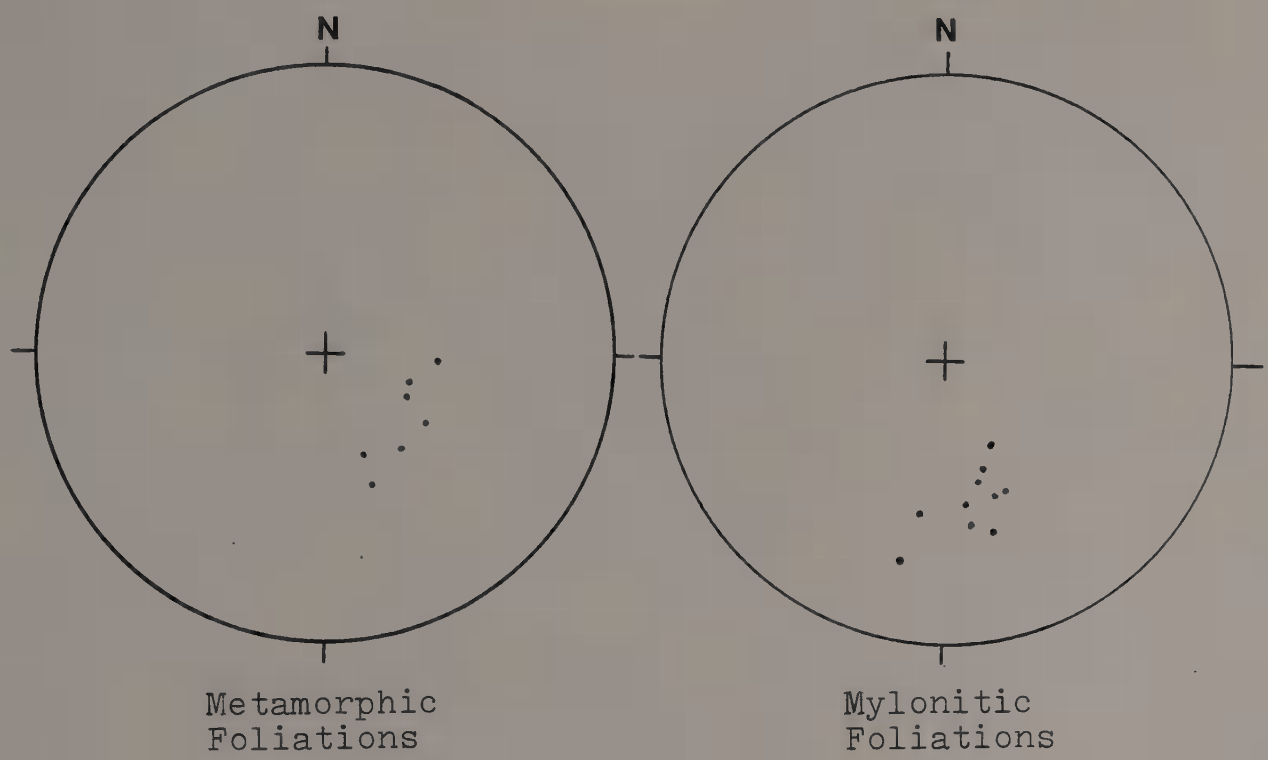


Figure 17. Metamorphic foliation measurements from Partridge Formation, station A, compared with mylonitic foliation measurements, station B.

feldspar grains having recrystallized tails, and undulose extinction in quartz. Evidence for brittle deformation involves features formed in an extensional environment, including healed and unhealed normal faults, and quartz and hematite veins. The ductile features present in these rocks are overprinted by the brittle features. This demonstrates that some rocks went through an early period of ductile deformation, accompanied by some combination of high temperatures, high confining pressures, and slow strain rates, followed by a later period of brittle behavior, where one or more of these conditions was changed to result in a brittle environment.

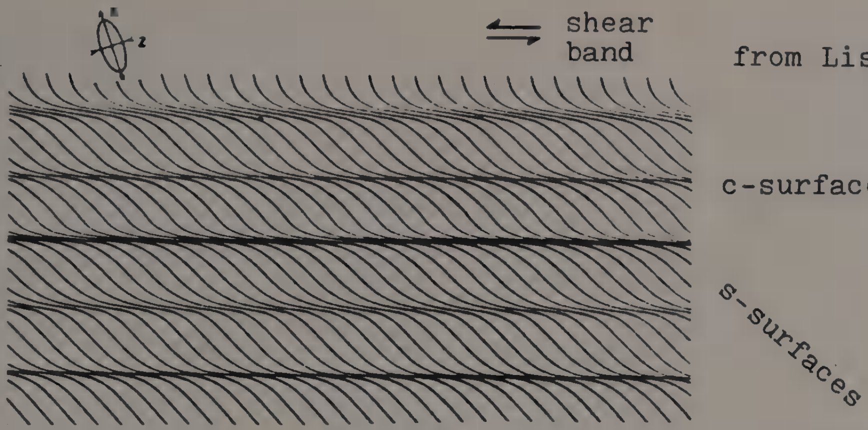
Simpson and Schmid (1983) and Lister and Snoke (1984) studied many details of mylonitic rocks. Two types of mylonites have been described. Type I S-C mylonites involve shear bands on a scale larger than that of the grain scale, and the mylonitic foliation anastomoses in and out of zones of relatively high shear strain. Both the S- and C-surfaces are obvious in the mesoscopic scale. Type II S-C mylonites involve well defined C-surfaces caused by displacement discontinuities and microscopic zones of very high shear strain. The S-surfaces are an oblique foliation commonly developed in masses of recrystallized quartz, characterized by elongated grains, and alignments of families of grains

with related orientations.

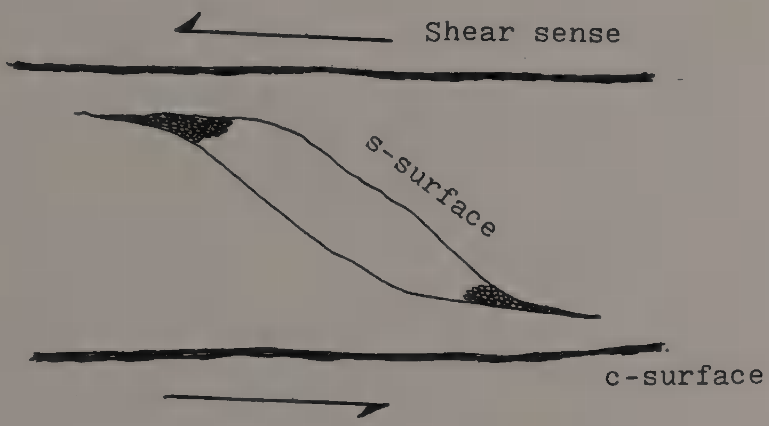
Elongate grains rotate toward parallelism with increasing strain rate. But when recrystallization takes place the process of elongation and realignment is restarted. If the oblique foliation is related to grain shape then the recrystallization process results in different oblique angles in different parts of the thin section. Figure 18 is an illustration of these ideas.

The mylonites from the French King Bridge area fit into the type II classification. They are products of heterogeneous strain rates imposed on the rocks. The rocks at station B are protomylonites formed by low strain rates at shallow depths within the ductile regime. However, on a microscopic scale higher strain rates existed to produce small areas with characteristics of orthomylonites and ultramylonites. These are seen in thin section.

Several examples of S-C fabrics are easily observed in thin section. Quartz and feldspar grains were deformed to create elongated grains and sigmoidal-shaped grains with tails of recrystallized material. Elongate grains have been rotated into the shearing direction and either form an angle with, or become parallel to the slip surfaces (Figure 19). An S-C fabric can be observed in this case with the S-surfaces defined by the long axes of the elongate grains,



Type I mylonite - involves shear bands on a scale larger than that of the grain scale, and the mylonitic foliation anastomoses in and out of zones of relatively high shear strain.



Type II mylonite - C-surfaces caused by displacement discontinuities and microscopic zones of very high shear strain. S-surfaces developed in adjacent masses of recrystallized quartz, characterized by elongated grains and alignments of families of grains with related orientations.

S-surfaces are related to the accumulation of finite strain.

C-surfaces are related to localized high shear strains.

Figure 18. Heterogeneous strain rates and S-C fabrics developed in mylonites.

and the C-surfaces defined by the slip planes. Flattened sigmoidal-shaped grains also form an S-C fabric (Figure 20). Here the S-surfaces are defined by the grain-shape foliation, which is oriented at an angle to the C-slip surfaces. Ideally, the tails of recrystallized material that trail off from both ends of the grain in the direction of shearing are also parallel to the C-surfaces. However, in two of the three examples given in Figure 20, these tails are parallel to the S-surfaces. Both of these S-C fabrics can be used as indicators to interprete a west-side-down motion direction for the border fault.

Mylonitization and recrystallization of quartz causes the formation of quartz subgrains seen in the tails of sigmoidal shaped quartz grains in Figure 20. Quartz subgrains also form along deformation bands bordering, and within the boundaries of elongate quartz rods (previously described in this chapter). Subgrain formation starts as parallel trains of grains. With increasing deformation, more trains are produced to form subgrain clusters (Figure 21). The combining of parallel subgrain trains results in a masonry texture referred to as a "mortar texture". These clusters therefore have a faint foliation which appears in thin section as parallel lines between the subgrain trains. This foliation also forms at an angle to the slip surfaces.

A west-side-down motion direction for the border fault is indicated by this S-C fabric example.

Minor folds developed within a C-surface from section B13B1 (Figure 22) provide a possible fourth example of an S-C fabric. A slip surface has been subsequently folded by the west-side-down shearing motion and axial planes developed which are subparallel to the dominant S-surface orientation present in adjacent unfolded rock. It is unclear however, whether the axial planes are themselves S-surfaces since they are a later feature then the S-C fabric in the immediate area of the thin section.

A cataclastic intrusion breccia was observed in B13B (Figure 23). This feature initiated parallel to a C-surface and was then injected into a weak area, cross-cutting other C-surfaces, and elongated quartz rods, resulting in a hook shaped feature. Cataclastic flow is indicative of very high strain rates where the rock is essentially turned into a fluid breccia and squirted into available cracks and weak areas. Mylonite development is indicative of lower strain rates. These rocks were therefore normally subjected to a low strain rate where mylonitization of quartz occurred, and conditions changed to impose a higher strain rate and cataclasite development. Conditions then returned back to a lower strain rate, and mylonitized the cataclastic breccia.

Figure 19. Sketch from section B13B showing elongate grains rotated in direction of shearing.

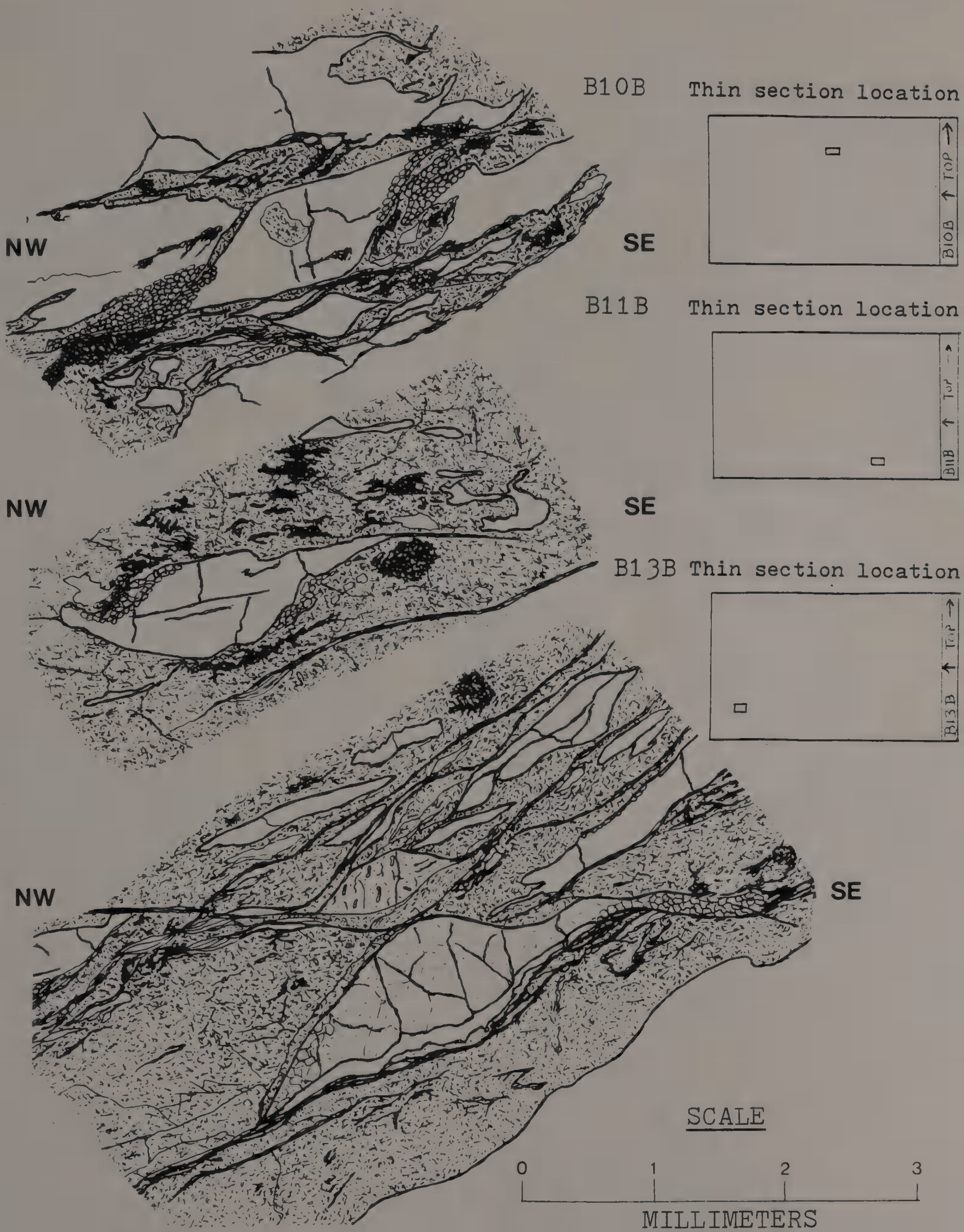


Figure 20. Sketches from sections B10-13B showing sigmoidal grains with recrystallized material.

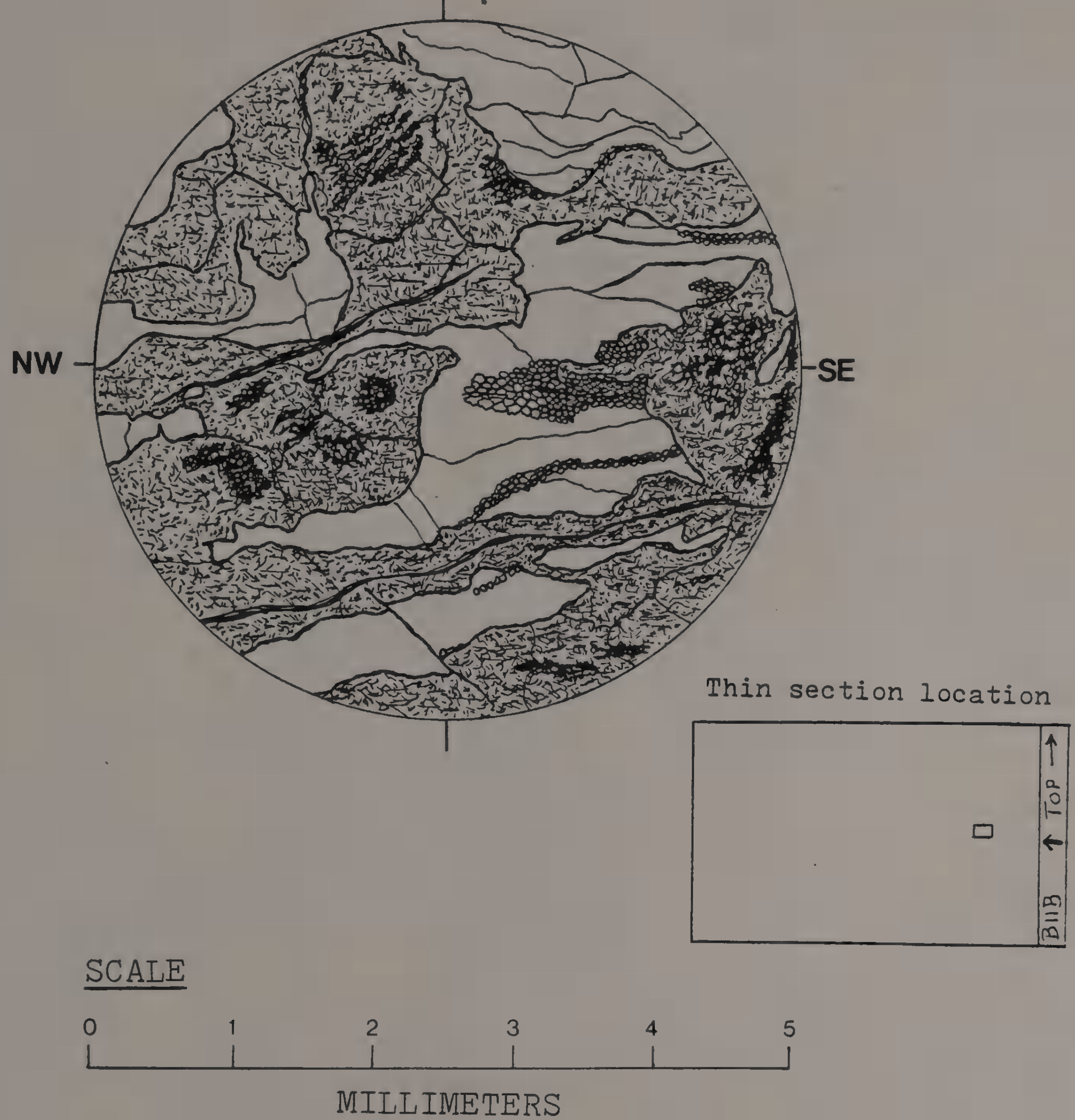


Figure 21. Sketch from section B11B showing subgrain clusters with a foliation.

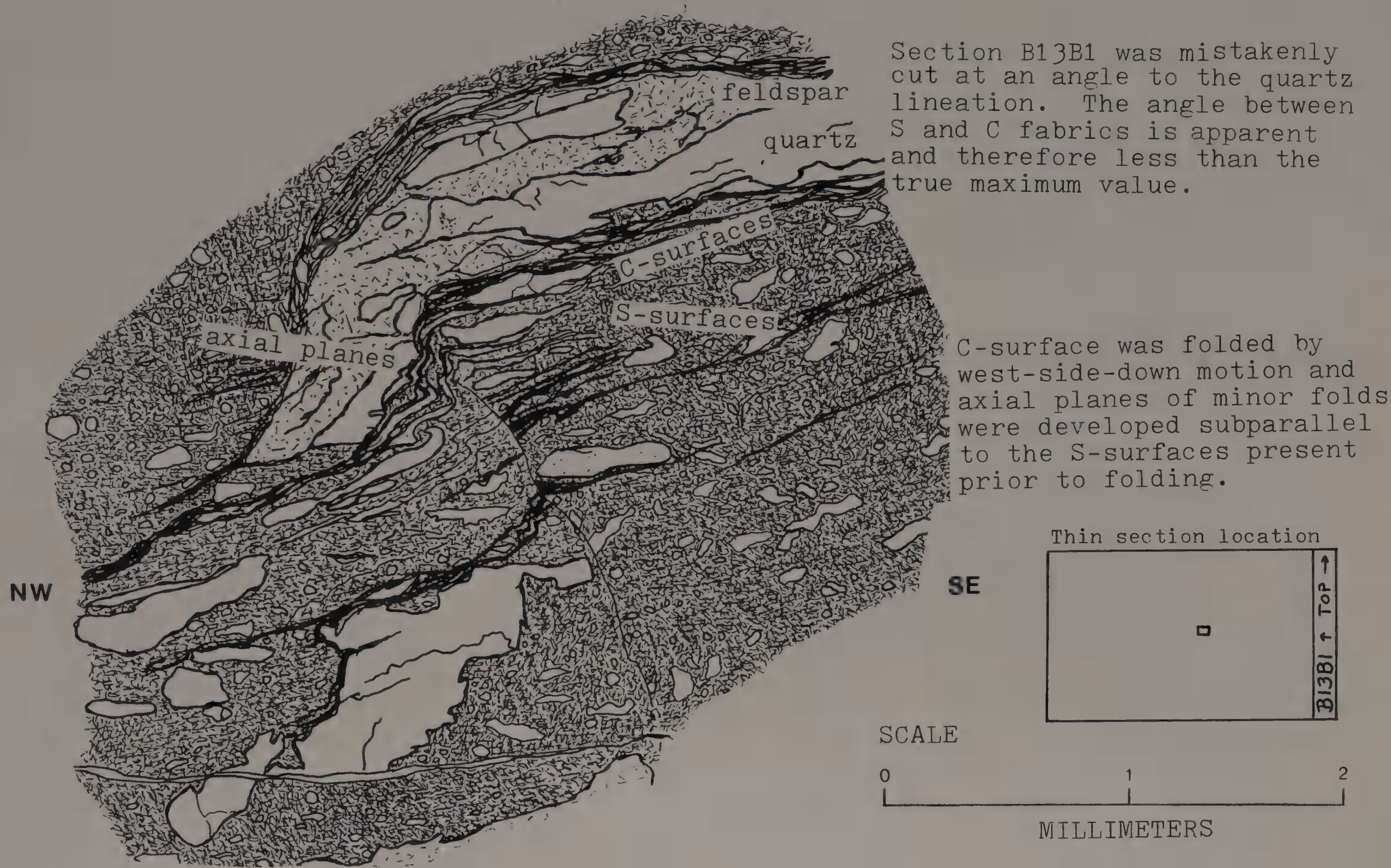
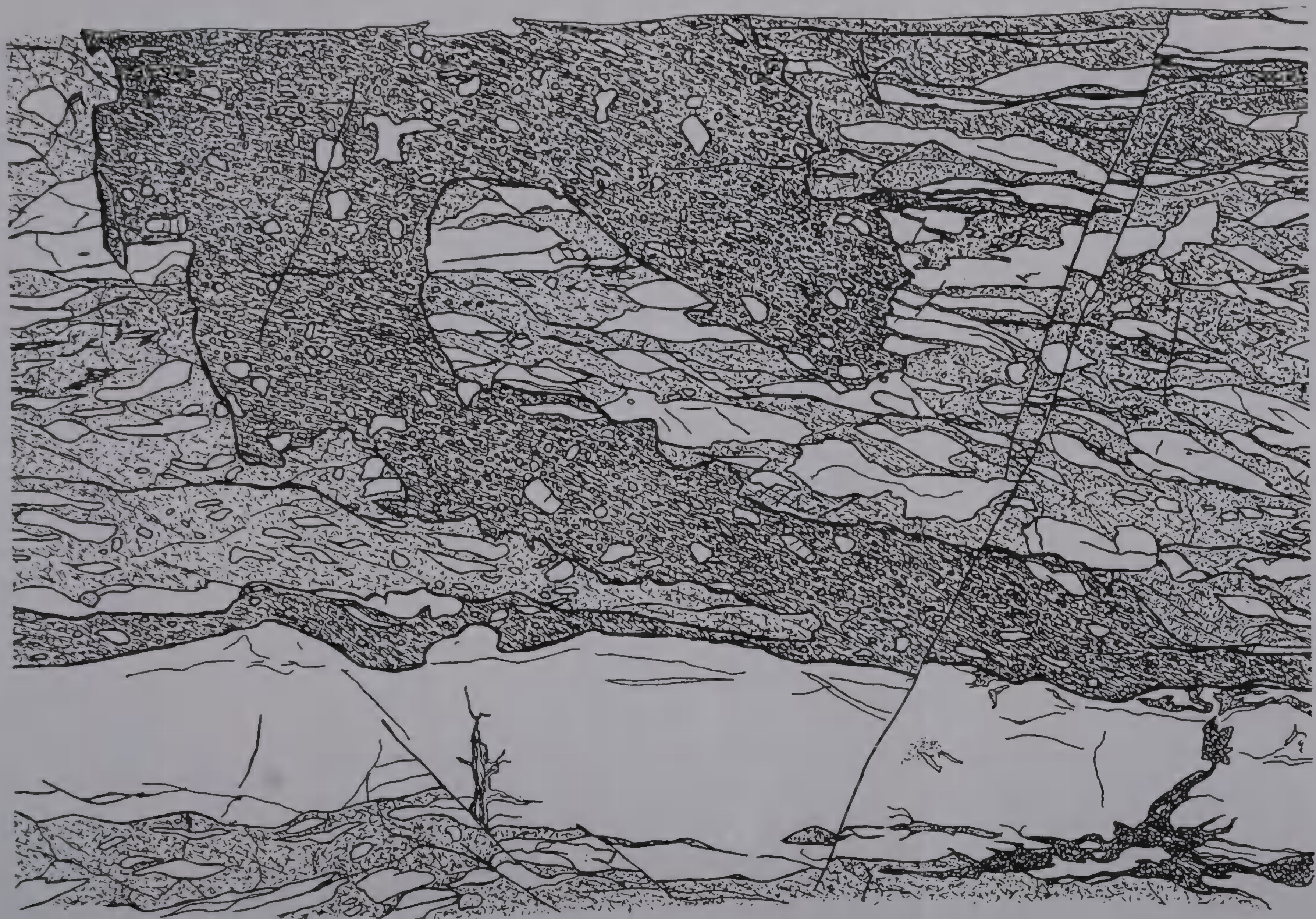


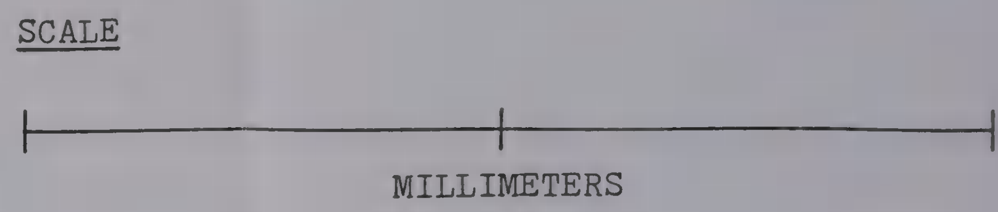
Figure 22. Sketch from section B13B1 showing folded C-surface with axial plane development subparallel to S-surfaces.

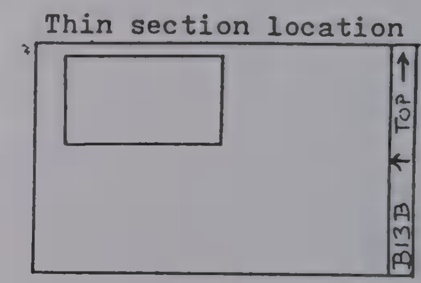
An S-C fabric was developed in the breccia injection that is similar to that found in the host mylonite. Temporary high strain rates imposed on rocks that were mostly formed under lower strain rate conditions, can be explained by asperities or irregularities on the fault surface.

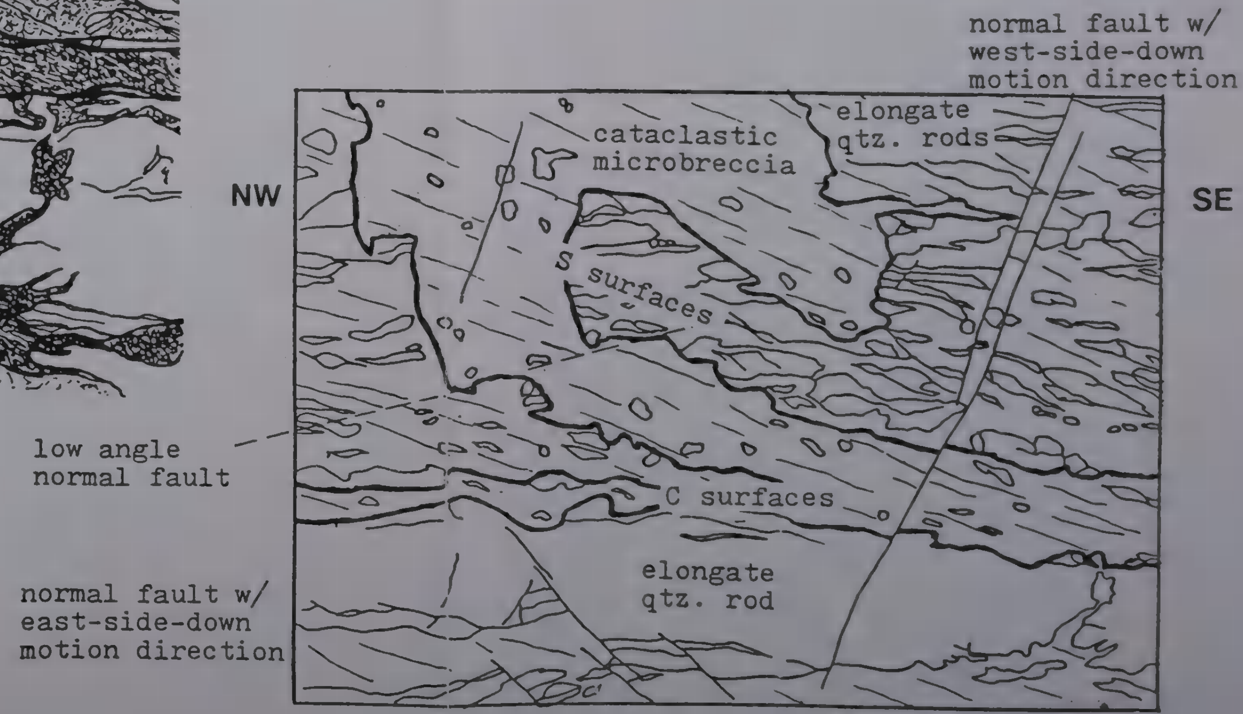
The second deformational phase that affected these rocks was of a brittle nature. Lower temperatures, lower confining pressures, or a higher strain rate were imposed on the mylonites which resulted in an extensional environment and produced brittle features that overprinted previous ductile ones. Normal faults and joint development accompanied this phase. Many faults were healed and are represented by fluid inclusion trains in thin section. Inclusion trains are oriented anywhere from an angle of zero to 74 degrees away from the mineral lineation. Angles tend to remain constant within a thin section.

Hydrothermal fluids invaded the rock and deposited quartz and hematite veins. Quartz appears to have been the first mineral deposited, followed later by specular hematite. Hematite veins can be seen cutting quartz veins in a few places. A later set of normal faults remained unhealed. These are small faults with negligible to 10 mm. of displacement. Most of the faults are parallel to each other within a given thin section, and exhibit west-side-









The cataclastic breccia is indicative of high strain rates. It originated along the slip surfaces (C planes), and was then injected into the mylonite, indicative of lower strain rates. The breccia injection was then overprinted with an S-C fabric similar to that of the host mylonite, indicating a return to the lower strain rates.

Figure 23. Sketch from section B13B showing a cataclastic breccia injected into mylonite.

down motion directions. Figure 23 shows normal faults cutting elongate quartz grains and other ductile features. In some cases, conjugate fractures with an east-side-down motion direction can also be observed. Unhealed minor faults are younger than joints but no relative age for the healed faults could be determined.

Summary of Mylonitic Rocks

Several general observations and conclusions can be made about the mylonites in the French King Bridge area.

1. Heterogeneous strain rates were imposed on rocks at depth in the footwall of the Connecticut Valley border fault. These rocks are now expossed at the French King Bridge locality and largely represent protomylonites and therefore were in the upper levels of the ductile regime. Rocks with orthomylonite and ultrmylonite characteristics are also obvious in thin section and represent heterogeneous strain rates.

2. These rocks fit into the Type II S-C mylonite classification as described by Lister and Snoke (1984). C-surfaces are well defined and S-surfaces are microscopic and are the oblique foliation developed in adjacent masses of recrystallized quartz, elongated grains, and alignments of groups of grains with related orientations. S-C fabrics in these mylonites indicate a west-side-down motion direction

for the border fault.

3. Mylonites in quartz are indicative of a lower strain rate. The mylonites were cut by an intrusion breccia which is characteristic of a very high strain rate. This breccia intrusion was subsequently mylonitized indicating a return to lower strain rates. The rocks probably hit an irregularity on the fault surface during motion, suggesting that the fault surface was not a smooth feature.

4. The mylonites were uplifted to shallower levels where an extensional environment prevailed. Features formed under these conditions, such as joints, veins, and minor faults, were developed and cut the previous ductile ones.

5. One style of joint strikes northeast, dips west and is believed to mimic the orientation of the border fault in this area. The mean strike for veins suggests an extensional stress oriented N66W-S66E. This same stress is indicated by the trend of the border fault in this area. Minor normal faults are seen in thin section and have a west-side-down motion direction.

CHAPTER 3

DESCRIPTIONS OF ROCK TYPES IN SILICIFIED ZONES

Introduction

Several types of cataclasite rocks are defined by Higgins (1971) and Wise et al. (1984) including breccias, microbreccias, gouge, and pseudotachylite. Of these, breccia, microbreccia, and pseudotachylite are found in the field area and will be discussed. Cataclasite rocks are the result of near-surface faulting events, and are indicative of high strain rates, low confining pressures and temperatures, in a stick-slip, seismic environment. They are characterized by a lack of foliation and little or no thermally produced effects. Hydrothermal fluids that invade these rocks may produce silicified fault breccia which is what has formed along the Connecticut Valley border fault. Breccias have angular to rounded fragments, formed by crushing or grinding, which have no specific orientation. Microbreccia is an intensely fractured cohesive breccia in which the fragments have no specific orientation and are set in a fine-grained matrix. Pseudotachylite is produced under more frictional conditions, creating a glass that essentially cements a microbreccia.

Four kinds of silicified rock were found in the field area. The first is a cemented quartz-rich breccia and

microbreccia, consisting mostly of partially strained to unstrained quartz, altered plagioclase, late-stage hematite and accessory pyrite. This is the most silicic of the four types, and is found in the East Mineral Hill and Mount Toby areas. The second kind of silicified rock is cemented quartz, altered plagioclase and chlorite breccia and microbreccia. Late-stage hematite and accessory pyrite are also present. This rock type is at an intermediate level of silicification and found at the Mount Toby and Leverett Pond areas. The third kind consists of cemented quartz, altered plagioclase, epidote and chlorite breccia and microbreccia. This type is the least silicified and is found in the Poverty Mountain, Harkness Road and Gulf Road areas. The fourth type appears as small veins consisting of a pink feldspathic rock enclosing areas of quartz-rich rock. This type is found in the Harkness Road area. Silicified rock at each area is discussed in detail in this chapter. Field and thin section descriptions, when available, are given to define the character of the rock and of the silicified zone as a whole.

East Mineral Hill Area

Unsilicified and Partially Silicified Rocks

Figure 24 shows a detailed geologic map for the East Mineral Hill area. The border fault in this area is splayed

into three parts, all of which trend northeast-southwest and dip west. The general trend for the fault in this area is N15E, and the dip is 40 degrees west as extrapolated from Ashenden and Robinson's 1973 data. A west-dipping layer of Fourmile Gneiss and a thin, west-dipping layer of Partridge Schist (Figure 1) are located to the east of the easternmost splay. A large gully is formed by this splay, and separates the large cliffs of Fourmile Gneiss from a west-dipping slice of partially silicified pegmatite to the west. The pegmatite is a ledge-forming rock making long narrow ridges. This unit is brecciated and consists of coarse-grained quartz, pink feldspar, and muscovite cemented with later specular hematite and quartz veins. The weathered surface is light-gray and weathering effects penetrate up to 2 centimeters into the interior of the rock. Silicification appears to have affected the western portion of the unit more than the eastern portion. West of, and in fault contact with the pegmatite, is the silicified zone. This also a west-dipping feature, and general outcrop orientations are believed to resemble the orientation of the fault in this area. West of the westernmost splay is Mount Toby Conglomerate.

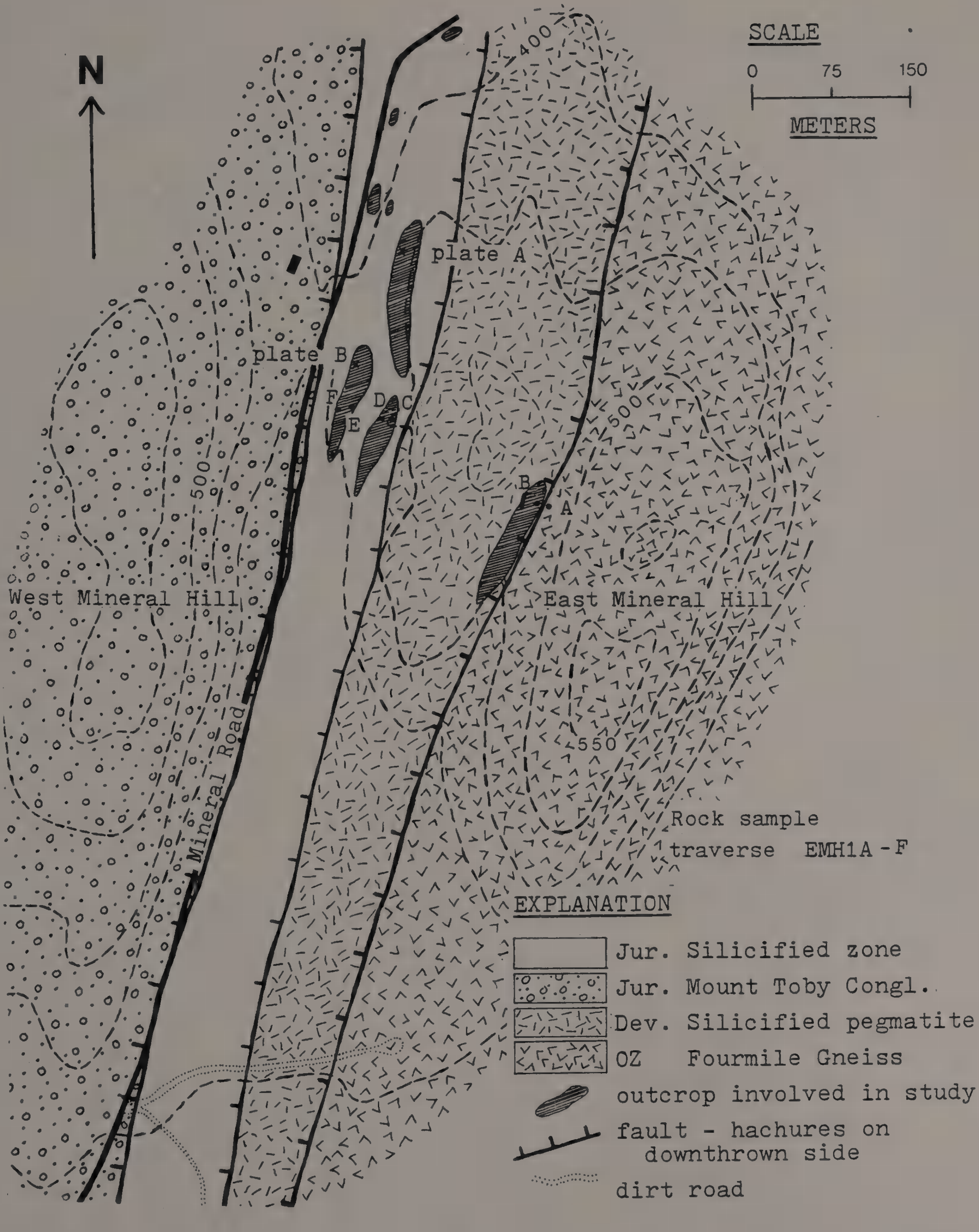


Figure 24. General geologic map of East Mineral Hill area.

Silicified Rocks

The silicified zone in this area is defined by two large quartz ribs, both consisting of the quartz-rich group of breccia and microbreccia. These are composed of massive, sugary-textured, crystalline quartz that is typically white with patches of gray, red, and orange staining penetrating into the surface of the rock. One outcrop surface has been glacially polished and outlines of former brecciated pieces can be detected. Quartz content, although extremely high throughout the entire zone, appears higher in the western side than in the eastern side. The eastern side has more recognizable plagioclase. Host or matrix quartz has a vuggy character. Two styles of veins are recognizable in outcrop scale. Larger veins act as feeders for smaller, branching veins. The larger veins tend to be fairly straight, occupying previous joint openings, and the smaller veins are randomly oriented, branching out from the larger veins into cracks and voids in the host rock. These randomly oriented veins form a vein network that has a "spider-web" effect. Overall, the zone appears to be uniform in terms of number of size of veins.

Thin Section Observations

An east to west rock sample traverse was performed in the southern portion of the area across the silicified and

partially silicified zones to determine rock type, textures, and to identify changes across the zone (Figure 24). One sample (EMH1A) was taken from the Fourmile Gneiss, one sample (EMH1B) was taken from the pegmatite, and four samples (EMH1C through F) were taken from the silicified zone. Thin sections were made from EMH1B through EMH1F, but not from EMH1A, because the Fourmile Gneiss in this area has not been affected by silicification. A detailed summary of thin section observations is given in table 2.

Sample EMH1B was taken from the eastern boundary of the silicified pegmatite. This rock consists of massive, anhedral, interlocking, coarse-grained feldspar, muscovite and quartz. Quartz (38%) appears as partially strained to unstrained, subhedral to euhedral grains. Feldspar (57%) occurs as microcline, orthoclase, plagioclase and microperthite. Sericite alteration occurs between feldspar grain boundaries. Hematite veins are present in outcrop and appear in thin section as tiny, randomly oriented veins. Quartz veins are also present in outcrop but are not represented in this one thin section. Grain size ranges from 0.5 to 8.0 mm with the larger sizes being more common. Cataclastic textures include cracked quartz and feldspar grains indicating grain size reduction, and subrounded feldspar fragments. The overall rock consists of

Table 2. Thin section observations: East Mineral Hill samples EMH1B - EMH1F.

	Silicified Pegmatite	Silicified Rock
Sample #	(east) EMH1B	EMH1C
Oriented sample	YES	YES
Quartz	mostly unstrained, subhedral to euhedral 38%	partially strained to unstrained//matrix: sub- to anhedral//patches: sub- to anhedral 80%
Feldspar	microcline: crosshatch twins//perthites: untwinned//orthoclase: untwinned 57%	altered, fragmented//(+) r<v weak, 70-80° curv.// albite twins//twinned & untwinned plag. 10%
Other	hematite 1% muscovite 5% sericite tr	hematite 5% sericite 5% yellow fibrous accessory w/ rod-like inclusions tr calcite tr
Mylonitic textures	NONE	NONE
Cataclastic textures	cracked qtz. cracked, angular and rounded fsp.	cracked, angular and rounded fsp.//some brecciation
Overall rock	interlocking, subhedral, grain-supported //no matrix	interlocking, anhedral matrix supporting interlocking coarser-grained areas
Foliation	NONE	NONE
Lineation	NONE	NONE
Color (hand sample)	light pink	off white
Grain size	0.5-8.0 mm	matrix: 0.1-2.0 mm patches: 2.0-3.0 mm
Quartz veins	NONE	no veins//patches: subhedral to euhedral grains
Epidote veins	NONE	NONE
Hematite veins	small, random	small, random//large braided, branching w/ included qtz. crystals// anhedral masses and flecks
Mineral overgrowths	NONE	pyrite on qtz.
Vugs	NONE	YES- occupied by qtz. and pyrite

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Table 2. continued

Silicified Rock

EMH1D	EMH1E	EMH1F (west)
YES	YES	YES
part. strained to un-strained//matrix: sub- to anhedral//patches: sub- to euhedral 94%	part. strained to un-strained//matrix: sub- to anhedral//veins: sub- to euhedral 88%	part. strained to un-strained//matrix: sub-anhedral//veins: sub- to euhedral 95%
altered, fragmented//(+) r<v weak, 70-80° curv.// plag. 5%	altered, fragmented//(+) r<v weak, 70-80° curv.// albite twins//twinned & untwinned plag. 10%	very altered-has turned to sericite
sericite 1% pyrite tr hematite tr	sericite 1-2% hematite tr	sericite 5% hematite tr
NONE	NONE	NONE
angular fsp. grains randomly dispersed through matrix	angular and rounded fragments dispersed through matrix//cata-clastic breccias	larger angular frag-ments dispersed through matrix
interlocking anhedral matrix supporting interlocking coarser-grained areas	interlocking, anhedral matrix supporting interlocking coarser-grained areas	interlocking, anhedral matrix supporting interlocking coarser-grained areas
NONE	NONE	NONE
NONE	NONE	NONE
off white	off white	off white
matrix: dust - 0.1 mm patches: 0.1 - 2.5 mm	matrix: dust - 0.3 mm veins: 0.1 - 1.0 mm	matrix: dust - 0.3 mm veins: 0.1 - 2.0 mm
patches subhedral to euhedral grains// no veins	veins- few and small// subhedral to euhedral grains	veins- up to 7.0 mm wide //some w/ comb structure //euhedral grains
NONE	NONE	NONE
small, random, braided	small, random, braided	small, random, braided //also anhedral masses in qtz. veins
pyrite on qtz.	NONE	pyrite on qtz.
YES some occupied by pyrite, others vacant	YES- appear to be vacant	YES- some occupied by pyrite, others vacant

interlocking, subhedral, grain-supported fragments with no matrix.

The rock of the silicified zone consists of 80% quartz in the east side to 90% in the west side of the zone. Quartz grains are partially strained and unstrained, and occur as small matrix grains and larger patch and vein grains. Feldspar is recognizable across the zone as relict grains and makes up 3% to 10% of the sections. In samples EMH1C through E, feldspar has percentages of 5% to 10%. A positive optic sign, a 70 to 80 degree curvature on a centered optic axis isogyre, and a weak r<v dispersion indicate that it is plagioclase toward the albite end of the series. Most of the grains are corroded and have begun to alter to sericite. Sericite alteration makes up another 1% to 5% of the sections. In sample EMH1F, only 3% recognizable feldspar is present as relict fragments, and 5% has been altered to sericite. No identifying information could be obtained, but most likely it is the same plagioclase as the rest of the traverse. Plagioclase grains are heavily altered and significant grain size reduction has taken place by brecciation. Specular hematite is present from trace amounts to 5%, and occurs as veins and anhedral masses.

Texture across the zone is an interlocking mosaic of

very fine-grained matrix enclosing coarser-grained areas, cut by quartz and hematite veins. Matrix grains range in style from euhedral to anhedral, with the anhedral style being the most common. These grains have smooth boundaries and commonly have embayments which are occupied by protrusions from other grains. Grain size decreases from east to west, approaching the border fault. The size range for the eastern side of the zone is 0.1 mm to 2.0 mm, and for the western side the range is very fine-grained to 0.3 mm. Very fine-grained matrix particles that are to small to be measured are referred to as "matrix dust".

Coarser quartz grains occur in veins and patches. Patches consist of quartz grains that are larger than matrix quartz, and have the same textural characteristics as the matrix, except that the grain shape is subhedral to euhedral. In thin section quartz veins occur as small, randomly oriented, branching, "spider-web" style features, but in the outcrop these small veins are seen to be offshoots from larger, straighter, feeder veins that follow previous joint openings. Patches are more common than veins in thin section, but cannot be seen in the outcrop scale. Grain size for both patches and veins decreases from east to west. For the eastern side the range is 0.3 to 2.0 mm, and for the western side, 0.1 to 2.0 mm.

Specular hematite veins are a common feature. These are very fine-grained, braided and branching veins that are commonly 1.0 mm wide or smaller, and are a later feature than the quartz veins which they commonly cut. One vein observed in EMH1C however, is a large 3 mm wide, braided, branching feature that tapers off at one end. Vein boundaries are highly irregular, with quartz crystals growing into them. The vein has included subhedral quartz crystals perhaps plucked from the sides of the fracture as the Fe-rich fluid passed through. Anhedral vugs lined with tiny subhedral to euhedral quartz crystals are found within the vein. Hematite also appears as anhedral masses, commonly with vacant rounded "holes" in their interiors, and appears to have been emplaced in the last stage. Vugs are common within the matrix and quartz patches. These are either vacant or lined with hematite. Vugs have either irregular or polygonal shapes with straight edges. The polygonal shapes were at one time occupied by accessory pyrite that was weathered out or plucked in the process of making the thin section. Accessory pyrite was found in all samples except EMH1E.

Mount Toby Area

Unsilicified and Partially Silicified Rocks

Figure 25 shows a geologic map for the Mount Toby area. Rocks to the east of the border fault in this area include the west-dipping amphibolites of the Erving Formation. The amphibolite is partially silicified where it borders the silicified zone and has abundant metamorphic quartz veins, plus many tiny veins related to silicification. The rock is light- to medium-gray and contains primary minerals identifiable in hand sample such as hornblende and biotite, unlike the rock of the silicified zone. The border fault near here trends N15W and has an estimated dip of 35 to 40 degrees southwest (Maher, 1979; Robinson, 1979). Two silicified zones occur along the east side of the fault in this area. One in the northern part of the map area occurs as a quartz rib trending N45W parallel to a secondary fault. The dip of this zone or the fracture it occupies is unknown. The second silicified zone trends parallel to the border fault and dips west. It is cut near its northern end by another secondary fault trending N35W, with an unknown dip. To the west of the border fault are exposed gray schist of the Rangeley Formation and biotite-muscovite granite, both in the hanging wall of the fault, and unconformably overlain by Mount Toby Conglomerate of the Deerfield basin.

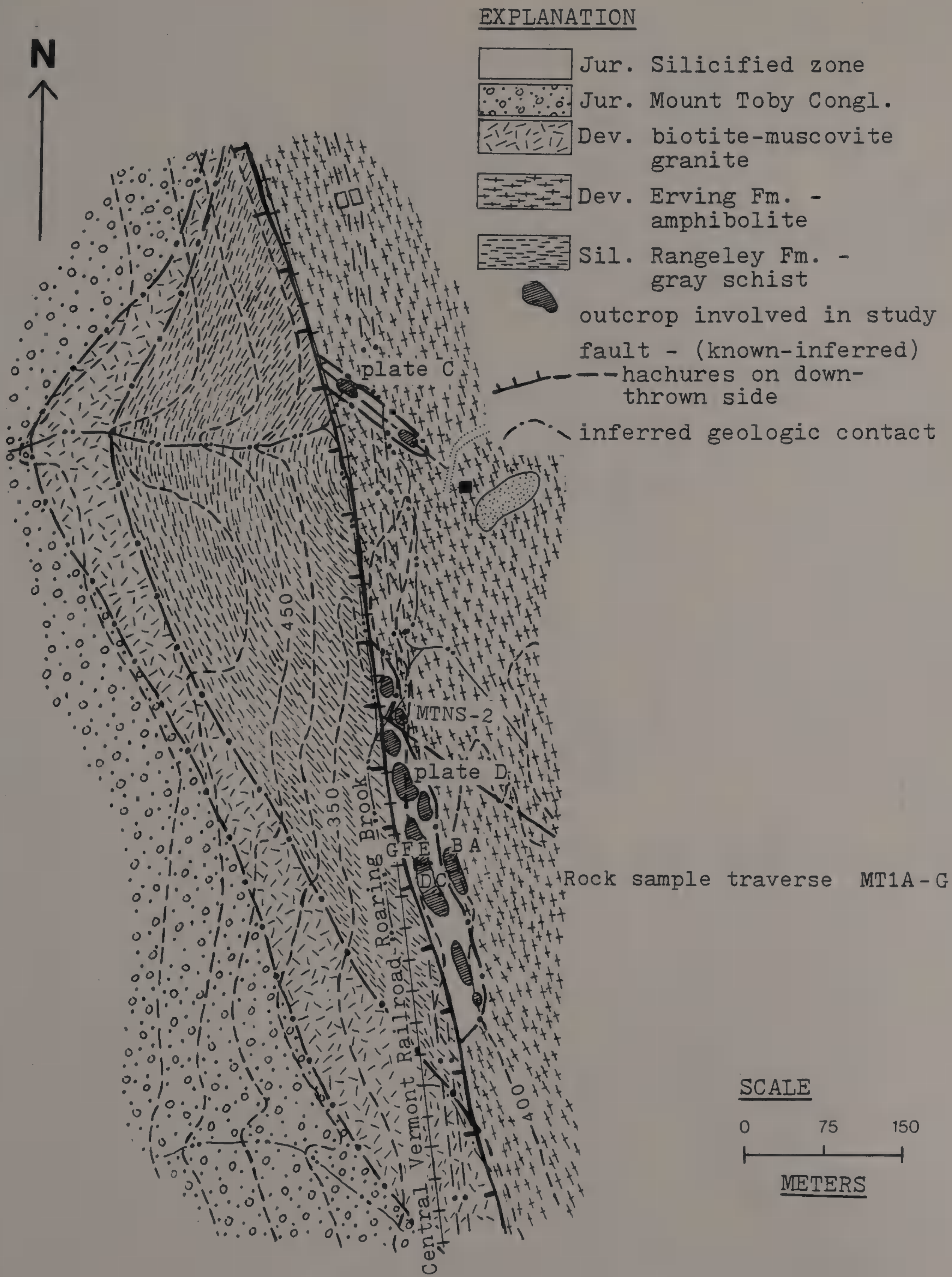


Figure 25. General geologic map of Mount Toby area.

Silicified Rocks

The Mount Toby area has two silicified rock types. One is quartz-rich breccia and microbreccia occurring in the quartz rib in the northern part of the map area. This rock is very fine-grained, sugary textured, crystalline, white quartz which is a precipitated fracture filling. The weathered surface is smooth, white and gray colored, with local red and orange staining effects. Small vugs are common, some lined with quartz crystals. Later white quartz veins are abundant but are commonly hard to distinguish because they are close in color to the host rock. The surface of the outcrop is heavily dissected with many randomly oriented joints.

The second silicified rock type in the Mount Toby area is the quartz-plagioclase-chlorite variety of breccia and microbreccia located along the east side of the Central Vermont Railroad tracks. The protolith is Erving amphibolite and pegmatites found within the amphibolite. This rock is light- to medium-gray, very fine-grained, vuggy quartz, with a local dark red "rusty" staining. Staining effects are much more pronounced in the northern portion where all surfaces appear red, than in the southern portion, where only small areas appear stained. Vugs are common in the host quartz and tend to be vacant cavities. These were

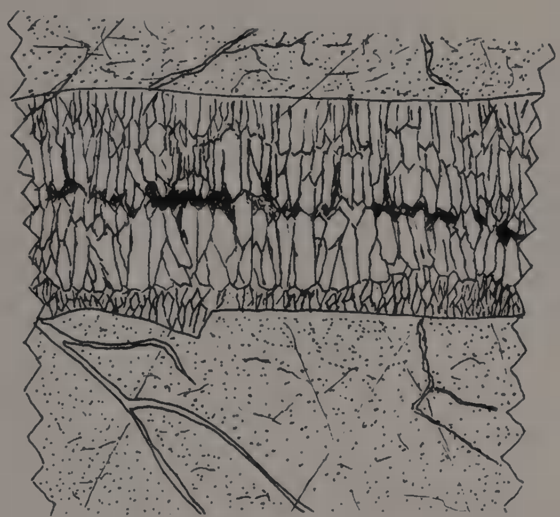
probably occupied by quartz crystals or sulfides. Vugs occupied by well formed quartz crystals are usually found within later quartz veins. Quartz veins are very abundant and occur as two styles. Larger, fairly straight veins that occupy previous joint openings, and smaller, randomly oriented, branching "spider-web" style veins that are offshoots of the larger veins into cracks and voids in the host rock. Some large quartz veins, one of which is 5 centimeters thick, exhibit a "comb" structure (Figure 26) where quartz crystals grow from the vein walls inward, meshing in the center, resembling the teeth of a comb. The zone appears uniform in terms of the number of veins present, but veins appear thicker toward the eastern edge than toward the western edge.

Thin Section Observations

A rock sample traverse was made from east to west across the southern part of the partially silicified rocks and the main silicified zone (Figure 25). Samples in the traverse included MT1A (east) through MT1G (west). MT1A and B are from the partially silicified rocks and MT1C through G are from silicified rocks. One sample MTNS-2 was taken from a partially silicified outcrop near the secondary fault that cuts the northern end of the main silicified zone. Sections from the partially silicified rock have characteristics

very similar to those from silicified rock so a zone description is based on the entire traverse. A detailed summary of thin section observations is given in table 3. The contact between the partially silicified and silicified rocks was inferred mostly by the color of the rocks in the field.

Estimated quartz content increases then decreases from 38%-40% in the east to 75% in the central area to 59% in the west. Quartz appears as very fine-grained matrix particles and as larger grains within veins and patches. Grain shape ranges from anhedral to subhedral, with the anhedral style being more common. Grains have smooth boundaries, commonly with embayments. Feldspar is present across the zone as relict fragments, most of which have a mottled appearance from alteration. Multiple twinning is evident in all sections except MT1B, indicating that the feldspar is within the plagioclase series. In sections MT1C through G, the grains are stained a yellowish-orange color due to the weathering of pyrite present in the rocks. Percentages for recognizable feldspar range from 5% to 10% in the eastern and central areas of the traverse, and 18% in the western area. Feldspar alteration occurs as two varieties. The first is sericite, and the second is a dark brownish-gray material with a branching or radiating structure. This



Five cm thick quartz vein exhibiting a "comb" structure. Quartz crystals develop from the silicic hydrothermal fluid, starting at the fracture walls and growing inward. They mesh in the center. Commonly hematite and sulfides are found at the meshing boundary. This sketch is from an unoriented hand sample collected from the southern part of the main silicified zone.

Figure 26. Sketch of large quartz vein with "comb" structures, from an unoriented hand sample - Mount Toby area.

Table 3. Thin section observations: Mount Toby samples MT1A - MT1G.

	Partially silicified Erving amphibolite	
Sample #	(east) MT1A	MT1B
Oriented sample	YES	YES
Quartz	strained euhedral to anhedral//embayed boundaries 38-40%	strained euhedral to anhedral//embayed boundaries 73%
Feldspar	brecciated, relict grains//albite twins 8-10%	brecciated, relict grains v. fine-grained within former grain boundaries 5%
Other	groundmass 43% sericite 5% hematite 2% pyrite tr	groundmass 16% sericite 5% hematite tr pyrite tr } 1% muscovite tr
Mylonitic textures	NONE	NONE
Cataclastic textures	brecciated fsp. grains// possible cataclastic breccia	brecciated fsp. grains// possible cataclastic breccia//fluid inclusions
Overall rock	subhedral to anhedral interlocking matrix supporting interlocking sub- to euhedral veins and patches	sub- to anhedral interlocking matrix supporting sub- to euhedral veins and patches
Foliation	NONE	possible qtz. planes
Lineation	NONE	NONE
Color (hand sample)	buff to light pink	grayish-pink
Grain size	matrix: dust - 0.1 mm veins+patches: 0.5 - 2.0 mm	matrix: dust - 0.1 mm veins+patches: 0.1 - 1.5 mm
Quartz veins	spiderweb up to 2.0 mm wide//unstrained, euhedral	spiderweb up to 1.5 mm wide//unstrained, sub- to euhedral
Epidote veins	NONE	NONE
Hematite veins	no veins//small anhedral masses	YES- small random//small anhedral masses
Mineral overgrowths	pyrite over qtz. some w/ skeletal features	pyrite in qtz. veins
Vugs	YES- vacant and occupied by pyrite	YES- vacant and occupied by pyrite

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Table 3. continued

Silicified Erving Amphibolite		
MT1C	MT1D	MT1E
YES	YES	YES
strained, euhedral to anhedral//embayed boundaries 80%	strained, euhedral to anhedral//embayed boundaries 88%	strained euhedral to anhedral//embayed boundaries 80%
brecciated, rounded relict grains and fragments 6%	v. altered//brownish color//some twins evident 10%	brecciated, relict grains evidence of twinning stained yellowish 3%
groundmass 10% sericite 3% hematite 1% pyrite tr	groundmass 20% hematite tr ┐ pyrite tr ├ 2% sericite tr ┘	groundmass 10% sericite 5% hematite 2% pyrite tr
NONE	NONE	NONE
cracked and rounded fsp.//fluid inclusions	crushed fsp.// breccia injections	crushed fsp.
sub- to anhedral interlocking matrix supporting sub- to euhedral veins and patches	sub- to anhedral interlocking matrix supporting sub- to euhedral veins and patches	sub- to anhedral interlocking matrix supporting sub- to euhedral veins and patches
possible faint foliation	NONE	NONE
NONE	NONE	NONE
buff to pinkish-buff	buff w/ darker bluish-gray areas	light blue-gray
matrix: dust - 0.5 mm veins: 0.2 - 2.0 mm	matrix: dust - 0.1 mm veins: 0.1 - 1.5 mm	matrix: dust - 0.1 mm veins: 0.01 - 8.0 mm
YES- larger and spiderweb styles	YES- only large style up to 2.5 mm wide	YES- only spiderweb style observed
NONE	NONE	NONE
small veins + small anhedral masses	NONE	small veins//anhedral masses and flecks
pyrite on qtz.	pyrite on qtz.	pyrite on qtz.
YES- vacant and occupied by qtz. + pyrite	YES- vacant and occupied by qtz. + pyrite	

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Table 3. continued

Sample #	Silicified Erving Amphibolite MT1F	MT1G (west)
Oriented sample	YES	YES
Quartz	strained euhedral to anhedral//embayed boundaries 60%	strained euhedral to anhedral//embayed boundaries 66%
Feldspar	lg. & sm. brecciated & rounded grains//stained yellowish 19%	lg. & sm. brecciated & rounded grains//stained yellowish-orange//very mottled 20%
Other	chlorite 10% hematite 5% sericite 5% pyrite 1%	chlorite 10% sericite 10% muscovite tr
Mylonitic textures	NONE	possible motion indicator west-side-down
Cataclastic textures	angular grain fragments	angular grain fragments
Overall Rock texture	sub- to anhedral inter-locking matrix support-ing sub- to euhedral veins and patches	sub- to anhedral inter-locking matrix support-ing sub- to euhedral veins and patches
Foliation	NONE	Possible faint cata-clastic
Lineation	NONE	NONE
Color (hand sample)	med. blue-gray	med. blue-gray
Grain size:	matrix: dust - 1.0 mm veins: 0.1 - 2.0 mm	matrix: dust - 0.3 mm veins: 0.1 - 0.5 mm
Quartz veins	YES- anhedral to sub-hedral grains// up to 3.0 mm wide// 2 ages obvious	YES- only spiderweb style observed
Epidote veins	NONE	NONE
Hematite veins	YES- small random// small anhedral masses	YES- small random
Mineral overgrowths	pyrite on qtz.	pyrite on qtz.
Vugs	YES- appear vacant	YES- vacant and occupied by pyrite

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Table 3. continued

Partially Silicified Erving Amphibolite
MTNS-1
NO
strained euhedral to anhedral//embayed boundaries 54%
small rounded grains stained brownish 15%
groundmass 15% chlorite 12% pyrite 3% hematite 1% apatite tr
NONE
cracked and rounded grains
sub- to anhedral interlocking matrix supporting sub- to euhedral veins and patches
faint metamorphic foliation
NONE
blue-gray qtz.-rich areas and pinkish sections
matrix: 0.1 - 0.5 mm veins: up to 0.8 mm
YES- random spiderweb style
NONE
YES- small random
pyrite
YES- occupied by qtz.

alteration looks very much like the feldspar alteration seen in the mylonites, however, in this case it does not contain pumpellyite grains. Percentages for sericite range from 5% to 8% and the other product has been combined with the feldspar percentages.

Other minerals identified in thin section include muscovite, hematite, chlorite and accessory pyrite. Chlorite is found in the western part of the zone as 10% of the sections. This is secondary resulting from the alteration of biotite. Remnant muscovite is found as trace amounts in MT1B and MT1G. Biotite is not commonly found in the amphibolite and muscovite never occurs. Perhaps these minerals were constituents of metamorphic pegmatites within the amphibolite. Hematite is found in trace amounts up to 3% as tiny randomly oriented veins and small anhedral masses in all thin sections except MT1D. Accessory pyrite is found across the zone and occupies vugs. The other 5% to 40% of the sections is groundmass consisting of very fine-grained quartz, feldspar, chlorite, and possible biotite and muscovite that has undergone a considerable amount of grain-size reduction.

Texture across the zone consists of a very fine-grained groundmass, supporting some larger relict grains of feldspar, cut by quartz and hematite veins. Grain size

remains fairly constant from east to west. Size ranges from very fine-grained "dust" to 0.1 mm in sections MT1A through F, and "dust" to 0.3 mm in section MT1G. Larger felspar grains range in size from 0.1 to 0.5 mm in the east, and 0.1 to 0.3 mm in the west. Grain size for quartz veins varies inconsistently across the zone, but the range for the entire zone is 0.01 to 2.0 mm. Quartz veins occur as two styles, larger feeder veins that are 2.5 to 3.0 mm wide, and the smaller branching, "spider-web" style that are 1.5 mm wide or less. The Mount Toby areas exhibits many more quartz veins in thin section than the East Mineral Hill area. Specular hematite is present as both vein fillings and as small flecks and anhedral masses. Hematite veins are present across the traverse except in MT1A and MT1D. Hematite veins are a later feature than, and commonly cut through quartz veins. Small flecks and anhedral masses are also found across the traverse except in MT1D. The anhedral masses of hematite may be the result of the weathering of pyrite. The hematite veins are precipitates from hydrothermal fluids. The "rusty" red staining observed in the field is also obvious in thin section and is a result of weathering of the pyrite. The staining effect is found across the zone, and is darkest in the western samples, and faintest in the eastern samples.

Small vugs are common in this rock, observed in all samples except MT1E, and are found in the matrix as well as later quartz veins. Those found in veins are either vacant or, more commonly, occupied by pyrite. Those found in matrix quartz tend to be vacant.

Section MTNS-2 represents a partially silicified rock but has most of the same characteristics as the silicified zone. This section has 54% strained, euhedral to anhedral quartz grains with smooth, embayed boundaries. Feldspar is present as 15% and occurs as small, rounded grains. Other minerals include chlorite (12%), hematite (1%), accessory pyrite (tr) and groundmass (15%). Grain size for the matrix ranges from 0.1 to 0.5 mm, and for veins, 0.1 to 0.8 mm. Grains all appear mottled, brownish- to light-orange, and show evidence of having been brecciated. Later quartz veins are represented by the small "spider-web" type.

Leverett Pond Area

Figure 27 shows a geologic map for the Leverett Pond area. The trend of the fault trace is N15W, and the dip, extrapolated from the Mount Toby area, is estimated to be 35 to 40 degrees southwest. A west-dipping Erving amphibolite unit, and small silicified zone, derived from the amphibolite, are located to the east of the border fault. Mount Toby Conglomerate is located to the west of the fault.

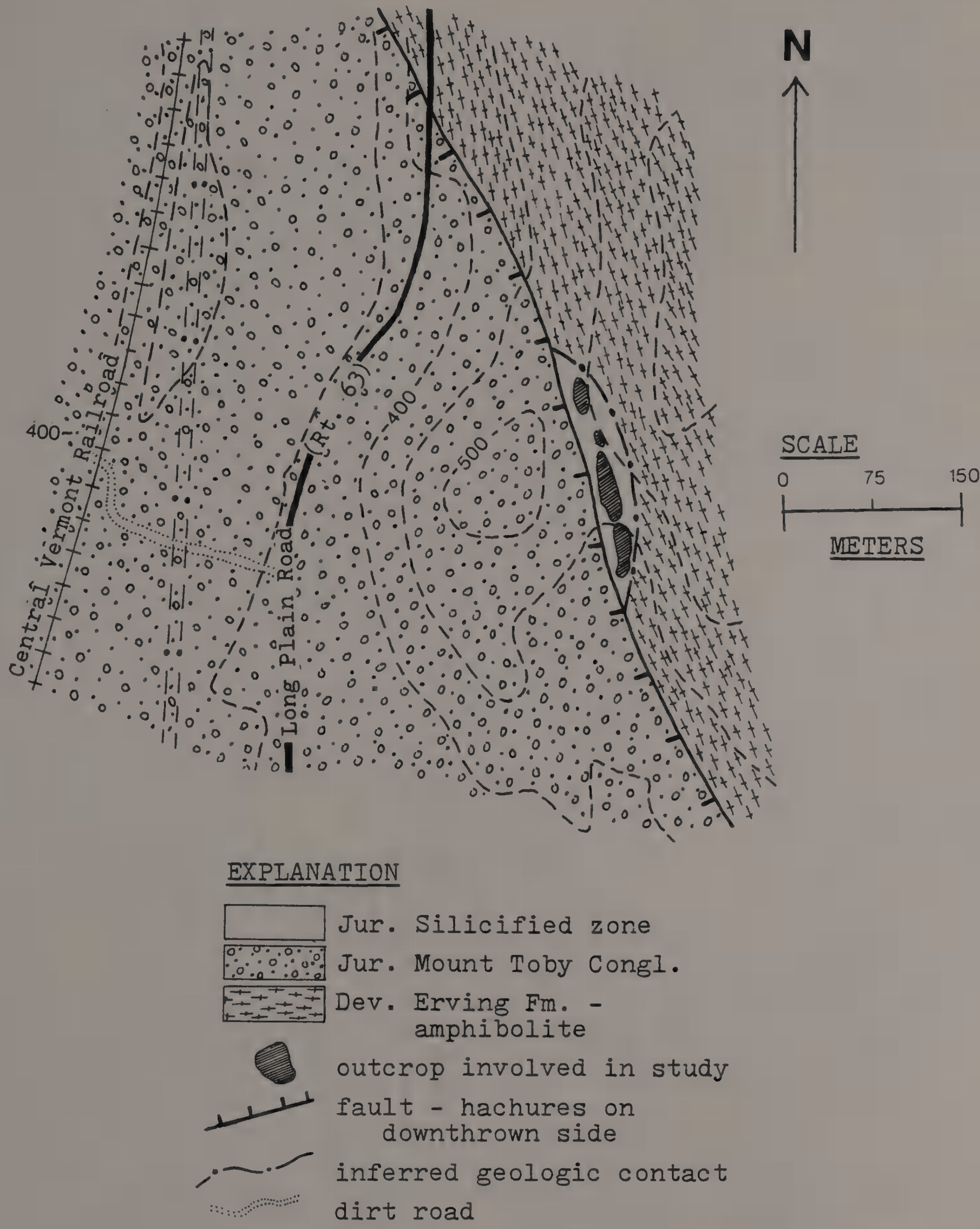


Figure 27. General geologic map of Leverett Pond area.

Neither rock type appears affected by the silicification process, nor do they exhibit extensive joint or late-stage quartz vein development. Metamorphic quartz veins are common in the amphibolite.

Silicified rock in this zone is of the quartz - plagioclase - chlorite type. It is massive, very fine-grained, sugary-textured quartz that is pinkish-tan, and gray when weathered. Moderately developed joint systems break the rock up into blocky sections and expose surfaces that are stained dark brown to orange in color. Surfaces that have been weathered for longer periods of time however, do not exhibit this effect. The silicified rock in this area resembles that of the main outcrop in the Mount Toby area. No thin sections were made for this zone.

Poverty Mountain Area

Unsilicified and Partially Silicified Rocks

Figure 28 shows a geologic map for the Poverty Mountain area. The border fault trends N10W and has an estimated dip of 44 degrees west (Jasaitis, 1983). To the east of the fault are west-dipping layers of unsilicified Dry Hill Gneiss, and partially silicified Mount Mineral Formation and Fourmile Gneiss. The estimated dip of these units is 30 degrees. Silicification effects in the gray mica schist of the Mount Mineral Formation include minor quartz replacement

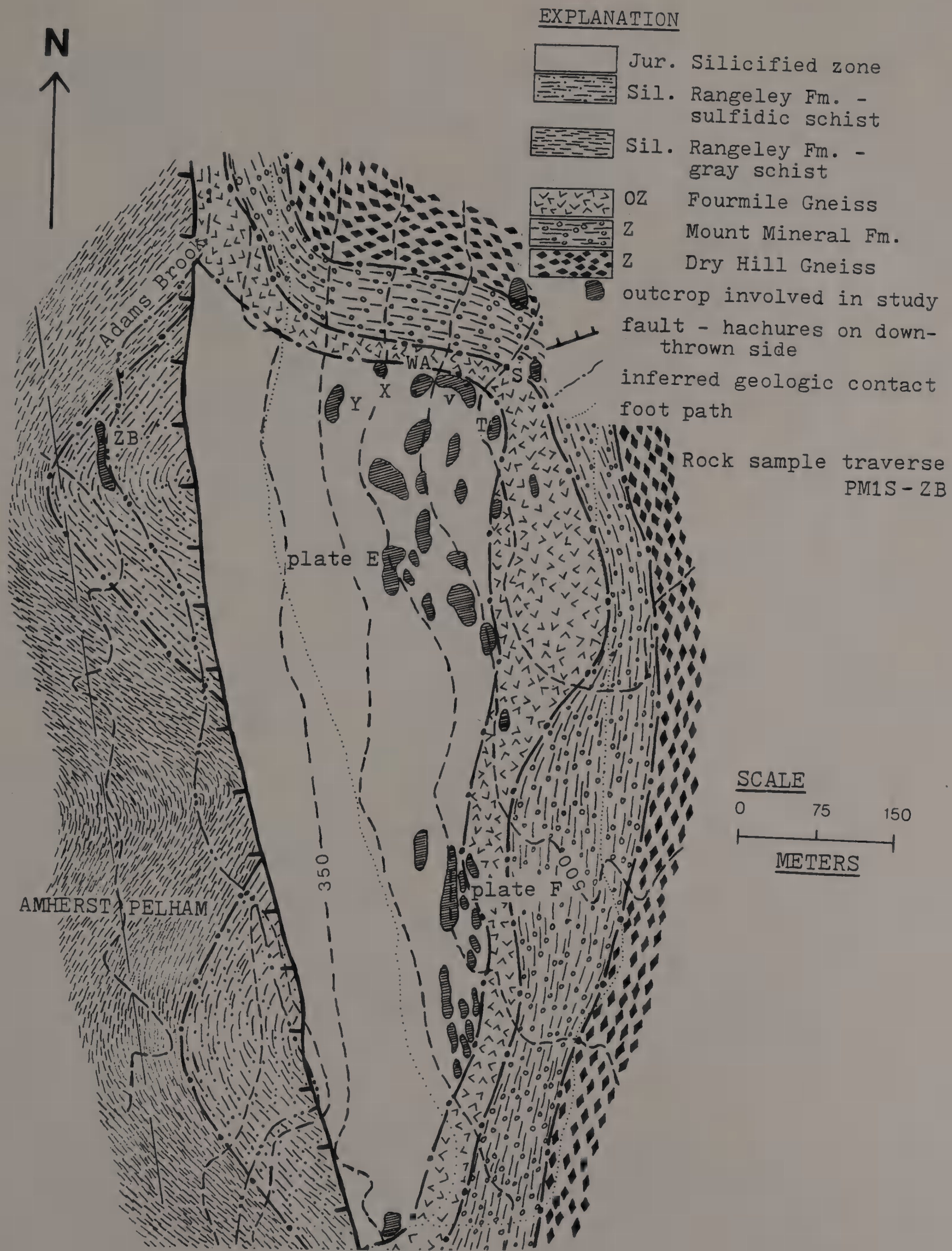


Figure 28. General geologic map of Poverty Mountain area.

and injection of quartz and epidote veins. The silicified Fourmile Gneiss has a cataclastic foliation and is in contact with the silicified zone. This zone a west-dipping slab of silicified Fourmile Gneiss that lies parallel to and borders the fault on the east. Maximum thickness of the silicified zone is estimated at 215 meters. To the west of the fault is exposed part of the Amherst inlier of downdropped gray and sulfidic schists of the Rangeley Formation. Sugarloaf Arkose basin fill unconformably overlies the Rangeley Schists outside the area of Figure 27 (Figure 1).

Silicified Rocks

The silicified rock in this zone is the quartz-feldspar-epidote-chlorite variety of breccia and microbreccia. The color of the rock changes from east to west from light pink and white feldspar grains that occur in a medium-gray matrix, to buff colored sections of feldspar that occur in a darker bluish-gray matrix. The weathered surface is commonly greenish-gray. The degree of silicification varies on a local scale, but overall the rock is more silicified on the western side of the zone than on the east. Feldspar is obvious in the field and decreases from east to west. Pale gray, very fine-grained quartz veins are abundant, some with a vuggy character. Both the large feeder veins and the

smaller, randomly oriented, "spiderweb" style, offshoot veins are obvious in the outcrop. Some larger veins form thin crusts on joint surfaces where rock from one side has been removed. The smaller veins commonly are intertwined into tight clusters that stand out in relief on the outcrop. Bright green epidote veins and dark red to black hematite veins are common in this unit and cross-cut the quartz veins. The zone appears to have more, and larger veins toward the western edge than toward the eastern edge.

The silicified zone crops out in a stream bed at the southern end of the map area. Where the stream runs over metamorphic rock the bed is fairly level, but where it runs across the silicified zone a small waterfall is developed on a cliff with an angle of 40 degrees. This 40 degree gradient is the dip of the overall outcrop and is believed to represent the dip of the border fault in this area.

<u>Thin Section Observations</u>

Seven samples were collected in an east to west traverse across the northern end of the map area through the partially silicified Mount Mineral Schist, silicified rock, and the sulfidic schist of the Rangeley Formation on the west wall of the border fault (Figure 28). Sample PM1S (hand sample only) is from the partially silicified Mount Mineral Schist. Samples PM1T (east), PM1V, PM1WA, PM1X and

PM1Y (west) are from the silicified rock. Sample PM1ZB is from the Rangeley Formation. A detailed summary of thin section observations is given in table 4.

Quartz content increases across the zone from 37% in the Mount Mineral Schist section in the east to 50% in the western edge of the silicified zone. Quartz grains are anhedral and are either strained or unstrained. Several feldspars are represented in thin section. Plagioclase has a positive optic sign in PM1X, PM1V and PM1WA, and multiple twinning is observed in all the sections. Plagioclase is present as untwinned grains as well. Orthoclase is untwinned and is identified by a negative optic sign in PM1T and PM1X. Other feldspars include microcline in PM1V, and microperthites in PM1WA and PM1X. Feldspar content remains relatively constant at 50% from east to west until PM1Y in the west where it drops to 20%.

Minor mineral constituents include biotite found in the eastern samples up to 10%, and muscovite, found also in the eastern samples in trace amounts. Biotite and muscovite are relict grains of the Fourmile protolith. Secondary chlorite is an alteration product of biotite, and is found across the zone. It occurs as wormy structures in section PM1V. Sericite is found in trace amounts between grain boundaries as an alteration product of feldspar. Accessory allanite is

Table 4. Thin section observations: Poverty Mountain samples PM1T, PM1V - PM1Y, PM1ZB.

	Partially Silicified Mt. Mineral Formation	Silicified Fourmile gneiss
Sample #	(east) PM1S- hand sample only	PM1T
Oriented sample	NO	YES
Quartz	18%	strained sub- to euhedral grains 37%
Feldspar	50%	plag.- twinned & un-twinned 10%//orthoclase lg. untwinned, r>v,(-), 70 curv.//perthitic structures 30%// 40% tot.
Other	musc. + bio. 30% sulfides 2%	biotite 10% sericite 10% muscovite 2% hematite 1% chlorite tr
Mylonitic textures	NONE	possible tails on a few fsp. grains
Cataclastic textures	angular fragments	cracked grains, some rounded grains
Overall rock texture		interlocking anhedral
Foliation	strong mica planes	weak mica planes
Lineation	NONE	NONE
Color (hand sample)	med. gray w/ light pink and white fsp.-rich areas	light pinkish-gray
Grain size	fine- to medium-grained	3.0 - 4.0 mm average
Quartz veins	NONE	NONE
Epidote veins	NONE	NONE
Hematite veins	YES- small random	YES- small random// orange staining
Mineral overgrowths	none apparent	hematite on fsp.
Vugs	none apparent	NONE

cont. next page

Table 4. continued

	Silicified Fourmile gneiss	
PM1V	PM1WA	PM1X
YES	YES	YES
anhedral strained 46%	strained larger grains/ mostly unstrained sub-grains 35%	strained larger grains// mostly unstrained sub-grains 42%
plag.-twinned & un-twinned, (+)//micro-cline//orthoclase-(-) //relict grains 33%	plag.-altered, (+), twinned & untwinned// perthitic struc. 42%	centered OA: (+) plag: twinned and un-twinned//some perthitic structures 45%
sericite 10% chl.(worms) 5% epidote 3% hematite 1% bio. tr pyr. tr musc. tr	chlorite 10% sericite 9% allanite 2% epidote 2% apatite tr	sericite 5% chlorite 5% epidote 3% allanite tr
subgrains w/ mortar texture	subgrains w/ mortar texture// 10% sub-grain development	very little subgrain formation
cracked fsp.// brec-ciation in veins and rounded grains	microbreccia injection// cracked and crushed grains	cracked fsp. grains
partially interlocking anhedral fsp. supported by mortar textured qtz. and cut by veins	partially interlocking anhedral fsp. supported by mortar textured qtz. and cut by veins	interlocking anhedral cut by veins
weak mica planes	weak mica planes	weak mica planes
NONE	weak qtz. rodding	NONE
pink fsp. and blue-gray areas	light pink to gray	pinkish-gray
matrix: up to 1.0 mm 3.0 mm for largest grains//fsp. 1-2 mm av.	qtz: 0.1 - 0.5 mm fsp: 2.0 - 3.0 mm	matrix: up to 1.0 mm fsp: 2.0 - 4.0 mm
patches// no veins	YES- small spiderweb style	YES- small spiderweb style
YES	no veins but indiv. grains of epidote	YES- assoc. w/ chlorite in veins
YES- small, braided	YES- small, braided	YES- small, random orientations
pyrite on qtz. + matrix		
NONE	NONE	NONE

cont. next page

Table 4. continued		
	Silicified Fourmile gneiss	Partridge Fm. in west wall of border fault
Sample #	PM1Y	PM1ZB
Oriented sample	YES	NO
Quartz	strained, anhedral larger grains//mostly unstrained subgrains 50%	very coarse-grained unstrained 50%
Feldspar	plag w/ twinning// untwinned plag// perthitic structures 25%	plag.-twinned & untwinned//r>v weak,(+)/ orthoclase-pinkish// perthitic struc. 34%
Other	groundmass 17% sericite 5% epidote 2% chlorite 1%(worms)	biotite 10% musc. 5% hematite 1% sericite tr
Mylonite textures	subgrain dev. w/ mortar texture	NONE
Cataclastic textures	crushed and rounded grains	massive, angular and rounded grains
Overall rock texture	v. fine-grained matrix w/ some mortar texture	interlocking sub-hedral// no matrix
Foliation	NONE	None observed in thin section but outcrop has a metamorphic fol-iation
Lineation	NONE	weak lineation
Color (hand sample)	blue-gray to green-gray	blue-gray to green-gray
Grain size	matrix: dust - 0.2 mm veins: 0.1 - 1.0 mm	1.0 mm in finer-grained part//8.0 - 12.0 mm in coarser-grained part
Quartz veins	YES- small random up to 1.0 mm wide	NONE
Epidote veins	some w/ chlorite in veins// epidote grains-fractured and rounded	NONE
Hemitite veins	NONE	YES- few, small, random
Mineral overgrowths	NONE	NONE
Vugs	YES- not common, vacant	NONE

found in PM1WA and PM1X. The presence of allanite supports a protolith of Fourmile Gneiss for the Poverty Mountain silicified zone

Texture across the zone changes somewhat from east to west. The eastern samples have interlocking anhedral grains, many of which have smooth but irregular boundaries with small embayments. Some matrix is present as well as some patches of coarser-grains, which are also interlocking. For the most part, the texture is grain-supported. Toward the west side the grains become slightly more rounded and more grain size reduction has taken place through brecciation. A larger proportion of grains are matrix supported. Overall, grain size decreases from east to west. Average grain size represented by the partially silicified Mount Mineral Schist thin section is 3.0 to 4.0 mm. The average grain size in the eastern boundary of the silicified zone is 0.1 to 1.0 mm for quartz and 1.0 to 2.0 mm for feldspar grains. The western boundary has a grain size from very fine-grained to 0.2 mm for matrix grains, 0.1 to 1.0 mm for larger quartz grains, and 2.0 to 4.0 mm for feldspar grains. The larger feldspar grain size near the fault as compared to farther from the fault was not a feature found in any other area.

Quartz veins, although abundant in outcrop, are not

well represented in thin section. Only the small "spider-web" style veins are present and only in the central and eastern samples. Quartz patches are found in PM1V. Both features are fine-grained and the largest veins are 1.0 mm wide. Hematite veins are also present as small randomly oriented, braided features. Veins are found in all samples except PM1Y, and no flecks or anhedral masses are observed. Vugs are generally absent, however a few are found on the western edge of the zone in PM1Y.

One sample (PM1ZB) was taken from the sulfidic schist of the Rangeley Formation on the western border of the fault. In thin section the rock consists of quartz, feldspar, biotite, and muscovite grains cut by a metamorphic pegmatite, consisting of quartz and muscovite, and later hematite veins. The schist has not been significantly affected by the silicification process except for the presence of the late hematite veins which cut all other features. Pegmatite quartz and muscovite is very coarse-grained, 8.0 to 12.0 mm for quartz and 4.0 to 6.0 for muscovite. Quartz grains not involved with the pegmatite are anhedral to subhedral and unstrained. As a whole, quartz constitutes 50% of the section. Feldspar (29%) occurs as plagioclase, with a positive optic sign and multiple twinning, and as orthoclase, which is untwinned and has a

light pink color. Orthoclase grains are partially altered to sericite, which constitutes another 5% of the section. The average grain size for feldspar, biotite, and non-pegmatite quartz, and muscovite grains is 1.0 mm.

Harkness Road Area

Figure 29 shows a geologic map of the Harkness Road area. The trend of the fault trace in this area is N30W, and a dip of 40 to 60 degrees southwest has been interpreted based on values estimated to the north and south of this area in other studies. Rocks located to the east of the fault include west-dipping layers of Dry Hill Gneiss, Mount Mineral Formation and Fourmile Gneiss. Rocks to the west of the fault include downdropped gray schist of the Rangeley Formation unconformably overlain by Triassic Sugarloaf Arkose.

This area consists of two silicified rock types and several fault-related features (Figure 29). Starting at the northern end of the map area at the base of a hill are fragments of a pink and white brecciated pegmatite. One thin section (HAK) was made from an unoriented sample. Quartz makes up 40% of the section and feldspar constitutes 60% of the section. The quartz is very coarse-grained subhedral, and unstrained. The feldspar group is represented by microcline, plagioclase, orthoclase, and

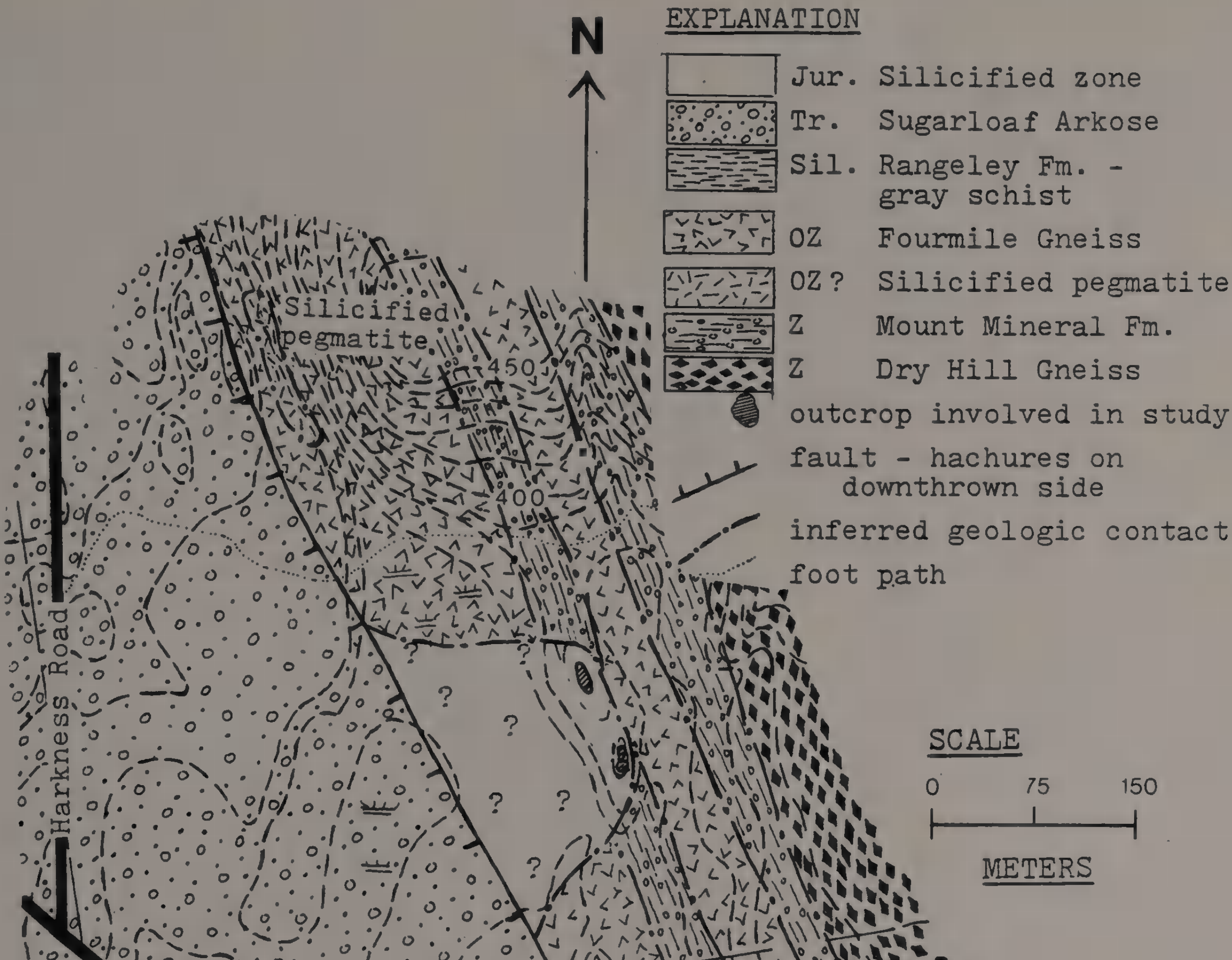


Figure 29. General geologic map for Harkness Road area.

microperthites. Microcline exhibits crosshatch twinning, plagioclase has albite twinning and a negative optic sign, and orthoclase is untwinned, mottled, and has a pinkish color. The microperthites have an orthoclase host with a negative optic sign, a strong r>v dispersion, and a curvature of 85-90 degrees on a centered optic axis isogyre. Minor mineral constituents include trace muscovite and trace sericite alteration.

Grain sizes are bimodal. Very coarse-grained quartz and feldspar averages 10.0 mm, and grains that have undergone brecciation average 0.1 to 0.2 mm. The rock consists of large anhedral, interlocking, grain-supported areas enclosing areas of brecciated, anhedral, fine-grained, interlocking but somewhat more rounded grains.

Silicified rock of the quartz-plagioclase-epidote-chlorite group of breccia and microbreccia is located 305 and 610 meters to the south along the fault trace on two raised hummocks in the swamp. No thin sections were made of this rock which is very similar in appearance to the rock in the Poverty Mountain area. It is resistant gray-weathering, greenish-gray and fine grained, with local areas of massive, sugary-textured, very-quartz-rich rock. The general geologic map of this area shows a silicified zone that extends from these outcrops down to the fault trace.

There is no other outcrop besides the small hummocks to justify this zone shape, so the shape is based on the relationships of the other silicified zones with respect to the border fault trace.

The gravel pit behind Mike's Speed Shop on Route 9 in Belchertown has one silicified rock type and two fault-related features which are less important to the study. The silicified rock is massive, and very fine-grained, with pink to reddish-pink and white feldspar rich areas enclosing areas of fine-grained quartz rich rock. It has been intruded into cracks in the host Fourmile Gneiss as veins up to 15 cm wide. Veins that were intruded parallel to the dip of the outcrop appear as small caps on the weathered surface. In most cases the bordering several millimeters of host Fourmile Gneiss has been hydrothermally altered to a fine-grained, greenish-gray boundary zone. No thin sections of this silicified rock type were made.

Two fault-related features in this area include pseudotachylite veins and massive sulfide deposits. Pseudotachylite veins are found in an outcrop of Fourmile Gneiss which also has silicified rock associated with it. This outcrop is located on the east side of, and parallel to the fault trace. The veins are very fine-grained and greenish-gray in color. They represent a brittle faulting

event where low confining temperatures and pressures, and high strain rates caused a fast release of stress, forming a brittle fault where a microbreccia was formed on the fault surface. This acted like a fluid and was squeezed into cracks and fractures on and near the fault surface, much like the cataclastic intrusion breccia found in the mylonites at the French King Bridge locality.

The second fault-related feature, a massive sulfide deposit, is a pyrite deposit incorporated into an outcrop of Fourmile Gneiss which is oriented on the east side of, and parallel to the fault trace. The pyrite deposit is capped by gossan which is all that is observed at the outcrop. Gossan caps are a heavy concentration of "limonitic" material derived from massive sulfide minerals or from their iron-yielding gossan, which has been leached in place and transported downward (Jensen and Bateman, 1981). The deposit is at least 2 meters thick but its orientation is not known because it appears as a weathered mound within a low swampy area. It is most likely that the pyrite deposit is a west-dipping vein below the ground surface that was emplaced on the east side of the fault zone, and that mimics the orientation of the fault surface. The pyrite vein would therefore have a trend close to N30W and a dip between 40 and 60 degrees to the southwest.

Gulf Road Area

Unsilicified and Silicified Rocks

Figure 30 shows a geologic map of the Gulf Road area. The trend of the border fault in this area is N40W, and a dip of 60 southwest (Guthrie, 1972) has been estimated. A west-dipping layer of Fourmile Gneiss and a west-dipping silicified zone, with a Fourmile Gneiss protolith, is in contact with the border fault on the east side. New Haven Arkose fills in the basin to the west of the fault.

Silicified rock at this locality is the quartz - plagioclase epidote - chlorite variety of breccia and microbreccia and consists of greenish-gray, massive, and very fine-grained areas enclosing large blocks of pinkish gray, fine-grained, massive quartz and feldspar rich areas. The greenish-gray areas have a platy, very thin-spaced fabric; however, no specific orientation could be obtained. Contacts between this and the quartz and feldspar blocks are generally distinct. Abundant quartz and hematite veins are present. Some quartz veins are very large, irregularly shaped, have a vuggy character, and have bluish-black hematite veins strung throughout. Large quartz veins are up to 3 cm thick and stand out in relief on the rock. Two epidote-rich, greenish-blue veins have an irregular shape with pieces of the light pink rock enclosed within. These

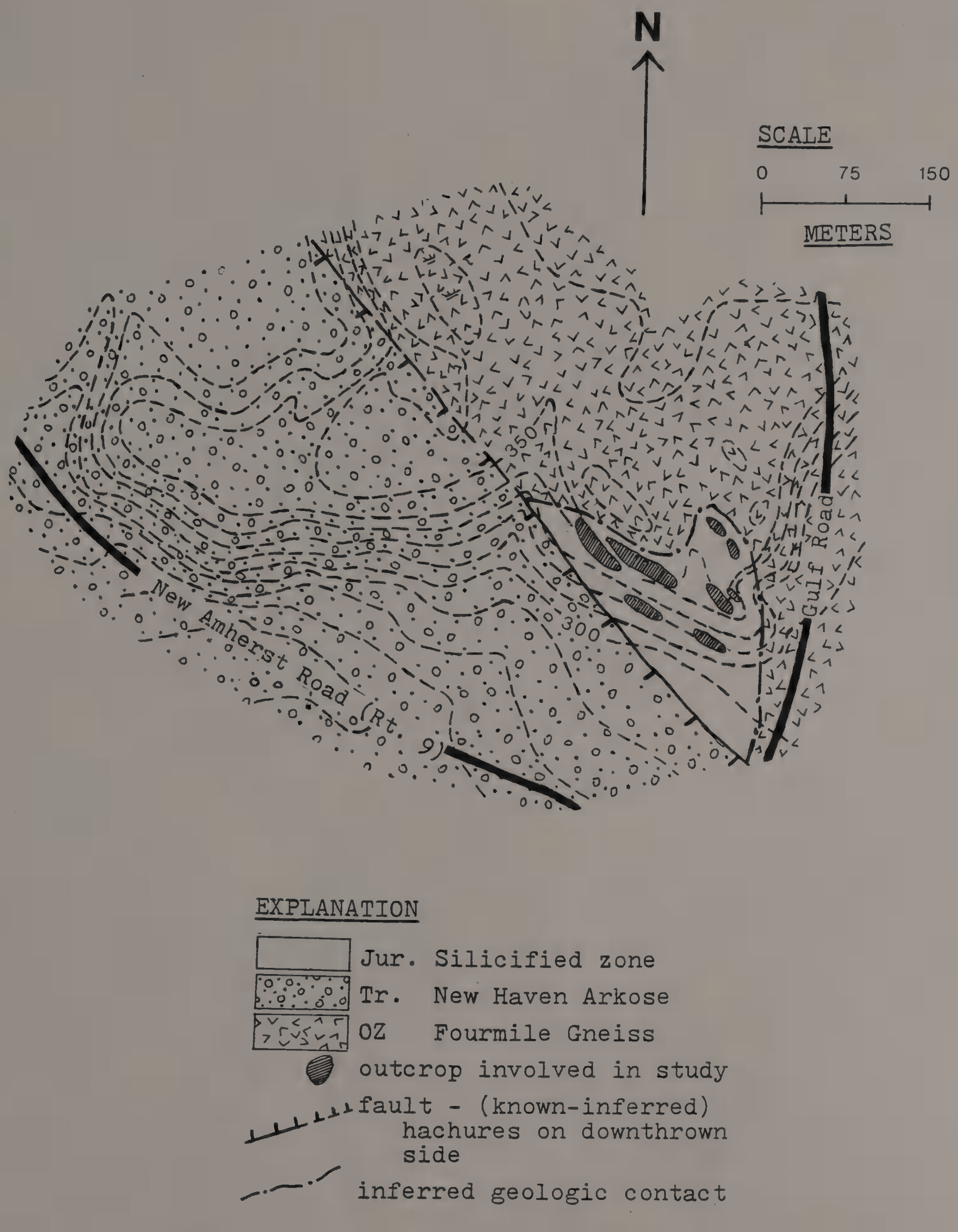


Figure 30. General geologic map for Gulf Road area.

cut off quartz veins indicating that epidote veins are a younger feature than the quartz veins.

Thin Section Observations

One thin section (GLFB2) was made from samples collected at this locality. In contrast to the other occurrences, quartz is not readily identifiable in thin section, which is deceptive because the rock in outcrop appears to have abundant quartz. Optically positive, twinned plagioclase appears to constitute 72% of the thin section. If quartz is present, it is altered or too fine-grained to make an identification, but is included in this 72%. Other mineral constituents include hematite 2%, epidote 10%, chlorite 1%, and trace muscovite. A black, opaque, super fine-grained matrix material constitutes the other 15% of the thin section.

Overall, the rock can be generalized by three separate descriptions. One consists of areas of 0.5 to 2.0 mm feldspar grains with little to no matrix. These areas are largely grain supported. The second type consists of areas of brecciated feldspars with an average grain size of 0.1 to 0.5 mm, largely supported by the black opaque matrix. The third type consists of rounded and brecciated 0.1 to 2.0 mm epidote grains and 0.1 to 0.5 mm feldspar grains arranged in veins, and supported by the black matrix. These veins

appear to flow around and commonly enclose areas of the first two styles.

Quartz veins, although present in outcrop, are not represented in this thin section. Epidote veins are common in outcrop and are seen in thin section, as previously mentioned, as well as small randomly oriented hematite veins.

CHAPTER 4

STRUCTURAL GEOLOGY OF SILICIFIED ZONES

Introduction

Structural features within the silicified rock at each map area between East Mineral Hill and Gulf Road were measured and plotted on equal area diagrams to try to determine any relationship of that area to the geometry of the border fault. Features that were considered are joints, veins, and fault surfaces, some with slickensides. Structural data were obtained both in the field and from thin sections of the silicified rock. Joints are the most prominent features in all of the map areas, and upon casual observation of the outcrop it appears that there are three and locally four distinct types. These four categories of joints that were obvious in the outcrops are:

1. A northeast- to northwest-striking, platy, west-dipping set.

2. A northeast- to northwest-striking, moderately east-dipping set.

3: A northeast- to northwest-striking set that is steeply dipping to the east and west.

4: An east- to west-striking set that is highly scattered but generally dips to the north and south.

The equal area diagrams for most map areas however, do

not strongly emphasize these groups. Instead, they are present as loosely clustered concentrations. Detailed outcrop maps for the East Mineral Hill, Mount Toby and Poverty Mountain areas were constructed in an attempt to isolate these apparent joint groups, and to collect data that may be more obvious on a closer inspection.

Quartz and hematite veins were precipitated into many of these joint openings, indicating later pulses of hydrothermal fluids into the silicified rock. Vein data are also plotted on equal area diagrams. For each map area, the trend of the fault is indicated on all equal area diagrams. Total joint and vein data, both with respect to north and to the fault trend, will also be discussed. Some structural data were interpreted from thin sections for the Mount Toby and Poverty Mountain areas.

East Mineral Hill Area

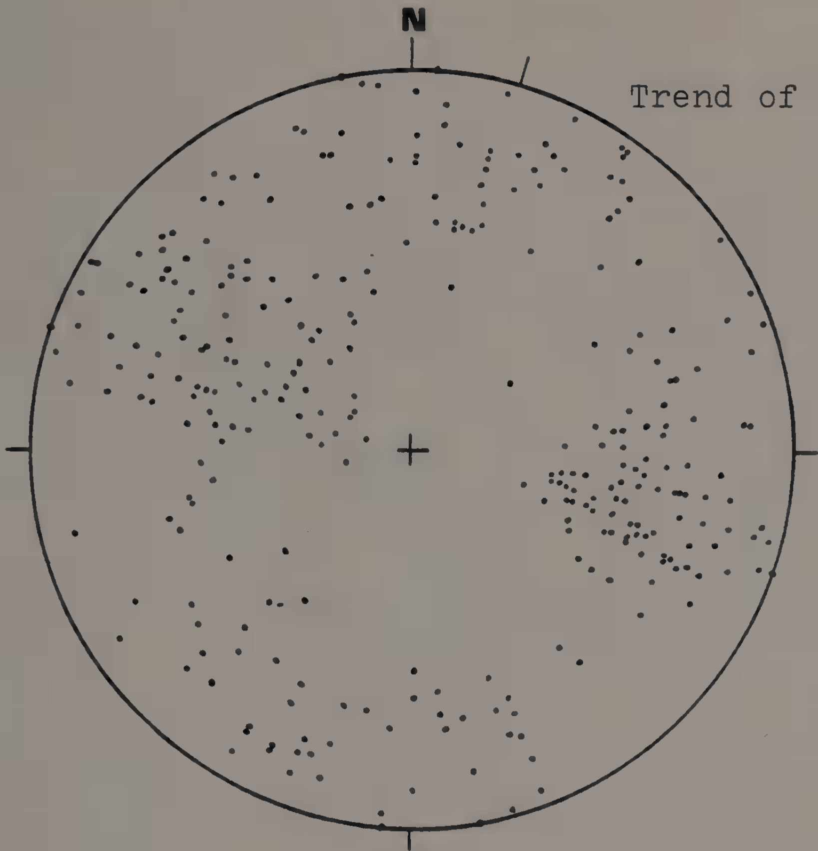
Structural field data for the East Mineral Hill area were obtained by a general survey, as well as by construction of two five-foot by five-foot detailed outcrop maps. The first of these maps is from an outcrop located in the north-central portion of the map area. The second is from an outcrop located in the southern portion of the map area (Figure 24).

The East Mineral Hill area has a moderately to locally

well developed joint system. Three groups of joints appear obvious in the outcrop scale. Two groups are northeast-striking; one has a platy, west-dipping character and the other is moderately east-dipping. The third group is east- and west-striking with steep dips to the north and south. The platy, west-dipping set commonly results in large, west-dipping outcrop surfaces that extend some distance through the outcrop. The other joints form blocky, rectangular trace patterns on the larger surfaces. When the rock is weathered, it breaks into these blocky, rectangular pieces. Some joint surfaces are mineralized by quartz or hematite. Relative ages of these joints are hard to distinguish but the north- and south-dipping scattered set may be a later feature because they commonly curve into the other types.

General Data

Joint data collected from each outcrop in the map area were combined, and poles to planes were plotted on an equal area diagram and contoured (Figure 31). The contour diagram shows the three loose joint clusters representing the groups mentioned. A strong northeast - southwest trend is represented which correlates with the N15E trend of the fault in this area. The west-dipping cluster of points, representing platy joints, has a mean orientation of N12E, 52NW. The strike of the joints mimics well the fault trend



N = 299

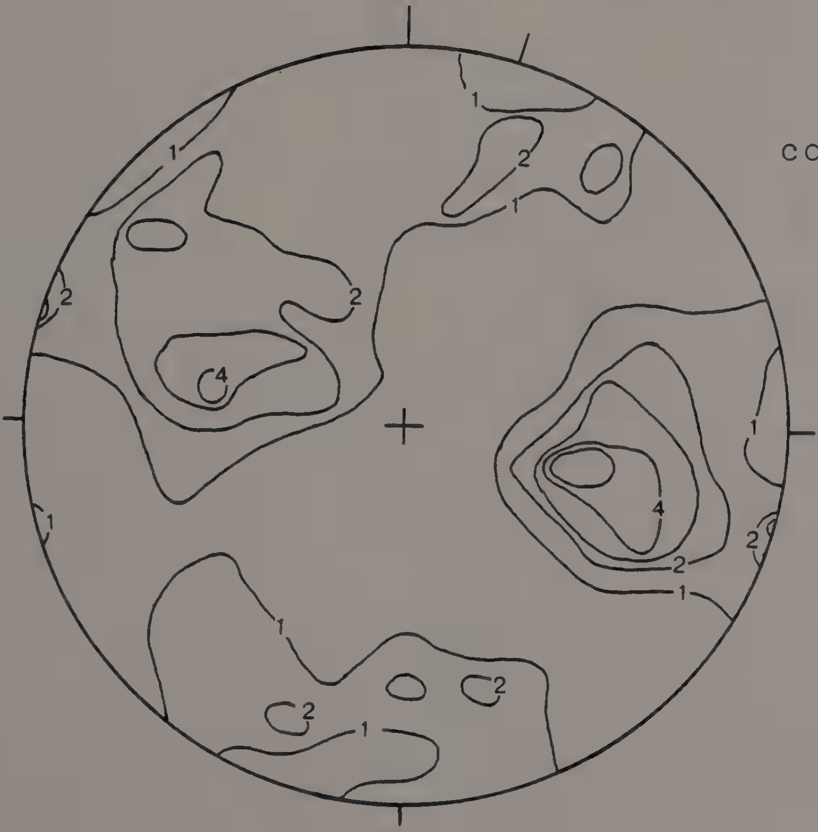


Figure 31. General joint data - East Mineral Hill area.

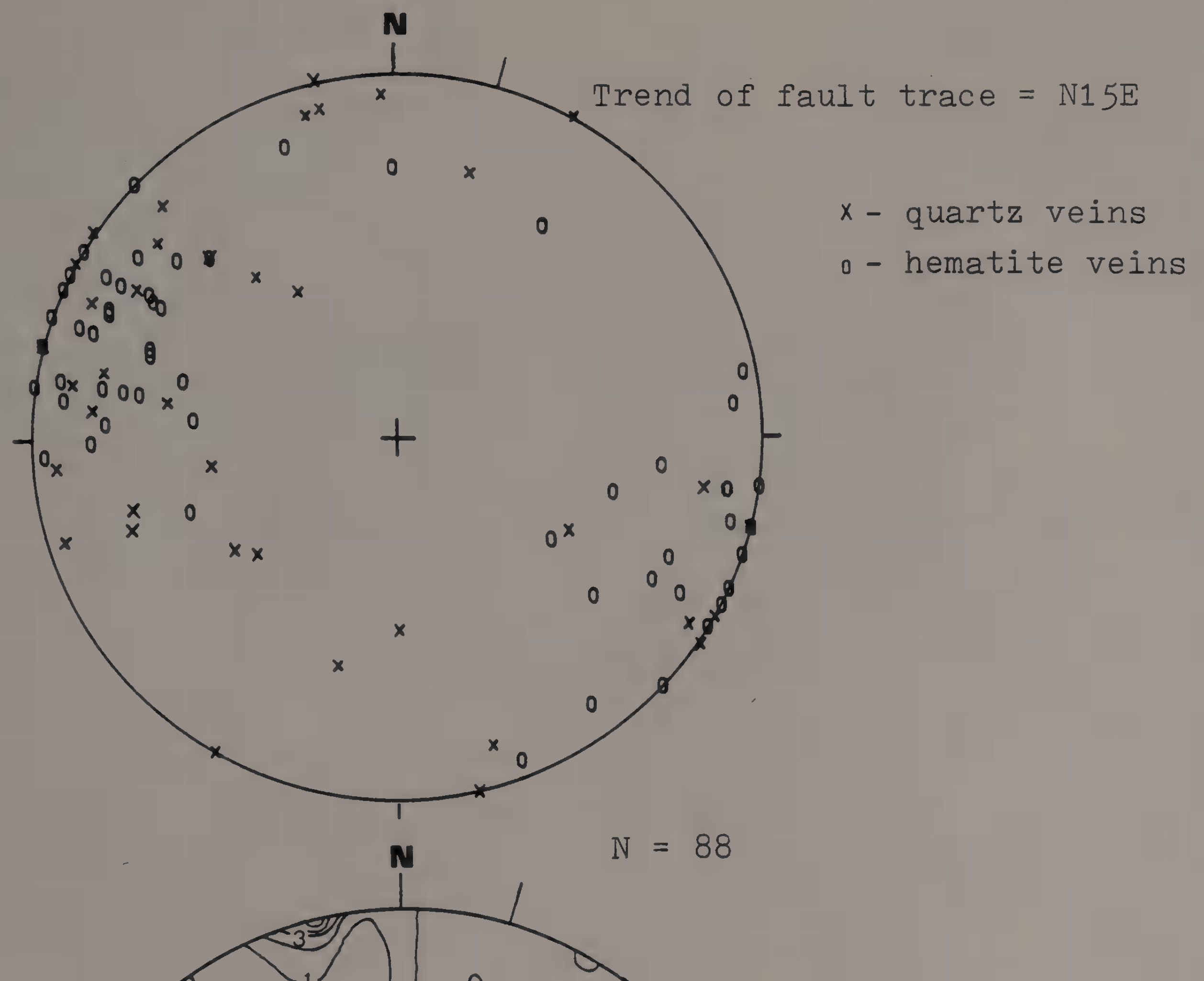


Figure 32. General vein data - East Mineral Hill area.

and the mean dip of these joints is believed to mimic the dip of the fault plane in this area. Quartz and hematite veins from each outcrop were measured and compiled (Figure 32). A mean strike of N24E is close to the N15E fault trend. An extensional stress suggested for the time of vein formation is N66W - S66E.

<u>Detailed Outcrop Maps</u>

Figures 33 and 34 represent detailed outcrop maps A and B for the East Mineral Hill area. Joint and vein orientations were measured, plotted, and contoured for map A (Figure 35), and map B (Figure 36). The outcrop from which map A was constructed is a large, west-dipping surface. The west-dipping joints are subparallel to this surface and tend not to crop out. These joints are therefore not well expressed in Figure 35 but a northeast - southwest trend is obvious which corresponds to the trend of the border fault. West-dipping joints are better represented in Figure 36 with a mean orientation of N16E, 51NW. The strike agrees well with the N15E fault trend and the 51 degree dip is again believed to represent the dip of the fault plane. Other joint types in Figure 36 show more scattering than was seen in Figure 35. The difference in degree of scattering between the two diagrams could represent differences between the north and south ends of the silicified zone.

Quartz and hematite veins were plotted and contoured for map A (Figure 37) and map B (Figure 38). As was the case with the joint data, vein data in Figure 37 is well clustered, and in Figure 38 is less clustered. In Figure 37 the mean strike is N16E, with steep dips to the northwest and southeast. In Figure 38 it is N20E with similar dips. These strikes agree with the results from the general survey, and the N15E trend of the border fault in this area.

Mount Toby Area

Structural data for the Mount Toby area were obtained using a general survey and construction of two five-foot by five-foot detailed outcrop maps. The first of these maps is located at the western edge of the quartz-rich outcrop in the northern part of the map area. The second map is from the central portion of the main silicified area that borders the Central Vermont railroad tracks (Figure 25). Some structural features were also observed in thin section. Since this area has two silicified zones, each oriented differently with respect to the border fault, data from each zone are treated seperately.

The quartz-rich zone in the northern part of the map area has moderately well developed joints that appear to be randomly oriented with respect to each other. The zone is oriented at an angle of 30 degrees to the border fault. The

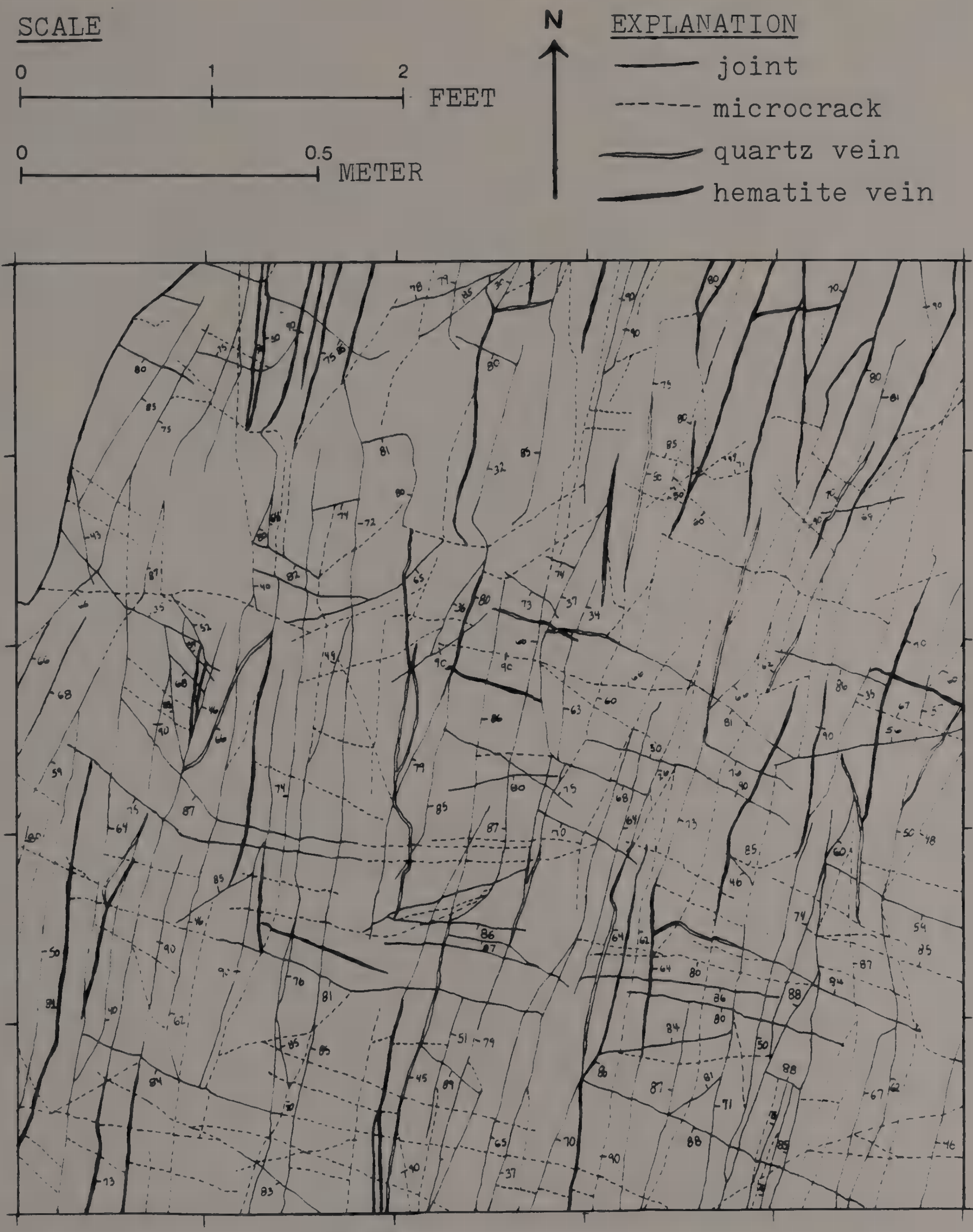


Figure 33. Detailed outcrop map A, East Mineral Hill area - north.

Figure 34. Detailed outcrop map B, East Mineral Hill area - south.

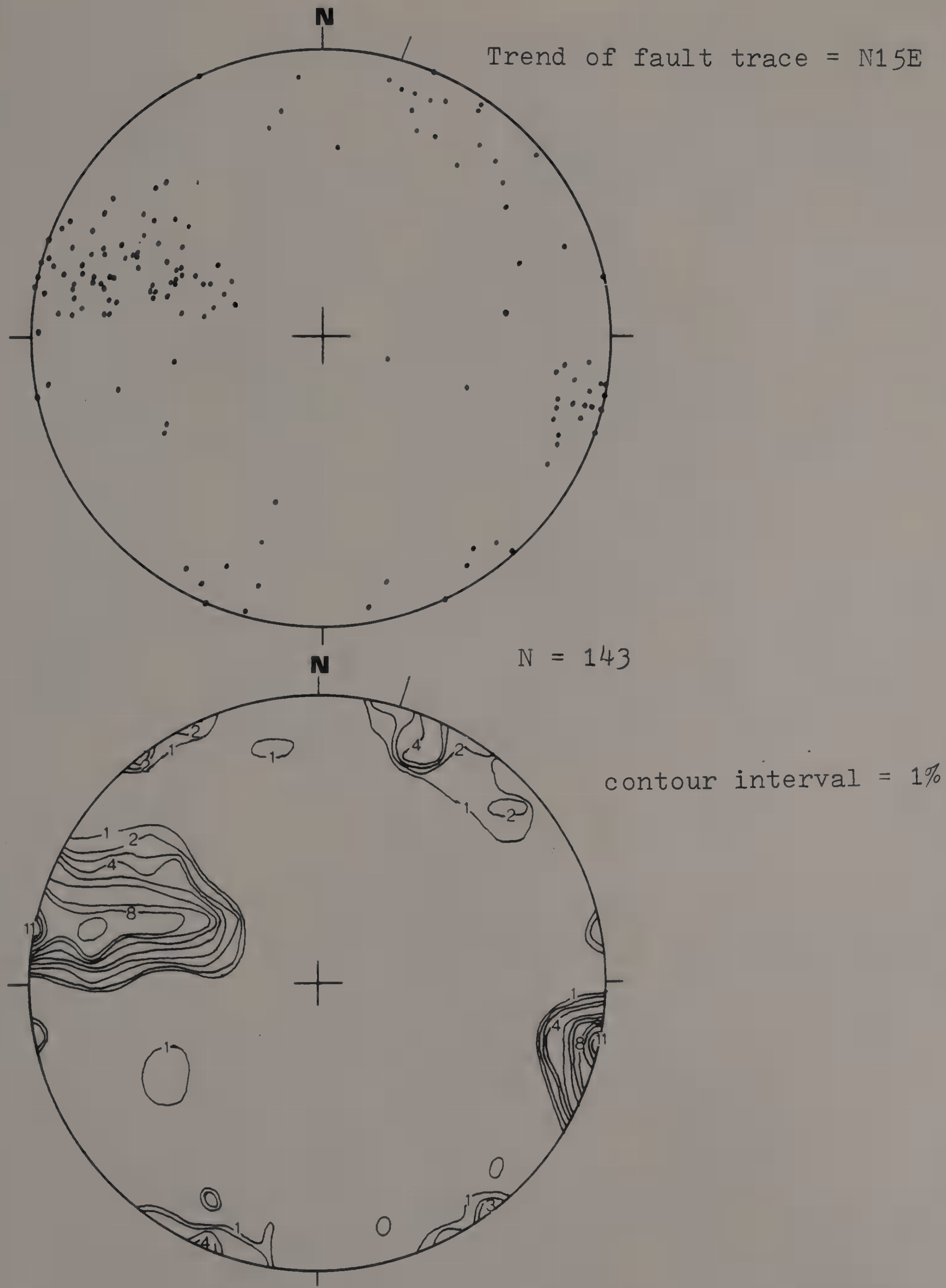


Figure 35. Joint data for detailed outcrop map A - East Mineral Hill area.

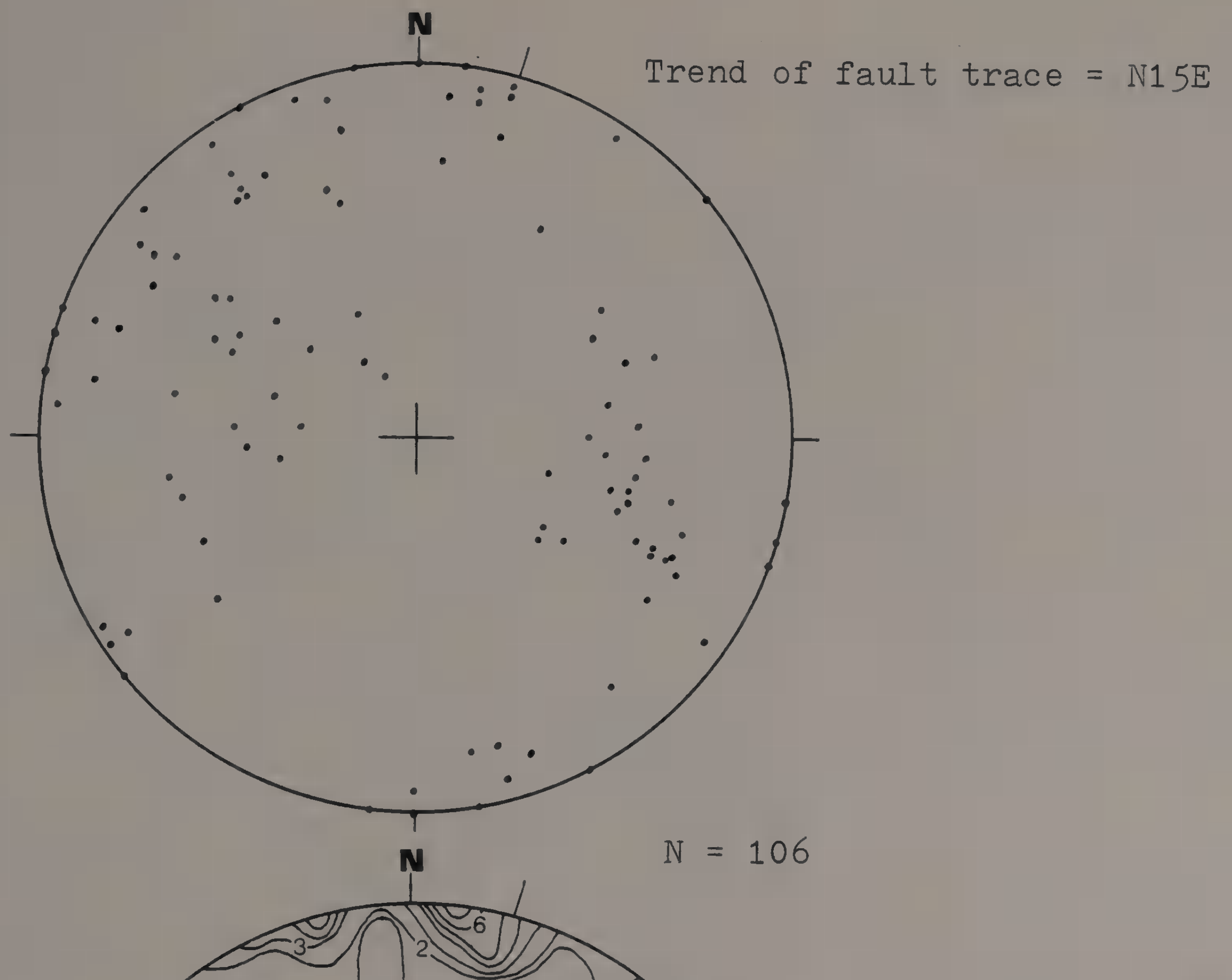


Figure 36. Joint data for detailed outcrop map B - East Mineral Hill area.

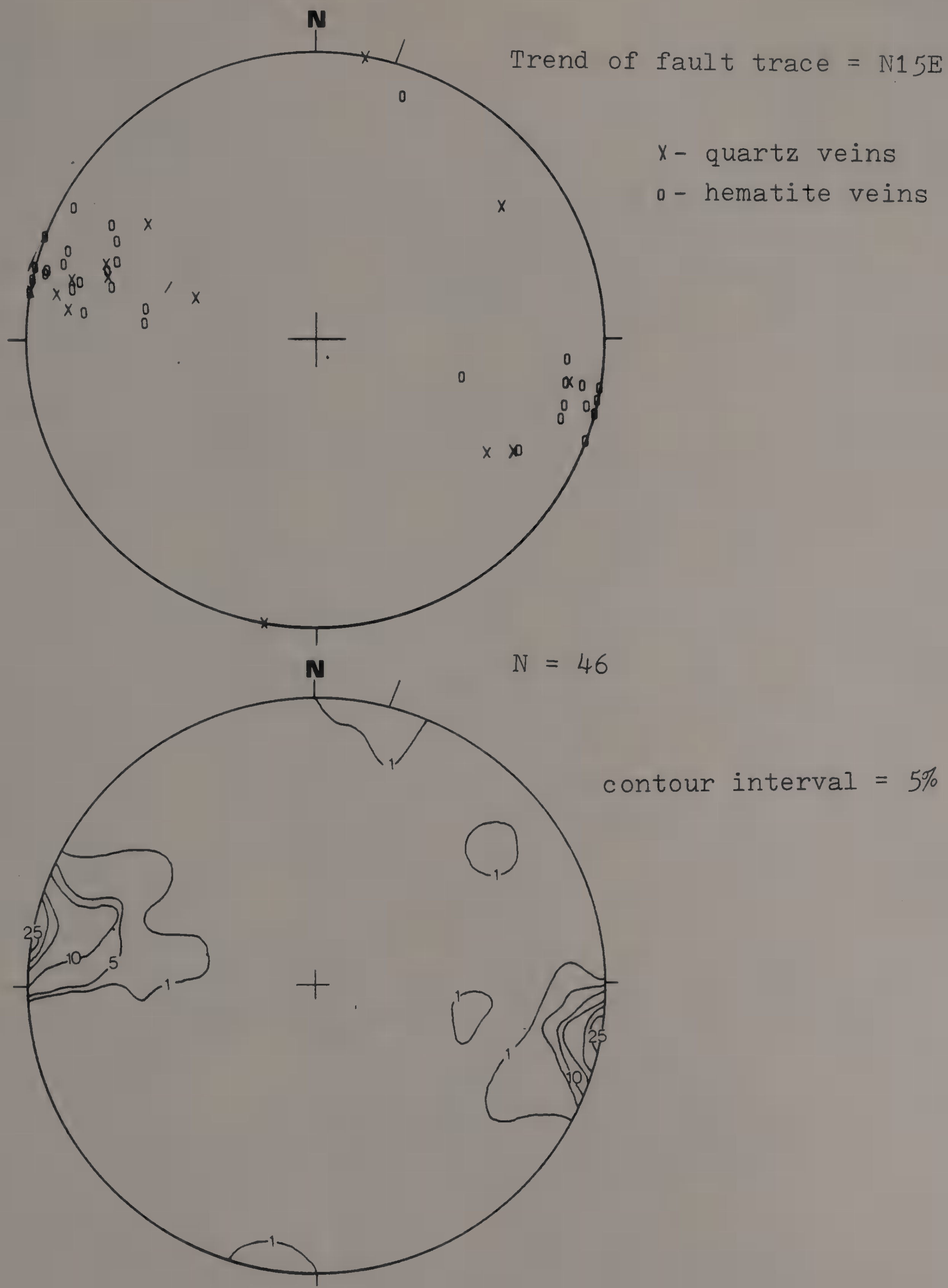


Figure 37. Vein data for detailed outcrop map A - East Mineral Hill area.

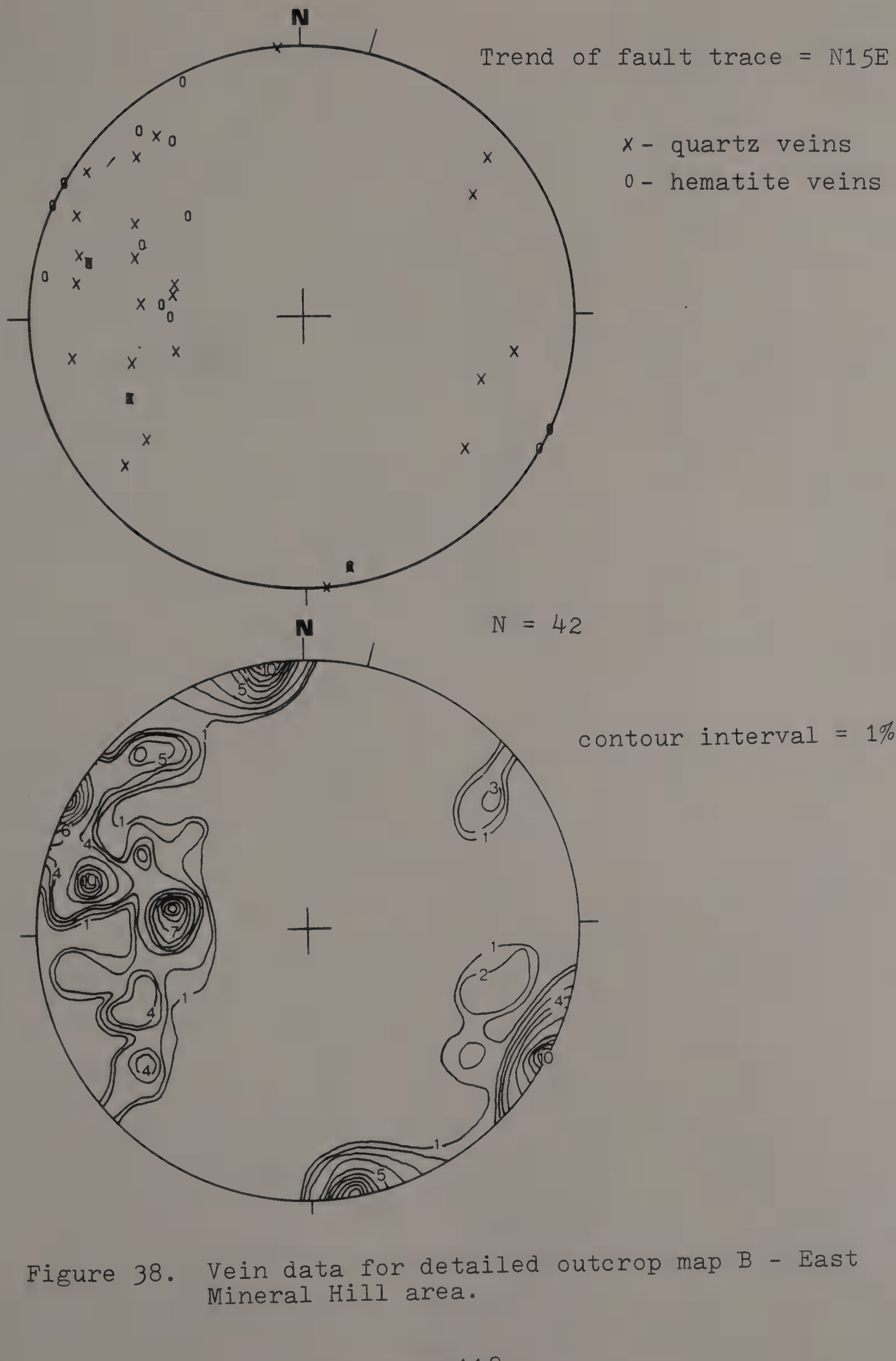


Figure 38. Vein data for detailed outcrop map B - East Mineral Hill area.

trend of the fault trace in this area is N15W and the trend of this outcrop is N45W. This appears to represent a large fracture filling in a splay off the main fault.

The main silicified zone is positioned parallel to, and in contact with the east side of the border fault. Joints appear as four very well developed groups. A northwest-striking, platy, west-dipping set forms large, west-dipping surfaces, forming slabs 5 centimeters to 1 meter thick. A second set is northwest-striking, platy and east-dipping, again forming slabs up to one meter thick. A northwest-striking set steeply dipping to the east and west, and an east-west striking set steeply dipping to the north and south are moderately well developed as smaller surfaces that break the larger slabs into rectangular brick-like blocks. The northern tip of this zone is cut by an apparent fracture that runs through a small gully with a N35W trend.

General Data

Joint data collected from the quartz-rich zone were plotted and contoured (Figure 39). A girdle of points is oriented with a rough trend of N60W - S60E. Vein data (Figure 40) shows some clustering of points. A mean strike of N67W was calculated which suggests an extensional stress of N23E - S23W. Both joint and vein data do not correspond to the orientation of the border fault, which is most likely

because of the obliqueness of the zone to the main fault.

Joint data collected from the main silicified zone (Figure 41) shows well the observed four joint groups. The data points are moderately clustered and show an orthoganal pattern. The west-dipping set is again significant with a mean orientation of N11W, 41SW that mimics the fault orientation of N15W, 35-40SW. A biased group of measurements (Figure 42) was taken and plotted to further express the close relationship between the orientations of the platy, west-dipping joints and the border fault. Vein data (Figure 43) shows some clustering and a mean strike of N44W. This strike does not agree with the N15W strike of the border fault.

Detailed Outcrop Maps

Figures 44 and 45 represent detailed outcrop maps C and D for the Mount Toby area. Data for map C, representing the quartz-rich zone, were plotted for joints (Figure 46), and for veins (Figure 47). The data in Figure 46 shows four loose clusters of points. None of these clusters agrees with the orientation of the fault. Quartz vein data for map C (Figure 47) has a rough N45W trend which again does not correlate to the trend of the fault. Quartz veins in this outcrop were difficult to measure due to lack of three-dimensional exposure and the similarity of color between the

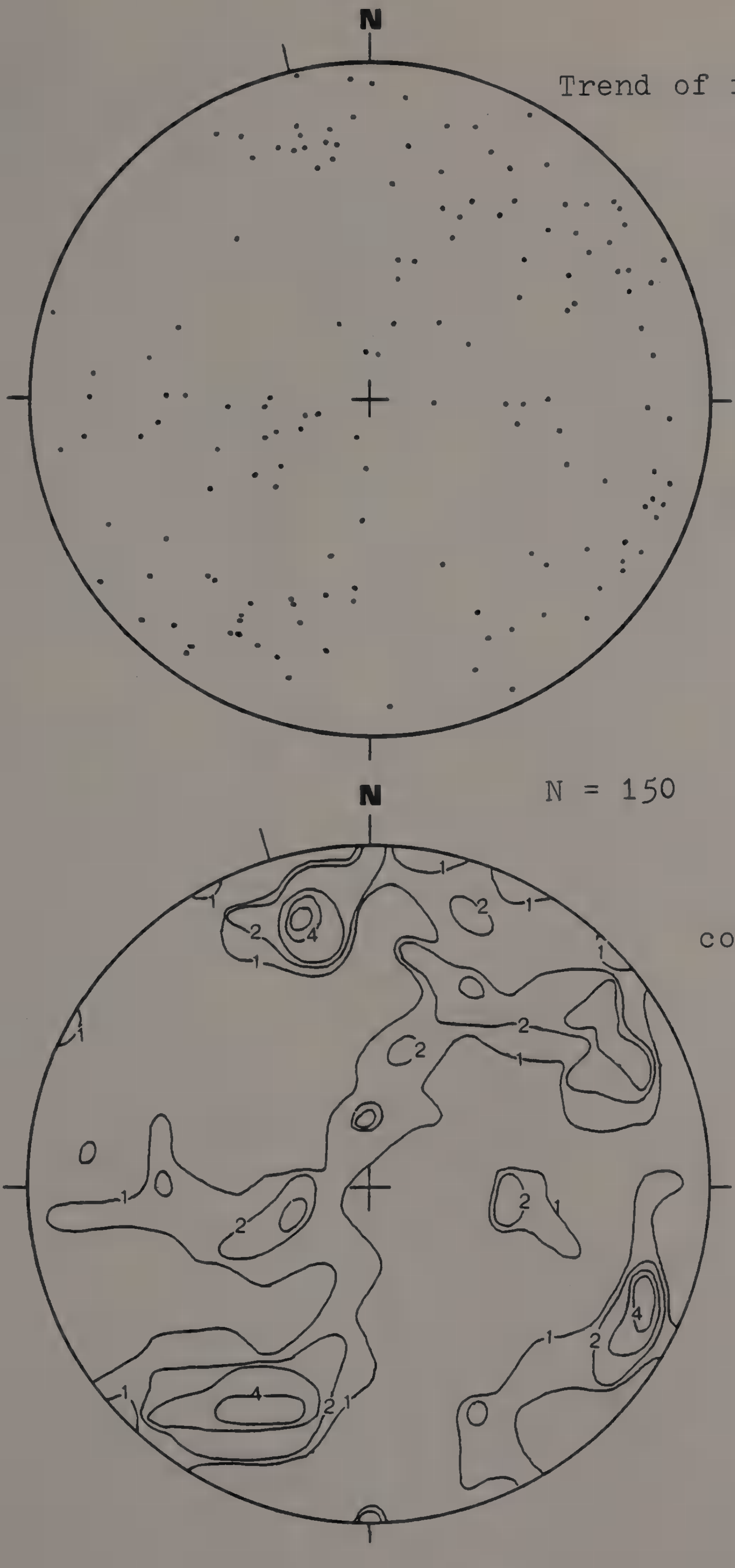


Figure 39. General joint data - quartz-rich zone, Mount Toby area.

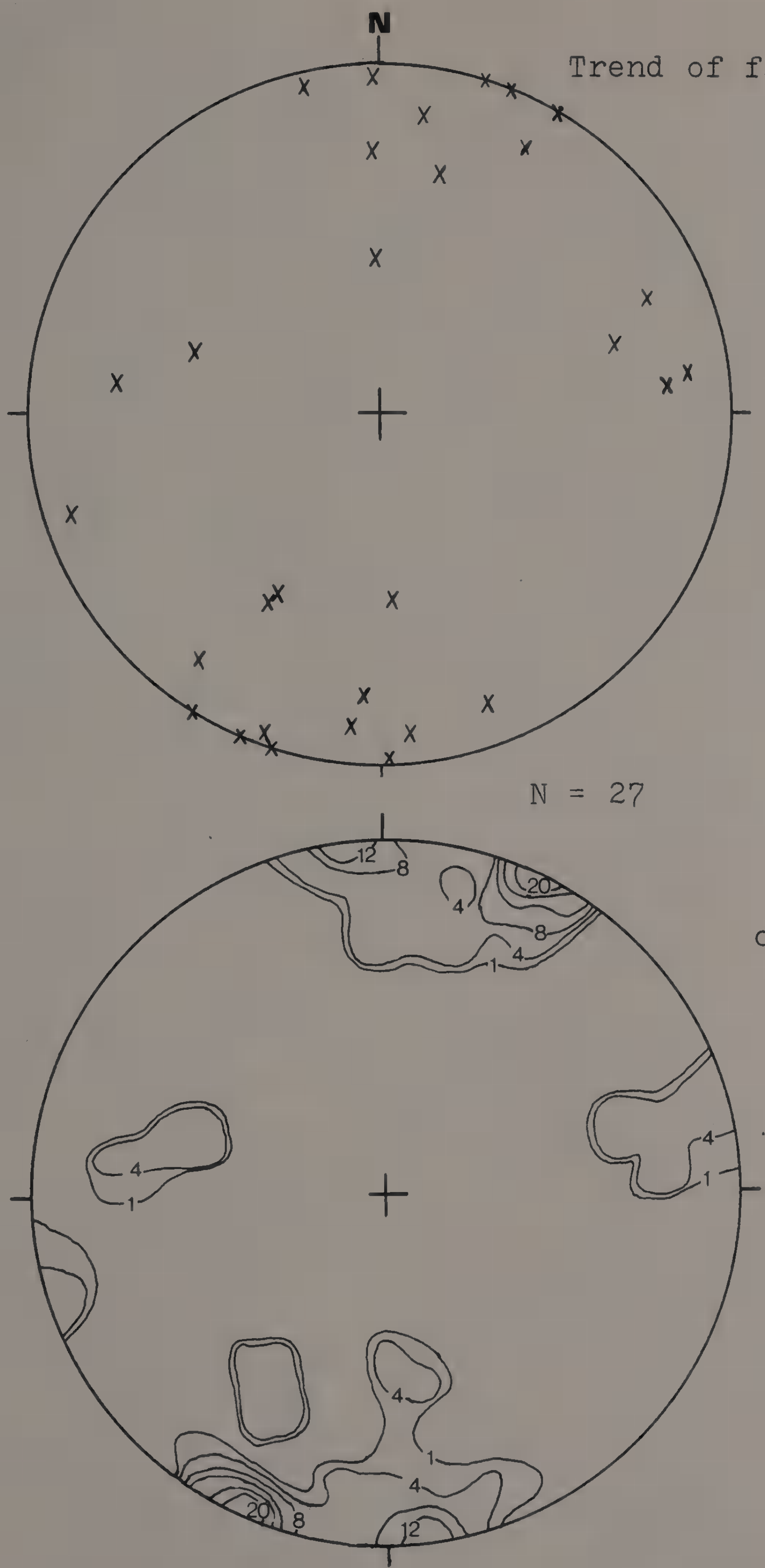
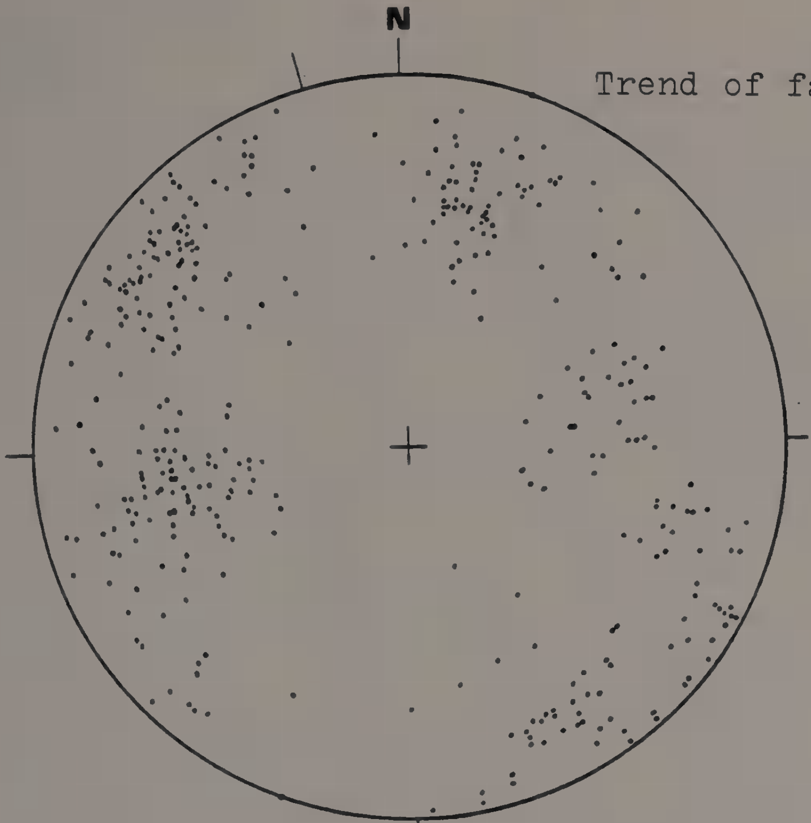
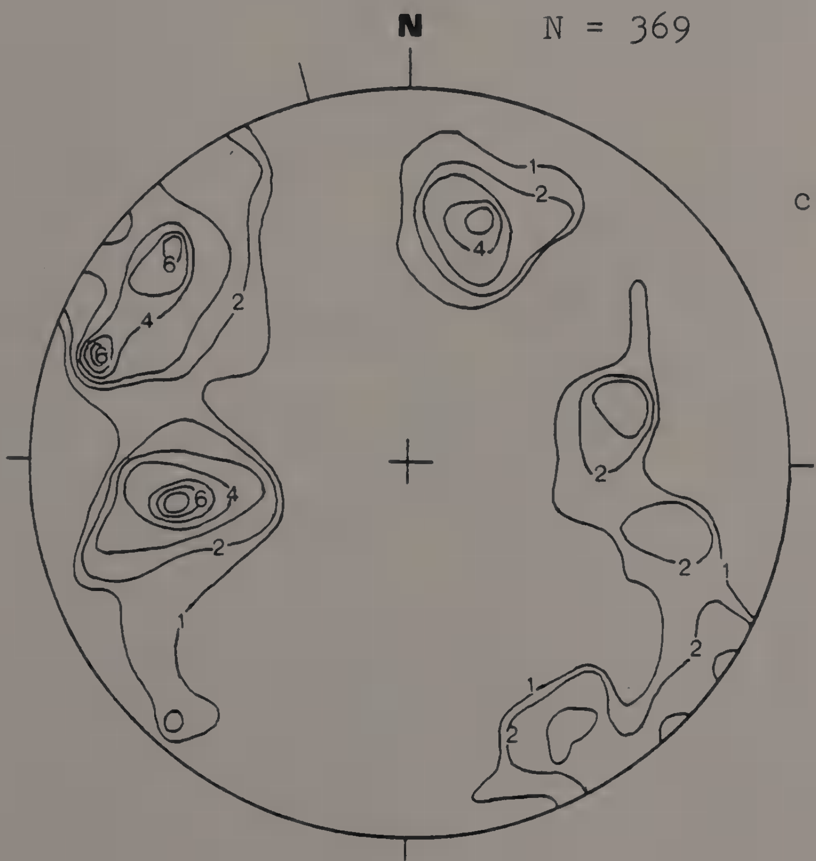


Figure 40. General vein data - quartz-rich zone, Mount Toby area.



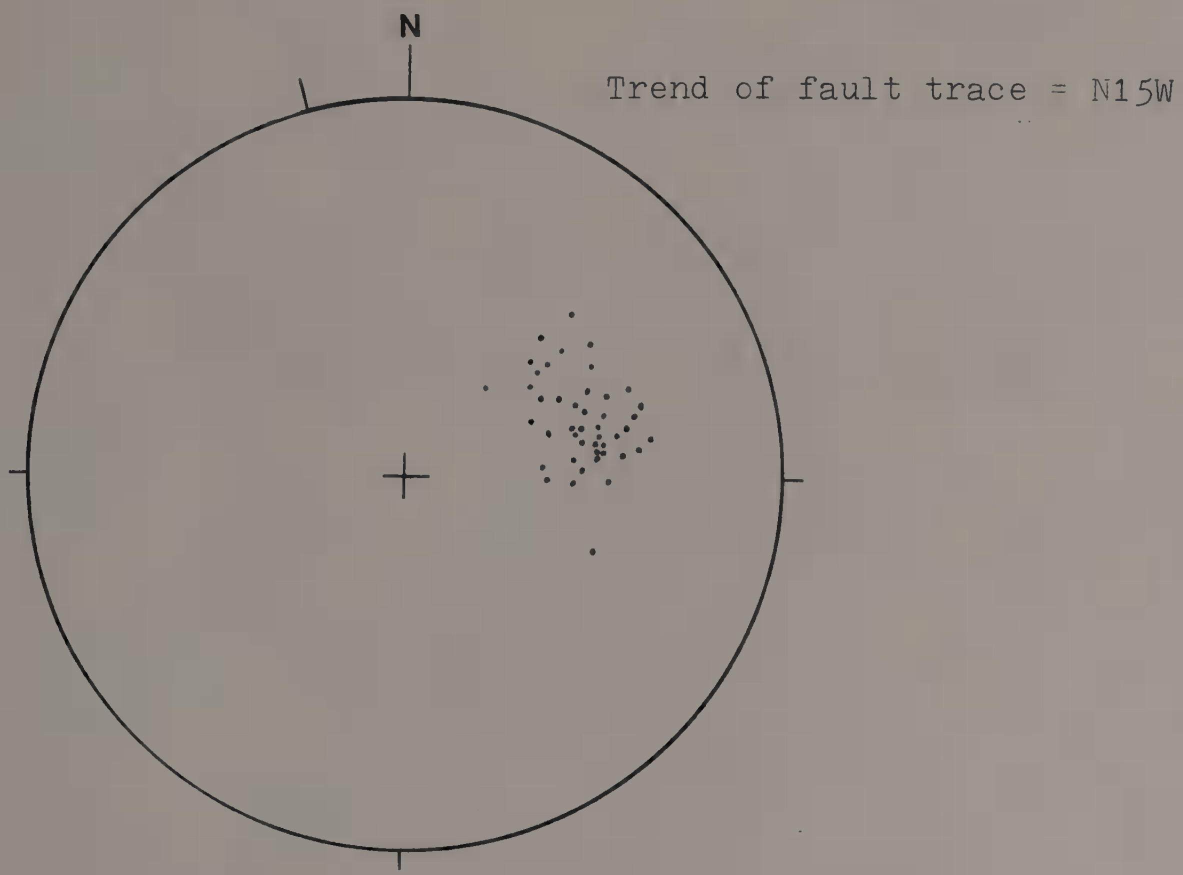
Trend of fault trace = N15W

N = 369



contour interval = 1%

Figure 41. General joint data - main silicified zone, Mount Toby area.



West-dipping joints with the platy character were measured and plotted seperately to demonstrate their orientation with relationship to that of the Connecticut Valley border fault.

Figure 42. West-dipping, platy joints - main silicified zone, Mount Toby area.

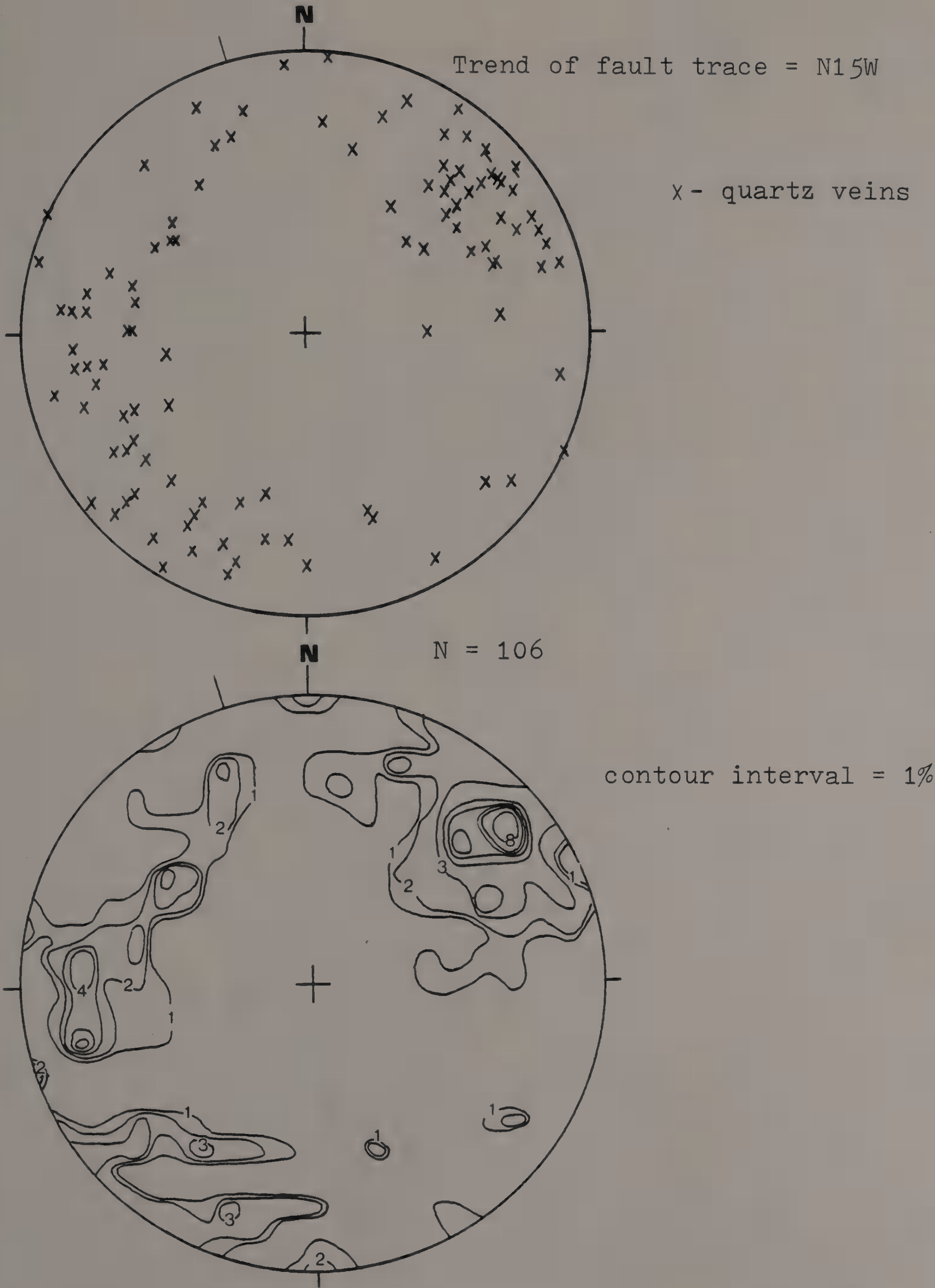


Figure 43. General vein data - main silicified zone, Mount Toby area.

veins and the host rock. Again, the disagreement between the map C data and the border fault is due to the obliqueness of the zone to the main fault.

Joint data for map D (Figure 48) show much better clustering with three main concentrations of points. A small group of joints are northwest-striking, platy and west-dipping, and a larger group are northwest-striking, platy and east-dipping. The west-dipping joints have a mean orientation of N13W, 45SW that mimics the N15W, 35-40SW orientation of the border fault. A large concentration of points is northeast-striking, and steeply dipping to the northwest and southeast. Quartz veins from map D (Figure 49) are very well clustered and have a mean strike of N15W which, unlike the vein data from the general survey, agrees well the the N15W trend of the border fault. The veins suggest a N75E - S75W extensional stress at their time of formation. This is the same as that suggested for the border fault in this area.

Thin Section Observations

Several structural details about quartz veins, foliation, and microbreccia veins were observed in thin section. Two styles of quartz veins are abundant. Large veins range in width from 1.5 to 3.0 mm and are found in all samples across the zone. Smaller random veins are 0.25 mm

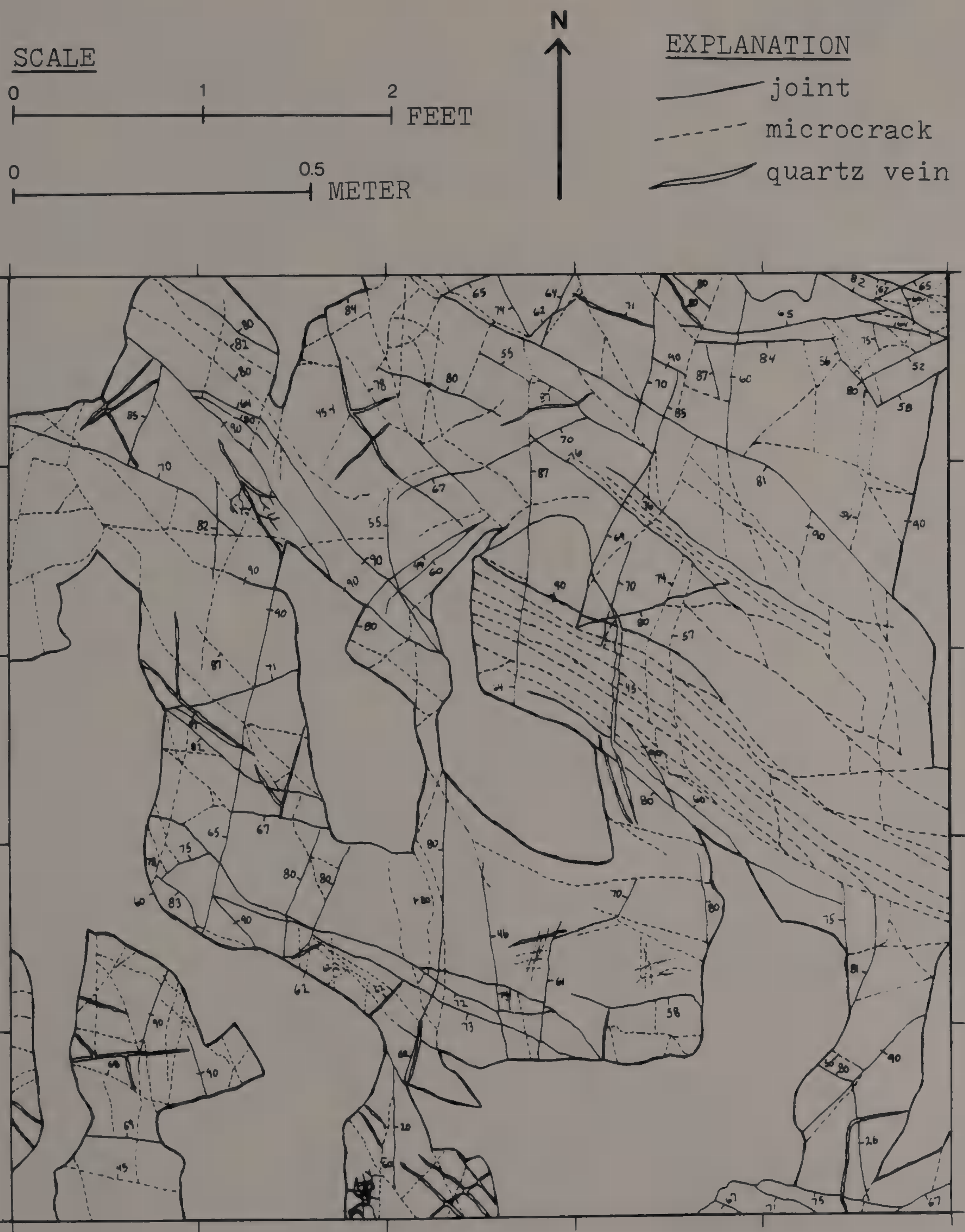


Figure 44. Detailed outcrop map C, Mount Toby area - quartz-rich zone.

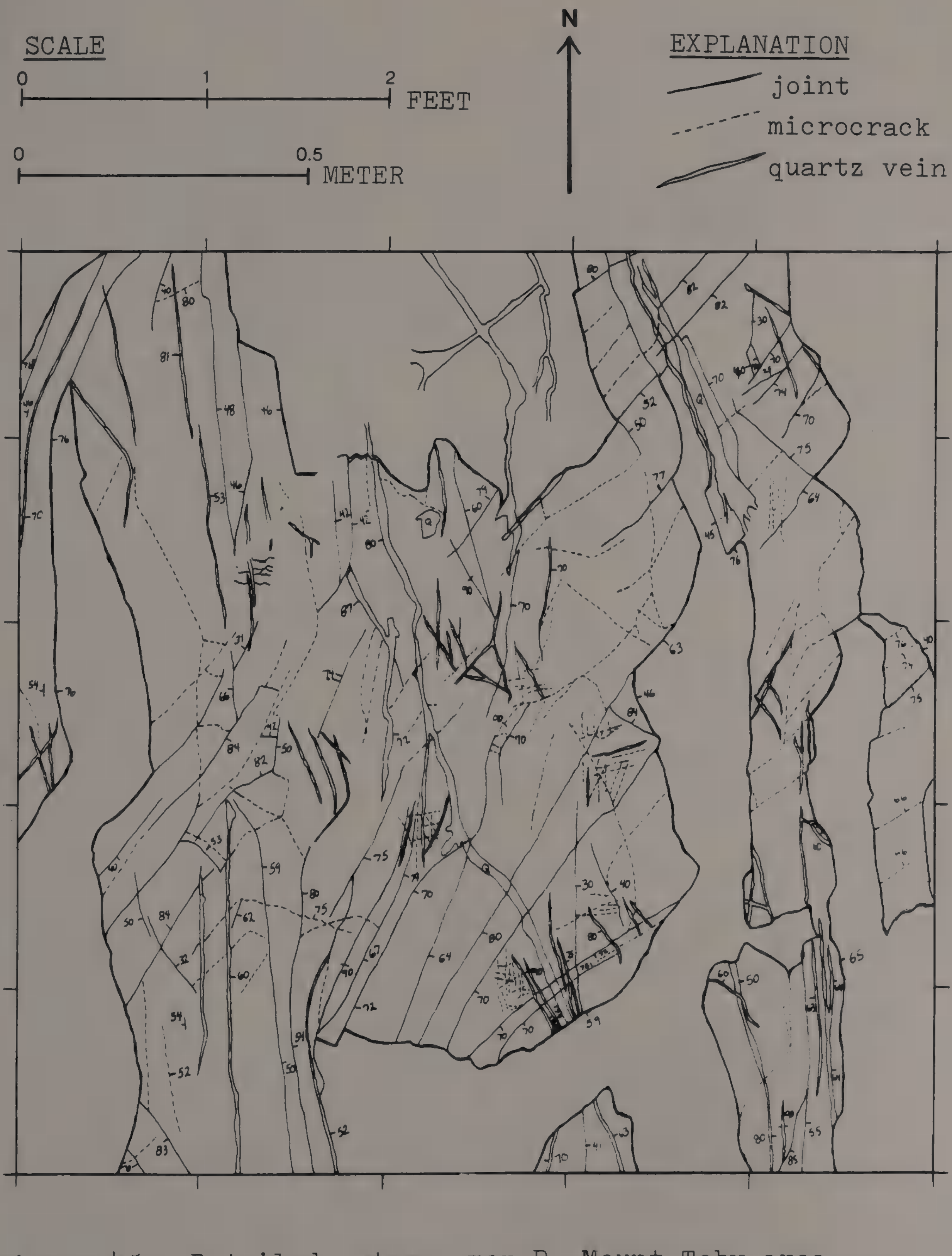


Figure 45. Detailed outcrop map D, Mount Toby area - main silicified zone.

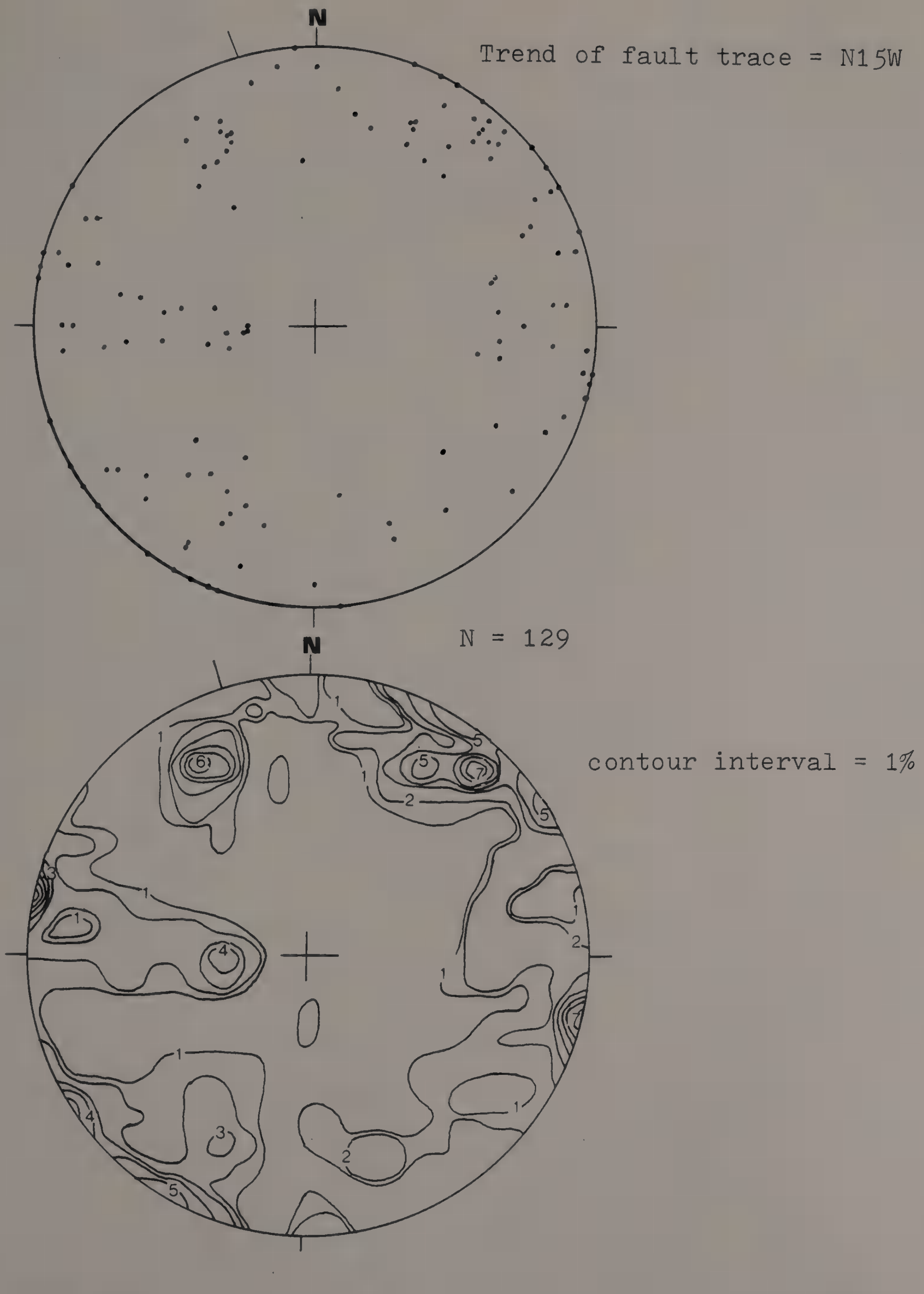


Figure 46. Joint data for detailed outcrop map C - quartz-rich zone, Mount Toby area.

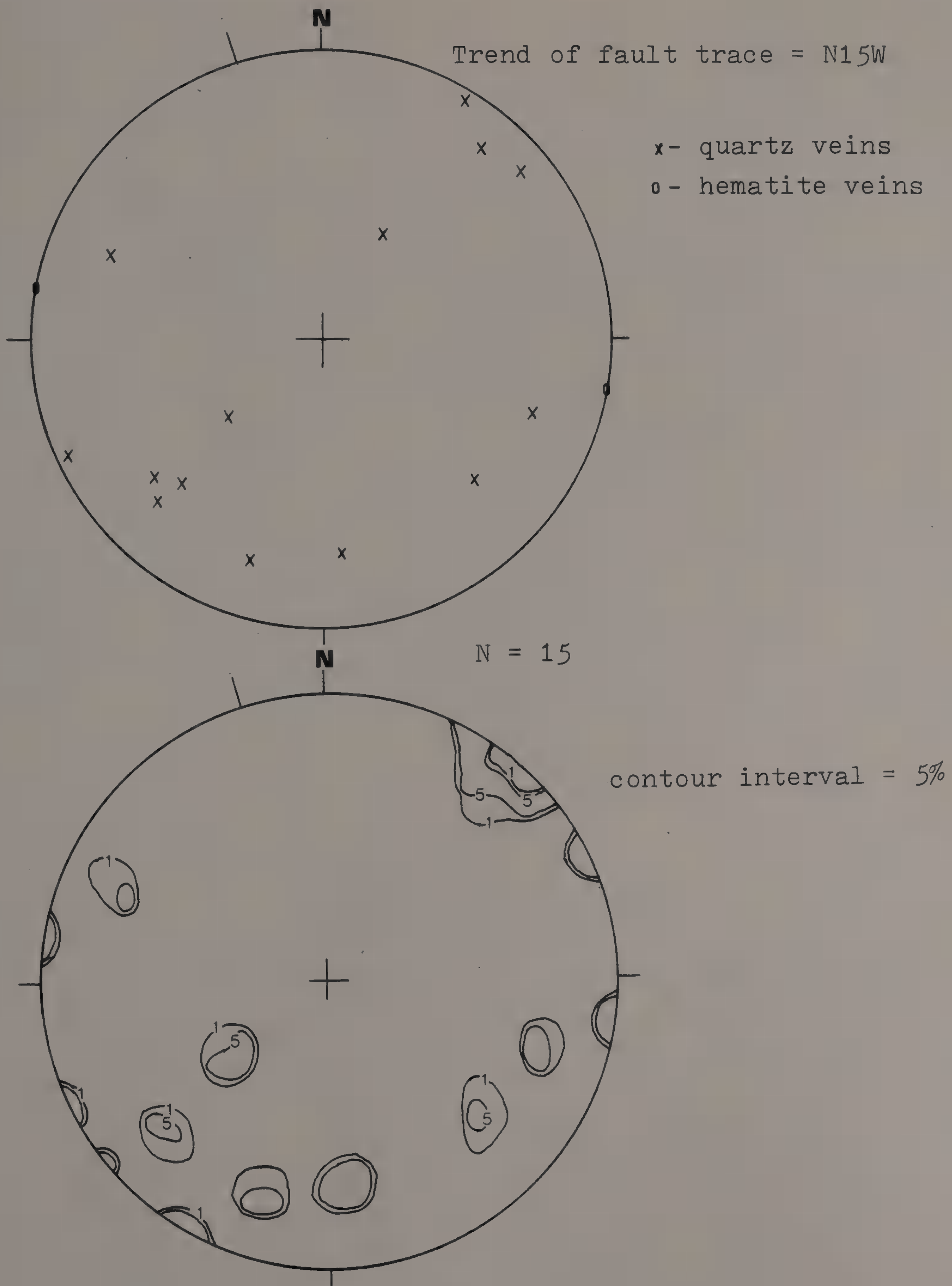


Figure 47. Vein data for detailed outcrop map C - quartz-rich zone, Mount Toby area.

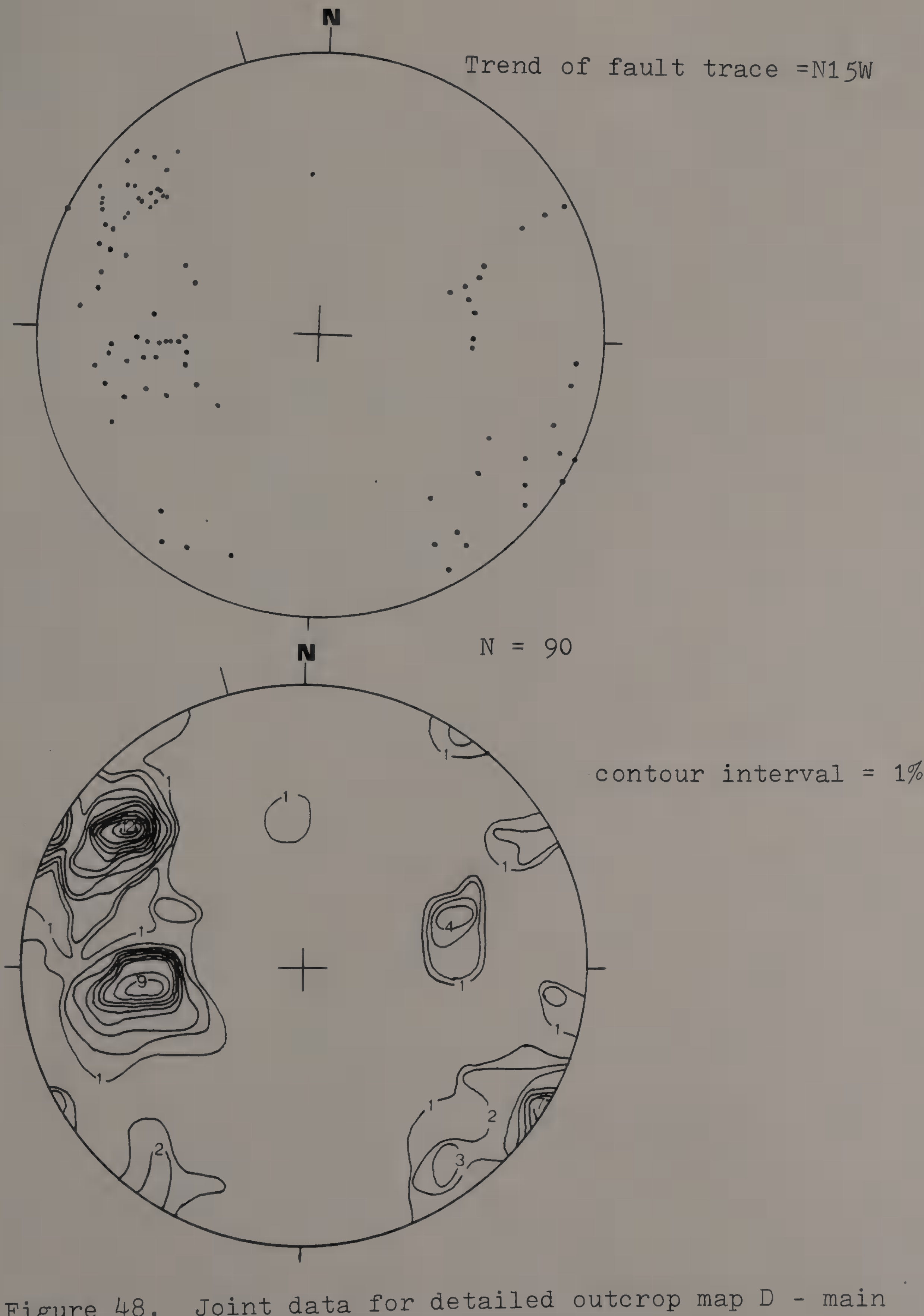


Figure 48. Joint data for detailed outcrop map D - main silicified zone, Mount Toby area.

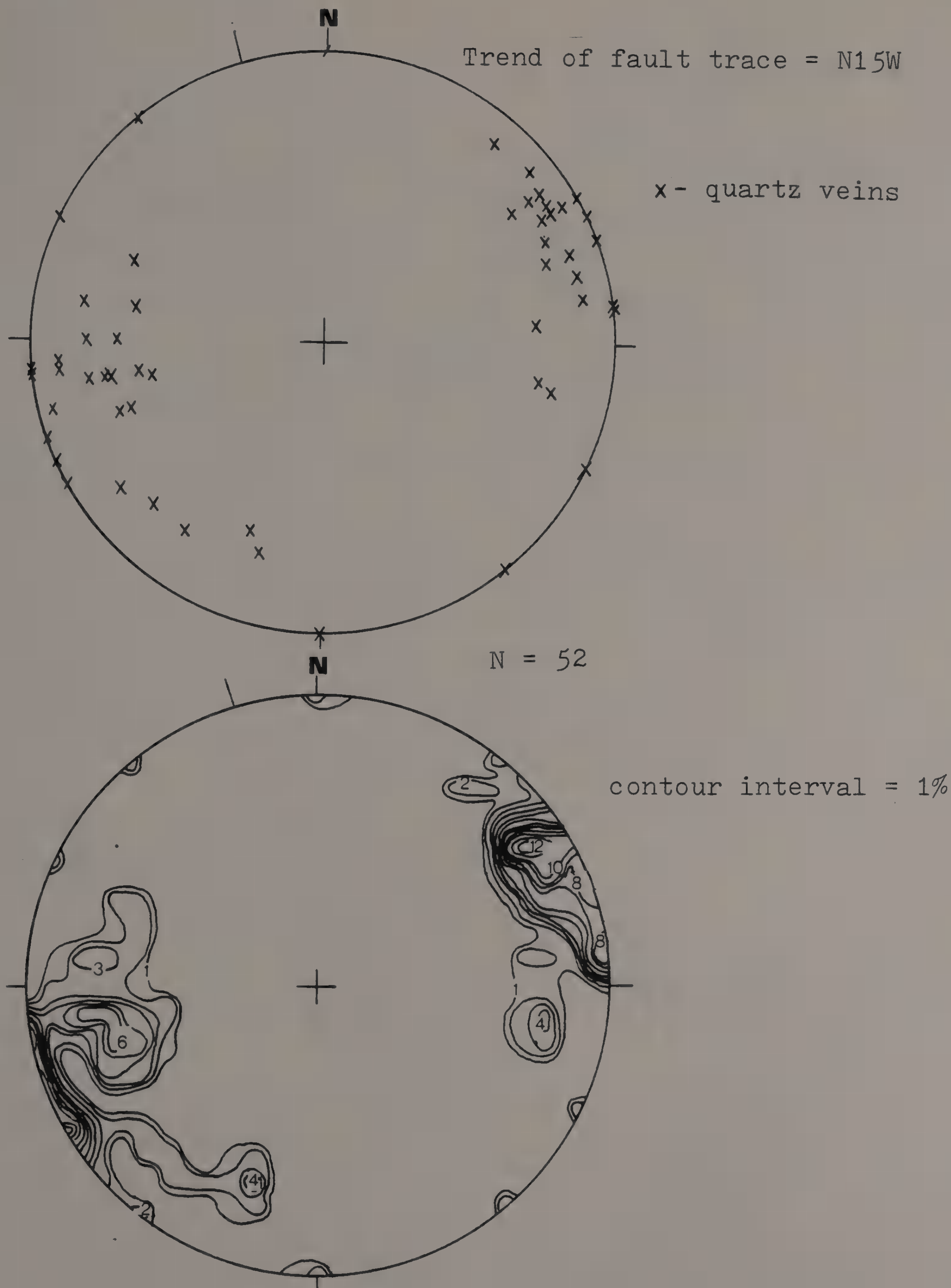


Figure 49. Vein data for detailed outcrop map D - main silicified zone, Mount Toby area.

wide or smaller, and are a local feature, not being found in every sample. A faint foliation is detectable in MT1B, MT1C, and MT1G. None of these possible foliations were detectable in the hand samples. They represent a metamorphic foliation that was mostly obliterated during silicification.

A third feature found only in MT1D is thin veins consisting of a microbreccia (Figure 50). These are very fine-grained, light colored veins that cut across coarser-grained areas of brecciated, angular quartz and feldspar fragments. The microbreccia acted as a fluid and was injected into cracks and between decaying grain boundaries.

Leverett Pond Area

The rock of the Leverett Pond Area resembles in character that from the Mount Toby area main silicified zone. Data were collected by a general survey only. Joints are moderately well developed and appear in outcrop to form four groups. A northwest-striking, platy, west-dipping set forms medium to large, west-dipping surfaces that are not so large as in the East Mineral Hill or Mount Toby areas. A northwest-striking, moderately east-dipping set forms medium to large, east-dipping surfaces. These surfaces are cut by less dominant, steeply east- and west-dipping, and north-

and south-dipping joints. The rock breaks into the same blocky features, not so well formed, as in the Mount Toby area. Joint data (Figure 51) show three major concentrations. Northwest-striking, platy, west- and moderately east- dipping joints are represented as large concentrations. An east-west set that dips to the south is also shown as a large concentration. The platy, west-dipping joint set, with a mean orientation of N11W, 52SW, is close to the N15W, 35-40SW orientation of the border fault in this area.

Vein data (Figure 52) are fairly scattered but have a rough mean strike of N42W which does not agree with the N15W trend of the border fault. Two fault planes were measured (Figure 53). One located on the west side of the zone is oriented N85E, 75E. The other is located on the east side of the zone and has an orientation of N26E, 80E, with associated slickensides of S75E, 79 degrees. This second fault has a dip-slip motion to the east. These faults are the youngest feature in the silicified zones and are apparently related to movements post-dating the main Mesozoic faulting event.

Poverty Mountain Area

Structural data for this area were obtained using a general survey as well as the construction of two

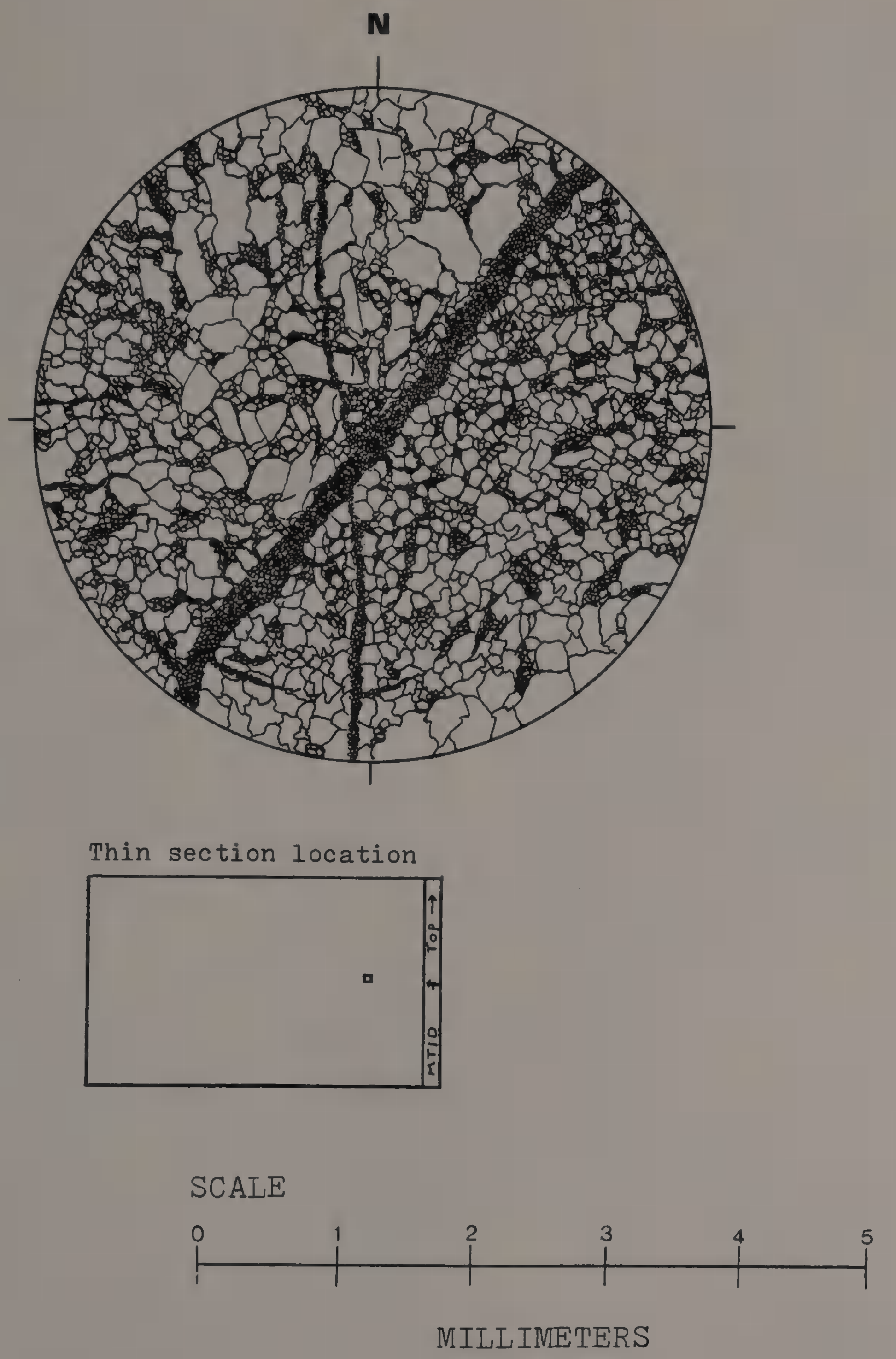
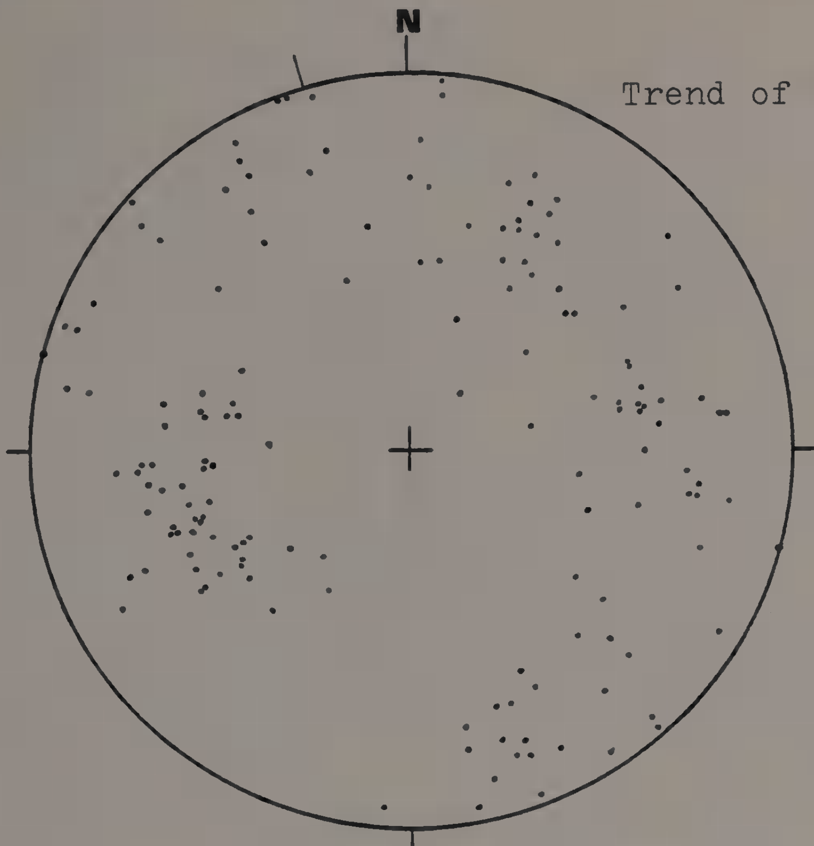
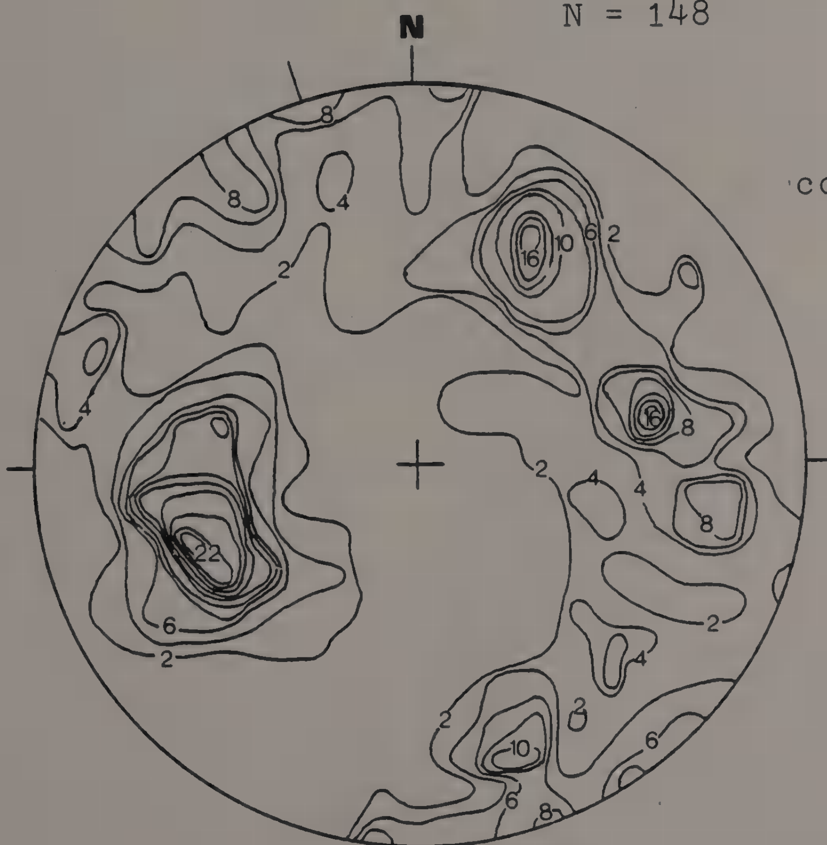


Figure 50. Sketch from section MT1D showing cataclastic microbreccia veins injected into silicified rock.



Trend of fault trace = N15W

N = 148



contour interval = 2%

Figure 51. General joint data - Leverett Pond area.

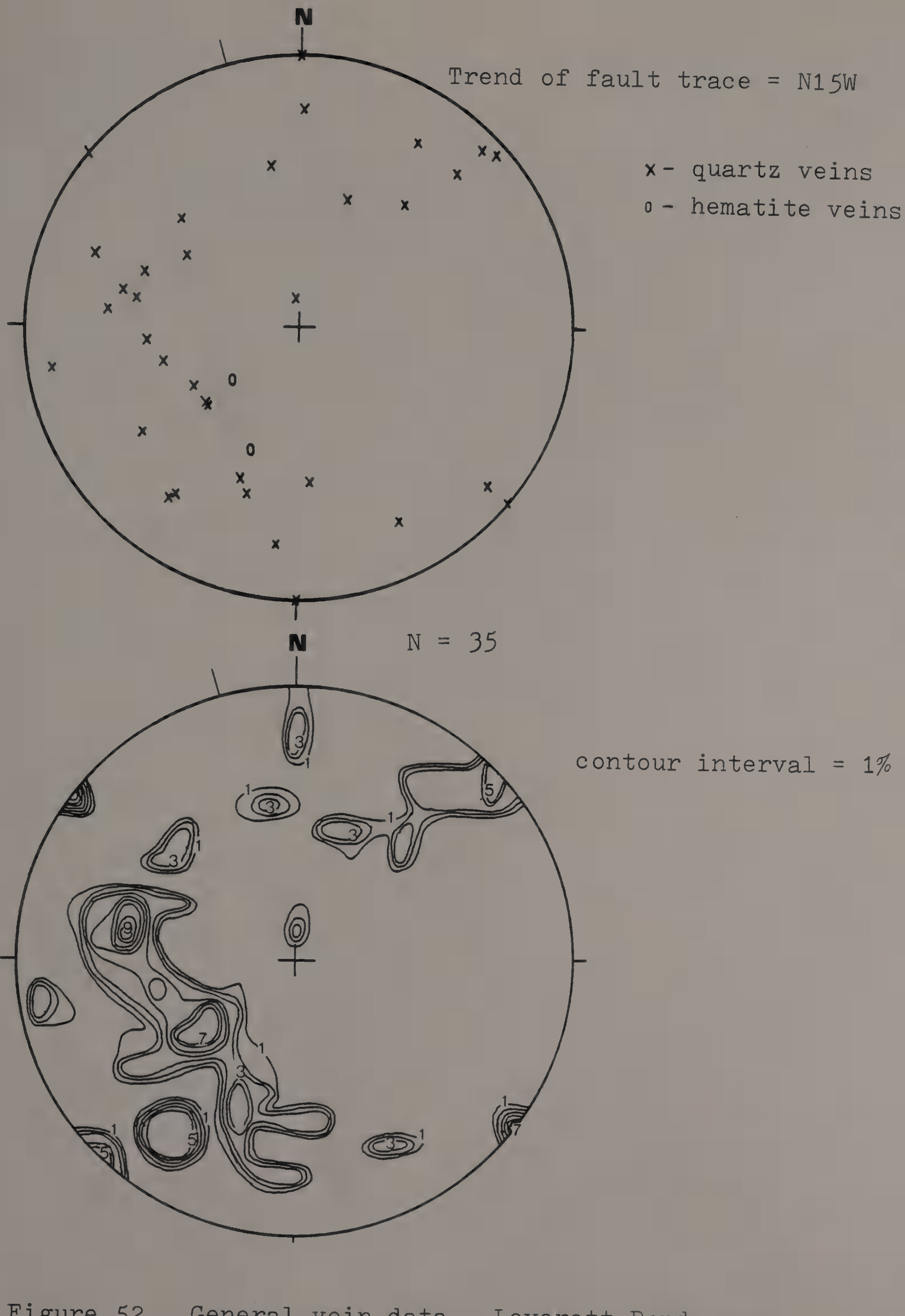
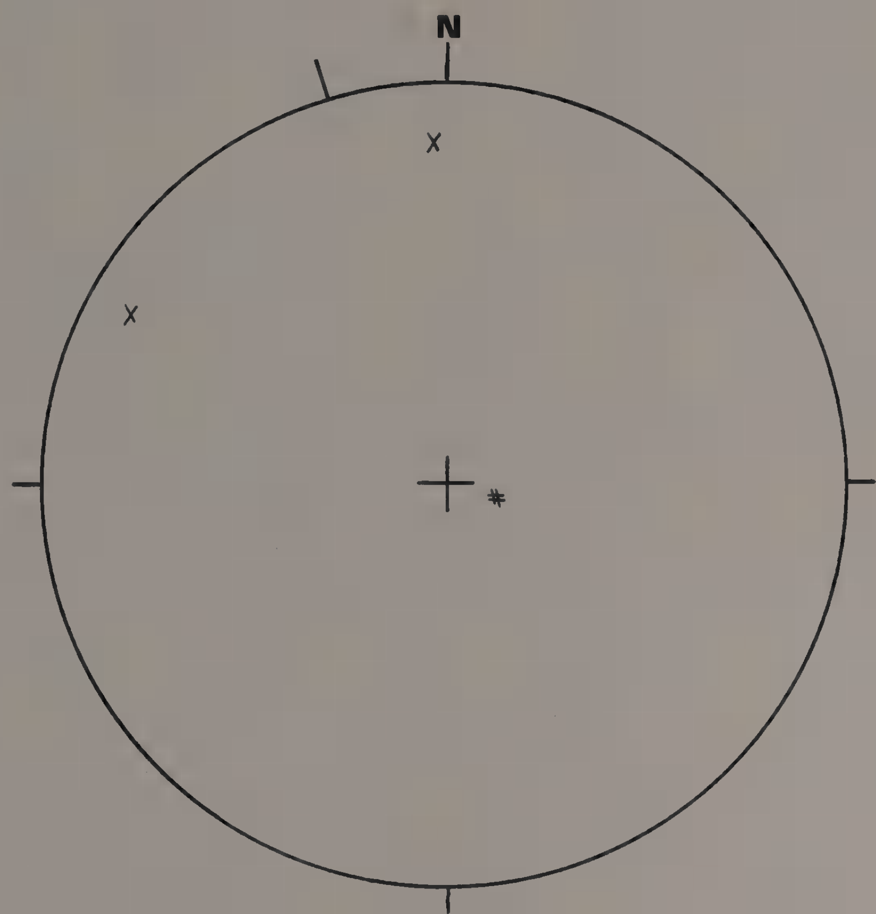


Figure 52. General vein data - Leverett Pond area.



Fault Data

x - fault planes
⋕ - slickensides

Figure 53. Fault data - Leverett Pond area.

five-foot by five-foot outcrop maps. The first of these maps was made on an outcrop located in the west-central portion of the map area. The second map is from an outcrop in the southern portion of the map area (Figure 28). Some structural data were also obtained by thin section observations.

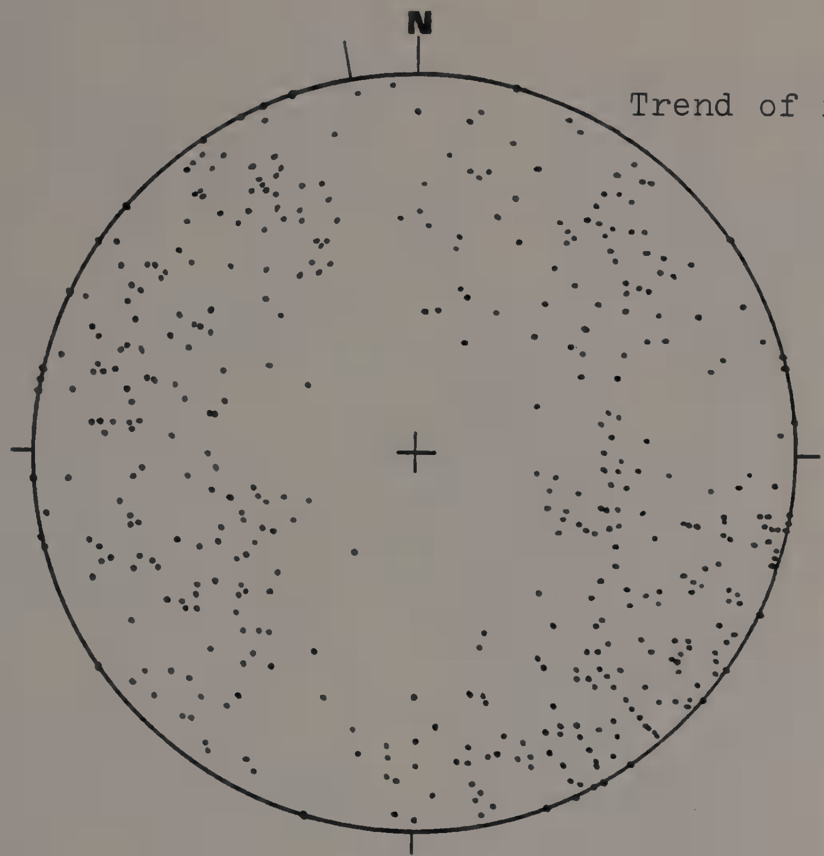
The Poverty Mountain silicified zone has a moderately to locally well developed joint system. In the areas where the joint system is well developed four types appear obvious in the outcrop. North-south striking, platy, west-dipping joints result in large, west-dipping outcrop faces. A north-south striking, moderately east-dipping set forms much smaller surfaces, as does an east-west striking set that dips steeply to the north and south. A north-south striking set that dips steeply to the east and west is present on a local scale. Quartz and hematite veins are abundant but are more common and generally thicker in the eastern side of the zone, away from the border fault. Several small faults are found, mostly concentrated in the north-eastern quarter of the map area.

<u>General Data</u>

Joint data were plotted and contoured (Figure 54) but show no strong concentrations of any of the types mentioned, although a north to northeast general strike is noticable.

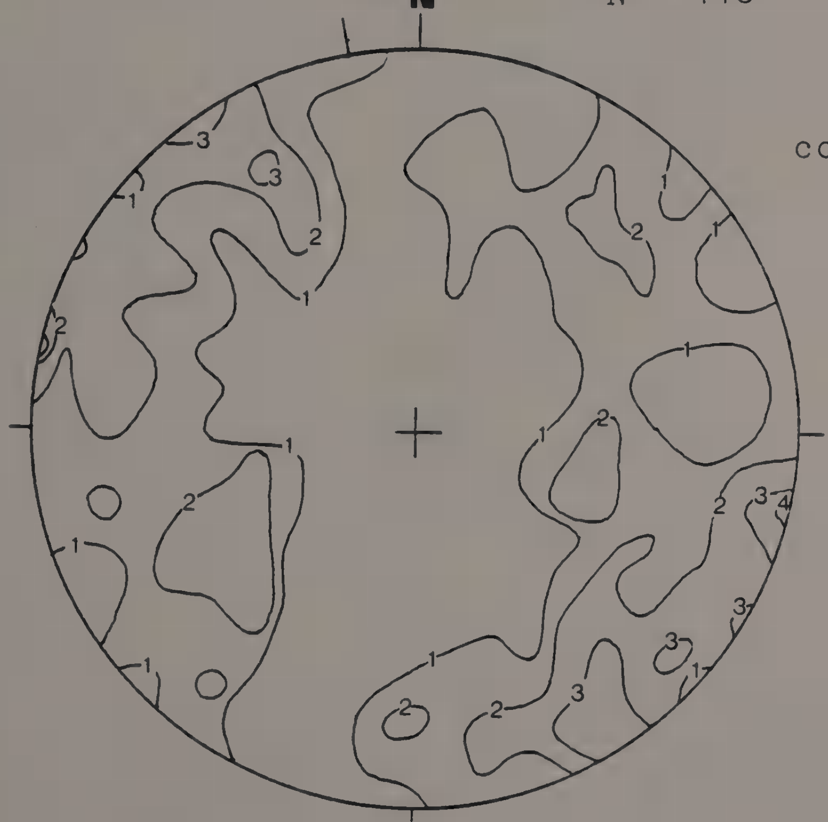
The strongest concentration of points is steeply dipping to the northwest and southeast. Measurements of joints that have the platy, west-dipping character were made to compare with the orientation of the border fault for this area. A mean orientation of N11E, 40NW was obtained which does not agree well with the N20W trend of the fault, but a dip of 40 degrees agrees well with the 44SW dip estimated for the fault in this area (Jasaitis 1983). A local warping of the regional structural fabric or a secondary fault may exist in this area to account for the differences in strike between joints and the fault. Some joints are mineralized by quartz or epidote. Quartz veins were measured and plotted (Figure 55) and have a mean strike of N34E which does not agree with the N10W trend of the border fault in this area. The same factors which influenced development of the joints had the same influence over vein development.

Fourteen minor fault planes were measured in the silicified zone, and another three were from partially silicified rock in the Poverty Mountain area. Most of these were concentrated in the northeast corner of the map area (Figure 56). Of the three faults measured in the partially silicified rock, two surfaces strike northeast and dip moderately southeast and the other is oriented N20W, 45E with slickensides oriented N18W, 09 showing strike-slip



Trend of fault trace = N10W

N = 448



contour interval = 1%

Figure 54. General joint data - Poverty Mountain area.

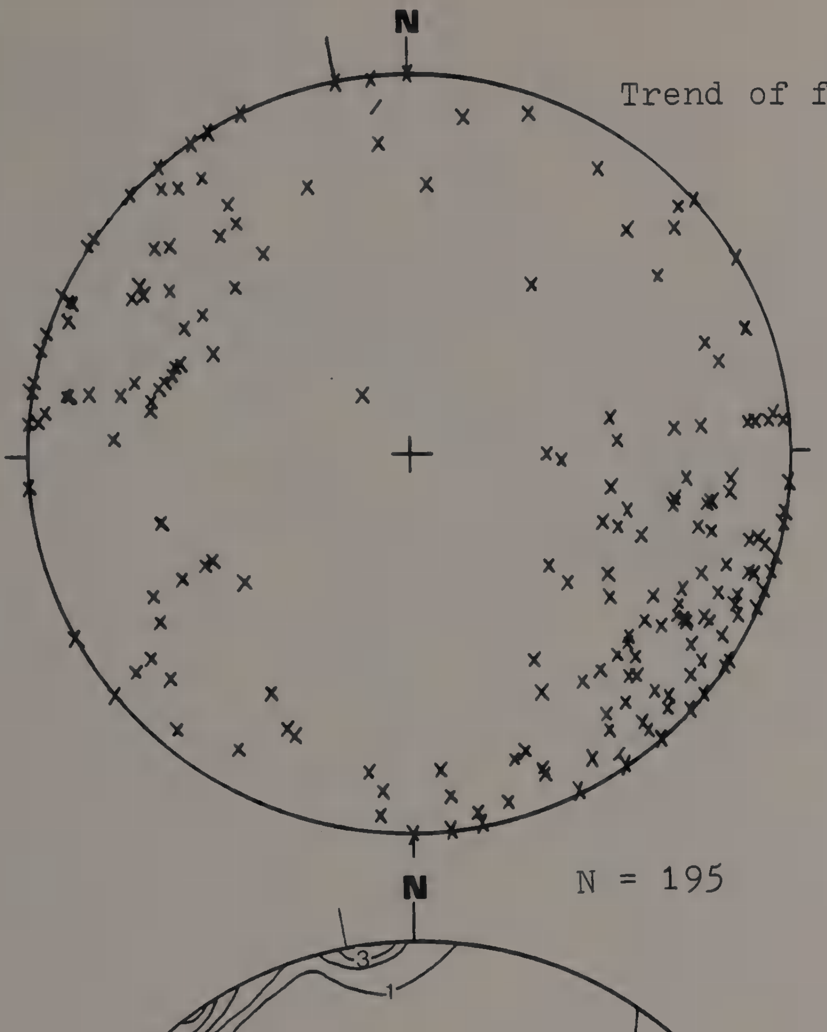


Figure 55. General vein data - Poverty Mountain area.

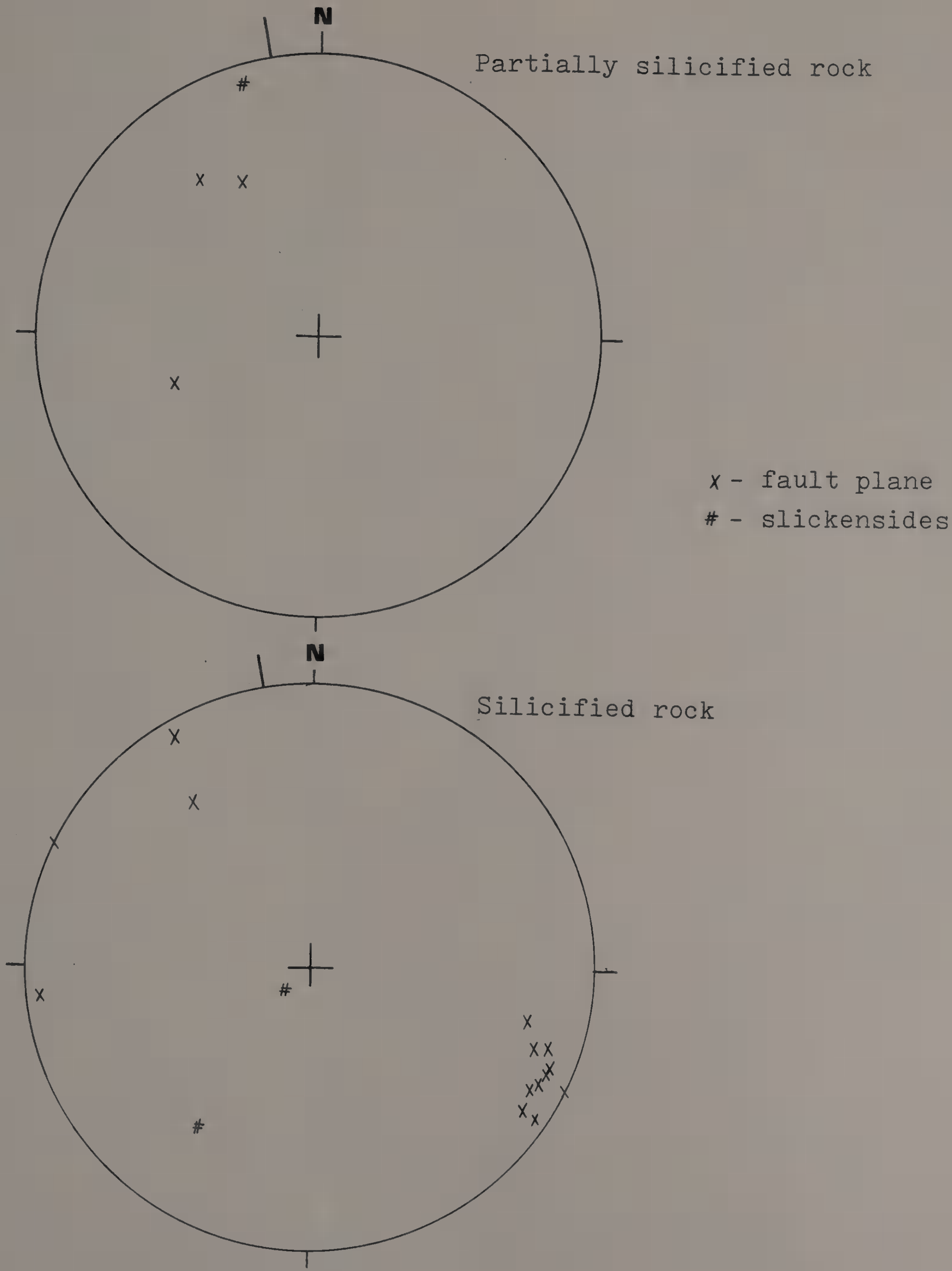


Figure 56. Fault data - Poverty Mountain area.

motion.

The fourteen fault surfaces measured in the silicified zone all strike north to northeast and dip steeply to the northwest and southeast. Two of these surfaces have associated slickensides, one of which shows a strike-slip movement sense, while the other shows a dip-slip movement sense. The average orientation for the fault surfaces is N29E, 83W. Minor faults do not agree with the border fault orientation and are younger than the silicification events.

<u>Detailed Outcrop Maps</u>

Figure 57 and 58 represent detailed outcrop maps E and F for the Poverty Mountain area. Data from both maps, when plotted on equal area diagrams, give similar results. Figure 59 represents data from map E, and Figure 60 represents data from map F. Three concentrations of points appear in both cases. Northeast-striking, platy, west-dipping joints are represented by very small clusters. This is because both maps were constructed on the large west-dipping surfaces to which the platy joints are parallel and therefore not easy to measure. A north-striking set that dips moderately to the east is represented by larger concentrations. A large concentration of points is east-west striking and dips steeply to the north and south. Mean orientations for the platy, west-dipping joints in Figure 59

is N09W, 42SW, and in Figure 60 is N10E, 44NW, whereas the orientation for the border fault is N10W, 44SW. In both cases the dips agree but there is a significant difference between strikes for joints and that of the border fault.

Quartz vein data were plotted for map E (Figure 61) and for map F (Figure 62). Data points in Figure 61 are few, and very scattered due to lack of three-dimensional vein surfaces at the locality where map E was contructed. However, many trends were present that had orientations between N20-40E trend. The mean strike for veins in Figure 62 is N22E which again does not support the trend of the border fault in this area.

Thin Section Observations

Structure interpreted from thin sections gives information about quartz, epidote and hematite veins, and minor fractures. As in the previous silicified zones, hematite and larger quartz veins trend in a N-S direction. The small random veins are a local feature. Epidote veins are common and are younger than most quartz veins. Minor late brittle faults are abundant, have steep dips, and a west-side-down motion direction. Minor faults are the youngest feature in this zone, cutting veins in the silicified rock.

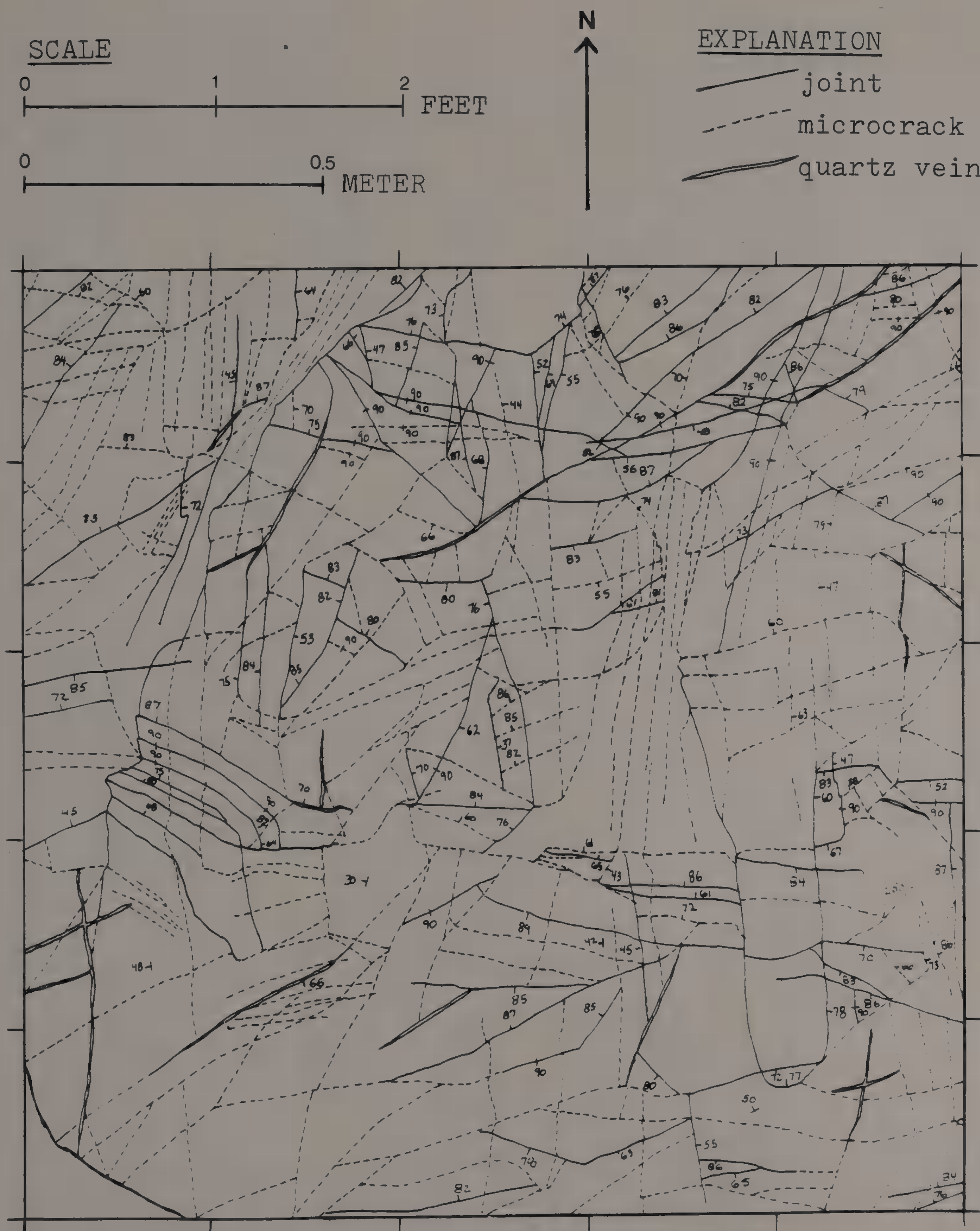


Figure 57. Detailed outcrop map E, Poverty Mountain area - west-central.

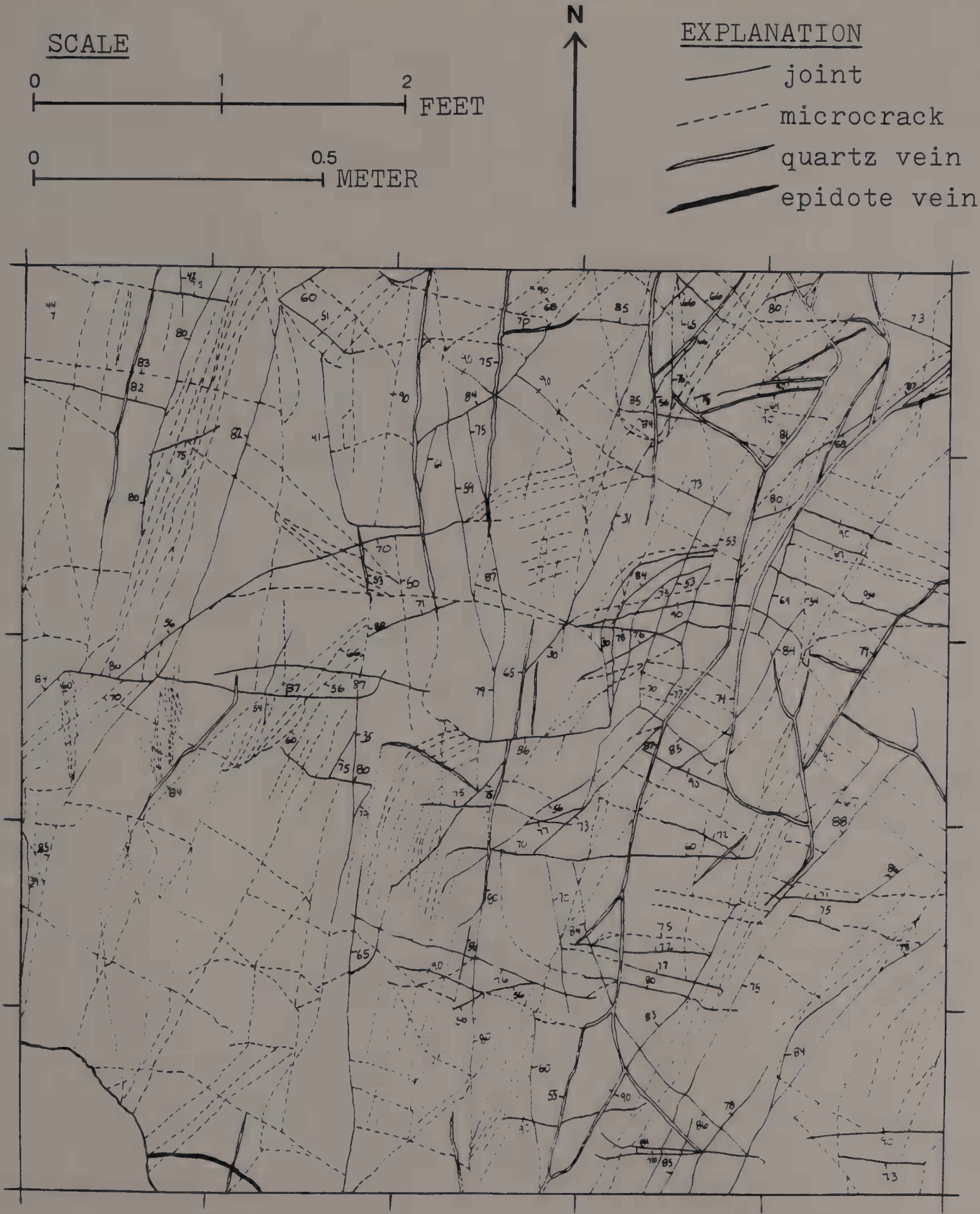


Figure 58. Detailed outcrop map F, Poverty Mountain area - south.

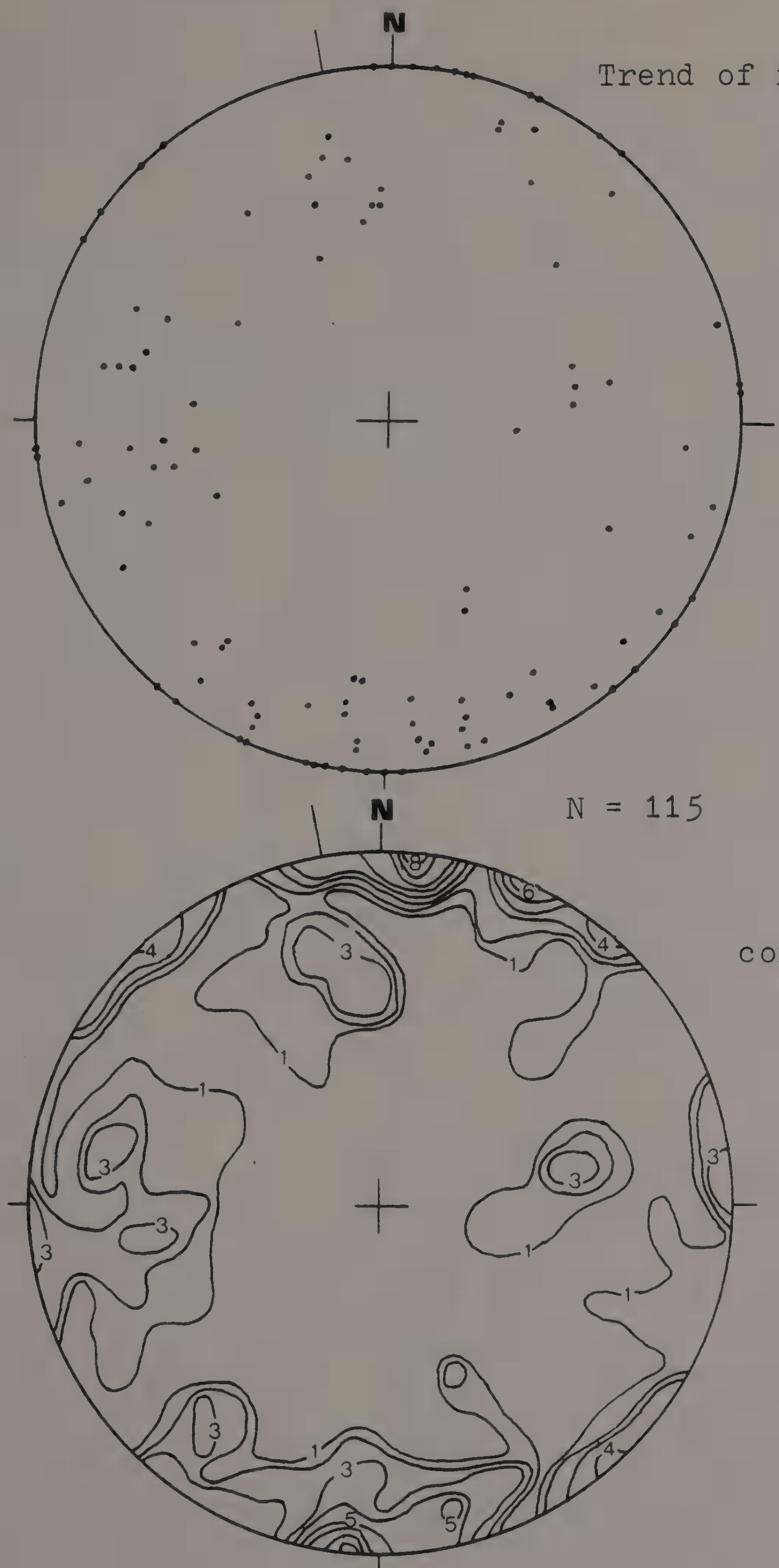


Figure 59. Joint data for detailed outcrop map E - Poverty Mountain area.

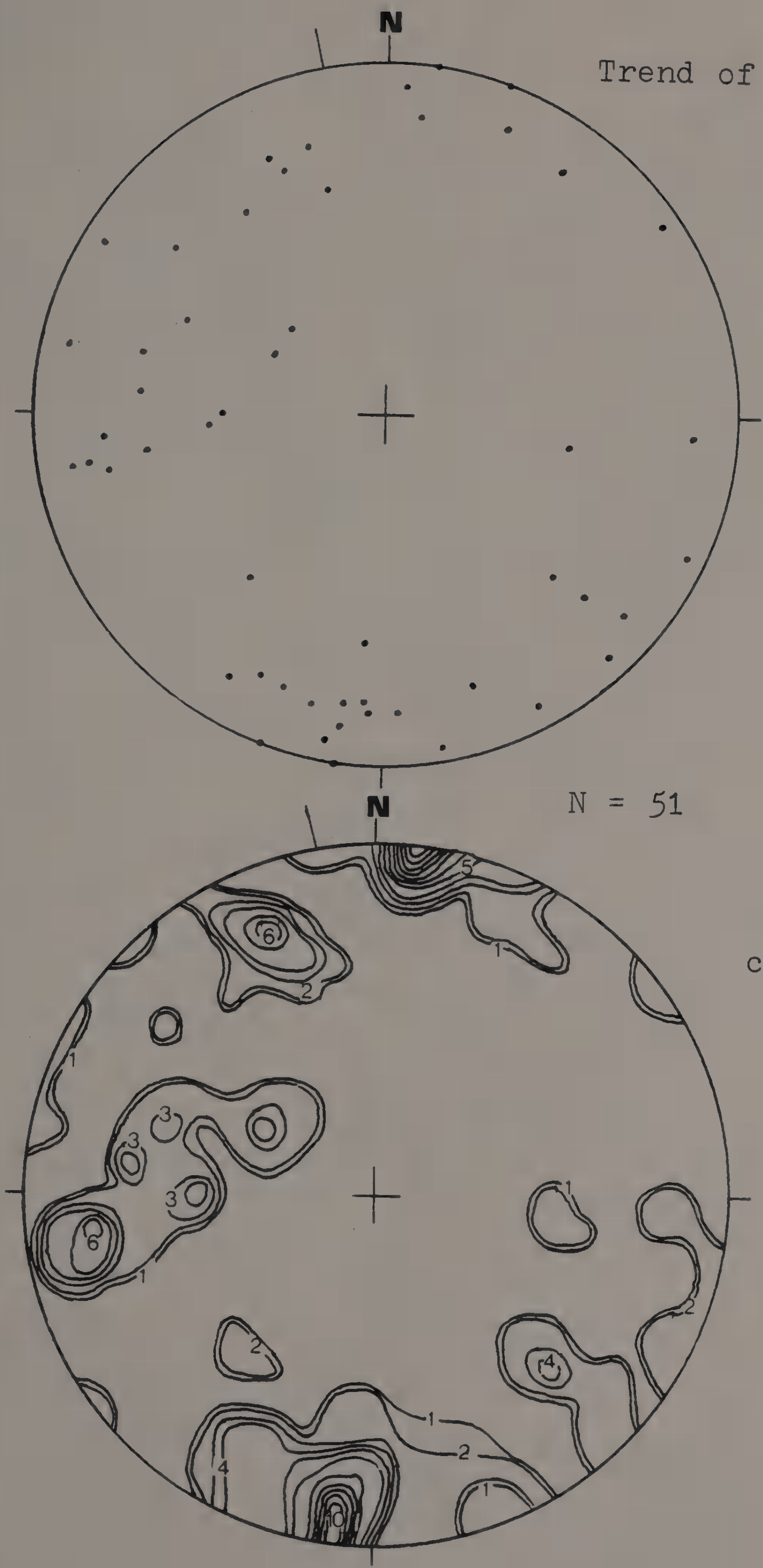


Figure 60. Joint data for detailed outcrop map F - Poverty Mountain area.

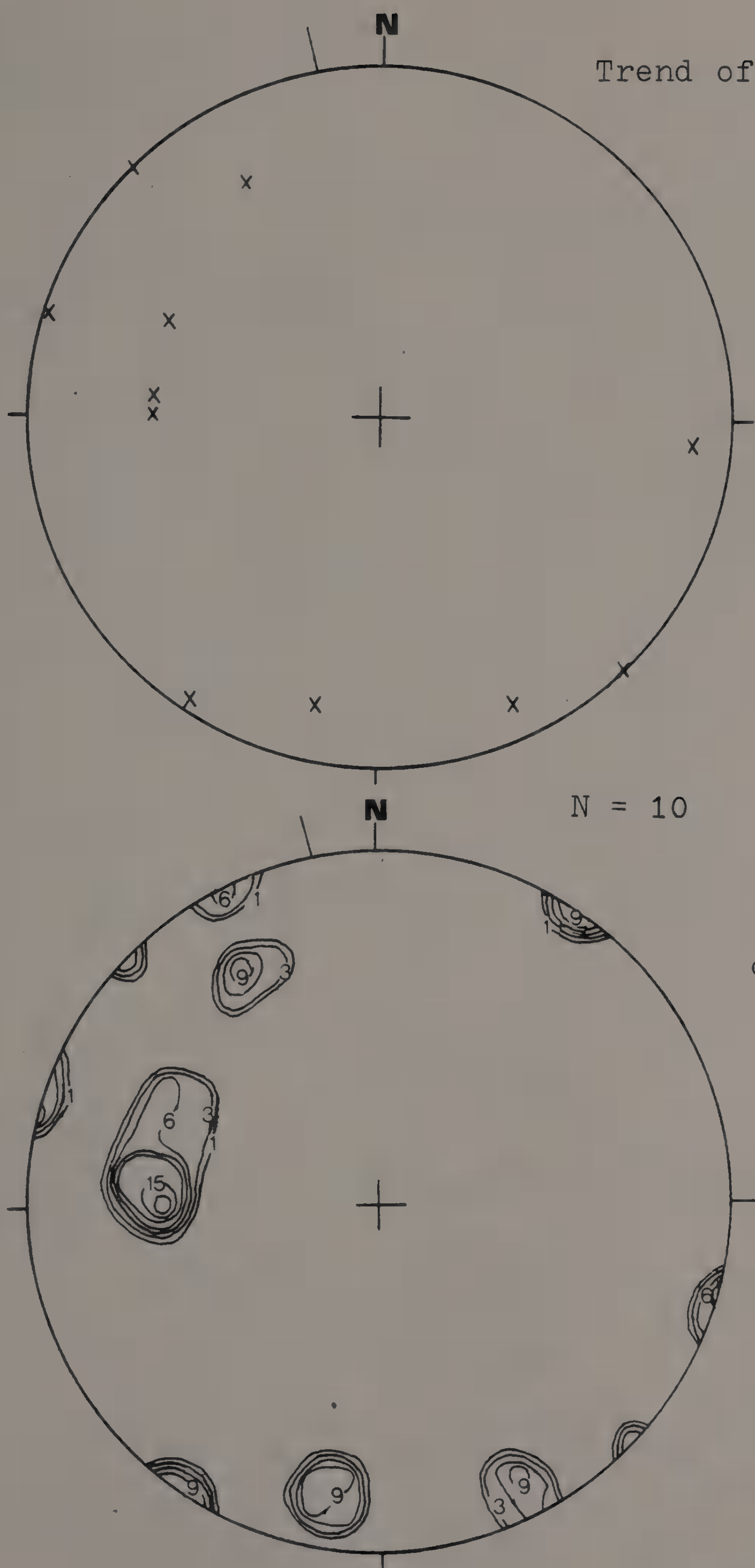
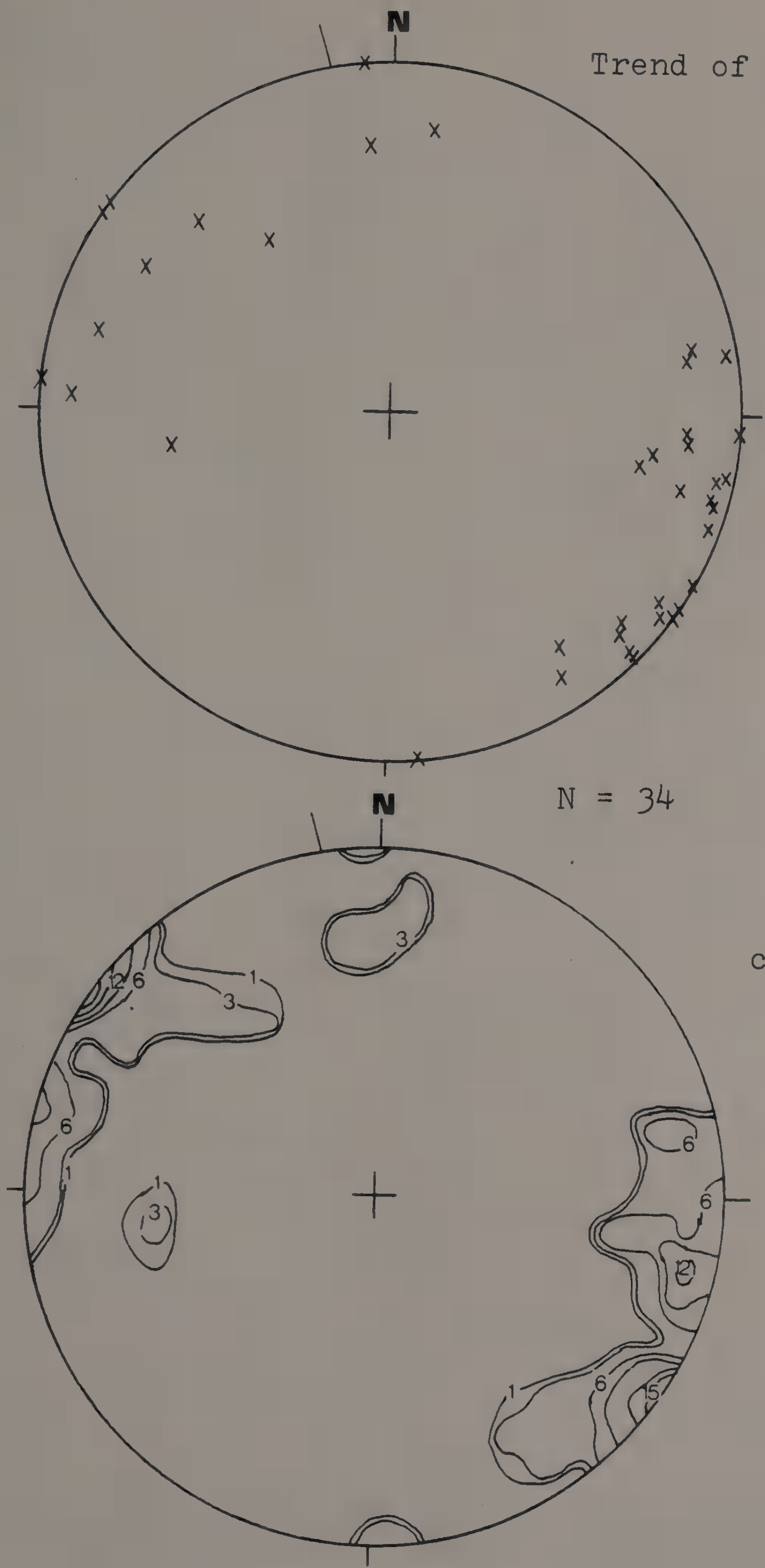


Figure 61. Vein data for detailed outcrop map E - Poverty Mountain area.



Trend of fault trace = N10W

x - quartz veins

N = 34

contour interval = 3%

Figure 62. Vein data for detailed outcrop map F - Poverty Mountain area.

Harkness Road Area

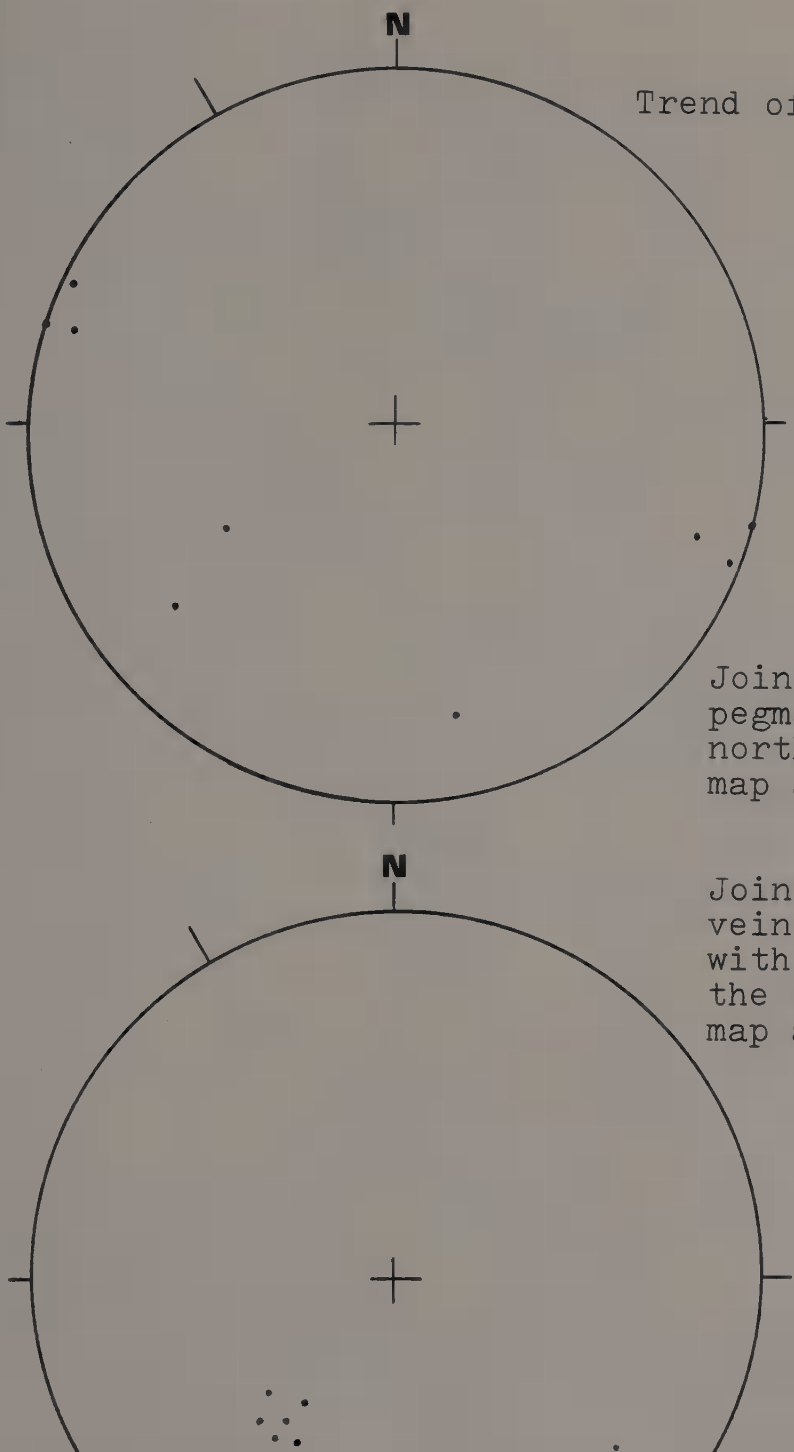
Structural data from the Harkness Road area were obtained using only a general survey. When field work for this project was started, it was assumed that the quartz and feldspar-rich rock in the northern part of the map area (Figure 29) was the remnant of a silicified zone. But joint data (Figure 63), as well as the rock description from the previous chapter, indicate that the rock is instead a partially silicified, brecciated pegmatite.

The pegmatite is found in a zone 3 meters wide and 30 meters long parallel to the east side of the border fault trace, as small broken outcrops. It was often questionable whether some of these outcrops were in place because there has been earth moving equipment on the site. Very little joint information was collectible because of this. No quartz veins related to silicification are obvious in this location. No data were collected from the silicified rock on the low hummocks 305 and 610 meters to the south due to lack of true outcrop.

Joint data were collected from a silicified mass developed parallel to the west-dipping grain of the Fourmile Gneiss (Figure 63). The silicified rock forms a small cap, about 1 meter in diameter, on the weathered surface of an outcrop which borders that fault trace. Two joint types are

represented one oriented N51W, 43NE and the other N53E, 76W. Neither of these sets bears much resemblence to any of the concentrations represented in previous map areas, nor do they appear to have any relationship to the geometry of the border fault. The Fourmile outcrop is roughly parallel to the N30W trending fault trace and has a smooth west-dipping face. A measurement of this face yields an orientation of N20W, 43SW. This orientation correlates with the N30W, 40-60SW orientation of the border fault.

Pseudotachylite veins (Figure 64) found in this same outcrop, have two relative ages. An older set has a mean orientation of N61E, 43SE and a younger set has a mean orientaion of N20E, 69NW. These veins penetrate 3.0 to 4.0 centimeters into the perimeter of the silicified rock cap, indicating some fault motion after the precipitation of the silicified rock veins. Since there are two relative ages of pseudotachylite veins, at least one of which cuts into hydrothermal precipitates, it can be concluded that hydrothermal precipitates formed some time before the Mesozoic faulting event ended. They were formed at depth but within an extensional environment. More than one faulting event brought these rocks closer to the surface on the footwall of the fault, and erosion eventually exposed them.

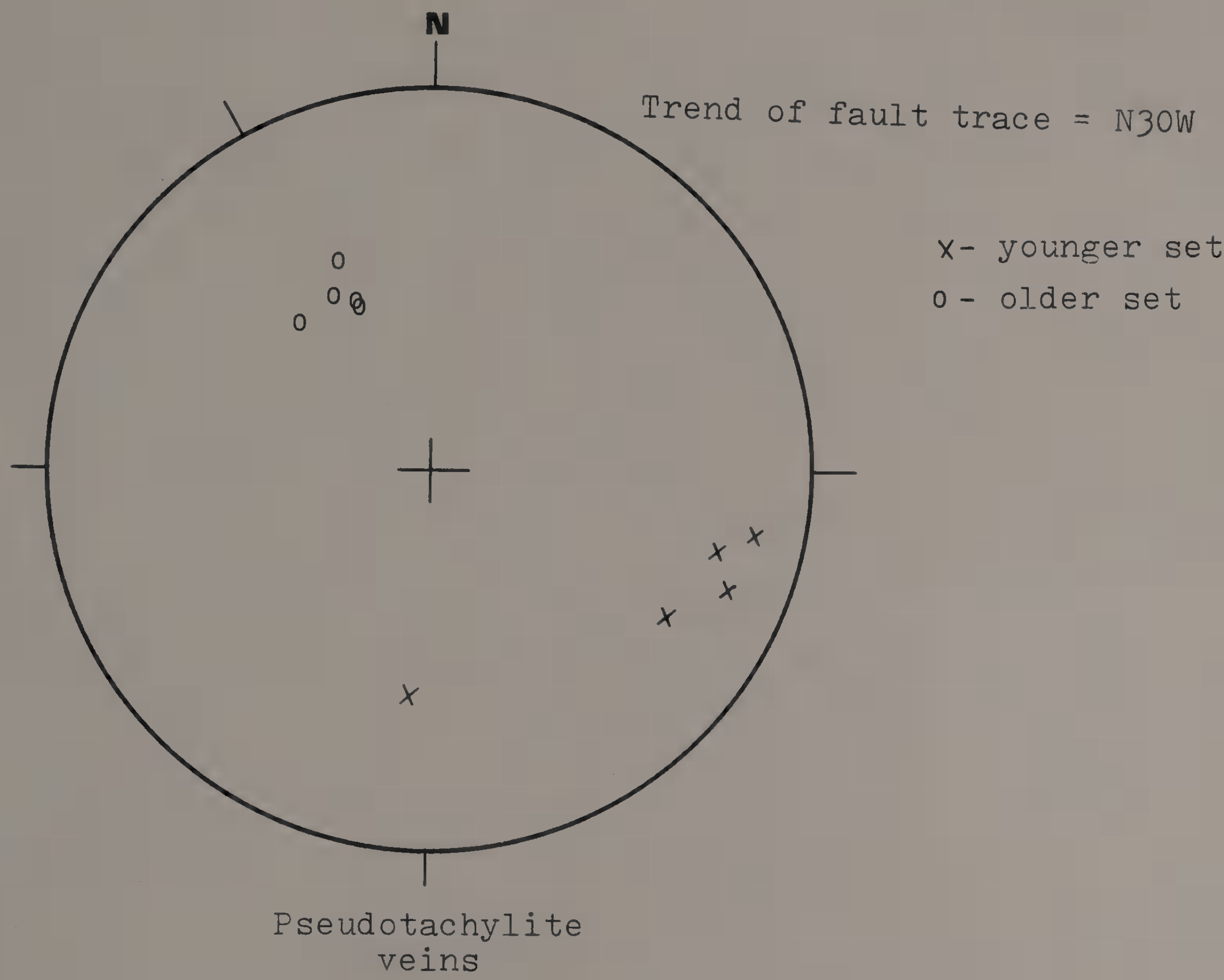


Trend of fault trace = N30W

Joints in silicified pegmatite at the northern part of the map area.

Joints in silcified quartz veins and small masses within Fourmile Gneiss at the southern part of the map area.

Figure 63. General joint data - Harkness Road area.



MEAN ORIENTATIONS

younger set: N20E, 69NW

older set: N61E, 43SE

Figure 64. Pseudotachylite vein orientations - Harkness Road area, south.

Gulf Road Area

Structural data from the Gulf Road area were obtained through a general survey. The joint systems in the rocks are moderately to poorly developed and form small outcrop surfaces. Some joints are mineralized by quartz or epidote, and no age relationships could be determined. The rock breaks into angular, irregularly shaped pieces, unlike the rectangular pieces of the Mount Toby area. Joint data (Figure 65), show only small concentrations on the contour diagram. Joints that have a platy, west-dipping character in outcrop were measured to compare with the orientation of the border fault. The mean orientation of these joints is N06W, 48SW which does not agree with the N40W, 60SW orientation for the border fault in this area. This discrepancy could be explained by a local warping of the structural grain or the fact that the border fault follows the edge of the Pelham dome, which cuts to the east in this area. The silicified zone may not have been influenced by dome structure in the same way that the border fault was.

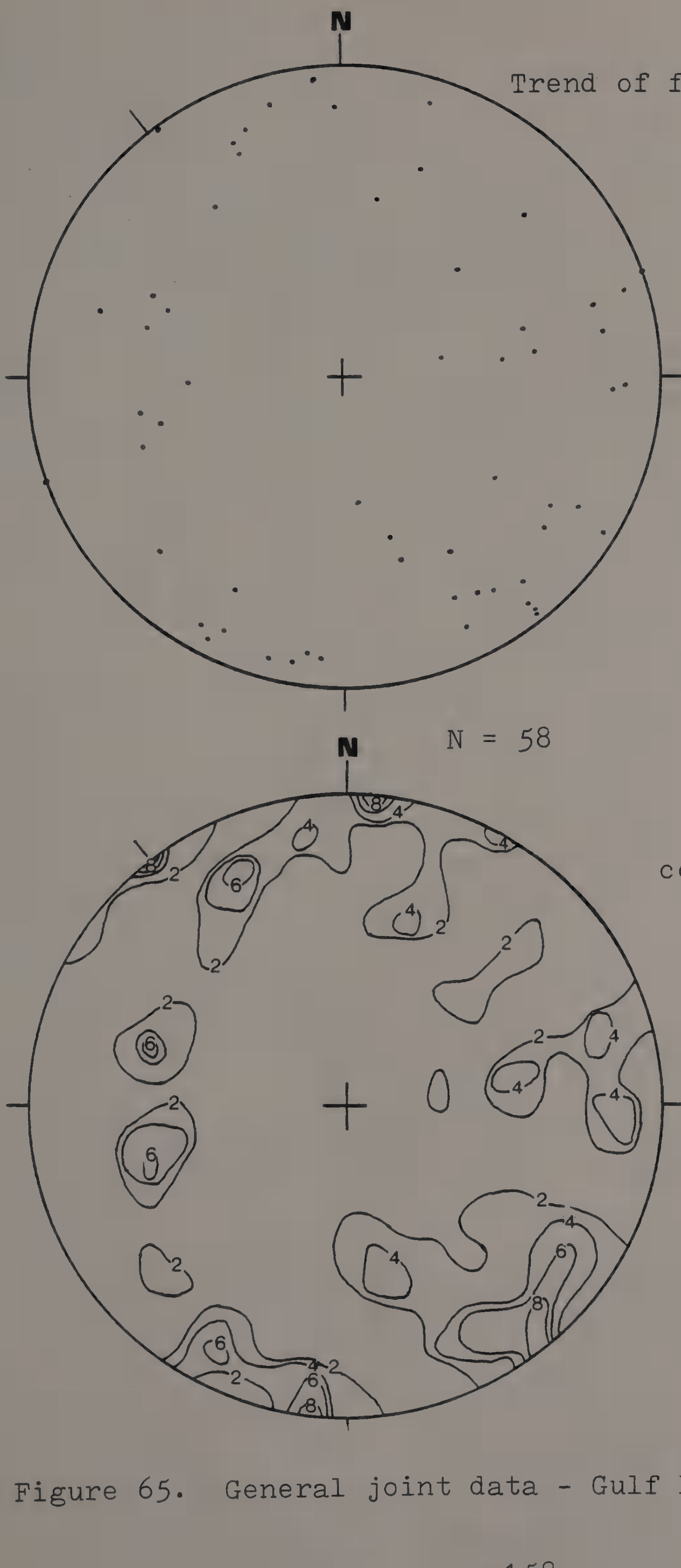
Quartz veins are abundant in this area but mostly as small, randomly oriented features. Some measurements for larger veins (Figure 66) were obtained and have a mean strike of N29E which does not agree with the trend of the border fault in this area. Epidote veins are common but

appear as small randomly oriented features. Four minor fault planes were measured that have northeast strikes with steep northwest and southeast dips (Figure 67). Minor faults do not have the same orientation as the border fault and are younger than veins within the silicified rock.

Discussion of Joints and Veins

Joint measurements from each of the seven map areas were combined and plotted on an equal area diagram with respect to geographic north (Figure 68). The radial pattern exhibited by the points shows a bias resulting from the subconscious rounding off of measurements in the field, so that when plotted, points appear at two and five degree intervals. This is not a desirable situation and efforts must be made to read instruments more carefully.

The data is very scattered but shows three concentrations of joints. Two joint groups are north-south trending, one dips moderately to the east, and the other dips moderately to the west. The third set trends northeast-southwest and dips steeply to the southeast and northwest. The fourth set trends east-west and dips moderately to the south. These same joints were plotted a second time with respect to the border fault (Figure 69). The fault trend for each map area was oriented north, and the new orientations for each data point plotted. The same



Trend of fault trace = N40W

x - quartz veins

N = 58

contour interval = 3%

Figure 65. General joint data - Gulf Road area.

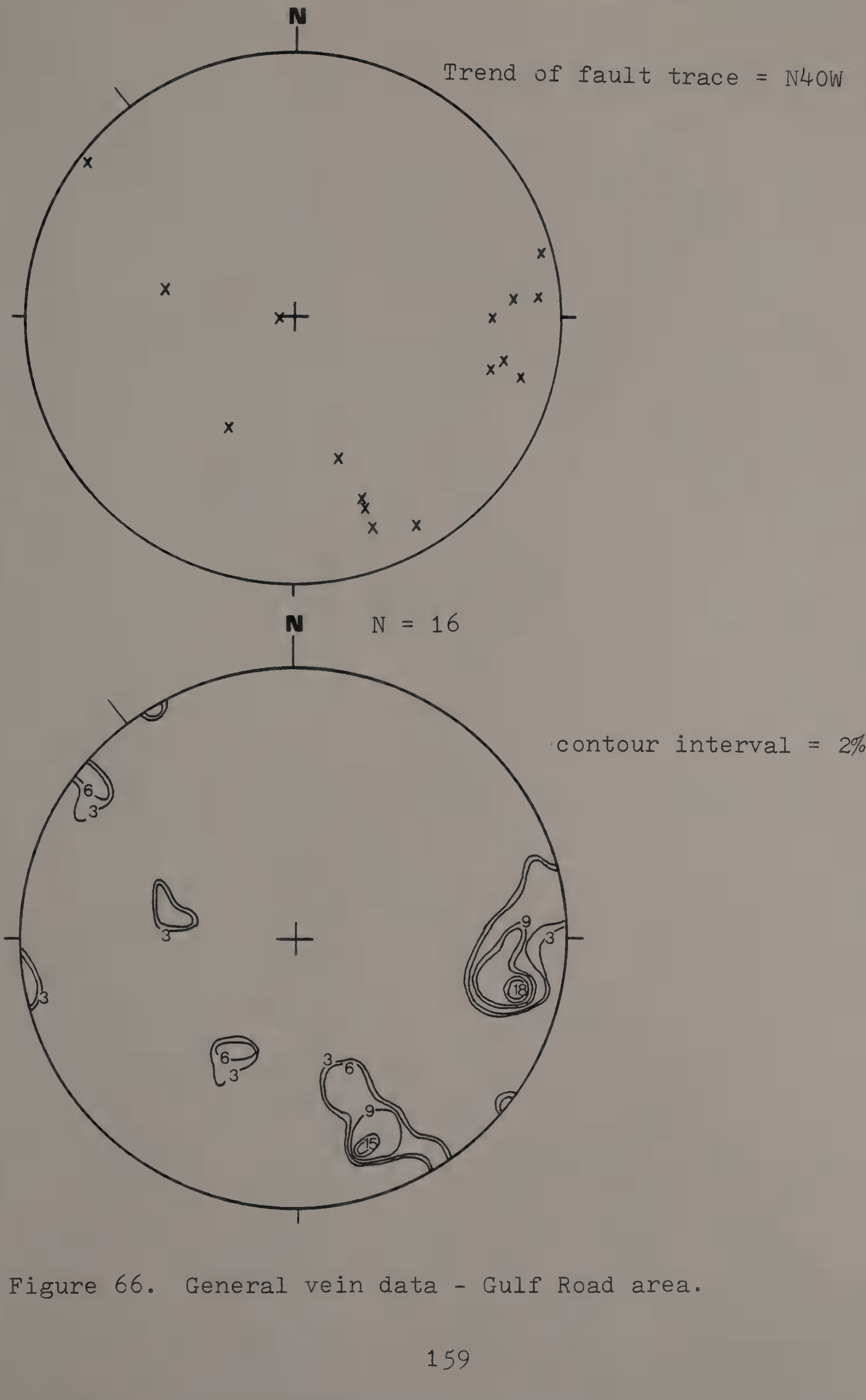
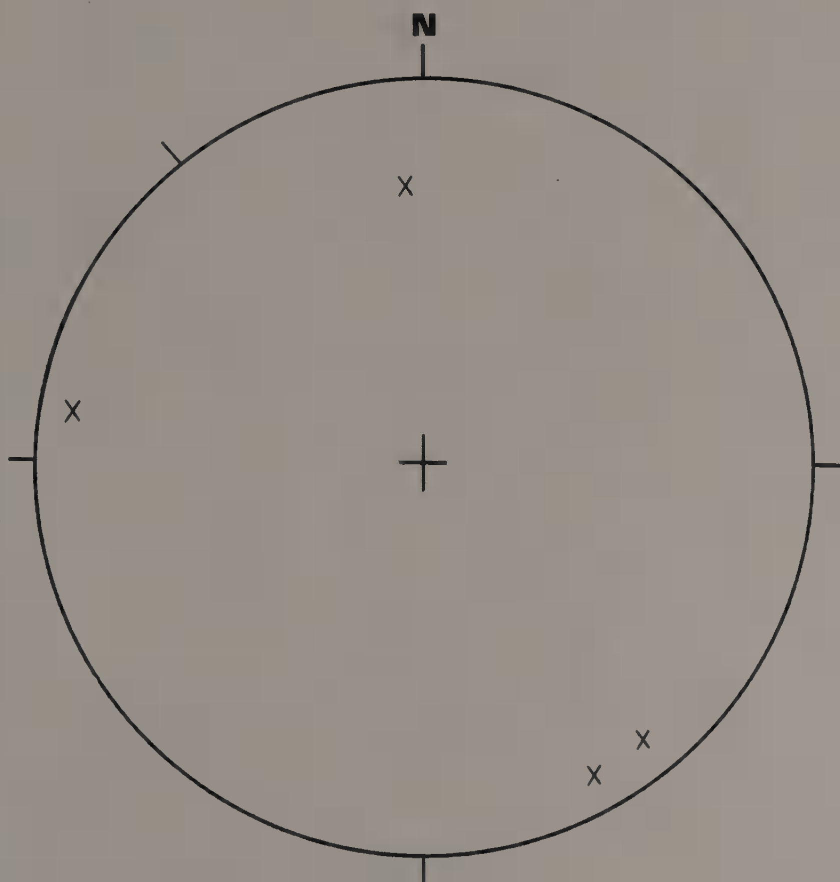


Figure 66. General vein data - Gulf Road area.



Fault Planes

Figure 67. Fault data - Gulf Road area.

three groups of joints are again represented with about the same intensities. The only significant difference between the two diagrams is that the clusters in Figure 69 have been rotated slightly to the west. With these results no conclusions about the forces that controlled the formation of these features can be made.

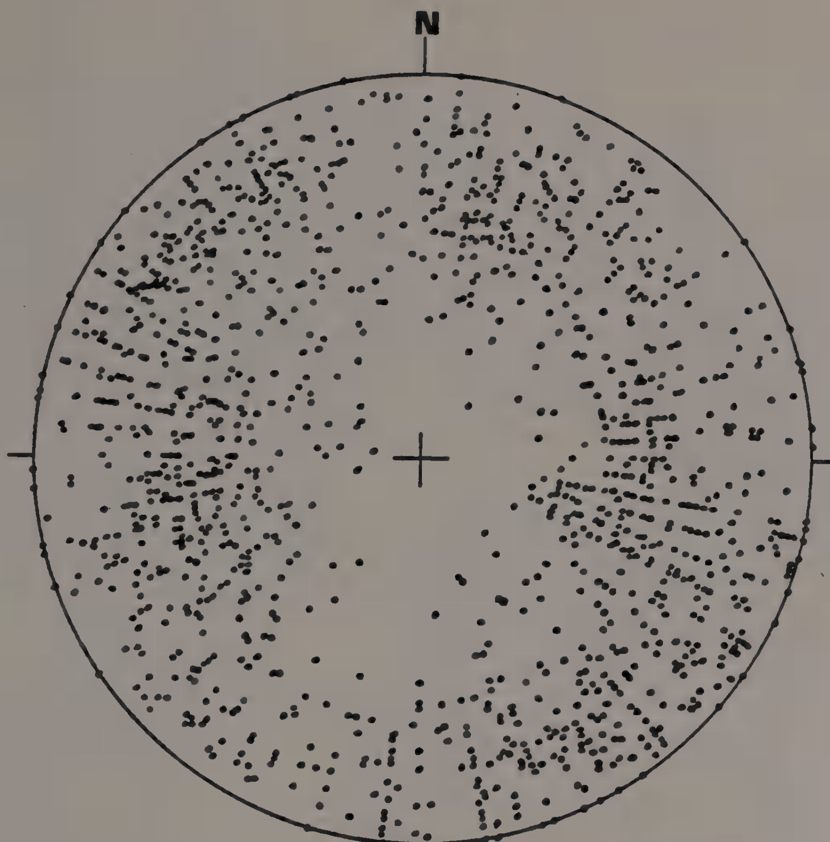
One problem with the compilation of this data is that the Poverty Mountain area, which does not support border fault geometry, is represented by much more data than any other area. This biases the results of the compilation so that it takes on the character of the Poverty Mountain data. To test this idea joint data from the East Mineral Hill, Mount Toby main zone, Leverett Pond and Gulf Road areas are plotted with respest to both north and to the border fault (Figure 70). Joint data from the French King Bridge mylonites were not used because the metamorphic foliation may have influenced joint development. Joint data from the Mount Toby quartz-rich zone were also not included because this zone is at an angle to the main fault.

The results of this compilation again show few differences between joints plotted with respect to north or to the border fault, except a slight counterclockwise rotation of the major concentrations. Still, no conclusions can be made as to whether joint formation is directly

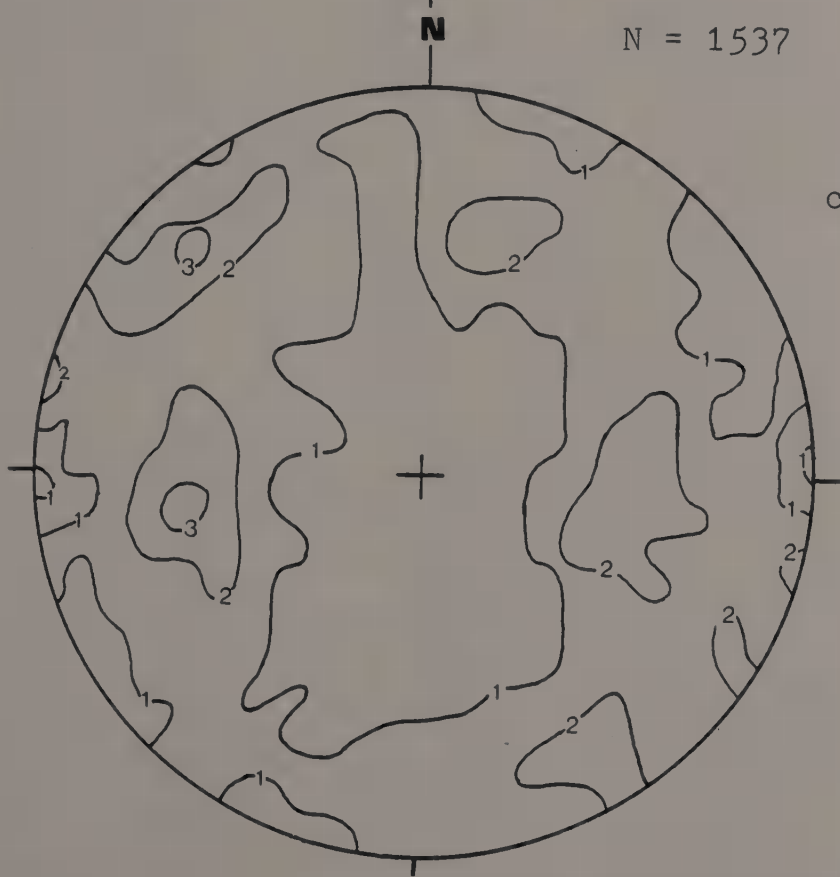
related to border fault geometry or to regional factors. However, it is far more obvious in the second compilation that a large number of joints mimic the trend of the border fault, and that the west-dipping joint set appears to mimic the average dip of the border fault plane.

Quartz vein measurements were also taken from each map area and combined with respect to geographic north (Figure 71). A vector mean of N15E, 87SE has been calculated. These same veins were also plotted with respect to the orientation of the fault trace (Figure 72). A northeast - southwest trend is still present but is not nearly so strong as in Figure 71. This means that quartz and hematite vein formation for the area between the towns of Millers Falls and Belchertown was controlled by a regional stress field, and not directly by the geometry of the Connecticut Valley border fault. An extensional stress oriented N75W-S75E is suggested at the time of vein formation. Chandler (1978) estimated an extensional stress of N68W for the Northfield Basin and Jasaitis (1983) estimated an extensional stress oriented N60W for the Amherst area during the early Mesozoic. The veins in the silicified zones are a later feature indicating that the stress field rotated counterclockwise over time.

Throughout this study it was assumed that fluids that



N = 1537



contour interval = 1%

Figure 68. Total joint data with respect to north.

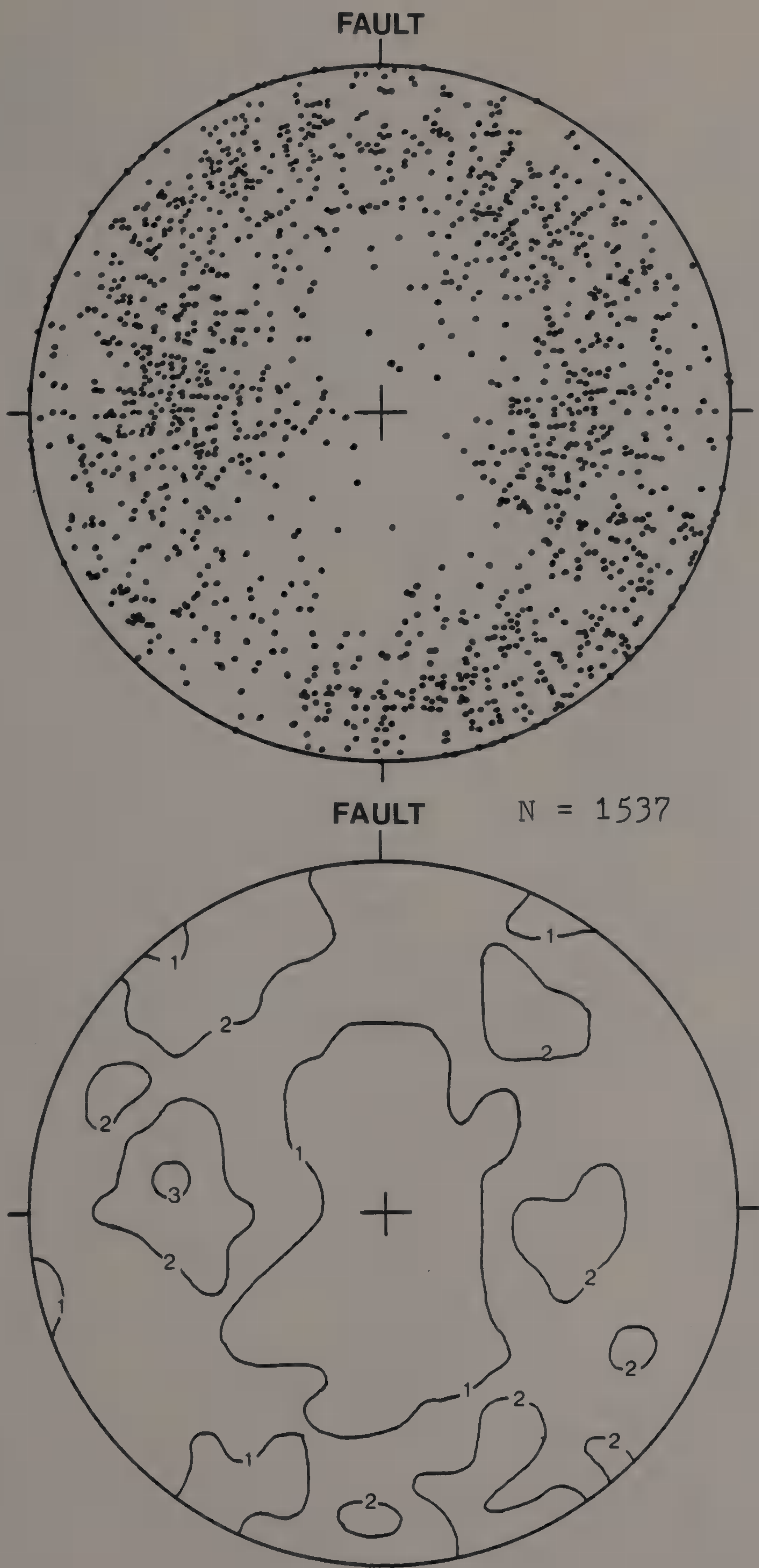
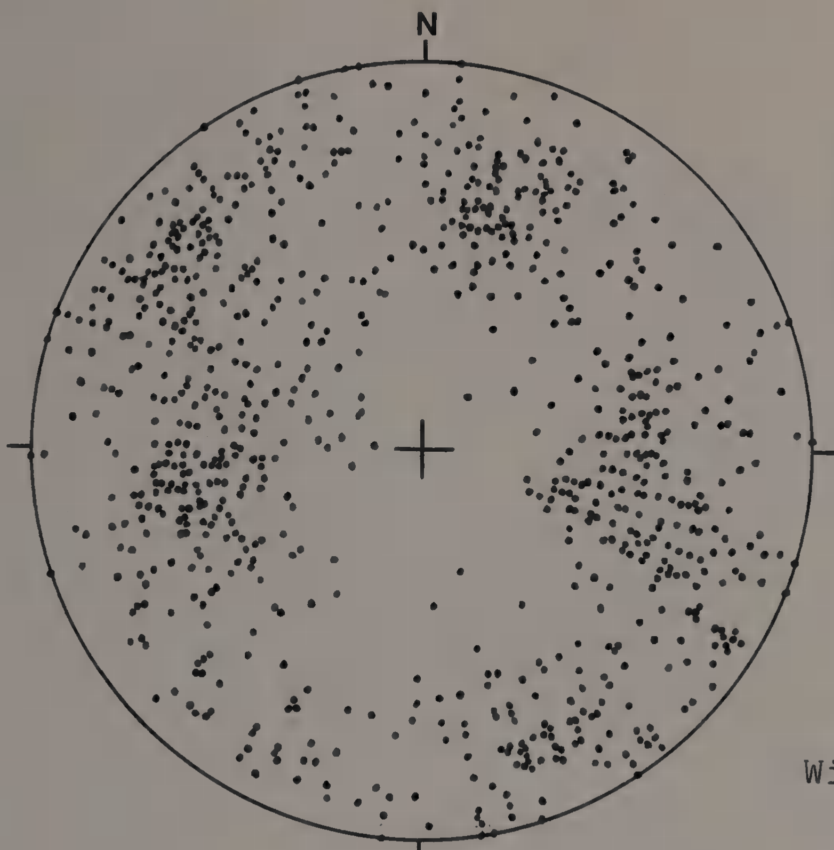


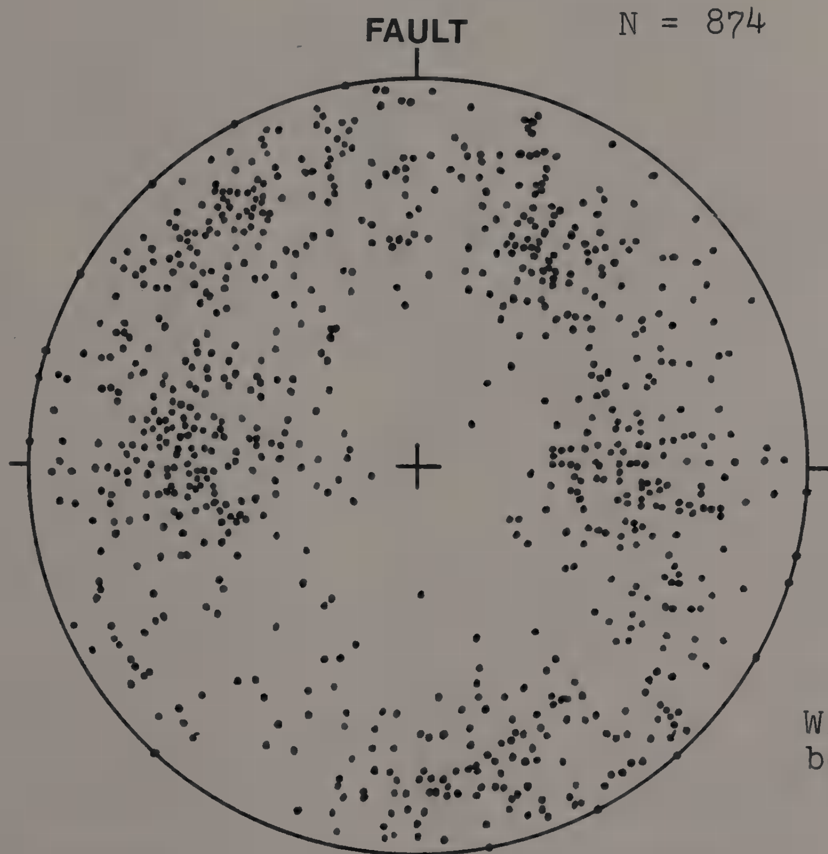
Figure 69. Total joint data with respect to border fault.



East Mineral Hill, Mount Toby main zone, Poverty Mtn., and Gulf Road joint data.

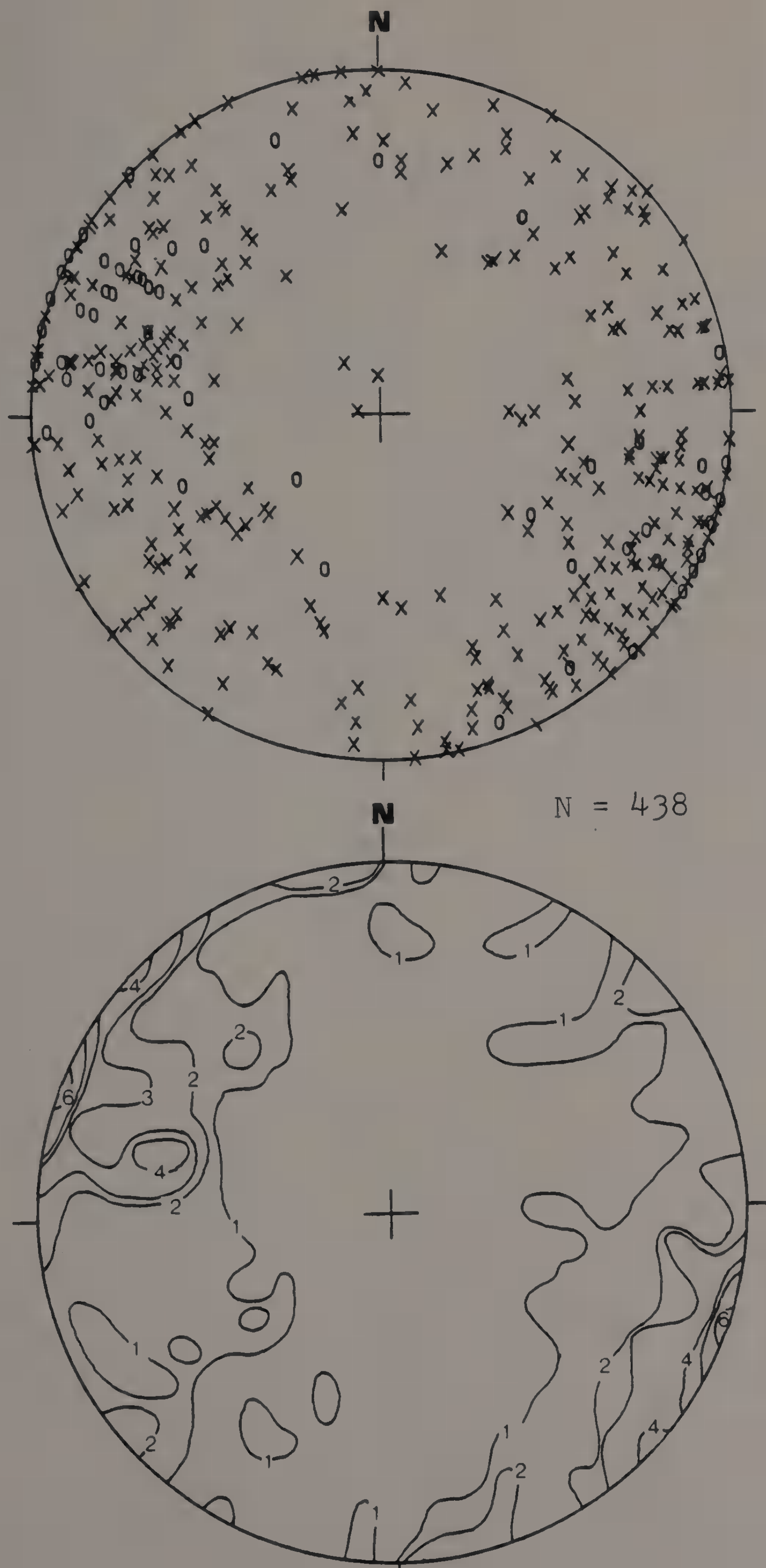
With respect to north.

N = 874



With respect to the border fault.

Figure 70. Total joint data for East Mineral Hill, Mount Toby main zone, Leverett Pond and Gulf Road areas, both with respect to north and with respect to border fault.



X - quartz veins
o - hematite veins

N = 438

contour interval = 1%

Figure 71. Total vein data with respect to north.

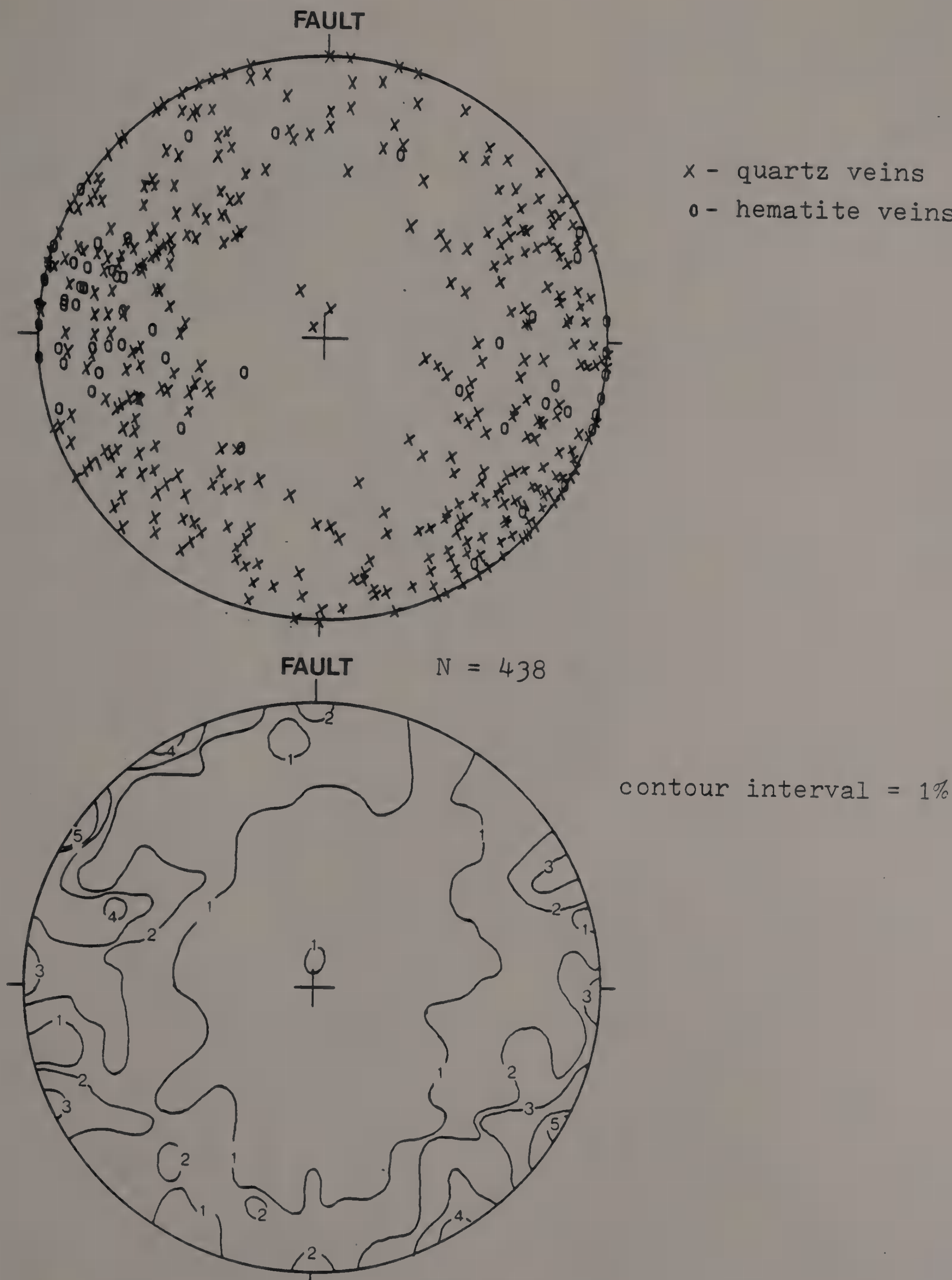


Figure 72. Total vein data with respect to border fault.

precipitated veins used joint openings as avenues of travel. If this were true than joint and vein data should have behaved in the same manner in the compilations. Because joint and vein data did not give similar results, it may be possible that joints are a younger feature than the veins, although this was difficult to determine in outcrop.

Summary of Silicified Rocks

Several observations and conclusions can be made about the silicified zones in the study area.

1. Four types of silicified rock have been identified.
    a. Quartz-rich cemented breccia and microbreccia.
    b. Quartz-feldspar-chlorite cemented breccia and microbreccia.
    c. Quartz-feldspar-epidote-chlorite cemented breccia and microbreccia.
    d. Small veins of a type consisting of a pink feldspathic rock enclosing areas of quartz-rich rock.

2. At least three periods of silicification have occurred. In the first period, due to very efficient circulation, large volumes of breccia were cemented. The second phase had limited circulation so formed recognizable quartz veins. The third period formed a second set of veins including quartz, specular hematite and epidote. These

veins are seen both cross cutting, and within, previous vein boundaries. Quartz veins occur as two general types; larger northeast- or northwest-striking types, and smaller randomly oriented veins that are offshoots from the larger veins into voids and cracks between breccia pieces.

3. In general the degree of silicification increases in the zones from east to west toward the fault. Grain size remains constant from east to west in some zones, and in others it decreases.

4. Most structural features exhibit northeast to northwest strikes and mimic the trend of the border fault in a majority of the silicified zones. West-dipping joints appear to mimic the dip of the border fault plane in many areas. Discrepancies may indicate a secondary fault or an irregularity of the fault plane that has influenced these features.

5. It is not clear whether joint formation is directly related to border fault geometry or to regional factors. Vein formation appears to be more related to regional stresses. A mean strike for veins plotted with respect to north is N15W suggesting an extensional stress of N75W-S75E. This does not correspond to the N60W or N68W extensional stresses suggested for the Northfield basin and Amherst area during the early Mesozoic. Vein formation in the silicified

zones occurred later and indicate a counterclockwise rotation of the stress field over time.

CHAPTER 5

SUMMARY AND CONCLUSIONS

The Connecticut Valley border fault is a normal, west-dipping fault. This statement is supported by S-C fabrics seen in thin sections of mylonitic rocks, which indicate a west-side-down motion. Minor brittle faults, found overprinting the mylonites and in silicified rocks, also have a west-side-down geometry. The presence of mylonitic rocks overprinted by brittle features indicates that some rocks were affected by the faulting process at a depth where a ductile environment prevailed. Heterogeneous strain rates were imposed on the rocks. This is seen as local lenses of rock with characteristics of orthomylonite and ultramylonite within a protomylonite. These rocks were formed in the upper level of the ductile environment and then were uplifted to nearer surface conditions where some combination of lower temperature, lower pressure, or an increased overall strain rate resulted in a brittle environment.

Sections of rock at near surface conditions were brecciated and hydrothermal fluids invaded volumes of rock replacing primary metamorphic minerals with new minerals, chiefly quartz and to a much lesser extent, specular hematite. There were at least three periods of hydrothermal invasion. The first phase effectively penetrated the

breccia masses, creating cemented breccia and microbreccia. The second pulse of fluids did not penetrate as effectively and precipitated quartz veins. The third pulse precipitated quartz as well as specular hematite and epidote veins. These are commonly seen crosscutting or within the boundaries of previous quartz veins.

A majority of joints and veins have a north-south trend that mimics or is close to the trend of the border fault. A platy, west-dipping joint type also mimics the dip of the fault plane in many areas. Discrepancies may indicate a secondary fault or an irregularity of the fault surface that influenced development of these features.

Analysis of combined joint data however, is inconclusive as to whether their formation was controlled directly by border fault geometry or by regional stresses. It appears that there must be some relationship between joint orientation and the border fault because of the similarity in orientations in many areas. Analysis of combined vein data indicates that vein development was controlled by regional stresses rather than directly by border fault geometry. An extensional stress oriented N75W during vein formation suggests a rotation of the regional stress field from the N60W and N68W extensional stresses estimated for the Northfield basin and Amherst area during the early

Mesozoic. It is not clear whether joint formation predates or postdates vein formation.

Below is a proposed sequence of events that occurred in the rocks immediately adjacent to, and in the footwall of, the Connecticut Valley border fault.

1. Initiation of faulting.

2. Development of mylonites at depth and brecciation of volumes of rock closer to the surface.

3. Pseudotachylite veins formed during brittle faulting.

4. Silicification of breccia masses and a second phase of pseudotachylite vein formation indicating that the brittle phase of faulting may have occurred as more than one non-continuous movement.

5. Possible joint development (joints older than veins).

6. Quartz vein precipitation.

7. Second episode of quartz vein precipitation as well as specular hematite and epidote vein formation.

8. Possible joint development (joints younger than veins).

9. Development of minor west- and east-dipping normal faults whose orientations do not correspond to that of the border fault.

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