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Bedrock Geology of the Stowe-Waterbury Area, North-Central Vermont

by
George Springston

March 15, 1997

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Executive Summary

This report describes the bedrock geology of an area on the eastern side of the Green Mountains in parts of the towns of Stowe, Morristown and Waterbury, Vermont (See Figure 1). The rocks are of late Precambrian to Ordovician age (roughly 600 million to 438 million years before present) and were originally deposited as sediments on what was then the eastern shore of North America.

The principal formations encountered in the area are the following: the Hazens Notch Formation, which consists of dark, rusty, graphitic schist and gneiss, the Underhill Formation, which consists of gray, magnetite-bearing chlorite schist, and the Ottauquechee Formation, which consists mostly of black, graphitic phyllite with interbedded layers of dark quartzite. These and other units are described in more detail in the section on Stratigraphy.

The geologic map (Plate 1) shows the distribution of these formations. The complex patterns seen on the map result from the rocks having been extensively deformed by folding and faulting during Ordovician time in a mountain-building event known as the Taconian orogeny. During this deformation, heat and pressure transformed the sedimentary rocks into the metamorphic rocks we see today.

Table of Contents

Figure

Appendix

Plates

Location

The study area is located in the northern part of Washington County and the southern part of Lamoille County in north-central Vermont. It encompasses parts of the towns of Stowe, Morristown, and Waterbury and is located on portions of the following U.S. Geological Survey 7.5 minute quadrangle maps: Mount Mansfield , Sterling Mountain, Stowe, and Bolton Mountain (see Figure 1).

Physiography

The study area is located in the Hudson-Green-Notre Dame Highlands physiographic province of Denny (1982, Figure 3), a region of high topographic relief which extends from the Hudson Highlands of New York for more than 850 kilometers to the mountains of the Gaspe Peninsula in Quebec. The area as a whole is characterized by high topographic relief, with elevations ranging from 3,620 feet on the ridge south of Madonna Peak near the eastern edge of the Mount Mansfield quadrangle to 592 feet on the shores of the Waterbury Reservoir in the western portion of the Stowe quadrangle. Relief is greatest in the west and more moderate in the east. Stewart (1961) divides the study area between two physiographic provinces: the Green Mountain province on the west and the less rugged Vermont Piedmont province on the east.

The principal streams are the West Branch, Sterling Brook, and the Miller River. These all drain into the Little River, which, in turn flows into the Waterbury Reservoir. Waters from the reservoir drain southward into the Winooski River.

Bedrock outcrops are widespread in the higher portions of the study area. In particular, they are often encountered along ridges and in stream valleys. At the middle elevations they are often absent from the smooth hillslopes themselves and can only be found on ridges and in stream valleys. Outcrops are uncommon in the lowlands due to thick surficial deposits. In particular, very few outcrops were encountered in the valley of the West Branch to the northwest of Stowe.

Landforms in the study area are, to a significant extent, controlled by the underlying bedrock. This is particularly well illustrated in the Stowe quadrangle, where the most prominent cliffs tend to be underlain by the magnetite schist of the Underhill Formation or the quartzites of the Ottauquechee Formation, both of which appear to be significantly more resistant to erosion than the rusty graphitic schist of the Hazens Notch Formation and the graphitic phyllite of the Ottauquechee Formation. The relationship is also shown be the fact that hills in the Stowe quadrangle tend to be elongate parallel to the strike of the principal foliation, changing their trend as the strike of the principal foliation changes.

Previous Work

Previous bedrock mapping in the study area is summarized in the quadrangle reports of Cady (1956), Albee (1957), Christman (1959), and Christman and Secor (1961). The results of these reports are summarized on the Centennial Geologic Map of Vermont by Doll and others (1961). Although much geologic research has been undertaken in central Vermont since the publication of

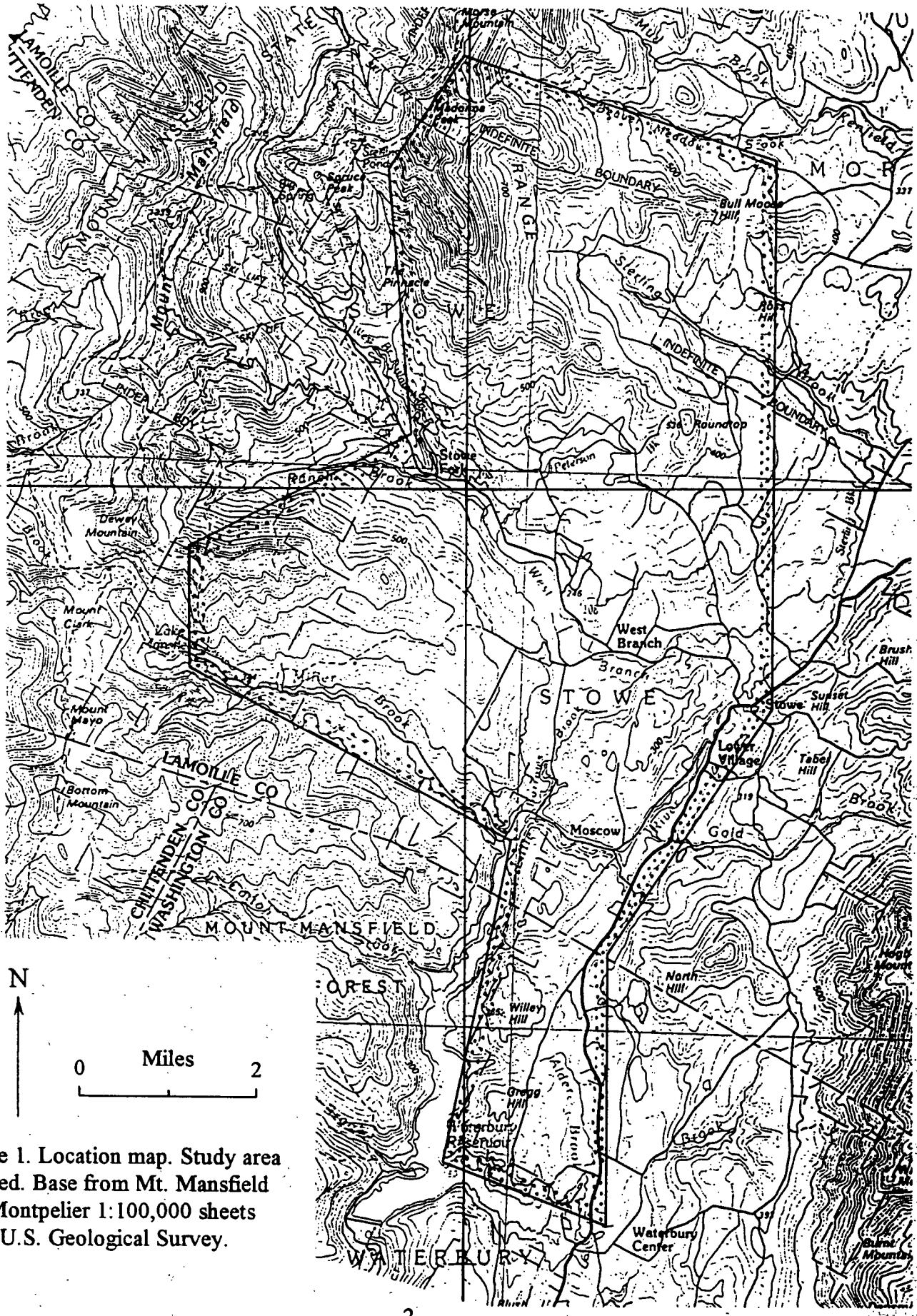

Figure 1. Location map. Study area stippled. Base from Mt. Mansfield and Montpelier 1:100,000 sheets from U.S. Geological Survey.

the 1961 map (see for example, Stanley and Ratcliffe, 1985), little had been done in the vicinity of the study area until the work of Peter J. Thompson and Thelma B. Thompson in the Camels Hump-Bolton Mountain area (1992). The present project extends their work to the east.

Regional Geologic Setting

The study area is located in the hinterland of the Taconic orogen, the site of a Middle Ordovician arc-continent collision associated with the closing of the Iapetus Ocean. A good overview of the tectonic history is given by Doolan (1996).

The area is underlain by the Underhill, Hazens Notch, Ottauquechee, and Stowe Formations. These rocks are of problematic Late Precambrian to Ordovician age. The Underhill Formation is interpreted to have been deposited on the eastern continental slope of the North American continent while the Hazens Notch, Ottauquechee, and Stowe Formations are interpreted to have been deposited on transitional or oceanic crust within a forearc basin setting located to the east (Stanley and Ratcliffe, 1985), Doolan, 1989). As the basin closed, the rocks were extensively folded and thrust faulted, having undergone at least three generations of deformation, and they have undergone regional metamorphism to chlorite to garnet grade (with higher grade rocks being present both to the west and to the east of the study area). The principal metamorphism appears to have taken place during the Taconian orogeny (Stanley and Ratcliffe, 1985).

Methods of Study

Field work was undertaken during the summer and fall of 1996. The work consisted of detailed mapping on 1:24,000 topographic quadrangle maps. Locations were determined with the assistance of a pocket altimeter frequently reset on points of known elevation. Color-infrared 1:40,000 scale aerial photos were used as a location aid in some areas. These were very useful and it is recommended that copies be made available to all researchers during the coming field season. Mappable lithologic units were traced out and outcrop-scale structural features (foliations, lineations, folds, etc.) were recorded.

For the detection of magnetite in hand specimens a finely balanced pencil magnet was found to be essential. This easily demonstrates the presence of rather small amounts of magnetite.

Field stations are labeled using the following system: BM = Bolton Mountain quadrangle, MM = Mount Mansfield quadrangle, SM = Sterling Mountain quadrangle, and ST = Stowe quadrangle.

Due to limited time and limited financial support, thin sections were not examined as part of this study. Although such work is of crucial importance to sophisticated geologic interpretations, there has been considerable petrographic analysis undertaken in surrounding areas and the results have been carefully examined (see references under Previous Work). I have collected a set of representative samples which will be made available to other researchers for further analysis.

Stratigraphy

Introduction

This section includes brief descriptions of each of the units shown on Plate 1. It is not intended to be exhaustive. The reader seeking a detailed discussion of the relevant stratigraphic questions should consult Doolan and others (1987), Stanley and Ratcliffe (1985), Thompson and Thompson (1992), and Walsh (1992).

The rocks of the study area are part of the pre-Silurian eastern cover sequence of Stanley and others (1987). At the time of the compilation of the 1961 state map it was believed that the formations described were part of a basically homoclinal sequence with the oldest rocks in the west and successively younger formations to the east. Current tectonic models suggest that the reality is far different: although the original stratigraphy may well have been fairly simple, multiple episodes of pre- to syn-metamorphic deformation have compressed and shuffled the rocks to the extent that age relationships between the units described below are very uncertain (Stanley and others, 1987). A possible scenario for the evolution of these rocks in shown in the interpretive palinspastic diagram for western New England from Stanley and Ratcliffe (1985, Plate 1, Figure 6).

Mt. Abraham Schist

The Mt. Abraham Schist consists of silvery-gray, magnetite-bearing chlorite-muscovite-quartz schist and phyllite without visible albite porphyroblasts and without graphite. It is shown on the map in two zones visited by Peter J. Thompson and Thelma B. Thompson (1997, unpublished manuscript map of portions of the Bolton Mountain and Mount Mansfield quadrangles submitted to Vermont Geological Survey). Although these zones were not visited by me, they are included on the map because the map pattern of this unit has been modified based on my observation of outcrops of the Underhill Formation on the ridge south of Madonna Peak, which had been mapped by Thompson and Thompson as Mt. Abraham Schist.

Underhill Formation

The Underhill Formation consists of pale green to gray chlorite-muscovite-quartz (-magnetite-albite) schist. Albite porphyroblasts, when present, are light tan, not dark gray. This is a quite distinctive unit in that magnetite is present in most outcrops. Note that detectable magnetite is not always present. It was found in the course of this study that gray chlorite-muscovite-quartz schist *without* discernible magnetite and without graphite is clearly associated with the magnetite-bearing schist traditionally described as Underhill Formation. As these two lithologies appear to be mixed together without some discernible structural relation, they are classed together as Underhill Formation. In practice, a contiguous set of outcrops of gray chlorite-muscovite-quartz schist without graphite was assigned to the Underhill Formation if *some* of the outcrops contained magnetite.

Hazens Notch Formation

The Hazens Notch Formation consists primarily of dark, rusty, graphitic chlorite-muscovite-biotite-quartz schist and gneiss and usually contains dark gray to black albite porphyroblasts. Large euhedral pyrites are common. Beds of dark gray foliated quartzite are common. Where possible, they have been broken out. Besides the rusty graphitic schist and gneiss which makes up the majority of the formation, there are a scattering of outcrops of similar schist and gneiss without graphite. As there is no discernible pattern observed in the distribution of these non-grpahitic outcrops, they are not divided out. An small body of greenstone was observed within the formation at the outlet of Lake Mansfield in the Bolton Mountain quadrangle.

Ottauquechee Formation

The Ottauquechee Formation is composed primarily of black, graphitic quartz-sericite phyllite with large euhedral pyrite cubes and interbedded dark quartzite layers. Some outcrops of slightly rusty quartz-chlorite-muscovite schist without graphite or magnetite are present in a zone to the north-northeast of the village of Moscow and extending over Cady Hill to Rt. 108 northwest of the village of Stowe. As these non-graphitic rocks were mixed in with outcops of graphitic phyllite and/or tan to dark gray quartzite, they were included within the unit called Ottauquechee Formation. A further complication is found upon examining a group of outcrops located to the south of the Village of West Branch, immediately to the east of Barrows Brook. Here, the typical Ottauquechee phyllite alternates with outcrops of magnetite schist which is typical of the Underhill Formation. These do not appear to be part of the Ottauquechee Formation and are perhaps best interpreted as thrust slices. the pattern of apparent thrust slices is discussed further under Structural Geology.

Two belts of greenstone are mapped within the Ottauquechee Formation on the ridges in the Town of Waterbury to the north of Waterbury Reservoir and immediately to the west of Alder Brook. Their extent is based on three outcrops observed by the author and on the map of Cady (1956).

The Ottauquechee Formation is of probable Cambrian age (Stanley and Ratcliffe, 1985).

Stowe Formation

The Stowe Formation consists of fine-grained, silvery green quartz-muscovite-chlorite-albite-magnetite schist. As this unit formed the eastern boundary of the work area, only a few outcrops were visited. The Stowe Formation is of probable Cambrian age.

Structural Geology

Introduction

This section describes the structural features observed in the outcrops and provides a brief discussion of the regional tectonic framework. The rocks of the study area appear to have undergone at least three phases of ductile deformation since their deposition: an early foliation-

forming event for which the details are not understood, tight to isoclinal folding and formation of a spaced cleavage parallel to the axial planes, and moderately open, upright folding and formation of an associated crenulation cleavage parallel to the axial planes of the folds. For brevity, these different structures will be referred to using standard structural nomenclature. The earliest known deformation event is called Dn, the next Dn+1, the next Dn+2, etc. Likewise a foliation related to Dn+1 would be labelled Sn+1 ("S" for "surface"), a fold formed during Dn+1 would be labelled Fn+1, and a lineation formed during this generation of deformation would be labelled Ln+1. Note that a feature which is labelled Sn in this report may not be contemporaneous with another author's Sn. Minor structural features are shown on Plate 3, the Structural Features Map, and on the equal area diagrams of Appendix A.

Although the protoliths of the rocks exposed in the study area were almost entirely sedimentary, there is little evidence of the original sedimentary layering. The only definite traces of bedding are the various quartzite layers which are within the Hazens Notch and Ottauquechee Formations. All other layering is of metamorphic origin.

Outcrop-Scale Structural Features

An early metamorphic foliation designated as Sn is the earliest fabric which has been observed. This is a segregation layering of quartz-rich or quartz-feldspar-rich and phyllosilicate-rich layers. Folds which could be clearly assigned to Fn were not observed. This Sn foliation is clearly observed at many outcrops to be deformed by the tight reclined folds of Fn+1.

An Sn+1 fabric is commonly observed to transect the Sn foliation. The Sn+1fabric usually takes the form of a spaced cleavage although in some outcrops it is a segregation layering similar to Sn. Reclined, tight to isoclinal folds formed during this deformation (Fn+1) commonly have concentrations of quartz in their hinge zones. These concentrations give rise to the prominent down-dip "quartz rods" (L2) observed on outcrop surfaces. Except for a few cases where measurements were taken in the hinge zones of Fn+2 folds, all quartz rods dipped generally eastward. The tightness of the Fn+1 folds means that most random measurements of Sn+1 surfaces will be on the limbs. In particular, see Sectors 2-5, and 7-12 in Appendix A. It is only in the sectors closest to the core of the axis of the Green Mountains that Sn+1 is more spread out (Sectors 1 and 6 in Appendix A). The asymmetry of Sn+1 folds is usually south-over-north (counterclockwise) but one case of north-over-south (clockwise) was observed. A probable Fn+1 fold is the map-scale fold indicated by the outcrop pattern of the Underhill Formation between Barrows Road and Luce Hill in Stowe.

An Sn+2 foliation is also commonly observed to transect the earlier foliations. This is usually in the form of a crenulation cleavage, although in a few instances it is better described as a spaced cleavage. It uniformly has a strike between north and north-northeast and a steep dip, usually to the east. The associated Fn+2 folds are commonly moderately open, upright folds with shallow plunges to the south or north. Where Fn+2 folds are well-exposed, they have an east-over-west asymmetry. Intersection lineations of Sn+2 on Sn+1 are quite common.

In several spots a faint crenulation cleavage was observed which appeared to transect Sn+2. This was so faint that its existence as a pervasive feature in the study area could never be determined with certainty.

Faults

The question of the extent of faulting has been an exceedingly difficult one to answer in this study. Given the structural style which has been proposed for the region (see particularly Stanley and Ratcliffe, 1985), it would appear at first glance that some direct evidence of faulting would be observable in the study area. There is certainly widespread evidence throughout the rocks of high strain, but there does not appear to be direct evidence of discrete zones of shearing. However, as carefully described by Strehle and Stanley (1986), the position of these rocks within the hinterland of the Taconic orogen indicates that faulting was pre-to syn-metamorphic and that direct evidence of early brittle deformation may have been largely destroyed during subsequent metamorphism. Thus, the principal indicator of faulting is the map pattern.

Certain parts of the map pattern can be explained by folding, such as the map-scale fold in the Underhill Formation located between Luce Hill and Barrows Road in Stowe, and other changes of lithology may be due to purely stratigraphic changes, but the overall pattern of alternating belts and the map-scale pinch-outs suggest that most of the lithologic units may be fault-bounded. If so, the evidence observed to date indicates that the faulting precedes the peak of metamorphism. Otherwise, more evidence of fault fabrics would have been preserved.

A prime example of a map pattern which is best explained by faulting is the zone mapped as Ottauquechee Formation located to the west of the village of Stowe. Several thrust faults are drawn on the map as a way of reconciling a rather complicated juxtaposition of outcops of apparent Underhill Formation with classic Ottauquechee rocks. This zone of rocks should be examined in greater detail to determine the extent of faulting and the deformation mechanisms involved.

It should be noted that although the thrust fault contacts are shown with the conventional toothed symbol for an east-over-westmovement sense, there is no direct evidence in the study area to support this. Rather, it is a reasonable supposition based on detailed analysis of rock fabrics at other sites within the Green Mountains (Strehle and Stanley, 1986).

Metamorphism

Previous research indicates that most of the study area is within the biotite zone, with only the westernmost portion of the area, in the vicinity of Lake Mansfield, being within the garnet isograd (Christman and Secor, 1961; Albee, 1968). As no petrographic work has been undertaken as part of this study, little additional information can be added except to note two occurrences of garnet within the study area: Garnet is present in a sample of rusty, non-graphitic chlorite schist from Station BM-32, located in the northeastern part of the Bolton Mountain quadrangle at elevation

1655 feet, UTM Coordinates (Zone 18): 4,926,800mN, 674,250mE. This is within the garnet isograd of Christman and Secor (1961, Plate 1), Doll and others (1961), and Albee (1968). A small amount of garnet-quartz coticule was observed in gray magnetite schist at Station SM-143, located in the southwestern part of the Sterling Mountain quadrangle at elevation 585 meters, UTM Coordinates (Zone 18): 4,932,300mN, 679,200mE. This is outside of the garnet isograd as mapped by Albee (1957, 1968).

Conclusions

The distribution of the lithologies has been shown to be much more complicated than previously thought. Although some of the pattern may be explained by folding, the overall alternation of Hazens Notch and Underhill lithologies, and the complex mix of lithologies which is mapped as Ottauquechee Formation are all probably the result of multiple episodes of thrust faulting at some time prior to the peak of metamorphism. Although much progress has been made in unraveling the outcrop patterns, further work is needed in the area to the south of Lake Mansfield in the Bolton Mountain quadrangle in order to tie in with the work of Thompson and Thompson (1992 and 1997 manuscript map submitted to Vermont Geological Survey).

Direct evidence of faulting has proven to be elusive. Detailed field mapping and petrographic analysis using the criteria of Strehle and Stanley (1986) and Stanley and others (1987) may shed some light on this problem, especially in the zone of faulting located within the western part of the belt of Ottauquechee Formation to the west of Stowe, but given the sporadic nature of the outcrops in critical zones the answers may well remain a mystery.

Acknowledgements

The Vermont Geological Survey provided funding for this project under Contract No. 0963430. Larry Becker and Marjorie Gale from the Vermont Geological Survey provided advice and encouragement throughout the project.

Peter Thompson introduced me to the field area and provided generous advice and assistance. Boz Wing, Lori Barg, Larry Becker, and Rose Paul each assisted me for one or more days in the field. I am particularly grateful to the landowners contacted during this study. They are too numerous to mention but they were uniformly helpful and supportive.

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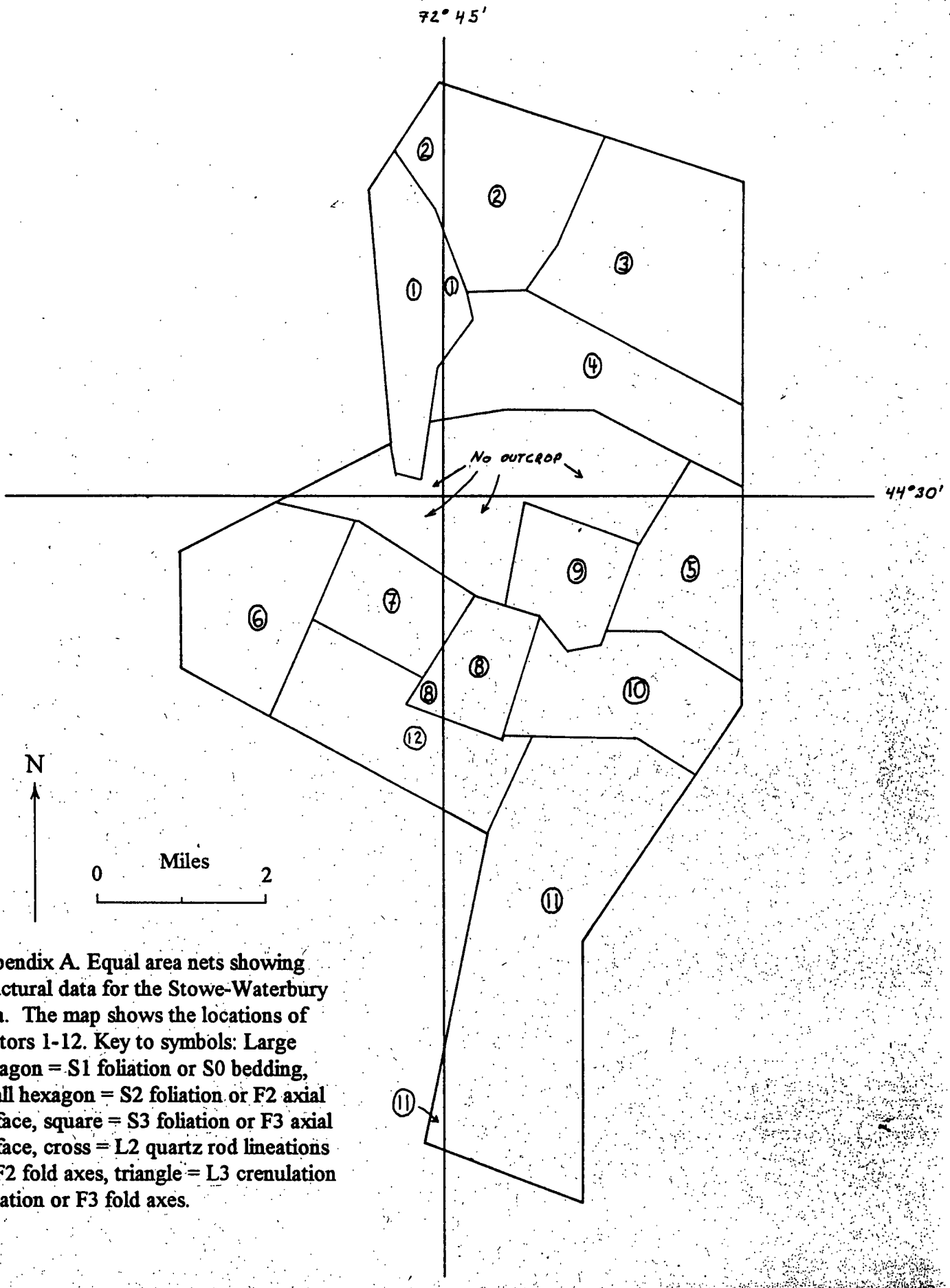
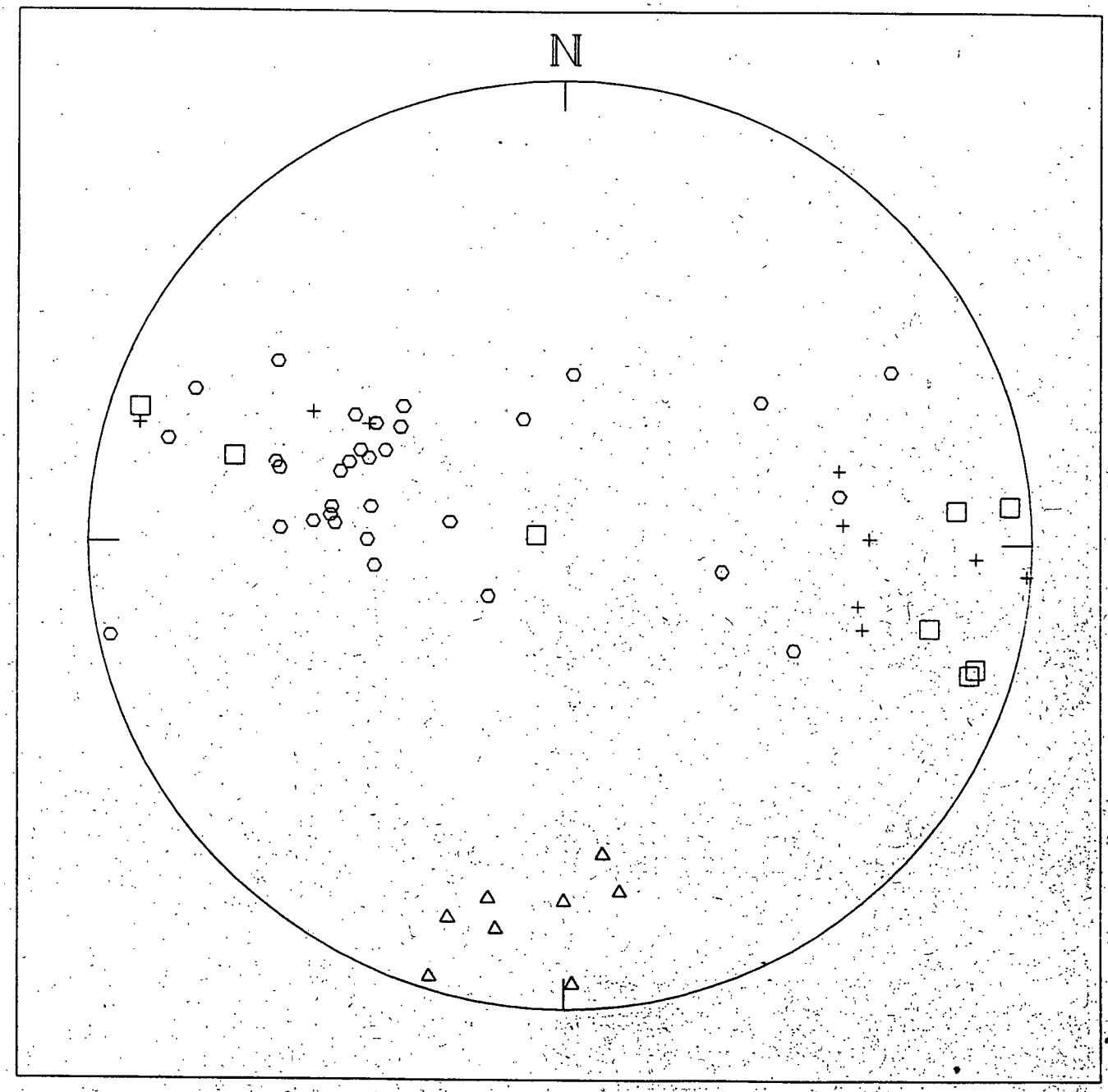


Appendix A. Equal area nets showing structural data for the Stowe-Waterbury area. The map shows the locations of Sectors 1-12. Key to symbols: Large hexagon = S1 foliation or S0 bedding, small hexagon = S2 foliation or F2 axial surface, square = S3 foliation or F3 axial surface, cross = L2 quartz rod lineations or F2 fold axes, triangle = L3 crenulation lineation or F3 fold axes.

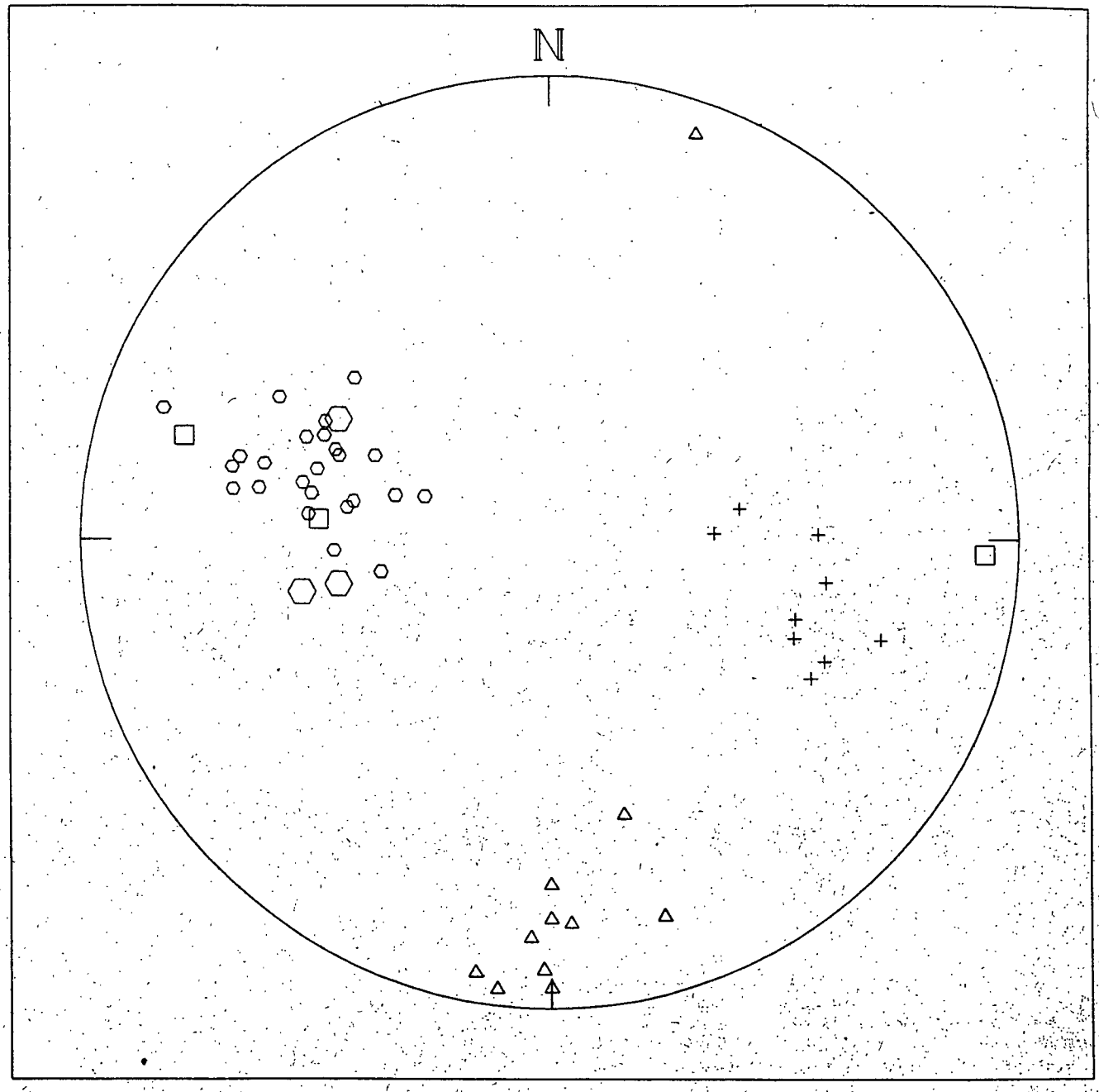
Sector 1

STERLING RIDGE



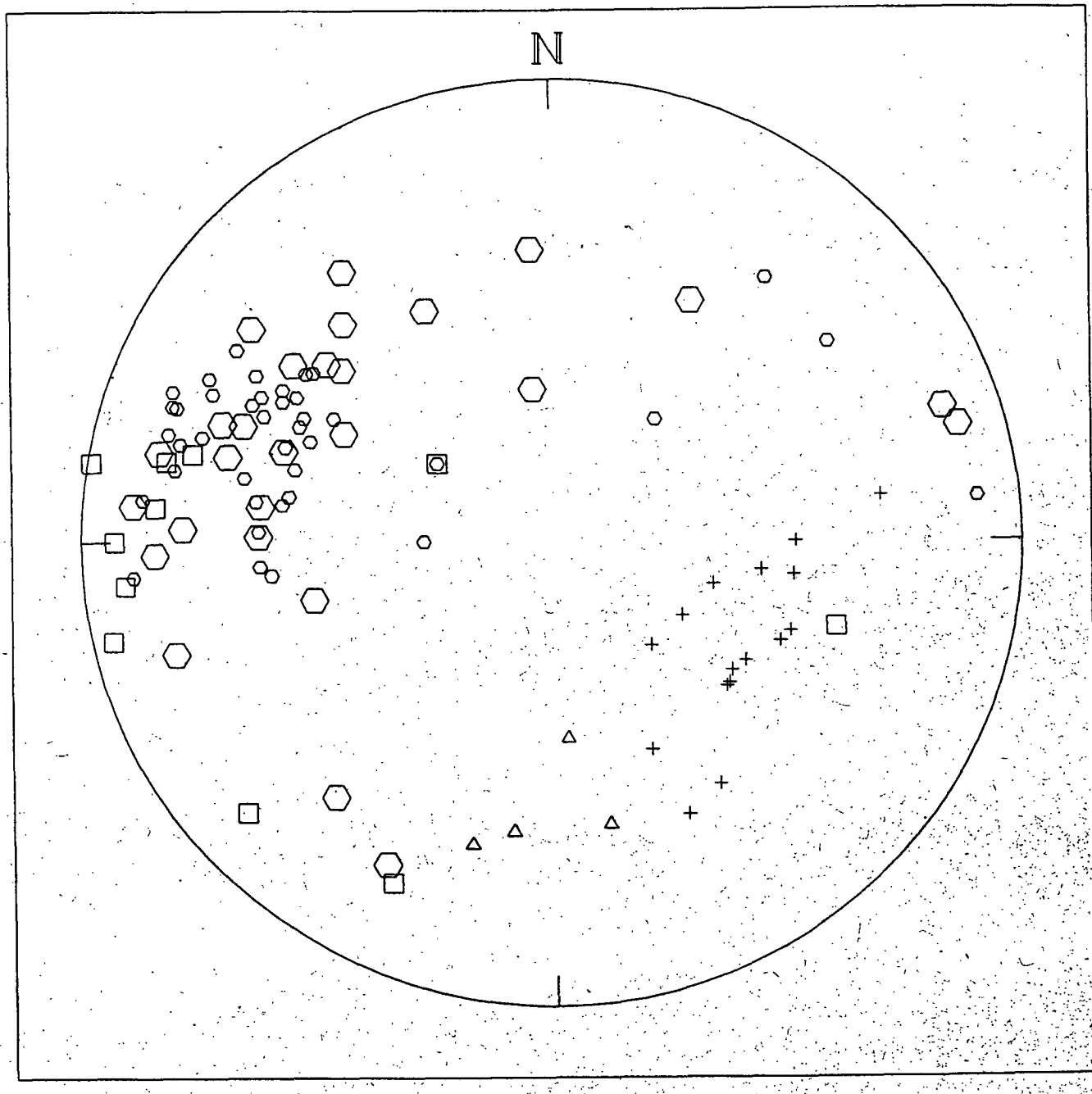
Sector 2

STERLING BROOK AREA



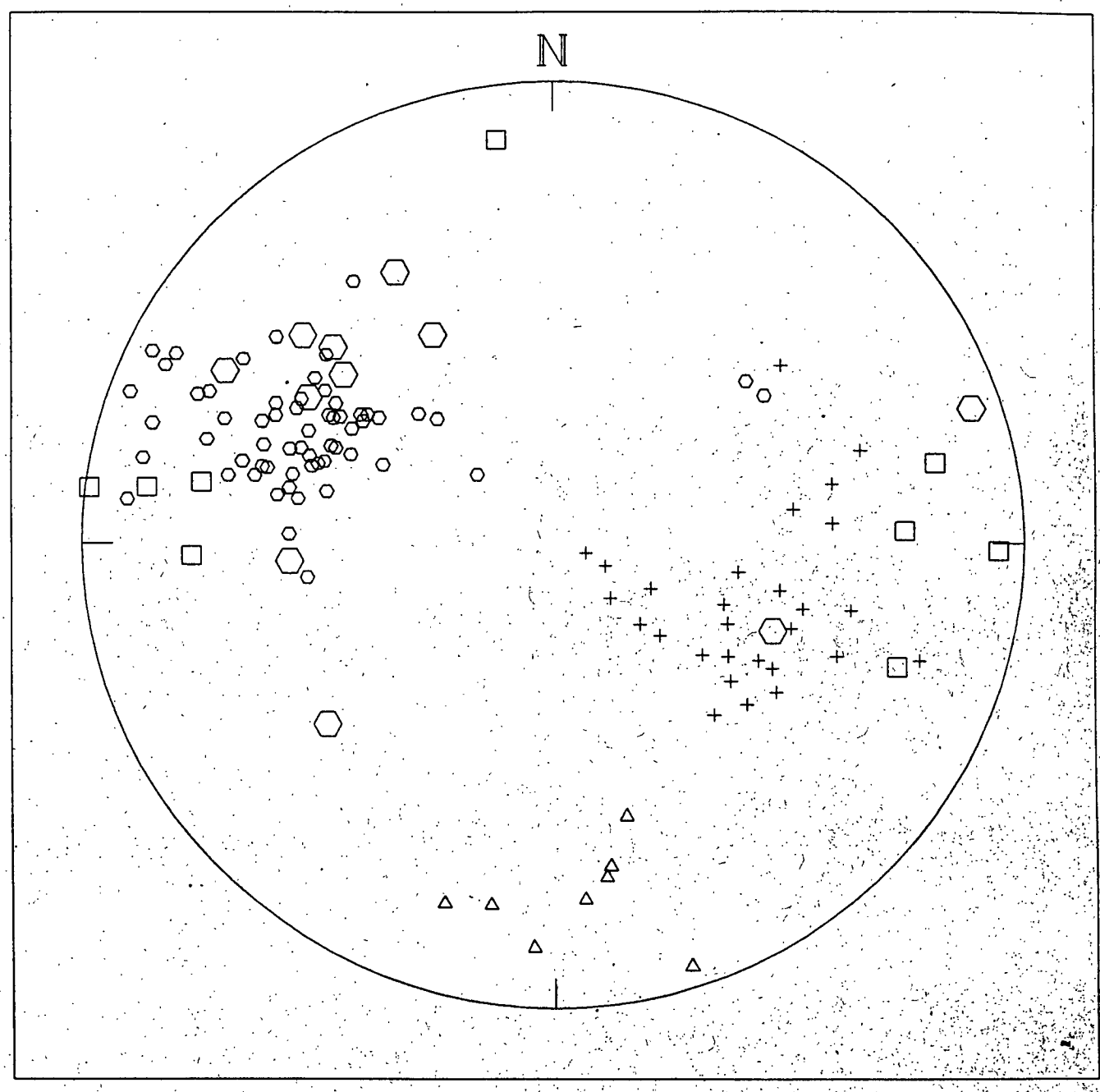
Sector 3

STERLING BROOK EAST

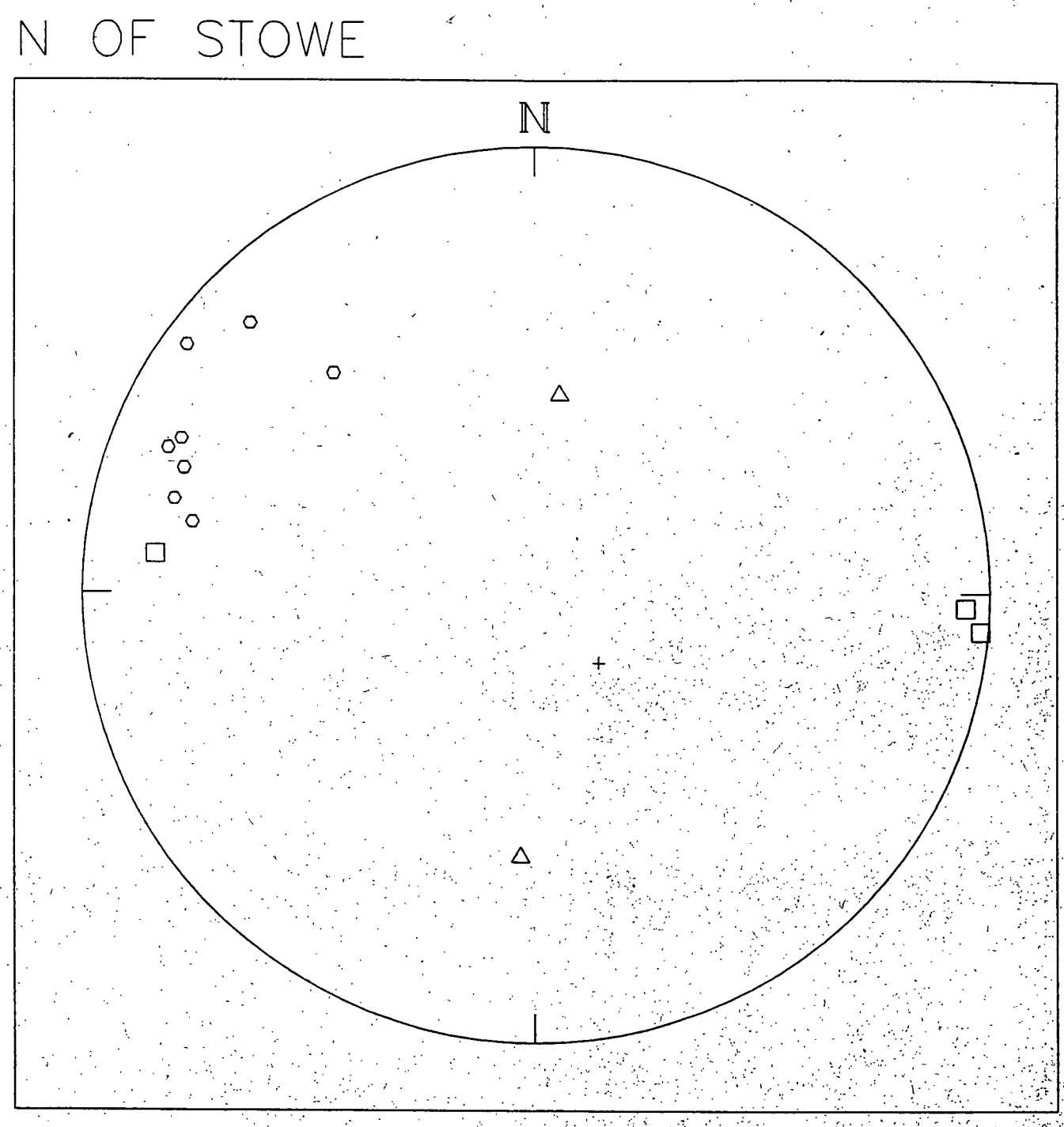


Sector 4

NORTHWEST OF ROUNDTOP

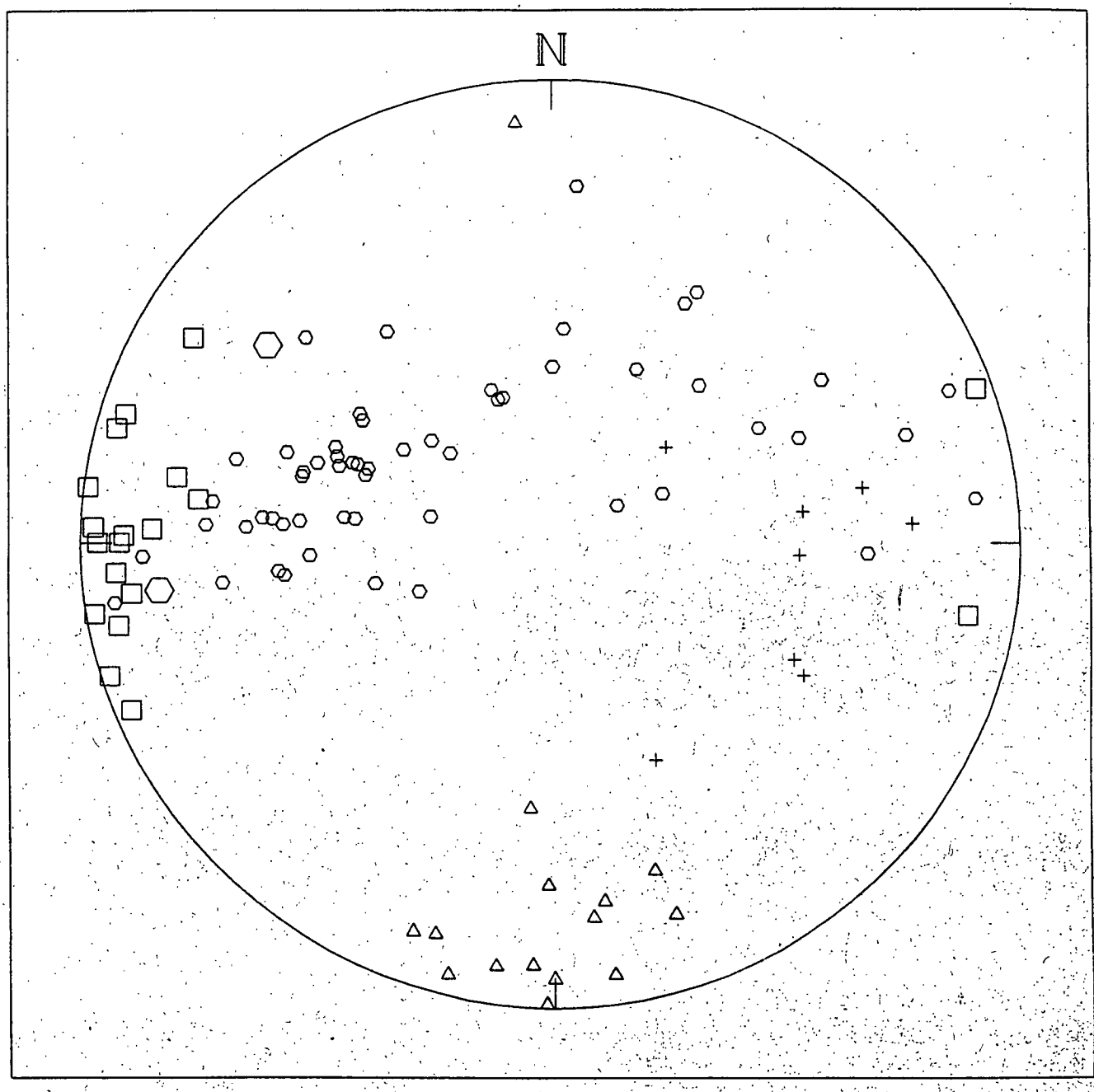


Sector 5



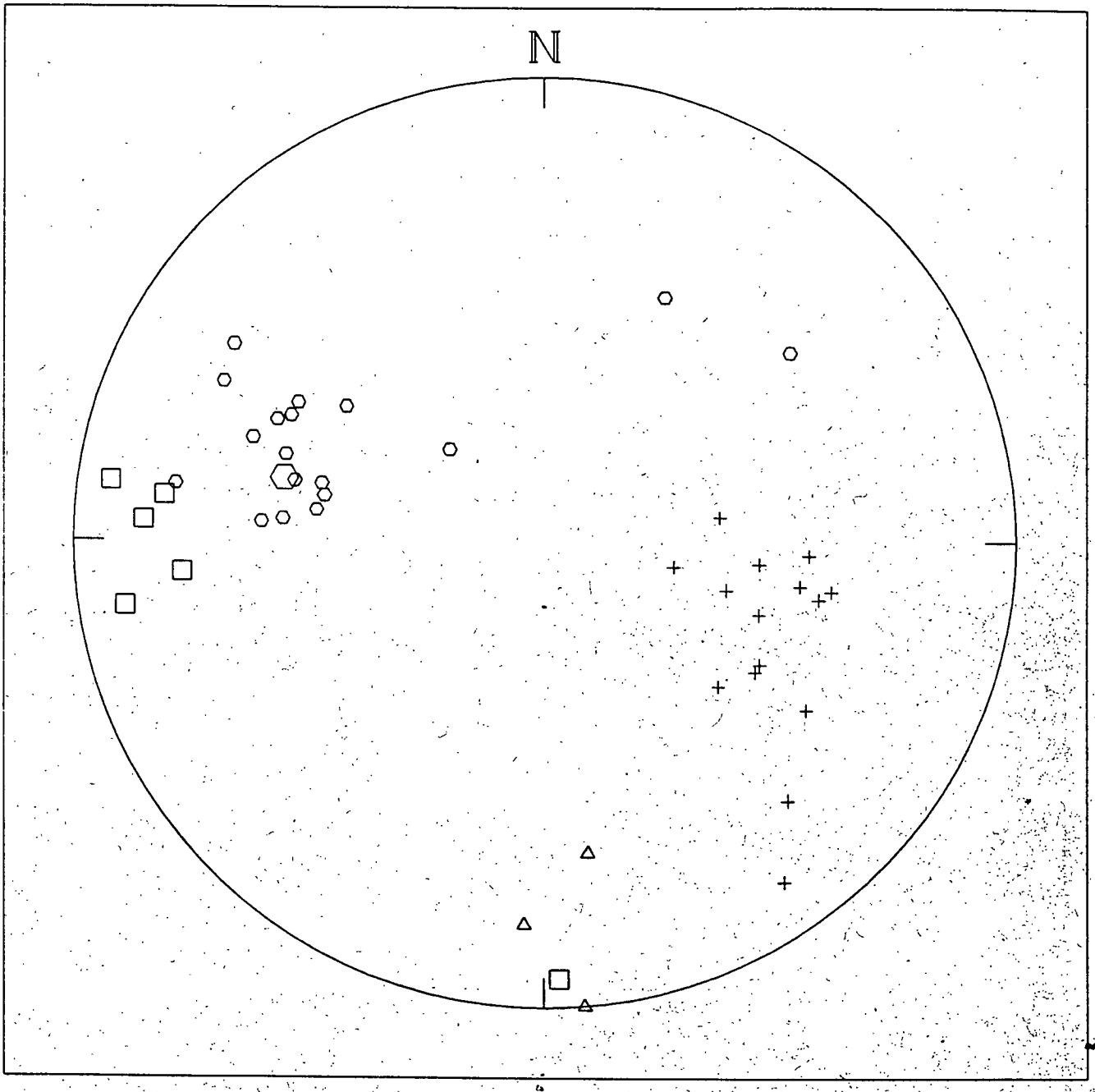
Sector 6

NORTH OF L. MANSFIELD



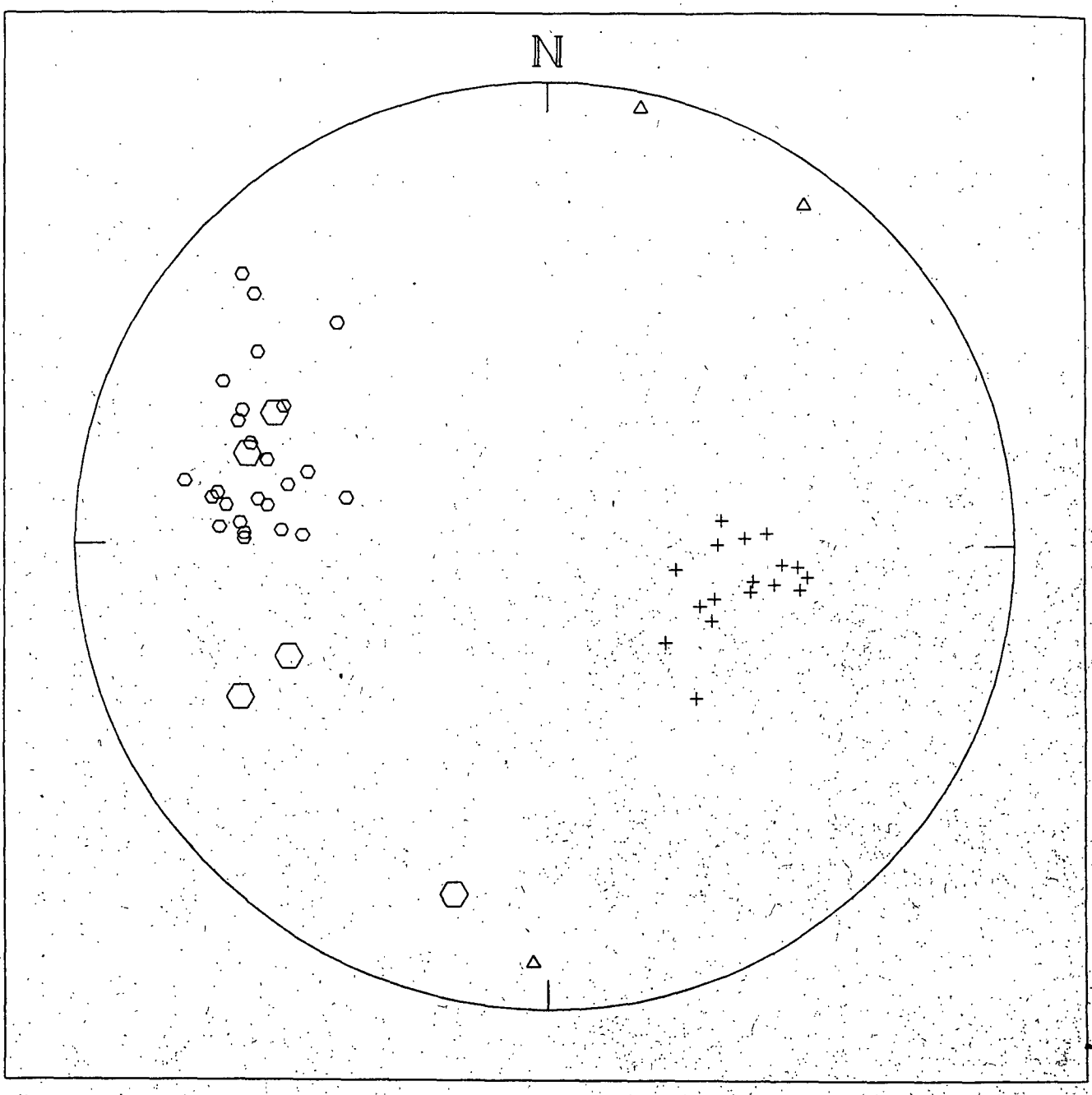
Sector 7

COUNTY ROAD AREA

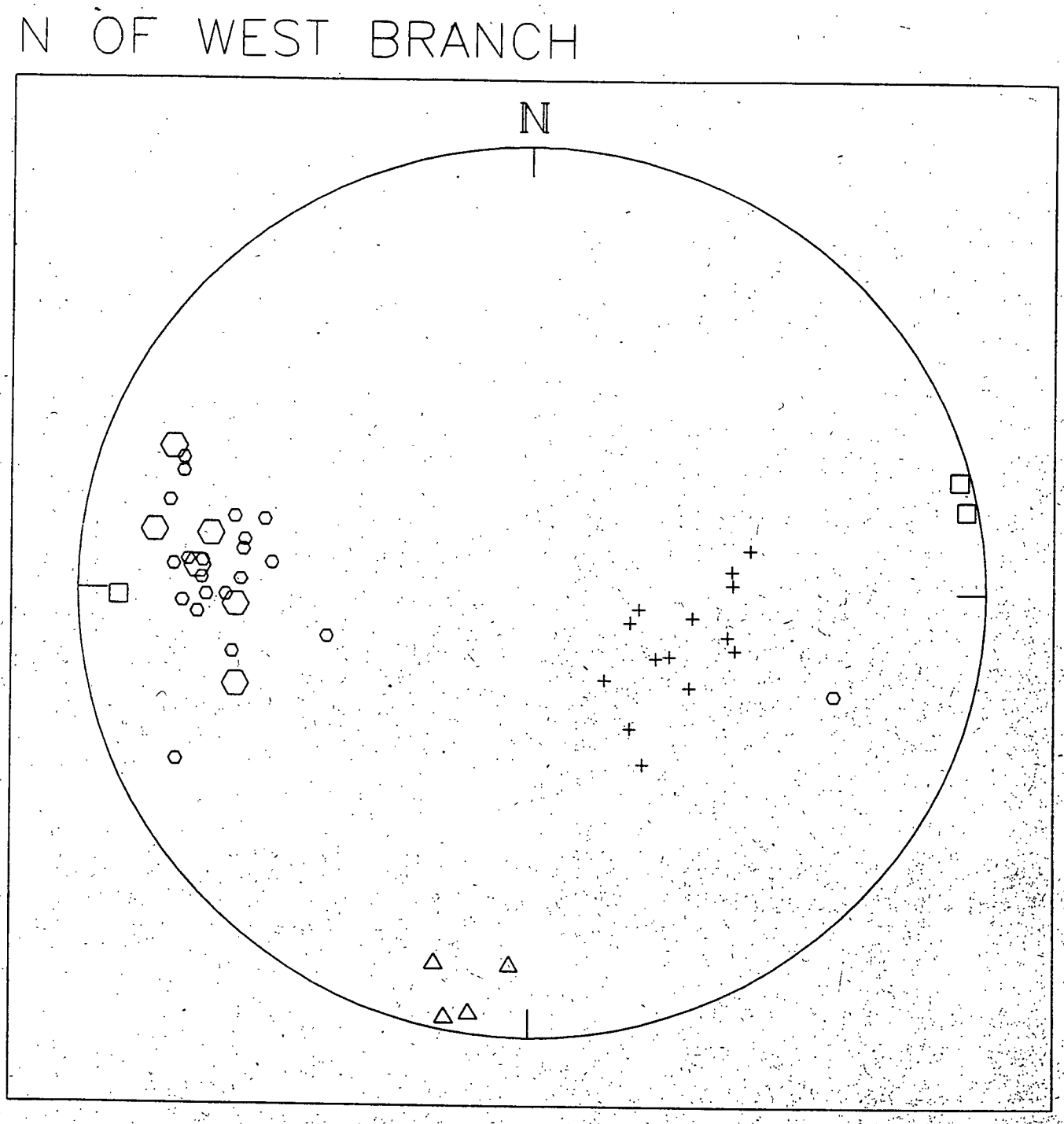


Sector 8

TRAPPS

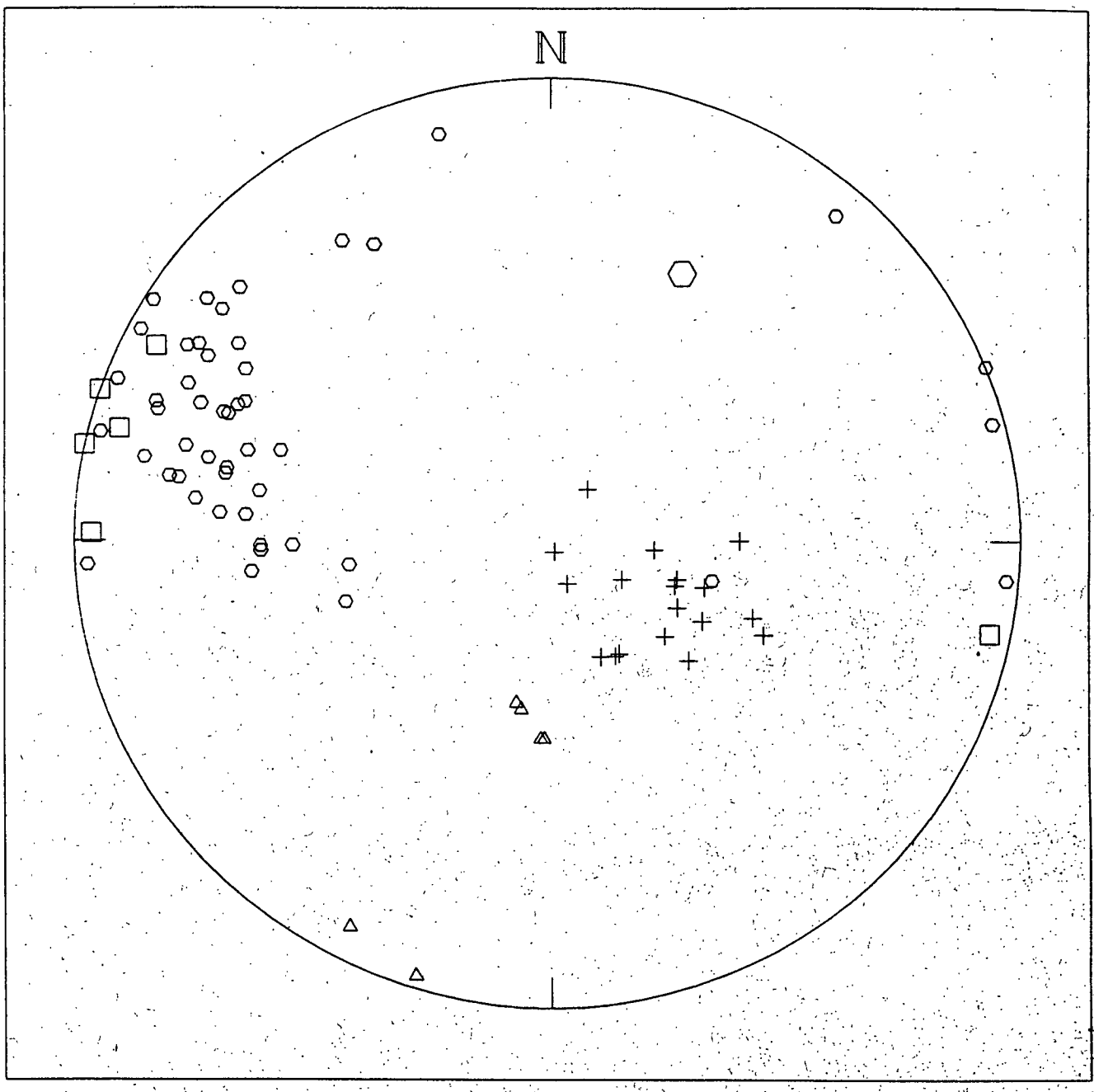


Sector 9



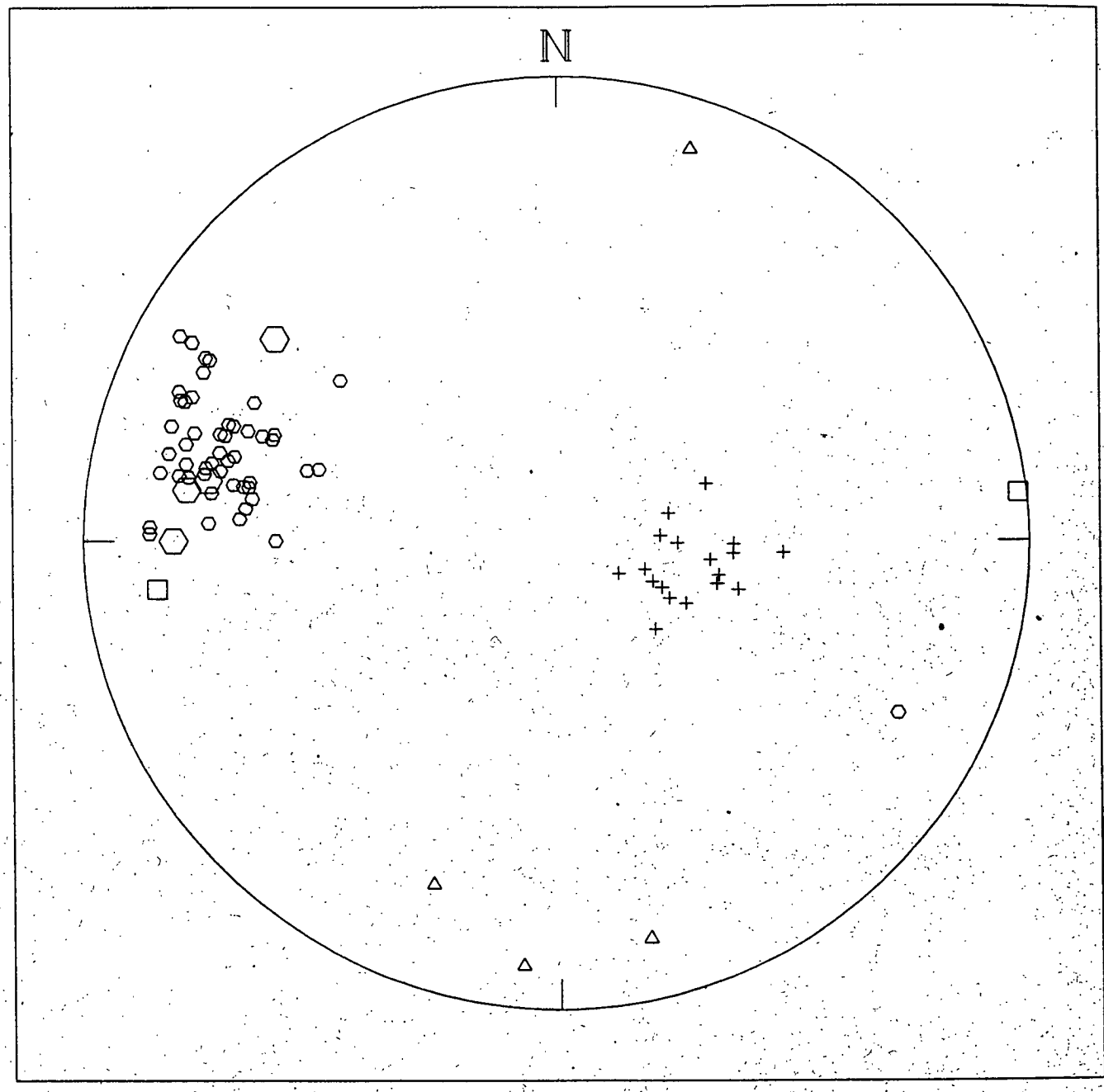
Sector 10

STOWE



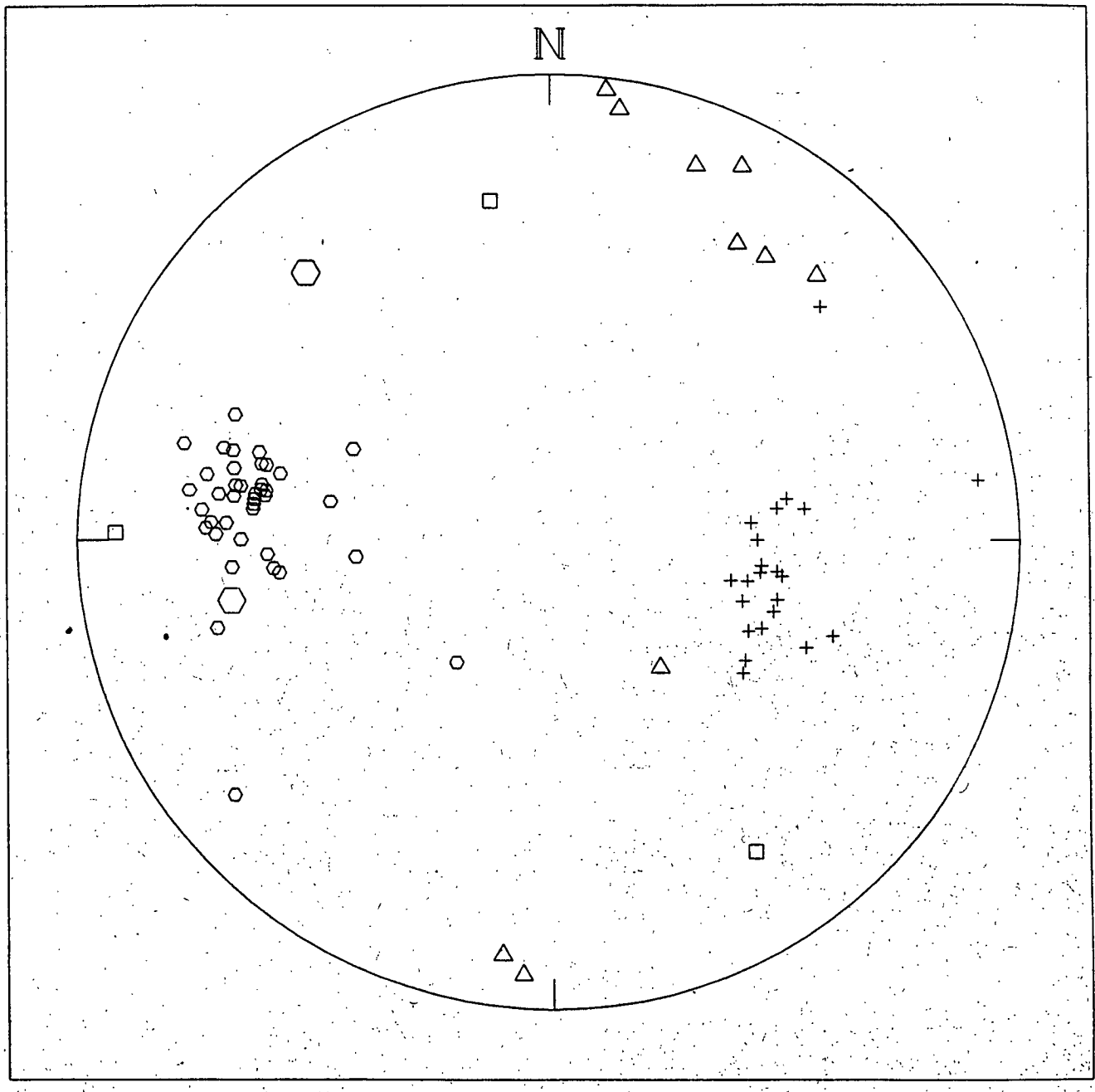
Sector 11

BARNES HILL AREA



Sector 12

MILLER BROOK AREA



72°47'30"
72°45'
72°40'
44°35'
44°30'
72°50'
44°22'30"

Mount Mansfield Quad.

Bolton Mountain Quad.

Sterling Mountain Quad.

Stowe Quad.

Descriptions of Rock Units
(Age relationships uncertain)

Stowe Fm.

Os	Fine-grained, silvery green quartz-muscovite-chlorite-albite-magnetite schist.

Ottauquechee Fm.

€o	Black, graphitic quartz-sericite phyllite with large euhedral pyrite cubes and interbedded dark quartzite. Beds of dark gray, foliated quartzite are common. Some outcrops of slightly rusty quartz-chlorite-muscovite schist without graphite or magnetite are present in the northern parts of this unit.
€oqd	Dark gray, foliated quartzite where mapped separately.
€oqt	Tan, foliated quartzite where mapped separately.
€og	Greenstone where mapped separately

Hazens Notch Fm.

€Zhn	Dark, rusty, graphitic chlorite-muscovite-biotite-quartz schist and gneiss, usually with dark albite porphyroblasts. Large euhedral pyrites are common. Beds of dark gray foliated quartzite are common. Includes some outcrops of dark, rusty schist without graphite.
€Zhnq	Dark gray foliated quartzite where mapped separately.
€Zhng	Greenstone where mapped separately.

Underhill Fm.

€Zu	Pale green to gray chlorite-muscovite-quartz (-magnetite-albite) schist. Albite porphyroblasts, when present, are light tan, not dark.

Mt. Abraham Schist

€Za	Silver-gray, magnetite-bearing chlorite-muscovite-quartz schist and phyllite without visible albite porphyroblasts and without graphite.

Bedrock Geology of the Stowe-Waterbury Area, North-Central Vermont

by
George Springston

Explanation

Contacts
Lithic contact. Dashed where approximate, dotted where inferred.

Thrust fault(pre-F3). Dashed where approximate, dotted where inferred.

Other Symbols
Latitude-longitude coordinates

Line of cross section

March, 1997

N
MN

0 Mile 1

72°47'30"
44°35'

72°45'

72°40'
44°35'

72°50'
44°30'

44°30'

N

44°22'30"
72°45'

44°22'30"
72°40'

Outcrop Map
Stowe - Waterbury Area
George Springston 3/97

Scale 1:24,000

72°47'30"
44°35'

72°45'

72°40'
44°35'

72°50'
44°30'

44°30'

PLANAR FEATURES
PRIMARY
BEDDING
SECONDARY
FOLIATION
Sn
Sn+1
Sn+2
AXIAL SURFACE OF FOLD
Fn+1
Fn+2
Fn+2 WITH VERTICAL DIP

LINEAR FEATURES
FOLD AXIS
Ln+1
Ln+2
Ln+2 SHOWING CLOCKWISE FOLD ASYMMETRY
MINERAL LINEATION
INTERSECTION LINEATION (Sn+2 ON Sn+1)
QUARTZ RODDING (PARALLEL TO Fn+1)
B.N. BOUDIN NECK LINE

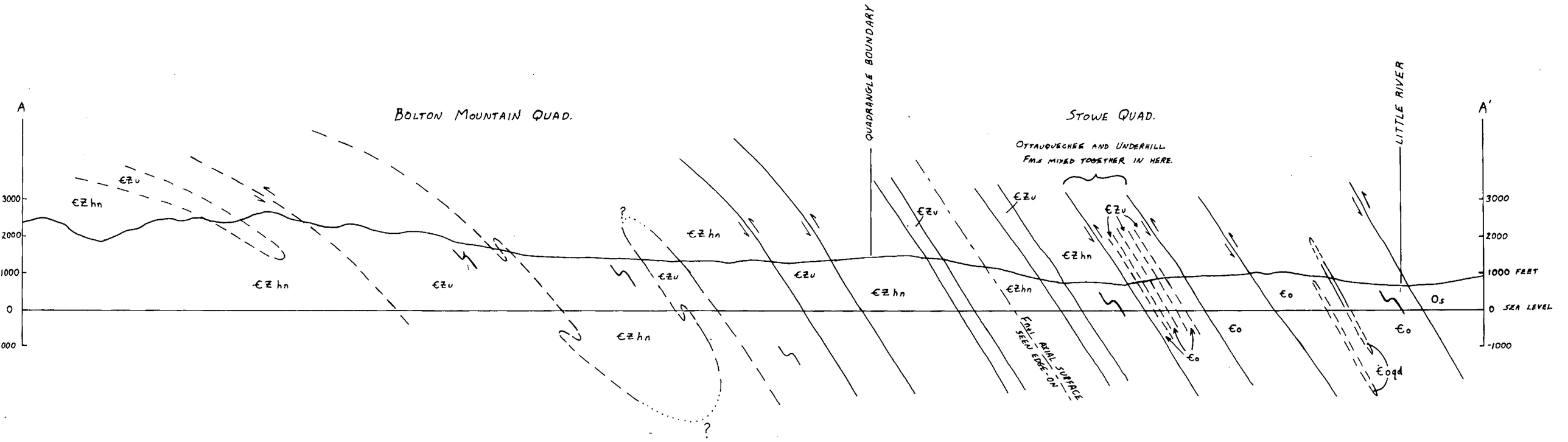
STRUCTURAL FEATURES MAP
STOWE - WATERBURY AREA
GEORGE SPRINGSTON 3/97

N

SCALE 1:24,000

44°22'30"
72°45'

44°22'30"
72°40'



GEOLOGIC CROSS SECTION
STOWE - WATERBURY AREA

SCALE 1:24,000, H=V

GEORGE SPRINGSTON
MARCH, 1997