



Internal deformation in the Backbone thrust sheet, Sawtooth Range, Montana
by Bethany A Ihle

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Earth Sciences

Montana State University

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Abstract:

The distribution and magnitude of internal deformation within thrust sheets is not well documented because internal deformation has generally been considered insignificant compared to shortening by thrust faulting across an entire thrust belt. However, in the Backbone thrust sheet in northwest Montana, internally deformed Middle Cambrian limestones are overlain by apparently undeformed shale and dolomite. The distribution, mechanisms and amount of internal deformation are documented using macroscopic, mesoscopic and microscopic structural elements for the purpose of determining their contribution to the overall shortening, the sequence of deformation and the mechanics of emplacement for the thrust sheet.

Macroscopic internal deformation varies laterally in the thrust sheet. Thrust faults create an imbricate zone at the leading edge whereas folds dominate the intraplate region. Mesoscopic internal deformation varies vertically with distance from thrust faults and lithology of the footwall. Three deformational domains are defined based on distribution of mesoscopic structural elements. Domain I, is proximal to the Backbone thrust and it is dominated by mesoscopic fault arrays and tectonic veins where Cambrian limestone is thrust over competent rocks. Where Cambrian limestone is thrust over shale, these features are less well-developed. Domain II is located in the strata overlying Domain I and in macroscopic intraplate folds. Domain II is cleavage dominated and contains mesoscopic folds, boudins and pencil structures. Domain III is the remaining undeformed strata in the upper part of the thrust sheet.

The important mechanisms of deformation in Domain I are faulting, extension fracturing, recrystallization and pressure solution. These mechanisms are significant at the mesoscopic and microscopic scales. Fault surfaces are affected by frictional sliding and pressure solution slip. The dominant mechanism of deformation in Domain II is pressure solution as indicated by spaced cleavage and pencil structures. Minor extensional fracturing is responsible for calcite veins and boudins.

Macroscopic folding and thrust imbrication contribute 55% internal shortening. Pressure solution deformation accounts for an additional 15% shortening; thus, total shortening due to internal deformation is approximately 70%. Fault zone deformation contributes simple shear strain and longitudinal shortening to internal deformation in Domain I.

The sequence of deformation in the Backbone thrust sheet is primarily constrained by geometric relationships between cleavage and structural elements. Cleavage formed early in the history of the thrust sheet, contemporaneously with microscopic strain. Macroscopic folding, formed during thrusting, postdates cleavage and passively rotated it into fans. Faulting was the final increment of deformation.

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MONTANA STATE UNIVERSITY
Bozeman, Montana

June 1988

APPROVAL

of a thesis submitted by

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency and is ready for submission to the College of Graduate Studies.

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ACKNOWLEDGEMENTS

Many individuals and funding sources were instrumental in getting me through this thesis. First I'd like to thank my funding sources, Chevron U.S.A, Tenneco and the Montana Geological Society who kept me in beer and supplies in the field. My advisor, Dr. David R. Lageson, suggested the project, guided my thinking on thrust sheet deformation and made comments which greatly improved this manuscript. Drs. James G. Schmitt and David W. Mogk served on the reading committee and contributed good ideas. Dr. John Childs provoked my thinking on the project and inspired me to continue. My student comrades were remarkable for their friendship and help during the stressful days. The remaining faculty and the office staff, especially Sara and Ann, are commended for handling the daily crises with a smile.

I'd like to thank Conrad Bressie who helped me overcome my fear of bears. My younger brother, Jack Ihle, made a noble effort to be interested in geology while serving five weeks as a field assistant. Thanks, Jack! Bill and Jimmie Jones of Dupuyer are given special thanks, for without their interest and generosity, this project would have taken much longer. It certainly would not have been as much fun!

Thanks, Craig, for your love and understanding.

Thanks, Monte, for the many things you taught me.

Last of all, I'd like to thank my family, especially my parents, Renee and Luther Ihle, for their support and encouragement, and for believing that I could do this.

TABLE OF CONTENTS

	Page
LIST OF TABLES.....	viii
LIST OF FIGURES.....	ix
LIST OF PLATES.....	xiii
ABSTRACT.....	xiv
INTRODUCTION.....	1
Purpose of Study.....	1
Area of Study.....	2
Previous Investigations.....	5
Methods of Investigation.....	6
GEOLOGIC SETTING.....	8
Deformation Zones.....	10
Zone I.....	12
Zone II.....	12
Zone III.....	12
STRATIGRAPHY.....	13
Paleozoic.....	13
Cambrian.....	13
Pentagon Shale.....	13
Steamboat Limestone.....	17
Switchback Shale.....	19
Devils Glen Dolomite.....	19
Devonian.....	19
Maywood Formation.....	19
Mississippian.....	20
Allan mountain Limestone.....	20
Castle Reef Dolomite.....	21
Mesozoic.....	21
STRUCTURAL ELEMENTS.....	22
Introduction.....	22
Macroscopic Structural Elements.....	29

TABLE OF CONTENTS--Continued

	Page
Backbone Thrust Sheet.....	30
Macroscopic Folds.....	31
Mesosopic Structural Elements.....	34
Faults.....	35
Lineations.....	42
Mesoscopic Folds.....	43
Cleavage.....	45
Cleavage in Thrust imbricates.....	47
Cleavage in Macroscopic folds.....	48
Cleavage in Mesoscopic folds.....	50
Cleavage Development.....	54
Boudins.....	54
Pencil Structure.....	57
Tectonic Veins.....	58
Extension Veins.....	59
Shear Veins.....	59
Summary.....	61
 MAGNITUDE OF INTERNAL DEFORMATION.....	 63
Fold Shortening.....	63
Thrust Imbrication.....	64
Pencil Structures.....	64
Cleavage.....	64
Boudins.....	65
En-Echelon Veins.....	66
Drag Folds.....	67
Fault arrays.....	67
Ooids.....	68
Data Collection and Method of Analysis.....	68
Thin Section Observations.....	76
Discussion.....	80
Domain I.....	80
Domain II.....	84
Microscopic Strain Summary.....	85
Summary.....	85
 DISCUSSION OF STRUCTURAL ELEMENTS AND INTERNAL DEFORMATION...	 87
Shortening.....	87
Sequence of Deformation.....	92
Mechanics of Emplacement.....	97

TABLE OF CONTENTS---Continued

	Page
CONCLUSIONS.....	99
REFERENCES CITED.....	102
APPENDICES.....	107
APPENDIX A. MEASURED STRATIGRAPHIC SECTIONS.....	108
APPENDIX B. OOID TRACINGS AND FRY DIAGRAMS.....	111

LIST OF TABLES

Table	Page
1. Cleavage association, morphology and orientation.....	46
2. Macroscopic-and mesoscopic-scale strain partitioning data from the Backbone thrust sheet.....	69
3. Ooid strain data.....	77

LIST OF FIGURES

Figure	Page
1. Generalized tectonic map of northwest Montana.....	3
2. Study area location map, Sawtooth Range.....	4
3. Sawtooth Range geometry, imbricate thrust systems.....	9
4. Structure contour map on top of crystalline basement.....	10
5. Lithotectonic units of the Sawtooth Range.....	11
6. Generalized stratigraphic column for the Swift Reservoir area.....	14
7. Stratigraphy of the Backbone thrust sheet.....	15
8. Intraplate macroscopic folds and thrust imbricates in Steamboat Limestone.....	22
9. Generalized geologic map of the study area.....	24
10. Cross section A-A' and table of mesoscopic structural elements	25
11. Cross section A'-A'' and table of mesoscopic structural elements.....	26
12. Cross section A''-A''' and table of mesoscopic structural elements.....	27
13. Cross section B-B' and table of mesoscopic structural elements.....	28
14. Poles to bedding, macroscopic and mesoscopic fold axes.....	32
15. Intraplate folds in Steamboat Limestone. Fold axes are moderately inclined, limbs nearly isoclinal.....	34
16. Step-like fault configuration developed at the base of the Backbone thrust sheet where limestone is thrust over shale.....	37
17. Close-up of Figure 16.....	37

LIST OF FIGURES--Continued

Figure	Page
18. Poles to faults, lineations and combined plot.....	38
19. Photomicrograph of fault zone deformation.....	41
20. Line sketches of mesoscopic folds.....	43
21. Diagram of the basic divisions of cleavage.....	46
22. Cleavage developed near thrust faults.....	47
23. Poles to cleavage formed near thrust faults and macroscopic folds, unrotated and rotated.....	49
24. Cleavage development in a mesoscopic fold.....	51
25. Photomicrograph showing relationship between cleavage and bedding.....	53
26. Slab photograph of cleavage in Steamboat Limestone.....	53
27. Boudins developed in Pentagon Shale.....	56
28. Boudin dimensions and shapes.....	56
29. Plot of boudin long axes and pencil structure lengths.....	57
30. Outcrop of pencil structures in Pentagon Shale.....	58
31. Outcrop of Steamboat Limestone at "p" containing abundant en-echelon vein sets.....	60
32. Poles to tectonic veins, singly occurring and en-echelon.....	60
33. Discontinuous boudins with d_{lx} defining width of each extension vein and l_{ox} defining width of each segment of host rock.....	66
34. Locations and sample numbers of oriented samples containing ooids.....	70
35. Tracing and manually-generated Fry diagram of sample SR2....	72
36. Tracing and manually-generated Fry diagram of sample SR5....	73
37. Tracing and manually-generated Fry diagram of sample SR12...	74

LIST OF FIGURES--Continued

Figure	Page
38. Tracing and manually-generated Fry diagram of sample SR15...	75
39. Flinn and Modified Flinn plots.....	79
40. Cross sections A-A' and A'-A'' with strain ellipses determined from the BC oriented plane.....	82
41. Cross sections A''-A''' and B-B' with strain ellipses determined from the BC oriented plane.....	83
42. Structural model for the Backbone thrust sheet.....	91
43. Timing and mechanisms of deformation.....	95
44. Measured stratigraphic section of the Pentagon Shale.....	109
45. Measured stratigraphic section of the Switchback Shale.....	110
46. Tracing and Fry Diagram of sample SR1, AC plane.....	112
47. Tracing and Fry Diagram of sample SR1, BC plane.....	113
48. Tracing and Fry Diagram of sample SR2, BC plane.....	114
49. Tracing and Fry Diagram of sample SR3, AC plane.....	115
50. Tracing and Fry Diagram of sample SR3, BC plane.....	116
51. Tracing and Fry Diagram of sample SR4, AC plane.....	117
52. Tracing and Fry Diagram of sample SR4, BC plane.....	118
53. Tracing and Fry Diagram of sample SR5, BC plane.....	119
54. Tracing and Fry Diagram of sample SR6, AC plane.....	120
55. Tracing and Fry Diagram of sample SR6, BC plane.....	121
56. Tracing and Fry Diagram of sample SR7, AC plane.....	122
57. Tracing and Fry Diagram of sample SR7, BC plane.....	123
58. Tracing and Fry Diagram of sample SR8, AC plane.....	124
59. Tracing and Fry Diagram of sample SR8, BC plane.....	125

LIST OF FIGURES--Continued

Figure	Page
60. Tracing and Fry Diagram of sample SR9, AC plane.....	126
61. Tracing and Fry Diagram of sample SR9, BC plane.....	127
62. Tracing and Fry Diagram of sample SR10, AC plane.....	128
63. Tracing and Fry Diagram of sample SR10, BC plane.....	129
64. Tracing and Fry Diagram of sample SR11, AC plane.....	130
65. Tracing and Fry Diagram of sample SR12, AC plane.....	131
66. Tracing and Fry Diagram of sample SR13, AC plane.....	132
67. Tracing and Fry Diagram of sample SR13, BC plane.....	133
68. Tracing and Fry Diagram of sample SR14, AC plane.....	134
69. Tracing and Fry Diagram of sample SR14, BC plane.....	135
70. Tracing and Fry Diagram of sample SR15, AC plane.....	136
71. Tracing and Fry Diagram of sample SR15, BC plane.....	137
72. Tracing and Fry Diagram of sample SR16, AC plane.....	138
73. Tracing and Fry Diagram of sample SR17, AC plane.....	139
74. Tracing and Fry Diagram of sample SR17, BC plane.....	140
75. Tracing and Fry Diagram of sample SR18, AC plane.....	141
76. Tracing and Fry Diagram of sample SR18, BC plane.....	142
77. Tracing and Fry Diagram of sample SR19, AC plane.....	143
78. Tracing and Fry Diagram of sample SR19, BC plane.....	144

LIST OF PLATES

Plate	Page
1. Geologic map of the Swift Reservoir area, Sawtooth Range, Montana.....	(in pocket)

ABSTRACT

The distribution and magnitude of internal deformation within thrust sheets is not well documented because internal deformation has generally been considered insignificant compared to shortening by thrust faulting across an entire thrust belt. However, in the Backbone thrust sheet in northwest Montana, internally deformed Middle Cambrian limestones are overlain by apparently undeformed shale and dolomite. The distribution, mechanisms and amount of internal deformation are documented using macroscopic, mesoscopic and microscopic structural elements for the purpose of determining their contribution to the overall shortening, the sequence of deformation and the mechanics of emplacement for the thrust sheet.

Macroscopic internal deformation varies laterally in the thrust sheet. Thrust faults create an imbricate zone at the leading edge whereas folds dominate the intraplate region. Mesoscopic internal deformation varies vertically with distance from thrust faults and lithology of the footwall. Three deformational domains are defined based on distribution of mesoscopic structural elements. Domain I is proximal to the Backbone thrust and it is dominated by mesoscopic fault arrays and tectonic veins where Cambrian limestone is thrust over competent rocks. Where Cambrian limestone is thrust over shale, these features are less well-developed. Domain II is located in the strata overlying Domain I and in macroscopic intraplate folds. Domain II is cleavage dominated and contains mesoscopic folds, boudins and pencil structures. Domain III is the remaining undeformed strata in the upper part of the thrust sheet.

The important mechanisms of deformation in Domain I are faulting, extension fracturing, recrystallization and pressure solution. These mechanisms are significant at the mesoscopic and microscopic scales. Fault surfaces are affected by frictional sliding and pressure solution slip. The dominant mechanism of deformation in Domain II is pressure solution as indicated by spaced cleavage and pencil structures. Minor extensional fracturing is responsible for calcite veins and boudins.

Macroscopic folding and thrust imbrication contribute 55% internal shortening. Pressure solution deformation accounts for an additional 15% shortening; thus, total shortening due to internal deformation is approximately 70%. Fault zone deformation contributes simple shear strain and longitudinal shortening to internal deformation in Domain I.

The sequence of deformation in the Backbone thrust sheet is primarily constrained by geometric relationships between cleavage and structural elements. Cleavage formed early in the history of the thrust sheet, contemporaneously with microscopic strain. Macroscopic folding, formed during thrusting, postdates cleavage and passively rotated it into fans. Faulting was the final increment of deformation.

INTRODUCTION

Purpose of Study

Deformation of rocks in fold and thrust belts includes elements of three fundamental processes: 1) translation along faults; 2) rotation of strata; and 3) internal deformation. Translations and rotations have been measured and integrated in regional scale studies which determine structural geometry, sequence of events and the amount of shortening in thrust belts (e.g. Royse and others, 1975, Dahlstrom, 1970). However, the distribution and degree of internal deformation and its contribution to shortening within thrust sheets is less well documented. Internal deformation has generally been considered insignificant compared to shortening across an entire thrust belt (Allmendinger, 1982, Elliott, 1976b).

In the Swift Reservoir area of northwestern Montana, internally deformed middle Cambrian strata are overlain by apparently undeformed upper Cambrian and Devonian strata in the Backbone thrust sheet (Singdahlson, 1986). This study was undertaken to address the significance of this internal deformation and the observed strain heterogeneity. More specifically, the goals of this study were: 1) to define the variation in style and intensity of internal deformation; 2) to identify the mechanisms that produced the deformation; 3) to quantify internal deformation and determine its contribution to shortening within the thrust sheet; and 4) to determine the sequence of

deformation and identify features which provide insight into mechanics of emplacement of the Backbone thrust sheet using macroscopic, mesoscopic and microscopic structural elements.

Understanding the internal deformation within thrust sheets is important for several reasons. First, internal deformation is not accounted for in constructing balanced cross sections, and yet it may represent a significant amount of the total shortening. Second, variations in the distribution of internal deformation have many implications for exploration geology including subsurface predictions of geometry and depth continuity of structures. Third, studies of internal deformation can provide constraints for determining the sequential development of thrust sheets (e.g. Simon and Gray, 1982) and may contribute to understanding the mechanical processes involved in emplacement of coherent thrust sheets (e.g. Reks and Gray, 1983; Allmendinger, 1982).

Area of Study

The Sawtooth Range of northwestern Montana is part of the Cordilleran foreland fold and thrust belt (Figure 1). It lies directly south of Glacier National Park and is characterized by complexly thrust and folded Paleozoic and lower Mesozoic sedimentary rocks. The Swift Reservoir study area is located in the northern part of the Sawtooth Range (Figure 2). The northwest trending Backbone thrust sheet in the Swift Reservoir area is composed of numerous smaller-scale thrust imbricates and intraplate folds; its surface trace is about 13 km long. The Backbone thrust places Cambrian and Devonian strata over

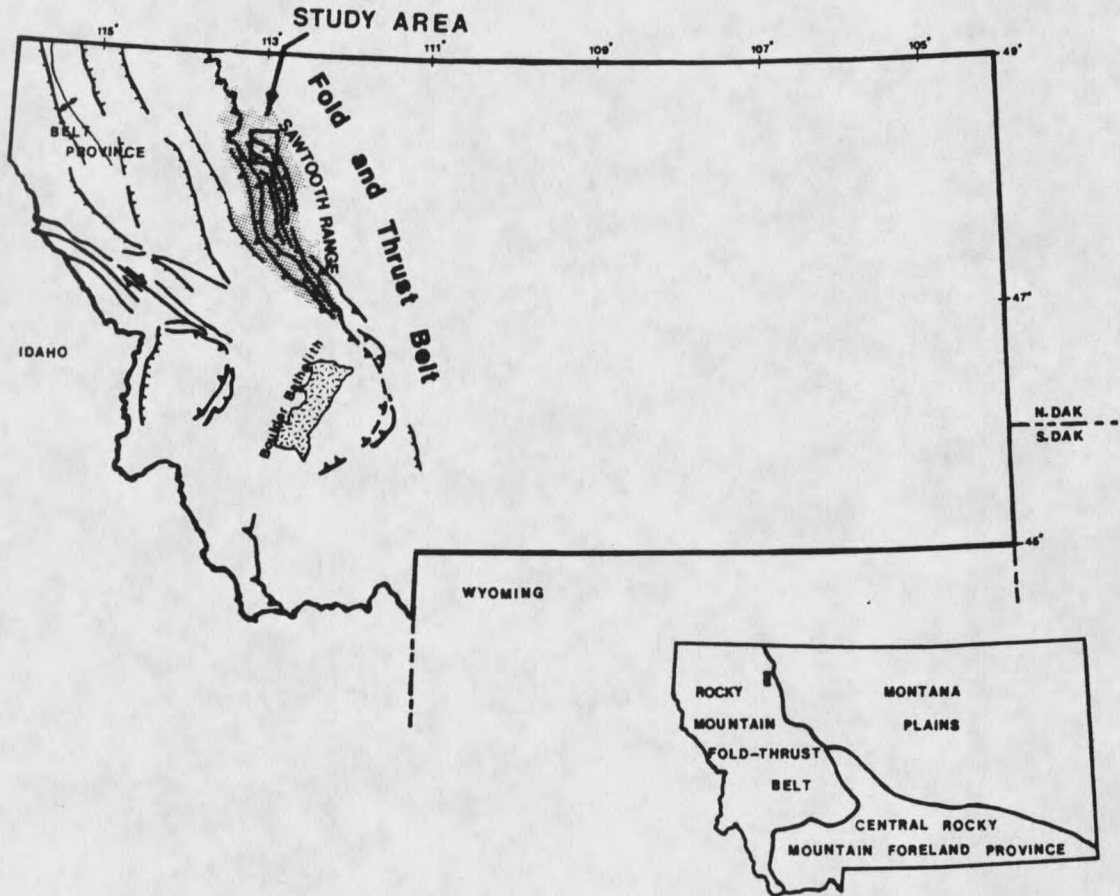


Figure 1. Generalized tectonic map of northwestern Montana (after Taylor and Ashley, 1986).

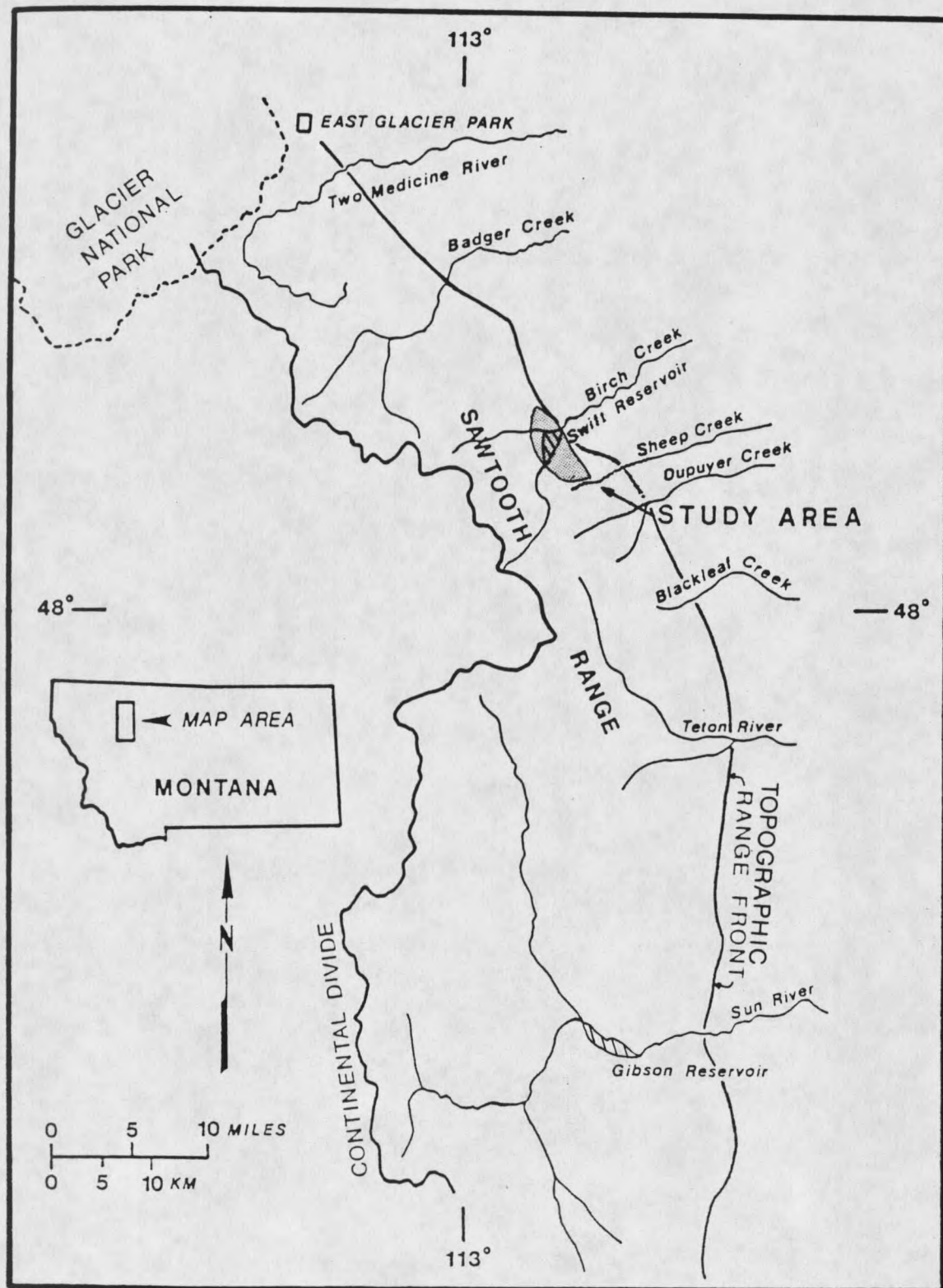


Figure 2. Study area location map, Sawtooth Range (from Singdahlsen, 1986).

Upper Paleozoic and Mesozoic strata. Excellent exposure of the Backbone thrust sheet and its footwall strata occur along the shores of Swift Reservoir and Birch Creek which flows normal to the strike of the thrust.

The study area is approximately 25 km west of the town of Dupuyer, Montana in Pondera and Teton Counties. Access to the area is by a maintained gravel road to the Swift Dam site, then by foot and horse trails. The area is covered by the Fish Lake and Swift Reservoir 7.5 minute United States Geological Survey topographic quadrangles.

Previous Investigations

Previous geologic studies of the Sawtooth Range and surrounding area provided an overall structural and stratigraphic framework for this study. Stratigraphic investigations by Deiss (1939) and Mudge (1972a) defined mappable units and lithologic characteristics of Paleozoic strata in the Sawtooth Range. Deiss (1943b), Mudge (1972b), and Mudge and Earhart (1980), have discussed the regional structural framework. Mudge (1982) also provided an excellent summary of the structural geology of the Sawtooth Range and surrounding area.

Several master's theses of the Swift Reservoir area provided the preliminary geologic mapping, structural analysis and stratigraphic interpretations needed to undertake this study. Most recently, Singdahlsen (1986) conducted geologic mapping and a structural analysis of the Mesozoic and Paleozoic units in the area from Swift Reservoir south to Dupuyer Creek. His work suggested that Swift Reservoir is on a structural culmination formed by polyphase deformation of the

Backbone thrust sheet. A study of the area directly west of Swift Reservoir by Feucht (1971) concentrated primarily on stratigraphy and deformational styles. His work provided the first estimates of principal stress directions for deformation from stereonet plots of bedding and fold axes.

Methods of Investigation

To achieve the defined study goals, field investigation, structural analysis, strain analysis and petrographic examination were performed. Field investigation was initiated in 1986 by conducting detailed geologic mapping of macroscopic structural elements at a scale of 1:8,000. Sites with good exposures of mesoscopic structural elements were then examined and are designated in the text by stations with small letters. At each station, orientations of geometric elements, kinematic indicators and their relationship to other structures were recorded. Sampling for petrographic study included oriented samples of rocks from fault zones, cleavage, vein-fill material and boudins. In addition, 19 oriented samples of oolites were collected for strain analysis; sampling and analytical procedures are discussed in a later section.

Structural analysis consisted of plotting geometric elements of both macroscopic and mesoscopic structures on lower hemisphere equal area stereonets. From these data, the areal kinematic axes were determined and local deviations noted. The pre-thrust orientation of cleavage was determined by rotating bedding back to horizontal.

Variations in internal deformation were determined by detailing the

distribution and intensity of development of macroscopic and mesoscopic structural elements. Petrographic inspection of cleavage and rocks from fault zones provided information on internal deformation at the microscopic scale. Deformation mechanisms were determined by comparing outcrop and petrographic observations with similar observations cited in literature covering other fold and thrust belts. The amount and significance of internal deformation was approximated by various techniques using macroscopic and mesoscopic structural elements. Microscopic strain was determined using the Fry Method (Fry, 1979) on the oriented samples containing ooids. These data were then analyzed to determine the sequence of deformation and a reasonable emplacement history for the Backbone thrust sheet.

GEOLOGIC SETTING

The Sawtooth Range is an arcuate salient within the Cordilleran foreland fold and thrust belt. It consists primarily of west-dipping, closely-spaced thrust faults and complex folds in Paleozoic and Mesozoic strata. The Sawtooth Range corresponds to Subbelt II in Mudge's (1982) subdivision of the Northern Disturbed Belt. Mudge (1982) also provides an excellent summary of tectonic and stratigraphic relations of the Sawtooth Range and surrounding region. Deformation in the fold and thrust belt, constrained by radiometric age dates and structural relationships, occurred primarily in the Paleocene (Mudge, 1982).

The overall geometry of the Sawtooth Range is characterized as an imbricate thrust system (Boyer and Elliott, 1982). An imbricate thrust system is defined by thrust sheets whose thrusts repeat the size and shape of the neighboring thrust so that the sheets overlap like roof tiles (Boyer and Elliott, 1982). Imbricate thrust systems are divided into two major types: imbricate fans and duplexes (Figure 3). Boyer and Elliott (1982) and Mitra (1986) suggest that the Sawtooth Range is a large duplex structure whose roof thrust (Lewis thrust) has eroded leaving the underlying thrust sheets exposed. Boyer and Elliott (1982) also suggest that the Sawtooth Range may be a trailing imbricate fan where the thrust with the largest displacement (Lewis thrust) was ramped behind a series of imbricate thrust sheets but never covered

them (Figure 3). In both interpretations, the deformation that formed the Sawtooth Range affected Paleozoic and Mesozoic rocks structurally below the Lewis thrust sheet.

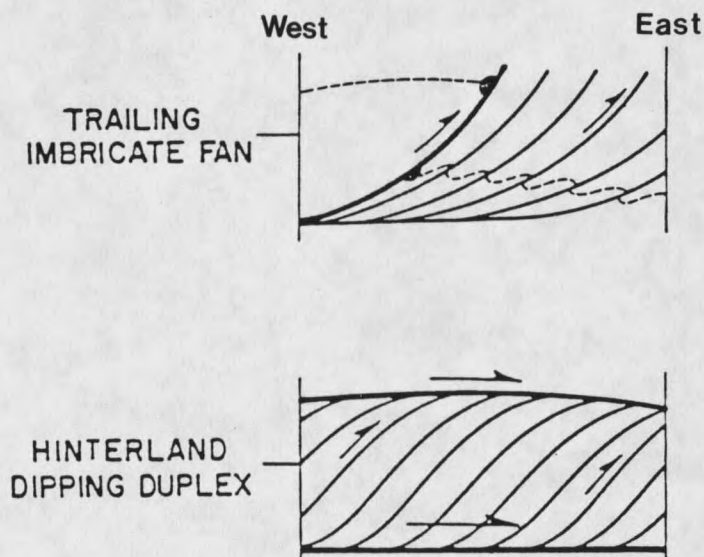


Figure 3. Sawtooth Range geometry generalized by two types of thrust system (from Boyer and Elliott, 1982).

The configuration of the Precambrian crystalline basement probably played an important role in the structural development of the Sawtooth Range (Mudge, 1982). The Sweetgrass Arch, composed of the Kevin-Sunburst Dome and the South Arch, is a basement high located just east of the central part of the Sawtooth Range. It is thought to have acted as a buttress which caused thrusts to ramp steeply during their translation eastward (Mudge, 1982). This high, established prior to Middle Jurassic sedimentation (Mudge, 1982), is reflected by northwest trending structure contours on top of the crystalline basement (Figure 6).

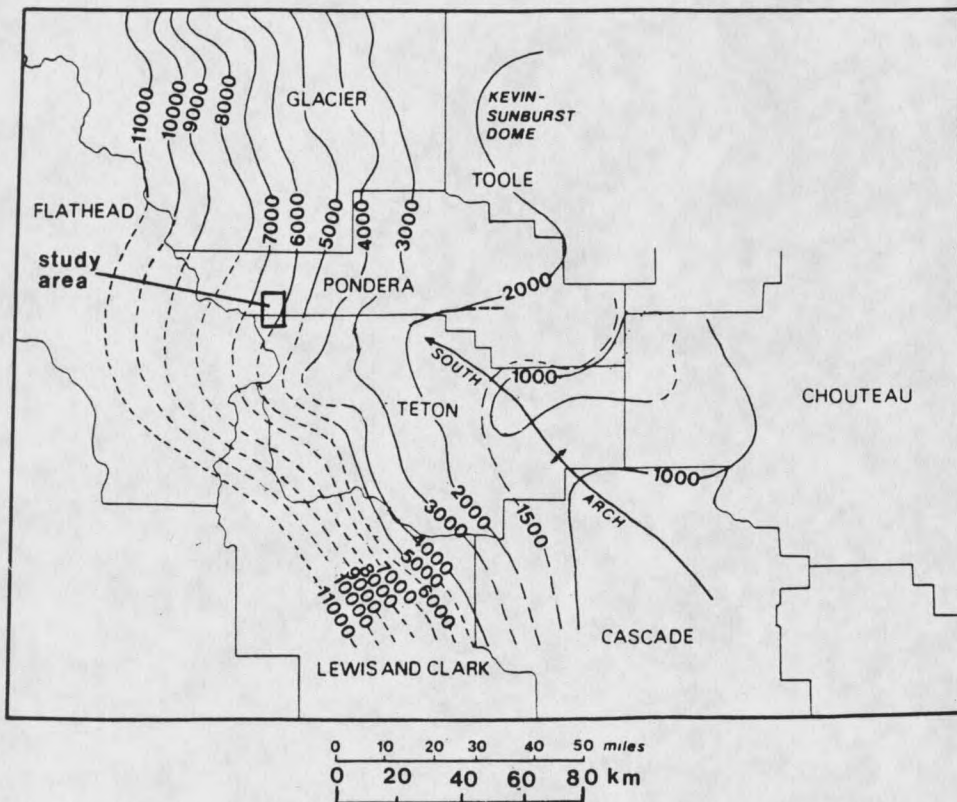


Figure 4. Structure map on top of the crystalline basement, in feet below sea level (after Mudge, 1982).

Deformation Zones

Lithologic contrasts in the stratigraphic succession of the Sawtooth Range create multilayer packages with competent and incompetent layers exhibiting different structural styles. These multilayer packages are often referred to as lithotectonic units (e.g. Mitra, 1986; Reks and Gray, 1983). Three lithotectonic units, or zones, are recognized in the Sawtooth Range (Figure 7) (Lageson and Ihle, 1987).

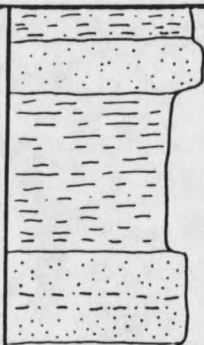
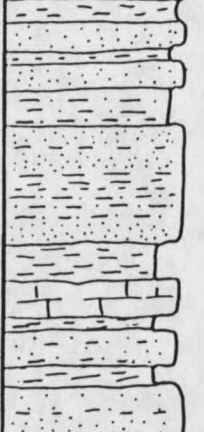
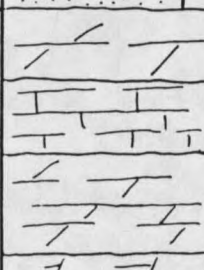
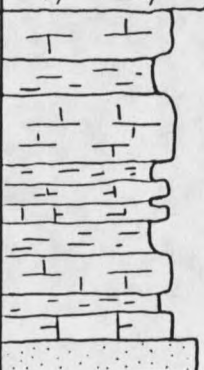
Stratigraphic Column		Lithotectonic Unit	Stratigraphy
Cretaceous		Interbedded limestone, sandstone, shale and mudstone - closely-spaced thrust faults and fold trains	Two Medicine Fm
			Virgelle Sandstone
			Telegraph Creek Fm
			Marias River Sh
			Blackleaf Fm
			Kootenai Fm
			Morrison Fm
			Swift Fm
			Rierdon Fm
			Sawtooth Fm
ZONE 3			1350 - 2000 m
Mid - Upper Jurassic		Massively-bedded dolomites and limestones - kilometer-scale concentric, chevron and box folds - imbricate thrust faults	Castle Reef Dol
			Allen Mountain Ls
			Three Forks Fm
			Jefferson Fm
			Maywood Fm
ZONE 2			175 - 550 m
Mid - Up Dev / Miss		Interbedded limestone and shale - tightly spaced disharmonic folds - thrust faults at all scales - spaced cleavage, fracturing, boudins, pencil structures	Devils Glen Dol
			Switchback Shale
			Steamboat Ls
			Pentagon Shale
			Pagoda Limestone
			Damnation Ls
			Gordon Shale
			Flathead Sandstone
ZONE 1			380 - 700 m
Mid - Upper Cambrian			

Figure 5. Lithotectonic units of the Sawtooth Range.

Zone I

Zone I is the Cambrian stratigraphic section containing interbedded shales and limestones. It is characterized by intensely folded and imbricated strata of all scales, and locally developed penetrative deformation. This penetrative deformation includes cleavage, boudinage, pencil structure and fault zone deformation. Zone I is the most highly deformed and internally strained of the three zones, and analysis of Zone I deformation in the Swift Reservoir area is the primary focus of this study.

Zone II

Zone II is the Devonian through Mississippian section, dominated by northerly trending thrust imbricates of massively bedded dolomite and limestone. The fold style of Zone II is characterized by kilometer-scale folds with chevron, concentric and box geometries. In a mechanical sense, Zone II forms a rigid, competent beam between Zones I and III.

Zone III

Zone III is the Jurassic and Cretaceous succession of interbedded marine and non-marine clastics. The structural style of Zone III is characterized by abundant, imbricate thrust faults with small offset and tight, asymmetric folds; however, penetrative deformation is less intense than that recorded in Zone I.

STRATIGRAPHY

Paleozoic and Mesozoic sedimentary strata are found in the study area (Figure 6). This study concentrates on deformation in the Middle Cambrian units; therefore, these will be discussed in detail (Figure 7). For more detailed descriptions of the remaining units, the reader is referred to Mudge (1972a). The carbonate classification scheme used is from Dunham (1962).

The style and mechanisms of deformation in the study area are closely associated with the lithologic character of stratigraphic units. During the course of field mapping, units defined in prior work (Mudge, 1972a) were found to be useful with some minor exceptions.

Paleozoic

Cambrian

Middle to Late Cambrian rocks are the oldest strata exposed in the Swift Reservoir area. The Cambrian section has been divided into nine formations in the Sawtooth Range (Deiss, 1939), but only the Middle Cambrian Pentagon Shale, Steamboat Limestone and Switchback Shale, and Upper Cambrian Devils Glen Dolomite are recognized in the study area.

Pentagon Shale. The Pentagon Shale is herein designated to be the shaley unit below the Steamboat Limestone. Controversy exists in the literature as to whether this shaley unit belongs to the basal Steamboat Limestone, or whether it is part of the Pentagon Shale.

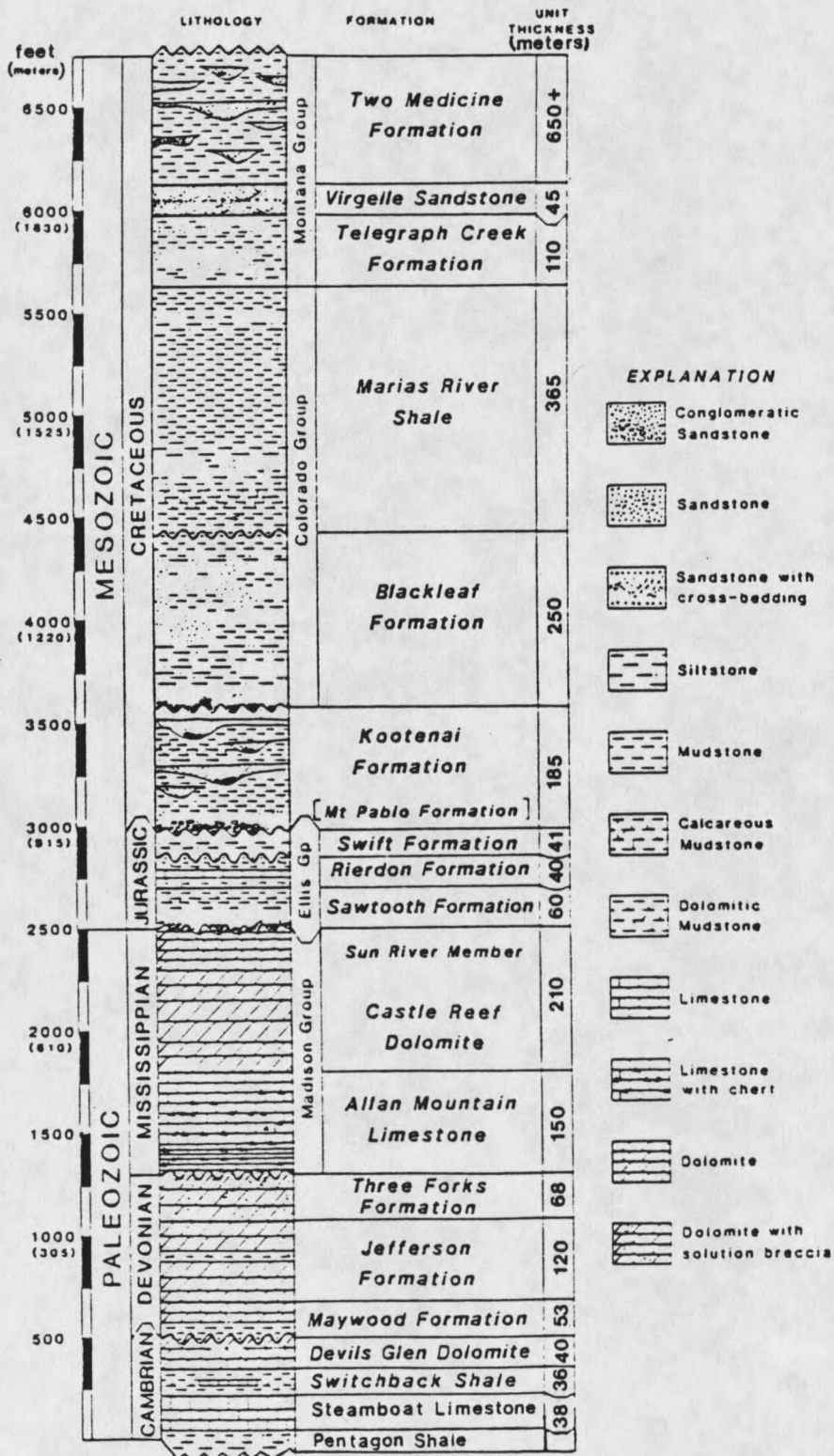


Figure 6. Generalized stratigraphic column of the Swift Reservoir area (after Singdahlsen, 1986).

STRATIGRAPHY OF THE BACKBONE THRUST SHEET

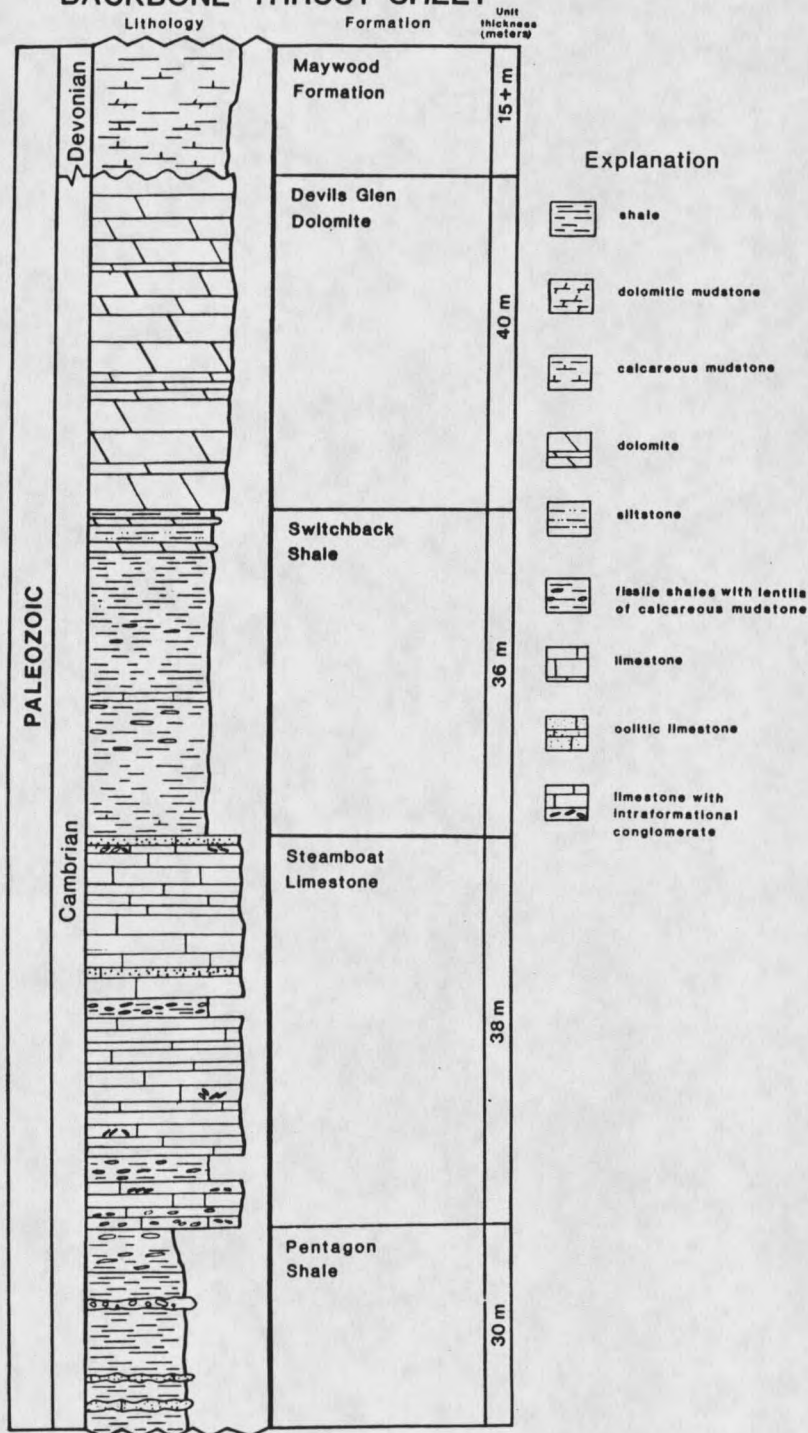


Figure 7. Stratigraphy of the Backbone thrust sheet in the Swift Reservoir area (from Feucht, 1971).

This stratigraphic problem was addressed because the Pentagon Shale is important for determining structural relationships in the field.

The controversy stems from the rapid changes in thickness and lithology which characterize Middle Cambrian units in the Sawtooth Range, and from the lack of accurate fossil identifications. Deiss (1939) measured 88 meters (m) of Pentagon Shale on Pentagon Mountain, about 30 kilometers (km) southwest of the study area, and believed that the formation thickened to the north. Theodosius (1955) tentatively identified fossils along the south fork of Whitetail Creek, about 8 km northwest of the study area, and indicated that a facies of the Pentagon Shale may be present there. Mudge (1972a) suggested that the Pentagon Shale is only of local extent near Pentagon Mountain because it is not present 35 km to the south in the Cambrian section of the Sun River Canyon. Feucht (1971) assigned this lowermost shale unit to the Pentagon Shale; his interpretation is based on extrapolation of the section northward as suggested by Deiss (1939). Singdahlsen (1986) assigned the shale to the basal part of the Steamboat Limestone based on lithologic similarities with shaly units of the Steamboat Limestone in the Sun River Canyon (Mudge, 1972a).

This study assigns the shaley unit to the Pentagon Shale rather than the Steamboat Limestone for two reasons. First, a thickness of greater than 20 m for the shale was measured in Phillips Creek (Appendix A). Deiss (1939) states that thicknesses of shaley intervals within the Steamboat Limestone generally do not exceed 4 m, therefore a separate unit is indicated. Second, Theodosius (1955) observed that the Pentagon Shale possibly exists north of Swift Reservoir. This

information, combined with Deiss' (1939) suggestion of a northward thickening section from Pentagon Mountain, indicates that Pentagon Shale crops out in the study area.

The Pentagon Shale consists primarily of maroon to chocolate brown, fissile, slightly micaceous, calcareous shale with several interbeds of resistant mudstone. A detailed measured partial section from Phillips Creek is found in Appendix A. The interbedded mudstones are wavy, up to 0.6 m thick, and are either fossiliferous or oolitic, or contain flat pebble, intraformational conglomerates. The mudstones are green-colored in outcrop and dark grey on fresh surfaces. A sequence of green shale with interbeds and lentils of mudstone and packstone lies immediately below the base of the Steamboat Limestone and probably represents the top of the Pentagon Shale.

The base of the Pentagon Shale was not seen in the study area because it is believed to be below or within a major decollement surface (Singdahlsen, 1986; Feucht, 1971). The Pentagon Shale crops out only in highly deformed areas and thus defies accurate thickness measurement. An approximate thickness of 40 m given by Feucht (1971) for the unit is considered reasonable.

Steamboat Limestone. The Steamboat Limestone is the most extensive unit in the study area and contains the best-developed deformational features. The unit was examined in both outcrop and thin section. It is marked at its base by an irregular surface that overlies the green- to tan-colored upper Pentagon Shale. The base is distinctive because it is locally an oncolitic packstone, 10-30 centimeter (cm) thick, with oncolites averaging 1 cm in diameter.

Above the basal layer is 1 to 2 m of medium gray, 3 to 6 cm-thick beds composed of flat-pebble intraformational conglomerate. Pale orange, fine-grained dolomite and clay partings are found between beds. The remainder of the Steamboat Limestone consists of light grey to dark grey-brown, thin- to medium-bedded mudstone and dolomitic mudstone, containing irregular tan-orange dolomite and clay lenses. Intervals of fossiliferous, micaceous fissile shale and green mudstone lentils within the Steamboat Limestone have been identified by other workers; however, none were conclusively identified in this study.

In outcrop, these rocks often have a characteristic "mottled" appearance. Intraformational conglomerates and fossiliferous beds containing ooids occur locally throughout the Steamboat Limestone. Approximately 38 m of Steamboat Limestone is present in the study area.

In thin-section, the Steamboat Limestone is composed predominantly of micrite with minor sparry calcite and fossil fragments. Roundish blebs of sparry calcite and dolomite are interspersed. The orange-tan colored lenses which define bedding and contribute to the mottled appearance are stylolitic solution seams, which formed parallel to stratification. These solution seams may be up to 2 cm thick and contain dolomite (75%), micrite (20-25%) and clay/silt sized material (< 2%). Dolomite rhombohedrons tend to be partially to wholly red-brown in color, well formed and have few overgrowths. Micrite occurs in blebs within the dolomite-filled seams. Silt and clay are concentrated near the edges of stylolitic seams. It is suggested that dolomitization and pressure solution during compaction and diagenesis obliterated bedding and produced the mottled appearance.

Switchback Shale. The Switchback Shale lies conformably above the Steamboat Limestone. It is generally poorly exposed and recognized primarily by the yellowish - buff color it imparts to the soil. The Switchback Shale is composed of alternating units of green or maroon shale with occasional lenses of thin- to thick-bedded, mottled mudstone. An incomplete section of 25 m was measured by the author (Appendix A). The estimate of 30 m thickness for the Switchback Shale by Feucht (1971) is considered reasonable.

Devils Glen Dolomite. The Devils Glen Dolomite crops out in only 1 locality. It rests conformably upon the Switchback Shale (Mudge, 1972a) and is a thick-bedded, white to light grey dolomite that weathers into light-colored, angular fragments. A thickness of 43 m was reported by Feucht (1971) in the vicinity of Swift Reservoir.

Devonian

Devonian strata disconformably overlie the Upper Cambrian Devils Glen Dolomite in the Sawtooth Range. At Swift Reservoir, Devonian strata have limited exposure.

Maywood Formation. The Middle and Upper Devonian Maywood Formation is divided into a lower mudstone member and an upper limestone member by Mudge (1972a). Only part of the lower mudstone member crops out in the study area. The lower member is composed of thin interbeds of greenish-grey and maroon mudstone and finely crystalline, yellow-grey dolomite. The Backbone thrust sheet is

composed of Pentagon Shale, Steamboat Limestone, Switchback Shale, Devils Glen Dolomite and the Maywood Formation (Figure 7).

Mississippian

The characteristic rugged ridgeline of the Sawtooth Range is formed by the massive, resistant, Mississippian Madison Group rocks which are exposed along the length of the range. In the Swift Reservoir area, these rocks lie structurally below the Backbone thrust sheet and have exerted an influence on the style of deformation in the Cambrian units.

The Madison Group is divided into two formations (Mudge and others, 1962): 1) the lower Allan Mountain Limestone, and 2) the upper Castle Reef Dolomite. Nichols (1984) revised the stratigraphic nomenclature of the Mississippian strata; however, exact member differentiation was not necessary for this study, so the existing simplified nomenclature of Mudge and others (1962) is retained. Total thickness of the Madison Group in the study area is estimated to be 365 m (Singdahlsen, 1986).

Allan Mountain Limestone. The Allan Mountain Limestone consists of three unnamed members (Mudge and others, 1962), whose characteristics could not be differentiated in the field due to structural complexity; they were mapped herein as one unit. Generally, the Allan Mountain Limestone is a thin-bedded, very fossiliferous, light to dark grey, argillaceous and dolomitic limestone. Irregular to nodular chert is found in the middle to upper portions of the formation.

Castle Reef Dolomite. The Castle Reef Dolomite has been divided into two members by Mudge and others (1962); however, they were not differentiated in this study. The Castle Reef Dolomite is characteristically a thick-bedded, medium- to coarsely-crystalline, light grey to white dolomite and dolomitic limestone. It is easily distinguishable from the underlying Allan Mountain Limestone.

Mesozoic

Mesozoic terrigenous clastic rocks are widely distributed east of the study area and beneath the Backbone thrust sheet on Major Steele Backbone ridge (Plate I). Recognition of individual formations was not necessary for this study and they were therefore mapped as a single, undifferentiated unit. The reader may refer to Cobban (1945, 1955), Mudge (1972a), Egan (1971), Feucht (1971), and Mudge and Rice (1982) for more complete descriptions of the formations involved. Singdahlsen (1986) provides a good synthesis of work on formations of Mesozoic age in the Swift Reservoir area. Mesozoic formations are primarily interbedded marine and nonmarine sandstones and shales of Jurassic through Cretaceous age.

STRUCTURAL ELEMENTS

Introduction

The distribution, morphology and mechanisms of deformation in macroscopic, mesoscopic and microscopic structural elements have been characterized. This information is utilized to determine how internal deformation varies in the Backbone thrust sheet and to determine the relative contributions of individual structural elements to shortening within the thrust sheet.

Macroscopic structural elements include thrust faults and folds. Numerous thrust faults create a zone of imbrication at the leading edge of the thrust sheet and folds proliferate in the intraplate region (Figure 8). Mesoscopic structural elements include outcrop-scale

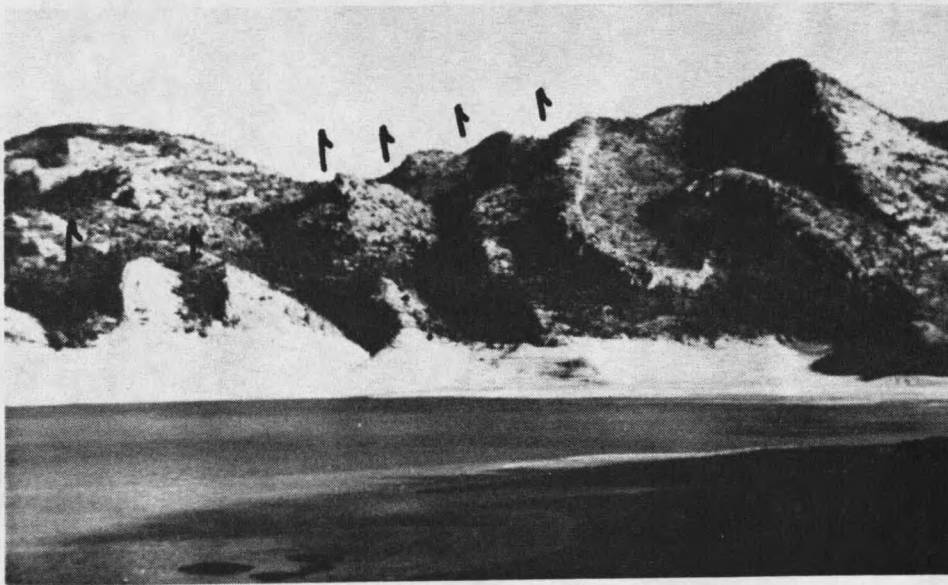


Figure 8. Intraplate folds and thrust imbricates in the Backbone thrust sheet. Swift Reservoir in foreground. View to the southwest.

folds, faults, cleavage, boudins, pencil structures, gouge and breccia, and tectonic veins. Mesoscopic structures were determined to have an approximately vertical distribution within the thrust sheet. This distribution is illustrated in cross sections which are normal to strike of the thrust sheet (Figure 9). These cross sections contain plots of the relative abundance of mesoscopic structural elements, which may be observed in field traverses through the study area (Figures 10 through 13).

Determination of "rare", "common", and "abundant" for the distribution of individual mesoscopic structures is based on qualitative outcrop observations. "Rare" indicates the feature is found only locally in outcrops; "common" indicates that the feature is found regularly in outcrops, and "abundant" indicates the feature is found throughout outcrops and is well-developed. Small letters correspond to field stations (Figure 9).

Examination of Figures 10 through 13 indicates that mesoscopic structural elements have a common association and distribution which defines three domains. Domain I is proximal to the Backbone thrust and its leading edge imbricates. In most outcrops, Steamboat Limestone is thrust over competent rocks (Figure 10) and the characteristic assemblage of mesoscopic structures includes fault arrays, tectonic veins and drag folds which may contain cleavage. Minor gouge and breccia are also seen. Where Steamboat Limestone is thrust over shale (Figure 13), there are markedly fewer faults and tectonic veins.

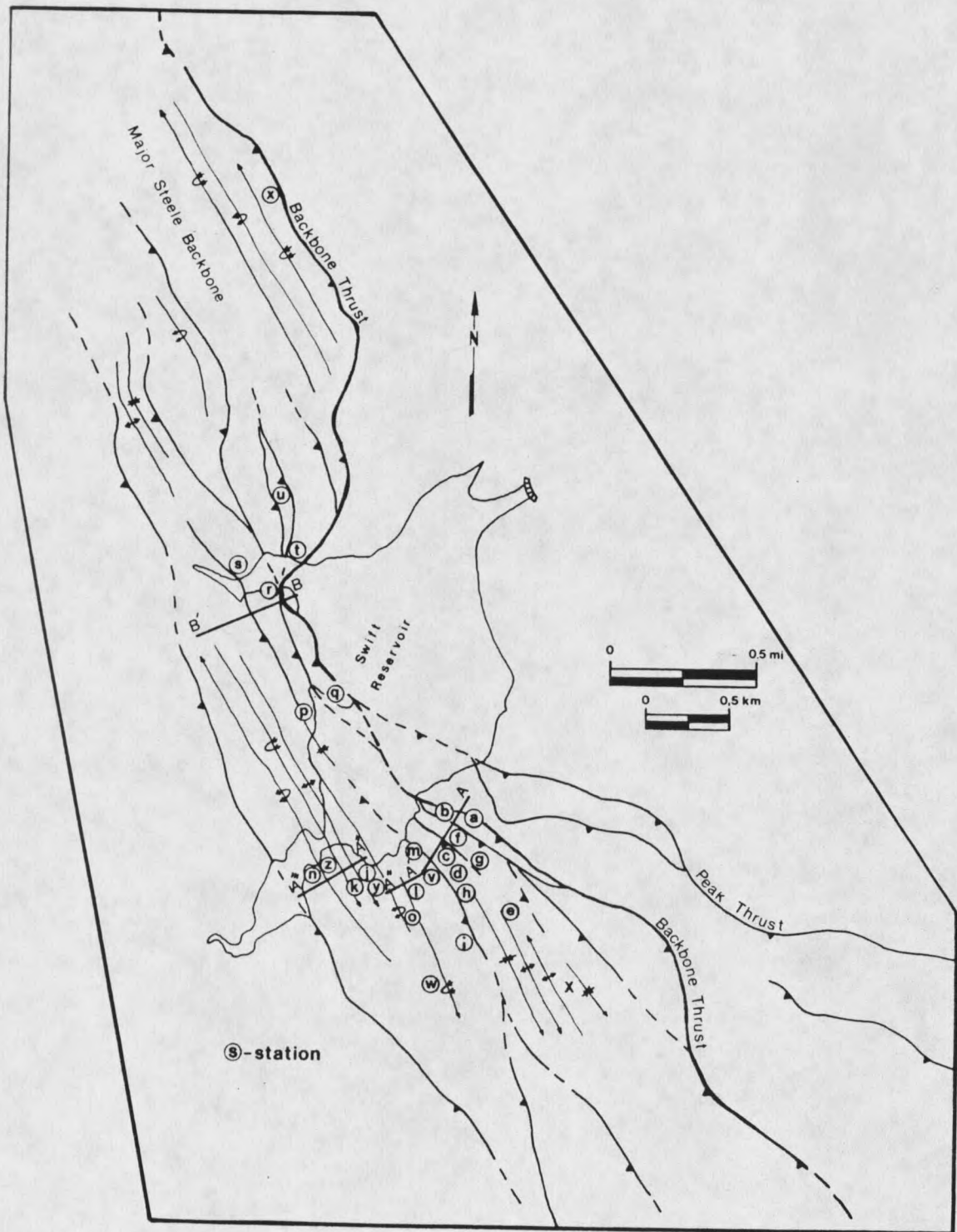


Figure 9. Generalized geologic map of the study area showing locations of measurement stations and cross sections.

FOLDS	c	r	r	r	r	c	c	c	c
FAULTS	c	r	r	r	c	c	a	c	a
Gouge/ Breccia	-	-	-	-	-	-	-	-	r
VEINS	c	r	-	-	r	c	a	c	a
Cleavage	r	c	c	a	c	c	-	-	-
Pencils	-	-	-	-	-	-	-	-	-
Boudins	-	-	-	-	-	-	-	-	-
	(m)	(h)	(c)	(d)	(e)	(g)	(f)	(b)	(a)

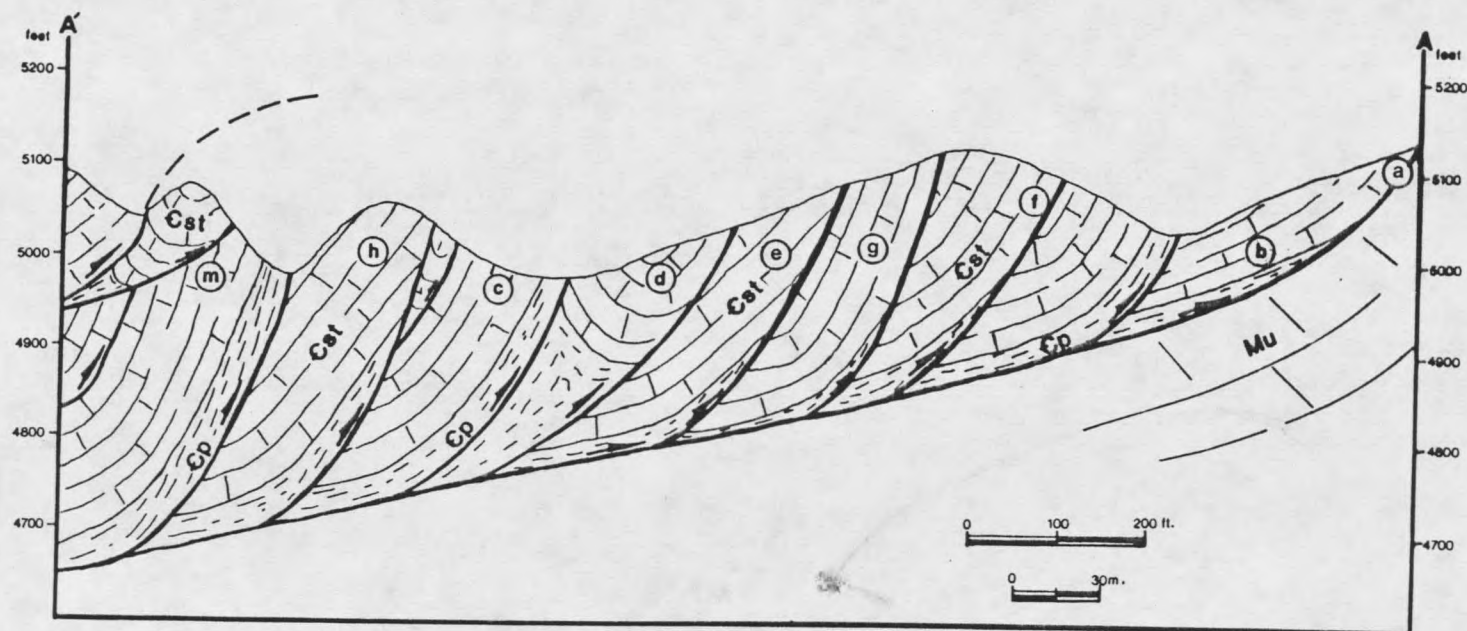


Figure 10. Cross section A-A' and table of mesoscopic structural elements showing their distribution at specific stations (circled letters) in the study area. a=abundant, c=common, r=rare, -=absent.

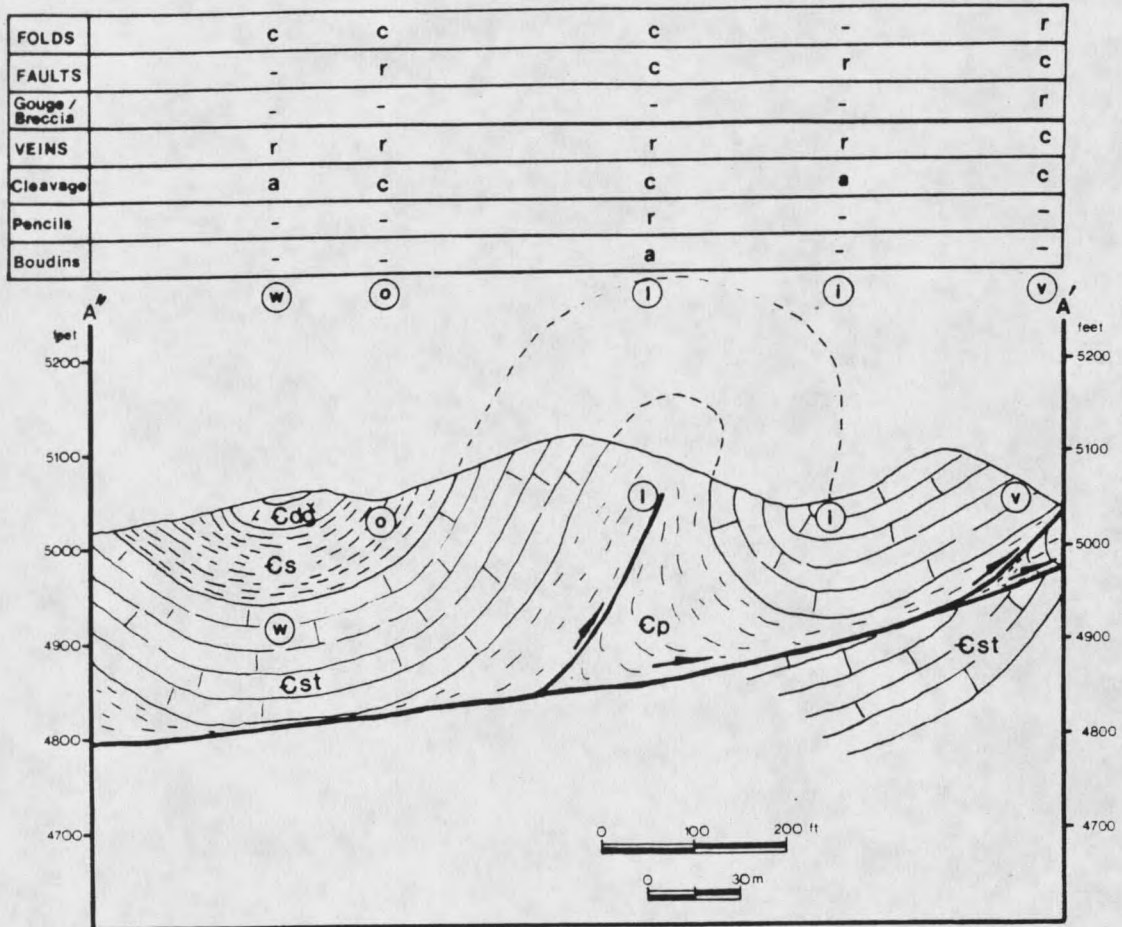


Figure 11. Cross section A'-A'' and table of mesoscopic structural elements showing their distribution at specific stations (circled letters) in the study area. a=abundant, c=common, r=rare, -=absent.

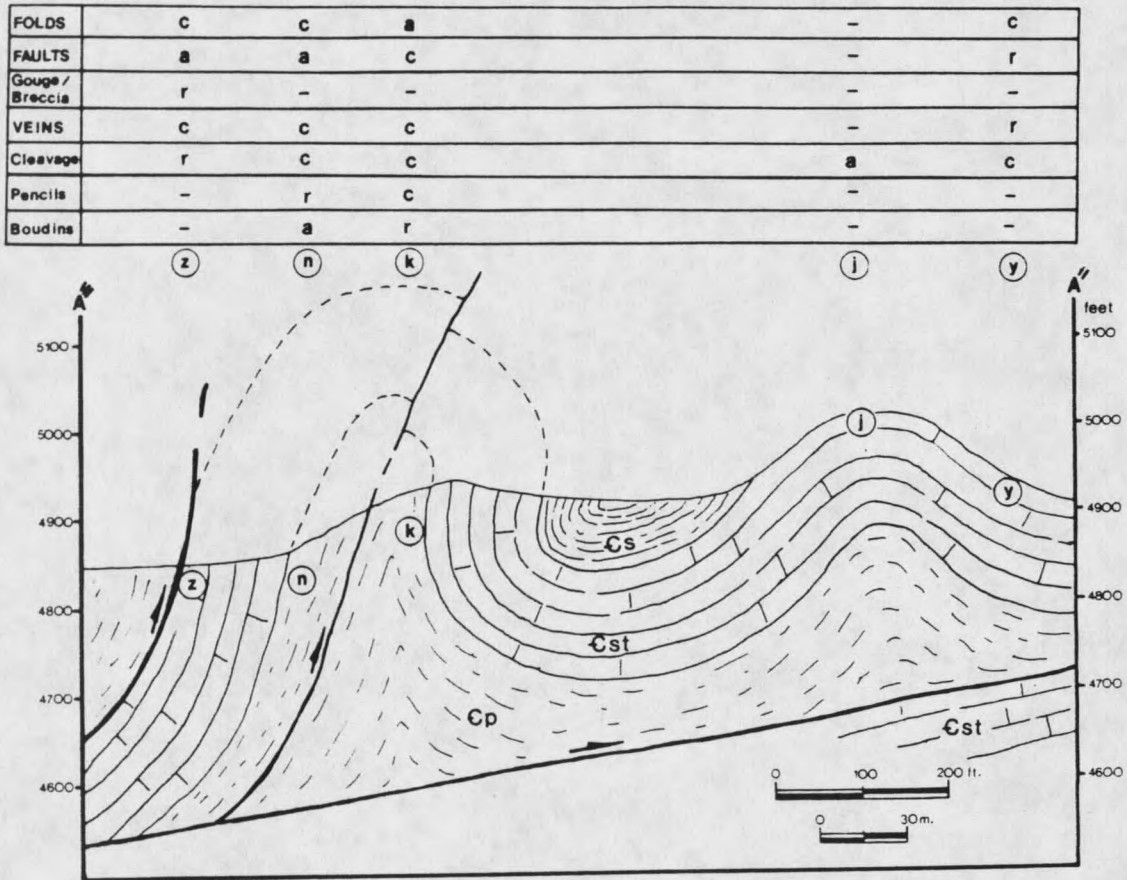


Figure 12. Cross section A''-A''' and table of mesoscopic structural elements showing their distribution at specific stations (circled letters) in the study area. a=abundant, c=common, r=rare, -=absent.

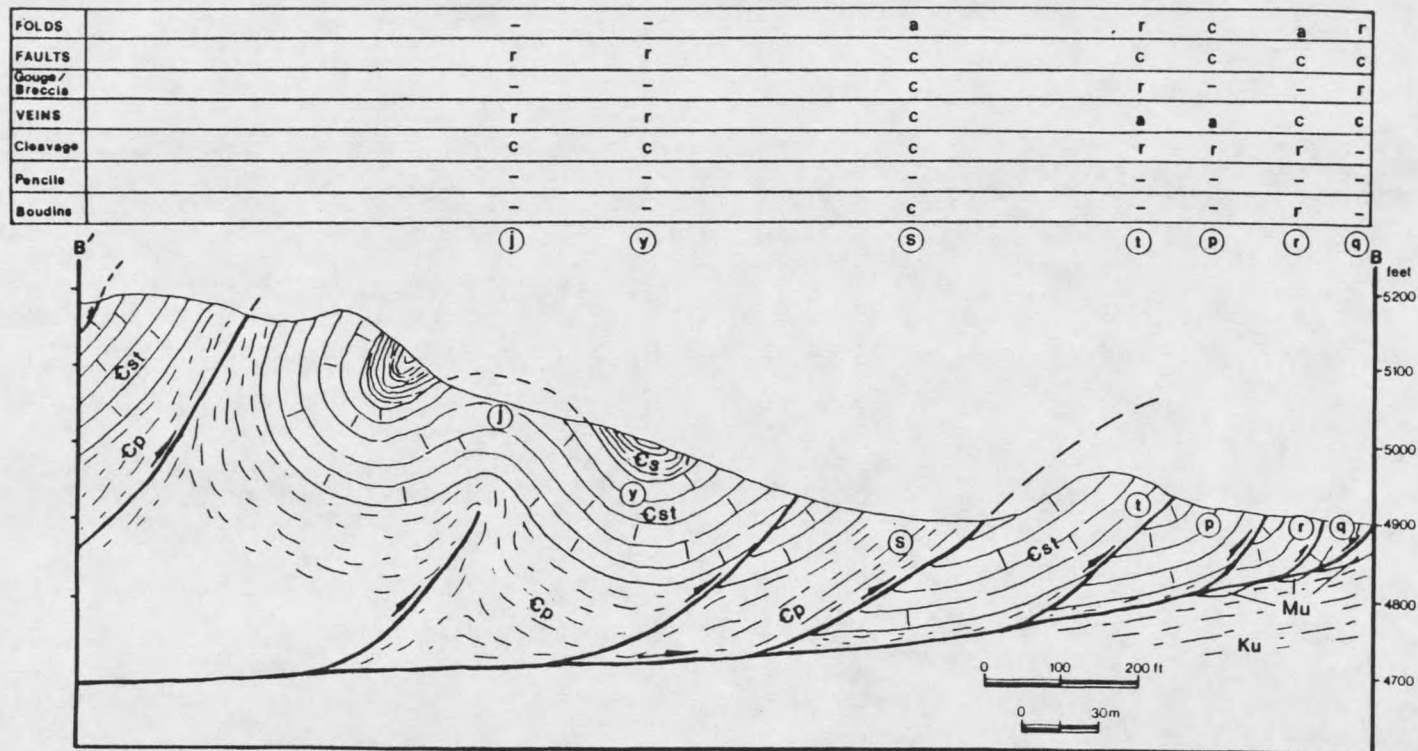


Figure 13. Cross section B-B' and table of mesoscopic structural elements showing their distribution at specific stations (circled letters) in the study area. a=abundant, c=common, r=rare, -=absent.

Domain II is found in the strata overlying Domain I (Steamboat Limestone) and in the macroscopic intraplate folds. It is characterized by spaced cleavage oriented at high angles to bedding. In addition, mesoscopic folds with well developed cleavage, tectonic veins, boudins and pencil structures are found in the cores of the macroscopic folds.

Domain III is the strata overlying Domain II in the region of intraplate macroscopic folds. This includes uppermost Steamboat Limestone, Switchback Shale, Devils Glen Dolomite and Maywood Formations (Figure 11). Domain III is characteristically undeformed.

The morphology, orientation and mechanisms of deformation of mesoscopic structural elements will be discussed to determine the variation in mesoscopic-scale internal deformation and its contribution to shortening in the thrust sheet, and the mechanisms which operated to produce deformation. Interrelationships between structural elements are useful for constraining the relative sequence of deformations for the thrust sheet.

Before mesoscopic structural elements are discussed in detail, the morphology and orientation of macroscopic structural elements will be addressed. Macroscopic structures provide insight to the internal deformation which occurs at the macroscopic scale and a framework for understanding mesoscopic- and microscopic-scale structural elements.

Macroscopic Structural Elements

Macroscopic structural elements include large-scale (up to several kilometers) thrust faults and folds. Two large thrust slices: the Peak

and Backbone thrust sheets (Singdahlson, 1986) are recognized in the area (Plate I). It is important to note that thrust faults are so closely spaced and complexly interrelated that few faults are continuous throughout the Sawtooth Range. Thus, the Peak and Backbone thrust faults are large features at the scale of this study, but they cannot be easily correlated with thrust faults in other parts of the range. Displacement on these faults is on the scale of kilometers. Only the Backbone thrust sheet will be discussed in the following section.

Backbone Thrust Sheet

The Backbone thrust sheet places Cambrian and Devonian strata over Upper Paleozoic and Mesozoic strata. The thrust sheet is locally composed of penetratively deformed Pentagon Shale, Steamboat Limestone and Switchback Shale that are conformably overlain by the relatively undeformed Devils Glen Dolomite and Maywood Formation (Figure 7). The Pentagon Shale is believed to be the basal decollement horizon in the Swift Reservoir area (Singdahlson, 1986; Feucht, 1971).

Several large, thrust imbricates within Cambrian strata occur west of the study area. These imbricates are believed to be part of the Backbone thrust system and were observed to have a similar style of deformation. This study, however, concentrates on the internal deformation which occurs within the easternmost slice of the Backbone thrust sheet and is centered around Swift Reservoir.

The Backbone thrust strikes an average of 325° and dips 16° to the southwest, as determined by three-point solutions. South of the study area, a dip of 40° to the southwest was determined by down-plunge projection (Singdahlsen, 1986). The surface trace of the Backbone thrust is approximately 12 km long.

The overall outcrop morphology of the Backbone thrust includes numerous anastomosing thrusts which create a zone of imbrication at the leading edge, and complex macroscopic folds in the intraplate region (Plate I). The zone of imbrication is composed of moderate- to steeply-dipping faults in the Steamboat Limestone whose combined displacements account for a significant amount of shortening within the thrust sheet.

Macroscopic Folds

Macroscopic folds dominate the intraplate region within the Backbone thrust sheet but may also occur near the leading edge of the sheet as on Major Steele Backbone ridge (Figure 9). Folds are composed predominantly of Steamboat Limestone.

Macroscopic folds have average wavelengths of 150 to 250 m, amplitudes from 30 to 60 m, and strike lengths from 100 to 3,000 m. Most folds are asymmetrical with vergence to the northeast, while others are symmetrical, upright folds. Bedding strikes predominantly to the northwest and dips both northeast and southwest (Figure 14). Folds with more steeply inclined axial surfaces occur near the leading edge of the sheet and are often nearly isoclinal.

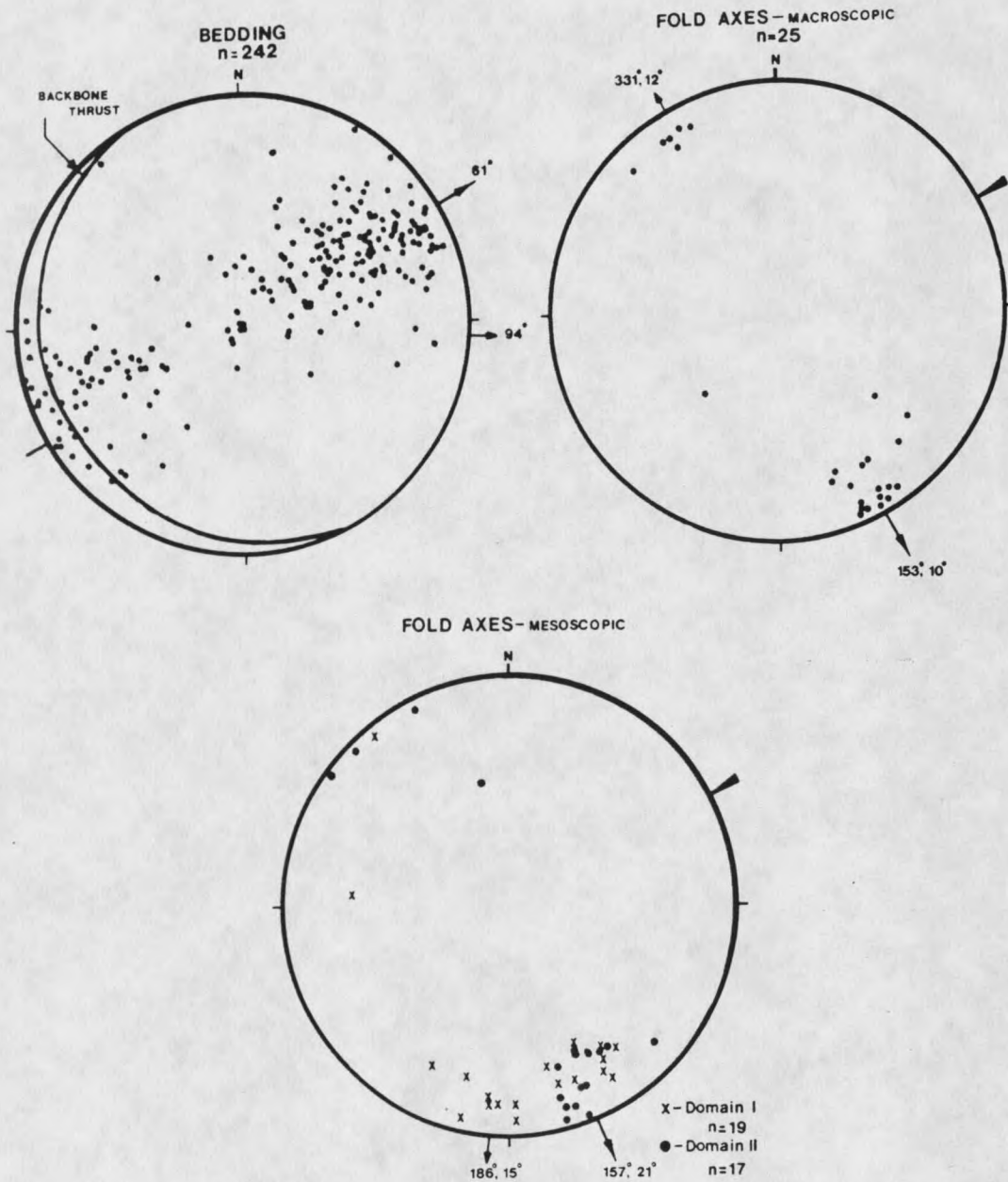


Figure 14. Poles to bedding, macroscopic and mesoscopic fold axes for the study area. Arrow at 61° azimuth indicates inferred transport direction. Mesoscopic fold axes show two orientations, 186°, 15° and 157°, 21°.

Fold geometry is class 1B (parallel) with a few folds exhibiting class 1C characteristics (cf. Ramsay, 1967). The geometric constraints of parallel or concentric folds requires a decollement at depth (Davis, 1984). Thus, many macroscopic folds must be detachment folds above a decollement.

Fold axes determined by stereonet and tangent diagram methods indicate that most folds trend approximately 153° and plunge an average of 12° southeast (Figure 14). Several folds trend 331° and plunge to the northwest from 10° to 15° .

The tectonic transport direction, as inferred from fold axes and bedding, is 61° . This is considered the direction of slip (or the a-kinematic direction) (Price, 1967) for the Backbone thrust sheet. Thus, the b-kinematic axis (or axis of rotation) (Price, 1967) is 151° which corresponds closely to the strike of the thrust sheet (Figure 14).

The primary folding mechanism recognized in macroscale folds is flexural-slip folding (Donath and Parker, 1964). Outcrop evidence for flexural-slip is exhibited by development of step fibers and slickensides between bedding planes and more intense deformation in hinge areas. Flexural-slip folding accomodates buckling by layer-parallel slip between layers (Davis, 1984). Evidence for flexural-flow folding in the study area is observed in several folds near the leading edge of the thrust sheet on Major Steele Backbone ridge. These folds have thickened hinge areas with respect to limbs (Figure 15).

Deformation at the macroscopic scale is most intense at the leading edge where inclined, nearly isoclinal folds may accompany thrust

imbricates. The abundance of folds within the sheet suggests that folding, along with thrust imbrication is an important intraplate shortening mechanism.



Figure 15. Intraplate folds in the Cambrian Steamboat Limestone. Folds are moderately inclined and nearly isoclinal. Note hinge thickening in circled area. View to northeast.

Mesoscopic Structural Elements

The following section discusses the distribution, morphology, and deformation mechanisms of mesoscopic structural elements. Differences between structural elements that are common to both Domains I and II are noted and petrographic observations are included where applicable. In some cases, the sites of structural element observations refer to measurement stations which are designated by small letters on Figure 9.

Faults

Mesoscopic contraction faults are the dominant type of fault in the Backbone thrust sheet. They are formed predominantly in a narrow zone proximal to the Backbone thrust and its imbricates, and characterize Domain I deformation. Contraction faults also occur in Domain II but are less significant to internal deformation.

Displacement on mesoscopic faults is difficult to determine; however, field relationships suggest that displacement averages 1 to 5 m. The collective displacement on mesoscopic faults is believed to account for a significant amount of shortening of the Backbone thrust sheet. Strike lengths probably do not exceed 100 m.

Mesoscopic faults are developed primarily within 10 m of the base of the macroscopic faults at the leading edge of the thrust sheet. In general, the intensity of their development varies with lithology of the footwall block and distance from the base of the macroscopic fault. Where limestone is thrust over similarly competent rock (Figure 10), mesoscopic-scale fault deformation is extreme, with bedding often totally obliterated by recrystallization and tectonic veins. Only a minor amount of gouge and breccia are seen. Where limestone is thrust over shale (Figure 13), mesoscopic faults and tectonic veins are markedly less well developed. In both situations, the intensity of faulting decreases very rapidly in a vertical sense away from the base of the macroscopic fault.

Fault geometry also varies with footwall lithology and distance from the underlying macroscopic fault. Where limestone is thrust over competent rocks, faults in the lower 5 m of Domain I occur in arrays of

bed-parallel and sub-bedparallel faults that form interleaved and stacked duplexes. These duplex fault arrays are penetrative at the scale of the thrust sheet, and divide the base of the sheet into numerous, small fault-bounded blocks. Duplexing may account for a significant amount of shortening and also produce thickening of strata adjacent to thrust faults (Wojtal and Mitra, 1986). Faults often intersect bedding at high angle, however, they continue to strike subparallel to the underlying thrust. Contraction faults in the upper 5 m of Domain I usually occur singly in bed-parallel or ramping configurations.

Where limestone is thrust over shale, faults predominantly occur singly and parallel to bedding. However, along one well exposed outcrop at station "r" where the Backbone thrust sheet is thrust over Mesozoic shale, faults developed bed-parallel until bedding was rotated to a high angle by faulting; faults continued to propagate at low angle, cutting through the upturned beds. This sequence of faulting resulted in a unique step-like configuration (Figures 16 and 17).

These observations indicate that internal deformation at the base of thrusts is significant within a relatively narrow (< 10 m thick) zone and is expressed primarily by intricate arrays of mesoscopic faults. Similar observations for the base of thrust sheets have been recorded by Ghisetti (1987) for the Central Appennines, and by Wojtal and Mitra (1986) and Lutz (1987) for the Southern Appalachians.

Poles to mesoscopic faults suggest two general orientations (Figure 18). The predominant strike of most faults is near 336° , subparallel to the strike of the Backbone thrust sheet; however, dips vary widely.



Figure 16. Step-like fault configuration where Steamboat Limestone is thrust over shales near station "r".



Figure 17. Close-up of Figure 16 showing offset on individual faults.

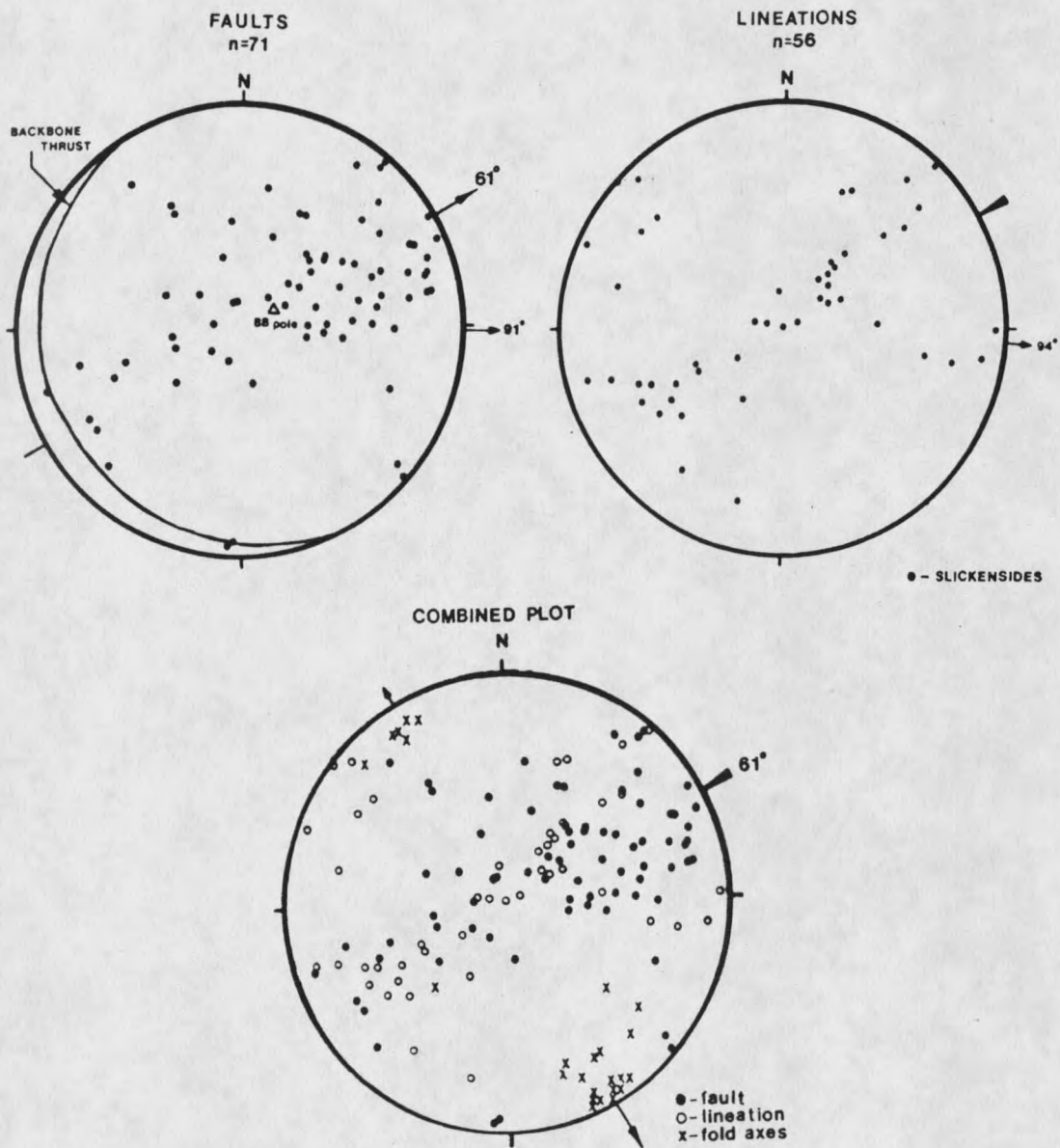


Figure 18. Poles to faults and lineations and combined plot of geometric elements. Arrows on azimuth are at 61° , the inferred transport direction. Small arrows near 90° indicate a minor secondary transport direction.

This is believed to be a reflection of the duplexing nature of the faults. The secondary locus of poles to mesoscopic faults indicates a north-south strike of fault planes. This second locus is found at stations "r" and "t" on the northwest side of the reservoir (Figure 13). These faults suggest that there was either local east-directed slip or passive clockwise rotation of the hanging wall during the progression of thrusting.

Petrographic observations of fault zone samples were made to determine the deformation mechanisms that accomodated faulting. These observations, in conjunction with mesoscopic observations, can be used to infer the conditions and sequence of deformation in Domain I.

Samples of Steamboat Limestone were taken at stations "a", "r" and "b". Samples "a" and "r" represent fault zone deformation where limestone is thrust over competent rock and shale, respectively. Both are sampled within 2 m of the base of the associated macroscopic fault. Sample "b" was taken where limestone is thrust over limestone, about 5 m from the base of the macroscopic fault.

Thin sections were cut perpendicular to bedding in both the transport direction (a-kinematic) and parallel to the strike (the b-kinematic) direction. Four features are common to all thin sections: 1) recrystallization of micrite into sparry calcite whose crystals may display twinning and deformation lamellae; 2) sutured stylolites distinguished by brown-black residue and dolomite rhombohedrons; 3) veins filled with sparry calcite; and 4) microfault zones. These deformation features observed are considered to be due to fault zone deformation rather than diagenetic processes based on petrographic

observations of the Steamboat Limestone in samples containing ooids and cleavage. Cross-cutting relationships showed no definitive deformation sequence common to all samples, however, pressure solution generally preceded faulting and many tectonic veins and recrystallization appear to be post faulting deformations.

Deformation in station "a" samples is most intense. Most of the original micrite is recrystallized to sparry calcite. Twinning and deformation lamellae are often observed in calcite crystals. Stylolites permeate the sample with no preferred orientation. Calcite-filled veins are abundant; some occur with stylolites and appear to be related to their formation, while others cross cut stylolites and microfaults. Microfaults are distinguished by thin (< 1 millimeter (mm) thick), linear to curvilinear calcite bands that often create microduplexes. Microfaults are oriented subparallel to bedding. Features observed in the samples from station "r" indicate that deformation is less intense than station "a". Stylolites, calcite veins and microfaults are less abundant. The most distinguishing feature is the formation of microfault layers that are distinguished by thin (< 1 mm thick) seams of calcite stacked one atop the other and separated by an opaque, brown residue (Figure 19). Their orientation and morphology suggest they are responsible for a significant amount of shear.

Samples from station "b" are the least deformed. They contain fewer stylolites and microfaults and a higher percentage of micrite.

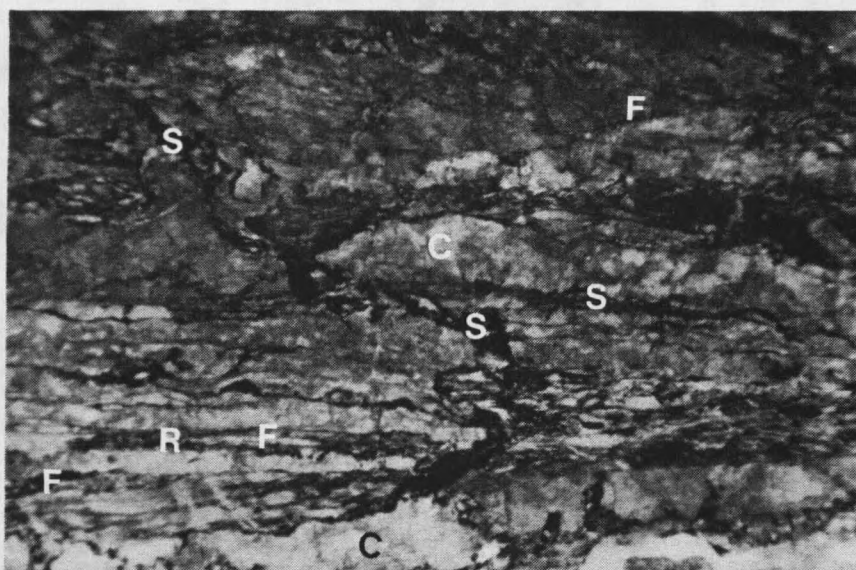


Figure 19. Photomicrograph of fault zone deformation from station "a". S=stylolites, F=microfaults, R=residue, C=calcite.

Calcite veins are oriented perpendicular to the direction of transport, suggesting extension in the transport direction. These observations indicate that the intensity of deformation decreases vertically away from the base of the thrust.

The important mechanisms of deformation indicated by the petrographic observations are recrystallization, pressure solution, extension veining and microfaulting. Twinning and deformation lamellae contribute a small amount of plastic deformation.

In summary, mesoscopic fault arrays occur in a zone near the base of thrusts and characterize Domain I deformation. This deformation is penetrative and may account for a significant amount of longitudinal shortening by pressure solution and duplexing at the mesoscopic and microscopic scales. These shortening mechanisms must also result in thickening of the strata, however, measurement of thickening was not

attempted. Deformation by simple shear is also indicated by zones of recrystallization and microfaults. Cross-cutting relationships suggest relatively coeval development of microstructures during the development of fault zones.

Lineations

Lineations consist of slickensides which are either polished grooves or coatings of calcite step fibers. They are commonly developed on mesoscopic fault planes in Domain I and between layers on fold limbs. Lineations indicate local directions of slip and the deformation mechanisms operating on the fault planes. Polished grooves indicate frictional sliding, and step fibers indicate pressure solution slip (Elliott, 1976b).

Domain I lineations are plotted in Figure 18. The two trends correspond closely to the poles to mesoscopic faults (Figure 18). The combined plots of poles to faults, lineations and mesoscopic and macroscopic fold axes (Figure 18) strongly support major transport of the Backbone thrust sheet to the northeast (61°) with a secondary trend near 90° . The coaxial nature of macroscopic and mesoscopic folds and faults suggests that internal thrust sheet deformation occurred only during one major period of activity. The secondary trend is believed to be due to passive reorientation which resulted from continued activity because of the localized distribution of these features.

Mesoscopic Folds

Mesoscopic folds occur in Domains I and II, primarily in the Steamboat Limestone. These folds have amplitudes ranging from 0.5 to 10 m with half wavelengths of 0.5 to 5 m. Examples of fold geometry for Domains I and II are shown in Figure 20.

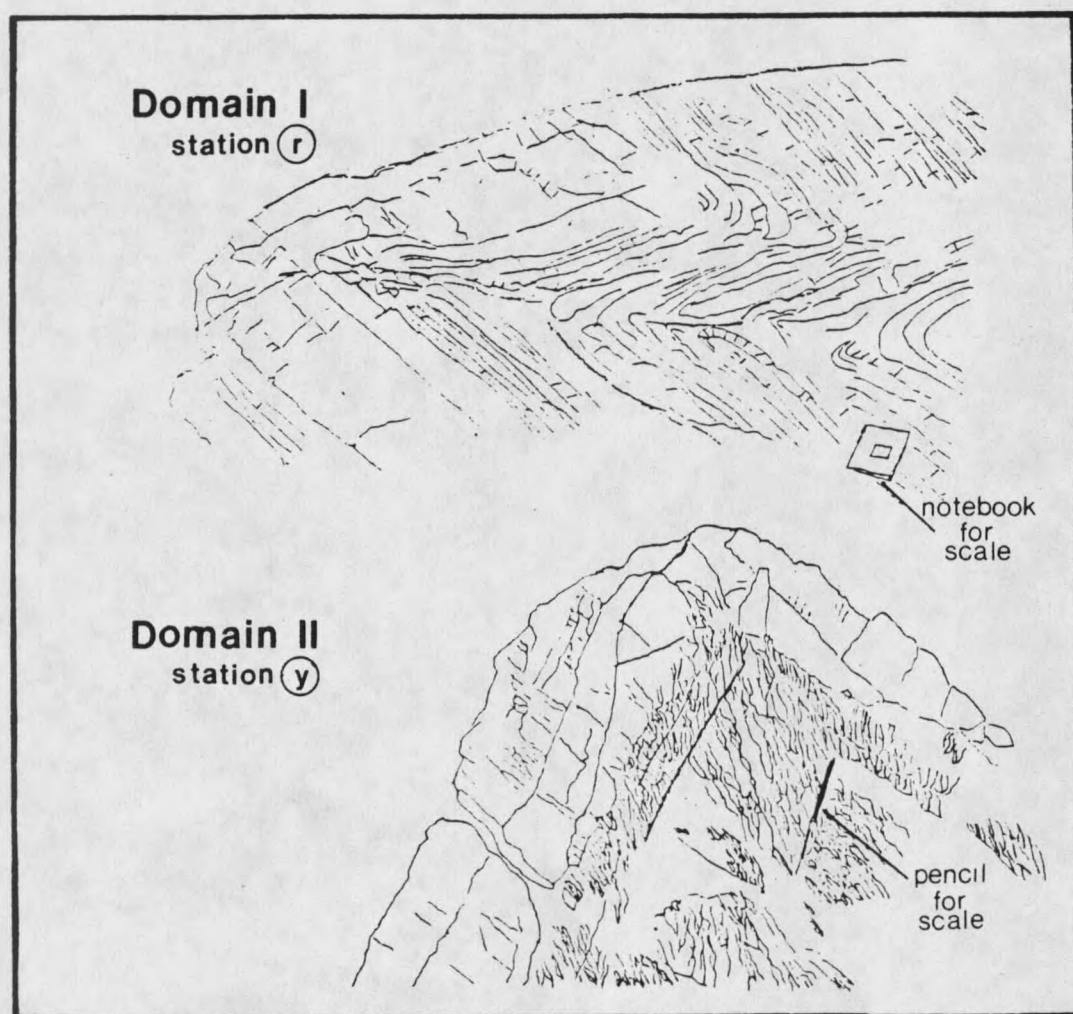


Figure 20. Line sketches from photographs of mesoscopic folds in Domains I and II. Note intense cleavage development in the core of the Domain II fold.

Domain I folds generally occur within the upper 5 m of the domain, whereas the lower 5 m of Domain I is dominated by mesoscopic faults and tectonic veins. These folds are usually recumbent with tight, chevron geometries. They commonly have sheared limbs and show disharmonic relationships in hinge regions (Figure 20). The fold geometry approximates class 1c (cf. Ramsay, 1967). Cleavage is often developed and will be discussed in more detail in a later section.

Mesoscopic folds formed in Domain II occur most often in the cores of larger macroscopic folds; a few are drag folds on fold limbs. Unlike Domain I, folds are usually upright and symmetrical with tight to open shapes and broad, rounded hinges (Figure 20). The fold geometry approximates class 1b (cf. Ramsay, 1967). Spaced cleavage is well-developed in these folds.

Axial traces of mesoscopic folds cluster near 157° , subparallel to the macroscopic fold axes (Figure 14). Fold axes plunge an average of 22° to the southeast or 6° to the northwest, similar to macroscopic folds. These orientations indicate coaxial development of mesoscopic and macroscopic folds. A secondary orientation near 185° occurs in several Domain I folds from stations "r", "b", and "c". The secondary locus of axes from Domain I indicates that the folds were either passively rotated in the hanging wall with continued thrusting or there was local eastward-directed shortening.

The morphology and orientation of Domain I folds indicates they are flexural-slip and flexural-flow folds formed during differential shear induced by thrusting. These folds contribute to the overall shortening and thickening of strata in Domain I. The upright, symmetrical nature

and orientation of Domain II folds suggests they were formed by longitudinal shortening during development of the larger folds. Thus, their contribution to shortening is not unique.

Cleavage

Well-developed, spaced cleavage formed by pressure solution is commonly found in the Cambrian Steamboat Limestone and less commonly in the Switchback Shale. Cleavage is characteristic of Domain II deformation and is considered a locally penetrative structure in the Backbone thrust sheet. Cleavage also occurs in some mesoscopic folds in Domain I. Singdahlsen (1986) is the only study that documents cleavage development in rocks of the Sawtooth Range.

The descriptive and non-genetic classification scheme of Powell (1979), is employed in describing cleavage morphology in the study area (Figure 21). Spaced cleavage is composed of cleavage domains and microlithons. Cleavage domains are the planes of preferred mineral orientation and microlithons are the undeformed rock between cleavage domains (Powell, 1979). In general, cleavage is recognized in outcrop by closely spaced fractures that occur at high angles to bedding.

Cleavage is formed in Domain II in three structural associations: within imbricates of the Backbone thrust sheet, and in macroscopic and mesoscopic folds. Cleavage morphology and orientation vary in each association. These variations are important indicators of the intensity and timing of deformation. Cleavage morphology and orientation are summarized in Table 1.

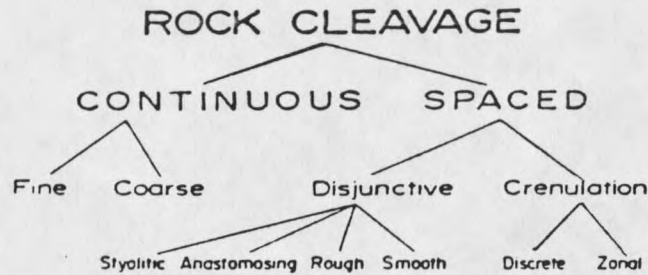


Figure 21. Diagram of the basic divisions of cleavage (from Powell, 1979).

Table 1. Cleavage association, morphology and orientation in Domain I. Domain II occurrence is noted in parenthesis.

ASSOCIATION	LITHOLOGY	MORPHOLOGY	INTENSITY	SPACING	$S_1 \wedge S_0$
Thrust Imbricate	Est	planar to subplanar, often cuts bedding, may also refract	moderate to strong	0.5 - 2.0 cm (Avg. 1.0 cm)	80°
Macroscopic Folds	Est	planar to anas- tomosing, individual domains slightly sinuous	hinge-strong limbs-moderate	0.5 - 1.0 cm 1.0 - 3.0 cm	backlimb-83° forelimb-77°
Mesoscopic Folds - near thrusts (Domain I)	Est	planar to curvi- planar and slightly sinuous, may be refracted, forms half fans	moderate to strong	0.25 - 3.0 cm	74°
- in cores of macroscopic folds	Est	subplanar to very sinuous, bedding often transposed be- yond recognition, refracts through layers, thin beds are more strongly cleaved than thick	hinge-very strong limbs-strong	1.0 cm 1.0 - 2.0 cm	73-84°
- on limbs of macroscopic folds	Est	planar to curvi- planar, somewhat sinuous	moderate to strong	1.0 - 1.5 cm	79°

Cleavage in Thrust Imbricates. Cleavage in Domain II thrust imbricates is best developed where Steamboat Limestone is thrust over competent rocks (Figure 10). Where limestone has been thrust over shale (Figure 13), cleavage is much less developed.

Cleavage surfaces are discrete with planar to subplanar out geometries that intersect bedding at high angles (Figure 22). Spacing varies from 0.5 to 2 cm with an average spacing of 1 cm. Cleavage seams often cut bedding, but are truncated by faults in every instance. Intensity of development is moderate to strong, based on cleavage morphology and distance between cleavage seams (after Alvarez and others, 1978). In several locations, cleavage seams were seen to curve asymptotically into fault zones.

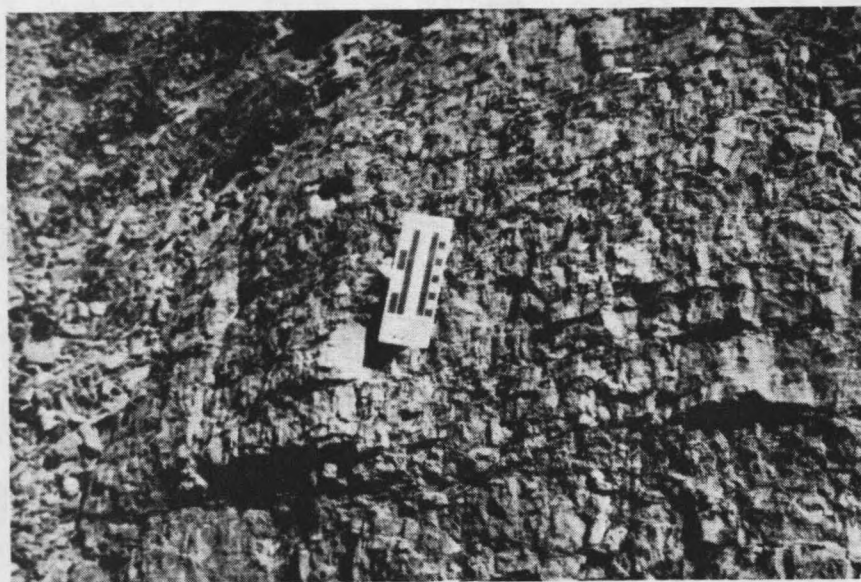


Figure 22. Cleavage developed near thrust faults. Long axis of scale is oriented subparallel to cleavage (S_1) which intersects bedding (S_0) at high angle.

A plot of poles to cleavage formed near thrust faults roughly shows two orientations: a set striking northwest and a set striking northeast (Figure 23). The northwest striking set is interpreted to have formed due to early layer-parallel shortening, prior to, or during early stages of faulting. However, after rotating cleavage with bedding to the horizontal, the cleavage is only approximately vertically oriented (Figure 23). To explain this, either shortening was not initially parallel to bedding, or more likely, the cleavage has been reoriented with respect to bedding during imbrication.

The formation of the northeast striking set is not easily explained. It is suggested that this set formed due to folding of the Backbone thrust sheet by emplacement of underlying thrust sheets (Singdahlson, 1986).

Cleavage in Macroscopic Folds. Spaced cleavage is developed in many of the macroscopic folds in Domain II. Cleavage appears as planar to anastomosing seams at a high angle to bedding. Development is most intense in hinge areas of folds where domain spacing averages less than 1 cm. Cleavage is less developed on fold limbs where intensity may vary from uncleaved to strongly cleaved. The average bedding-cleavage intersection angle is 83° on west-dipping limbs and 77° on east-dipping limbs; thus, cleavage exhibits a divergent fanning geometry.

This fanning geometry is seen in a plot of poles to cleavage for macroscopic folds (Figure 23). Where bedding is restored to horizontal, the cleavage is generally subvertical, indicating formation by layer-parallel shortening (Figure 23).

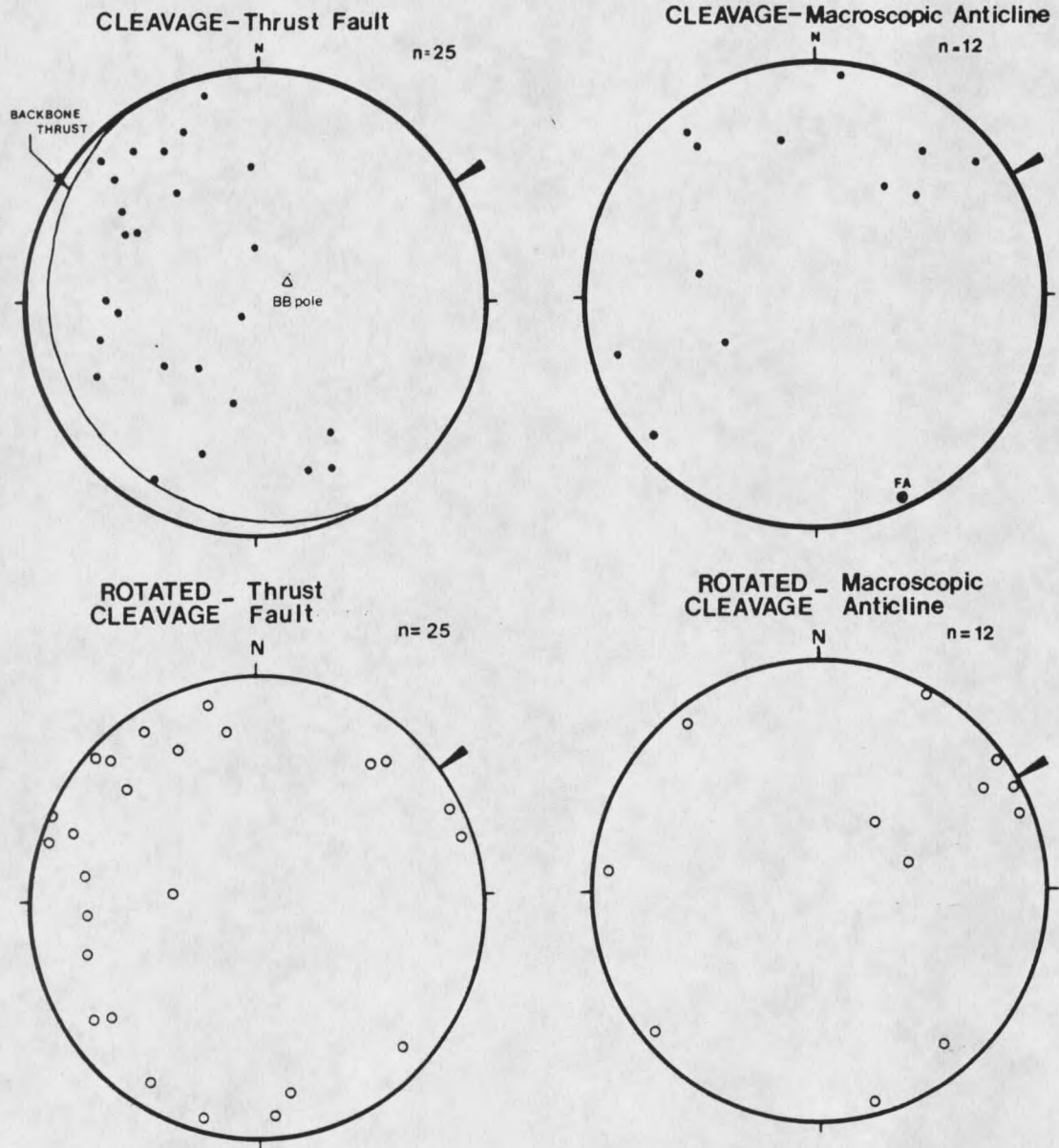


Figure 23. Poles to cleavage formed near thrust faults and in macroscopic folds, unrotated and rotated with bedding to horizontal.

The fanning geometry of cleavage and its high angle to bedding suggests that cleavage formed prior to macroscopic folding during an interval of horizontally-directed, layer-parallel shortening. Subsequent folding passively rotated cleavage to its present position. The lower cleavage-bedding intersection angle on the east limb of folds suggests that the cleavage may have been reoriented during flexural-slip of the fold layers. Cleavage formation and folding are coaxial events based upon the general parallelism of cleavage planes and fold axes (Figures 14 and 23). The more intensely developed cleavage in hinges is possible due to late hinge tightening during translation of folds above fault surfaces.

Cleavage in Mesoscopic Folds. Spaced cleavage is developed in most of the mesoscopic folds in Domain II and in several folds in Domain I. In general, cleavage occurs at high angle to bedding and fans around the folds, similar to macroscopic folds. However, refraction through layers is common, which indicates that cleavage development and folding are concurrent (Ramsay and Huber, 1983), unlike cleavage in macroscopic folds.

Cleavage in Domain I folds is best developed in hinge areas and forms half-fans. The half-fan geometry is due to obliteration of cleavage on limbs by shearing. Folds with evidence of flexural-flow in hinges only showed cleavage on limbs.

Spacing of cleavage seams averages 1 cm in hinge areas and about 2 cm on limbs, indicating moderate to strong development. Domains are planar to curvilinear and may be refracted through layers. Cleavage was seen to curve asymptotically into local slip layers which suggests

concurrent development of cleavage and faults in Domain I (Mittra and others, 1984). Thus, folding, faulting and cleavage development in Domain I were relatively coeval deformations.

Cleavage in Domain II folds occurs in the Steamboat Limestone and Switchback Shale, and unlike cleavage in Domain I folds, is present on limbs and hinges. Cleavage domains have subplanar to very sinuous geometries.

Spacing of domains averages less than 1 cm in hinge areas and 1.5-2.0 cm on limbs, indicating moderate to very strong development (Alvarez and others, 1978). The strongest development of cleavage seen was in hinge areas of several of these folds, where bedding is often transposed beyond recognition. Cleavage makes broad fans around folds and is commonly refracted (Figure 24). The fanning geometry is

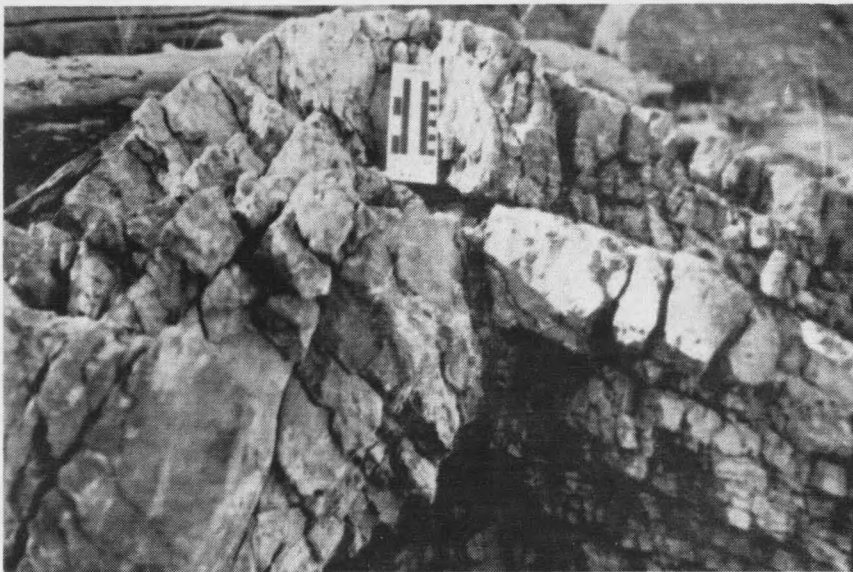


Figure 24. Cleavage development in a mesoscopic fold. Note refraction through layers.

indicative of cleavage formation prior to folding (Mittra and other, 1984), whereas refraction suggests concurrent folding and cleavage development (Ramsay and Huber, 1983). It is suggested that cleavage in Domain II folds formed prior to folding and was then intensified and refracted as the cores of macroscopic folds experienced continued shortening.

In thin section, cleavage is characterized by linear to anastomosing seams which cut bedding. Cleavage domains are usually defined by a brownish residue of clay and silt-size particles and minor phyllosilicates, and some domains contain well-formed dolomite rhombohedrons (Figure 25). Bedding and calcite veins may be offset by cleavage domains. Incipient cleavage development is seen as a thin, sinuous concentration of light brown material oriented at a high-angle to bedding. These features indicate that cleavage development was a result of the pressure solution process (Durney, 1972; Alvarez and others, 1976).

Associated with cleavage development are fibrous and sparry calcite-filled veins that are oriented sub-perpendicular to cleavage domains. Figure 25 shows thin section relationships of cleavage and bedding. In cut slab, cleavage domains are more numerous, sinuous, and have more complex patterns than are evidenced in outcrop (Figure 26).

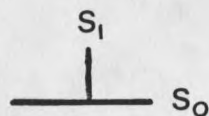
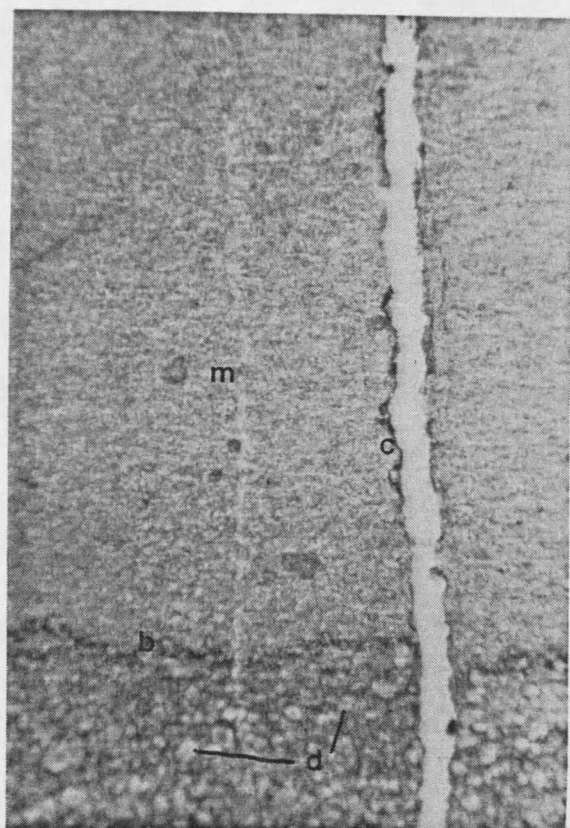


Figure 25. Photomicrograph showing relationship of cleavage and bedding. Note offset of bedding along cleavage seam. Bedding=b, microlithon=m, cleavage=c, dolomite rhombohedron=d.

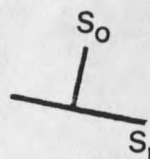
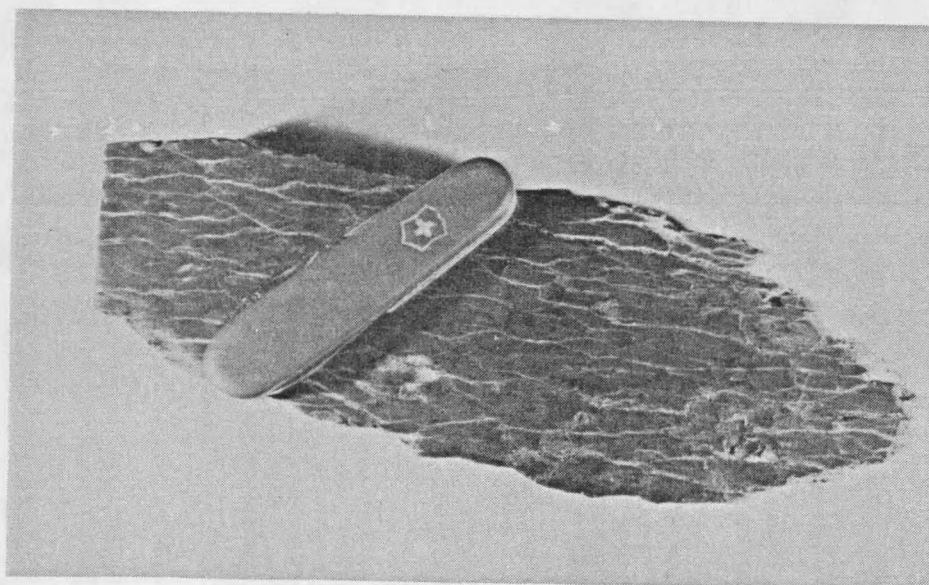


Figure 26. Slab photograph of cleavage in Steamboat Limestone. Sample is from station "y" and is cut perpendicular to bedding.

Cleavage Development.

The outcrop and thin section relationships described above indicate that cleavage in the Steamboat Limestone was formed by pressure solution processes. Pressure solution is considered one of the principal mechanisms responsible for the formation of cleavage in low-grade metamorphic rocks (Engelder and others, 1981). Several studies concluded that pressure solution cleavage development is controlled by lithology (Wanless, 1979), structural position and strain (Wanless, 1979; Marshak and Engelder, 1985). These studies indicate that a 10% clay-quartz matrix is necessary for limestone to be susceptible to efficient deformation by rock-water interactions and cleavage development. In limestones with less than 10% clay-quartz matrix, shortening occurs by twinning (Marshak and Engelder, 1985).

These results were tested in two samples exhibiting well-developed cleavage in the Steamboat Limestone. The samples were dissolved with an excess of HCl until a non-carbonate residue remained. The remaining residue, clay and other insolubles, comprised less than 2% of the initial weight of each sample. This suggests that lithology is not the primary factor controlling cleavage development in the Cambrian Steamboat Limestone. Therefore, cleavage development is primarily attributed to structural position and strain.

Boudins

Discontinuous boudins are observed in the cores of macroscopic anticlines and at the base of thrust faults in the competent layers of Pentagon Shale. Boudins are the individual structures formed by the boudinage process. At low metamorphic grade, boudins are

discontinuous, that is, formed by extension perpendicular to bedding (Mullenax and Gray, 1984). Boudin development is commonly related to folding and thrust faulting (Wilson, 1982).

Boudin shapes vary from rectangular to pinch-and-swell, to completely disconnected (Figure 27). Boudin geometry and terminology is shown in Figure 28. En-echelon boudin structure is also present suggesting that layering was oblique to the principal extension direction during deformation (Ramsay and Huber, 1983).

Boudin thickness averages 3 cm and widths range from 2 to 20 cm. Long axes of boudins are usually oriented parallel to fold axes, the b-kinematic direction (Wilson, 1982). Fibrous, calcite-filled fractures in neck areas measure up to 2 cm in length and are local indicators of extension.

A plot of boudin long axes is seen in Figure 29. The average trend of the long axes is northwest-southeast, which deviates from the trend of macroscopic fold axes by greater than 20° in a counter-clockwise direction. An explanation for this asymmetry may be that the boudins were passively rotated after folding by continued motion on the Backbone thrust sheet. An alternate explanation for the asymmetry is that the boudins formed initially at an oblique orientation to macroscopic structures due to complex local stresses. The orientation and association of boudins with larger structures suggests boudins formed during macroscopic folding and motion on the Backbone thrust.



Figure 27. Boudins developed in competent mudstone and packstone beds in Cambrian Pentagon Shale. Note pencil for scale.

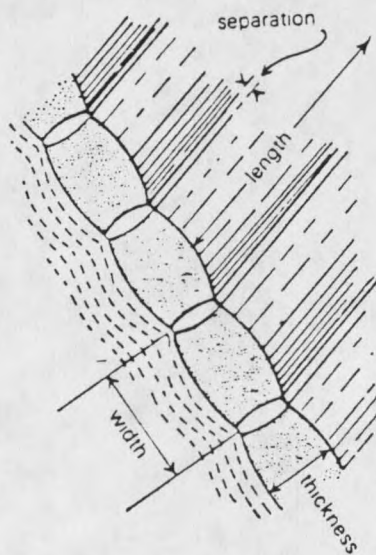


Figure 28. Boudin dimensions and shapes (from Wilson, 1982).

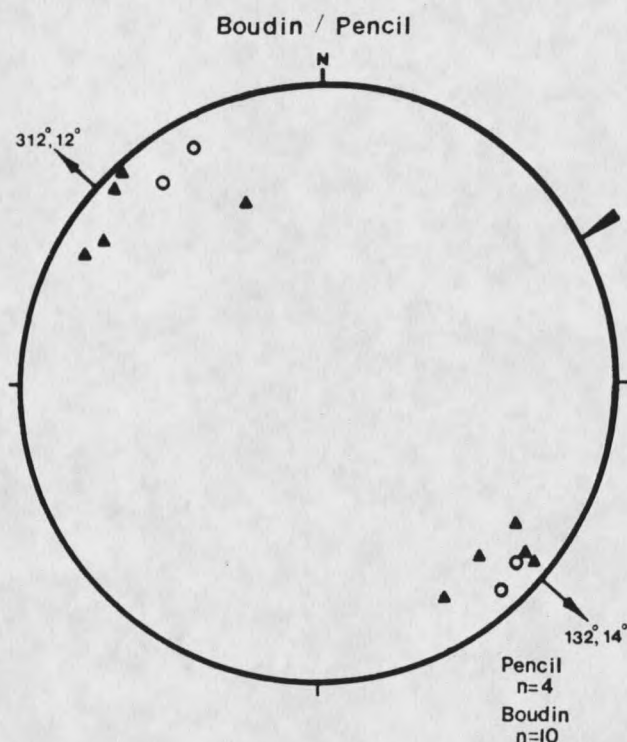


Figure 29. -- Plot of boudin long axes and pencil structure lengths. Trend of macroscopic fold axes is $153^{\circ}, 10^{\circ}$.

Pencil Structure

Pencil structures (Cloos, 1947) are elongate, angularly terminated fragments that developed in the competent mudstone layers in the Pentagon Shale (Figure 30). Pencils are formed on the upright, northeast limb of a macroscopic anticline near station z. Boudins also occur in the same fold on the southwest limb. Pencils are a strain-dependent fabric element and are formed by the intersection of bedding and weak, spaced cleavage (Ramsay and Huber, 1984). Therefore, pencils probably formed as a result of shortening by pressure solution in the mudstone layers in the Pentagon Shale.



Figure 30. Outcrop of pencil structures in competent mudstones and packstones of the Pentagon Shale. Note scale in center of photo.

Long axes of pencil structures trend from 132° to 139° , which is similar to boudin long axes (Figure 29). Although there are few measurements of the trend of pencil structures, the agreement between pencil orientation and boudin long axes and their occurrence within the same fold suggests that their formation was coaxial and nearly contemporaneous. Thus, while macroscopic folding compressed the forelimb and developed pencil structures, localized extension and boudinage occurred on the more gently-dipping backlimb.

Tectonic Veins

Calcite-filled veins occur throughout the study area but are most prevalent in Domain I. Their orientations and field relationships indicate their formation was coeval with development of the structural elements in the Backbone thrust sheet. They vary in size from

microscopic fissures to veins up to 5 cm in width. Most veins are 0.5 to 1 cm wide and 1 to 2 m in length. Two types are recognized: extension and shear veins.

Extension Veins. Extension veins occur singly or in en-echelon arrays. Vein-fill material is either fibrous calcite, blocky calcite or both. An exceptional exposure of numerous en-echelon vein sets is shown in Figure 31.

Poles to single veins are plotted in Figure 32. These poles approximate the dilation directions of the calcite fibers (Ramsay, 1981) and indicate extension in two directions: parallel to the direction of tectonic transport, and parallel to the trend of fold axes.

The shear directions for 14 en-echelon vein sets were determined from the method of Ramsay and Huber (1983) (Figure 32). Shear directions range from 50° to 140° . This wide range contradicts other indicators of shear (faults, fold axes, lineations) which define a predominant direction of transport (Figure 18), and are thus enigmatic.

Shear Veins. Shear veins are primarily developed in Domain I on bedding and fault surfaces. Shear veins are identified by fibrous calcite steps that form at a low angle to the slip surfaces.

Figure 32 is a plot of poles to shear veins. Two broad orientations are seen: a northwest-striking set and a northeast-striking set. The first set indicates variably oriented planes which

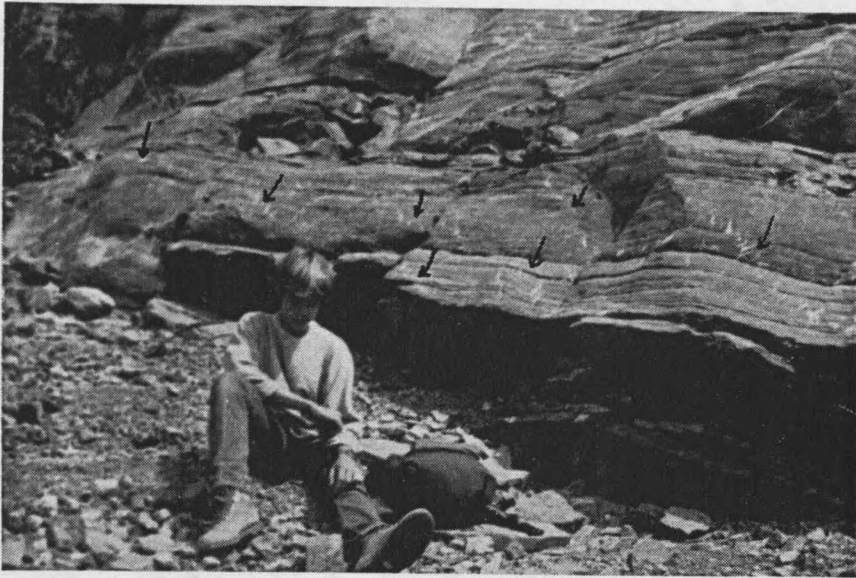


Figure 31. Outcrop of Cambrian Steamboat Limestone at station "p" with abundant en-echelon vein sets. Arrows point to individual sets.

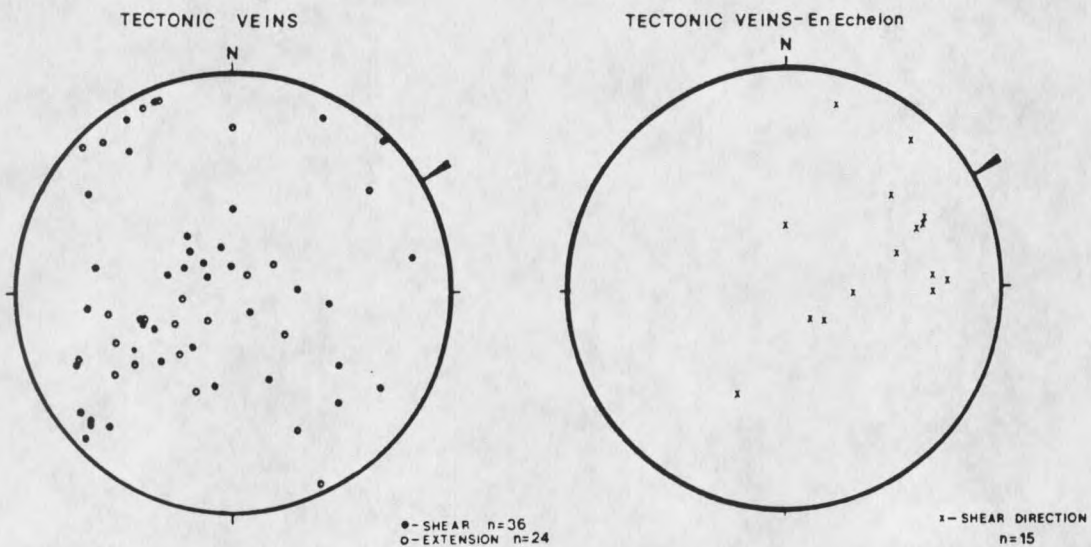


Figure 32. Poles to singly-occurring and en-echelon tectonic veins. Open circles are poles to extension veins. Closed circles are poles to shear veins. X corresponds to shear directions for en-echelon veins.

reflect the duplexing nature of mesoscopic faults. The northeast-striking set of planes are subvertically oriented. They are interpreted as tear faults which accomodate local differential movement.

Summary

Internal deformation in the Backbone thrust sheet includes macroscopic, mesoscopic and microscopic structural elements. Macroscopic folds and faults have a lateral distribution with faults predominating in a zone of imbrication at the leading edge and folds occurring in the intraplate region. Mesoscopic structural elements define three deformation domains which are distributed within macroscopic structures. The vertical distribution of these deformation domains in the hanging wall is dependent on the distance from thrust faults and the lithology of the footwall.

Domain I is proximal to the thrust faults. It is dominated by mesoscopic faults and tectonic veins and contains recumbent drag folds and minor gouge and breccia where Steamboat Limestone is thrust over competent rocks. Where Steamboat Limestone is thrust over shale, there are markedly fewer faults and tectonic veins. No breccia or gouge are seen.

Domain II is located in the strata overlying Domain I and in macroscopic folds. Domain II is cleavage dominated and contains upright mesoscopic folds, boudins, tectonic veins and pencil structures. Domain III is the remaining undeformed strata in the upper part of the thrust sheet.

At the macroscopic scale, the important mechanisms of deformation were folding and faulting. Mesoscopic- and microscopic-scale mechanisms of deformation operated simultaneously in Domain I and include: faulting, extension fracturing, recrystallization and pressure solution. Fault surfaces also experienced frictional sliding and pressure solution slip. The dominant mechanism of deformation for Domain II is pressure solution which is exhibited by development of cleavage and pencil structures. Minor extension fracturing is responsible for calcite veins and boudins.

MAGNITUDE OF INTERNAL DEFORMATION

The magnitude of internal deformation was estimated at the macroscopic, mesoscopic and microscopic scales to ascertain their relative contributions to overall shortening within the Backbone thrust sheet. Internal deformation may be divided into two categories: longitudinal strain caused by layer-parallel shortening or extension; and shear strain caused by proximity to thrust faults. The internal deformation features measured include; macroscopic folding and thrust imbrication, mesoscopic pencil structures, cleavage, boudins, en-echelon veins, drag folds, and fault arrays; and microscopic ooids.

Fold Shortening

Macroscopic intraplate folds contribute significantly to the total shortening of the Backbone thrust sheet. Longitudinal strain due to buckling of layers in the Steamboat Limestone was determined by comparing folded length with arc-length of layers in cross sections A'-A'' and A''-A''' (Figures 11 and 12). Fold shortening ranges from 7 to 160 m for individual folds and collectively accounts for over 300 m of shortening. These shortening values average 25% per fold and are considered to correspond to an average of 25% shortening for the intraplate region of the thrust sheet, based on the pervasive nature of the folds.

Thrust Imbrication

Macroscopic thrust faults contribute a significant amount to shortening by imbrication at the leading edge of the thrust sheet. Longitudinal strain was measured by comparing the length of the imbricated region in cross sections A-A' and B-B' (Figures 10 and 13), with the length of the section with bedding restored to its pre-thrust configuration. The amount of shortening measured was approximately 30%. This value, combined with 25% shortening by folding in the intraplate region, gives an overall value of 55% shortening at the macroscopic scale for the thrust sheet.

Pencil Structures

Pencil structures are a strain-dependent fabric that forms between bedding fissility and cleavage (Ramsay and Huber, 1983). Reks and Gray (1983) developed a method for quantifying pencil strains in siltstone and mudstone of the southern Appalachian Mountains. Their work shows that pencils are formed when minimum principal strains (Z) range from 9-26% longitudinal shortening. Such pencil structures are found at station n (Figure 9).

Cleavage

Cleavage-related strain was qualitatively estimated due to a lack of suitable features for quantitative analysis in the Steamboat Limestone. Since cleavage strain varies with spacing and morphology of cleavage domains (Alvarez and others, 1978) (Table 1), it was possible

to determine percent values of cleavage-related longitudinal shortening for Domain II.

Cleavage in Domain II associated with thrust faults has moderate to strong development that corresponds to layer-parallel shortening values of 4-35%+. Cleavage associated with macroscopic and mesoscopic folds is most widespread with moderate development corresponding to shortening values of 4-25%.

Boudins

Boudins are found in competent packstone and mudstone intervals in the upper Pentagon Shale at stations "n", "j", and "s" (Figure 9). Calcite vein-filling in the neck regions of the boudins records extensional strains perpendicular to bedding using the following relationship:

$$R = 1 + \frac{\sum dlx}{\sum lox} \quad (\text{Mitra, 1979})$$

where R is the axial ratio (ellipticity) of the strain ellipse in the XZ plane, dlx is the width of each calcite vein and lox is the width of each segment of host rock (Figure 33). Strain values (R) for boudins from 16 measurements range from 1.1-1.3, which correspond to 10 - 30 % layer-parallel extension. Calcite veins in boudins indicate that extension occurs locally in a predominantly contractional deformation regime.

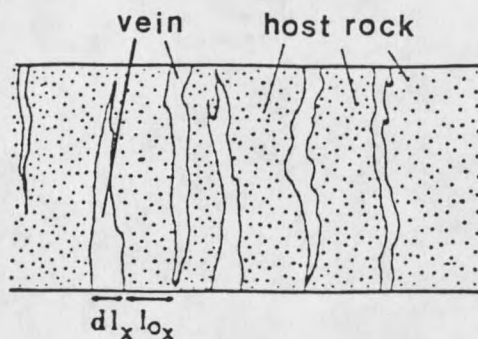


Figure 33. Discontinuous boudins with dl_x defining width of each tension vein and lo_x defining width of each segment of host rock (from Mitra, 1979).

En-Echelon Veins

En-echelon vein arrays are found in the Steamboat Limestone at stations "m", "p" and "q" in Domain I (Figure 9). Shear strain was determined by measuring the change of orientation of sigmoidal veins, using the method outlined by Ramsay and Huber (1983, p. 23-25). Shear strain values (γ), based on 13 measured vein arrays, average 0.5 which indicates that individual displacements by shearing are small. From shear strain values, the component of shortening was calculated by the following:

$$\lambda_2 = 0.5(\gamma^2 + 2 - \gamma(\gamma^2 + 4)^{0.5}) \quad (\text{Ramsay and Huber, 1983})$$

where

$$\lambda_2 = (1 + e_2)^2.$$

Then shortening, or e_2 is found by the following:

$$e_2 = (\lambda_2)^{0.5} - 1.$$

Calculated shortening values range from 10% to 28% with an average value of 20%.

Drag Folds

Mesoscopic drag folds are commonly found in Domain I. An estimate of the magnitude of longitudinal strain which they contribute was determined by comparing the measured bedding length with the fold amplitude of 6 recumbent folds. Shortening values range from 47% to 61% and average 52%. Although these folds are not homogeneously distributed, the magnitude of shortening which they imply for the Domain I may be an indicator of the magnitude of shortening that occurs by fault arrays.

Fault Arrays

A preliminary estimate of shortening by Domain I fault arrays was made, based on values determined for drag folds and en-echelon veins. En-echelon veins indicate a low value of 20% shortening and drag folds a higher value of 52% shortening. Shortening by fault arrays may be most closely approximated by the higher value, based on the intensity of deformation observed in outcrop and thin section. However, the abundance of calcite-filled veins in fault zones indicates that extension negates a large, though unmeasured, percentage of the shortening, therefore, the resultant total shortening may be much less. A more reasonable estimate for the resultant shortening by fault arrays is 20% to 30%.

Strain determinations of macroscopic and mesoscopic structural elements are given in Table 2. The scale, location, lithology, strain parameter and percent shortening are listed.

Ooids

Ooid-bearing beds of the Steamboat Limestone and Pentagon Shale were analyzed for finite strain within the Backbone thrust sheet. Microscopic strains are compared with mesoscopic and macroscopic strain indicators and related to the deformation history of the Backbone thrust sheet.

In general, deformation of ooids is due to pressure solution generated by layer-parallel shortening. However, in proximity to fault zones, deformation is the result of pressure solution and simple shear. The amount of microscopic finite strain recorded by ooids is low.

Data Collection and Method of Analysis

Nineteen oriented samples containing ooids were collected at various localities throughout the Backbone thrust sheet (Figure 34). Two thin section cuts were made for each sample using an A-B-C coordinate system which is an application of the right-hand rule. The A-axis is parallel to strike, the B-axis is parallel to the dip direction and the C-axis is oriented down and perpendicular to the AB plane. Cuts were made mutually perpendicular to each other in the AC and BC planes under the assumption that these two planes contain (or closely approximate) two of the three principal planes of the finite strain ellipsoid. The validity of this assumption is verified by orientations of structural elements such as cleavage and fold axes.

Table 2. Strain determinations and percent shortening for macroscopic and mesoscopic structural elements.

MACROSCOPIC SCALE

MARKER	LOCATION	LITHOLOGY	STRAIN PARAMETER	Z SHORTENING
fold	n	Cst	$Z=0.60$ (163 m)	-60%
fold	z	Cst	$Z=0.07$ (8 m)	-7%
fold	k	Cst	$Z=0.14$ (21 m)	-14%
fold	o	Cst	$Z=0.49$ (82 m)	-49%
fold	y	Cst	$Z=0.11$ (17 m)	-11%
fold	w	Cst	$Z=0.18$ (24 m)	-18%
thrust imbricates		Cst	Z	-30%

MESOSCOPIC SCALE - Domain I

en-echelon veins	p	Cst	$xz=0.48$	-21%
en-echelon veins	q	Cst	$xz=0.66$	-28%
en-echelon veins	a	Cst	$xz=0.21$	-10%
drag folds		Cst	Z	-52%
fault arrays		Cst	Z	-20-30%

MESOSCOPIC SCALE - Domain II

cleavage	fold/thrust	Cst	Z	-15%
boudin	j	Cp	$e_z=0.18$	+18%
boudin	s	Cp	$e_z=0.18$	+18%
pencil	z	Cp	γ/Z	-9-26%

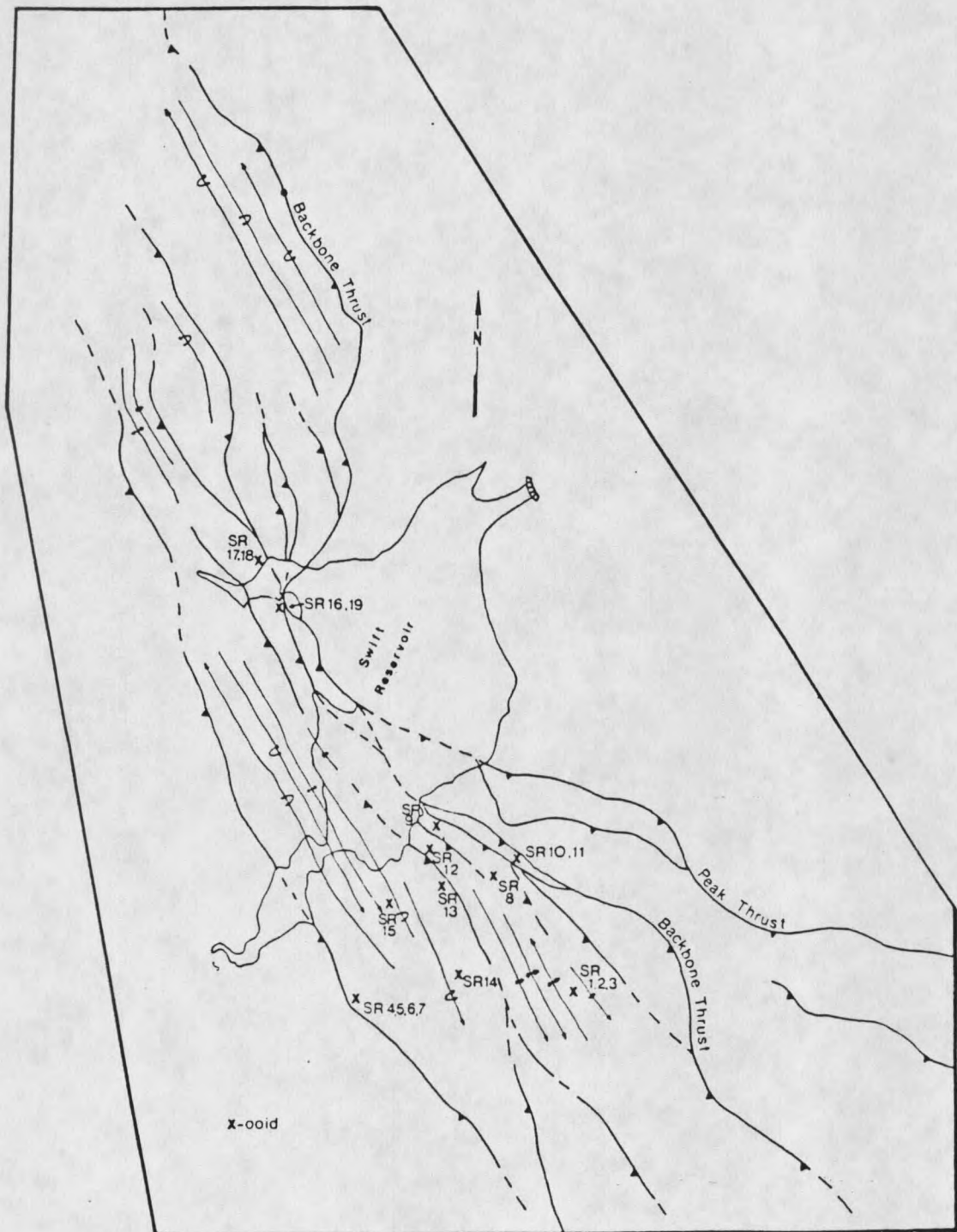


Figure 34. Locations and numbers of oriented samples containing ooids.

The thin sections were projected individually onto a wall to trace the outlines of ooids and mark their centers. An average of 85 ooids per slide were traced. Sample numbers and axes were recorded on the tracings and four representative samples were chosen (Figures 35a - 38a). The remaining sample tracing results are in Appendix B.

Ooids did not usually show elliptical shapes thus, the Fry method (1979) of strain analysis was used. The Fry method (1979) is a rapid, practical method of strain analysis which can provide an accurate first approximation of the strain ellipse from the distribution of spherical particles without the use of a computer (Ramsay and Huber, 1983). For a detailed explanation of the Fry method, the reader is referred to Ramsay and Huber (1983) and Johnson (1985).

Using this method, strain patterns were produced from the sample tracings. Strain manifests itself as a vacancy field in the center of an overlay sheet (Figures 35b to 38b). From the shape of the vacancy field, the ellipticity ($R = 1+e_1 / 1+e_2$) or strain ratio, and orientation of the long axis of the strain ellipse relative to the A or B axes (0) were determined (Figures 35b to 38b).

The ellipticity values for the cut planes, AC and BC, represent two of the three principal strain ratios R_{xy} , R_{yz} or R_{xz} and the third strain ratio was calculated by:

$$R_{xz} = (R_{xy}) (R_{yz}) \quad (\text{Ramsay and Huber, 1983, p. 170}).$$

Thus, the strain ratio for the AB plane was also determined.

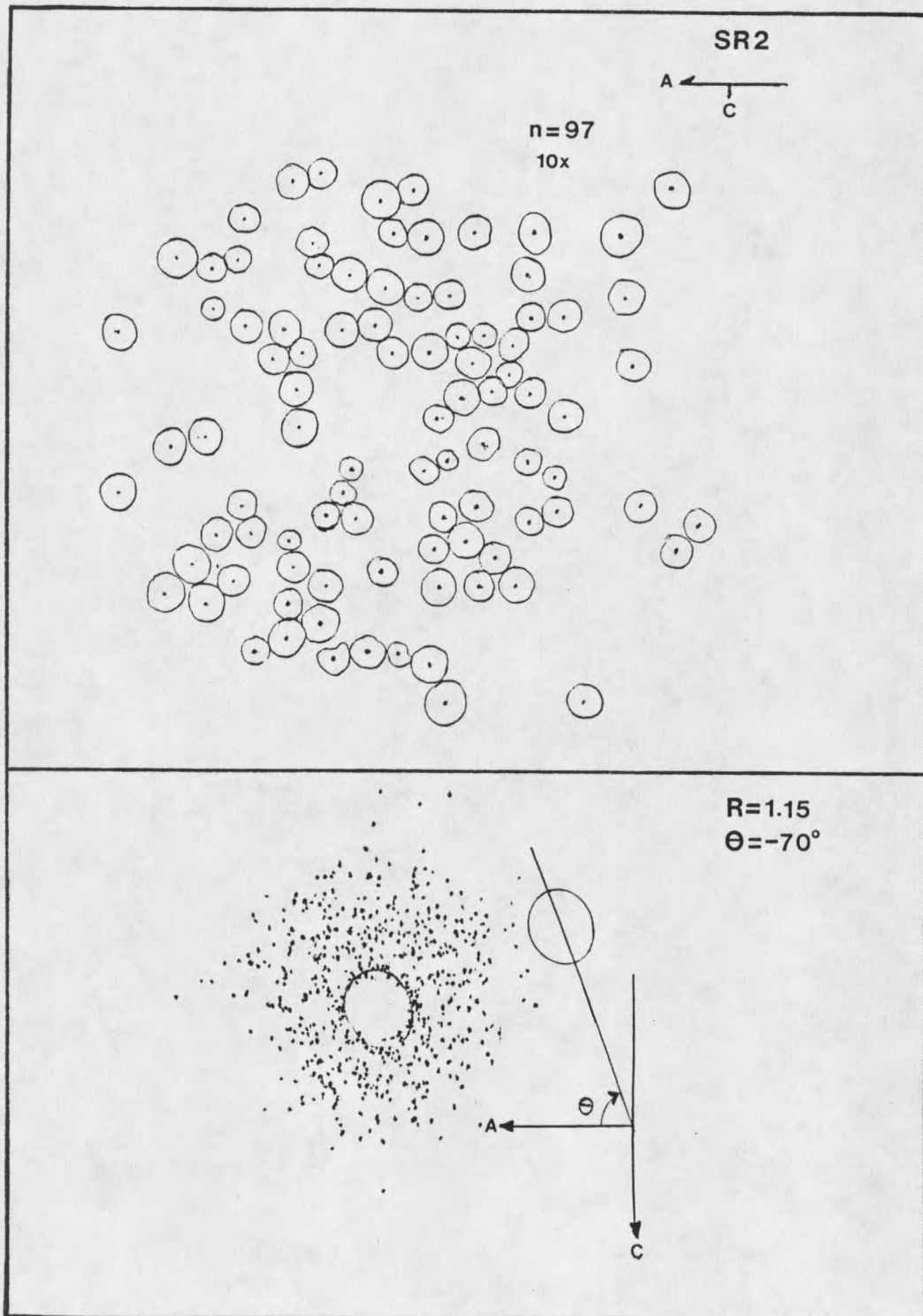


Figure 35. a. Tracing of ooids from sample SR2, AC plane. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse of circle sketched in. R =ellipticity, θ =long axis orientation.

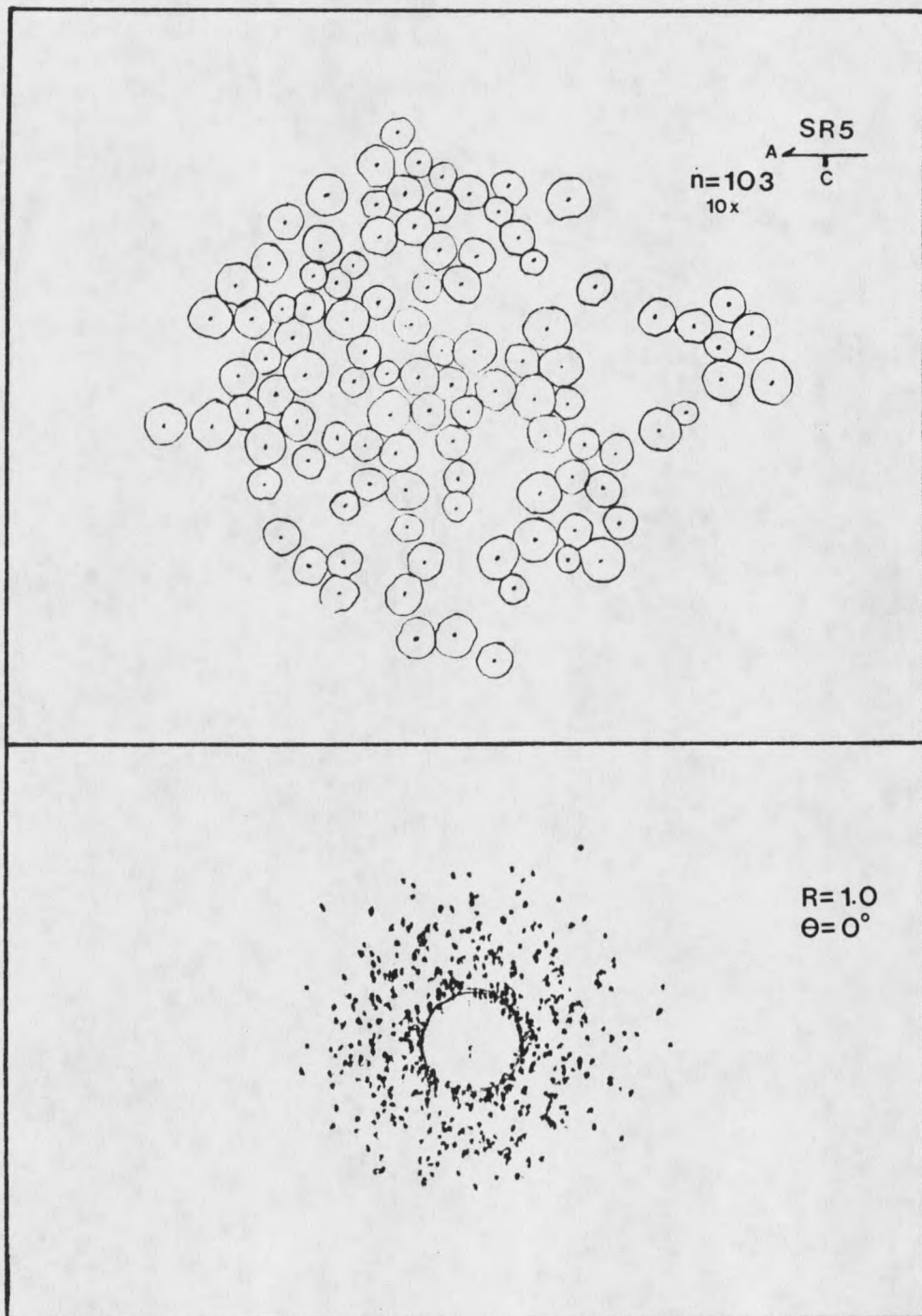


Figure 36. a. Tracing of ooids from sample SR5, AC plane. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

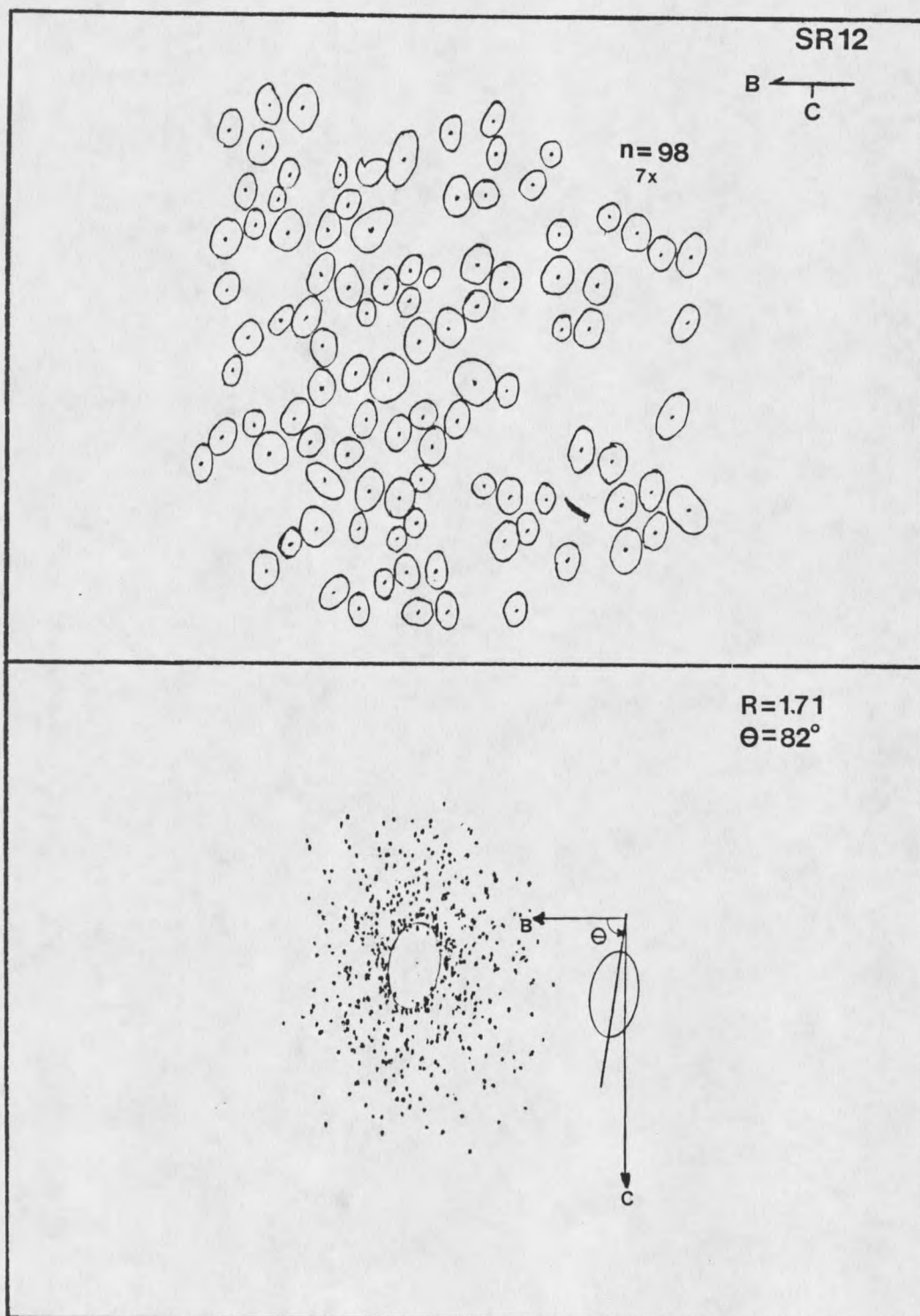


Figure 37. a. Tracing of ooids from sample SR12, BC plane. Magnified 7x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

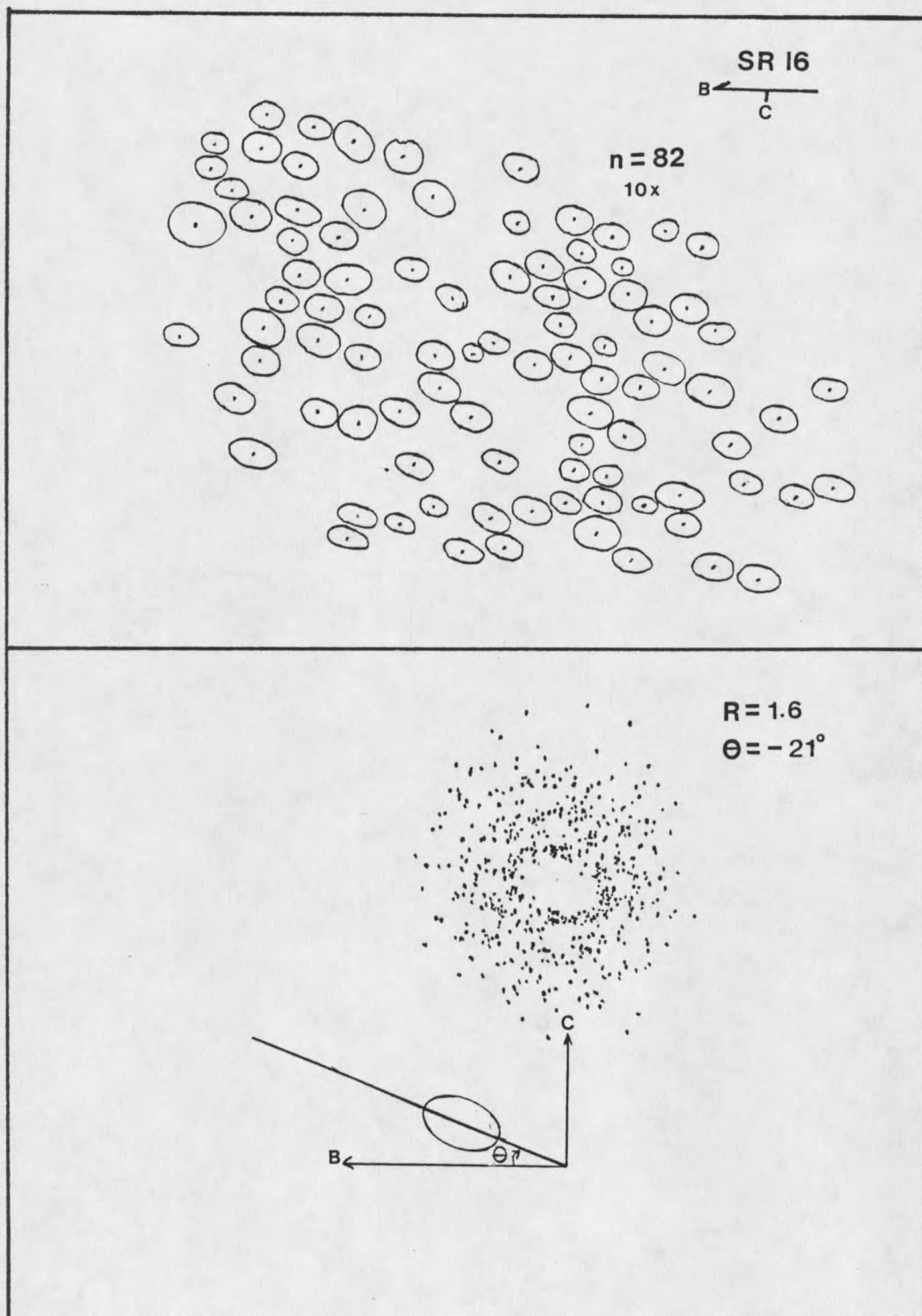


Figure 38. a. Tracing of ooids from sample SR16, BC plane. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

Determination of the correct principal strain ratio (R_{xy} , R_{yz} , or R_{xz}) for each plane was accomplished by convention by designating the XZ plane the cut plane with the largest strain ratio. This establishes the principal directions X and Z with respect to the A-B-C axes and the principal directions for the remaining two planes can easily be determined. The principal strain ratios, the cut planes to which they correspond, and their determined values (R) are recorded on Table 3.

The shape of the strain ellipsoid is determined using a Flinn graph (Flinn, 1962) and modified Flinn graph (Ramsay and Huber, 1983) (Figure 39). Ellipsoid shapes are described using the parameter "k", which is determined by the principal plane strain ratios, R_{xy} and R_{yz} . K-values indicate whether ellipses have flattened, constrictional or plane strain forms. K-values for the Flinn graph (k_F) and modified Flinn graph (k_R) are listed in Table 3 and plotted in Figure 39.

Thin Section Observations

Individual ooids in the Steamboat Limestone and Pentagon Shale range in diameter from 0.3 to 1.0 mm and average 0.5mm. Oolites are generally well-sorted. Many ooids show replacement by secondary micrite, sparry calcite or dolomite rhombohedrons. Other grains found with ooids include fossil fragments, peloids and pellets. However, ooids are the predominant grains in the thin sections examined. Using the classification scheme of Dunham (1962), the oolites are classified as ooid wackestones or packstones.

Table 3. Ooid strain data

Sample	Orientation of marked face	Plane	Axial Ratio (Ellipticity)	Long axis orientation (θ)	k(F)	k(R)	Interpretation	Domain
SR1	330, 81 sw	AC BC AB	Rxz = 1.75 Ryz = 1.41 Rxy = 1.24	-53° -2°	.58	.62	flattened parallel strike	II
SR2	334, 81 ne	AC BC AB	Rxz = 1.19 Rxy = 1.13 Ryz = 1.05	-70° 53°	2.6	2.50	prolate parallel strike	II
SR3	315, 70 sw	AC BC AB	Rxz = 1.13 Rxy = 1.0 Ryz = 1.13	90° 0°	0	0	flattened parallel strike	II
SR4	349, 02 ne	AC BC	1.0 1.0				no strain	II
SR5	338, 84 sw	AC BC AB	Rxy = 1.0 Rxz = 1.17 Ryz = 1.17	0° 87°	0	0	flattened perpendicular to bedding	II
SR6	323, 73 ne	AC BC AB	Rxz = 1.41 Rxy = 1.0 Ryz = 1.41	-74° 0°	0	0	flattened subparallel to strike	II
SR7	322, 60 ne	AC BC AB	Rxy = 1.21 Rxz = 1.26 Ryz = 1.04	59° -67°	5.25	4.86	prolate at high angle to bedding	II
SR8	327, 71 sw	AC BC AB	Rxz = 1.49 Ryz = 1.18 Rxy = 1.26	-10° 30°	1.44	1.4	prolate subparallel to bedding	I
SR9	346, 35 sw	AC BC AB	Rxy = 1.0 Rxz = 1.22 Ryz = 1.22	0° -57°	0	0	flattened at high angle to bedding	I
SR10	340, 24 sw	AC BC AB	Rxy = 1.16 Rxz = 1.34 Ryz = 1.15	89° -73°	1.07	1.06	prolate subperpendicular to bedding	I
SR11	337, 83 sw	AC BC	R = 1.47 insufficient data	-62°			insufficient data	

Table 3. Continued

Sample	Orientation of marked face	Plane	Axial Ratio (Ellipticity)	Long axis orientation (θ)	k(F)	k(R)	Interpretation	Domain
SR12	335, 54 sw	AC BC AB	Rxy = 1.15 Rxz = 1.48 Ryz = 1.48	-57° 82°	.31	.35	flattened perpendicular to bedding	I
SR13	305, 46 sw	AC BC AB	Rxy = 1.0 Rxz = 1.15 Ryz = 1.15	0° -62°	0	0	flattened at high angle to bedding	I
SR14	338, 74 ne	AC BC AB	Rxy = 1.15 Rxz = 1.2 Ryz = 1.04	55° 68°	3.75	3.56	prolate at high angle to bedding	II
SR15	326, 85 ne	AC BC AB	Ryz = 1.18 Rxz = 1.25 Rxy = 1.06	8° -44°	.33	.35	inclined at moderate angle to bedding	II
SR16	0, 50 w	AC BC AB	Ryz = 1.44 Rxz = 1.6 Rxy = 1.11	-44° -21°	.25	.28	flattened subparallel to bedding	I
SR17	324, 45 sw	AC BC AB	Ryz = 1.0 Rxz = 1.51 Rxy = 1.51	0° 4°	∞	-	prolate parallel to bedding	I
SR18	340, 42 sw	AC BC AB	Rxz = 1.38 Ryz = 1.25 Rxy = 1.10	-25° -61°	.40	.42	flattened subparallel to bedding	I
SR19	6, 54 sw	AC BC AB	Ryz = 1.42 Rxz = 1.76 Rxy = 1.24	7° -1°	.57	.61	flattened parallel to bedding	I

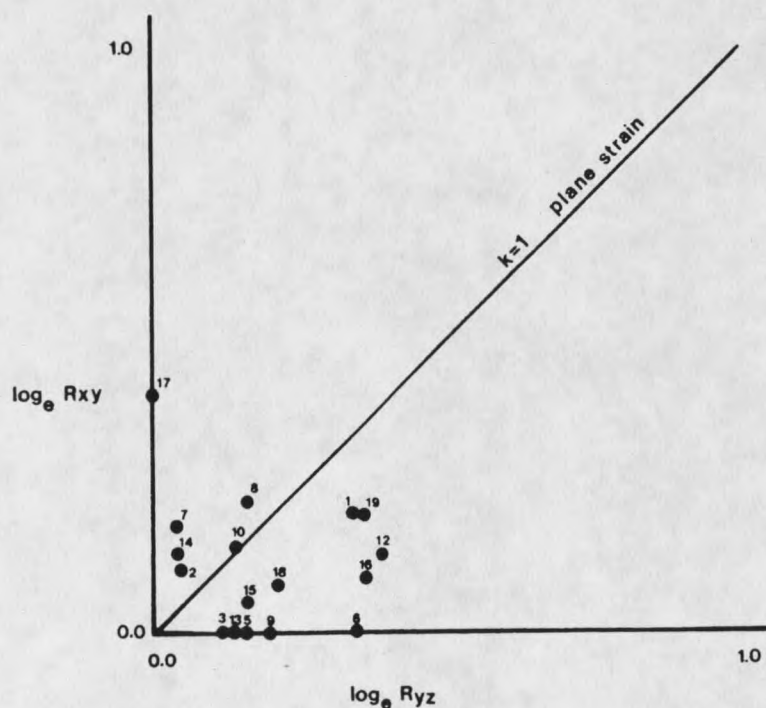
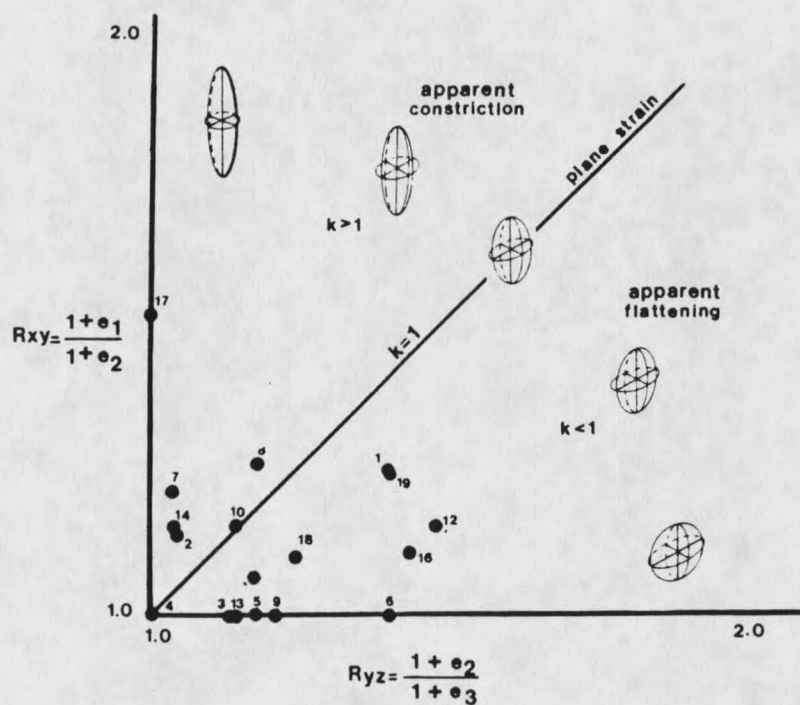


Figure 39. a. Flinn diagram showing shapes of strain ellipsoids for k -values (From Ramsay, 1967). Numbered dots correspond to k -values for samples recorded on Table 3. b. Modified Flinn diagram (From Davis, 1984). Numbered dots correspond to k -values recorded on Table 3.

Structures associated with the oolites include stylolites and suture contacts, extension veins and microfault zones. Stylolites and sutured contacts occur between grains and on grain margins, which are generally oriented parallel or perpendicular to bedding. Extension veins and microfaults are found in several samples in proximity to thrust faults. These structures indicate that pressure solution and brittle deformation mechanisms were responsible for the strain recorded by the Fry method.

Discussion

Overall, microscopic strain recorded by ooids appears to be low, with strain ratios (ellipticities) ranging from 1.0 (no strain) to 1.76 and averaging 1.26. Layer-parallel shortening ratios in the dip direction average 1.29:1. Layer-parallel shortening ratios in the b-kinematic or strike directions average 1.24:1. Only one sample (SR4) showed no strain in either the AC or BC planes.

Strain ellipsoid shapes and orientations are partitioned with respect to Domains I and II. These data are listed on Table 3 for each sample. K-values determined for the samples indicate that flattening deformation is the most prevalent; however, several samples show constrictional deformation (Figure 39).

Domain I. Vertical cross sections perpendicular to the regional strike show Domain I ellipticity values (R) for the BC plane ranging from 1.15 to 1.76 (Figures 40 and 41). Average ellipticity is 1.42. Strain ellipsoids show two general orientations: 1) flattened or prolate at high-angles to bedding in the dip direction; or 2) flattened or prolate subparallel to bedding, with the direction of maximum

shortening perpendicular to bedding. Flattening strains are more common than constrictional strains.

Samples SR12 and 13 are flattened subperpendicular to bedding suggesting layer-parallel shortening. Sample SR9 is flattened at oblique angles to bedding, which may be due to simple shear on bedding planes during flexural-slip folding. Samples SR16, 18 and 19 are flattened subparallel to bedding. Thin sections show pervasive stylolites and microfaults, suggesting that flattening is due to shear zone deformation rather than sedimentary compaction. Samples SR8 and 17 are prolate parallel to bedding with long axes parallel to the strike direction; shortening parallel to bedding combined with rotation of particles may be the responsible for these ellipsoids. Sample SR10 is prolate at high angle to bedding, indicating constrictional strains may be predominant at the thrust front; this sample most closely approximates plane strain.

Deformation in Domain I is interpreted to have followed the general path of early layer-parallel shortening due to pressure solution, which led to the development of ellipsoids flattened at high angle to bedding. During transport of the thrust sheet, some flattened ellipsoids may have been rotated while others experienced constrictional strain. The final stage was flattening or shear strain subparallel to bedding as indicated by samples obtained close to fault zones. This deformation sequence is generally seen as the samples get progressively closer to the leading edge of the Backbone thrust.

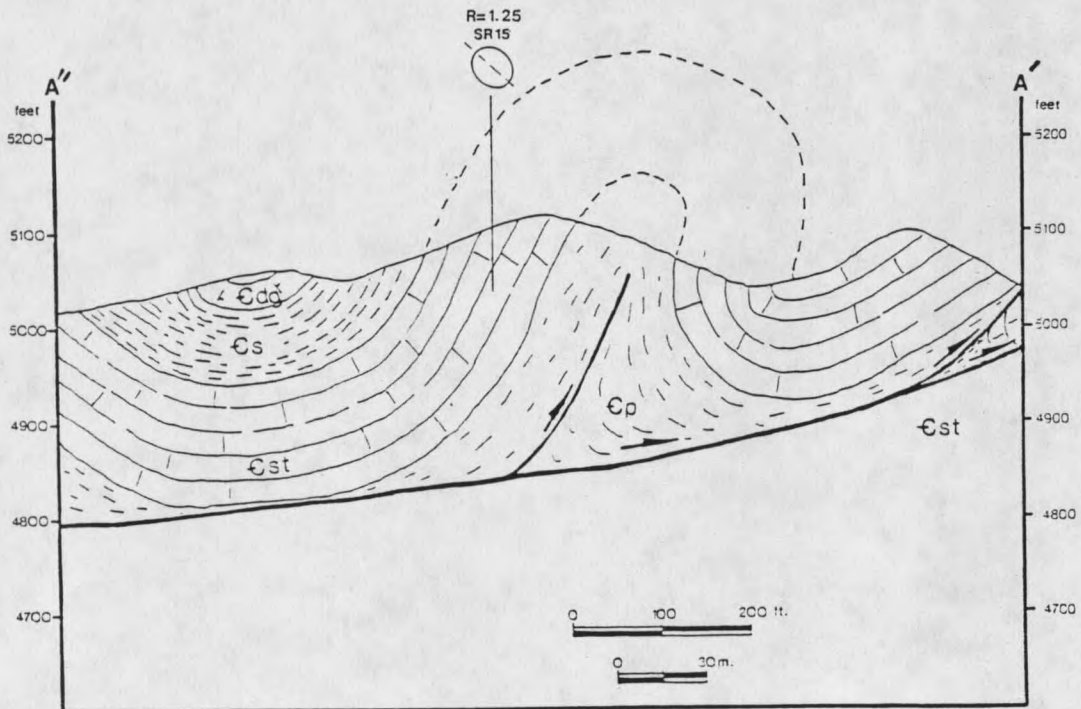
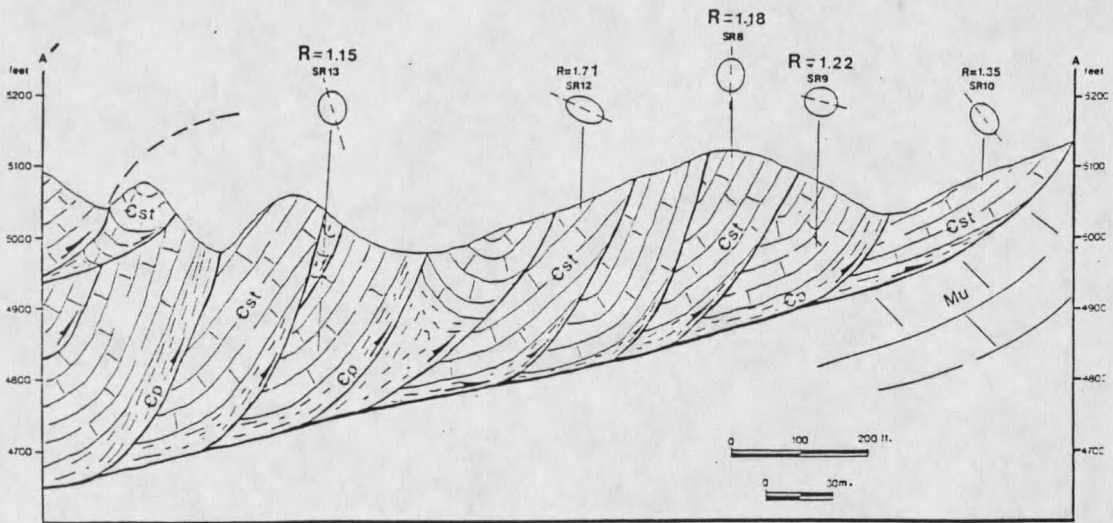


Figure 40. Cross sections A-A' and A'-A'' with strain ellipses determined from the BC oriented plane.

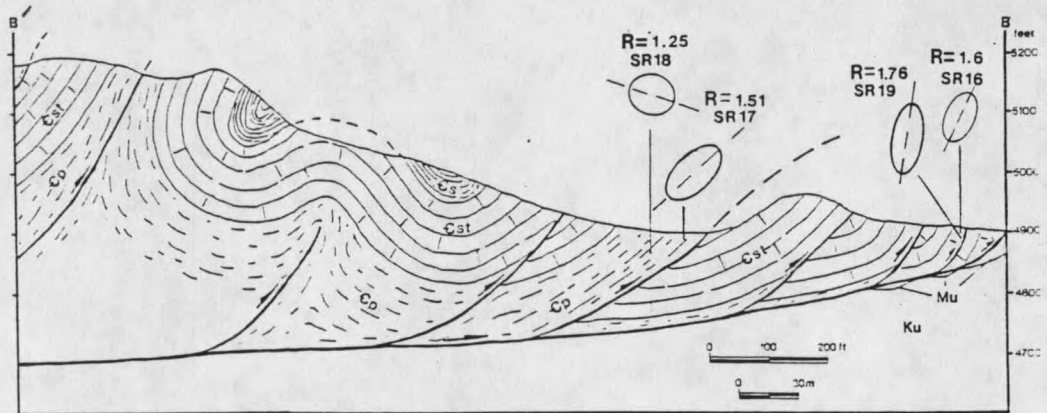
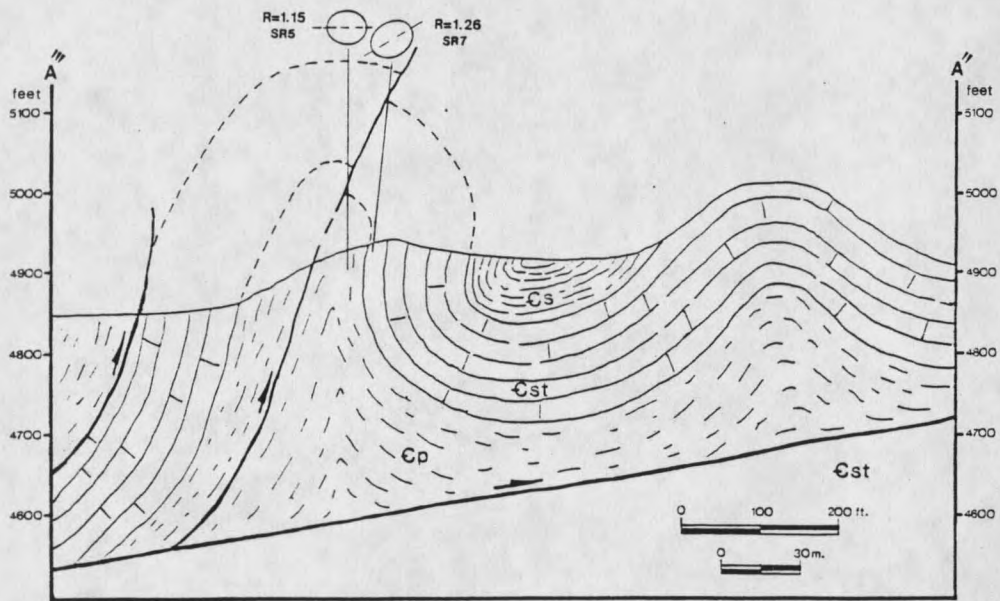


Figure 41. Cross sections A''-A''' and B-B' with strain ellipses determined from the BC oriented plane.

Domain II. Strains developed in Domain II have slightly lower values than those from Domain I. Domain II samples show ellipticities ranging from 1.0 to 1.41, with an average of 1.17 for ellipses in the BC plane (Figures 40 and 41). Strain ellipsoids show two general orientations: 1) flattened or prolate subperpendicular to bedding in the dip direction; and 2) flattened or prolate subperpendicular to bedding in the strike direction. The first group includes samples SR5, 7 and 14, and layer-parallel shortening in the dip direction similar to Domain I is suggested. Those ellipsoids flattened perpendicular to bedding in the strike direction include samples SR1, 3 and 6; their formation is due to layer-parallel shortening in the strike direction. The constrictional form of SR2 is probably due to superposition of strike-directed shortening after early shortening in the dip direction. One sample, SR15 showed flattening parallel to bedding. Thin section observations showed bed-parallel stylolites but lacked microfaults and extension veins, suggesting that sedimentary compaction was an important process for this sample.

Most of the ooid deformation in Domain II is interpreted to be the result of early layer-parallel shortening in the dip direction. Strike-parallel shortening is also evidenced in several samples. This compression may be the result of late folding of the Backbone thrust sheet, as suggested in the section on cleavage.

Layer-parallel shortening, determined by the orientation of strain ellipsoids from Domain II oolites, is analagous to shortening indicated by the orientation of cleavage domains. In addition, both deformations are the result of pressure solution. This suggests that the

microscopic deformations responsible for ooid strain are expressed mesoscopically by the formation of cleavage. Therefore, these deformations are contemporaneous, coaxial, and record similar strains.

Microscopic Strain Summary

An average ellipticity (strain ratio) of 1.26 for all samples suggests that deformation, overall, is low. In general, BC planes record higher strains than AC planes, indicating deformation is higher in the dip direction than in the strike direction. Strain in Domain I is only slightly higher than Domain II. This implies that the oolite strains from Domain I are not representative of the extreme deformation in fault zones that is observed on the outcrop and in thin section. Indeed, no samples were found within a fault zone that contained intact ooids.

The correlation between microscopic deformation and cleavage formation established in the previous section suggests that the amount of shortening recorded by cleavage is also recorded by oolites. Cleavage development indicates local shortening values from 4-35%+ for Domain II in macroscopic folds and thrust imbricates. Microscopic strain is more homogeneously distributed (Mitra, 1979) and, therefore, it is herein suggested that microscopic strain and cleavage development represent an average of 15% layer-parallel shortening prior to macroscopic folding and thrust imbrication.

Summary

Macroscopic folds and thrust imbricates are responsible for the most significant measurable longitudinal strain in the Backbone thrust

sheet. Macroscopic folds account for 25% shortening in the intraplate region, where thrust imbrication provides an additional 30% shortening at the leading edge. Thus, total shortening at the macroscopic scale is estimated at 55%.

Domain I fault arrays, drag folds and en-echelon vein arrays may contribute as much as 52% to shortening by longitudinal and shear strains; however, the abundance of extension veins indicates that a more reasonable range of values is 20% to 30% shortening. Strain measurements from analysis of oolites average 1.42 for Domain I. Strain ellipsoid shapes indicate that the most common directions of shortening are subperpendicular and subparallel to bedding. The resultant shortening for Domain I is in addition to the amount of shortening by macroscopic imbrication; however, its distribution is within a relatively narrow zone, unlike Domain II cleavage.

The development of spaced cleavage in Domain II and oolite strain analysis suggest that approximately 15% layer-parallel shortening preceded macroscopic folding, thrust imbrication and Domain I faulting. Pencil structures contribute locally to longitudinal strain in the Pentagon Shale. Boudin development indicates that localized extensions occurred within a predominantly contractional regime.

DISCUSSION OF STRUCTURAL ELEMENTS AND INTERNAL DEFORMATION

The variation in distribution of structural elements and the magnitude of internal deformation have been established for the Backbone thrust sheet in the previous chapters using macroscopic, mesoscopic and microscopic structural elements. The importance of these data is that they indicate where shortening is most significant and how much shortening has occurred within the thrust sheet. Interrelationships between structural elements are also useful for constructing a sequence of deformation for the Backbone thrust sheet. In addition, observations of the morphology and mechanisms of fault zone deformation provide important insight into thrust sheet emplacement processes.

Shortening

Macroscopic folds and thrust imbricates contribute most significantly to total shortening within the thrust sheet and their combined values indicate approximately 55% shortening. Mesoscopic structural elements within Domains I and II contribute shortening that is temporally or spatially unique from macroscopic deformation. Cleavage development predates macroscopic deformation; therefore, 15% shortening is added to the macroscopic value for a combined total shortening of 70%. Domain I fault zones contribute an estimated 20% to 30% shortening at the base of thrust imbricates which is believed to be contemporaneous with thrust imbrication. Because the distribution of

Domain I deformation is in relatively narrow zones, these shortening values have not been added to the total shortening value.

It is important to note that the internal deformation and total shortening determined is within the easternmost slice of the Backbone thrust sheet which is centered around Swift Reservoir. Presumably, the slices of the Backbone thrust sheet which are found west of the study area have similar style of internal deformation and magnitude of shortening.

Orogenic shortening across thrust belts has been reported by numerous workers to average approximately 50% (e.g. Royse and others, 1975, Boyer and Elliott, 1982). This study suggests 70% shortening occurred in the Backbone thrust sheet by internal deformation; therefore, combined orogenic and internal shortening values for the Swift Reservoir area appear to be 120%.

Although some structural elements, such as gouge, breccia, pencils, and boudins account for only a small amount of internal deformation, they are important because they are kinematic indicators and demonstrate the manner in which strain was accommodated during deformation (Mitra, 1979).

The penetrative nature of Domain I fault arrays and microscopic deformation suggests that shortening values should be high; however, a significant amount of extension is also observed in the abundance of calcite veins. A resultant shortening of 20% to 30% for Domain I appears reasonable. Shortening decreases vertically within the domain as the intensity of mesoscopic- and microscopic-scale deformation decreases.

Because cleavage development is the most significant deformation in Domain II and is believed to have preceded fault zone deformation, there is an apparent heterogeneity in the distribution of shortening between Domains I and II. The difficulty arises due to a lack of evidence for shortening in Domain II which developed simultaneously with Domain I fault zone deformation. Two suggestions are offered to explain this inequity: 1) the previously developed cleavage was intensified in Domain II thrust imbricates during fault zone deformation, or 2) mesoscopic fault arrays effectively detached Domain I from the upper strata in thrust imbricates which resulted in a paucity of Domain II deformation.

Domain III consists of the apparently undeformed strata above Domain II. This lack of deformation may be due to incompetent behavior in the Switchback Shale which effectively separates the deformation in the Steamboat Limestone from the overlying competent Devils Glen Dolomite and Maywood Formation. The upper part of the Steamboat Limestone commonly shows no deformation which indicates that the lower boundary of Domain III is an approximate one that may not be entirely controlled by lithology.

Oolite strain ratios (R) average 1.26 for Domains I and II. These low values are believed to be due to two factors: 1) no samples were obtained from the most intensely deformed areas of the thrust sheet, and 2) oolite strain is primarily attributed to pressure solution deformation which ceased to be important with onset of folding and thrusting, except in Domain I fault zones. Thus, oolite strain predominantly reflects an early pre-thrusting stage of deformation.

No measurements of volume gain or loss were included in this study, but k -values from oolite strain analysis consistently failed to plot along the axis of plane strain (Figure 39) indicating some degree of volume change has indeed occurred. Pressure solution activity may have been responsible for a significant loss of material if the thrust sheet was not a closed system during deformation.

The distribution of shortening at the macroscopic- and mesoscopic-scales defines a distinct structural style for the Backbone thrust sheet. This structural style is shown in the thrust sheet model in Figure 42. The macroscopic geometry of the Backbone thrust sheet is characterized by a frontal zone of imbricate thrusts and an intraplate zone of tightly spaced folds. Superposed on this macroscopic geometry are vertically distributed deformation domains defined by groups of mesoscopic structural elements. The character of Domain I deformation is due to vertical variations in longitudinal and shear strain above thrust faults. In Domain II, only longitudinal strain with resultant cleavage development is considered significant.

These observations are important for several reasons. First, published cross sections of the Montana thrust belt (e.g. Mudge, 1982; Boyer and Elliott, 1982; Mitra, 1986) are minimum strain sections in that they show the overall style of folding and the amount of fault translation, but they do not show internal deformation within thrust sheets (Lageson and Ihle, 1987). This study indicates that internal deformation within a thrust sheet is variably distributed and may account for shortening values in excess of 70%. Thus, the variation and magnitude of internal deformation may be significant and should be

BACKBONE THRUST SHEET

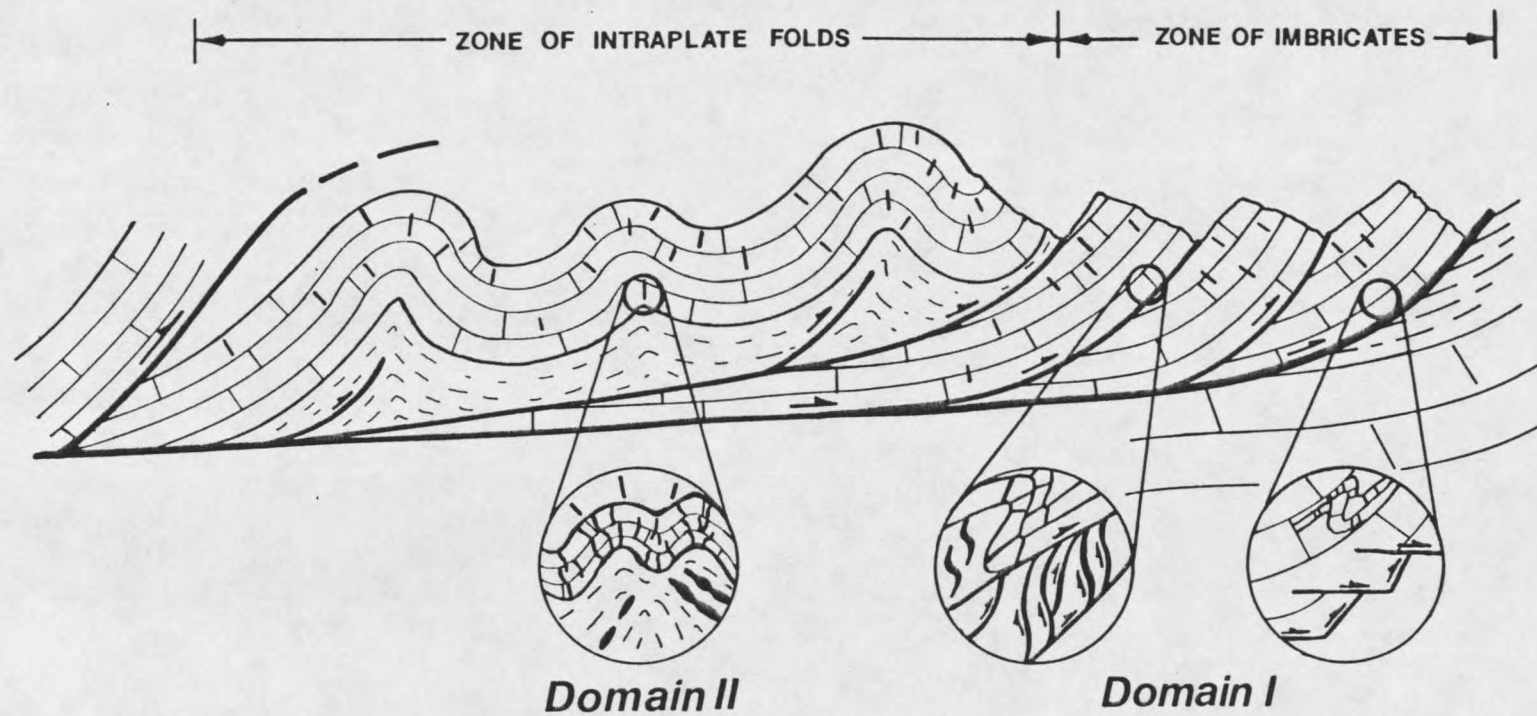


Figure 42. Structural model for the Backbone thrust sheet showing the distribution of macroscopic zones of deformation and mesoscopic domains of deformation.

incorporated in the construction of balanced cross sections and palinspastic restorations. It is noted, however, that the distribution and magnitude of internal deformation observed in the Backbone thrust sheet should only be applied to other thrust sheets where similarities in lithology, structural style and deformation history can be established.

Second, vertical variations in structural style are commonly seen on the regional scale (e.g. Lageson and Ihle, 1987; Mitra, 1987; Mudge, 1982). This study indicates that lateral as well as vertical variations in structural style can also occur at the scale of the individual thrust sheet and should be recognized when attempting to interpret the subsurface style and geometry of a thrust sheet. These variations are important for making subsurface predictions of reservoir geometry, fracture patterns and depth continuity of structures.

Third, studies of internal deformation within thrust sheets can provide insight into the mechanical processes involved in the the emplacement of large overthrust sheets. This will be discussed in the next section which details the relative sequence of deformation and offers observations on the mechanics of thrust sheet emplacement.

Sequence of Deformation

A sequence of deformation for the Backbone thrust sheet is proposed from observations of geometric relationships between mesoscopic and macroscopic structural elements. This sequence indicates that a significant change in the dominant mechanism of deformation occurred during the history of the thrust sheet. Several

lines of evidence also suggest that the Backbone thrust sheet was folded subsequent to its emplacement. The relative sequence and mechanisms of deformation are illustrated in Figure 43.

Many macroscopic folds show spaced cleavage fans (Figure 23) with cleavage remaining subperpendicular to bedding at all bedding attitudes (Table 1). This indicates Domain II cleavage development occurred prior to macroscopic folding and was passively rotated into a fanning geometry by the folding (Mitra and others, 1984; Johnson, 1985).

Cleavage in thrust imbricates has roughly two orientations (Figure 23) but remains subperpendicular to bedding at all bedding attitudes (Table 1). Formation of the northwest-striking set is interpreted to coincide temporally with the cleavage developed in macroscopic folds. The variability in orientation of cleavage planes is believed to be due to reorientation during translation thrust imbricates.

Thus, layer-parallel shortening by pressure solution characterizes the earliest deformational phase of the Backbone thrust sheet. Spaced cleavage and oolite strain ellipsoids flattened perpendicular to bedding are the result of this early phase of shortening. The compression which generated pressure solution was oriented subhorizontally to the northeast at 61° .

Mitra and Yonkee (1985) suggest that early cleavage development in the Utah-Wyoming-Idaho thrust belt occurs soon after emplacement of a preceding major thrust. Emplacement induces elevated pressure and temperature conditions favorable for cleavage formation. The existing thrust sheets in the Sawtooth Range, however, are characteristically much more highly imbricated than the Utah-Wyoming-Idaho thrust belt.

making it unlikely that emplacement of a single thrust sheet was responsible for cleavage development. Thus, development of cleavage in the Swift Reservoir area may be evidence for earlier superposition of the Lewis thrust sheet over this area, resulting in the development of the Sawtooth Range as a major duplex.

Macroscopic folding and thrust faulting followed the early pressure solution phase and passively rotated cleavage with bedding. Folding is believed to have occurred during translation along the regional decollement, while imbrication probably resulted from ramping of the Backbone thrust sheet through competent strata. Bedding surfaces ornamented with frictional grooves or calcite step fibers indicate that folding occurred by flexural-slip processes. Overall, these structures indicate that brittle deformation processes associated with folding and thrusting have replaced earlier pressure solution deformation.

Mesoscopic structures which developed during the folding and thrusting phase include mesoscopic fault arrays, drag folds, tectonic veins and gouge and breccia in Domain I, and folds, pencil structures and boudins in Domain II. Fault zone deformation obliterated early cleavage development in Domain I, however, intensification of cleavage in the upper portions of thrust imbricates may have occurred to keep pace with shortening in Domain I. Simultaneous opening of extension fractures as well as shearing during mesoscopic faulting is believed to be responsible for the numerous tectonic veins in Domain I. Drag folds formed during differential shearing along planes of slip. Gouge and breccia may have formed late in the thrusting because breccia clasts were entirely Mississippian dolomite and Steamboat Limestone.

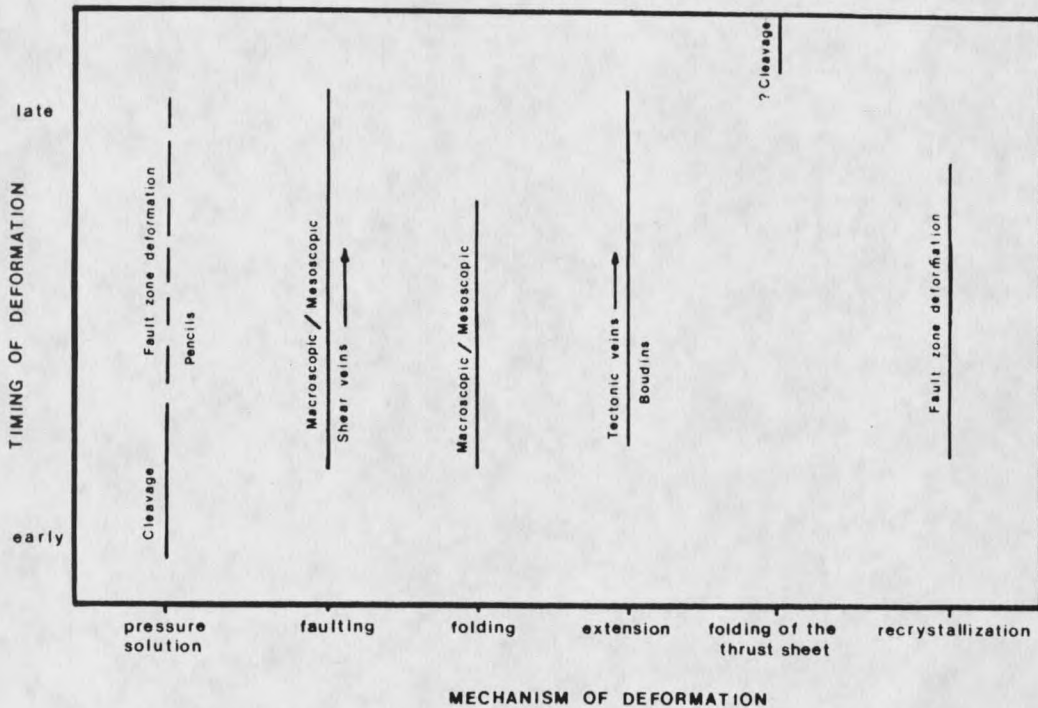


Figure 43. Diagram showing the relationship between relative timing of deformation and the mechanisms of deformation.

Mesoscopic folds in Domain II formed during macroscopic folding due to crowding in fold cores. Many of these small folds contained refracting cleavage which indicates that the cleavage and folds developed simultaneously (Mitra and others, 1984). Development of pencil structures coincides with shortening on a steepened fold limb while boudins indicate local extensions occurred during folding and thrusting.

Microscopic observations of fault zone deformation indicate that several processes were operating simultaneously in Domain I during thrusting. These processes include microfaulting, pressure solution, extension veining and recrystallization. The preliminary nature of these observations indicates that more work needs to be done to differentiate the importance of each process and a relative sequence for these deformations.

Continued thrusting caused some macroscopic folds to develop asymmetrical to nearly isoclinal geometries at the leading edge of the thrust sheet. Balanced cross sections also require that some of the asymmetric folds be cored by thrusts. This indicates simultaneous development of folds above a propagating thrust fault (Dahlstrom, 1970). Many intraplate folds have concentric geometries which require a detachment at depth. These folds are believed to have developed early in the thrusting by buckling and then were carried passively as detachment folds during motion on the thrust sheet.

Cleavage was not observed to cut fault surfaces, thus fault translation was the final stage of deformation. However, the asymptotic curving of cleavage into local fault planes suggests that some cleavages remained kinematically active during that faulting (Mitra and others, 1984). The absence of low angle faults which cut fold limbs is further evidence for passive behavior of macroscopic folds during the final stages of thrusting.

Several lines of evidence indicate that the Backbone thrust sheet was deformed after its emplacement. Singdahlsen (1986) suggests that the Swift Reservoir area is a structural culmination formed by folding

of the Backbone thrust sheet by motion on structurally lower thrusts. He cites a change in dip of the thrust sheet along its trace, and down-plunge projections as evidence for folding of the thrust sheet. Additional evidence for folding of the thrust sheet has been found in this study. The northeast-striking cleavage (Figure 23) which cuts the previously mentioned northwest-striking set, and the oolite strain ellipsoids which are flattened parallel to the strike direction, may indicate that localized strike-parallel shortening occurred. Folding of the Backbone thrust sheet is proposed as the mechanism for this deformation.

Mechanics of Emplacement

Many mechanical models have been developed to explain the emplacement of thrust sheets, based on the assumption that frictional sliding was the process that occurred along the base of a thrust sheet (e.g. Hubbert and Rubey, 1959; Gretener, 1981). Deformed zones developed along the base of thrusts are given as evidence for frictional sliding (Wojtal and Mitra, 1986). A closer look at the deformational features in fault zones in the Backbone thrust sheet indicates that although frictional processes are important, they may be accompanied by others which are also significant.

Evidence for the reduced role of frictional sliding includes abundant sutured stylolites, a fine-grained residue between microfaults, recrystallization and a paucity of cataclastic features. The abundance of sutured stylolites and residue between microfaults indicate that pressure solution was an important deformation process in

fault zones and provided for ductile slip along layers. Sequences of highly recrystallized rock in fault zones provide further evidence for the importance of fluid activity in moving thrust sheets. Gouge and breccia were rarely seen in the area of study, suggesting that cataclastic shear zone processes were relatively unimportant in the development of the Backbone thrust sheet.

The deformation features observed in fault zones indicate that pressure solution and recrystallization are important processes during faulting. Thus, it appears that a model which employs only frictional sliding assumptions for emplacement of foreland thrust sheets may not be valid. From a sedimentologic standpoint, evidence indicating that pressure solution features are common in fault zones in the carbonate rocks of the study area, may not be suprising. Limestones that have been subjected to overburden or tectonic stresses commonly deform by pressure solution processes (Wanless, 1979).

CONCLUSIONS

1. Structural elements which contribute to internal deformation in the Backbone thrust sheet include: macroscopic folds and faults and; mesoscopic faults, folds, cleavage, boudins, pencil structures and tectonic veins.
2. Macroscopic thrust faults create an imbricate zone at the leading edge of the thrust sheet. Macroscopic folds predominate in the intraplate region.
3. Mesoscopic structural elements have a vertical distribution which is dependent on distance from thrust faults and lithology of the footwall rocks. Three domains of deformation are defined; Domain I occurs within 10 m of the Backbone thrust sheet and is fault dominated, Domain II occurs in the strata overlying Domain I and is cleavage dominated, Domain III is the remaining undeformed strata.
4. Domain I mesoscopic fault arrays occur in duplex geometries. Microscopic observations indicate microfaulting, extension fracturing, pressure solution and recrystallization are the most significant mechanisms of deformation in Domain I.
5. Domain II spaced cleavage generally occurs at high angles to bedding and its mechanism of deformation is pressure solution.
6. Macroscopic folding and faulting contribute the most significant amount of internal deformation and shortening to the thrust sheet. Folds accomodate 25% shortening in the intraplate region while fault imbricates account for approximately 30% shortening. The combined

magnitude of shortening at the macroscopic-scale is 55%. Oolite strain analysis and spaced cleavage suggest approximately 15% layer-parallel shortening by pressure solution prior to macroscopic folding. Therefore, total shortening by internal deformation is approximately 70%.

7. The sequence of deformation for the Backbone thrust sheet includes:

a) early layer-parallel shortening by pressure solution with development of spaced cleavage and microscopic oolite deformation, b) macroscopic folding and thrusting which passively rotates cleavage into fanning geometries in folds and reorients cleavage in thrust imbricates, c) continued faulting which obliterates cleavage in Domain I by development of mesoscopic fault arrays. Macroscopic folds are carried passively or propagate above blind thrusts. Thrust faulting is the final stage of deformation, and d) folding of the thrust sheet by imbrication of underlying units, resulting in development of the Backbone thrust sheet as a structural culmination.

8. Emplacement of thrust sheets involves a variety of processes. The assumption of thrust sheet emplacement models of only frictional processes occurring at the base of thrust sheets may be incorrect for emplacement of the Backbone thrust sheet.

9. Microscopic observations of structural elements have implications for more detailed study. First, fault zone deformation at the microscopic scale was not utilized in a quantitative manner; yet its intensity indicates this deformation is significant. Second, microscopic structures suggest that interaction of low temperature fluids is prolific during cleavage formation and fault zone

deformation. Future work in these areas may provide better values for the magnitude of fault zone deformation and greater understanding of the geochemical processes which occur during deformation by thrust sheet emplacement.

10. By studying the variation and magnitude of internal deformation in thrust sheets, useful insight into the development of petroleum reservoirs in internally deformed thrust sheets may be provided. In addition, these information are necessary for accurate measurements of shortening, which are the key to palinspastic restorations and reasonable thrust sheet models.

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APPENDICES

APPENDIX A
MEASURED STRATIGRAPHIC SECTIONS

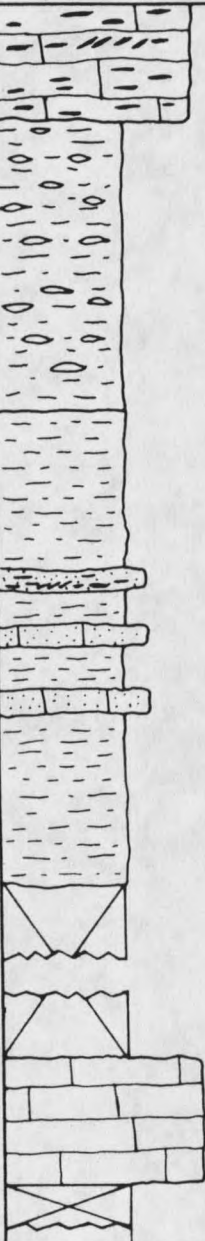
Era	System	Column	Thickness (m)	Lithology
Paleozoic	Cambrian			STEAMBOAT LIMESTONE mudstone—gray, thin to medium bedded; basal oncolitic layer, numerous in traformational conglomerate beds
			12	PENTAGON SHALE Shale—light green and brown, calcareous, slightly micaceous, fissile, non fossiliferous; mudstone lentils are abundant, 1-3 cm thick, non- fossiliferous, may be oolitic or conglomeratic
				Shale—same as below
			18	Mudstone—dark gray, resistant, beds 1-15 cm thick with wavy surfaces, oolitic or intraformational conglomerate, conglomerate clasts are flattened parallel and at high angle to bedding; green shale interbeds
				Shale—maroon to chocolate brown, calcareous, slightly micaceous, fissile, non- fossiliferous
			25	Covered—float consisted of maroon shale, possibly highly deformed
			5	STEAMBOAT LIMESTONE (?) mudstone—dark gray brown, weathers light gray, beds 1-5 cm thick; light orange interbeds
				Covered

Figure 44. Partial measured section of the Pentagon Shale from Phillips Creek (Plate I).

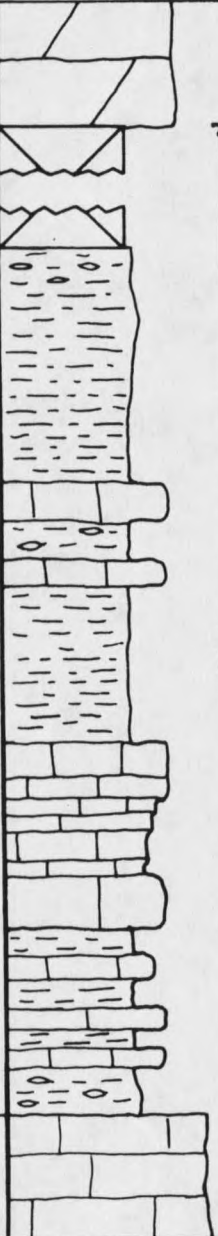
Era	System	Column	Thickness (m)	Lithology
Paleozoic	Cambrian			DEVILS GLEN DOLOMITE
			20	SWITCHBACK SHALE Covered
			5.5	Shale-green and maroon, fissile, lentils of mudstone in upper 1.5 m
			2	Mudstone and Shale mudstone-dark gray, mottled shale-dark green with mudstone lentils
			2.5	Shale-dark green, fissile
			3	Mudstone-dark grey, beds 5-20 cm thick, irregularly shaped, orange layers of clay and dolomite between beds gives interval a mottled appearance
			3	Mudstone and Shale mudstone-dark gray, resistant, beds 2 cm thick shale-dark green, fissile, with lentils of mudstone
				STEAMBOAT LIMESTONE

Figure 45. Measured partial section of the Switchback Shale from station "z" (Figure 10).

APPENDIX B

OOID TRACINGS AND FRY DIAGRAM

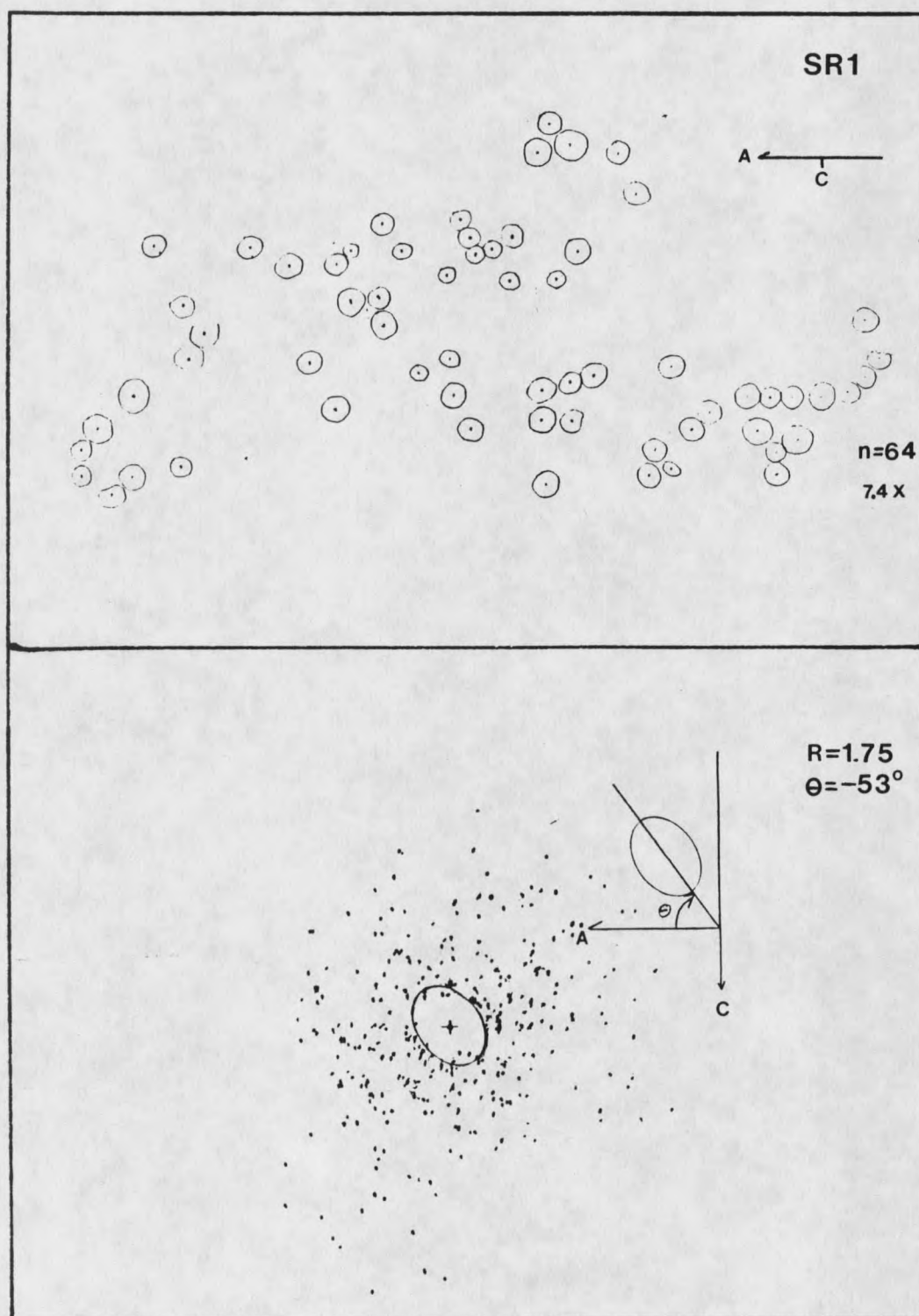


Figure 46. a. Tracing of ooids from sample SR1, AC axes. Magnified 7.4x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axes orientation.

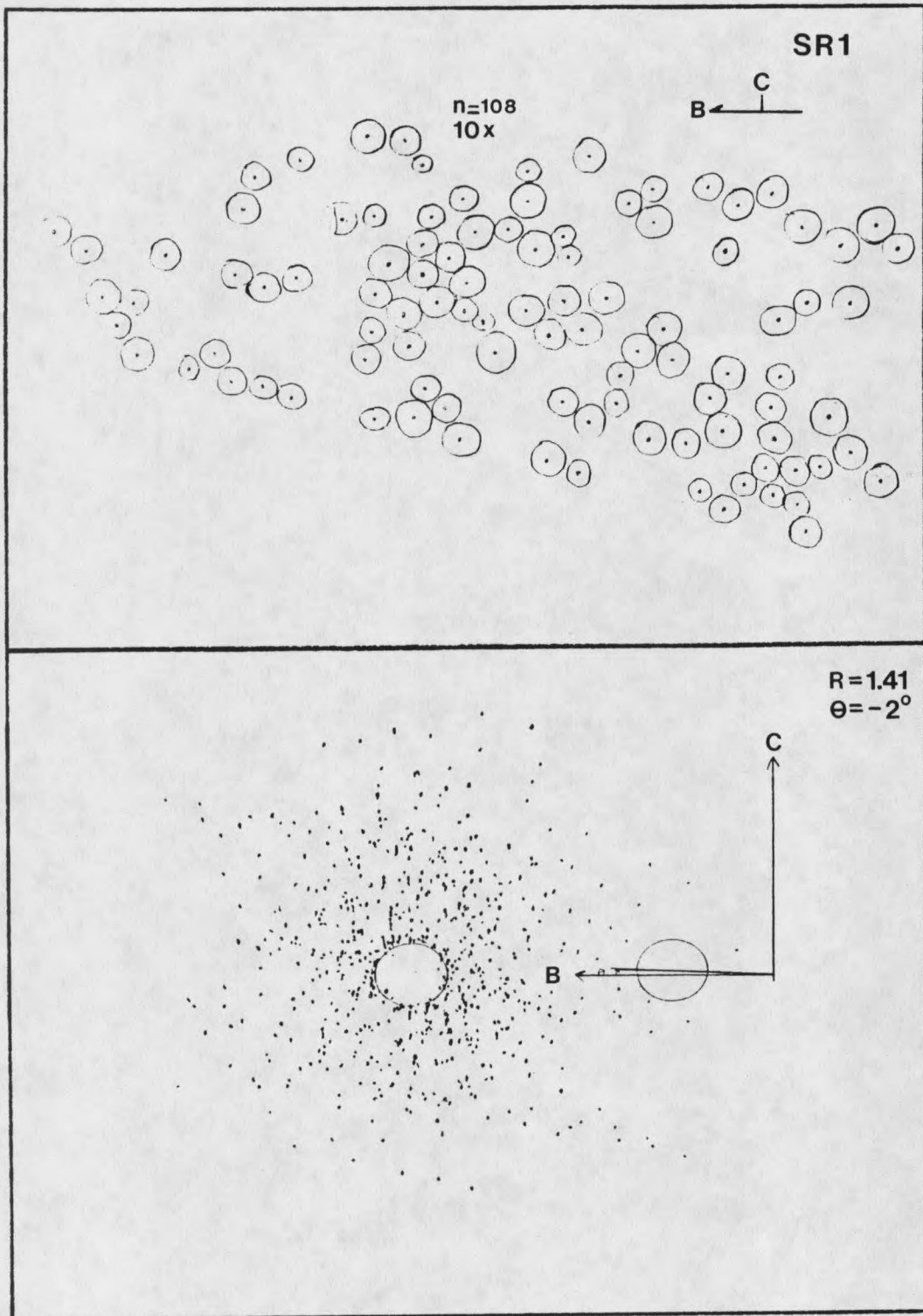


Figure 47. a. Tracing of ooids from sample SR1, BC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

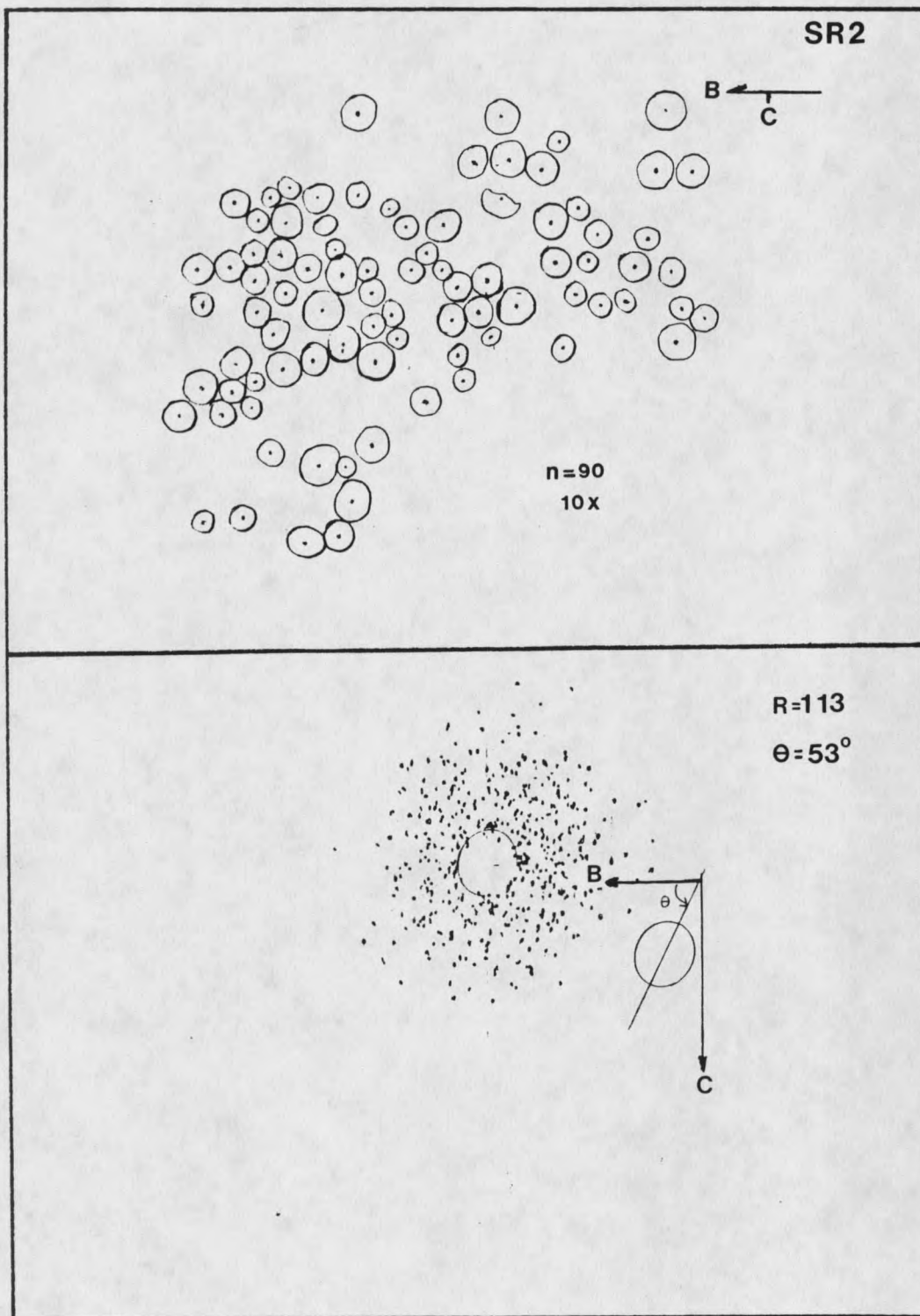


Figure 48. a. Tracing of ooids from sample SR2, BC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

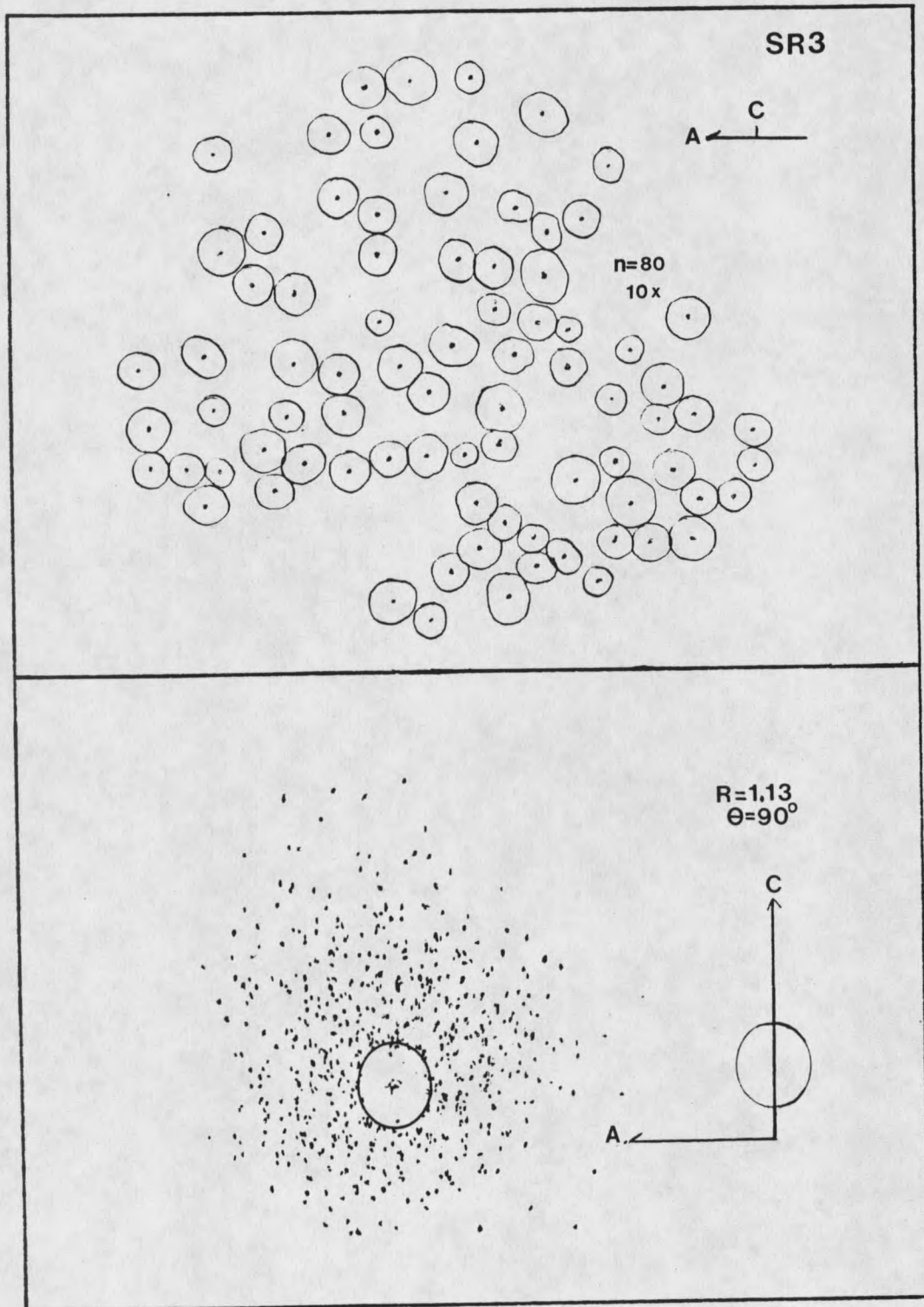


Figure 49. a. Tracing of ooids from sample SR3, AC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

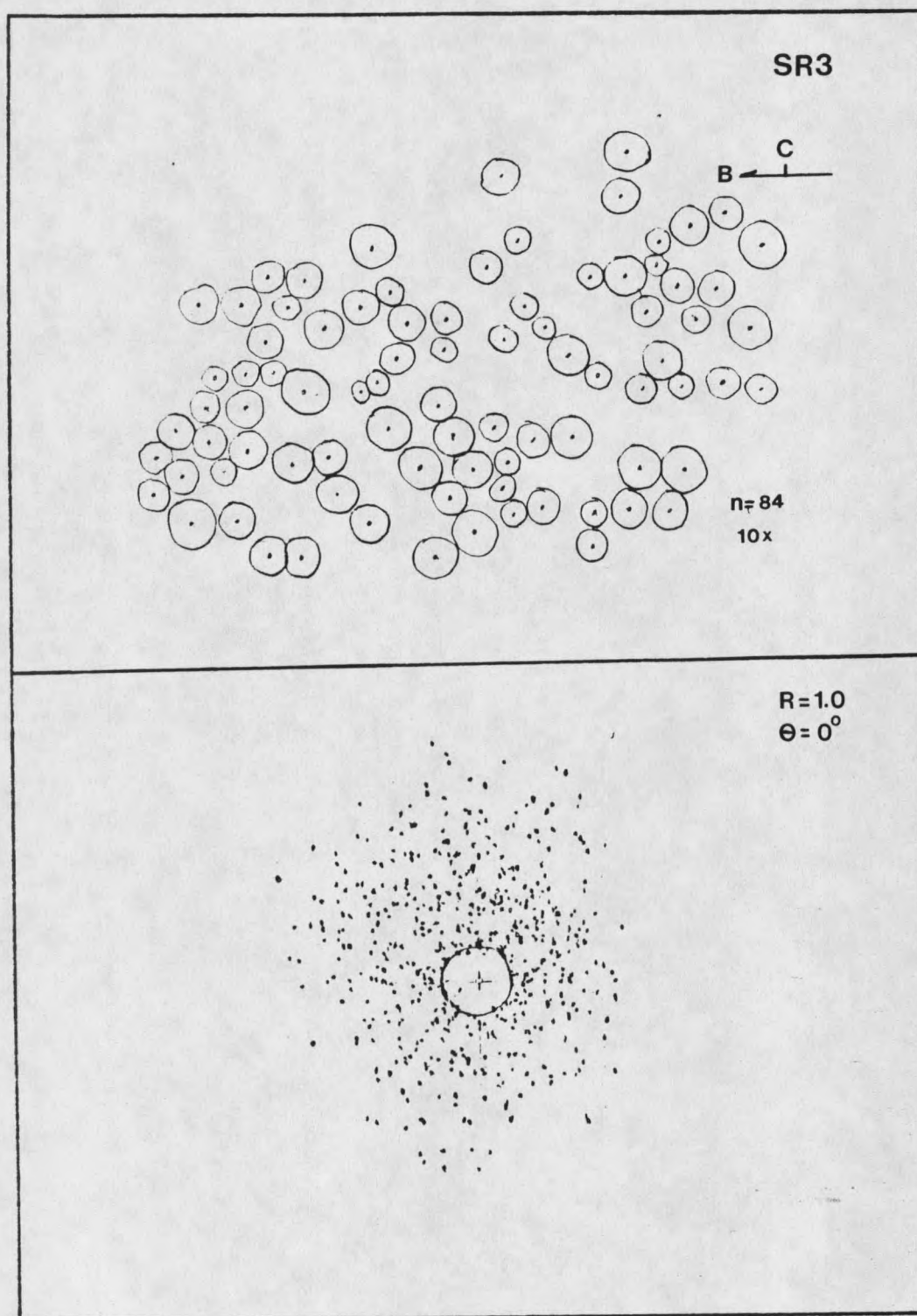


Figure 50. a. Tracing of ooids from sample SR3, BC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

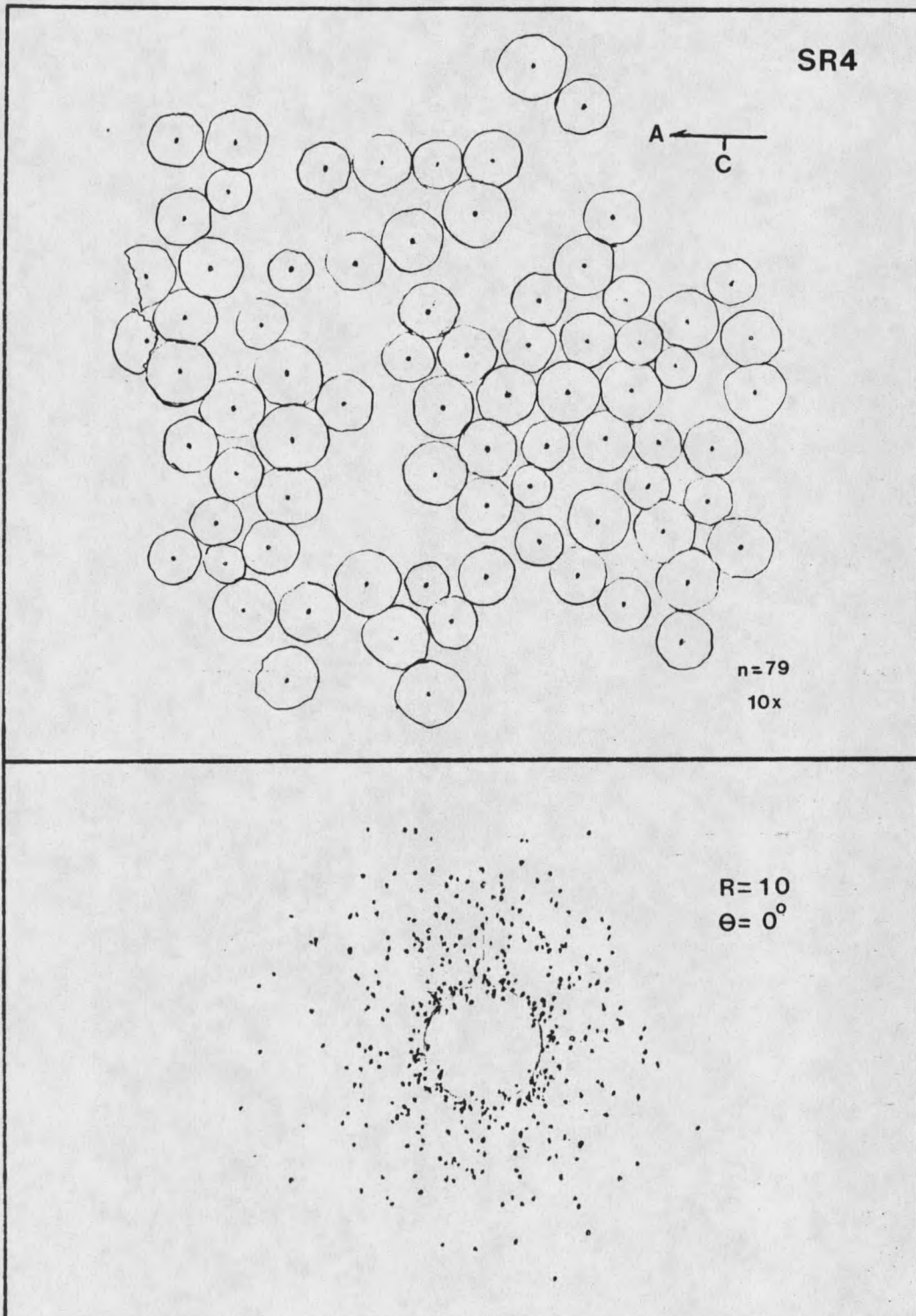


Figure 51. a. Tracing of ooids from sample SR4, AC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

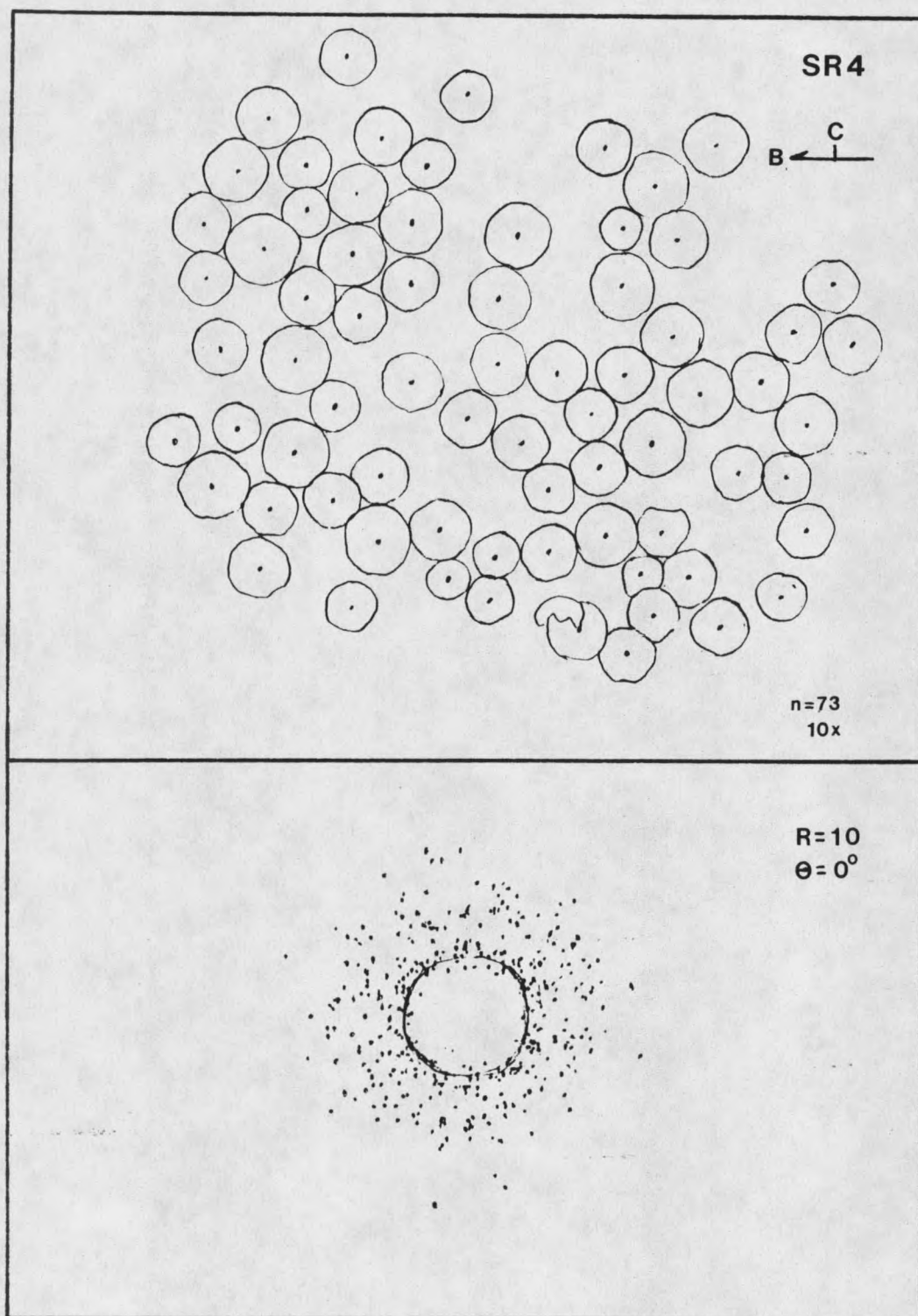


Figure 52. a. Tracing of ooids from sample SR4, BC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R=ellipticity, θ =long axis orientation.

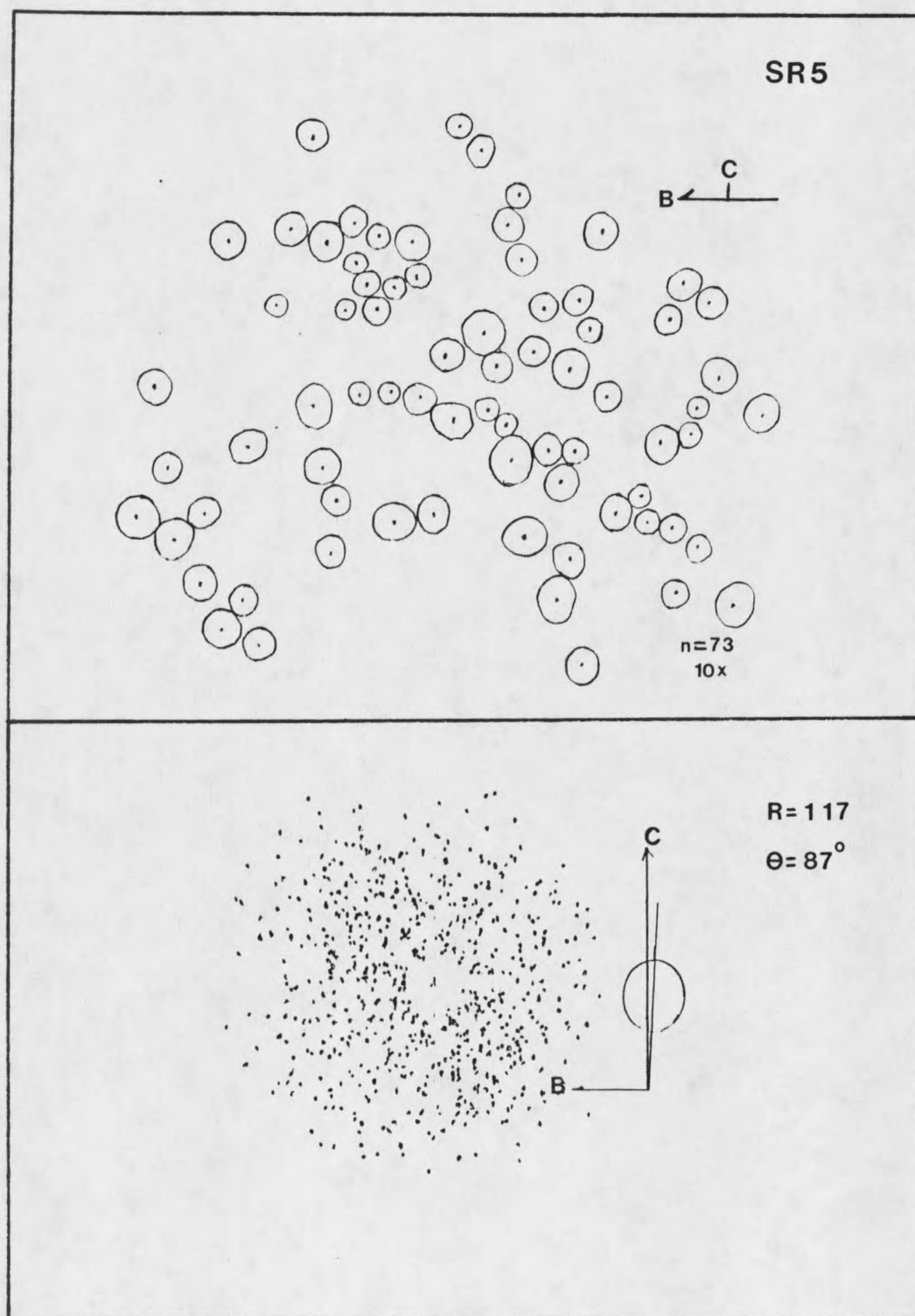


Figure 53. a. Tracing of ooids from sample SR5, BC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

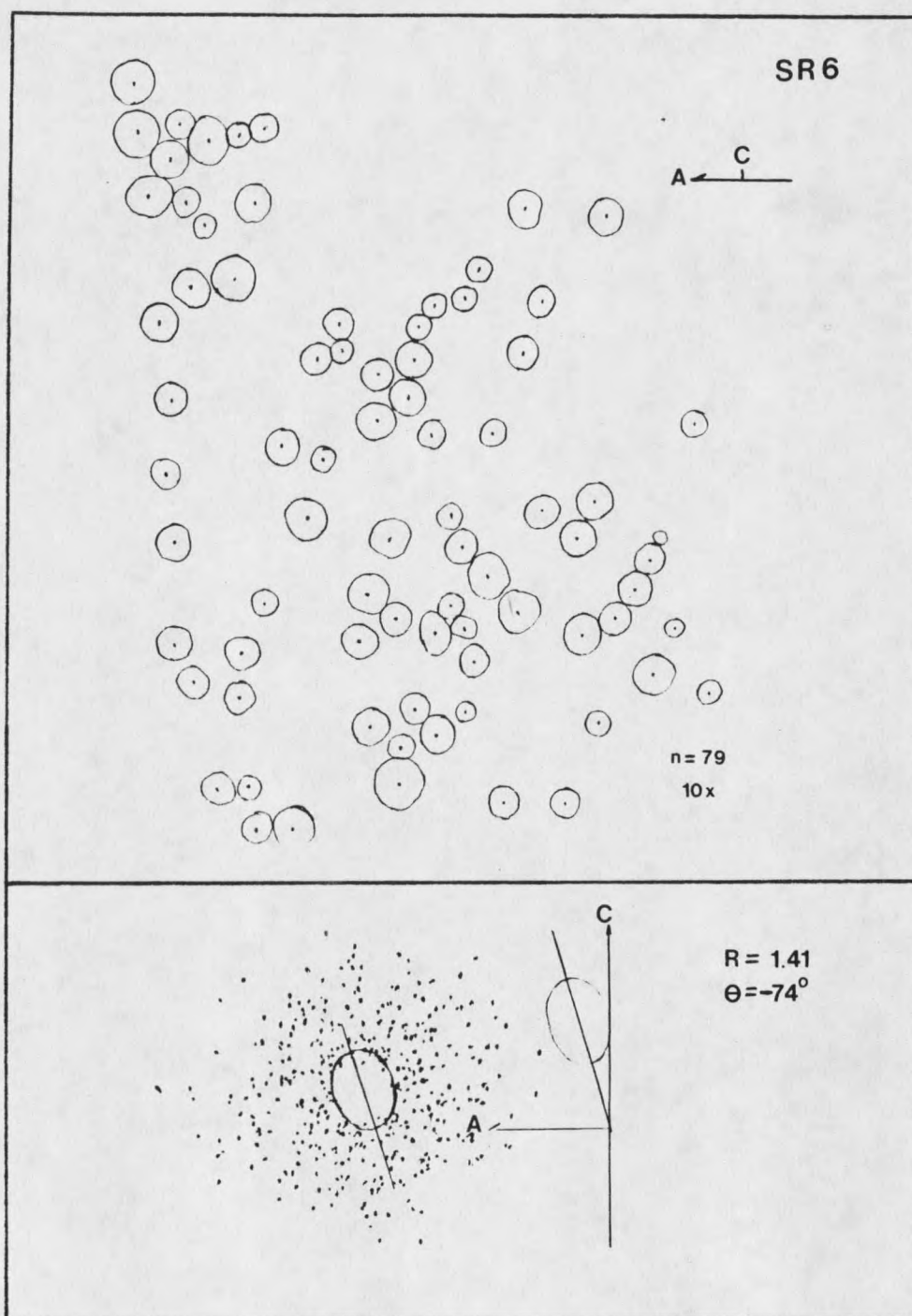


Figure 54. a. Tracing of ooids from sample SR6, AC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

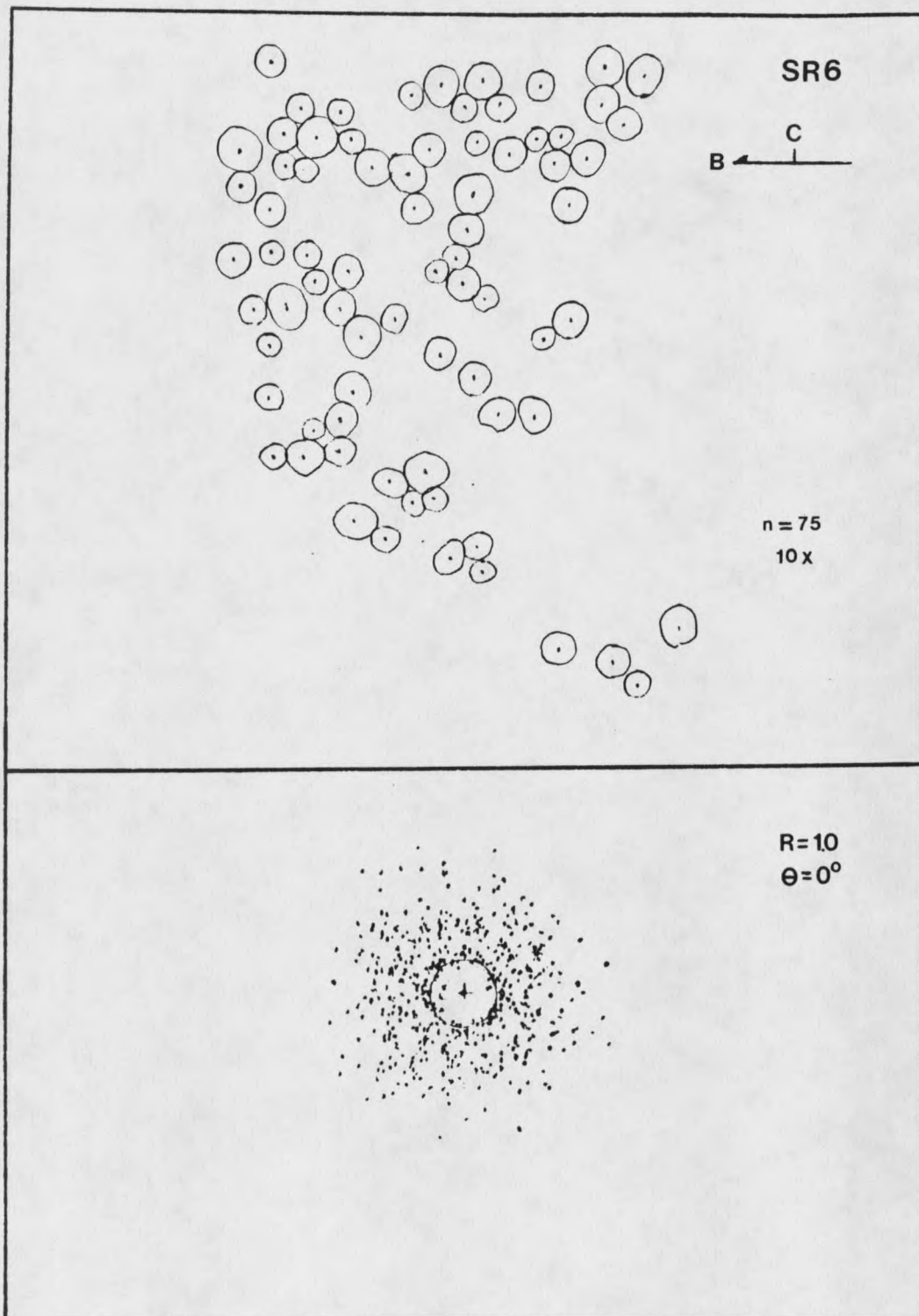


Figure 55. a. Tracing of ooids from sample SR6, BC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse orf circle sketched in. R=ellipticity, θ =long axis orientation.

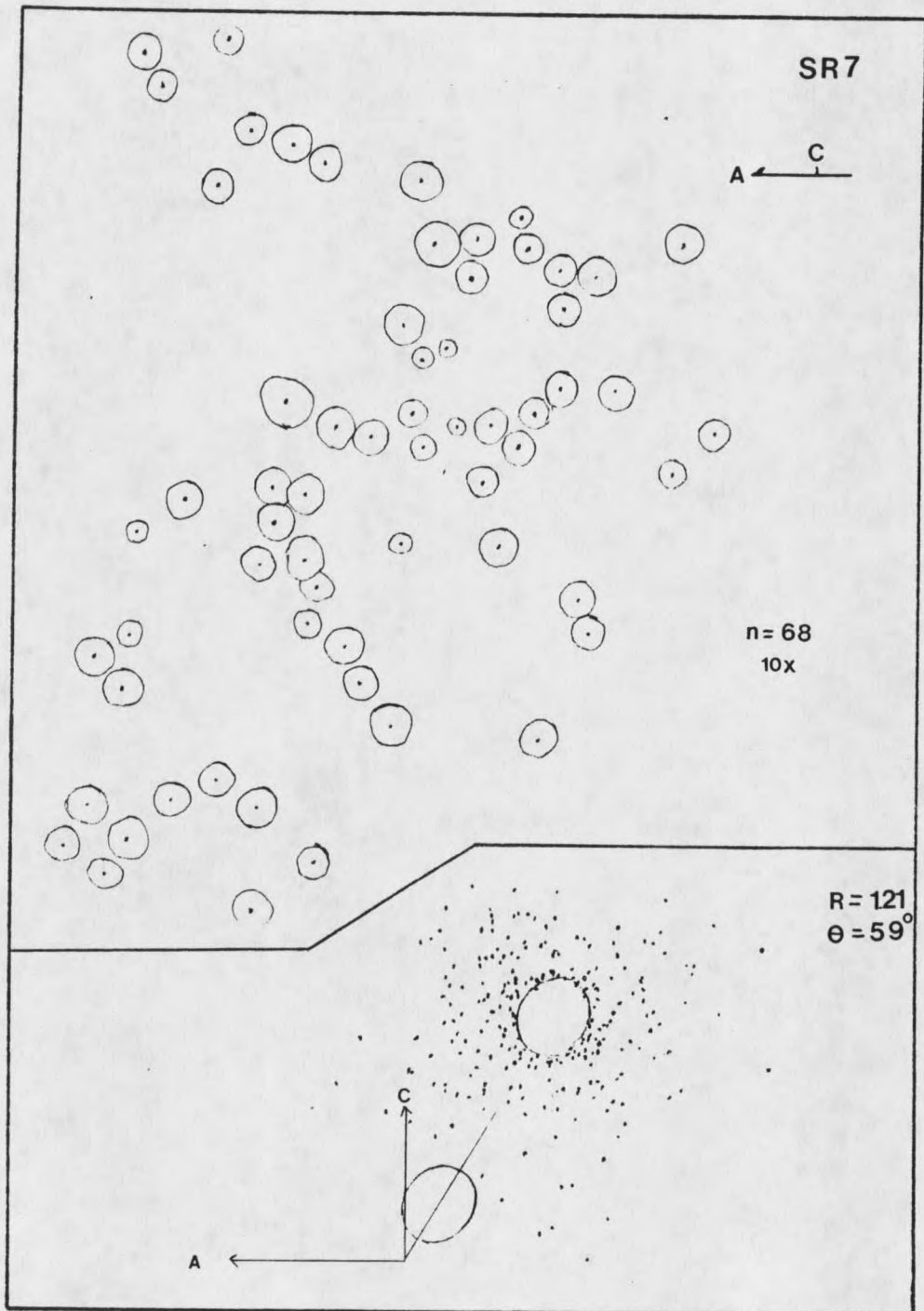


Figure 56. a. Tracing of ooids from sample SR7, AC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

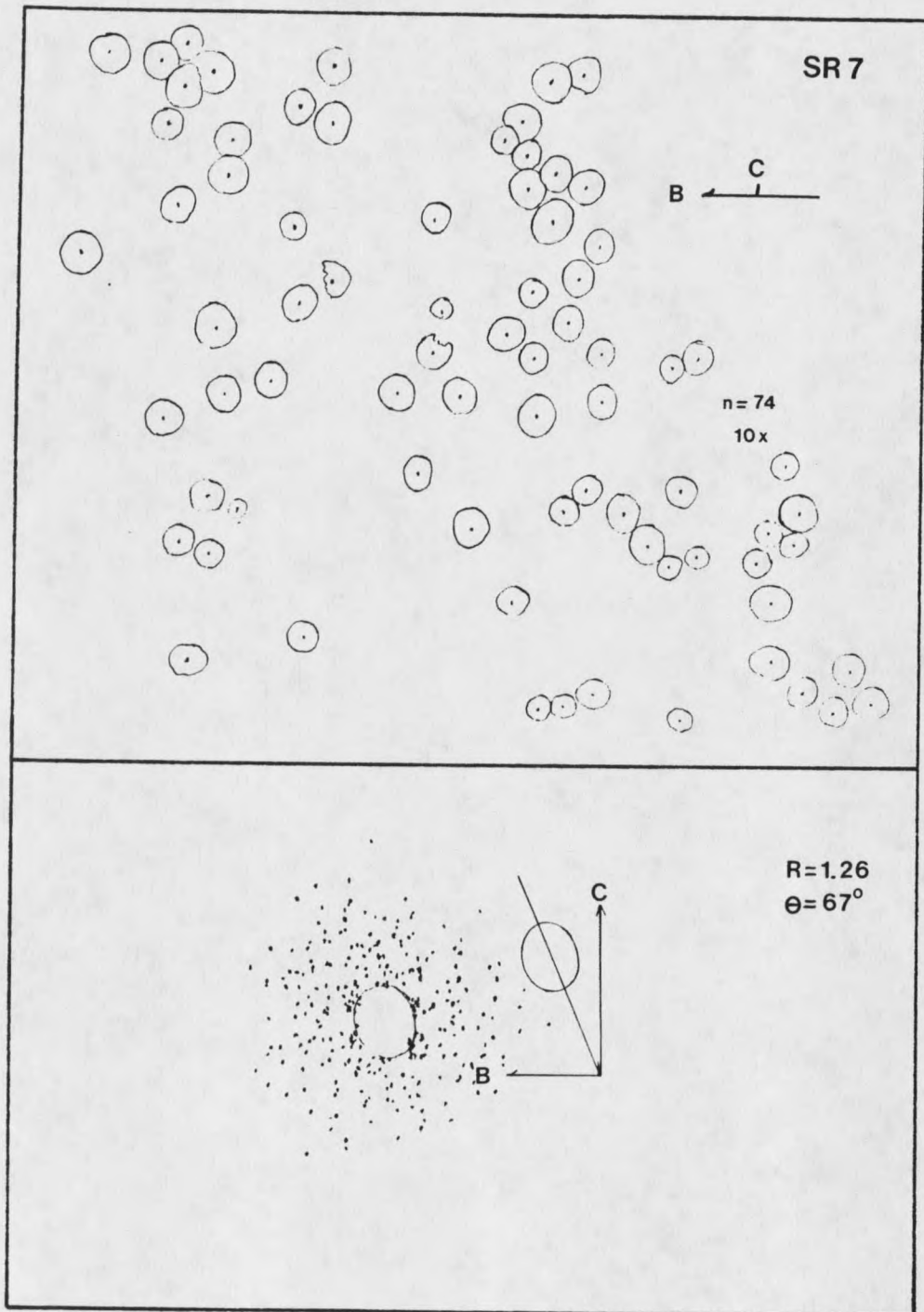


Figure 57. a. Tracing of ooids from sample SR7, BC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

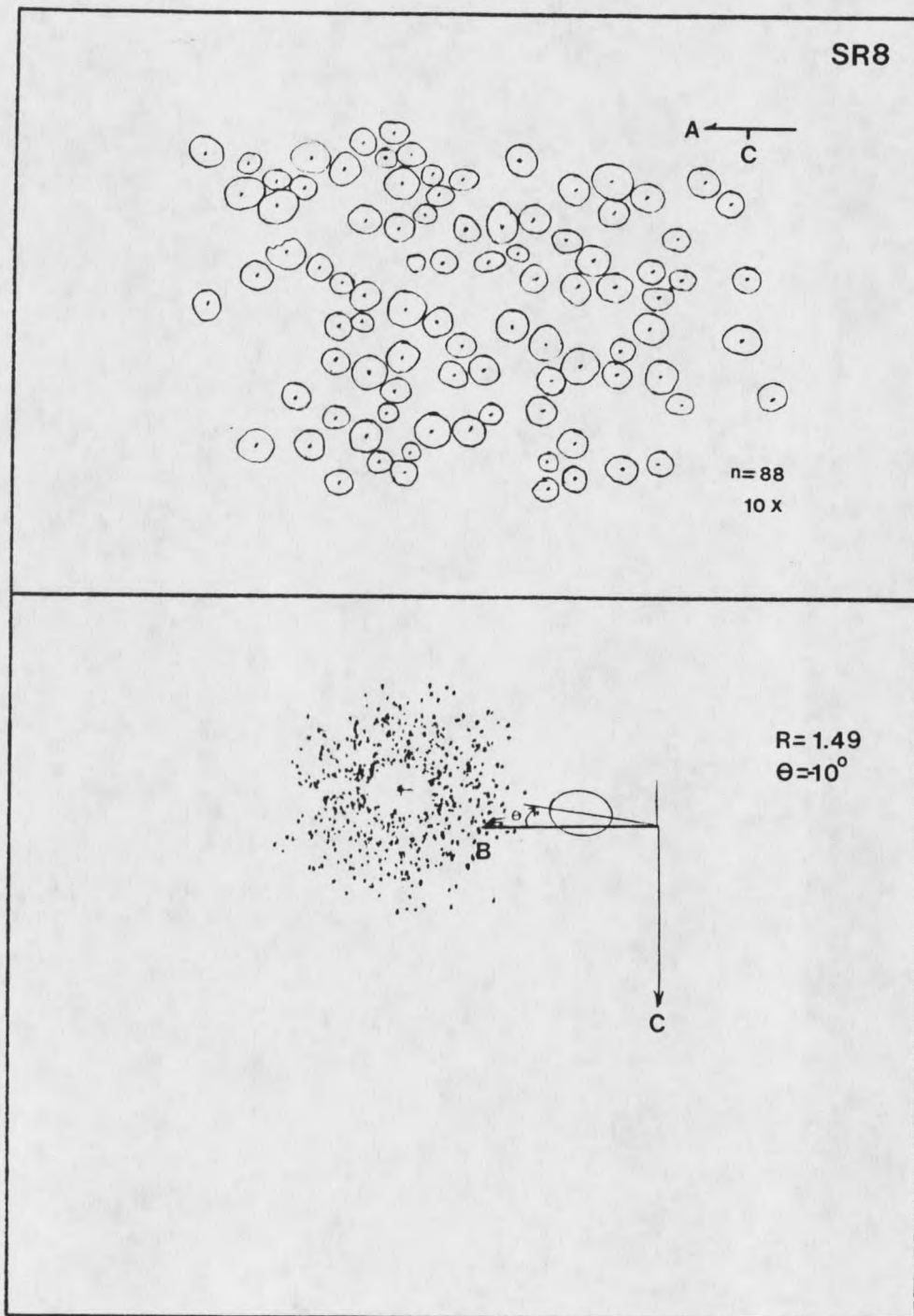


Figure 58. a. Tracing of ooids from sample SR8, AC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R=ellipticity, θ =long axis orientation.

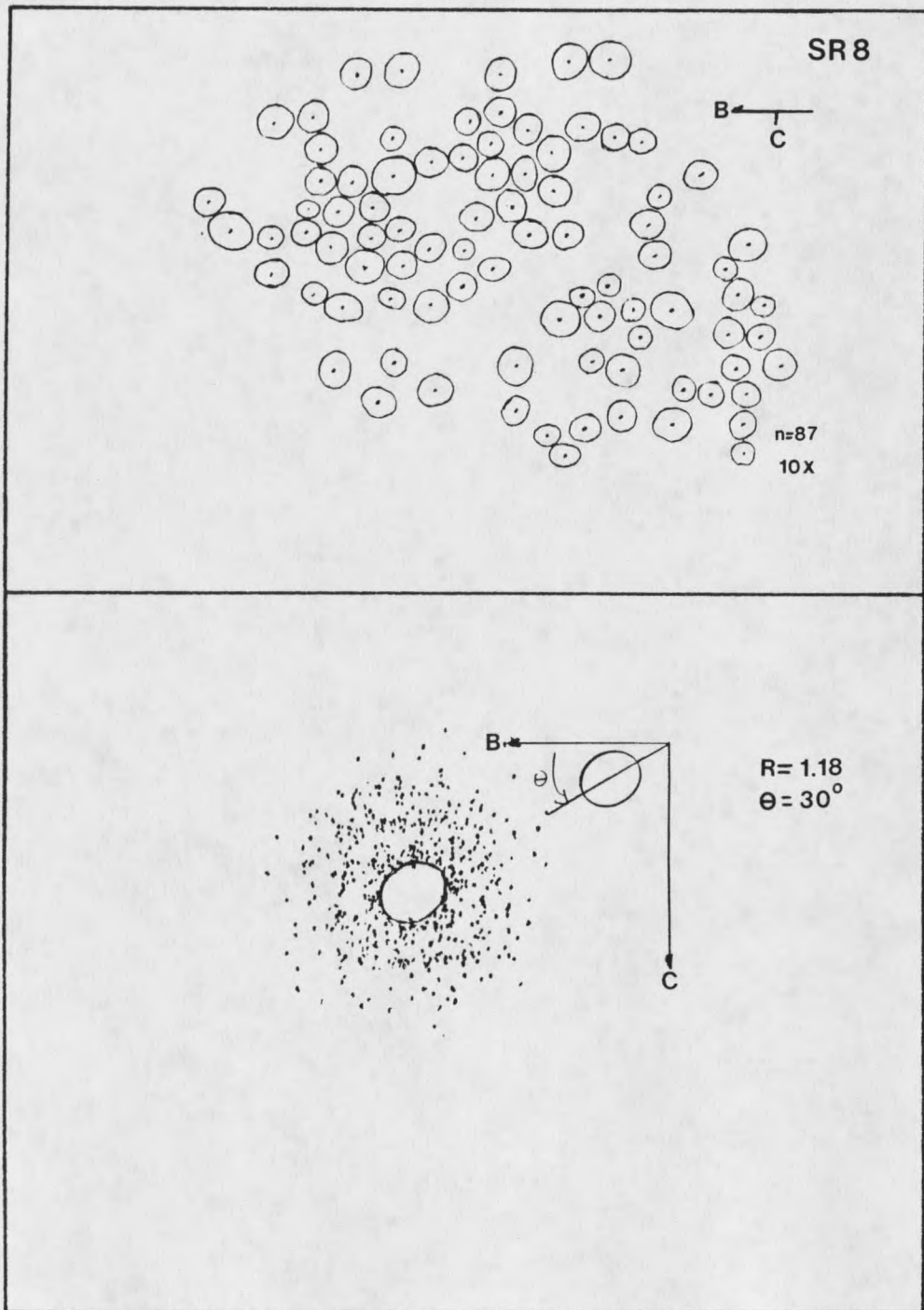


Figure 59. a. Tracing of ooids from sample SR8, BC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R=ellipticity, θ =long axis orientation.

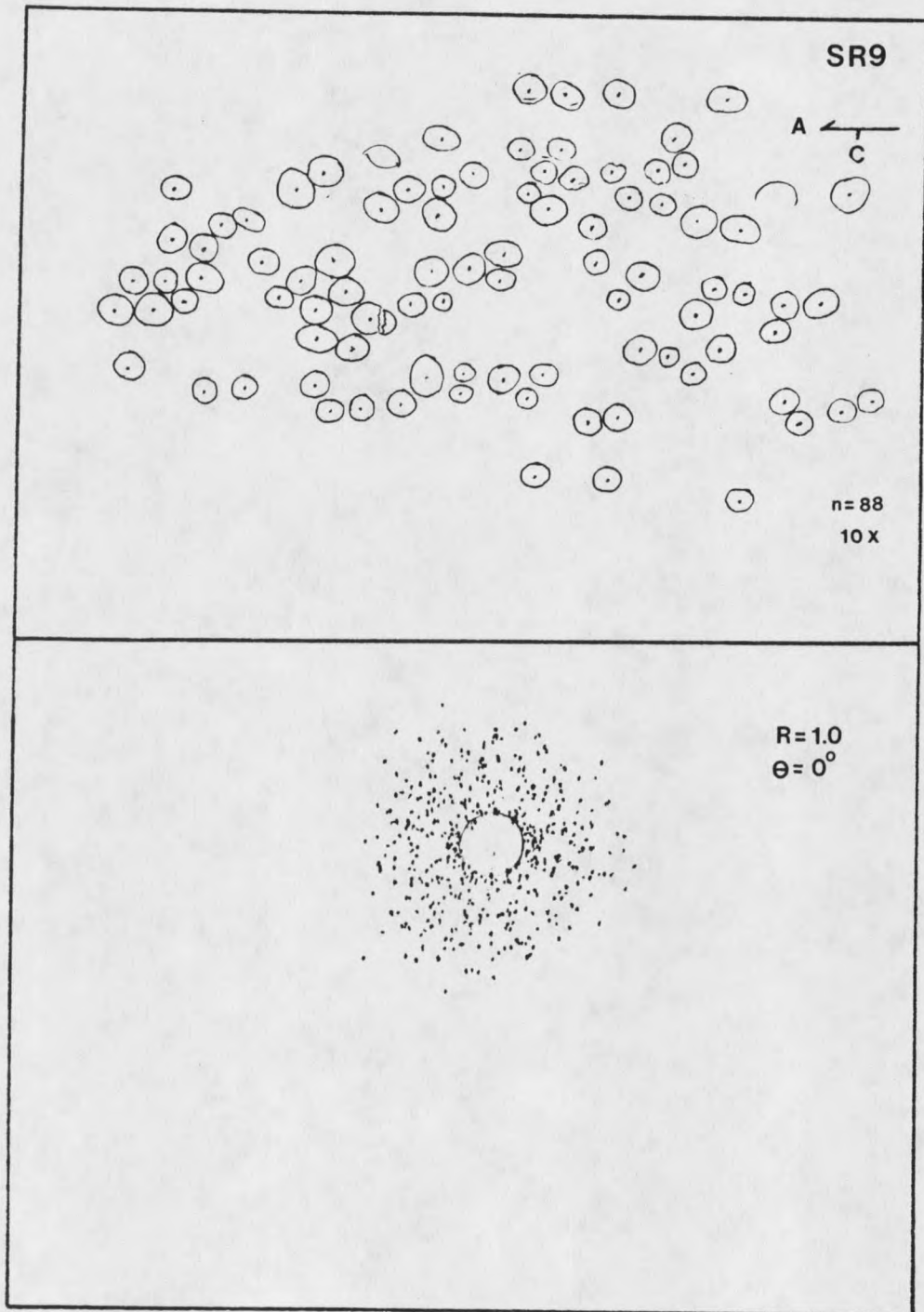


Figure 60. a. Tracing of ooids from sample SR9, AC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

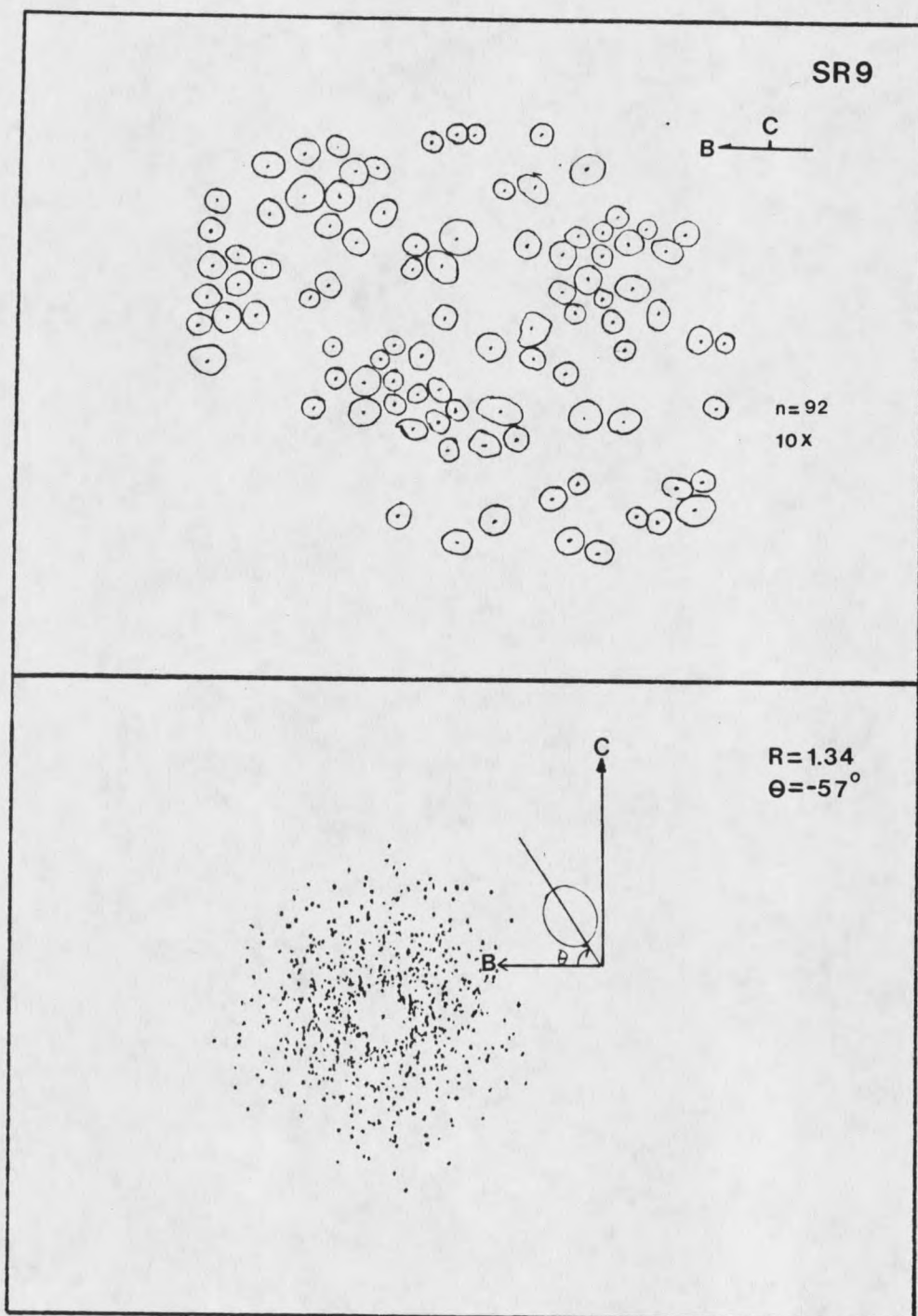


Figure 61. a. Tracing of ooids from sample SR9, BC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

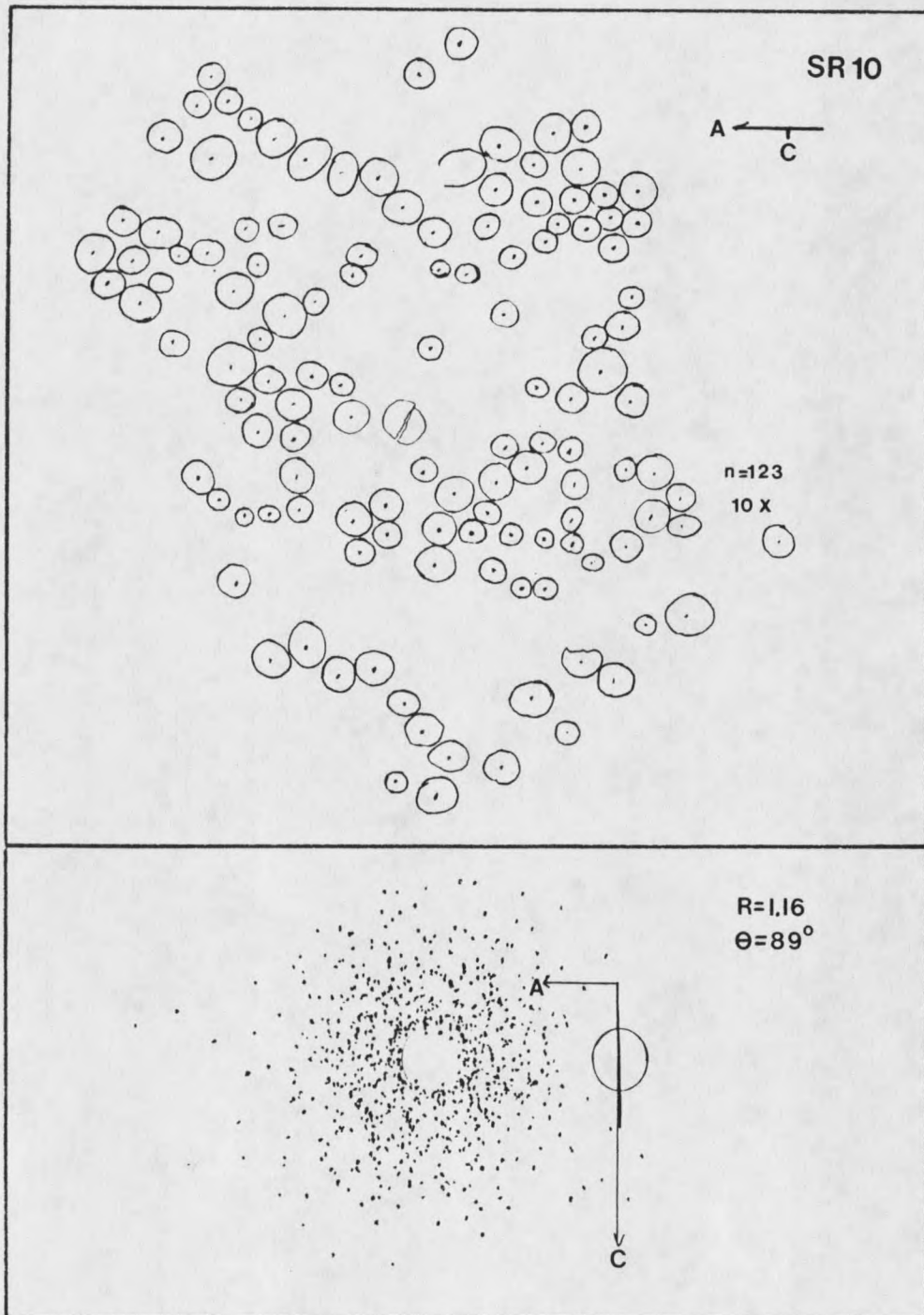


Figure 62. a. Tracing of ooids from sample SR10, AC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

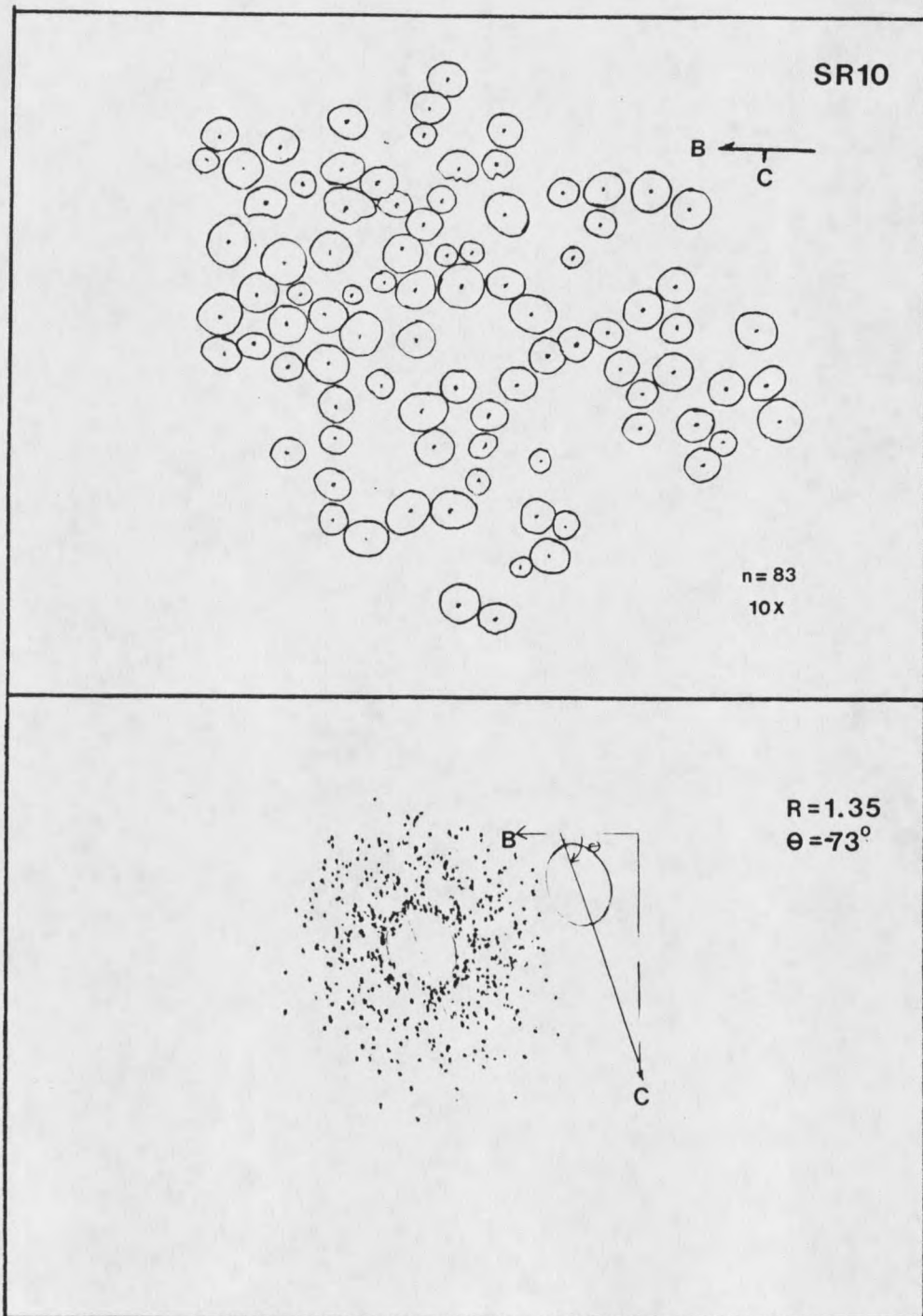


Figure 63. a. Tracing of ooids from sample SR10, BC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

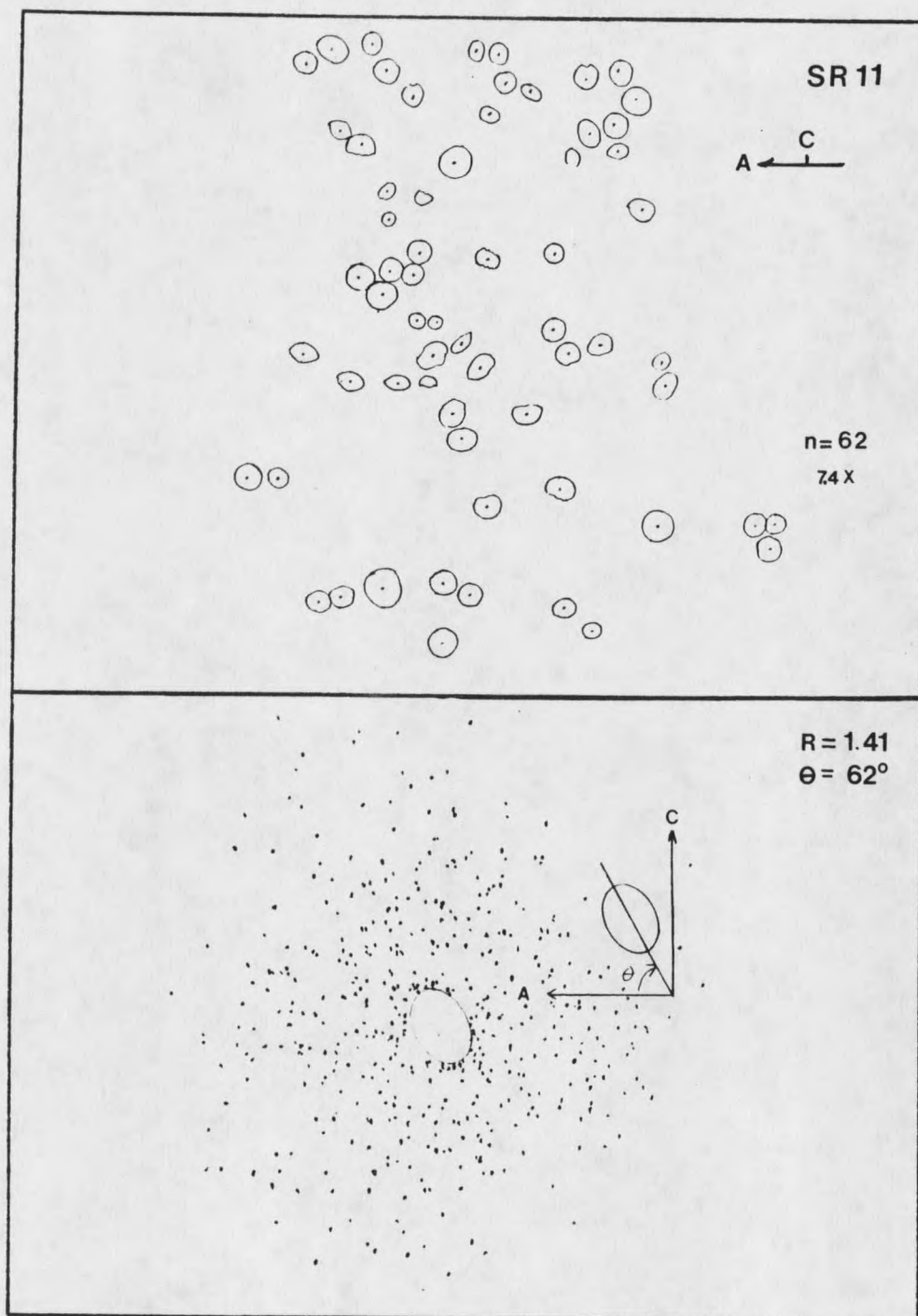


Figure 64. a. Tracing of ooids from sample SR11, AC axes. Magnified 7.4x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

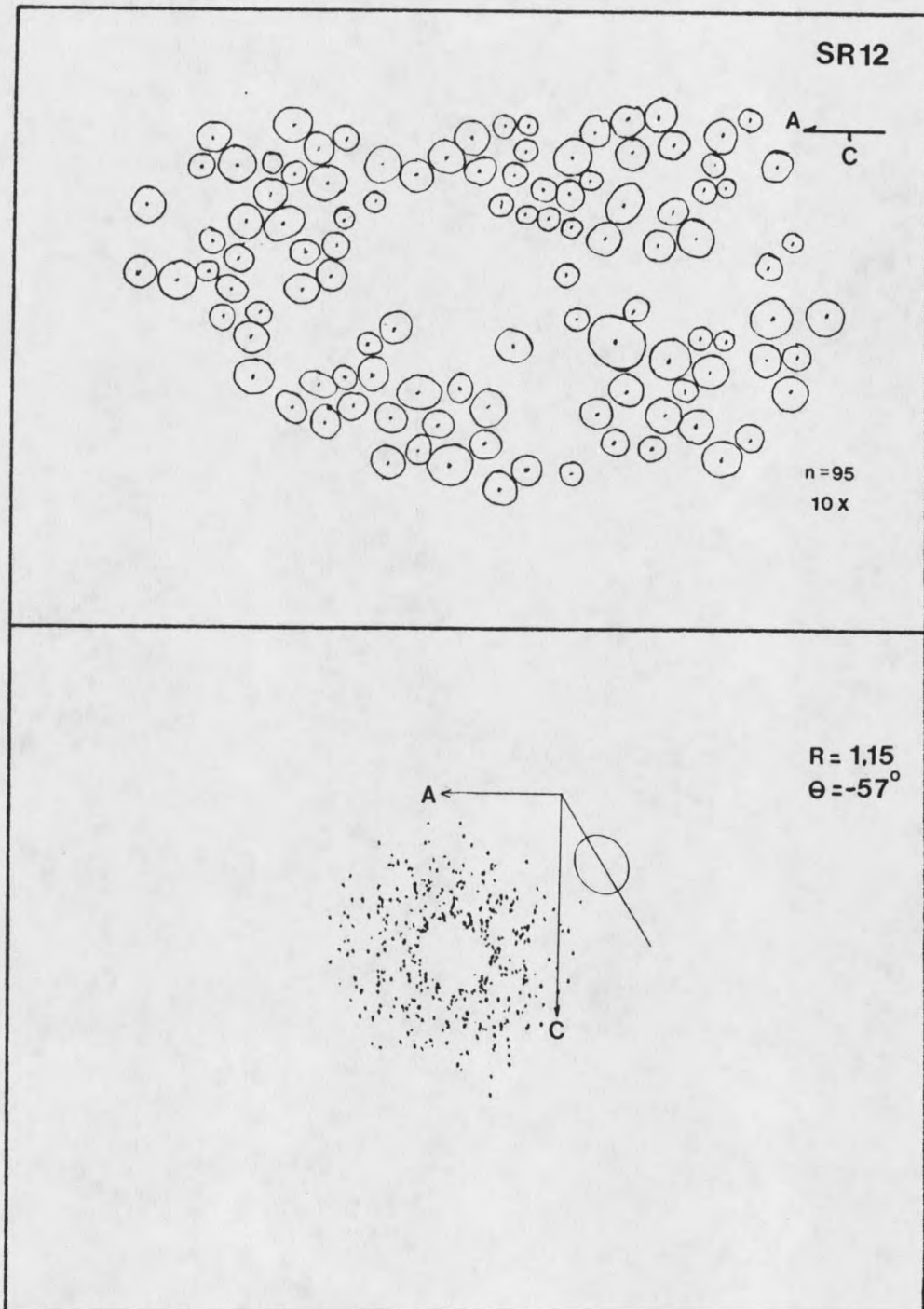


Figure 65. a. Tracing of ooids from sample SR12, AC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

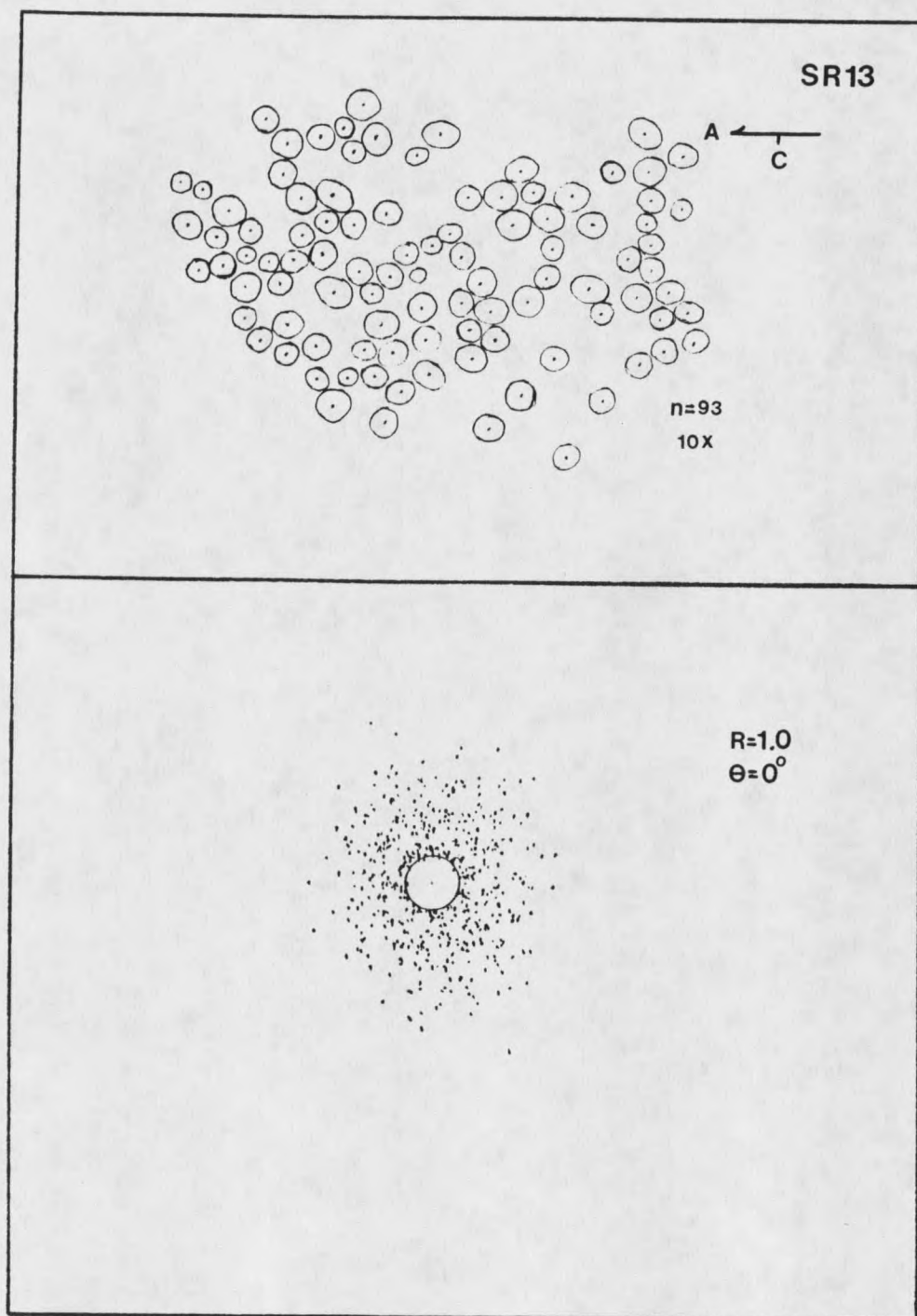


Figure 66. a. Tracing of ooids from sample SR13, AC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

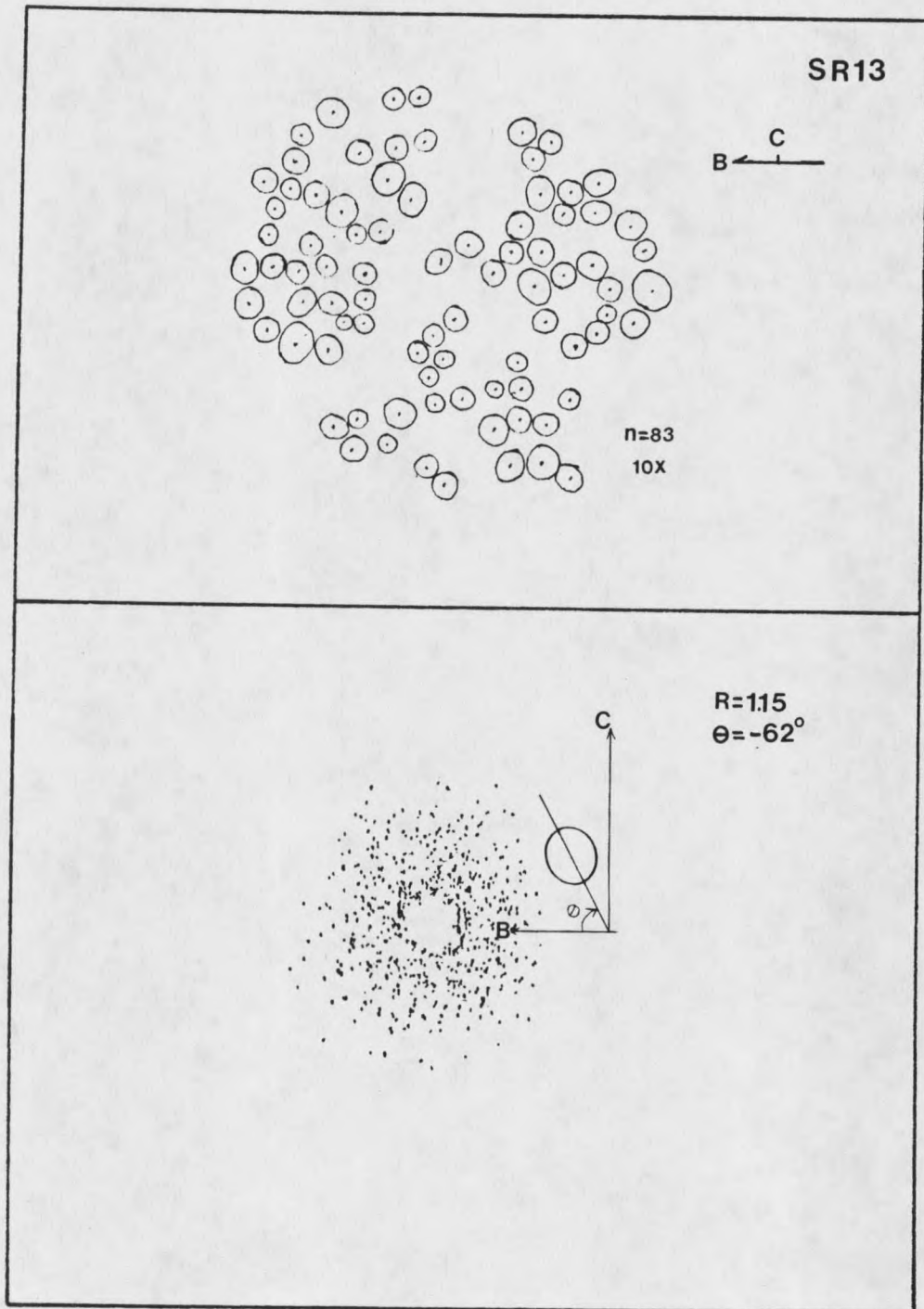


Figure 67. a. Tracing of ooids from sample SR13, BC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

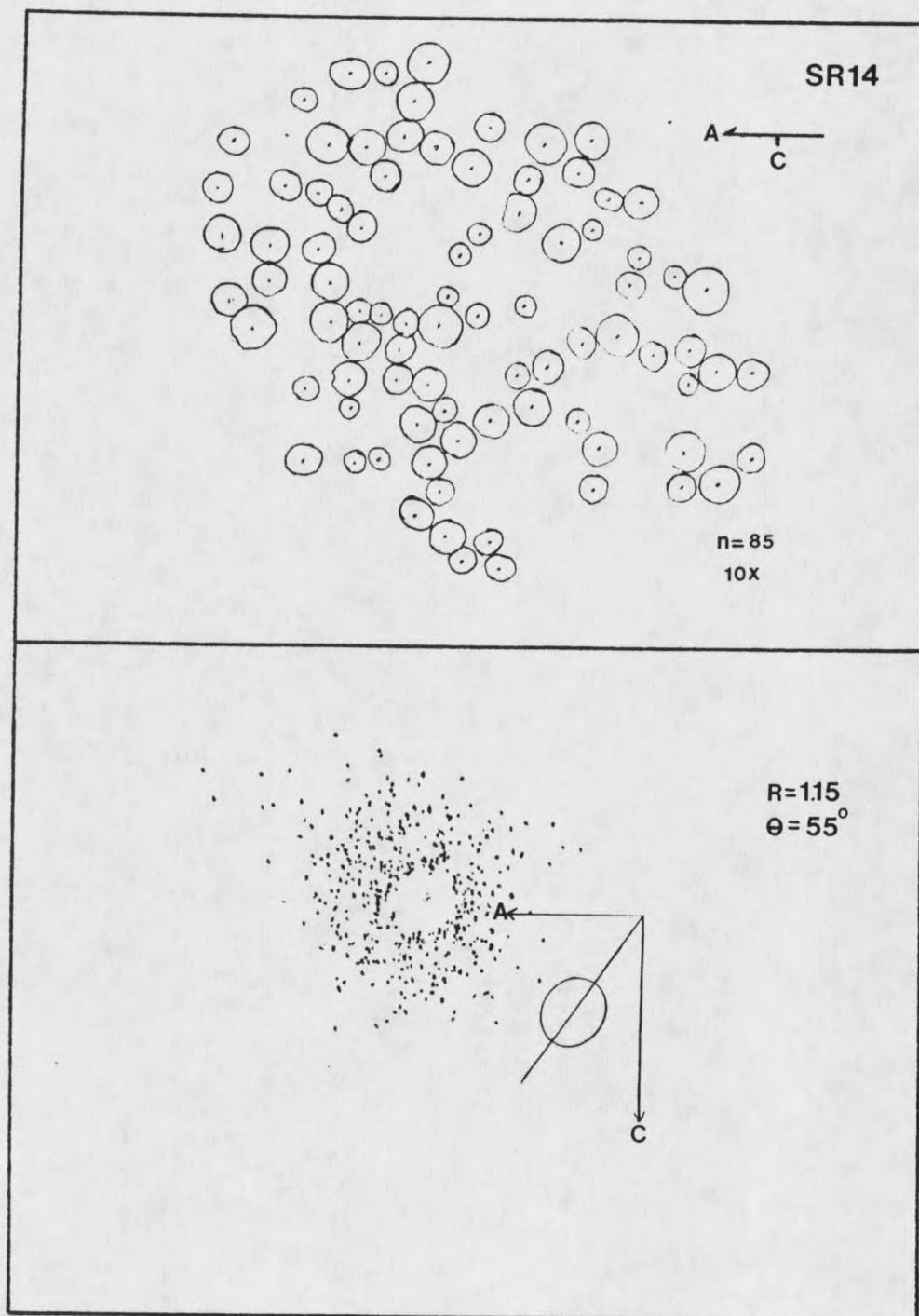


Figure 68. a. Tracing of ooids from sample SR14, AC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

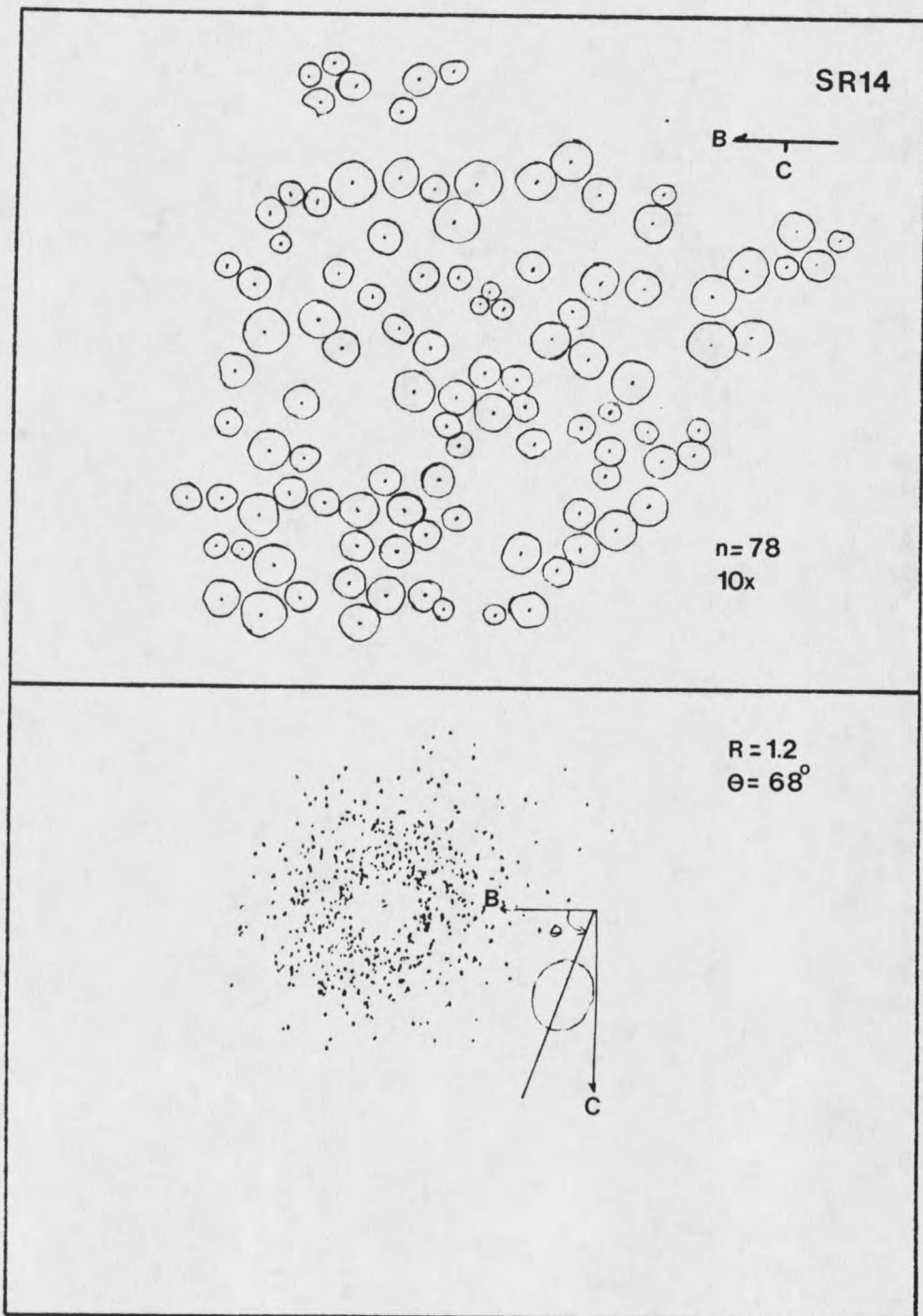


Figure 69. a. Tracing of ooids from sample SR14, BC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

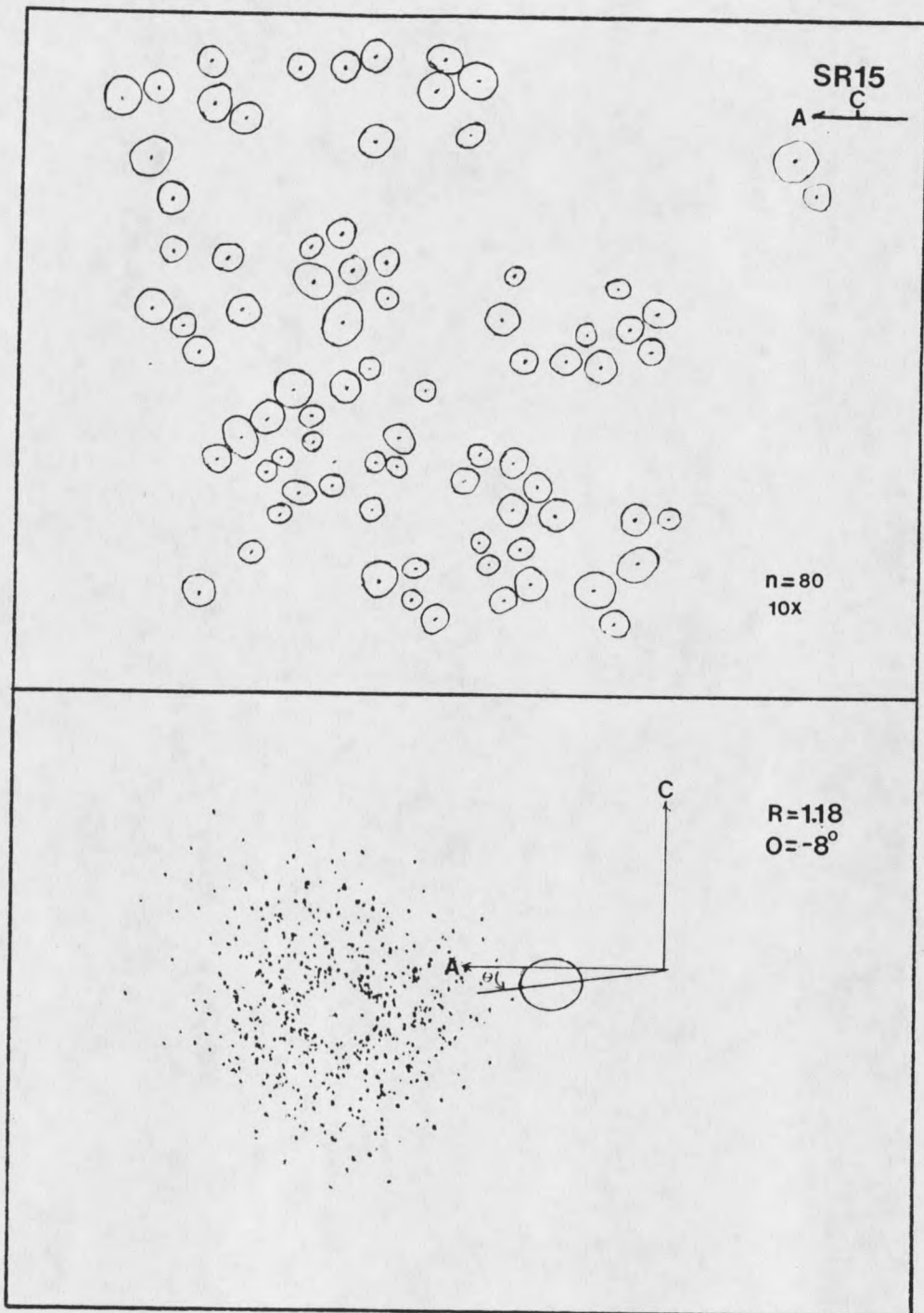


Figure 70. a. Tracing of ooids from sample SR15, AC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

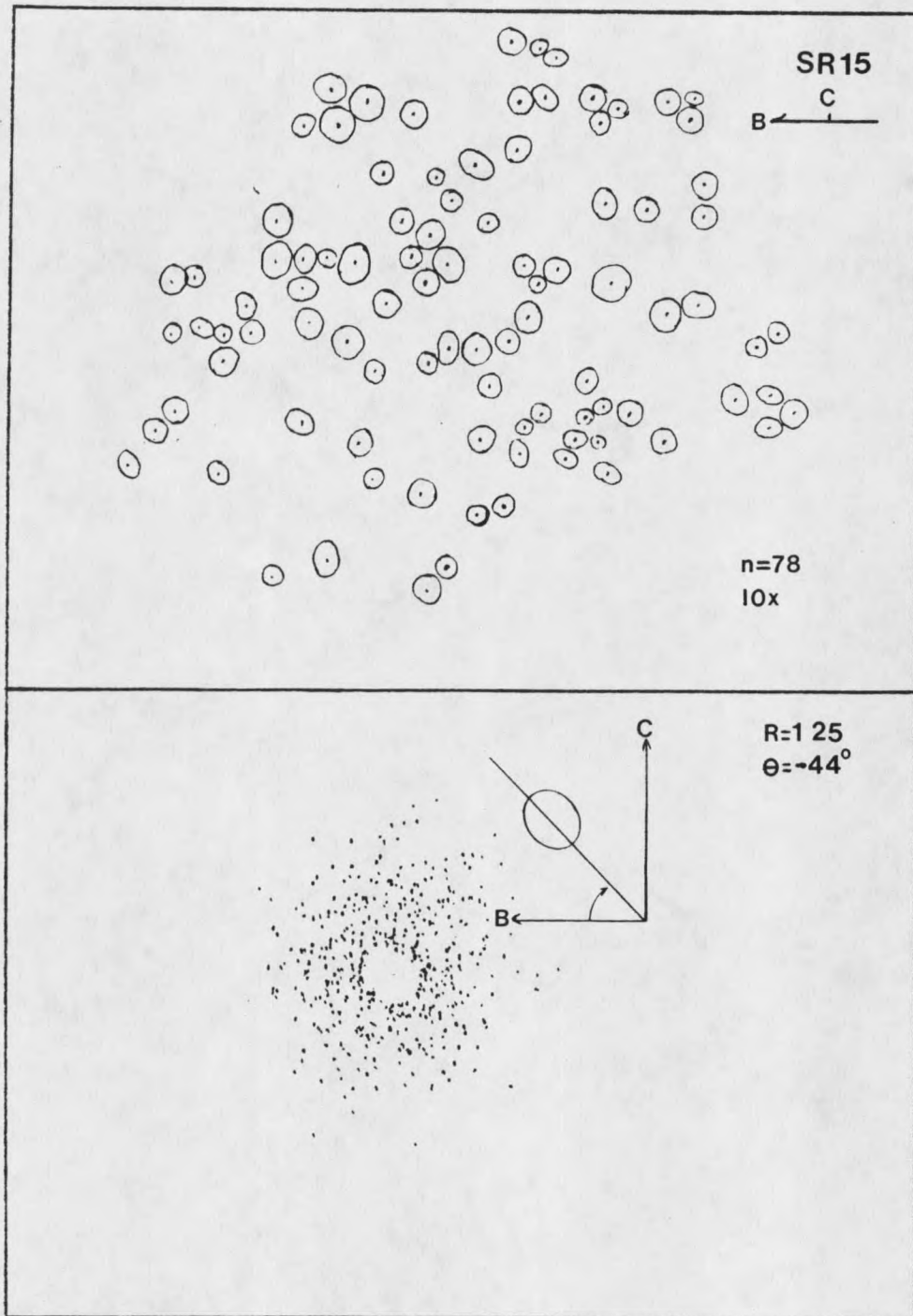


Figure 71. a. Tracing of ooids from sample SR15, BC axes. Magnified $10\times$. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

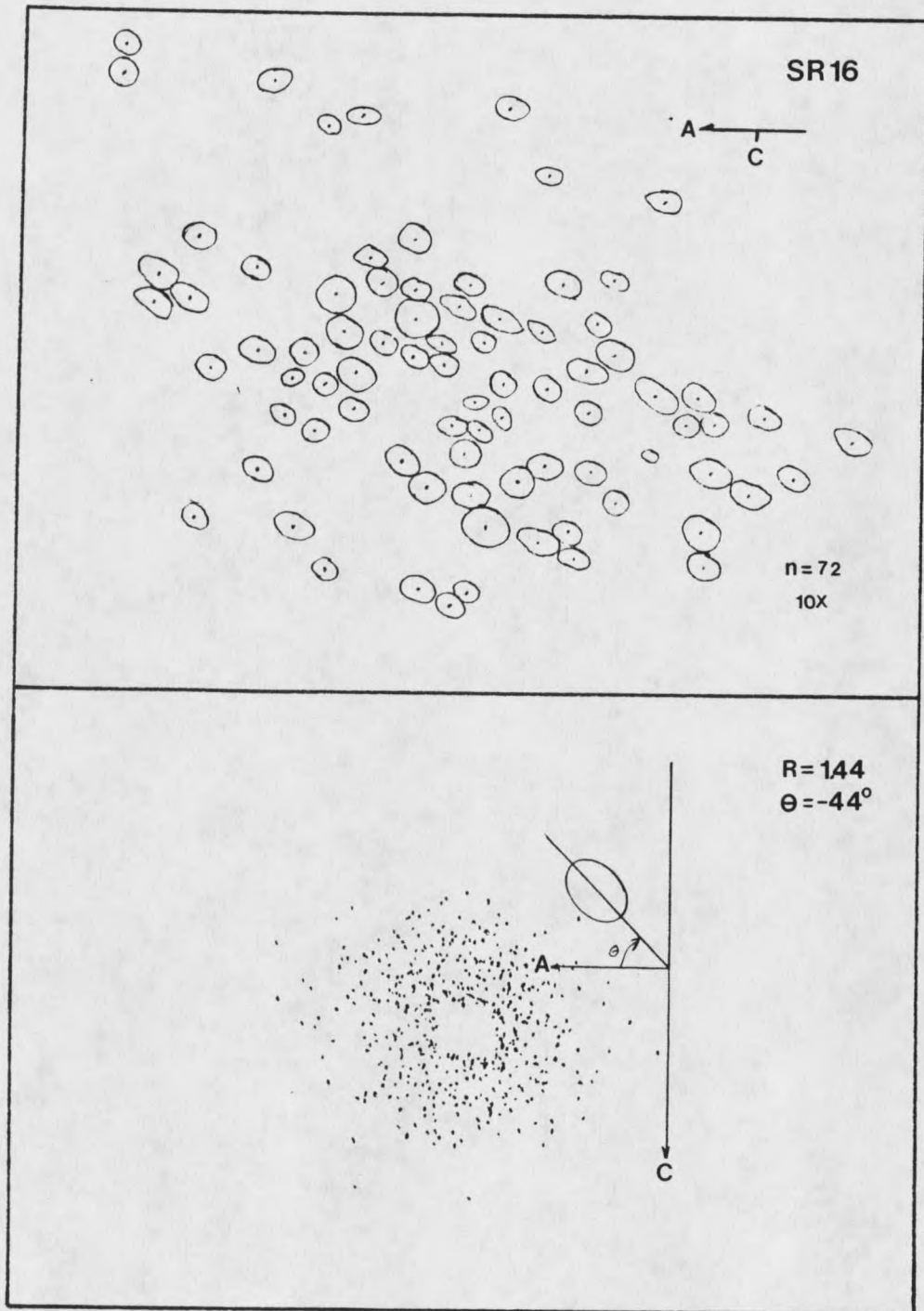


Figure 72. a. Tracing of ooids from sample SR16, AC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

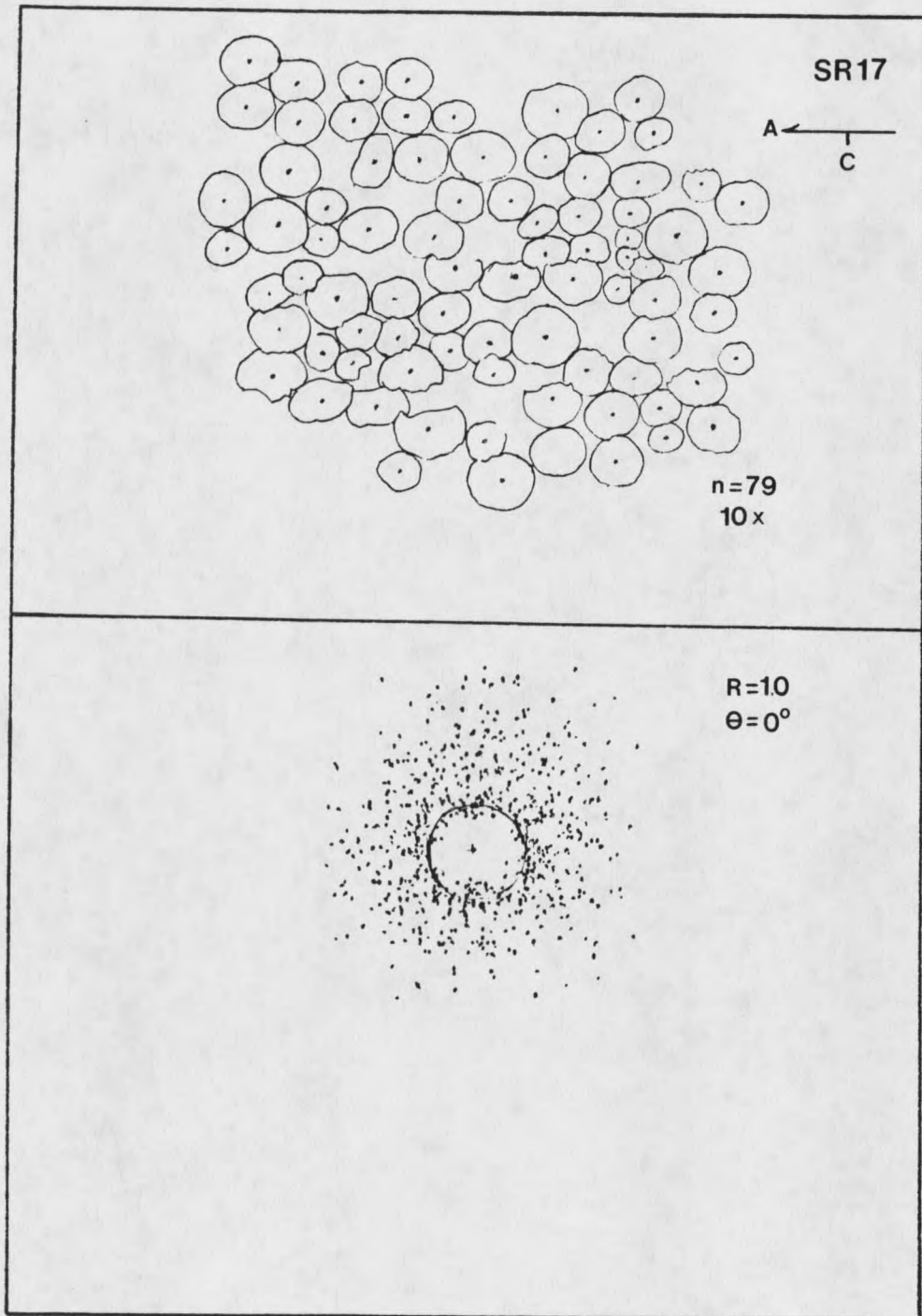


Figure 73. a. Tracing of ooids from sample SR17, AC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

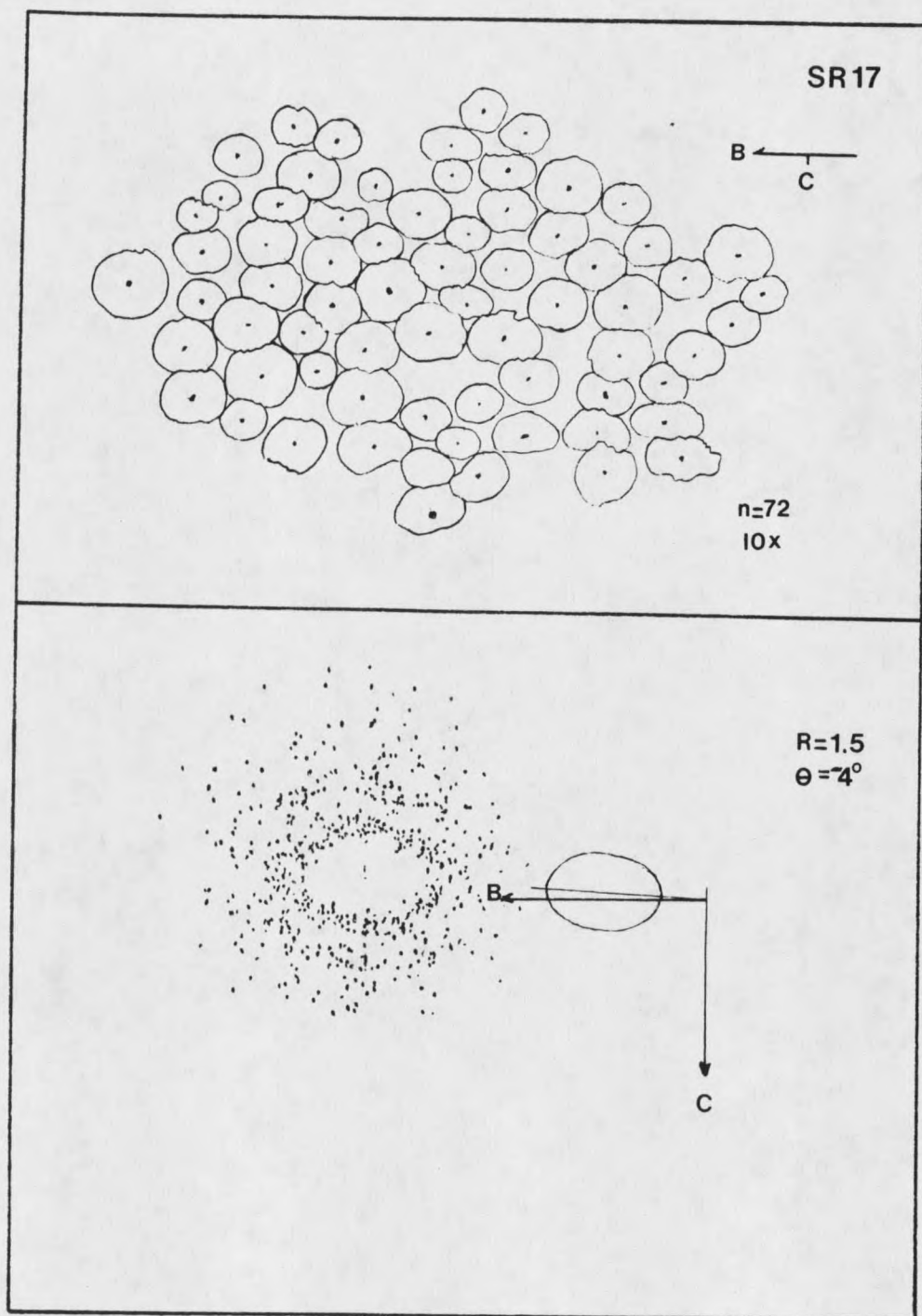


Figure 74. a. Tracing of ooids from sample SR17, BC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

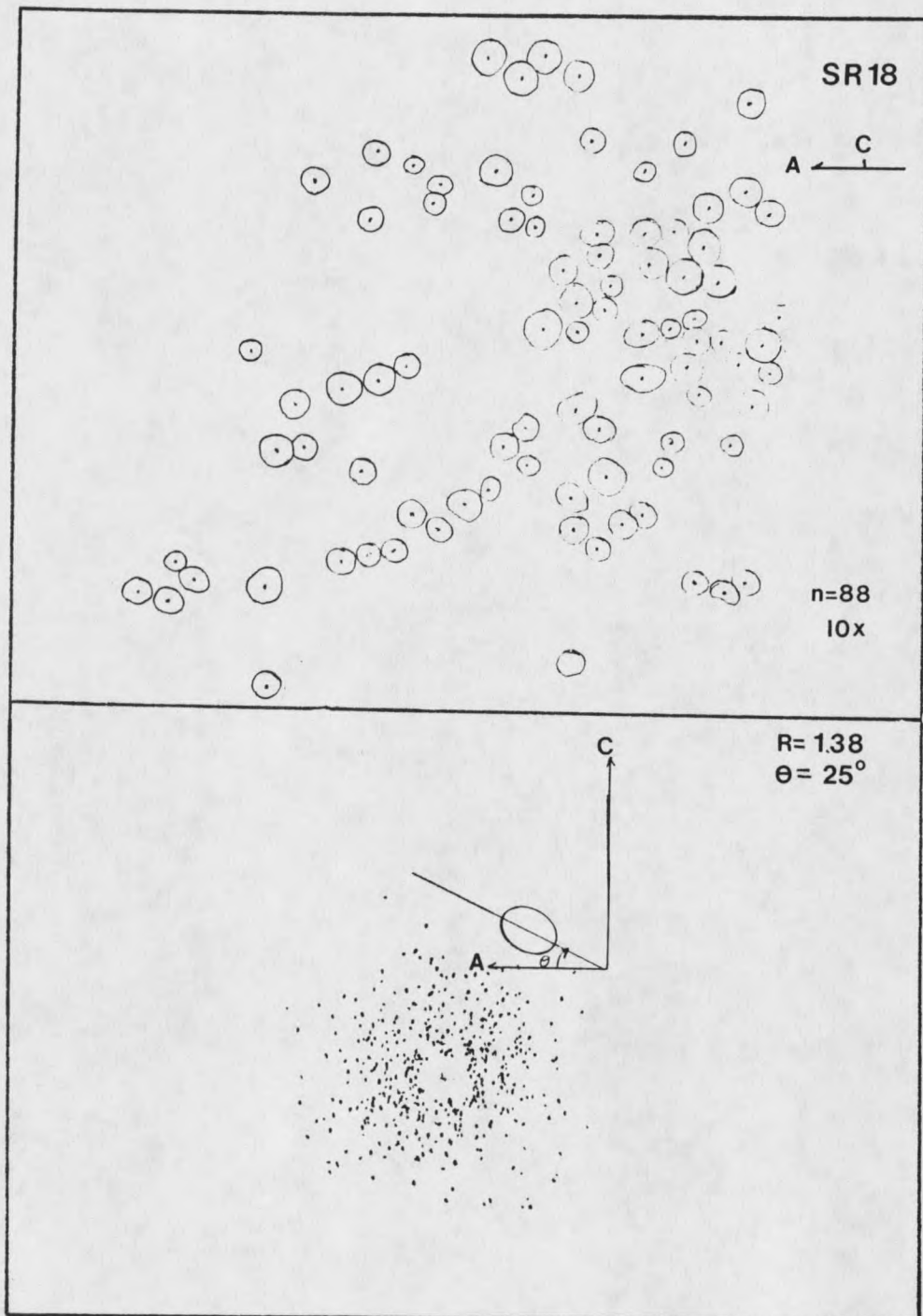


Figure 75. a. Tracing of ooids from sample SR18, AC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

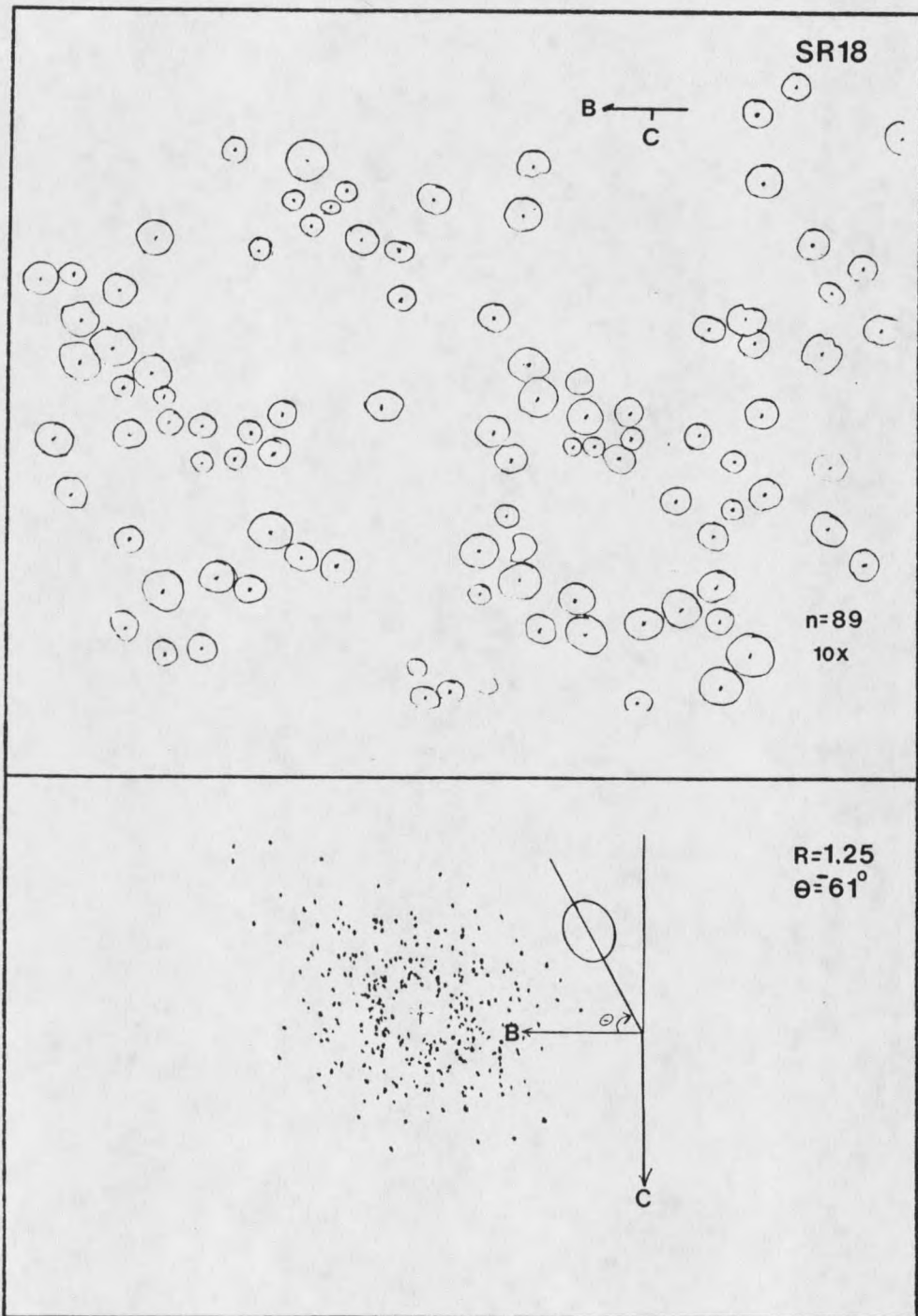


Figure 76. a. Tracing of ooids from sample SR18, BC axes. Magnified 10x. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

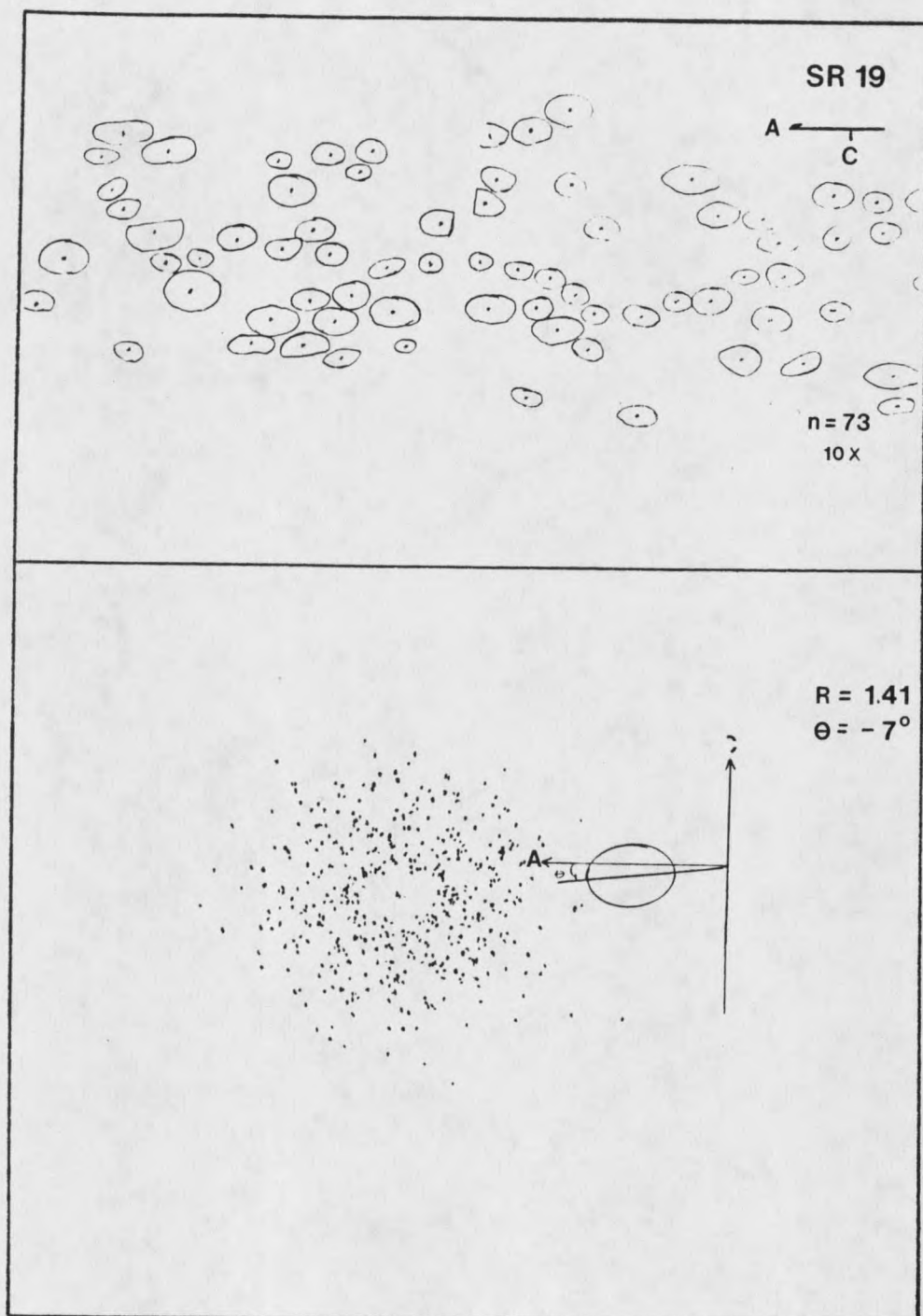


Figure 77. a. Tracing of ooids from sample SR19, AC axes. Magnified 10x. b. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R=ellipticity, θ =long axis orientation.

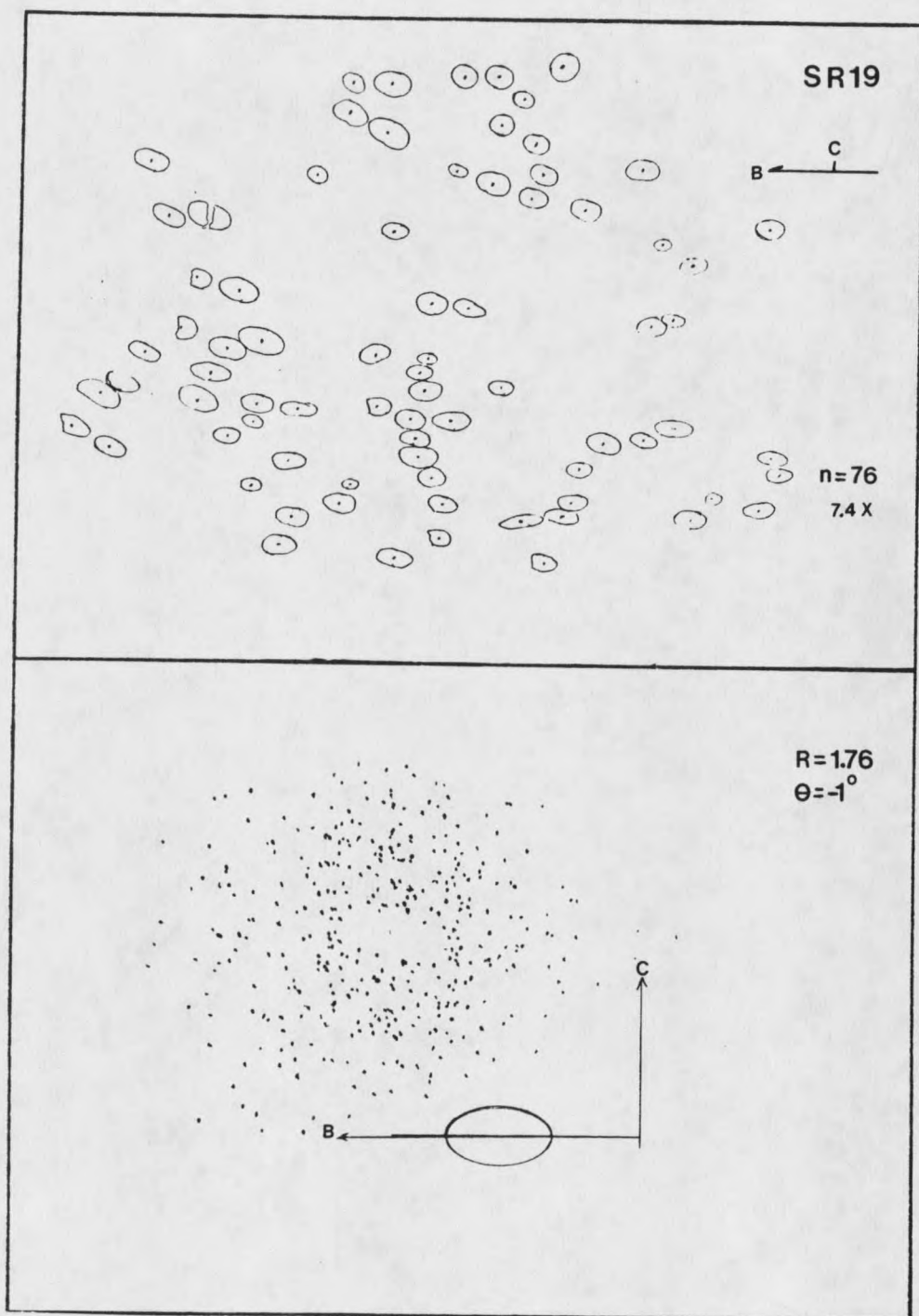
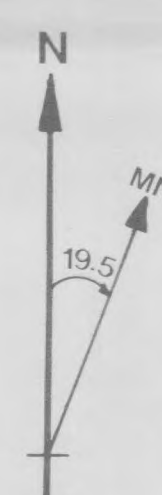
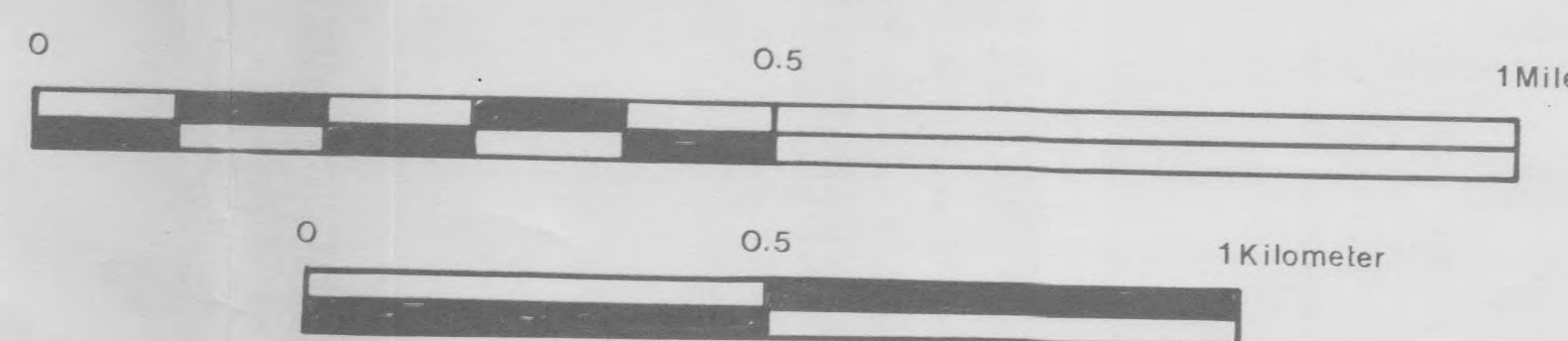


Figure 78. a. Tracing of ooids from sample SR19, BC axes. Magnified 7.4x. Manually generated Fry diagram of above sample with best fit ellipse or circle sketched in. R =ellipticity, θ =long axis orientation.

GEOLOGIC MAP OF THE SWIFT RESERVOIR AREA, SAWTOOTH RANGE, MONTANA



Scale 1:8,000



MAP UNITS

Cretaceous -	[Ku]	Cretaceous Undifferentiated
Jurassic -	[Ju]	Jurassic Undifferentiated
Mississippian -	[Mu]	Mississippian Undifferentiated
Devonian -	[Dm]	Devonian Maywood
	[CdG]	Devils Glen Dolomite
	[Cs]	Switchback Shale
	[Est]	Steamboat Limestone
	[Ep]	Pentagon Shale

EXPLANATION

---	contact, dashed where inferred
▲---	thrust fault, dashed where inferred
≡---	tear fault, dashed where inferred
⤴	anticline
⤵	syncline
⤴⤵	overturned anticline
⤵⤴	overturned syncline
72	strike and dip of bedding
39	strike and dip of overturned bedding

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