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THE STRUCTURE AND STRATIGRAPHY OF THE PEN ARGYL MEMBER OF THE MARTINSBURG FORMATION IN LEHIGH AND BERKS COUNTIES, PENNSYLVANIA

BY

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THE STRUCTURE AND STRATIGRAPHY OF THE PEN ARGYL MEMBER OF THE MARTINSBURG FORMATION IN LEHIGH AND BERKS COUNTIES, PENNSYLVANIA

by

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TABLE OF CONTENTS

Title Page -	i
Certificate of Approval - - - - - - - - - - - - - -	ii
Acknowledgments - - - - - - - - - - - - - - - - - -	iii
List of Tables - - - - - - - - - - - - - - - - - - -	vii
List of Plates - - - - - - - - - - - - - - - - - - -	vii
List of Figures - - - - - - - - - - - - - - - - - -	viii
Abstract -	1
Introduction -	4
Purpose of Study	4
Geologic Setting	4
Area of Study	5
Scope and Method of Study	8
Martinsburg Formation - - - - - - - - - - - - - - -	11
Previous Work and Regional Geology of the Martinsburg Formation	11
Lithology of the Martinsburg Formation	18
Bushkill Member	18
Ramseyburg Member	19
Pen Argyl Member	20
Age of the Martinsburg Formation	31
Metamorphism of the Martinsburg Formation	35
Small Scale Structures in the Pen Argyl Member - -	38
Slickensides	38
Intersections of slaty cleavage and bedding-	38
Intersections of slaty cleavage and strain-slip cleavage	41
Bedding	44
Cleavage	48
Grain	61
Folding in the Pen Argyl Member - - - - - - - - - -	65
Hansen Fold Classification - - - - - - - - - - - - -	78
Faulting in the Pen Argyl Member - - - - - - - - - -	81

Regional and Structural Geology - - - - - - - - - 91

Slatedale Quadrangle 97
New Tripoli and New Ringgold Quadrangles 114

Summary of Regional Fabric - - - - - - - - - - - - 137

Timing of Deformation - - - - - - - - - - - - - - 139

Conclusions - - - - - - - - - - - - - - - - - - - 146

References - 151

Appendix A - 157
Slate Quarries of Lehigh and Berks Counties

Vita - 214

LIST OF TABLES

Table		Page
1	Fold History of the Pen Argyl Member - - - - -	77
2	Hansen Fold Classification - - - - - - - - - - -	80
3	Deformational History of the Pen Argyl Member -	144

LIST OF PLATES

Plate

1 Geologic Map of the Pen Argyl Member in the New Ringgold Quadrangle

2 Geologic Map of the Pen Argyl Member in the New Tripoli Quadrangle

3 Geologic Map of the Pen Argyl Member in the Slatedale Quadrangle

4 Quarry Locations for the New Ringgold Quadrangle

5 Quarry Locations for the New Tripoli Quadrangle

6 Quarry Locations for the Slatedale Quadrangle

7 Geologic Cross-Sections

LIST OF FIGURES (Main Text)

Figure		Page
1	Physiographic map of Pennsylvania - - - - - - - -	6
2	Quadrangle location of present study - - - - -	7
3	Interpretations of Martinsburg stratigraphy - -	15
4	Typical "ribbon beds" - - - - - - - - - - - - - - -	22
5	Graded graywacke beds - - - - - - - - - - - - - - -	23
6	Cross-bedded graywacke - - - - - - - - - - - - - -	24
7	Cross-bedded siltstone lenses - - - - - - - - - -	25
8	Photomicrograph of a graywacke in the Pen Argyl Member -	27
9	Photomicrograph of the typical Pen Argyl claystone slate - - - - - - - - - - - - - - - - - - -	29
10	Contour diagram of slaty cleavage-bedding intersections in the entire study area - - - -	40
11	Contour diagram of slaty cleavage-bedding intersections in the entire study area south of the maximum for figure 10 - - - - - - - - -	42
12	Contour diagram of poles to slaty cleavage associated with lineations of figure 11 - - - -	43
13	Contour diagram of slaty cleavage-strain-slip cleavage intersections in the entire study area -	45
14	Contour diagram of poles to upright bedding in the entire study area - - - - - - - - - - - - - - -	46
15	Contour diagram of poles to overturned bedding in the entire study area - - - - - - - - - - - - -	47
16	Slaty cleavage refraction - - - - - - - - - - - - -	51
17	Photomicrograph of a graywacke-claystone slate contact -	52
18	Crenulated slaty cleavage planes - - - - - - - -	53

Figure		Page

Figure		Page
19	Slaty cleavage and strain-slip cleavage in a sample of the Pen Argyl slate - - - - - - - - -	54
20	Contour diagram of poles to slaty cleavage in the entire study area - - - - - - - - - - - - - -	59
21	Contour diagram of poles to slaty cleavage in the Mahantango Formation in the Palmerton quadrangle -	60
22	Diagram of slate structure - - - - - - - - - - -	62
23	Contour diagram of poles to grain in the entire study area - - - - - - - - - - - - - - - - - - -	64
24	Anticline in the Manhattan quarry - - - - - - -	67
25	Ramsay fold classification - - - - - - - - - - -	68
26	Bedding plane slickensides in the Manhattan quarry -	69
27	Sigmoidal tension gashes - - - - - - - - - - - -	70
28	Kink folds - - - - - - - - - - - - - - - - - - -	73
29	Down plunge view of kink folds - - - - - - - - -	74
30	Photomicrograph of a kink fold - - - - - - - - -	75
31	Fault related slaty cleavage rotation in the Hess quarry - - - - - - - - - - - - - - - - - - -	83
32	Fault related strain-slip cleavage - - - - - -	84
33	Possible fault models for the Eckville fault -	87
34	Contour diagram of poles to slaty cleavage in Slatedale quadrangle - - - - - - - - - - - - -	93
35	Subdivisions of the Slatedale quadrangle for fabric studies - - - - - - - - - - - - - - - - -	95
36	Contour diagram of poles to slaty cleavage planes in domain 1 of the Slatedale quadrangle - - - -	96
37	Contour diagram of poles to slaty cleavage in domain 2 of the Slatedale quadrangle - - - - -	97

Figure		Page
38	Contour diagram of poles to slaty cleavage in domain 3 of the Slatedale quadrangle - - - - -	98
39	Contour diagram of poles to slaty cleavage in domain 4 of the Slatedale quadrangle - - - - -	99
40	Contour diagram of poles to slaty cleavage in domain 5 of the Slatedale quadrangle - - - - -	100
41	Contour diagram of poles to upright bedding in the Slatedale quadrangle - - - - - - - - - - -	102
42	Contour diagram of poles to overturned bedding in the Slatedale quadrangle - - - - - - - - - - -	103
43	Contour diagram of slaty cleavage-bedding intersections in the Slatedale quadrangle - - -	105
44	Contour diagram of slaty cleavage-bedding intersections south of the maximum of figure 43 and associated slaty cleavage - - - - - - -	106
45	Contour diagram of slaty cleavage-bedding intersections in domain 1 of the Slatedale quadrangle - - - - - - - - - - - - - - - - - - -	108
46	Contour diagram of slaty cleavage-bedding intersections in domain 2 of the Slatedale quadrangle - - - - - - - - - - - - - - - - - - -	109
47	Contour diagram of slaty cleavage-bedding intersections in domain 3 of the Slatedale quadrangle - - - - - - - - - - - - - - - - - - -	110
48	Contour diagram of slaty cleavage-bedding intersections in domain 4 of the Slatedale quadrangle - - - - - - - - - - - - - - - - - - -	111
49	Contour diagram of slaty cleavage-bedding intersections in domain 5 of the Slatedale quadrangle - - - - - - - - - - - - - - - - - - -	112
50	Contour diagram of slaty cleavage-strain-slip cleavage intersections in the Slatedale quadrangle - - - - - - - - - - - - - - - - - - -	113
51	Contour diagram of poles to strain-slip cleavage in domain 7 of the Slatedale quadrangle - - - - - - - - - - - - - - - - - - -	115

Figure | Page

52 Contour diagram of poles to slaty cleavage in domain 7 of the Slatedale quadrangle - - - - - 116

53 Stereoplot of slaty cleavage-bedding intersections in domain 1 of the New Tripoli quadrangle - 119

54 Contour diagram of poles to slaty cleavage in the New Tripoli and New Ringgold quadrangles - 120

55 Subdivision of the New Tripoli and New Ringgold quadrangles for fabric studies - - - - 122

56 Contour diagram of poles to slaty cleavage in domain 1 of the New Tripoli quadrangle - - - - 123

57 Contour diagram of poles to slaty cleavage in domain 2 of the New Tripoli quadrangle - - - - 124

58 Contour diagram of poles to slaty cleavage in domain 3 of the New Tripoli and New Ringgold quadrangles - - - - - - - - - - - - - - - - - - - 125

59 Contour diagram of poles to upright bedding in the New Tripoli and New Ringgold quadrangles 128

60 Contour diagram of poles to overturned bedding in the New Tripoli and New Ringgold quadrangles - - - - - - - - - - - - - - - - - - - 129

61 Contour diagram of slaty cleavage-bedding intersections in the New Tripoli and New Ringgold quadrangles - - - - - - - - - - - - - - 130

62 Contour diagram of slaty cleavage-bedding intersections in domain 1 of the New Tripoli quadrangle - - - - - - - - - - - - - - - - - - - 132

63 Contour diagram of slaty cleavage-bedding intersections in domain 2 of the New Tripoli quadrangle - - - - - - - - - - - - - - - - - - - 133

64 Contour diagram of slaty cleavage-bedding intersections in domain 3 of the New Tripoli and New Ringgold quadrangles - - - - - - - - - 134

65 Contour diagram of slaty cleavage-strain-slip cleavage intersections in the New Tripoli and New Ringgold quadrangles - - - - - - - - - - - 136

ABSTRACT

The Pen Argyl Member, the upper claystone slate member of the Martinsburg Formation, was studied in three quadrangles in Lehigh and Berks Counties, Pennsylvania. Graptolites collected from the Pen Argyl Member at Lehigh Gap indicate a lower Upper Ordovician (Edenian-Maysvillian) age for the Pen Argyl Member. The Pen Argyl Member in this area is located on the normal limb and in the brow of the large, recumbent Musconetcong nappe. It is a deep water flysch deposit emplaced by turbidity currents from a southeasterly source. Sedimentologic and structural evidence show that the Pen Argyl Member overlies the sandy middle Ramseyburg Member, thus supporting the tripartite subdivision of the Martinsburg Formation.

Field and thin section study indicates that the penetrative slaty cleavage formed in an indurated rock probably by pressure solution and neocrystallization under lower greenschist facies metamorphism. Strain-slip cleavage formed as a result of a stress couple operating parallel to the slaty cleavage that transposed the slaty cleavage into a more spaced cleavage. Both cleavages are believed to have formed within the same stress continuum and in close succession.

Analysis of the folds in the Pen Argyl Member

indicate six phases of major and minor folding. The earliest folding, F_1, resulted in the development of the recumbent nappe. F_2 folds can only be determined statistically; these axes plunge either northeast or southwest Asymmetric folds, F_3, and associated F_4 crenulations formed within the same stress continuum. F_5 folds are large open folds and are exemplified by the Mosserville anticline. Kink folds, F_6, and associated crenulations are fault related and were the last folds to form.

Faults in the Pen Argyl Member range from small displacements along slaty cleavage to large reverse faults. The largest of these, the Eckville fault, is recognized throughout the three quadrangle area. It is a high angle reverse fault that separates the Shochary sequence from the Pen Argyl Member to the north.

Detailed fabric analysis of the Pen Argyl Member indicates that (1) the strike of the slaty cleavage is consistent throughout the study area, (2) bedding strikes are undulose indicating that the rocks were folded prior to slaty cleavage development, (3) slaty cleavage-bedding intersections indicate an early northeast-southwest fold set and a later east-west trend of fold axes, and (4) slaty cleavage-strain-slip cleavage intersections indicate two periods of strain-slip cleavage development, the later period being fault related.

Synthesis of field work and fabric data suggest that the Pen Argyl Member was deposited in the waning stages of flysch deposition during the Taconic orogeny. The nappe, F_1, was formed at this time as a result of stress generated by plate convergence to the southeast. Further Taconian deformation of the normal limb of the nappe resulted in the northeast-southwest plunging F_2 folds. Initial Alleghenian deformation resulted in the F_3 asymmetric folds and slaty cleavage, S_1. Later in the same stress continuum the F_4 crenulations and strain-slip cleavage, S_2, formed. Subsequently, F_5 open folding occurred. Kink folds and crenulations, F_6, and strain-slip cleavage, S_3, formed in conjunction with late Alleghenian reverse faults such as the Eckville fault.

INTRODUCTION:

Purpose of Study:

The study of the Pen Argyl Member was carried out in conjunction with the Central Appalachian Tectonic History project of Avery A. Drake, Jr. and others of the United States Geological Survey.

The Pen Argyl Member is the upper claystone slate unit of the Martinsburg Formation (Drake and Epstein, 1967) and the outcrop belt of the Pen Argyl Member is referred to as the "slate belt". The present study is beneficial in that the Pen Argyl Member is well suited to recording the deformational effects of the numerous orogenic events that have made their presence felt throughout the Central Appalachian fold system. The study of the Pen Argyl Member is part of a larger regional project designed to gain more knowledge of the Martinsburg Formation and its relation to the numerous other rock types within the Great Valley of eastern Pennsylvania. Solutions to the problems described below will greatly enhance out knowledge of the Paleozoic of southeastern Pennsylvania.

Geologic Setting:

The Pen Argyl Member of the Martinsburg Formation of east-central Pennsylvania crops out along the northeastern edge of the Appalachian Great Valley (see figure 1). The Great Valley is bounded on the south by Precambrian crystalline rocks of the Reading Prong and on the north by the Silurian sandstone-quartzite ridge or Blue Mountain which marks the southern margin of the Valley and Ridge.

The Great Valley is underlain by Cambrian and Ordovician carbonate rocks which are overlain by middle Wildernesian (Trentonian) to lower Maysvillian pelites and graywackes. The graywackes and shales form the hills north of the low-lying carbonate valley. To the west, near Kutztown and extending west of Harrisburg, Taconic-type allochthonous units named the Hamburg klippe by Stose (1946) are present. This area is topographically distinct from the carbonate-pelite-graywacke sequence to the north and east.

Natural outcrops of the Pen Argyl Member are quite sparse and data were collected mainly in the numerous slate quarries in the area.

Area of Study:

The area of this study were those parts of the Slatedale, New Tripoli, and New Ringgold 7½-minute quadrangles underlain by the Pen Argyl Member. Figure 2 shows the location of the study area. This area was previously mapped by Behre (1933) but detailed mapping was needed to clarify the numerous problems described below.

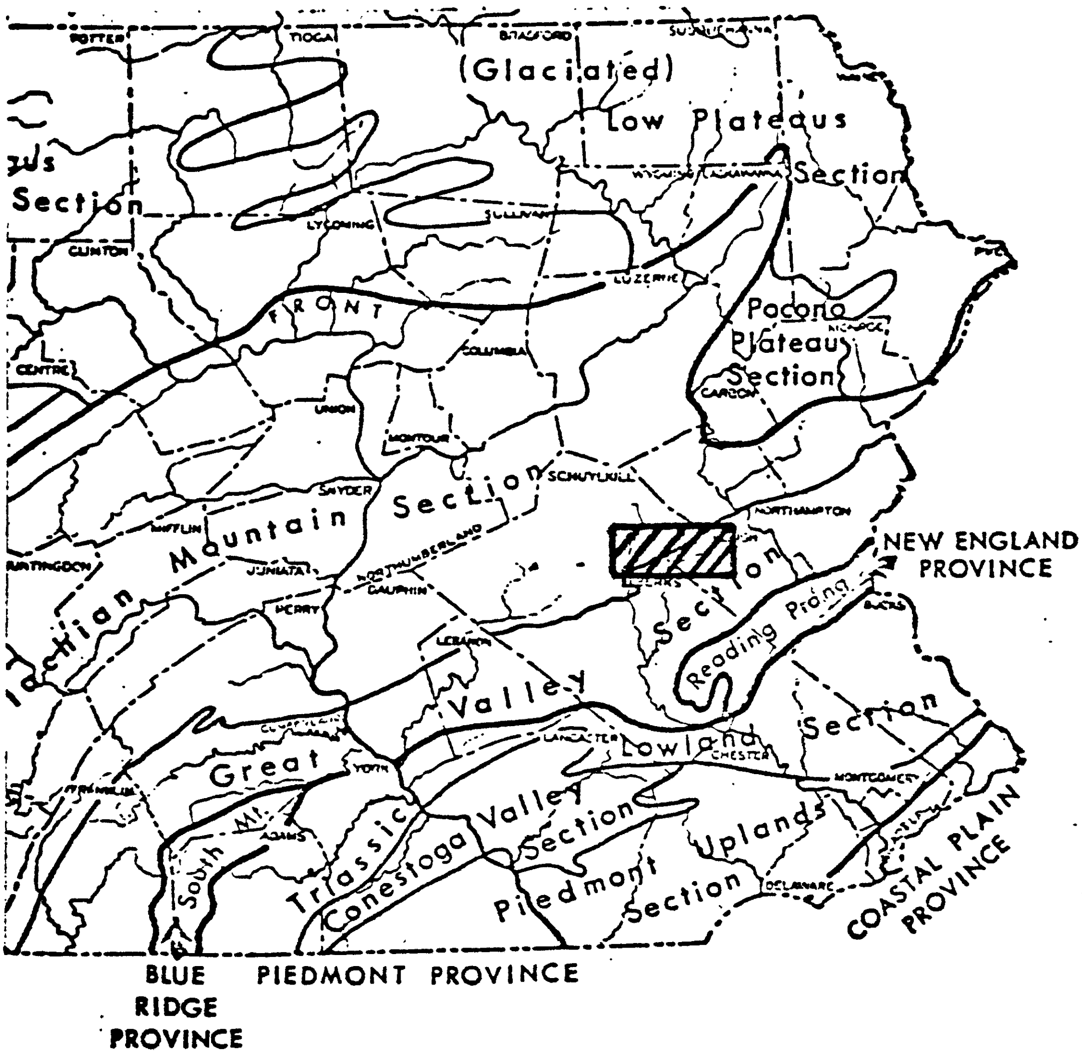


Figure 1: Physiographic map of eastern Pennsylvania (from the Pennsylvania Geological Survey). The study area of this report is shown by the ruled lines.

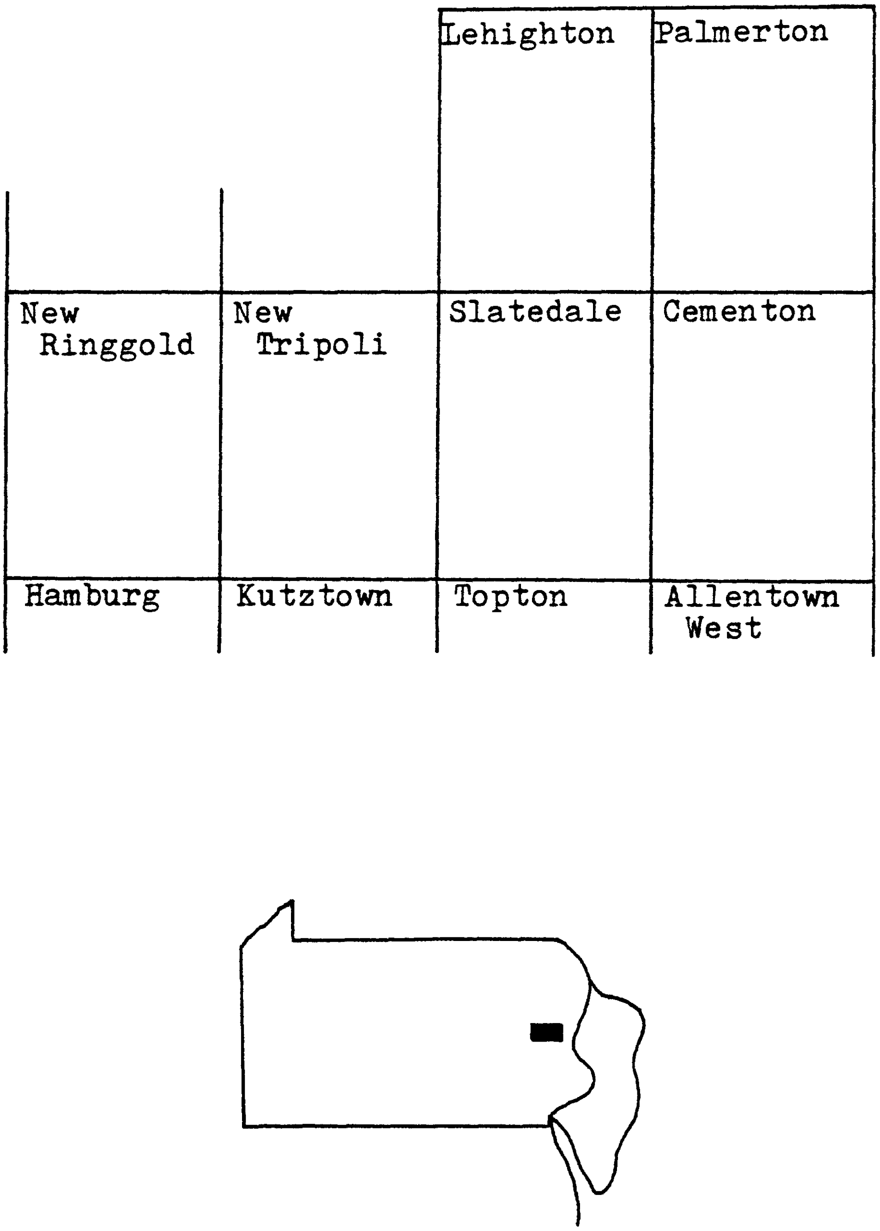


Figure 2: Quadrangle and general location of the present study. The Pen Argyl Member of the Martinsburg Formation was mapped in the Slatedale, New Tripoli, and New Ringgold quadrangles.

Scope and Method of Study:

Several structural and stratigraphic problems of the Martinsburg Formation have remained unsolved despite the long history of work in east-central Pennsylvania. Problems that are dealt with in this paper are described below.

The stratigraphic and structural relation of the Pen Argyl Member of the Martinsburg Formation to the Shochary sequence is a very important problem in this area. The essence of this problem is whether the Shochary sequence is in fault or stratigraphic contact with the Pen Argyl Member. Considerable effort was directed toward a search for evidence bearing on support or rejection of the existence of the Eckville fault which Behre (1933) believed separated the Shochary sequence from the slate belt rocks to the north.

The relations of the Pen Argyl Member to the allochthonous Hamburg Klippe rocks of Stose (1946) is another problem that was investigated. No klippe rocks have been described as far north as the outcrop belt of the Pen Argyl Member, thus establishing the presence of rocks that could be correlated with the klippe rocks within the outcrop area of the Pen Argyl Member would be quite significant.

The structural and, more importantly, stratigraphic relationships of the Pen Argyl Member to the Ramseyburg Member of the Martinsburg Formation is of great importance. A.A. Drake, Jr. and J.B. Epstein (1967), working to the northeast of this study area found that the Pen Argyl Member overlies the Ramseyburg Member which in turn overlies the Bushkill Member of the Martinsburg Formation. All of these units are lithologically distinct, thus proving the tripartite subdivision of the Martinsburg Formation in eastern Pennsylvania. This view has recently been challanged by T.O. Wright and others (1978) who maintain that the Martinsburg Formation is actually made up of two members. It was hoped that the present study would lead to a solution of this controversy that has existed for well over half a century.

Gaining an understanding of the structural and stratigraphic relations of the Pen Argyl Member to the rocks mentioned above is essential to any regional tectonic synthesis. An appreciation of which deformational features formed during the Taconic orogeny and which features formed during the Alleghenian orogeny was also a goal of this study.

Detailed field work in the relevant parts of the three quadrangles mentioned above began in May, 1977 and was completed in October, 1977. Numerous field checks were made throughout the winter months. As the Pen Argyl

Member is covered by glacial deposits at many places the best exposures are limited primarily to the abundant slate quarries in the area. Quarries of the Slatington and Lynnport slate districts were visited and studied.

Local and regional fabric studies constituted a large part of the analytical work. A computer program (Warner, 1969) for the construction and contouring of pole diagrams was adapted for use on the computer at Lehigh University and was an invaluable aid in the fabric analysis. Ten samples of both the graywacke and claystone-slate were thin-sectioned for petrographic and microstructural study.

MARTINSBURG FORMATION:

Previous Work and Regional Geology of the Martinsburg Formation:

The Martinsburg Formation was named by Keith (1894) for outcrops of calcareous shale near Martinsburg, West Virginia. It forms a continuous outcrop belt along the Appalachian Valley except in east-central Pennsylvania where allochthonous rocks designated as the Hamburg Klippe by Stose (1946) are found. The Martinsburg Formation is continuous into the Delaware Valley and probably into northern New Jersey and southern New York. It is generally believed that the Martinsburg Formation, which consists of 9,800 to 12,800 feet of interbedded slate, graywacke, sandstone, and siltstone, is made up of three members (Drake and Epstein, 1967).

The internal subdivision of the Martinsburg Formation in eastern Pennsylvania has been the subject of geological debate for almost 100 years. Basing their interpretation on faunal and structural evidence, many workers investigating the area west of the Lehigh River believed in a bipartite subdivision of the Martinsburg consisting of a lower shale-slate unit and an upper sandstone unit (Stose, 1910; Willard and Cleaves, 1939; B.L. Miller and others, 1941; Willard, 1943; Mosely, 1953; Wright and others, 1978). C.H. Behre (1933) working in the area between the Delaware and Schuylkill Rivers proposed a tripartite subdivision of the Martinsburg Formation consisting of a lower thin bedded shale-slate unit, a slate-graywacke unit, and a thick-bedded slate unit in ascending order. This subdivision was proposed in Behre's classical work on the commercial slates of Pennsylvania (1933). Other proponents of the tripartite subdivision of the Martinsburg included Dale (1906, 1914), B.L. Miller (1925), and B.L. Miller and others (1939).

Stose (1930), working in the same area as Behre, restated his belief in a bipartite subdivision of the Martinsburg Formation. He felt that Behre's upper unit was actually the lower unit repeated in the north limb of a regional syncline. This view has been used on the most recent Pennsylvania State Geologic map (Gray and others, 1960).

Recent detailed structural and stratigraphic work by A.A. Drake, Jr. and J.B. Epstein of the United States Geological Survey (1967) indicates that the Martinsburg Formation can be divided into three distinct units similar to Behre's division. They are, in descending order, the Pen Argyl, Ramseyburg, and Bushkill Members.

In this study structural and stratigraphic evidence has supported the extension of the work of Drake and

Epstein to the area west of the Lehigh River. In the Slatedale quadrangle, where the contact between the Pen Argyl and Ramseyburg Members generally dips to the south, the beds are clearly overturned as shown by graded bedding, cross-bedding, and cleavage-bedding relationships. Thus it was structurally and stratigraphically demonstrated that the Pen Argyl Member does indeed overlie the Ramseyburg Member west of the Lehigh River. In addition to this, bipartite proponents would be hardpressed to explain the differences between the thickness of slate beds in the Pen Argyl Member and the Bushkill Member if they are considered to be the same unit. Pen Argyl beds can commonly attain a thickness of 20 feet whereas Bushkill beds seldom exceed 3 to 4 inches in thickness.

Little mention has been made of the work on the Martinsburg Formation of the Delaware Valley and New Jersey. Sanders (1883), Lesley (1892), and Lewis and Kummel (1915) proposed a bipartite subdivision of the Martinsburg for the Delaware Valley and New Jersey and their interpretation is probably correct as the Pen Argyl Member is buried beneath the Shawangunk Formation in New Jersey. The Pen Argyl Member is not exposed at the Delaware Water Gap or in the area to the east of it. Thus only the Bushkill Member and Ramseyburg Member are exposed across most of New Jersey. Despite this Offield (1967) described a similar three-unit sequence of psammitic and pelitic Ordovician rocks in southeastern New York.

Differences in stratigraphic and structural interpretations of the Martinsburg have resulted in varying thickness estimates. Stose (1930), a bipartite proponent, maintained that the thickness was on the order of 3,000 feet whereas tripartite proponents such as Behre stated a thickness of at least 10,000 feet. Drake and Epstein (1967) have estimated the thickness of the sequence as 9,800 to 12,800 feet. Figure 3 taken from Drake and Epstein (1967) summarizes the interpretations of Martinsburg stratigraphy of previous workers.

As mentioned earlier, Stose (1930) and Willard (1943) espoused the existence of a regional syncline in the Martinsburg outcrop belt thus suggesting a bipartite stratigraphy. Detailed field mapping by members of the United States Geological Survey (Drake, McLaughlin, and Davis, 1961, 1967; Drake, 1967a, 1967b; Davis, Drake, and Epstein, 1967; Drake, Epstein, and Aaron, 1969) indicates "that the Martinsburg Formation and older rocks are involved in a highly complicated, refolded, crystalline-cored nappe de recouvrement, the Musconetcong nappe (Drake and Epstein, 1967)." Field work undertaken in this study indicates that west of the Lehigh River the Pen Argyl Member lies in the normal limb or brow of this nappe and

Worker		Subdivision	Thickness
Lesley (1892)	bipartite	Upper Series Lower Series	6,000 feet
Lewis and Kummel (1915)	bipartite	Upper Sandy Member Lower Shaly Member	3,000 feet
Stose (1930)	bipartite	Lower Shaly Member (repeated in a syncline) Upper Sandy Member Lower Shaly Member	3,000 feet
Behre (1933)	tripartite	Upper "Soft" Slate Member Middle Sandy Member Lower "Hard" Slate Member	11,800 feet
Willard (1943)	bipartite	Dauphin Shale (repeated in a syncline) Shochary Sandstone Dauphin Shale	3,000-4,000 feet
Drake and Epstein (1967)	tripartite	Pen Argyl Member Ramseyburg Member Bushkill Member	9,800-12,800 feet

Figure 3: Interpretations of the Martinsburg stratigraphy by previous workers (from Drake and Epstein, 1967).

has a northward-dipping monocline-like appearance as suggested by Behre.

This study of the Pen Argyl Member in Berks and Lehigh Counties has substantiated the tripartite subdivision of the Martinsburg Formation by showing that the Pen Argyl Member does indeed overlie the Ramseyburg Member thereby showing that a regional syncline as proposed by Stose and Willard does not exist.

The Shawangunk Formation of Silurian age was not studied as a geologic unit but the nature of its contact with the Pen Argyl Member was studied in some detail. Field mapping by Epstein and Epstein (1969) in rocks of Ordovician to Devonian age in eastern Pennsylvania indicated that rocks of differing lithology and competency have different styles of deformation. They were able to recognize four rock sequences or lithotectonic units each of which had been deformed semi-independently of the rocks above and below. Each of the lithotectonic units is separated from the unit above and below by a décollement. Epstein and Epstein (1969) and Epstein (1971) have described the Martinsburg-Shawangunk contact as a zone of detachment between the Martinsburg Formation and older rocks (lithotectonic unit 1) and the Shawangunk Formation (lower part of lithotectonic unit 2). This northwest dipping décollement has been named the Blue Mountain décollement. The contact is not exposed within the study area but can be seen at the Lehigh Water Gap. This locality has been described in detail by Epstein and Epstein (1969).

Other evidence for the Blue Mountain décollement was found in the Bake Oven Knob area northwest of Slatedale. Here the strike of the Shawangunk outcrops is oblique to the regional trend of the Pen Argyl Member. In addition, microscarps on bedding-plane slickensides in the Shawangunk within 200 feet of the contact indicate northwest movement of the overlying beds.

Differences in size and style between folds in the Shawangunk and Martinsburg aid in the justification of the décollement. The décollement has taken up differences in shortening between the two lithologic units. Whereas folds of the Shawangunk Formation are concentric, flexural slip folds, folds of the Pen Argyl Member are similar, and often close to recumbent and passive folding is dominant over flexural slip. Wavelengths differences are also quite distinct. Wavelengths in the Silurian rocks average about 1 mile with amplitudes ranging from 1,500 to 5,000 feet (Epstein and Epstein, 1969) while wavelengths in the folds of the Pen Argyl Member west of the Lehigh River average about 500 to 1,000 feet with amplitudes of up to 2,500 feet. Although disharmonic folding caused by ductility contrasts are common in the rocks of Silurian age and younger it is lacking in the Pen Argyl Member.

For additional evidence in support of the décollement found outside the area of study the reader is referred to Epstein and Epstein (1969), Epstein (1971), and Epstein and others (1974).

In addition to being a décollement the contact is an erosional surface as shown by the unconformable contacts that can be seen at the Lehigh (Epstein and others, 1974) and Schuylkill (Burtner, Weaver, and Wise, 1958) Gaps.

Lithology of the Martinsburg Formation:

The Bushkill and Ramseyburg Members were not studied in detail in this investigation and only brief lithologic descriptions will be given for them. A more detailed description can be found in Drake and Epstein (1967) and Drake (1969).

Bushkill Member: The Bushkill Member crops out in the southeastern corner of the Slatedale quadrangle. It is the lowest unit of the Martinsburg Formation and is a claystone slate. Beds in the Bushkill Member seldom exceed a thickness of 2 to 4 inches and are usually thinner. Slaty cleavage is the dominant planar feature. Mineralogically, the Bushkill Member consists mainly of quartz and lesser amounts of sericite and chlorite. Albite and calcite are also present in variable amounts.

The contact of the Bushkill Member and underlying Jacksonburg Formation is generally considered to be conformable and gradational. This has been noted in the area to the northeast by Drake and Epstein (1967) and in the area to the south by Sherwood (1964). The contact with the overlying Ramseyburg Member is also transitional and is placed beneath the lowest prominant graywacke bed.

Drake and Epstein (1967) have estimated the thickness of the Bushkill Member to be about 4,000 feet, more than the estimate of 2,250 feet of Willard (1943) and less than the 5,000 feet estimated by Behre (1933).

Ramseyburg Member: The Ramseyburg Member consists of interbedded slate and graywacke. Graywacke makes up about 20 to 30 percent of the unit (Epstein and others, 1974). Graywacke beds are often very calcareous and are readily leached. Graded bedding, convolute laminations, sole marks, and other sedimentary structures lead McBride (1962) to suggest that the graywackes were deposited by turbidity currents in a deep water environment.

The Ramseyburg Member grades into the overlying Pen Argyl Member and the contact is placed at the last graywacke bed exceeding one foot in thickness.

Epstein (Epstein and others, 1974) has estimated the thickness of the Ramseyburg in the Lehighton and Palmerton quadrangles to between 2,700 and 3,000 feet. This thickness is somewhat less than Behre's (1933) estimate of 4,200 feet but much greater than Willard's (1943) estimate of 750 feet and reflects differences in structural interpretations. The Ramseyburg Member includes rocks referred to by Behre (1933) as the middle sandy member. It also includes the unit he called the Bangor beds, a name proposed for a sequence of several prominant graywacke-slate intervals that have been quarried in the Bangor area.

Lithologically, the Ramseyburg is typified by about 34 percent quartz, 16 percent rock fragments, 8 percent authigenic calcite, and 5 percent feldspar. The remainder consists of fine grained detritus and minor accessory minerals (Drake and Epstein, 1967).

Pen Argyl Member: The Pen Argyl Member is well exposed in the numerous slate quarries to the west of the Lehigh River. It is a thick-bedded claystone slate unit and like the Bushkill and Ramseyburg Members is a flysch deposit. The Pen Argyl Member in the study area is correlative with the Pen Argyl Beds of Behre (1933).

The Pen Argyl Member consists of thick-bedded, dark gray (N3) to medium-light gray (N6), dusky-yellow-weathering (5Y6/4) claystone slate intercalated with thinner beds of quartzose slate or subgraywacke and grayish-black (N2) thin carbonaceous claystone slate beds often referred to as "ribbons" by quarrymen. This rock type occurs in cycles, a typical cycle starting with quartzose slate followed by the thick-bedded claystone slate and, finally, by the carbonaceous "ribbon" beds (figure 4).

Sedimentary structures such as graded beds (figure 5), cross-beds (figure 6), sole marks, and structures similar to ripple marks (figure 7) were noted in the Pen Argyl Member.

Several samples of slate and graywacke were collected from the Pen Argyl Member in the Slatedale and New Tripoli quadrangles and thin sections were made from them. Grain sizes in the samples studied ranged from 0.005 mm in the slate to 0.2 mm in the graywackes and the textures ranged from well to poorly sorted.

Graywacke is generally found at the bottom of the sedimentary sequence described above. It is typically medium-dark-gray (N5) and much harder than the slate. The graywacke is generally poorly sorted. Both lithic and feldspathic graywackes (classification of Pettijohn, 1957) were observed. The lithic graywackes are typified by pieces of limestone that can be seen in thin section. In general, the graywackes are characterized by a matrix consisting of fine grained muscovite or sericite and

Figure 4: Typical "ribbon beds" found in the East Saegersville quarries. The black beds are carbonaceous. Slatedale quadrangle.

Figure 5: Graded graywacke beds. The darker beds are discolored by the presence of oxidizing heavy minerals. Note how the color change is gradational indicating that the bed is graded. The sample is from the waste pile of the East Saegersville quarries. Slatedale quadrangle.

Figure 6: Well developed cross-bedding in a bed in the Parry quarry. The hammer head lies on bedding and the pick point lies against a slaty cleavage plane. Slatedale quadrangle.

Figure 7: Cross-bedded lenses of siltstone. The lenses are sedimentary in origin and not the result of boudinage. They may represent sand waves. Cross-bedding is well developed in the troughs of the lenses. Slatedale quadrangle.

calcite with pyrite and other opaques (figure 8). "Floating" in the matrix are angular grains of quartz. Detrital grains of very clean albite are also common. A small amount of detrital microcline was also noted. Sphene and zircon are quite conspicuous in thin section as are numerous rounded pyrite crystals. A graywacke collected at Lehigh Gap contains euhedral pyrite crystals as large as 0.5 cm suggesting that some of the pyrite is authigenic. Calcite is present as both authigenic cementing material in the feldspathic graywackes and as detrital grains in the lithic graywackes. Very thin layers of dark carbonaceous material and opaque minerals are quite common in these rocks. The "floating" minerals constitute about 30 to 60 percent of the rock and quartz is generally the dominant "floating" mineral (35 percent) followed by plagioclase feldspar (5 percent), phyllosilicates (5 percent), and calcite (1 to 15 percent).

Slate occurs next above a graywacke bed in the sequence. Quartz grains in the slate are angular and commonly appear to be truncated at the contact with the cleavage folia suggesting pressure solution. The majority of the quartz grains are elongated parallel to cleavage. Very fine-grained quartz is common in the pressure shadow areas associated with the porphyroblasts (figure 9).

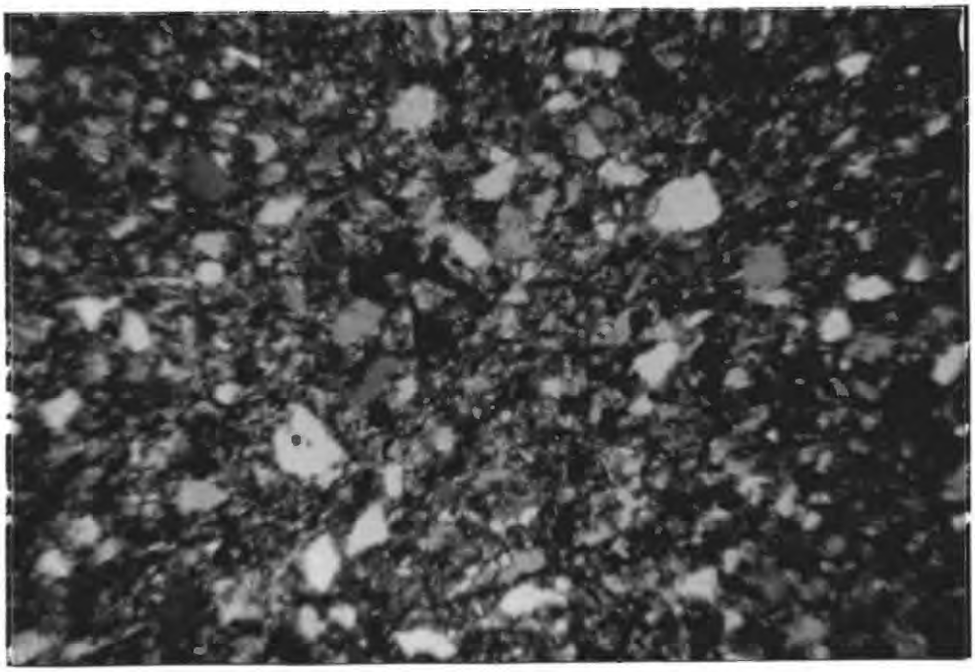


Figure 8: Photomicrograph of a sample of graywacke from the Pen Argyl Member. Kalbach quarry, New Tripoli quadrangle. Quartz is the dominant mineral with phyllosilicates, plagioclase feldspar, calcite, and opaques. Length of field-0.8 cm.

Chlorite and sericite constitute the greater part of the matrix and interstitial material. Porphyroblasts of both muscovite and chlorite are common and are 5 to 10 times the size of the interstitial material (figure 9). The chlorite shows a deep blue anomalous interference color indicating that it is pennine.

Plagioclase, not seen in thin section in slate, was identified only by X-ray diffraction. It is probably the result of metamorphism (Epstein, 1971). Black carbonaceous material constitutes the slaty cleavage folia. This appears to be a residue after pressure solution of the more mobile constituents. Pyrite and ilmenite can be seen in hand speciman due to conspicuous oxidation. The oxidation of these minerals commonly affords one with a means of determining tops of beds (figure 5).

Numerous major oxide analysis of slates and graywackes from the Pen Argyl Member and other members of the Martinsburg Formation were presented in Epstein and others (1974). The authors cited the low alumina to soda and silica to alumina ratios as indicative of an immature sedimentary suite when compared to a mature suite such as the Shawangunk Formation. This is also supported by the mineralogical and textural evidence cited in the preceeding discussion.

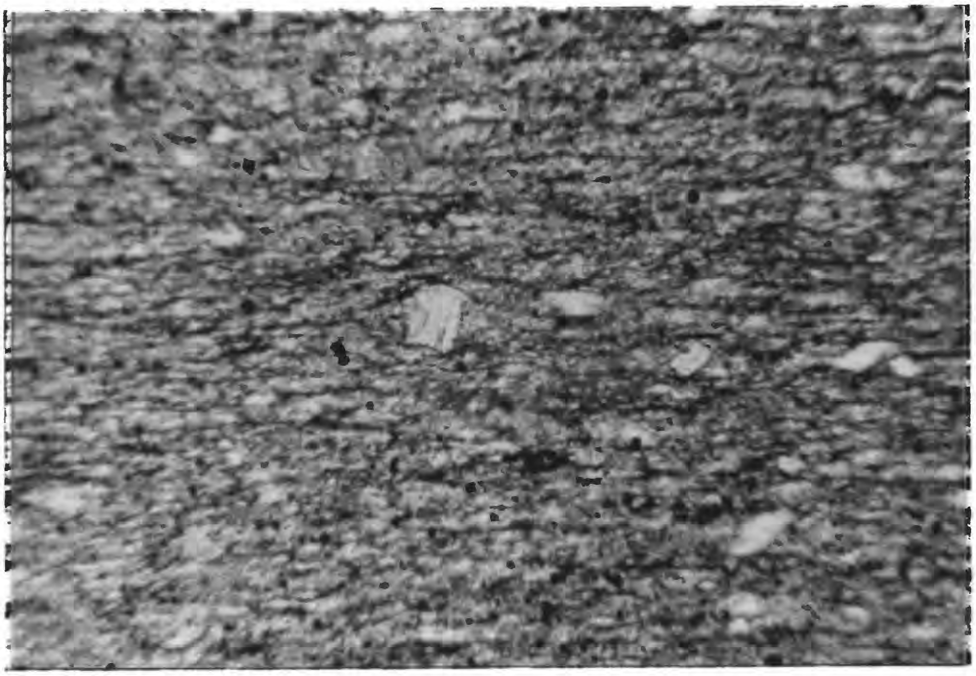


Figure 9: Photomicrograph of the claystone slate showing a porphyroblast of chlorite with quartz "eyes" or pressure shadow fillings. Truncated quartz grains are also present in this sample. Sample from the waste pile of the Big Franklin quarry, Slatedale quadrangle. Nicols uncrossed. Length of field-0.8 cm.

Typically but not always following the claystone-slate unit in an upward-fining sequence are grayish-black (N2) to black (N1) highly carbonaceous slates (figure 4). These are generally fine grained, graphite-rich, and less calcareous than the thick-bedded slates. Pyrite is also a very common mineral constituent of these rocks.

The approximate thickness of the Pen Argyl Member was determined in the New Ringgold, New Tripoli, and Slatedale quadrangles by the use of cross-sections. It should be noted that the values obtained are probably somewhat high as a result of tight folding. Thicknesses obtained in the Slatedale quadrangle range from 2,700 to 3,150 feet. These calculations are based on cross-sections drawn from the Slatedale quadrangle through the Lehighton quadrangle and are quite similar to thicknesses obtained by Epstein (Epstein and others, 1974) for the Palmerton quadrangle.

Study of Plate I and II indicates that the width of the outcrop belt of the Pen Argyl Member decreases to the west. There are several reasons that may account for this. One reason for the "thinning" of the slate belt is that an undetermined amount of the Pen Argyl Member may have been faulted out by the Eckville fault which, as will be discussed later, is a high angle reverse fault. A second reason is that an undetermined amount of slate may be covered by the Silurian rocks to the north. One other possibility is that the excessive thinning of the outcrop belt to the west is the result of extreme erosion prior to the deposition of the Silurian rocks. The absence of considerable Pen Argyl Member in the New Ringgold and New Tripoli quadrangles is probably the result of a combination of all of the factors mentioned above.

Behre (1933) maintained that his upper member was about 2,600 feet thick with a westward reduction to 0 in the Eckville area. Maximum thickness estimates in this study of 3,150 to 2,700 feet are somewhat higher than those of Behre although he estimated a thickness of 4,415 feet along the Little Bushkill in Northampton County. It should be noted that the thickness values obtained in all quadrangles may be somewhat lower than the actual values as an unknown thickness of the Pen Argyl Member may be covered by the Shawangunk Formation.

Age of the Martinsburg Formation:

As mentioned earlier, the contact between the Martinsburg Formation and the Jacksonburg Formation is conformable. Conodont studies by Barnett (1965) indicate that the Jacksonburg Formation can be correlated with the Richland, Kirkfield, and Shoreham Formations of New York. Conodont collections of J.B. Epstein, identified by J.W.

Huddle of the United States Geological Survey support Barnett's conclusions and indicate that the Jacksonburg Formation is no older than the Richland Formation which is upper Wildernessian (Cooper, 1954) or upper graptolite zone 12 of Berry (Berry, 1970). Thus the Martinsburg Formation appears to be as old as late Wildernessian to early Barnveldian (late zone 12 to early lower subzone of zone 13) (Epstein and Berry, 1971).

Berry and Epstein (1971) collected graptolites from the Pen Argyl Member from between 80 and 100 feet south of the contact of the Pen Argyl and Shawangunk Formation at Lehigh Water Gap. These fossils, indicative of upper subzone of zone 13 or late Edenian to early Maysvillian, have been used to place the upper age limits for the Martinsburg Formation.

Recent paleontological collecting by T. Wright and others (1978) in the area underlain by the Martinsburg Formation and Shochary Ridge sequence west of the Lehigh River has resulted in an interesting hypothesis. Basing their conclusions on detailed paleontological work they propose a bipartite subdivision of the Martinsburg much in the same way as Stose (1930). They report graptolites from the *Diplograptus multidens* to *Climacograptus spiniferus* zone of Riva within, what they believe to be, the Pen Argyl Member and Bushkill Member. Graptolites of the

Climacograptus spiniferus zone were reported from the Ramseyburg Member and Shochary sequence, thus indicating these rocks to be younger than both the Pen Argyl Member and the Bushkill Member. It is interesting to note that Aldrich (1967) reported fossils representative of the lower subzone of graptolite zone 13 in the Bushkill Member near Seemsville, Pennsylvania. This age is older than the age of the supposed Bushkill and Pen Argyl Members noted by Wright and others.

In addition to equating the Pen Argyl Member with the Bushkill Member, Wright and his co-workers stated that the rocks on Shochary Ridge are the Ramseyburg Member. The Ramseyburg Member and Shochary sequence are lithologically distinct. The Shochary sequence is highly fossiliferous, containing articulated crinoids, brachiopods, gastropods, and trilobites whereas the Ramseyburg contains only sparse fossil debris. The age of the Shochary sequence is given as late Middle Ordovician and is equivalent with the Sherman Falls Limestone of the Trenton Group of New York (Peter Lyttle, written communication, 1978). This age is based on diverse shelly fauna in the Shochary sequence.

The sedimentological differences between the Shochary sequence and the Ramseyburg Member are great and reflect completely different depositional environments. Whereas the Ramseyburg Member is a flysch deposit emplaced in deep water by turbidity currents the Shochary sequence consists of shallow water turbidites, probably prodeltaic sands. Channels within the Shochary sequence are filled with fossil debris and pyrite (Peter Lyttle, written communication, 1978) which help to differentiate it from the Ramseyburg Member. Movement along the Eckville fault has resulted in the juxtaposition of the Ramseyburg Member and the Shochary sequence.

Three localities along the railroad grade at Lehigh Gap yielded good graptolites. Graptolites were collected from 3 feet, 12 feet, and 60 feet beneath the contact of the Martinsburg Formation and the Shawangunk Formation. The fossils were collected from the Pen Argyl Member. The graptolites found within 15 feet of the contact are closer to the contact than any previous collection. Dr. W.B.N. Berry of the Department of Paleontology of the University of California identified the fossils. Graptolites in the upper two collections were identified as *Climacograptus spiniferus Ruedemann* and the graptolites from the lower collection were identified as *Climacograptus spiniferus Ruedemann*, *Diplograptus*, and possibly *dicranograptid*. Berry assigned an age of upper subzone of zone 13 (*Orthograptus truncatus intermedius* zone). He thinks that they may be coeval with the Cobourg Limestone of the Trenton Group and correlative with Eden-Lower Maysville.

An interesting observation made by Berry is that the presence of only Cimacograptus spiniferus in the upper two collections might suggest a shallowing upward sequence.

Thus from data collected in the study and other investigations it appears that the Pen Argyl Member is upper subzone of zone 13 (late Edenian to early Maysvillian) in age.

Metamorphism of the Martinsburg Formation:

Behre (1933) believed that the slate in the Martinsburg Formation was the result of metamorphic recrystallization. A very complete petrographic analysis is given by Behre in which he cites chlorite and sericite as the principal metamorphic minerals. Bates (1947) felt that the mica in the slate (Pen Argyl Member) was illitic and not sericitic but he thought that the illite was a metamorphic mineral. McBride (1962) stated that both a 2M muscovite polymorph and chlorite were present and that the slate had resulted from metamorphism. Maxwell (1962), on the other hand, maintained that the formation of the slaty cleavage was the result of dewatering and diagenesis and not metamoprhism. He went on to state the age of the cleavage as Taconian and not Alleghenian. Maxwell felt that illite was present in amounts greater than that of sericite or muscovite. Epsetin (1971) questioned this hypothesis and illustrated that although pore water pressure did play a role in the development of the slaty cleavage it was not as important as thought by Maxwell. Some of Epstein's arguements will be presented below. Samples of slate X-rayed by Epstein showed a great amount of the 2M muscovite polymorph and lesser amounts of the 1M polymorph. Yoder and Eugster (1955) showed that the 2M polymorph which Epstein called "sericite" is the stable form at the higher temperatures associated with metamorphism whereas the 1M polymorph, equated by Epstein to "illite", is stable under diagenetic conditions. It is important at this point to stress that the presence of the 2M polymorph does not prove metamorphism, although it may strongly suggest it. It may indicate a source rock rich in this polymorph.

Epstein reasoned that at the time of the Alleghenian event the top of the Martinsburg Formation was covered by about 24,000 feet of sediments ranging in age from Silurian to Pennsylvanian, therefore the lower part of the Martinsburg was covered by about 35,000 feet of sediments. If a geothermal gradient of $1^{o}/100$ feet (approximately 30^{o} per kilometer) is assumed, temperatures at the base of the Martinsburg Formation would have been approximately 350^{o} C., well within the limits of metamorphism. Epstein (1974) suggested that slaty cleavage development occurred at or just below greenschist facies metamorphism. He noted a great deal of evidence indicative of pressure solution. His evidence and evidence found in this study will be discussed in a latter section concerning the slaty cleavage.

SMALL SCALE STRUCTURES IN THE PEN ARGYL MEMBER:

Planar and linear elements are abundant in the Pen Argyl Member and are extremely useful in the determination of structure. Lineations include intersections of bedding and slaty cleavage, intersections of slaty cleavage and strain-slip cleavage, fold axes, and slickensides. Planar features include bedding, slaty cleavage, strain-slip cleavage, and grain.

Slickensides: Although easily recognized in pieces of waste rock bedding-plane slickensides are not commonly found in outcrops. Epstein and others (1974) noted a mean trend of N.67°W. for bedding-plane slickensides in the Martinsburg Formation in the Lehighton and Palmerton quadrangles. Slickensides become more abundant toward the Martinsburg-Shawangunk contact and are especially noticeable at Lehigh Gap (Epstein and Epstein, 1969). The slickensides indicate that the overriding beds moved to the northwest presumably due to movement along the Blue Mountain décollement.

Intersections of Slaty Cleavage and Bedding: The intersection of slaty cleavage and bedding was measured in the field where possible or calculated using the stereographic net. The lineation produced by this intersection is approximately parallel to and therefore represents the axes of the folds in which it occurs. This lineation, however, can only be considered as an approximation of the regional fold axis as the slaty cleavage commonly fans the folds. Despite this, slaty cleavage-bedding intersections do give a good representation of axial trends.

Figure 10 is an equal area projection of slaty cleavage-bedding intersections for the three quadrangles mapped in this investigation. The maximum for the area, 4° S.75°W., is quite similar to the maximum obtained from data to the northeast from the Lehighton and Palmerton quadrangles (Epstein and others, 1974) and the Stroudsburg quadrangle (Epstein, 1971). It is apparent from this data that the Pen Argyl Member in the Slatedale, New Tripoli, and New Ringgold quadrangles is characterized by a gentle westward plunge.

An interesting feature of the fabric diagram is that the lineations plot on a girdle. This girdle was interpreted by Epstein (Epstein and others, 1974) as an indication of rotation of the lineations to the south. The girdle is present in the fabric diagrams of the Lehighton and Palmerton quadrangles but, oddly enough, not present in the diagram for the Stroudsburg quadrangle (Epstein, 1971). To test the significance of these girdles, fabric diagrams showing lineations from points lying to the south of the concentration of points that

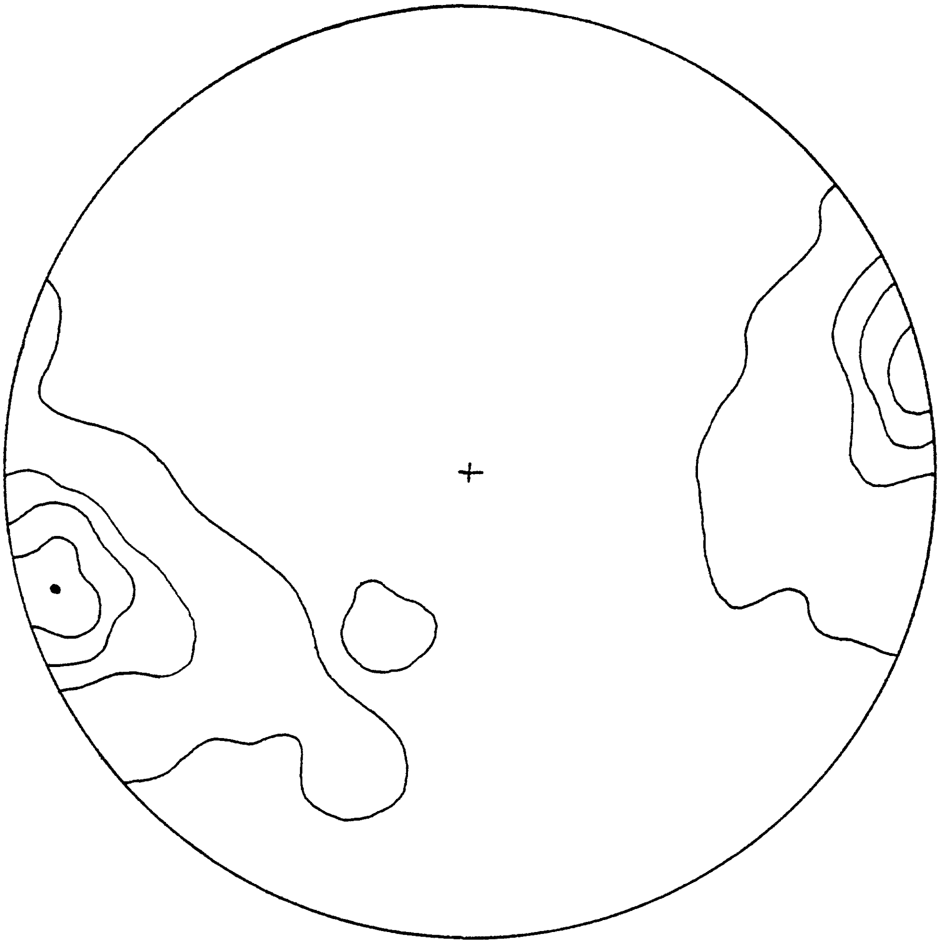


Figure 10: Equal area projection of slaty cleavage-bedding intersections in the New Tripoli, New Ringgold, and Slatedale quadrangles. Maximum-4° S.75°W; n-113; Contour interval-10%/1% area;

surround the maximum in figure 10 were constructed along with a pole diagram for the slaty cleavage associated with these lineations (figures 11 and 12, respectively). The diagrams show that whereas the intersections have been rotated to the south there has been no associated rotation of the slaty cleavage. Thus it appears that the cleavage formed during the later period of folding with the early generation folds plunging in a more southerly direction. Epstein (Epstein and others, 1974) arrived at these conclusions and proposed that the early folds formed during the Taconic orogeny and the later folds formed during the Alleghenian orogeny. He noted a similar girdle in plots of the Silurian and younger rocks but felt that this was due to a late Alleghenian event as the rotation was not as pronounced as in the Ordovician rocks. It is possible to argue that the girdles are the result of a single, prolonged event and not separate events. However, there should be some cleavage rotation if this were the case.

Intersections of Slaty Cleavage and Strain-Slip Cleavage: In areas within the Slatedale, New Tripoli, and New Ringgold quadrangles slaty cleavage has been crenulated. Strain-slip cleavage parallels the axial planes of the crenulations. The intersection of the slaty cleavage and the strain-slip cleavage serves as an approximation of the axes of the crenulations much in the same manner as the

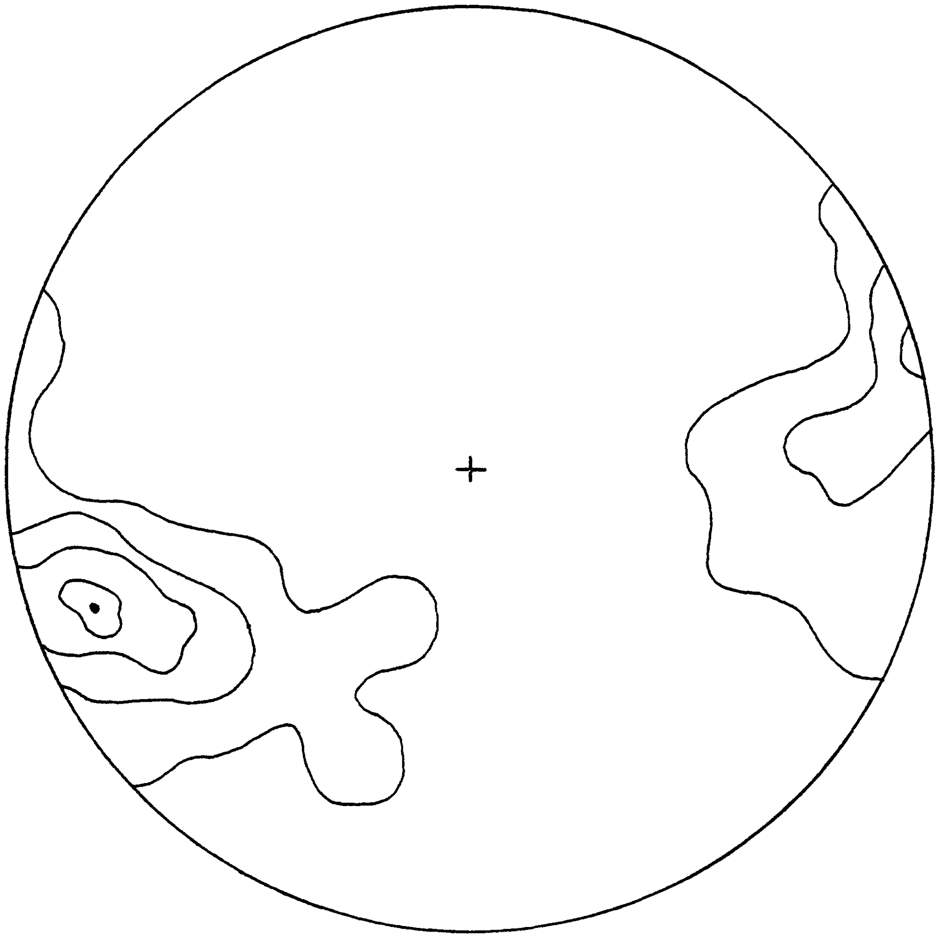


Figure 11: Equal area projection of slaty cleavage-bedding intersections in the New Tripoli, New Ringgold, and Slatedale quadrangles south of the maximum for figure 10. Maximum-9^{o} S.71^{o}W.; n-67; Contour interval-10%/1% area;

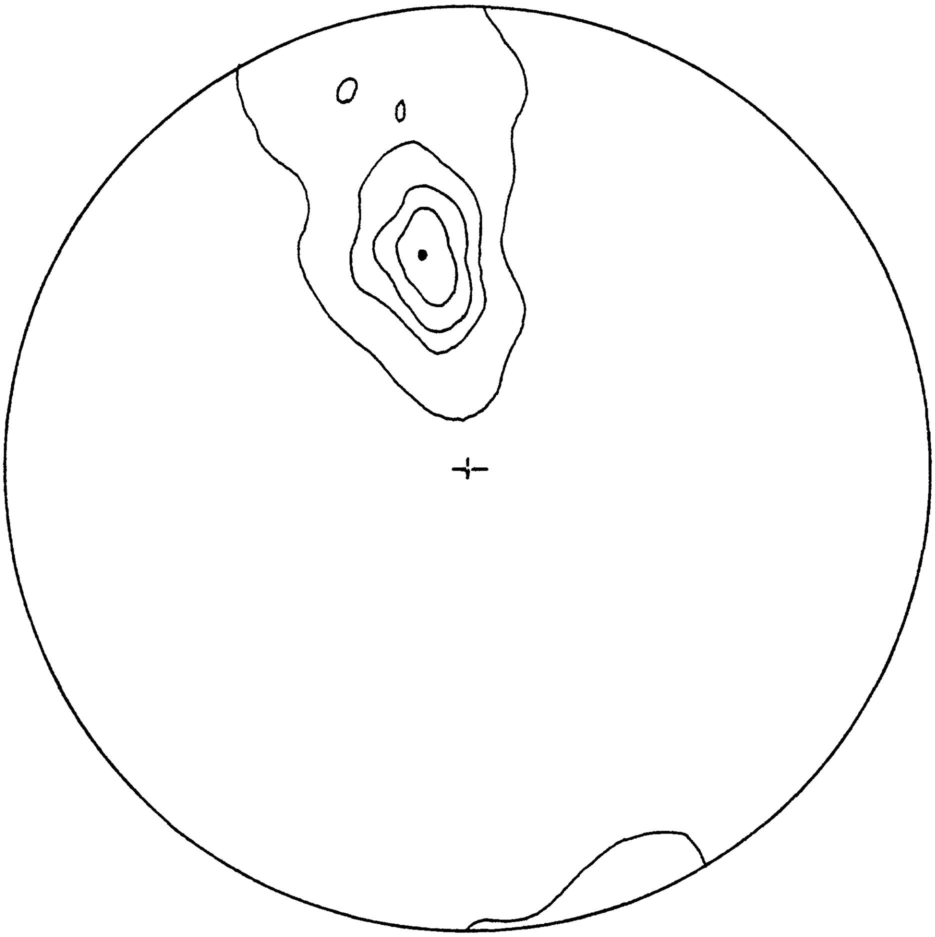


Figure 12: Equal area projection of poles to slaty cleavage associated with the slaty cleavage-bedding intersections of figure 11. Maximum-N.77°E.52°SE.; n-67; Contour interval-10%/1% area;

slaty cleavage-bedding intersections serve as an approximation of the fold axes.

Figure 13 is an equal area projection of slaty cleavage-strain-slip cleavage intersections for the entire map area. A maximum of 10° S.78°W. is indicated which is quite close to the maximum for the slaty cleavage-bedding intersection, 4° S.75°W. It would thus appear that the formation of the slaty cleavage and strain-slip cleavage was the result of a unidirectional force or close to it. In actuality this may not be the case as more detailed studies to be discussed later will show variations from quadrangle to quadrangle.

If the slaty cleavage was formed during the Alleghenian orogeny as suggested by Epstein (Epstein and others, 1974) the formation of the strain-slip cleavage may represent a secondary pulse after the main Alleghenian event, or the strain-slip cleavage may have formed in the same stress continuum and not as a separate pulse.

Bedding- Bedding was used to determine fold geometry. In general, the low angle southwest plunge of the fold axes as determined from the slaty cleavage-bedding intersections is substantiated by the slightly arcuate girdles of the bedding fabric diagrams.

Figures 14 and 15 are equal area projections of poles to normal and inverted bedding, respectively, for the

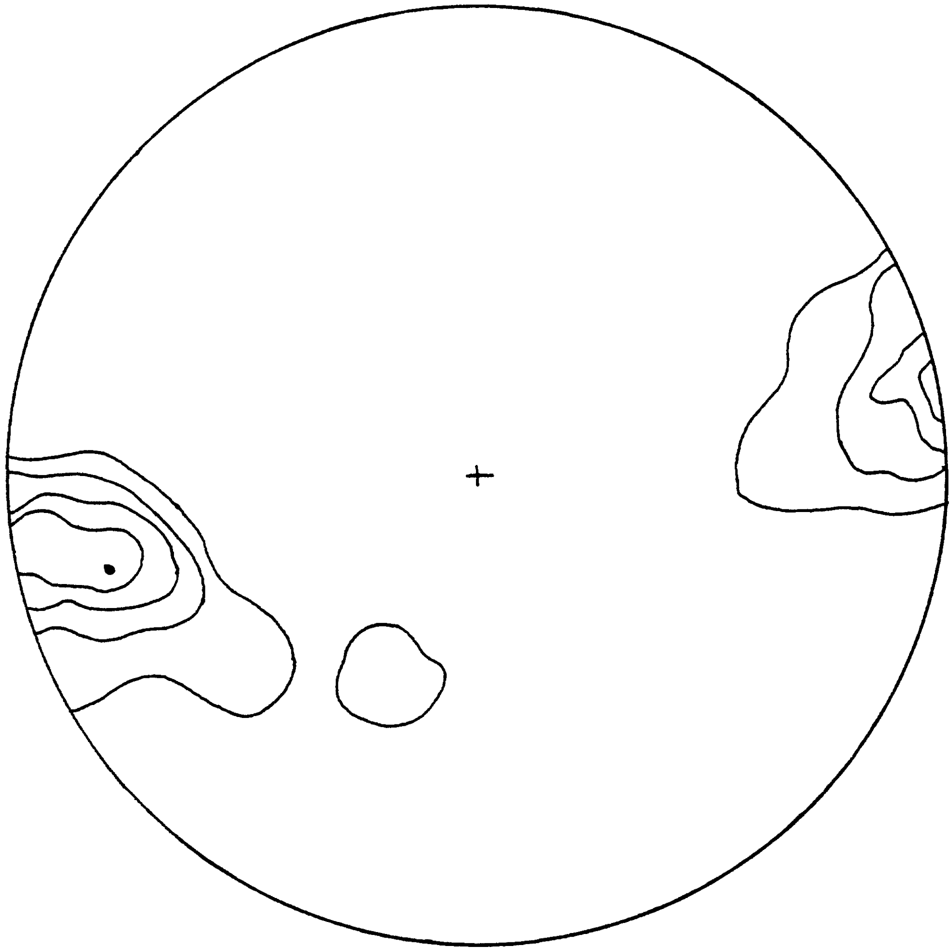


Figure 13: Equal area projection of slaty cleavage-strain-slip cleavage intersections in the New Tripoli, New Ringgold, and Slatedale quadrangles. Maximum-10° S.78°W.; n-17; Contour interval-11%/1% area;

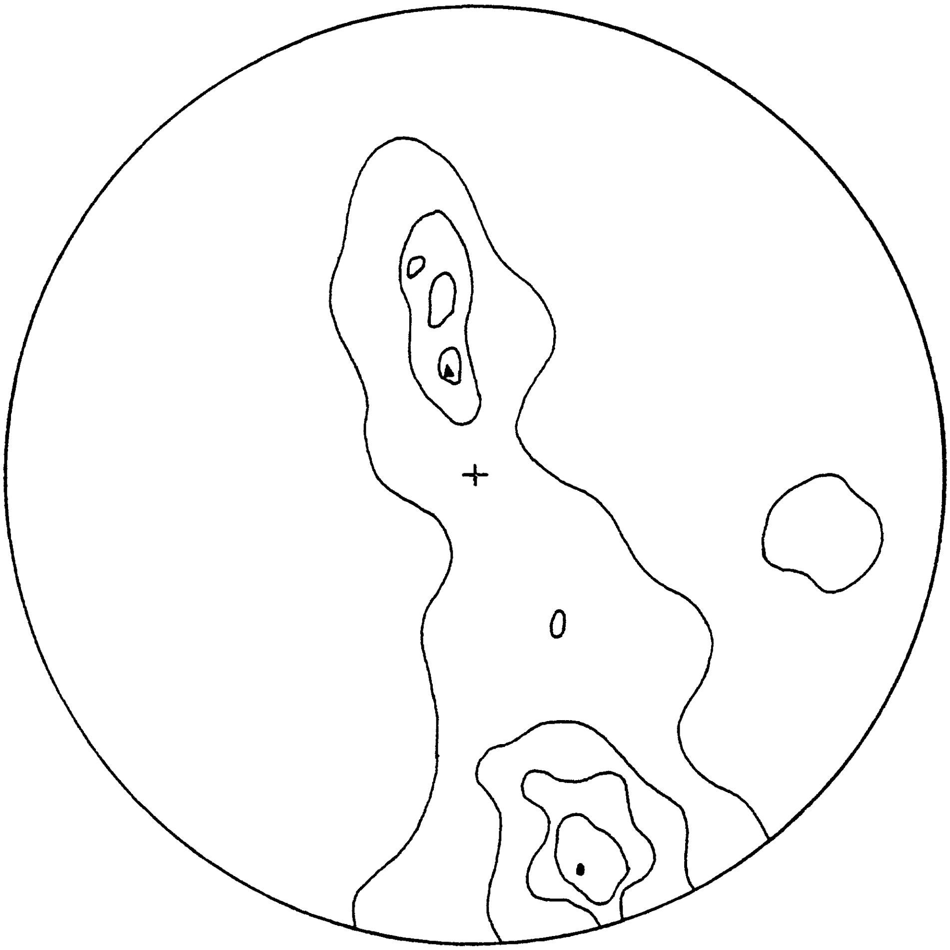


Figure 14: Equal area projection of poles to upright bedding in the New Tripoli, New Ringgold, and Slatedale quadrangles. Maximum-biased (dot)-N.75°E.89°SE., unbiased (triangle)-N.75°E.25°SE.; n-92; Contour interval-5%/1% area;

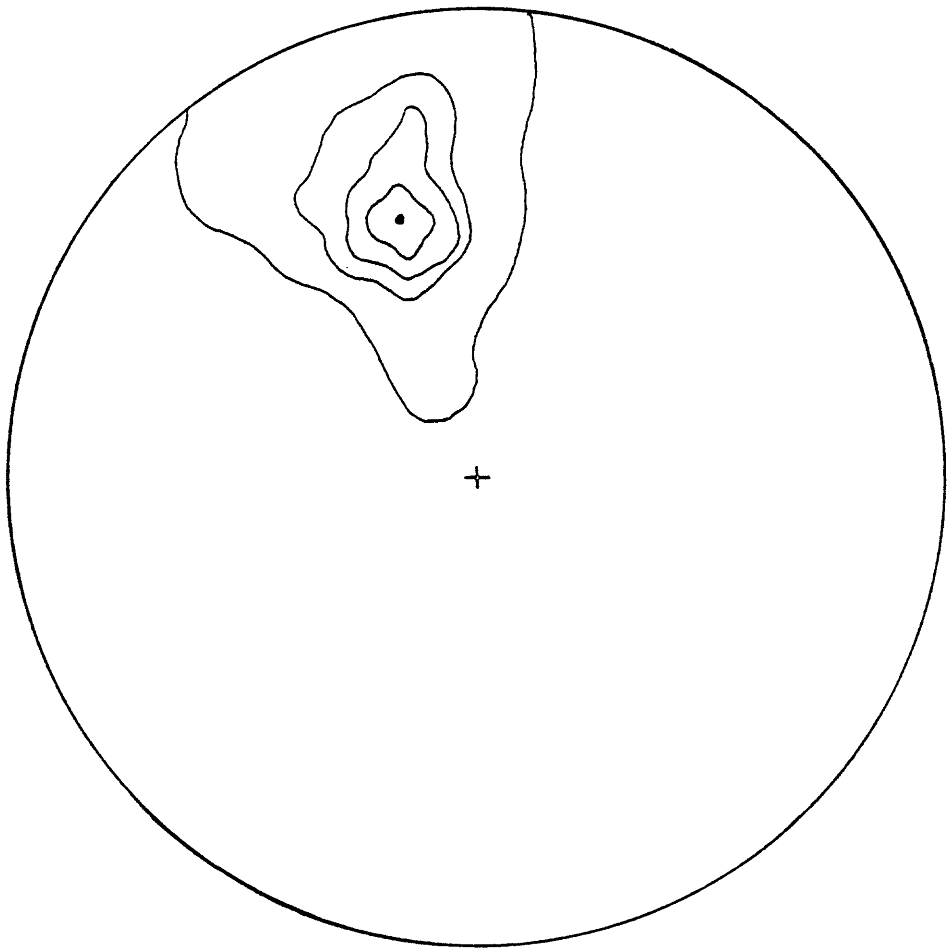


Figure 15: Equal area projection of poles to overturned bedding in the New Tripoli, New Ringgold, and Slatedale quadrangles. Maximum-N.72°E.61°SE.; n-34; Contour interval-10%/1% area;

entire map area. The maximum for the overturned beds is N.72°E.61°SE. and that for the unbiased normal limb (see discussion in Appendix A) is N.75°E.25°SE. By plotting the maxima on a great circle a dihedral opening angle of 37° was obtained. Thus folds within the slate belt may be generalized as close folds in the sense of Fleuty (1964). These types of calculations can be done only where the data are statistically meaningful.

Average attitudes of axial planes were calculated by plotting the great circle to a pole midway between the maximum for the upright and overturned limbs. A value of N.71°E.43°SE. was obtained and is fairly close to the cleavage maximum, N.77°E.50°SE. indicating that slaty cleavage is essentially axial planar.

The fact that the folds are not cylindrical is evident from the separate girdles for inverted and normal bedding and also from the lack or parallelism of slaty cleavage-bedding intersections within a single fold.

<u>Cleavage</u>- Cleavage is the dominant planar element in the Pen Argyl Member. In general three types of cleavage were noted: (1) a flow or slaty cleavage, (2) strain-slip cleavage, and (3) fracture cleavage. Slaty cleavage, as defined by Ramsay (1967), is a penetrative surface resulting from the preferred alignment of the phyllosilicates. The alignment is presumed to have formed

normal to the maximum finite compressive strain during deformation. Strain-slip cleavage, often referred to as fracture cleavage by other workers (Leith, 1905; Behre, 1933; King, 1956) forms by the transposition of an original S-plane, generally a cleavage plane. This may occur with or without neocrystallization. Fracture cleavage is a close spaced jointing in which the fracture surface is not determined by the preferred orientation of mineral grains.

The slaty cleavage is typified by folia of muscovite, chlorite, and quartz oriented parallel to each other and separated by thin layers or microlithons of unoriented crystals of quartz, micas, and calcite. Porphyroblastic mineral growth is common (figure 9). Crystals of chlorite and muscovite are commonly as large as ten times the size of the groundmass material.

The slaty cleavage is related to the folds in that it is subparallel to the axial planes of the folds and symmetrically fans the folds. The common type of cleavage fan in the Pen Argyl Member is the normal cleavage fan of Ramsay (1967). The normal cleavage fan is also called a convergent cleavage fan and is characterized by a downward convergence of the slaty cleavage from the axial surface of an anticline. Cleavage fanning is quite common on an outcrop scale in the Pen Argyl Member (figure 24).

Refracted slaty cleavage is common in sequences of varying composition (figure 16). It is generally steeper in the more competent units such as graywacke as opposed to the less competent claystone slate. In a transitional sequence the cleavage refraction is produced by variations in the strained state of each of the different rock types. Cleavage refraction is also evident in thin section. Figure 17, a photomicrograph of a graywacke-claystone slate contact in the Pen Argyl Member, shows a sudden directional change of cleavage folia upon entering the graywacke. The change in direction of the folia is the result of cleavage refraction upon entering the graywacke.

Strain-slip cleavage is characterized by the mechanical rotation of a previous S-plane, usually a previous cleavage plane resulting in a crenulation of the early S-plane (figures 18 and 19). The formation of strain-slip cleavage results from a stress couple acting parallel to the early S-plane, slaty cleavage in the case of the Pen Argyl Member. With continued stress the phyllosilicates are transposed resulting in an asymmetric crenulation of the initial S-plane. As stress continues the shorter limbs of the crenulations become so stretched that they become planes of weakness with small thrusts occurring along them. These planes, the strain-slip planes, are essentially axial planar to the crenulations.

Figure 16: Cleavage refraction in a sample from the Blue Mountain quarry. Beds dip to the left and slaty cleavage dips to the right. Note the compass in the center of the photograph for size comparison. Slatedale quadrangle.

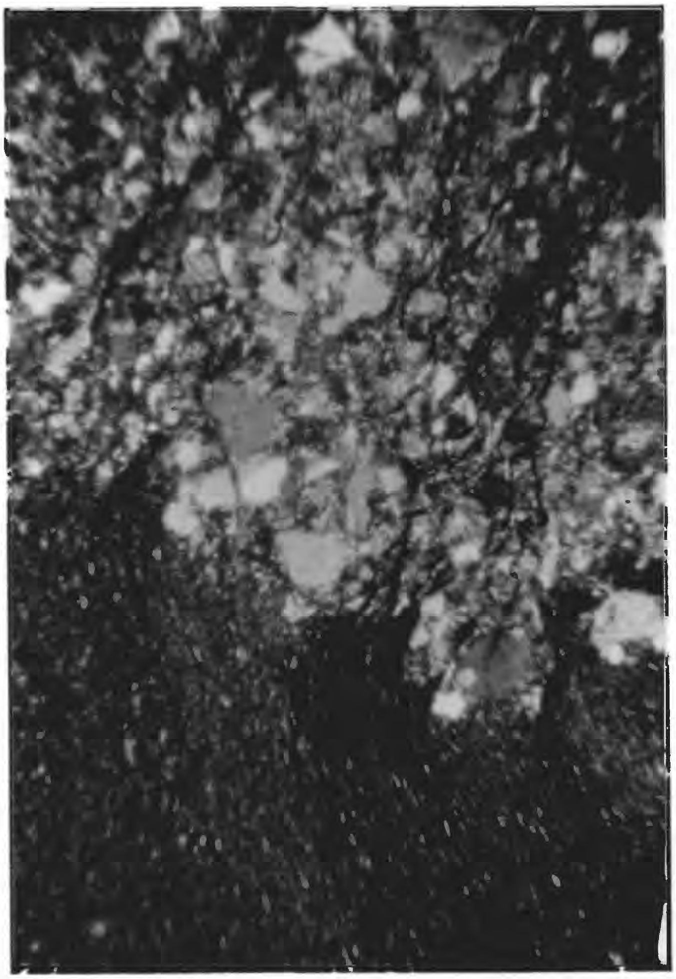


Figure 17: Photomicrograph of a graywacke-claystone slate contact. Note the refraction of the cleavage folia in passing from the graywacke into the slate. Sample from the waste pile associated with the Big Franklin quarry, Slatedale quadrangle. Nicols crossed. Length of field-0.8 cm.

Figure 18: Crenulated slaty cleavage planes. The sample is from waste pile of the Ellis Owen quarry. Slatedale quadrangle.

Figure 19: Slaty cleavage is horizontal and strain-slip cleavage is approximately vertical. Note how the slaty cleavage has been warped. The sample is from the waste pile of the Ellis Owen quarry. Slatedale quadrangle.

Thus the original foliation has been transposed into a new, more spaced foliation.

Regionally, strain-slip cleavage development increases in intensity to the southeast, a fact noted by Behre (1933) and Epstein (1971). In New Jersey the development of strain-slip cleavage has been so intense that it has obliterated the earlier slaty cleavage resulting in a second "slaty" cleavage. Thus it appears that if the forces producing the strain-slip cleavage are allowed to proceed to completion a second penetrative cleavage may form as suggested by Broughton (1946).

Fracture cleavage is commonly well developed in the massive graywacke beds. This cleavage is closely spaced jointing in which there is little or no mineral alignment. Fracture cleavage is formed as a result of a stress couple and is generally inclined to the greatest principal stress at an angle of about 30° (Billings, 1956).

The formation of the slaty cleavage in the Martinsburg Formation of eastern Pennsylvania has been the subject of geological debate for at least 50 years. Behre (1933) believed that the rocks were consolidated prior to deformation. This is contrary to the ideas of Maxwell (1962) who maintained that the slaty cleavage at the Delaware Water Gap area was the result of mechanical rotation of the clay minerals during soft sediment deformation. This deformation, he further stated, was aided by high pore water pressure and not metamorphism. Field evidence for this theory consists of several clastic dikes sub-parallel to the penetrative slaty cleavage at the Delaware Water Gap. Carson (1968), working in the Port Jervis south area of northern New Jersey, lent support to Maxwell's theory of slaty cleavage formation. He related the progressively well developed slaty cleavage to increasing overburden and the resultant higher water pressures.

J.B. Epstein (Epstein and Epstein, 1974; others, 1971) and A.G. Epstein (Epstein and Epstein, 1969) have rejected the soft sediment theory in detailed arguments. They have argued that although dewatering may have initiated slaty cleavage formation the cleavage formed mainly by a combination of mechanical reorientation, pressure solution, and neocrystallization under metamorphic conditions and after the rock was indurated.

Alterman (1973) restated the beliefs of Maxwell in support of soft-sediment deformation. She based her interpretations on microstructures in the Pen Argyl Member between the Lehigh and Delaware Rivers. Her arguments were essentially those of Maxwell and were subject to the same pro-metamorphism arguments leveled against Maxwell.

Holeywell and Tullis (1975) working in the Lehigh Gap area questioned the conclusions of all previous workers who have argued for mechanical rotation whether during soft-sediment deformation or during metamorphism. They suggested that the preferred orientation of the micas associated with the slaty cleavage may be the result of a solution and neocrystallization process that is not well understood at this time. Their work showed that only a minimum amount of mechanical reorientation may have taken place in the formation of the slaty cleavage. The reader is referred to this paper for a more detailed discussion of this important contribution.

Recent work of Groshong (1976) suggests that pressure solution may have been an important factor in the development of the slaty cleavage in the Martinsburg Formation. He cited the truncation of quartz grains against cleavage folia and pressure shadows around porphyroblasts as evidence for pressure solution and the mobility of quartz. Groshong maintained that the cleavage laminae are made up of low mobility constituents. The sandstone dikes of Alterman (1973) and Maxwell (1962) were interpreted as precleavage, soft-sediment deformational structures associated with dewatering and mechanically rotated into their present position.

Beutner and others (1977), working in the Bushkill Member, used pre-cleavage calcite veins to show that slaty cleavage formation in the Martinsburg Formation had occurred in lithified sediments and was not related to dewatering. Beutner, in a recent paper (Beutner, 1978) soundly discounted the dewatering hypothesis for the development of the slaty cleavage. He noted breccia fragments of uncleaved Martinsburg pelite "floating" in a pre-cleavage vein filled with calcite.

Figures 20 and 21 are equal area projections of poles to slaty cleavage in the Pen Argyl Member in the Slatedale, New Tripoli, and New Ringgold quadrangles and for the Mahantango Formation in the Palmerton quadrangle (data from Epstein and Epstein, 1969), respectively. The differences in trend are almost negligible. The inference here is that the tectonic forces that produced the Devonian and Ordovician cleavages are essentially the same, Alleghenian.

The fact that the beds were lithified at the time of slaty cleavage formation is evident from the numerous bedding-plane slickensides disrupted by slaty cleavage (see figure 26). This is especially well documented in the Manhattan quarry in the Slatedale quadrangle.

In this report the metamorphic (lower greenschist facies)-pressure solution theory for the origin of the slaty cleavage is proposed. Dewatering, although admittedly it may have played a role in the initiation of the slaty cleavage, has not played the role assigned it by the proponents of soft-sediment deformation. Evidence for pressure solution is present throughout the thin sections that were studied. Examples of truncated quartz grains

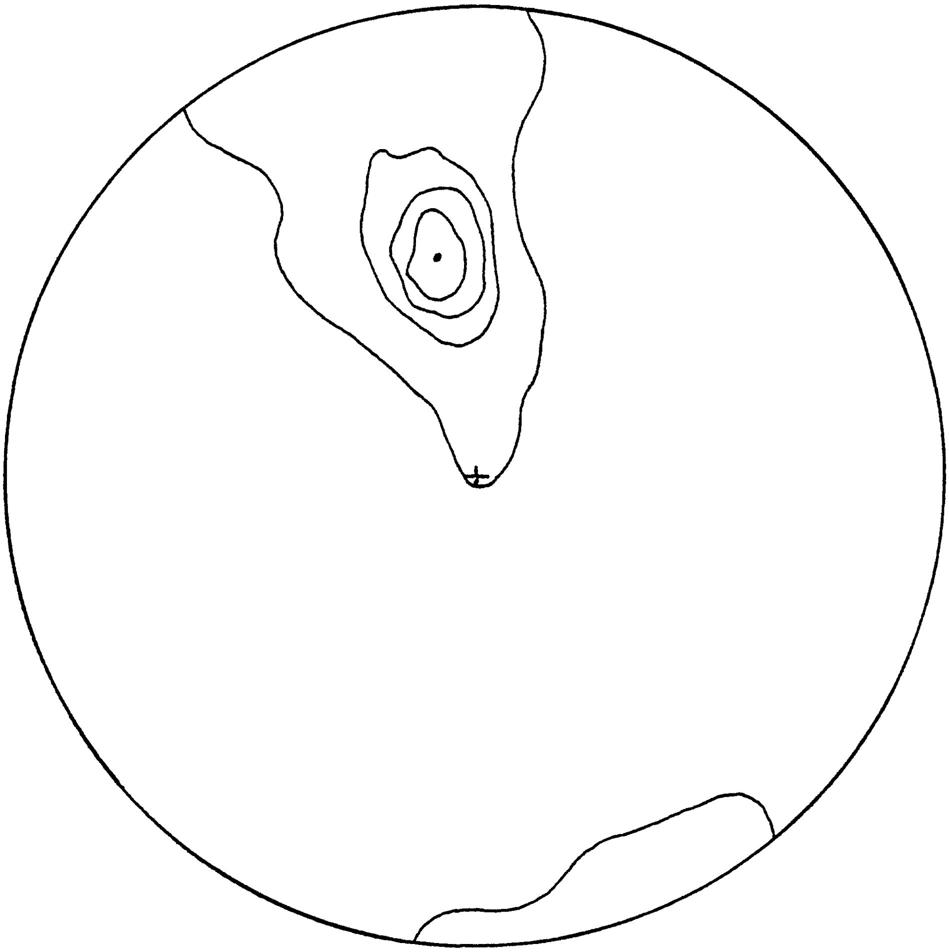


Figure 20: Equal area projection of poles to slaty cleavage in the New Tripoli, New Ringgold, and Slatedale quadrangles. Maximum-N.77°E.50°SE.; n-163; Contour interval-10%/1% area;

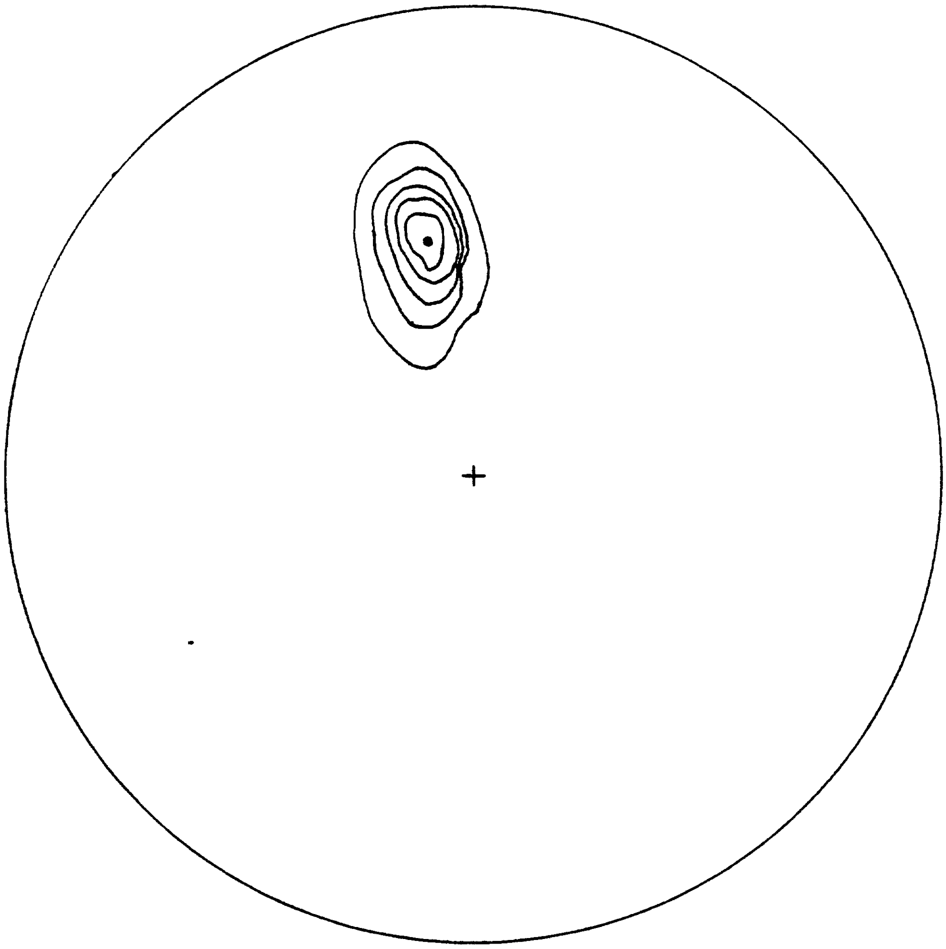


Figure 21: Equal area projection of poles to slaty cleavage in the Mahantango Formation (Devonian) of the Palmerton quadrangle (from Epstein and Epstein, 1969). Maximum-N.79°E.42°SE.; Contour interval-9%/1% area;

and pressure shadows filled with quartz and phyllosilicates are quite common. The movement of the silt "tongues" of Alterman (1973) may have been facilitated by the movement of the quartz and connate water squeezed out of the rock. It is also possible that the water released from the metamorphism of the hydrous minerals may have aided in the formation of the silt tongues.

Grain: Behre (1933) described grain as a "second direction of ready fracture far less marked than that of the (slaty) cleavage." He indicated that although the grain planes were not often sharply defined they were consistent and marked a definite structural feature of the slate. Behre, along with numerous other workers (Sharpe, 1849; Leith, 1905; Dale, 1914) believed that grain in slate was determined by the parallelism of minerals such as rutile and quartz, much in the same way that slaty cleavage is the result of the parallel orientation of the phyllosilicates. Thus in a diagrammatic representation of slate structure (figure 22) the plane a-b is defined as the slaty cleavage plane and the a direction or the direction of tectonic transport can also be referred to as the grain direction.

Grain was measured in numerous quarries along the slate belt during the course of the field work. Measurements were averaged as the grain surfaces are commonly undulose and not well defined. Grain is easily

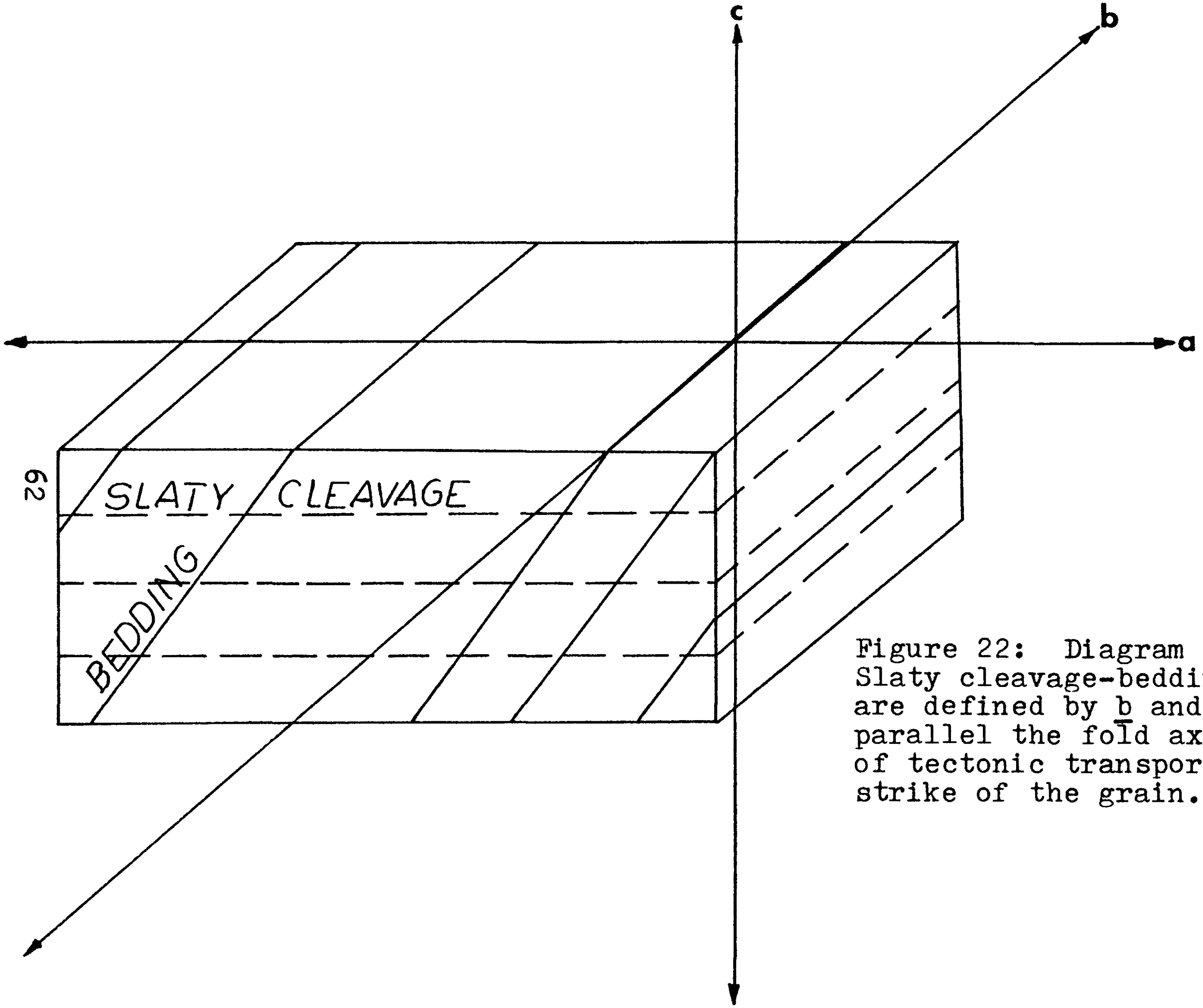


Figure 22: Diagram of slate structure. Slaty cleavage-bedding intersections are defined by b and are assumed to parallel the fold axis. The direction of tectonic transport is a which is strike of the grain.

differentiated from strain-slip cleavage by differences in trend. It differs from jointing by its ill-defined surfaces. Despite obvious problems in measurements, 28 grain attitudes were obtained. A pole diagram showing these measurements along with the average trend of the slaty cleavage in the three-quadrangle area can be seen in figure 23. Several observations can be made upon inspection of this diagram; (1) it is quite evident that the grain is very steep, in fact no grain planes dipped less than 73°; (2) it can be seen that the average trend of the slaty cleavage (N.77°E.), is not perpendicular to the trend of the grain (N.26°W.). This variation from a perpendicular relationship may not be significant in thatthe given planes are quite undulose and consequently relations between the two trends depends on the actual point of measurements on the grain planes. Pole figure goniometer studies of elongated quartz in oriented thin sections of the slates would be useful in solving this problem in that the role of quartz in grain development would be better understood.

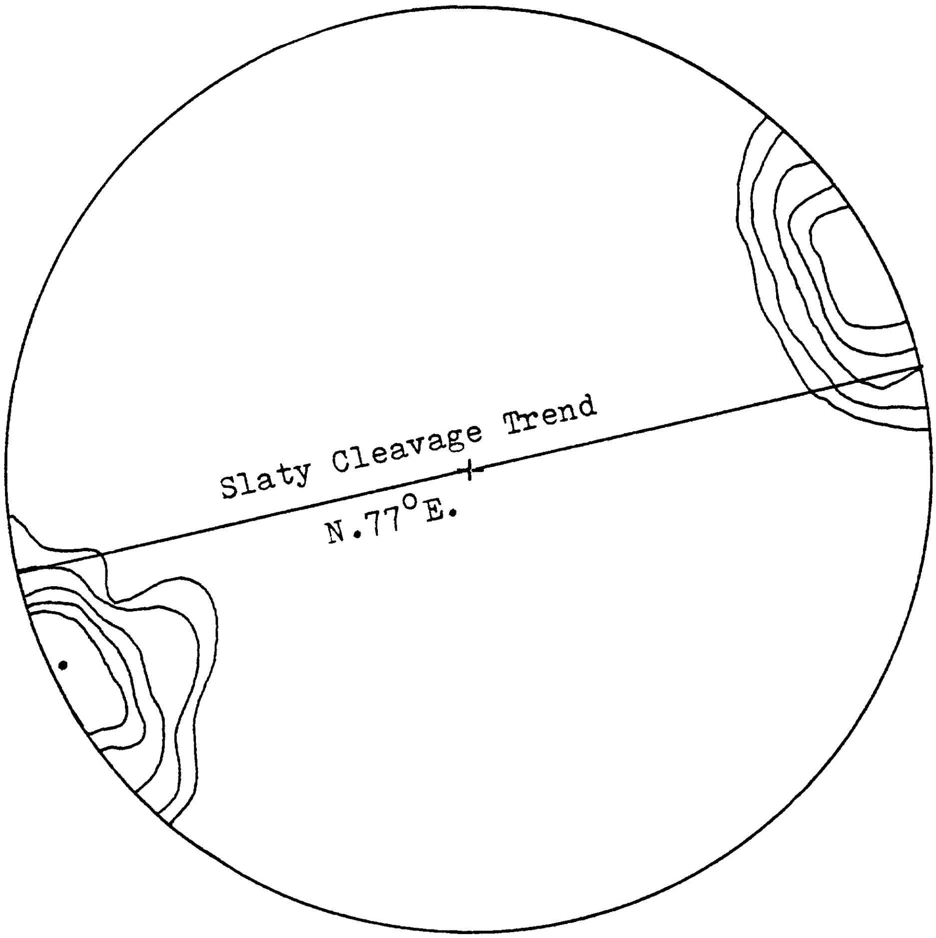


Figure 23: Equal area projection of poles to grain planes in the New Tripoli, New Ringgold, and Slatedale quadrangles. Maximum strike of grain-N.26°W.; n-28; Contour interval-0%, 5%, 15%, 25%, 35%;

FOLDING IN THE PEN ARGYL MEMBER:

Folds in the Pen Argyl Member range from crenulations of the slaty cleavage to folds that effect the entire outcrop pattern such as the Mosserville anticline (see Plate II).

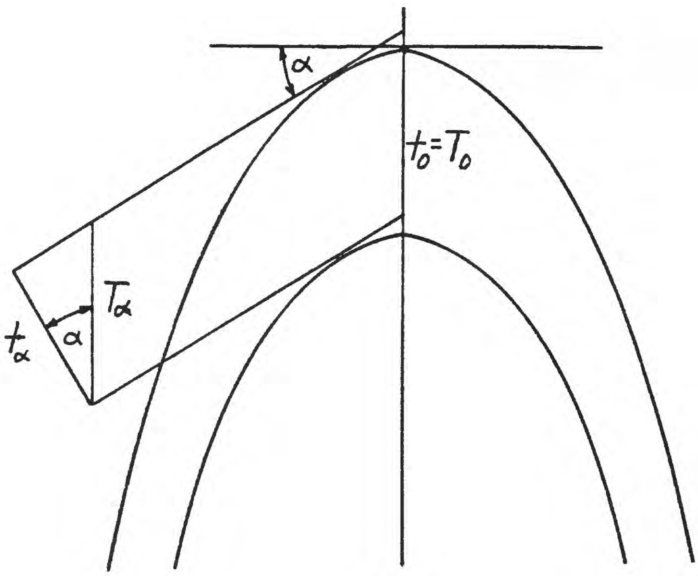
Previously it was noted that plots of slaty cleavage-bedding intersections showed girdles indicating rotation of the lineations (see figure 10). From fabric studies it was concluded that the lineations lying to the south of the maximum along the girdle were the result of an early period of folding or warping of the nappe limbs, lacking slaty cleavage. These folds, to be referred to as F_2 folds (F_1 is the nappe) are hard to recognize in the field and are best distinguished by detailed fabric work. The F_2 folds refolded the F_1 fold or the Musconetcong nappe. The F_2 folds show a more southerly trend than the F_3 folds to be discussed below.

The F_3 folds, the common type of folds present in the Pen Argyl Member, are asymmetric and are generally characterized by thickened crests and limbs. The folds are generally closed (average dihedral opening angle of 37°) to isoclinal in which case bedding and slaty cleavage are parallel on the limbs.

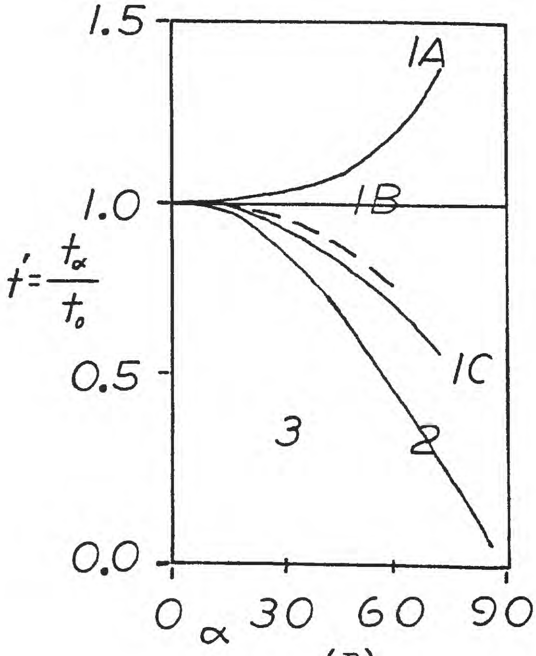
Dip isogon studies (Ramsay, 1967) of the F_3 anticline exposed in the Manhattan quarry (figure 24) in the Slatedale quadrangle (Plate III) indicate that it is a Class 1C fold (figure 25) in the classification of Ramsay. Ramsay states that these folds commonly result from flattening of Class 1B buckle folds. Evidence of buckling prior to the development of the slaty cleavage is quite common in this quarry. Bedding plane slickensides offset by the slaty cleavage (figure 26) are indicative of flexural slip folding or buckling followed by flattening and movement along the slaty cleavage planes. Small sigmoidal tension gashes indicative of shearing or tangential longitudinal strain in a buckled sequence were also noted (figure 27). Thus a two part history of this fold is indicated: (1) early buckling resulting in Class 1B folds followed by (2) flattening of the 1B fold to form Class 1C folds typified by thickening of the crestal areas and thinning of the limbs accompanied by passive slip movement along the slaty cleavage planes. It is apparent that the initial folding occurred in an indurated sequence of sediments.

The folds described above are commonly fanned by the slaty cleavage which is subparallel to the axial planes of the folds. The plunge of the fold axes as determined by slaty cleavage-bedding intersections is 4° S.75°W. As mentioned earlier an average axial plane for these folds was calculated using bedding plane data and is quite similar to the slaty cleavage maximum indicating that the

Figure 24: East wall of the Manhattan quarry located about 1,000 feet north of Slatedale. Cleavage fanning of the axial plane is quite apparent from this view. Note the displacement along the fault on the south limb of the fold. Slatedale quadrangle.



(A)



(B)

Figure 25: Fold classification based on the work of Ramsay (1967). Part A shows the method of study of the fold. Part B shows the data obtained (dashed line) from the study of an overturned anticline exposed in the Manhattan quarry. The fold is clearly a Class 1C fold. Refer to text for explanation.

Figure 26: Slickenside zone along bedding planes in the Manhattan quarry. The slickensides have been wrinkled as a result of movement along the slaty cleavage planes. Slatedale quadrangle.

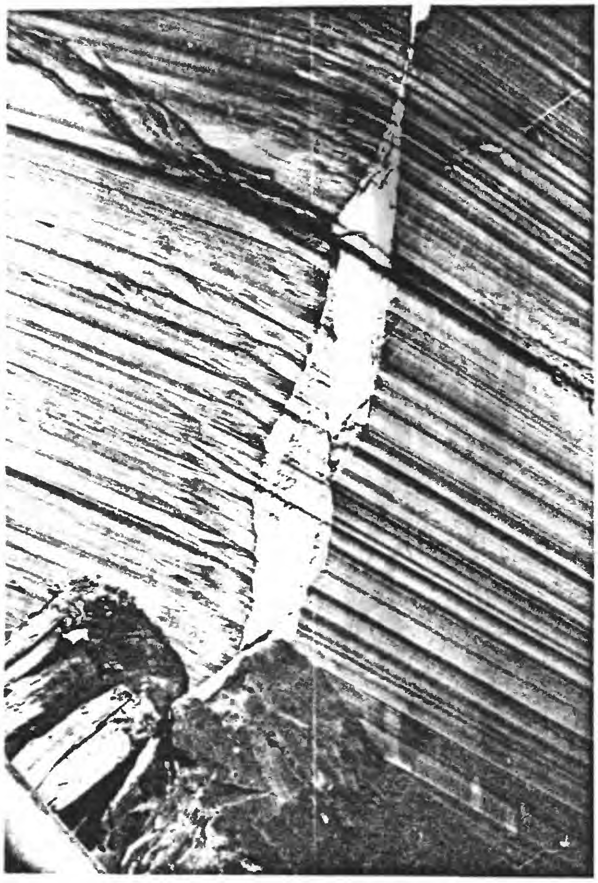


Figure 27: Small, sigmoidal tension gashes at the contact of two beds indicative of flexural slip folding. Manhattan quarry, Slatedale quadrangle.

slaty cleavage is axial planar to the folds.

The slaty cleavage has been wrinkled into small crenulations on a regional scale and these crenulations will be referred to as F_4 folds. These small folds are typically asymmetric and illustrate the sense of rotation. As mentioned earlier, the intersection of the slaty cleavage and the strain-slip cleavage approximates the axes of the crenulations. It was also shown that the slaty cleavage-strain-slip cleavage and slaty cleavage-bedding intersections are essentially parallel thus indicating that the two lineations formed in close succession, probably within the same stress continuum. Thus F_3 and F_4 were formed in close succession without any major interruptions in their development.

The Mosserville anticline in the New Tripoli quadrangle is the largest fold within the Pen Argyl Member west of the Lehigh River. It is proposed that this fold formed somewhat later than the F_3 asymmetric folds and associated axial planar cleavage and the F_4 crenulations. Thus the Mosserville anticline is an F_5 fold. Reasons for this relative age assignment will be discussed in a latter section. The anticline is actually an "anticlinorum" as numerous smaller asymmetric folds have formed on it. As shown by the geological map of the New Tripoli quadrangle (Plate II) the fold plunges to the southwest and deflects the outcrop pattern of the Pen Argyl Member. In a recent paper (Wright and others, 1978) the existence of the anticline was challanged and an eastward plunging syncline was proposed in its place. This infers that the Pen Argyl Member is overlain by the Ramseyburg Member. This view is incorrect as detailed field work shows that this fold is indeed a westward plunging anticline exposing the Ramseyburg Member in the core.

Kink folds are quite common in the three-quadrangle area. They are apparently related to movement along the Eckville fault, a late feature that will be discussed in detail later. Evidence for this can be found in the abundance of kink folding in exposures just north of the fault in the New Tripoli and New Ringgold quadrangles and the almost total lack of them in the Pen Argyl Member of the Slatedale quadrangle. Movement along the Eckville fault has apparently transposed the slaty cleavage planes resulting in the kink folds. Figures 28 and 29 illustrate the typical kink folding in the Pen Argyl Member. This type of fold results from the mechanical reorientation and transposition of an earlier S-plane which in this case is the slaty cleavage. Figure 30 is a photomicrograph of a kink fold from an area typified by well developed kink folding in tie New Tripoli quadrangle. As kink folds are the last folds to form and are related to late faulting they have been designated as F_6 folds.

Table 1 shows a suggested fold history of the Pen

Figure 28: Complex kink folding in a sample from quarry $\underline{d}$ of the Mosserville quarries. The sample is from the adjacent waste piles. New Tripoli quadrangle.

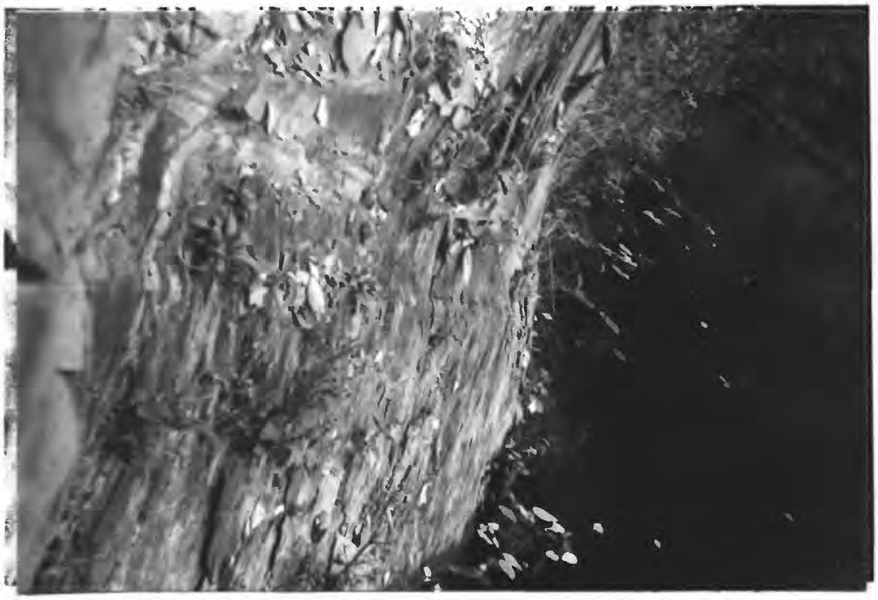


Figure 29: Down plunge view of kink folding of slaty cleavage in the north wall of the Daniels quarry. The slaty cleavage dips south. The rotation sense of the kink fold is counterclockwise. New Tripoli quadrangle.

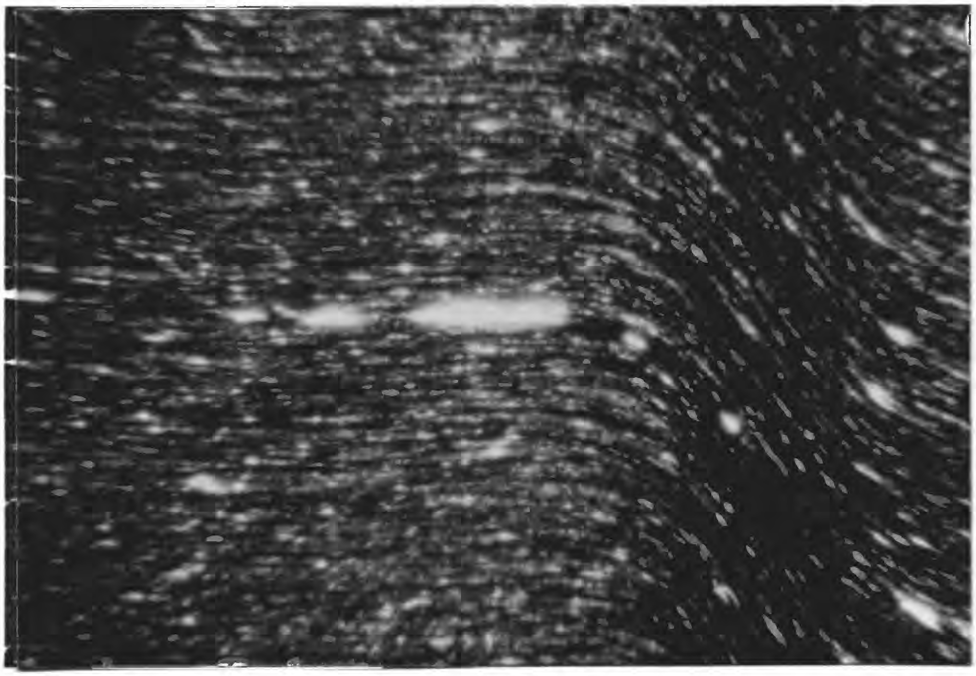


Figure 30: Photomicrograph of a kink fold of the slaty cleavage planes illustrating the mechanical rotation and reorientation of the phyllosilicates. Sample from an outcrop in the New Tripoli quadrangle. Nicols uncrossed. Length of field-0.8 cm.

Argyl Member based on field observations. Exact ages for the different fold events have not been included on the table as they will be discussed later. The earliest folding is the large scale nappe folding, F_1. Refolding of the normal limb of the nappe occurred sometime after its emplacement. These folds termed F_2 folds, formed without the development of an axial planar slaty cleavage and are recognized by fabric studies only. The F_2 folds show a more southerly trend than the F_3 folds to be discussed now. The asymmetric F_3 folds are the common folds in the slate belt. The formation of the penetrative slaty cleavage was essentially concomitant with the F_3 folding. Small crenulations formed as a result of a strain couple along the slaty cleavage. The crenulations or micro-folds are referred to as F_4 folds and probably formed as part of the same stress continuum that formed the F_3 folds. F_5 folds are represented by the Mosserville anticline. The Mosserville anticline formed after the development of the slaty cleavage and the F_3 and F_4 folds. The last folds to form were those types of folds related to movement along late faults (Eckville fault). These F_6 folds are typified by crenulations and kink folds.

Table 1

DESCRIPTION OF FOLD EVENTS IN THE PEN ARGYL MEMBER

Fold Event	Description
F_1	Development of the Musconetcong nappe. The Pen Argyl Member of this report is located on the brow and normal limb of the nappe.
F_2	Open folding of the normal limb of the nappe. No slaty cleavage development. Approximate trend of these folds-S.65°-70°W.
F_3	Asymmetric, isoclinal to closed folds superimposed on the F_2 folds. Folding initially developed by buckling with resultant parallel folds. This was followed by flattening and the formation of similar folds. The trend of these folds based on slaty cleavage-bedding intersections-S.74°-76°W.
F_4	Crenulations of the slaty cleavage. Strain-slip cleavage formed within the same stress continuum that formed the F_3 folds and resulted from a stress couple operating parallel to slaty cleavage planes. Axial trend of the crenulations-S.78°W.
F_5	Mosserville anticline-large open fold formed somewhat after the F_3 and F_4 folds but prior to movement along the Eckville fault.
F_6	Kink folds and crenulations related to movement along the Eckville fault.

HANSEN FOLD CLASSIFICATION:

Hansen (1971) detailed 12 properties of mesoscopic folds. They are listed below and some have been used in study of the folds in the Pen Argyl Member. The 12 properties of folds do not really represent a true classification but are more a means of describing folds. The properties or elements are listed below:

(1) type of geometry (ie., similar versus parallel),

(2) nature of the hinge and limbs (ie., broad versus sharp),

(3) ratio of short-limb height to width,

(4) ratio of depth to width,

(5) length and character of the hinge line,

(6) cylindricity,

(7) relation to cleavage,

(8) relation to mineral lineations,

(9) mean and standard deviation of ratios of short limb height to width,

(note: properties 9 through 12 involve groups of folds and not the individual fold)

(10) mean of ratio of depth to width,

(11) preferred orientation of fold axes,

(12) asymmetry (counterclockwise versus clockwise rotation in a down plunge view).

Of the 12 properties listed numbers 1, 2, 5, 6, 7, 8, 11, and 12 can be applied to the folding in the Pen Argyl Member. On the basis of these properties, folds in the Pen Argyl Member west of the Lehigh River can be characterized as shown in Table 2.

The method of Hansen is unique in that it employs not only the fold geometry but also the numerous structures involved with the folding. It was for this reason that classification scheme was presented.

Table 2

PROPERTIES OF F_3 FOLDS IN THE PEN ARGYL MEMBER

Properties of Individual Folds	F_3 Folds
1) type of geometry	generally similar
2) nature of hinge and limbs	small to moderate curvature of hinge with curved limbs
5) length and character of hinge line	no definate data but extrapolation indicates that they are long (ie., not contained within the outcrop) and somewhat undulose
6) cylindricity	the lack of parallelism of slaty cleavage-bedding intersections within a fold indicates that the folds are not cylindrical
7) relation to cleavage	well developed slaty cleavage is essentially axial planar to folds
8) relation to mineral lineation	elongated quartz indicates the direction of tectonic transport which is approximately perpendicular to the fold axes
Properties of Groups of Folds	
11) preferred orientation of fold axes	southwest plunging preferred orientation
12) asymmetry	all folds, with a few exceptions, are asymmetric. The regional sense of rotation for the F_3 folds in a downplunge view is clockwise

FAULTING IN THE PEN ARGYL MEMBER:

In his study of the slate belt in central eastern Pennsylvania Behre (1933) described six types of faults that he recognized in the field. His classification is fairly sound and will be used here to describe the faults in the Pen Argyl Member west of the Lehigh River. This classification is given below:

(1) faults of large displacement such as thrust faults,
(2) smaller faults of moderate slip and inclined to fold axes (small thrust faults),
(3) bedding-slip faults,
(4) small faults in calcareous beds,
(5) movement along bedding planes (Behre felt that these were not true faults),
(6) movement along slaty cleavage (Behre felt that these were not true faults).

All these faults except type 4 were found west of the Lehigh River. The Pen Argyl Member in the New Ringgold and New Tripoli quadrangles is bounded on the south by a major reverse fault, the Eckville fault of Behre. Interbedded pelites and graywackes (IPG on Plates I and II) grading up into the typical graywacke-pelite sequence of Shochary Ridge are found immediately south of the fault. The Eckville fault is a fault of major displacement. Field evidence for the fault is quite abundant. The most obvious evidence of movement is the rotation and crumpling of slaty cleavage near the fault. This is especially well shown in the Hess quarry near Lynnport in the New Tripoli quadrangle. Here, the slaty cleavage changes dip from 60°SE. to horizontal within about 100 feet (figure 31). Based on outcrops in the stream flowing south adjacent to the quarry the fault has been placed about 200 feet from the south edge of the quarry although it may be somewhat closer. In a series of outcrops about 2,500 feet northwest of the church in New Tripoli slaty cleavage has been rotated from dips of 75°SE. to 27°SE. within an outcrop width of about 150 feet indicating that the fault is just to the south of these outcrops. Figure 54 is an equal area projection of poles to slaty cleavage in the New Tripoli and New Ringgold quadrangles. The conspicuous wide range in cleavage dip results from the presence of the Eckville fault in these quadrangles. The effects of the fault can be seen by comparing the diagram for the New Tripoli and New Ringgold quadrangles with a similar diagram for the Slatedale quadrangle (figure 34). In addition to the rotation and crumpling of the slaty cleavage a well developed strain-slip cleavage was noted proximal to the fault (figure 32). The strain-slip cleavage has obviously formed as a result of movement along the Eckville fault. This strain-slip cleavage has an orientation that is different than that of the strain-slip cleavage developed

Figure 31: West wall of the Hess quarry. The slaty cleavage has been rotated from a dip of 60°SE. to a horizontal position at the south side of the quarry. Note the numerous north-dipping joints. New Tripoli quadrangle.

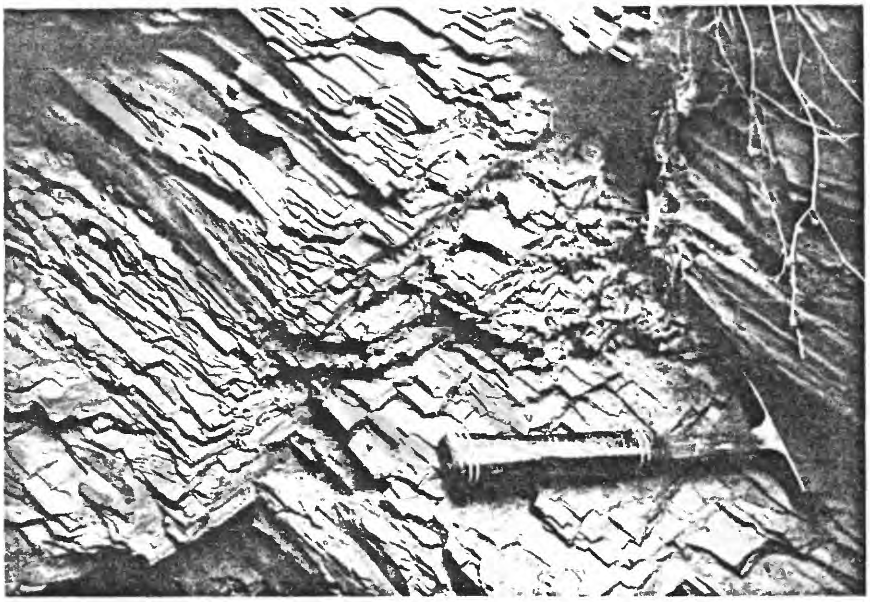


Figure 32: Well developed strain-slip cleavage associated with movement along the Eckville fault. Slaty cleavage dips to the south (right) and strain-slip cleavage dips to the northwest (left). Outcrop approximately ½ mile west of New Tripoli, New Tripoli quadrangle.

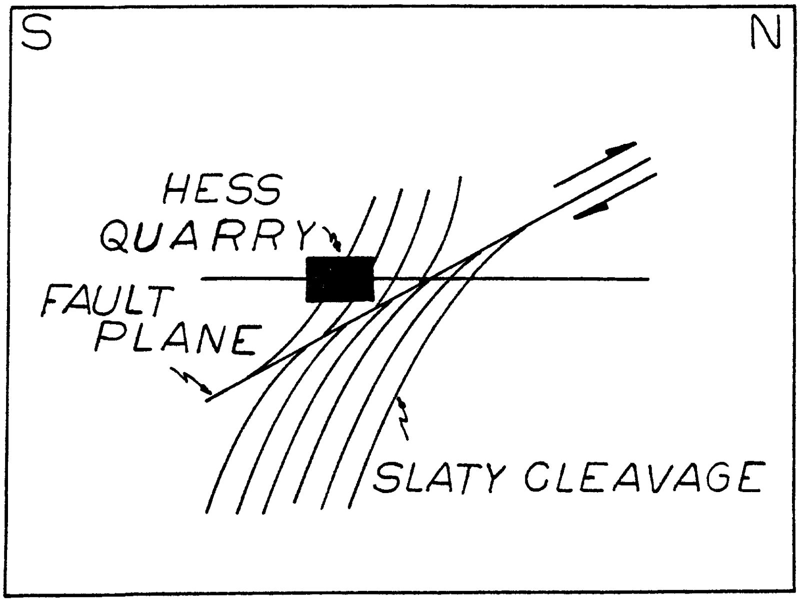
away from the fault the importance of which will be discussed later.

Deformation structures attributed to the fault are also present in the rocks south of the fault. High angle, small displacement reverse faults, tight folding, and a generally chaotic deformation of the interbedded pelite and graywacke can be seen in outcrops located about 2,000 feet north of Bolich Church in the New Ringgold quadrangle and about 2,000 feet south of Jacksonville in the New Tripoli quadrangle, both located well south of the fault.

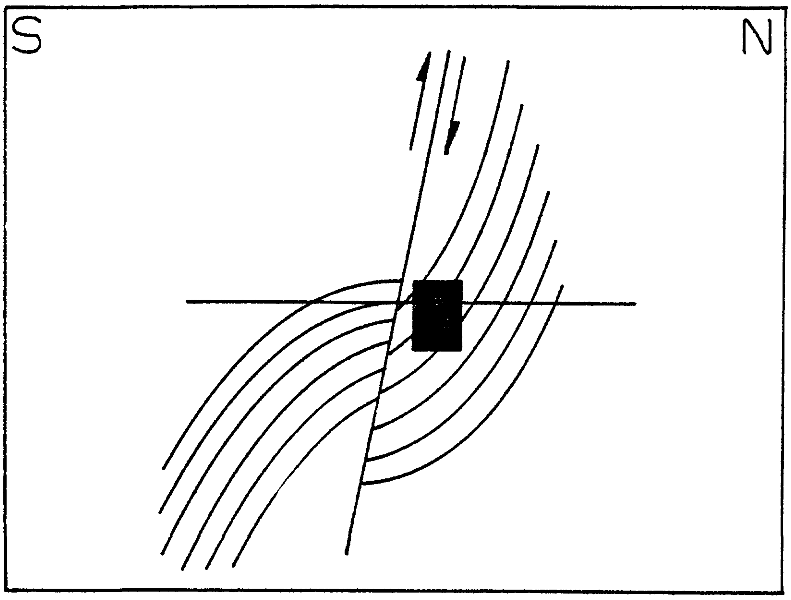
Behre (1933) noted a linear arrangement of springs along the trend of the Eckville fault in the slate belt thereby lending further support to the presence of the fault. He also noted an offset of the Shawangunk Formation in the elbow of the Blue Mountain near Eckville. This offset is so prominant that it is easily recognized on aerial photographs and topographic maps. The offset itself may either be due to dip slip movement along the fault plane exposing lower rocks as a result of thrusting or to strike-slip movement, or to a combination of both. A large kink fold plunging steeply to the north was found in the Pen Argyl Member slightly north of the Eckville fault in an area northwest of New Tripoli. The rotation sense of this kink fold is clockwise which is the rotation sense that would be required to produce the offset of the Shawangunk Formation north of Eckville.

Behre maintained that the Eckville fault was a low angle thrust fault but it is more likely that, at the present level of erosion, the fault is actually a high angle reverse fault in which the dip of the fault plane is greater than that of the slaty cleavage. Figure 33 shows a diagrammatic explanation of this reasoning. Part A shows the required position of the Hess quarry relative to the Eckville Fault if the fault is a low angle thrust. If the fault plane dips at an angle less than that of the slaty cleavage it would have to be located below the quarry to obtain the sense of cleavage rotation seen in the quarry. This is hard to imagine as Shochary Ridge rocks brought into fault contact with the Pen Argyl Member are exposed within 250 feet to the south of the quarry suggesting that the Eckville fault crops out to the south of the quarry. Part B shows the regional position of the quarry compatable with a fault plane dipping at an angle greater than that of the slaty cleavage. The rotation of the slaty cleavage and the presence of Shochary Ridge rocks to the immediate south of the quarry suggest this model for the Eckville fault.

In summary, the Eckville fault appears to be a high angle reverse fault with some strike-slip movement, which may or may not have been contemporaneous with the dip-slip movement.



(A)



(B)

Figure 33: Diagram of the possible models result-in the rotation of the slaty cleavage seen in the Hess quarry. Model A does not seem appropriate as outcrop patterns suggest that the fault plane is located to the south of the quarry and not to the north lending support to Model B.

A small reverse fault can be seen in the Manhattan quarry, located just north of Slatedale. This fault, a high angle reverse fault inclined to the axial plane of the fold, could not be traced on the surface and apparently has little lateral extent.

Bedding-slip faults, type 3 of Behre's classification, are common in all of the quadrangles. This type faulting is typically associated with tight folding in which most of the movement has taken place along or at low angles to the bedding. It is generally believed that bedding-slip faulting can also occur in response to pressure or strain and stress in the hinge area of the folds. The average dihedral opening angle of the folds within the Pen Argyl Member west of the Lehigh River is 37° which is probably tight enough to produce this type of faulting. Bedding-slip faulting is well developed in the Manhattan quarry (figure 26). Behre's type 5 fault, movement along the bedding planes is common in the Ramseyburg Member where it wrinkles the bedding surfaces but is not common in the Pen Argyl Member. Faults of this type are present in "runs" of graywacke-rich slate such as the area of the Big Franklin quarries in the eastern part of the Slatedale quadrangle.

In his study of the slate belt Behre maintained that movement along slaty cleavage should not be considered true faulting but should be treated as slip. In this study it will be treated as slip in that displacement is minor but it should be noted that faults of great displacement are known to occur parallel to slaty cleavage. Slip along cleavage planes is well documented in the Manhattan quarry (figure 26). Behre has mentioned that movement along slaty cleavage planes is most noticible in the hard slate or Bushkill Member. He noted that quartz and calcite could be seen lying parallel to cleavage planes in numerous localities. Both Dale (1914) and Behre (1933) described movement along zones parallel to the slaty cleavage as thick as 15 inches. These occurrences can probably be better described as faulting and not slip. Occurrences of this type have not been noted in the Pen Argyl Member as this type of movement may not have been common in the soft slate or Pen Argyl Member.

It is difficult to determine relative ages of the faults west of the Lehigh River as they are not commonly well exposed over great distances. It is assumed, however, that the Eckville fault was the latest fault to form with other minor faults forming concomitant with or slightly later than the folding. Evidence for this assumption exists in the fact that bedding-slip faults and movement along bedding planes and cleavage have been shown to be related to folding. Detailed field work in the New

Tripoli and New Ringgold quadrangles indicates that the Eckville fault truncates the fold axes implying that the Eckville fault formed after the folding and its associated faulting.

REGIONAL AND STRUCTURAL GEOLOGY:

An understanding of the regional and structural geology of the Pen Argyl Member and its relations to the other rocks in the area west of the Lehigh River are the prime objectives of this study. The quadrangles studied were subdivided (figures 35 and 55) to allow for a more detailed analysis of small structural variations that might be present.

Slatedale Quadrangle:

The Slatedale quadrangle (Plate III) exposes the Pen Argyl Member, Ramseyburg Member, and the Shochary sequence. The Pen Argyl Member is exposed in a belt along the northern part of the quadrangle. It is bounded to the north by the Shawangunk Formation and to the south by the Ramseyburg Member. The Ramseyburg Member is exposed within the main outcrop belt of the Pen Argyl Member in the western part of the quadrangle. These rocks are exposed in the core of a northward overturned anticline about 1 mile north of the village of Jordan Valley. The contact between the Shawangunk Formation and the Pen Argyl Member is, as stated earlier, a décollement. Outcrops within the Shawangunk Formation lending support to the presence of the décollement were found in the Bake Oven Knob area and have been described in another section. The contact of the Pen Argyl Member and the underlying Ramseyburg Member is a gradational contact, being placed above the last thick graywacke bed of the Ramseyburg. Structural and stratigraphic evidence cited earlier indicates that the Pen Argyl Member overlies the Ramseyburg Member thus lending support to the tripartite subdivision of the Martinsburg Formation. The contact of the Ramseyburg and the Shochary sequence is a fault. This fault is the Eckville fault which was traced from the New Tripoli quadrangle into the Slatedale quadrangle. Field work by members of the United States Geological Survey indicates that the fault may extend into the Cementon quadrangle to the east.

The Pen Argyl Member in the Slatedale quadrangle, as in the other quadrangles to be discussed, lies in the normal limb or brow of the large nappe postulated by Drake (1969). Recent mapping by Peter Lyttle of the United States Geological Survey in the Ramseyburg Member of the Slatedale quadrangle indicates that these rocks are regionally inverted and may be the inverted limb of the nappe.

Figure 34 shows an equal area projection of poles to slaty cleavage in the Slatedale quadrangle. A maximum of N.79°E.51°E. can be seen and although there is a fairly wide variation in the dip of the cleavage the strike appears to be quite constant. The statistical cleavage maximum for the Slatedale quadrangle is quite similar to

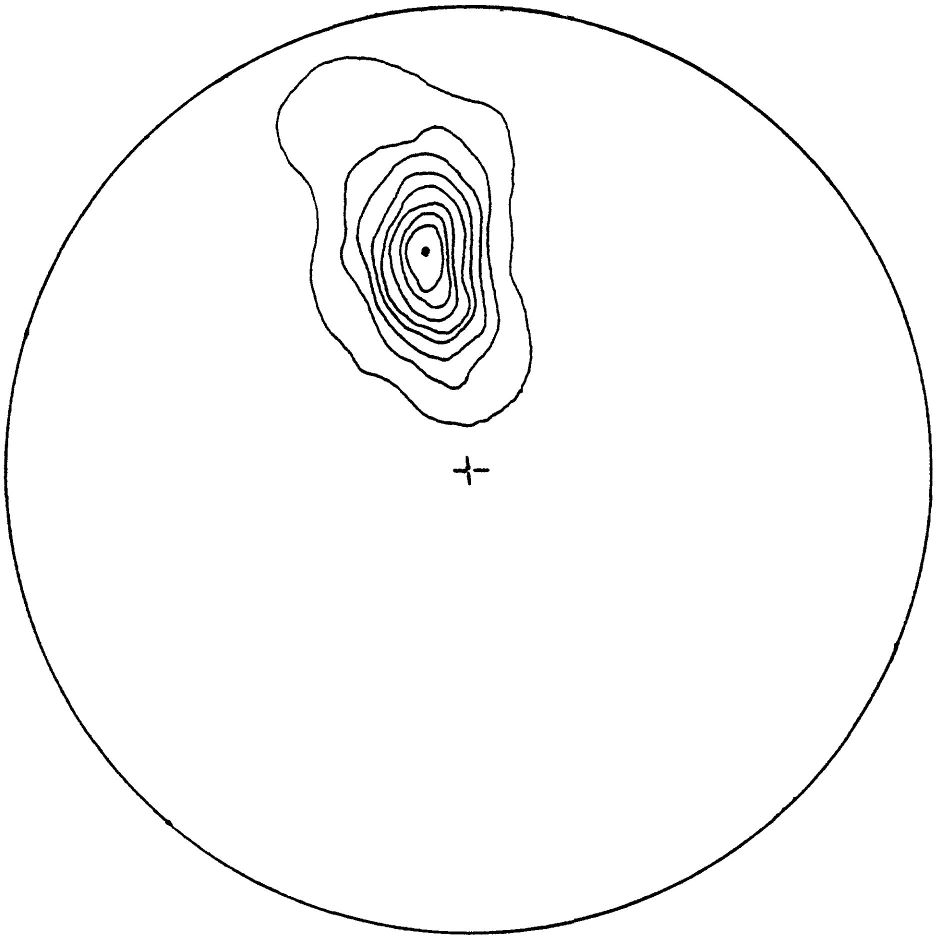


Figure 34: Equal area projection of poles to slaty cleavage in the Slatedale quadrangle. Maximum- N.79°E.51°SE.; n-93; Contour interval-5%/1% area;

that of the Lehighton quadrangle to the north, N.78°E.50°SE., and the Palmerton quadrangle to the northeast, N.76°E.52°SE. (data from Epstein and others, 1974). Thus, on a regional scale the slaty cleavage trend is quite constant.

The Slatedale quadrangle has been subdivided (figure 35) and equal area diagrams of poles to slaty cleavage for each of the domains were constructed (figures 36, 37, 38, 39, and 40). Domains 1, 2, and 3 form an east-west traverse across the quadrangle while domains 4 and 5 form a north-south traverse. In going from east to west, domains 1 to 3, two changes can be noted; (1) the strike maximum changes from N.76°E. in domain 1 to N.80°E. in domain 3 and (2) dip maximum increase from 46°SE. in domain 1 to 54°SE. in domain 3. From south to north (domain 4 to 5) the strike of the cleavage remains essentially the same, N.78°-80°E., but the average dip increases from 50°SE. in domain 4 to 58°SE. in domain 5. It appears that although variations in strike of the slaty cleavage within the Slatedale quadrangle may be small and within the limits of error the dip varies quite systematically, apparently steepening to the northwest. It should be noted here that as the great majority of structural data for this quadrangle was taken from outcrops and quarries in the eastern half of the quadrangle structural trends of the west-

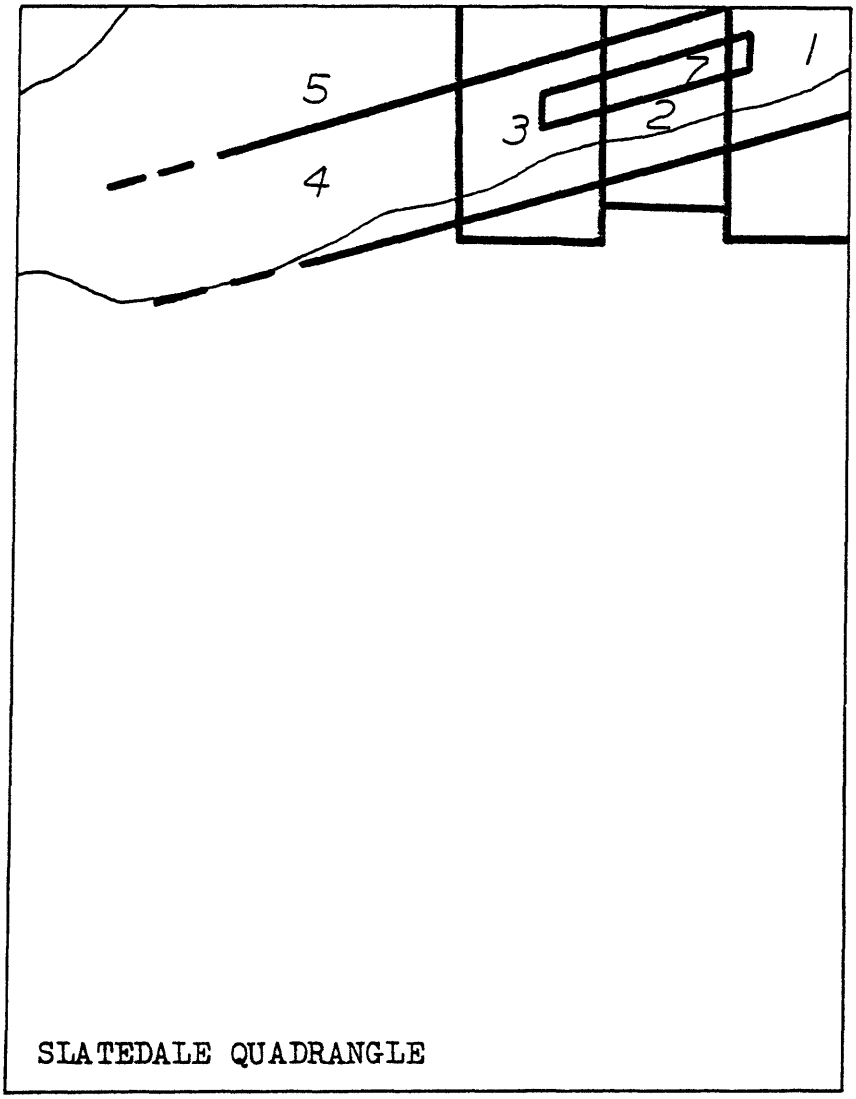


Figure 35: Subdivision of the Slatedale quadrangle. Domains 1, 2, and 3 constitute an east to west traverse of the quadrangle while domains 4 and 5 constitute a south to north traverse. Domain 7 is contained within parts of domains 1, 2, and 3 and was used to study strain-slip cleavage relations.

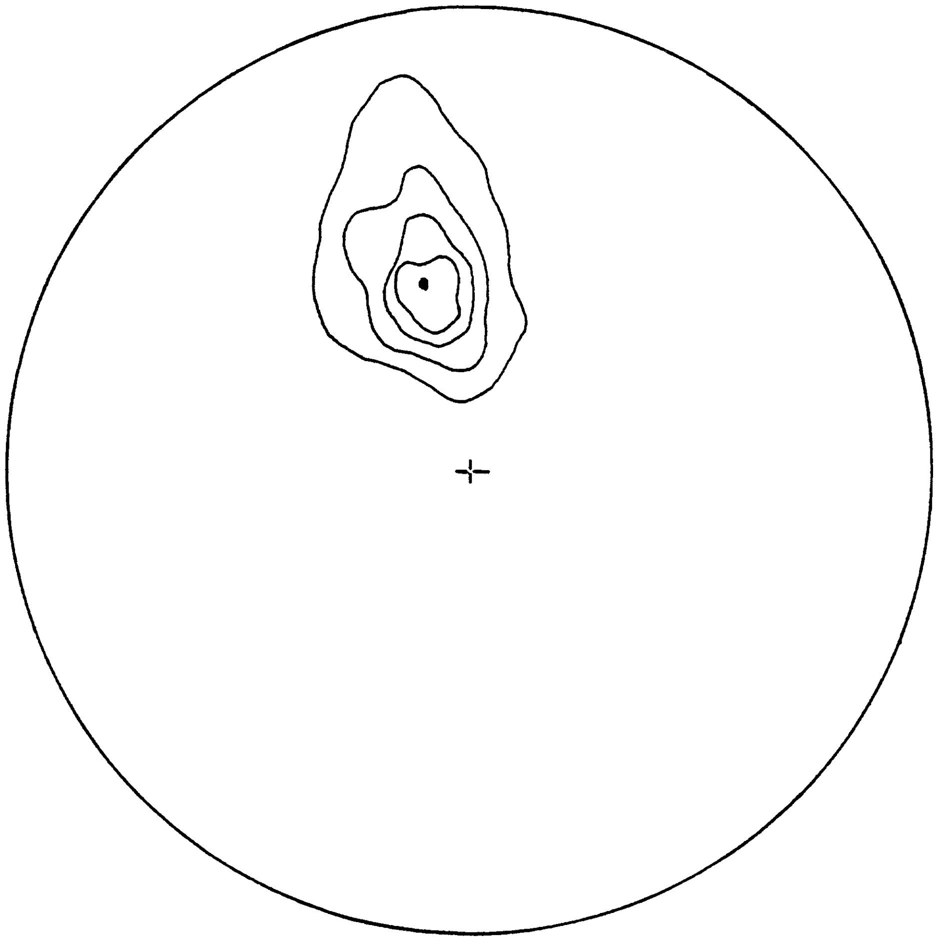


Figure 36: Equal area projection of poles to slaty cleavage in domain 1 of the Slatedale quadrangle. Maximum-N.76°E.46°SE.; n-36; Contour interval-11%/1% area;

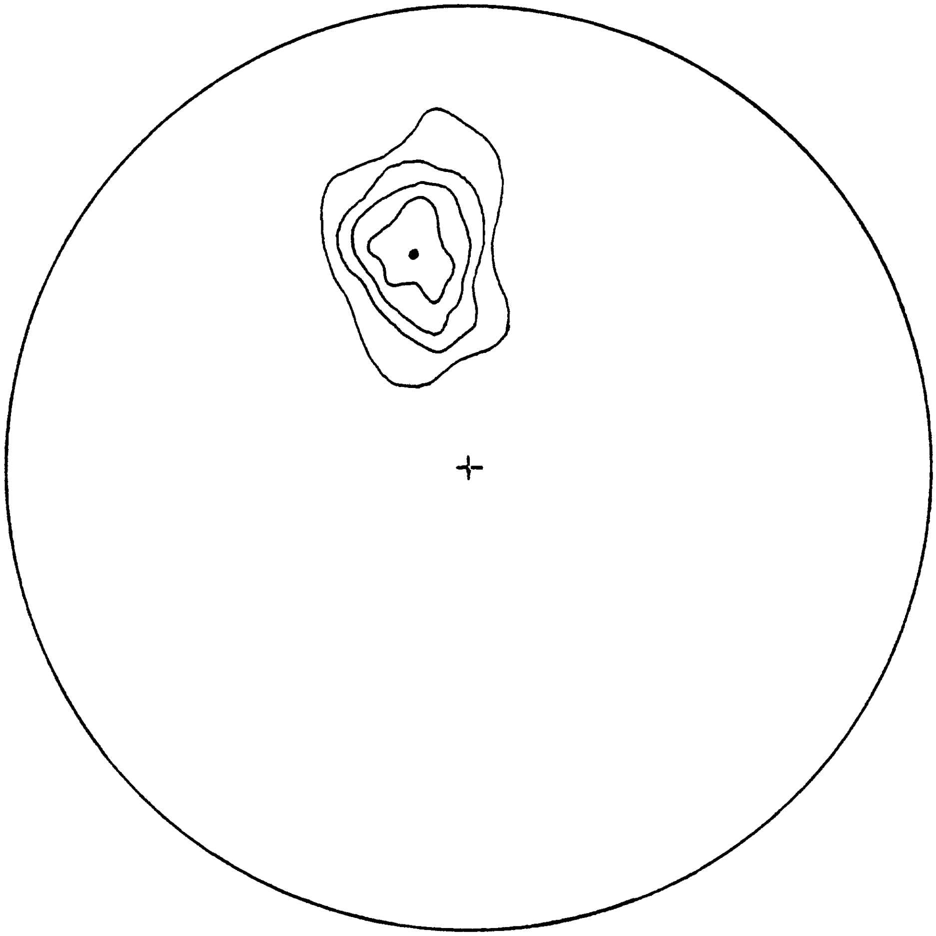


Figure 37: Equal area projection of poles to slaty cleavage in domain 2 of the Slatedale quadrangle. Maximum-N.78°E.52°SE.; n-26; Contour interval-11%/1% area;

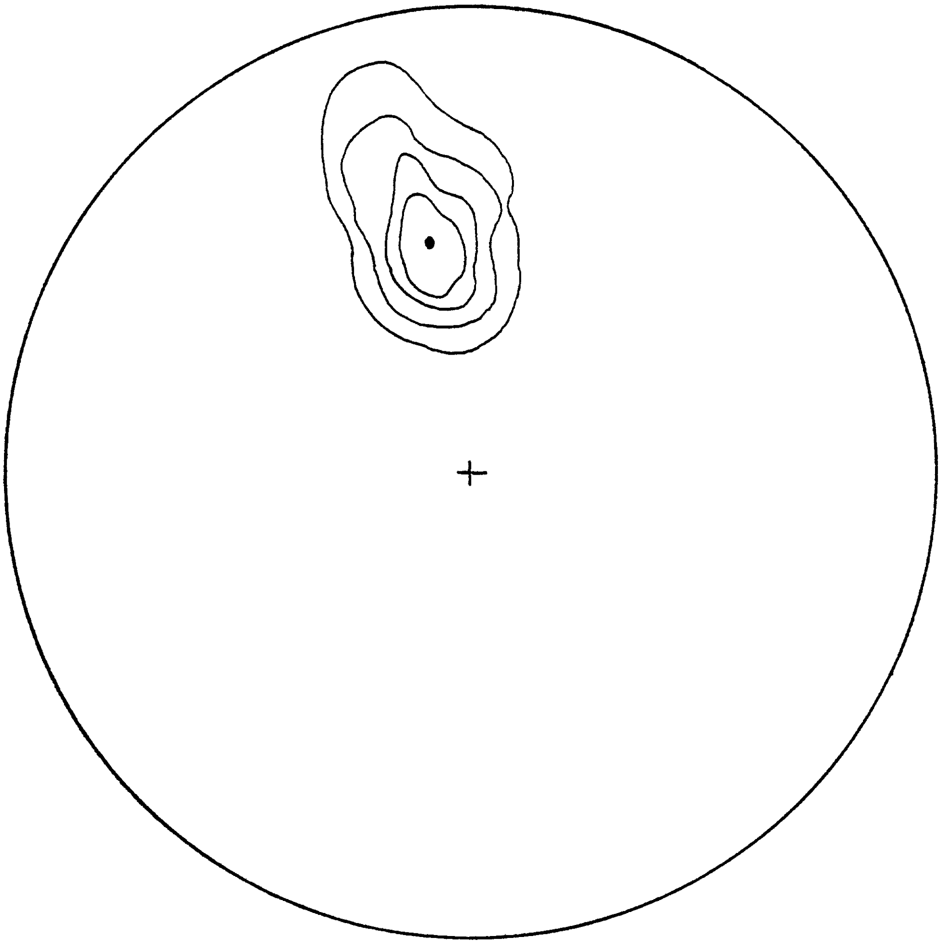


Figure 38: Equal area projection of poles to slaty cleavage in domain 3 of the Slatedale quadrangle. Maximum-N.80°E.54°SE.; n-16; Contour interval-11%/1% area;

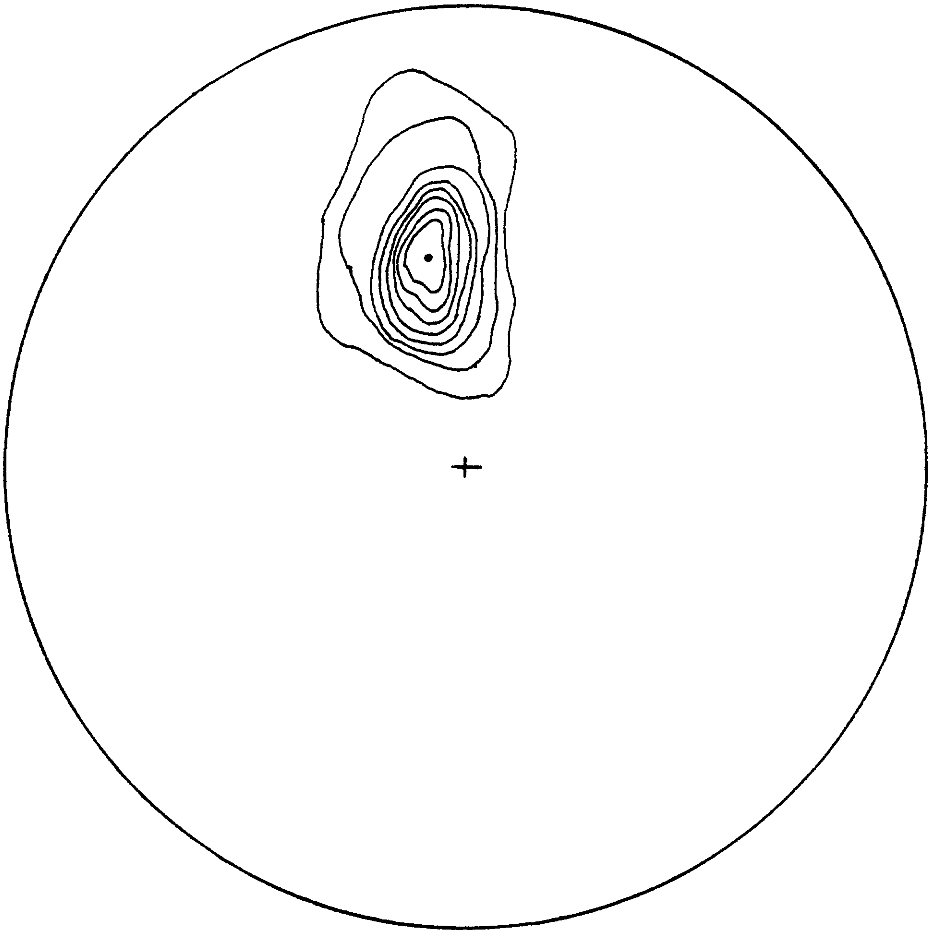


Figure 39: Equal area projection of poles to slaty cleavage in domain 4 of the Slatedale quadrangle. Maximum-N.80°E.50°SE.; n-59; Contour interval-5%/1% area;

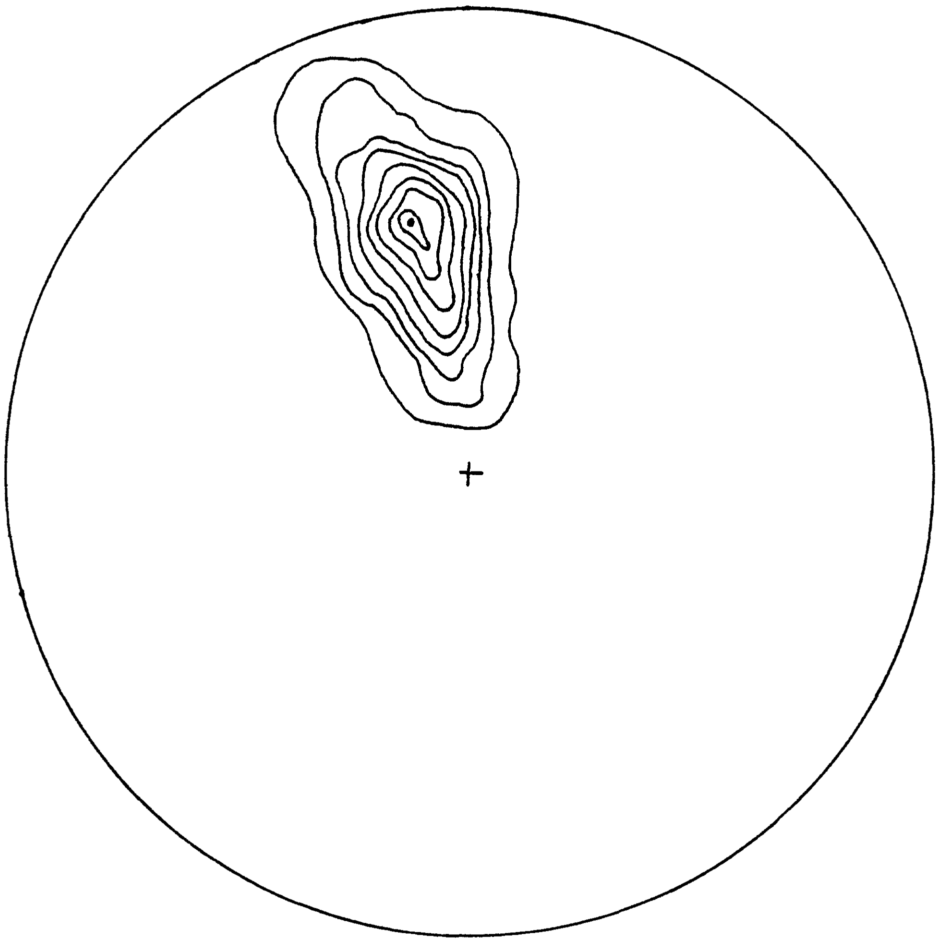


Figure 40: Equal area projection of poles to slaty cleavage in domain 5 of the Slatedale quadrangle. Maximum-N.78°E.58°SE.; n-32; Contour interval-5%/1% area;

ern half can only be obtained by extrapolation from trends present in the eastern half of the Slatedale quadrangle and the eastern part of the New Tripoli quadrangle.

Figures 41 and 42 show equal area projections of poles to bedding planes for normal and overturned beds, respectively. As mentioned earlier, two maxima for normal beds were the result of quarrying operations (see discussion in Appendix A). The secondary maximum, N.77°E.27°SE., is taken as the true maximum for normal bedding. That the folds are not cylindrical is clearly indicated by the presence of distinct girdles for the normal and inverted beds.

The average dihedral opening angle of the folds in the Slatedale quadrangle, calculated in the manner described earlier, is 52° which is rather large when compared to values obtained for the Pen Argyl Member to the north and northeast (Epstein and others, 1974).

An average axial plane for the folds was calculated. The value determined for the Slatedale quadrangle was N.79°E.52°SE., essentially parallel to the slaty cleavage maximum, N.79°E.51°SE. indicating that the slaty cleavage is axial planar to the folds.

Bedding trends were studied in each of the five domains described above. Beds in domain 1 have an average strike of N.69°E. while in domain 2 the average strike is

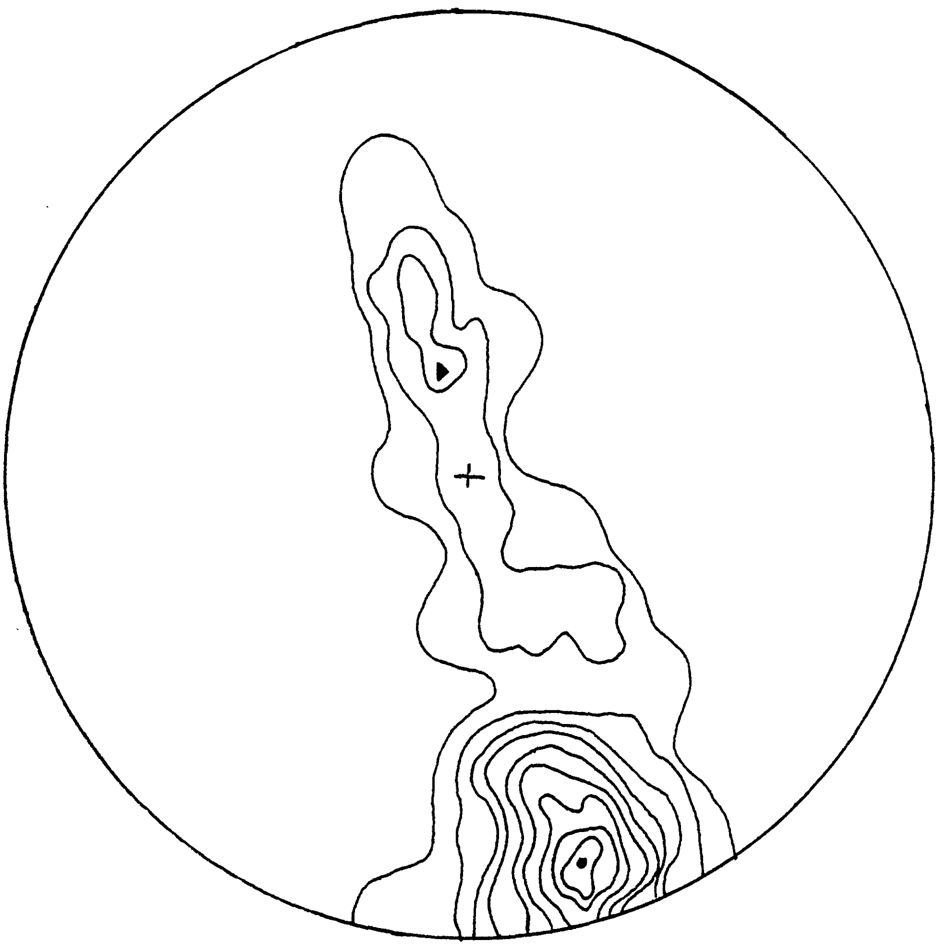


Figure 41: Equal area projection of poles to upright bedding in the Slatedale quadrangle. Maximum-biased (dot)-N.75°E.83°NW., unbiased (triangle)-N.77°E.27°SE.; n-60; Contour interval-5%/1% area;

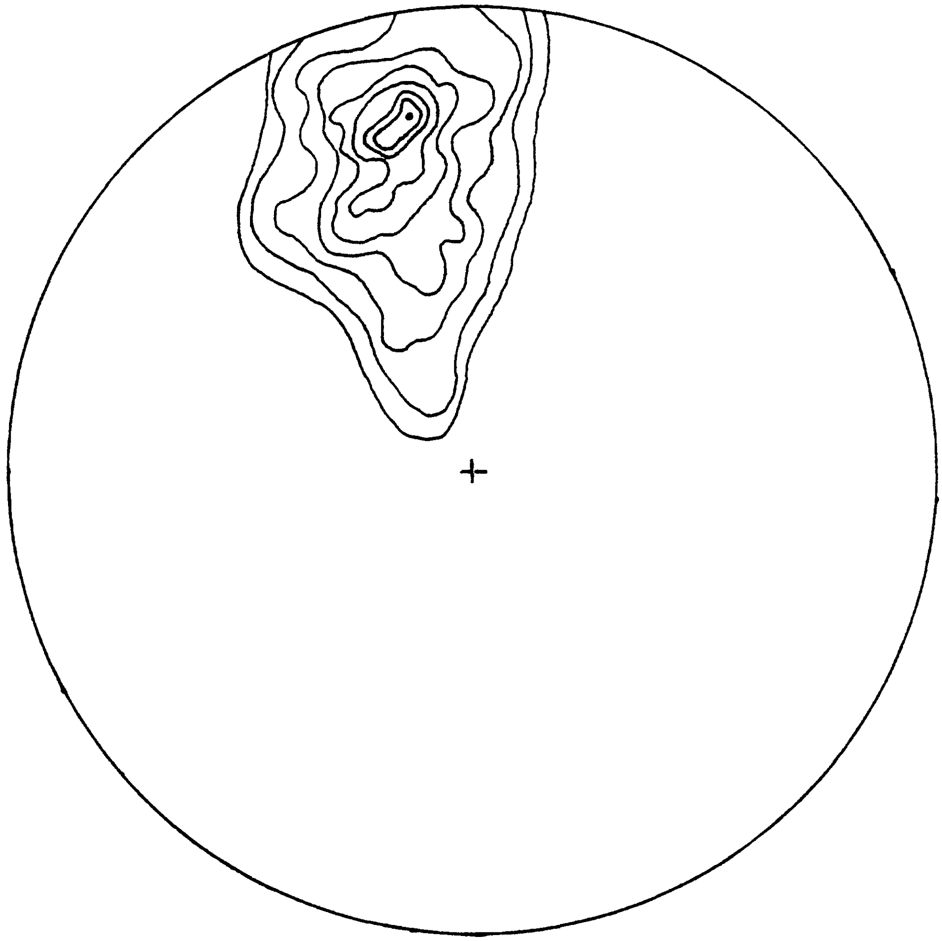


Figure 42: Equal area projection of poles to overturned bedding in the Slatedale quadrangle. Maximum-N.81°E.79°SE.; n-20; Contour interval-3%/1% area;

N.77°E. This change in strike is quite conspicuous on the geologic map of the Slatedale quadrangle (Plate III). The strike of the beds in domain 3 is essentially that of domain 2. The change from domain 4, N.78°E., to domain 5, N.77°E., is not very conspicuous. Thus it appears that beds in the Slatedale quadrangle make a substantial change in strike in the eastern part of the quadrangle. As no associated variation in slaty cleavage trend was noted the variation in strike of bedding can be attributed to some pre-slaty cleavage movement or folding.

As mentioned earlier, slaty cleavage-bedding intersections can be used to approximate the bearing and plunge of fold axes. Figure 43 is an equal area projection of slaty cleavage-bedding intersections for the Slatedale quadrangle. A maximum of 4° S.74°W. was noted along with a conspicuous girdle indicative of southward rotation of the lineations. This rotation may indicate the presence of an early set of folds oriented in a more southerly direction. Figure 44 is an equal area projection of slaty cleavage-bedding intersections and the slaty cleavage associated with the lineations south of the points that surround the maximum of figure 43. It is quite apparent that the maximum has been rotated to the south with no rotation of the slaty cleavage (compare slaty cleavage plot with figure 34). Thus two periods of folding may be indicated by the two maxima.

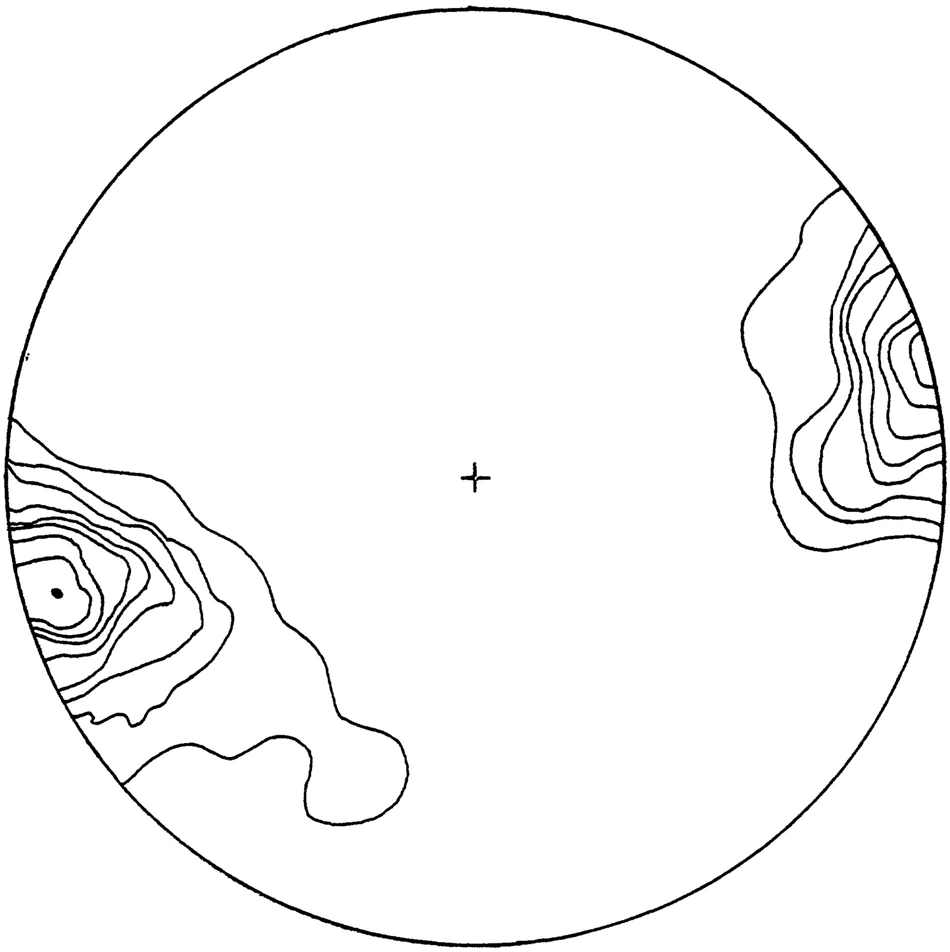


Figure 43: Equal area projection of slaty cleavage-bedding intersections in the Slatedale quadrangle. Maximum-4° S.74°W.; n-69; Contour interval-5%/1% area;

Figure 44: Equal area projection of slaty cleavage-bedding intersections south of the maximum of figure 43 and associated slaty cleavage for the Slatedale quadrangle.
Maximum-slaty cleavage-bedding intersections-8° N.86°E.
slaty cleavage-N.78°E.50°SE.
n-22
Contour interval-5%/1% area

Figures 45, 46, 47, 48, and 49 are equal area projections of slaty cleavage-bedding intersections in domains 1, 2, 3, 4, and 5, respectively. In going from domain 1 to domain 3 the maximum changes from 6° S.73°W. to 3° S.76°W. and finally 4° S.77°W. in domain 3. Once again, although not as conspicuous as in the case of bedding, a change in trend from east to west is noticeable. Of particular interest is the lack of a pi-girdle in the diagram for domains 2 and 3 (figures 46 and 47, respectively). This may indicate that early folding was localized. Little change was noted in going from domain 4, 4° S.77°W., to domain 5, 2° S.74°W.

Strain-slip cleavage or crenulation cleavage is present regionally in the Slatedale quadrangle. Slaty cleavage-strain-slip cleavage intersections were assumed to approximate the bearing and plunge of the axes of the small crenulations. Figure 50 shows an equal area projection of slaty cleavage-strain-slip cleavage intersections within the Slatedale quadrangle. Although a slight near vertical pi-girdle is shown no appreciable rotation in strike is apparent. The maximum of 2° S.83°W. is rotated somewhat north of the slaty cleavage-bedding intersection maximum for the quadrangle. This indicates that the forces producing the crenulations were oriented somewhat differently than those that produced the slaty cleavage and associated folds.

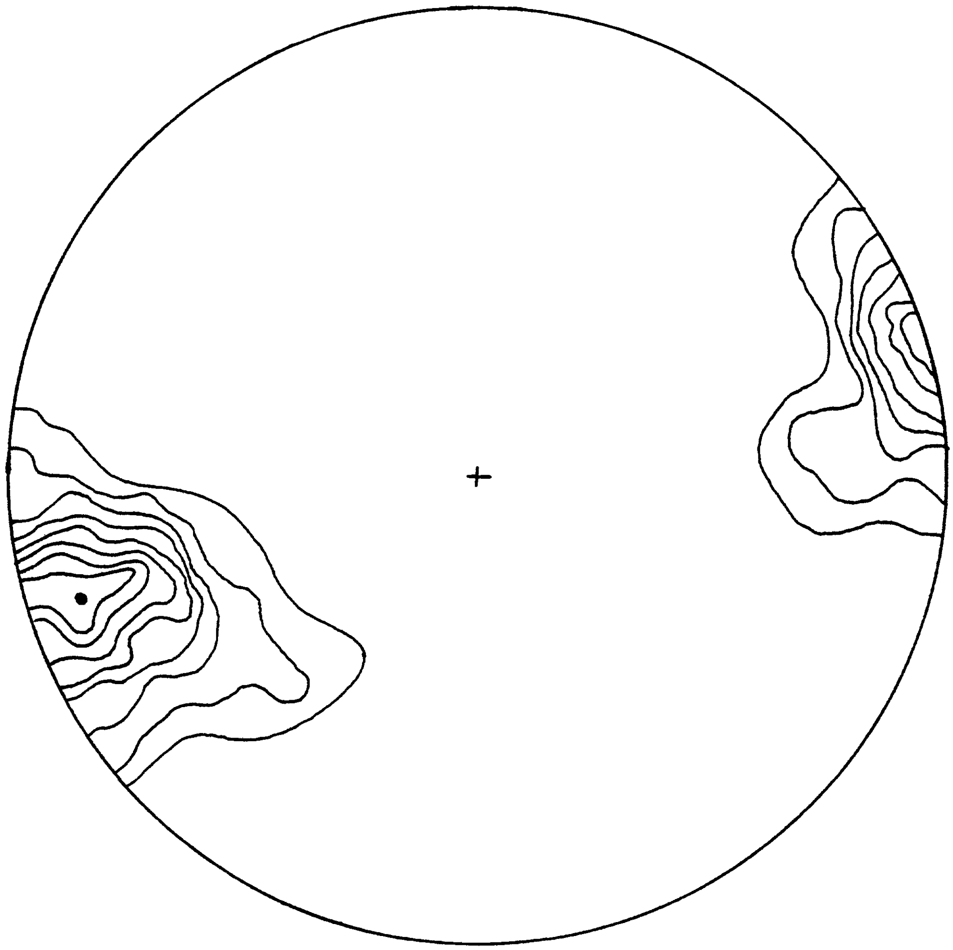


Figure 45: Equal area projection of slaty cleavage-bedding intersections in domain 1 of the Slatedale quadrangle. Maximum-6° S.73°W.; n-31; Contour interval-5%/1% area;

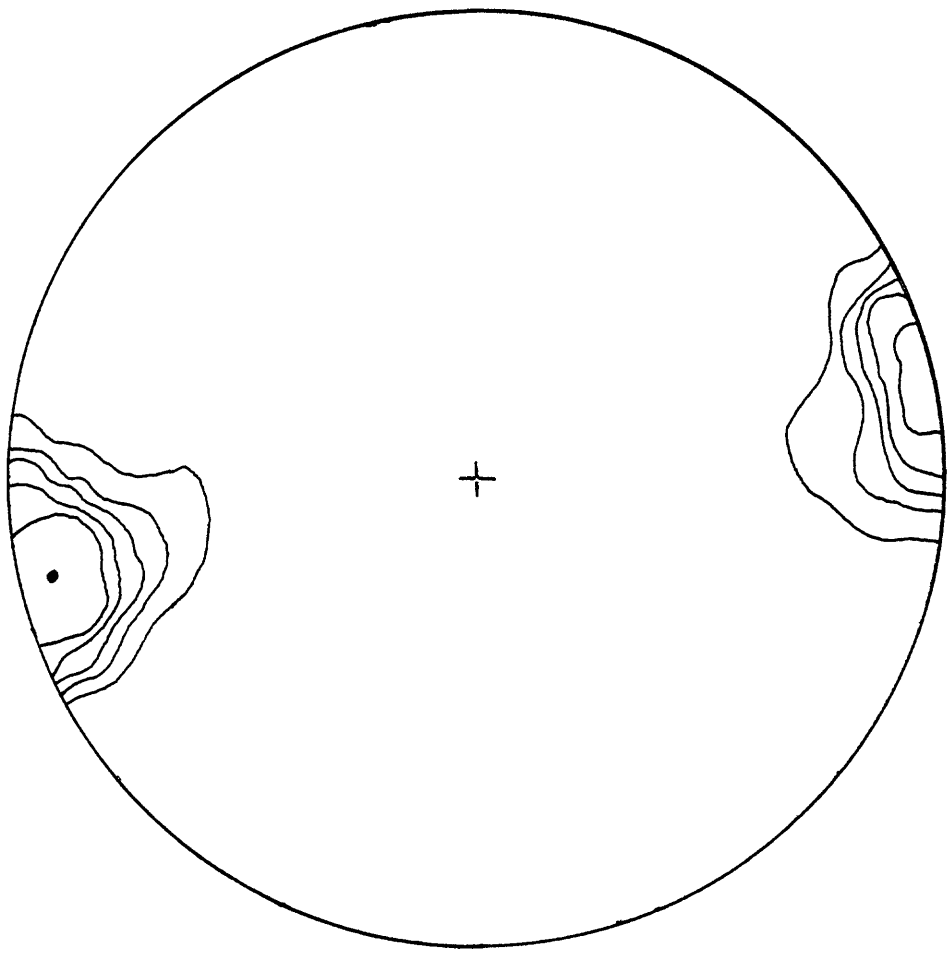


Figure 46: Equal area projection of slaty cleavage-bedding intersections in domain 2 of the Slatedale quadrangle. Maximum-3° S.76°W.; n-22; Contour interval-0%, 10%, 20%, 30%, 35%;

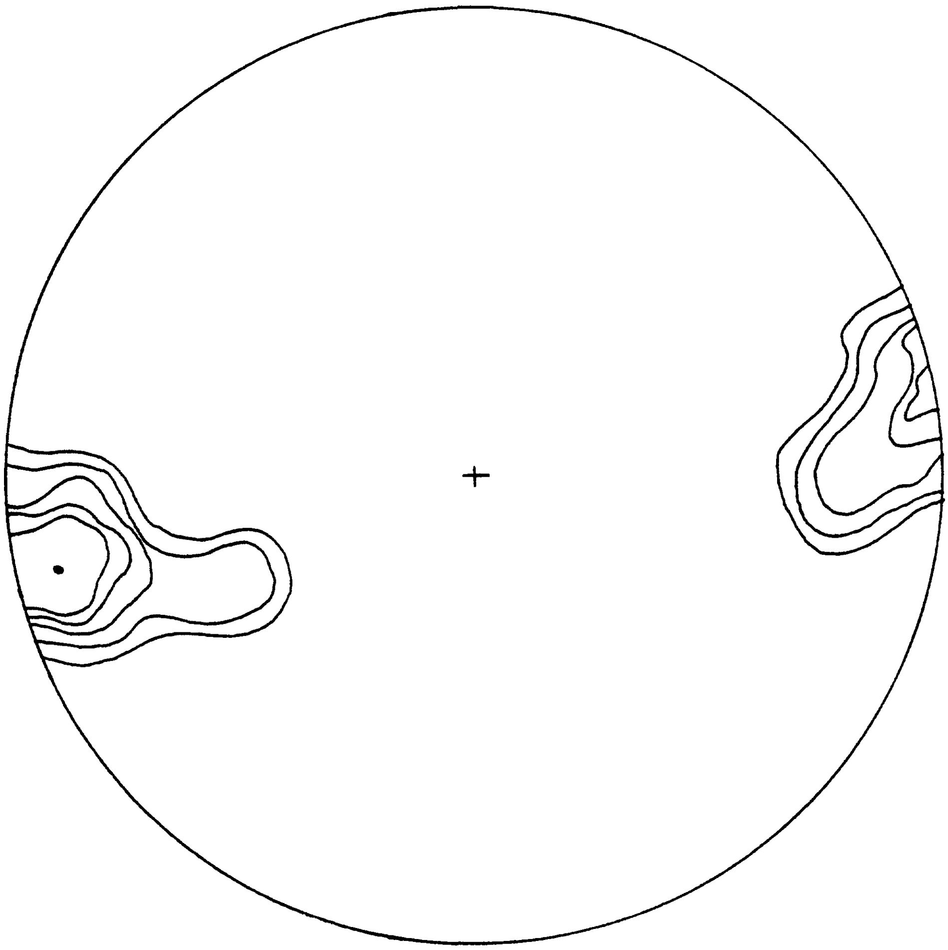


Figure 47: Equal area projection of slaty cleavage-bedding intersections in domain 3 of the Slatedale quadrangle. Maximum-4° S.77°W.; n-9; Contour interval-0%, 11%, 22%, 33%, 35%;

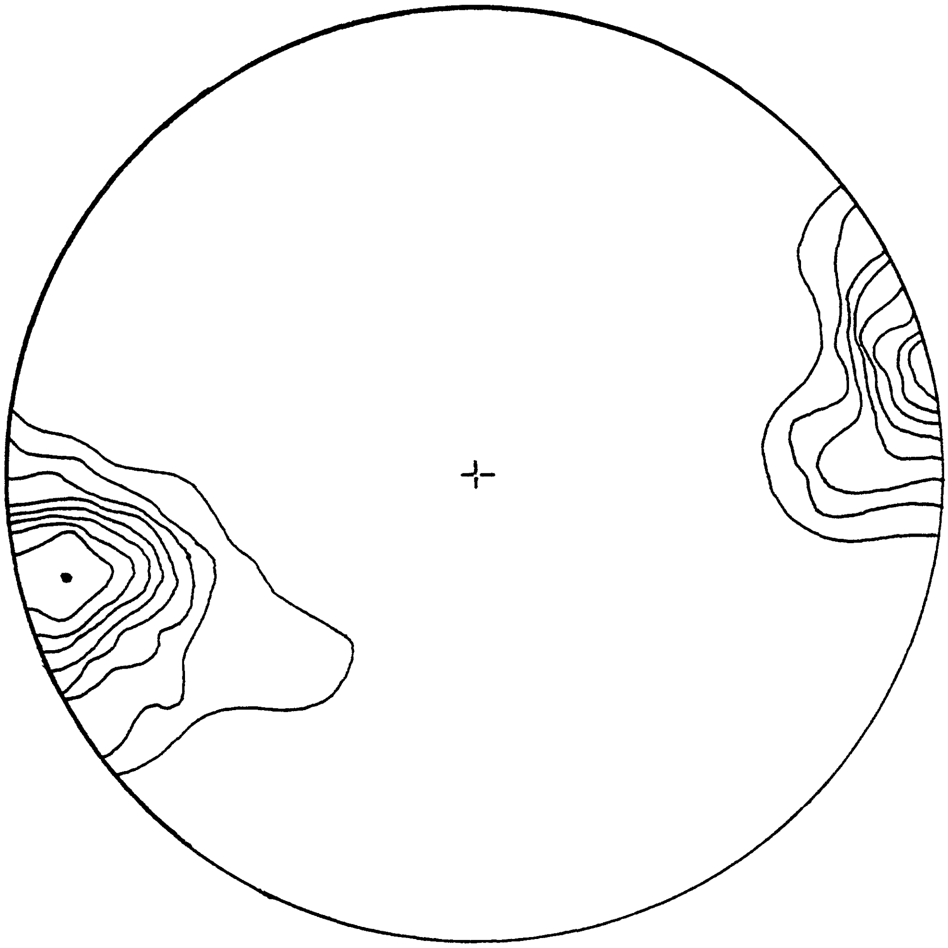


Figure 48: Equal area projection of slaty cleavage-bedding intersections in domain 4 of the Slatedale quadrangle. Maximum-4° S.77°W.; n-49; Contour interval-5%/1% area;

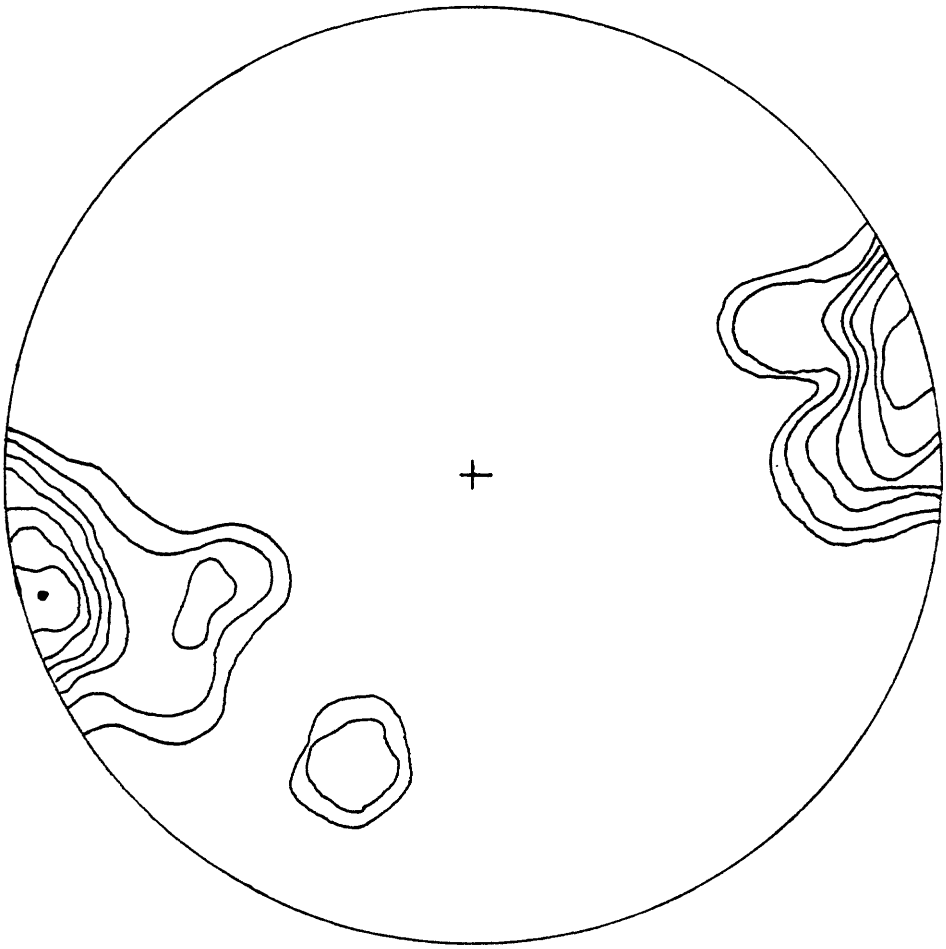


Figure 49: Equal area projection of slaty cleavage-bedding intersections in domain 5 of the Slatedale quadrangle. Maximum-2^{o} S.74^{o}W.; n-19; Contour interval-5%/1% area;

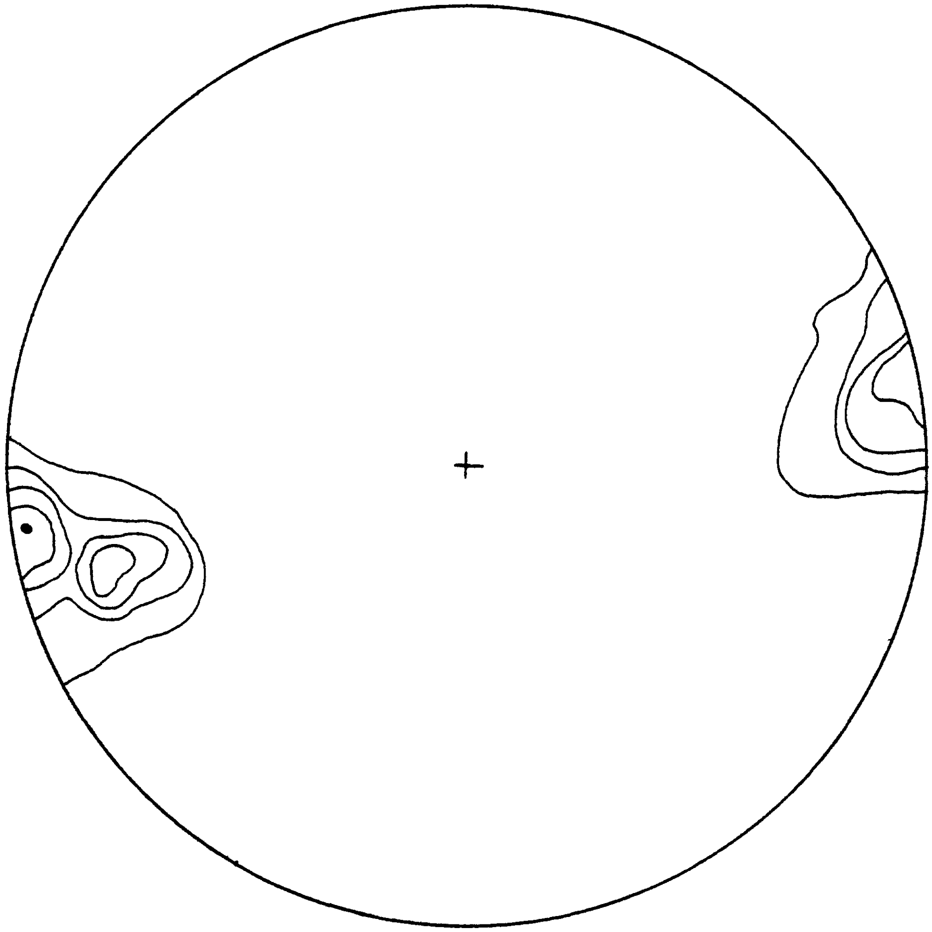


Figure 50: Equal area projection of slaty cleavage-strain-slip cleavage intersections in the Slatedale quadrangle. Maximum-2° S.83°W.; n-10; Contour interval-0%, 10%, 20%, 30%, 35%;

Domain 7 (see figure 35) of the Slatedale quadrangle is characterized by a well developed strain-slip cleavage in which transposition of the slaty cleavage has been so complete that a "new" spaced set of cleavage planes has formed in some areas. Figures 51 and 52 are equal area projections of poles to strain-slip cleavage planes and slaty cleavage planes, respectively, in domain 7. The difference in strike between the slaty cleavage maximum, N.77°E.52°SE., and the strain-slip cleavage maximum, N.88°E.27°NW., is further evidence for local variations in stress orientation during the formation of the two sets of cleavage. It is interesting to note that when the slaty cleavage maximum and strain-slip cleavage maximum are placed on the same great circle their angular separation is 90° indicating that the slaty cleavage has been transposed to a position perpendicular to its original position.

Cross-sections A'-A and B'-B, drawn across the outcrop belt of the Pen Argyl Member, are shown on Plate VII. Cross-section B'-B was constructed across an area of Ramseyburg rocks present within the main outcrop belt of the Pen Argyl Member. The Ramseyburg has been exposed in the core of the Jordan Valley anticline (see Plate III).

<u>New Tripoli and New Ringgold Quadrangles</u>:

The Pen Argyl Member is exposed in a belt continuing

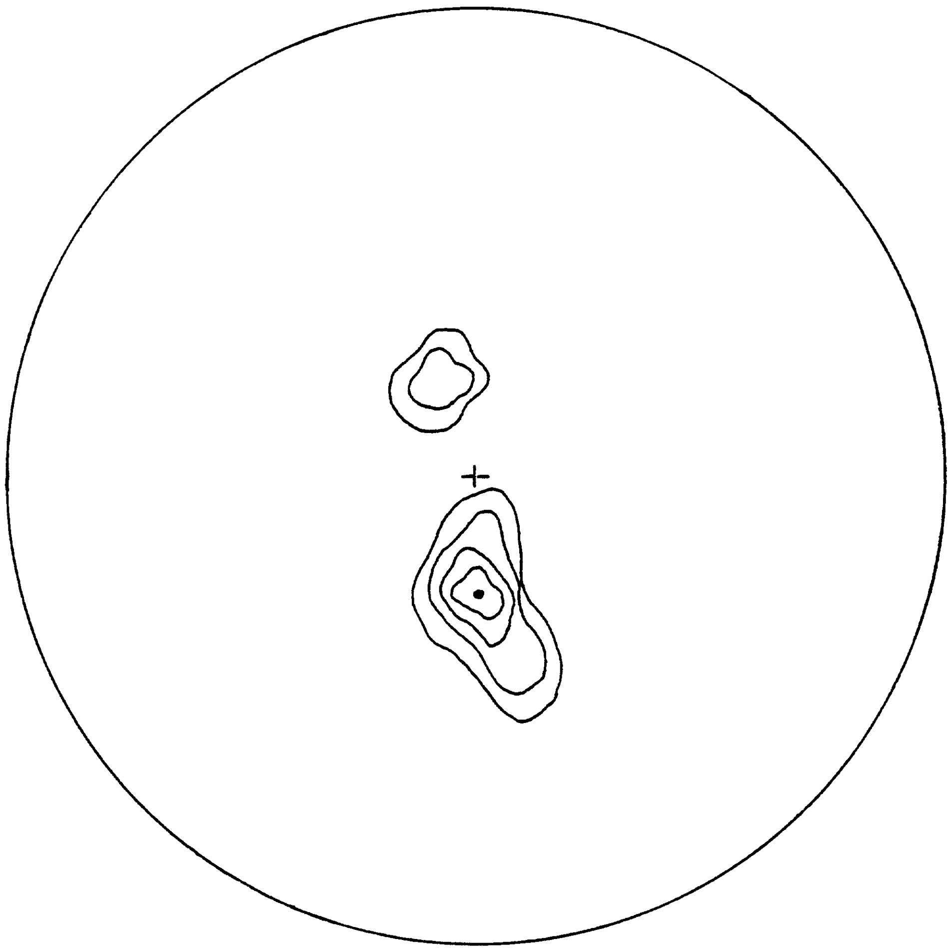


Figure 51: Equal area projection of poles to strain-slip cleavage in domain 7 of the Slatedale quadrangle. Maximum-N.88°E.27°NW.; n-7; Contour interval-0%, 14%, 28%, 35%;

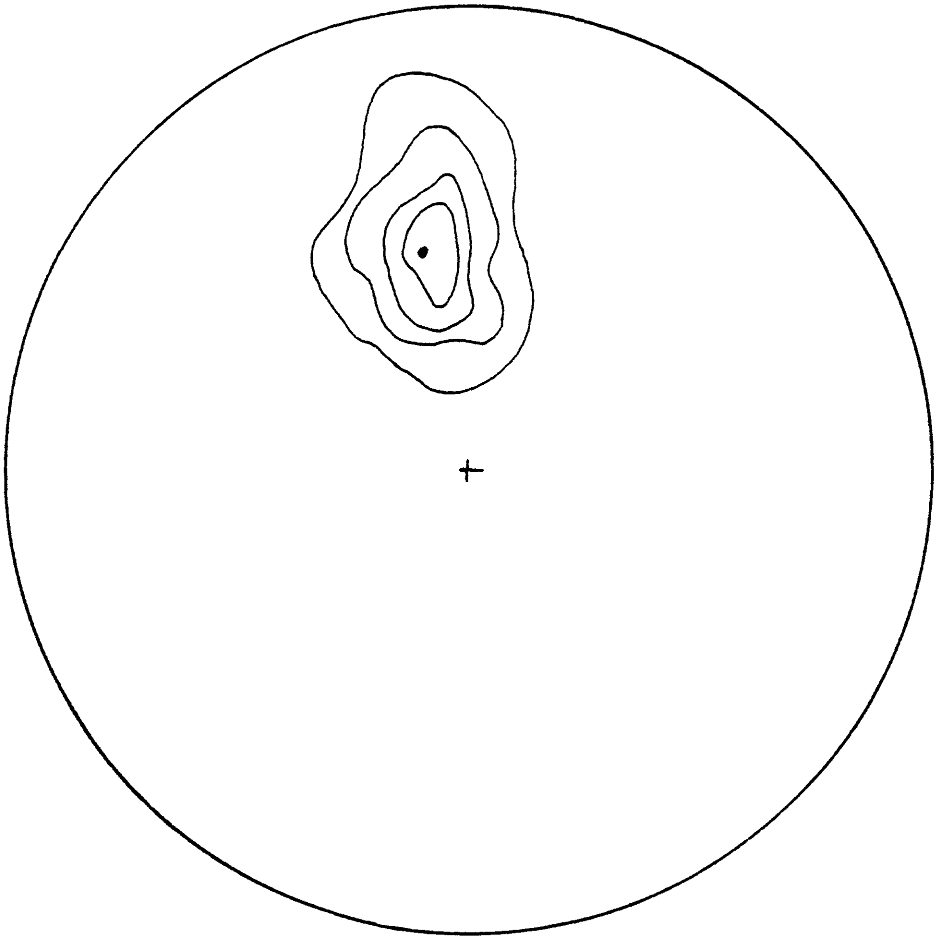


Figure 52: Equal area projection of poles to slaty cleavage in domain 7 of the Slatedale quadrangle. Maximum-N.77°E.52°SE.; n-26; Contour interval-10%/1% area;

from the west side of the Slatedale quadrangle through the New Tripoli quadrangle (Plate II) and almost to the west edge of the New Ringgold quadrangle (Plate I) north of Eckville where it plunges under the Silurian ridge. The slate belt is 3 to 4 miles wide north of New Tripoli but thins down to an outcrop width of about ½ mile north of Eckville in the New Ringgold quadrangle. The Pen Argyl Member is bounded on the north by the Shawangunk Formation, the contact of which is the Blue Mountain décollement, and on the south by the interbedded pelite and graywacke of the Shochary sequence. This contact is the Eckville fault (see cross-sections D'-D and E'-E, Plate VII). This fault extends to the west where Wood (1973) has mapped it in the Silurian rocks of the Orwigsburg quadrangle.

The Pen Argyl Member in the New Tripoli and New Ringgold quadrangles is best exposed in the abandoned slate quarries of the Lynnport slate district. Quarrying in the New Ringgold quadrangle was limited soley to the eastern portion of the quadrangle.

The divergence of the outcrop pattern in the east part of the New Tripoli quadrangle is the result of the Mosserville anticline. As mentioned earlier the presence of the anticline has recently been challanged by T.O. Wright and others (1978) who have proposed, in its place, an eastward plunging syncline. Strong supporting evidence indicating that the fold is an anticline has been found near the small village of Mosserville. In a small quarry (Quarry a, Mosserville quarries) about 400 feet south of Mosserville, slate beds can be seen dipping to the south. A three-foot thick graywacke bed is also exposed in this area. As one progresses south along the small stream that flows south from Mosserville the beds continue to dip to the south and the graywacke beds present to the north give way to the typical thick beds of the Pen Argyl Member indicating that the graywacke is stratigraphically lower than the thick-bedded claystone slate. The contact of the Pen Argyl Member and the Ramseyburg Member has been placed slightly south of quarry a of the Mosserville quarries.

Further evidence supporting the presence of the Mosserville anticline includes the slaty cleavage-bedding intersections for the eastern part of the New Tripoli quadrangle (figure 53) which show a strong preferred orientation indicating a regional plunge to the southwest. This along with the outcrop pattern is suggestive of an anticline plunging to the southwest. Plate VII shows a cross-section (Cross-section C'-C) across the anticline.

Figure 54 shows an equal area projection of poles to slaty cleavage in the New Tripoli and New Ringgold quadrangles. The poles are distributed in a girdle indicating a wide variation in dip with a rather constant strike. The great variance in dip which is not seen to the east in

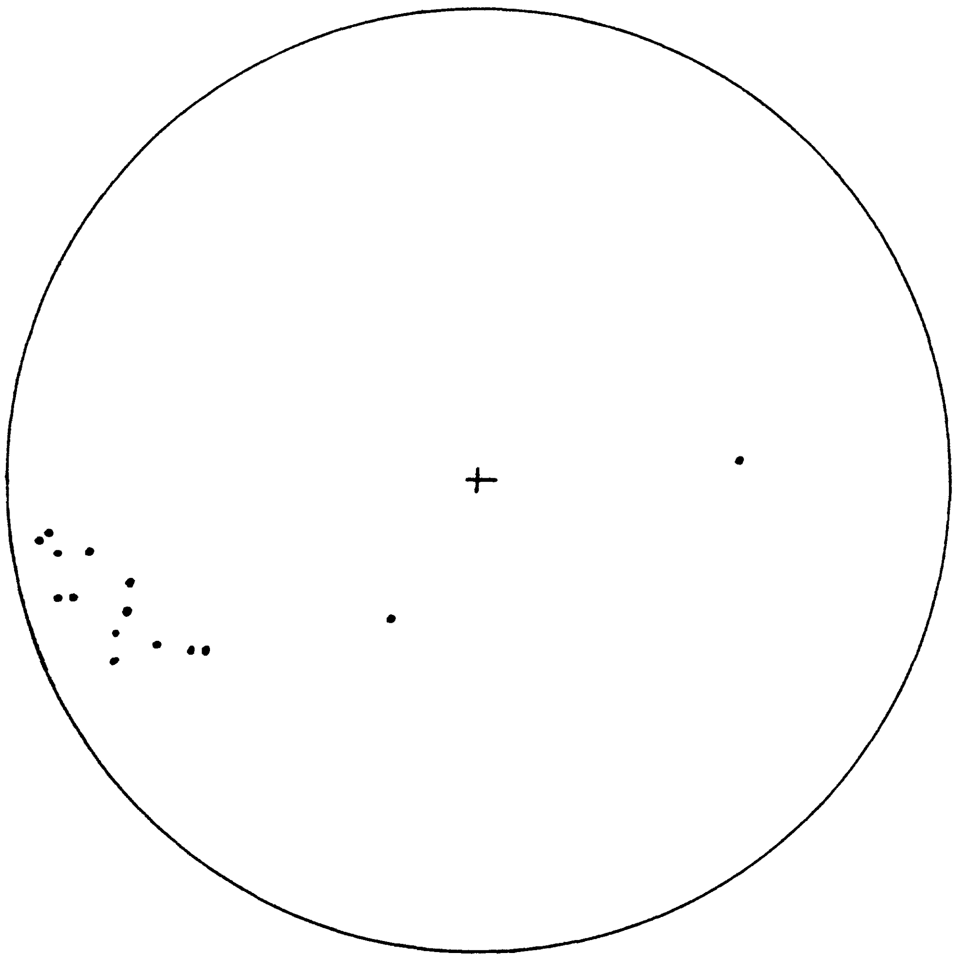


Figure 53: Stereoplot of slaty cleavage-bedding intersections in domain 1 of the New Tripoli quadrangle.

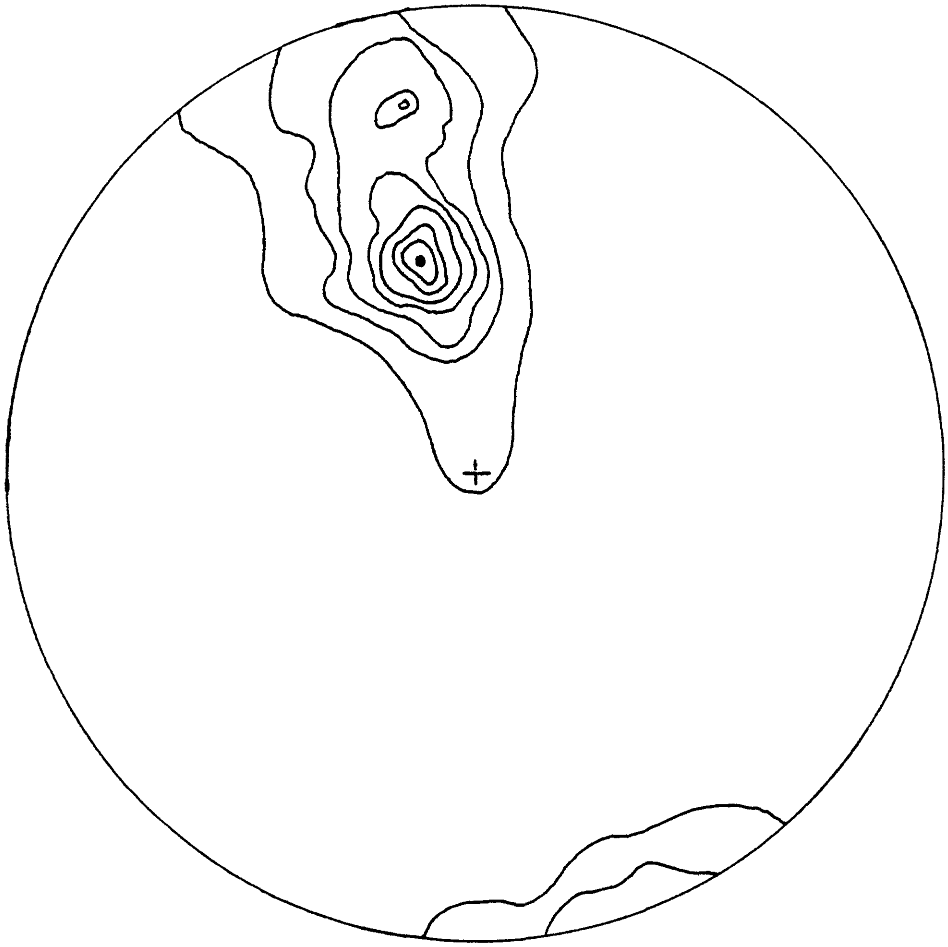


Figure 54: Equal area projection of poles to slaty cleavage in the New Tripoli and New Ringgold quadrangles. Maximum-N.76°E.50°SE; n-70; Contour interval-5%/1% area;

the Slatedale quadrangle or to the northeast in the Palmerton and Lehighton quadrangles is attributed to cleavage rotation produced by movement along the Eckville fault. Note that both the lowest and highest dips can be found within this area. This indicates that the folds in these quadrangles tend to be more upright than folds to the east, a point noted by Behre (1933). The maximum for the New Tripoli and New Ringgold quadrangles is N.76°E.50°SE., quite close to that of the Slatedale quadrangle, N.79°E.51°SE. This indicates that the trend of the slaty cleavage is quite constant throughout the three quadrangle area in which the Pen Argyl Member was mapped. The New Tripoli and New Ringgold quadrangles have been subdivided into three domains (figure 55) for detailed study. Figures 56, 57, and 58 are equal area projections of poles to slaty cleavage in domains 1, 2, and 3, respectively. The slaty cleavage maximum in domain 1 strikes N.73°E. and dips 54°SE. The wide variation in dip seen in figure 54 is not shown in figure 56. As was mentioned earlier, attitudes had to extrapolated from the central part of the Slatedale quadrangle to the west because of a lack of outcrops in that part of the quadrangle. The statistical strike of slaty cleavage in domain 3 of the Slatedale quadrangle is N.80°E. As a result, the trend of the slaty cleavage must shift about

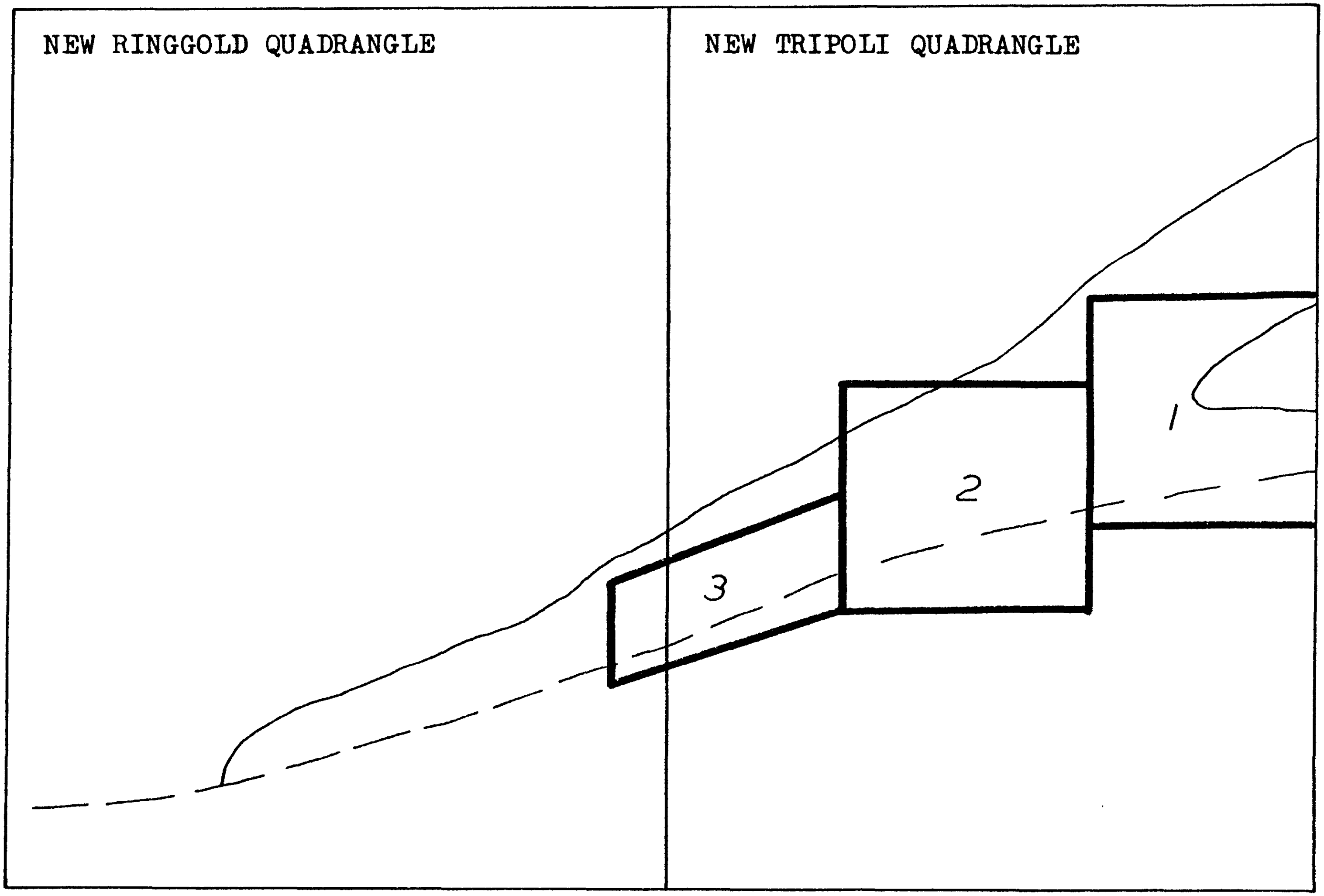


Figure 55: Subdivision of the New Tripoli and New Ringgold quadrangles.

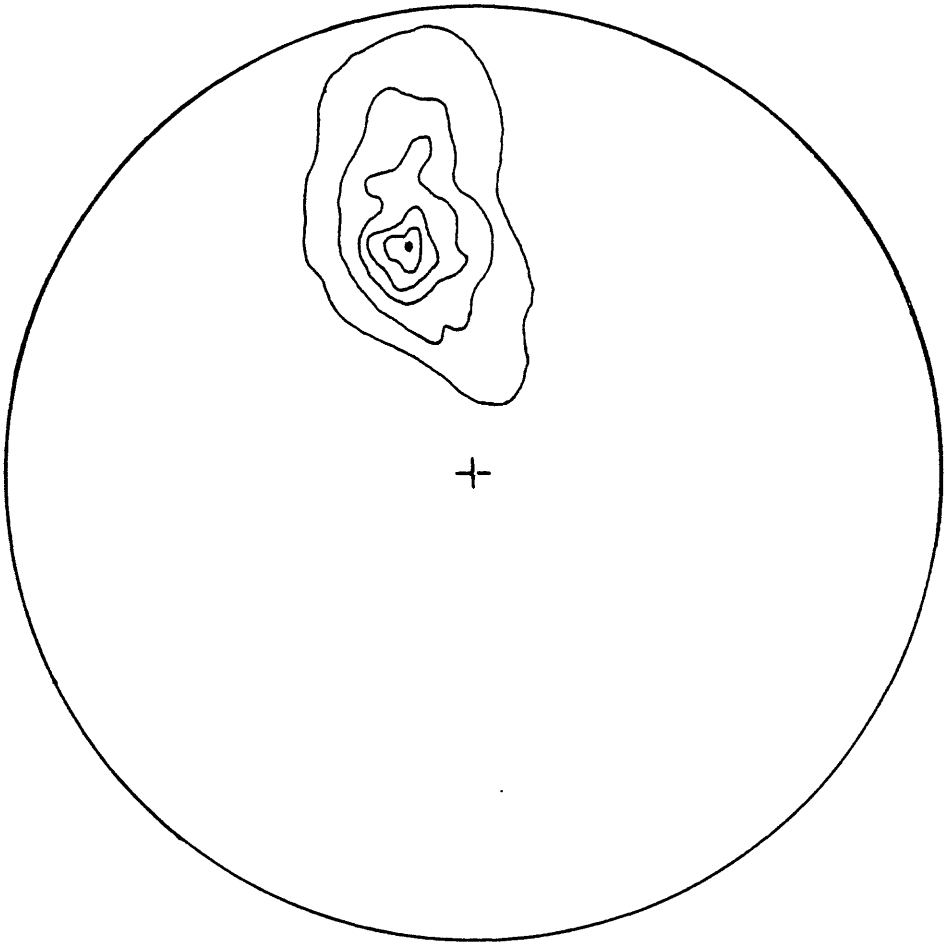


Figure 56: Equal area projection of poles to slaty cleavage in domain 1 of the New Tripoli quadrangle. Maximum-N.73°E.54°SE.; n-27; Contour interval- 0%, 10%, 20%, 30%, 35%;

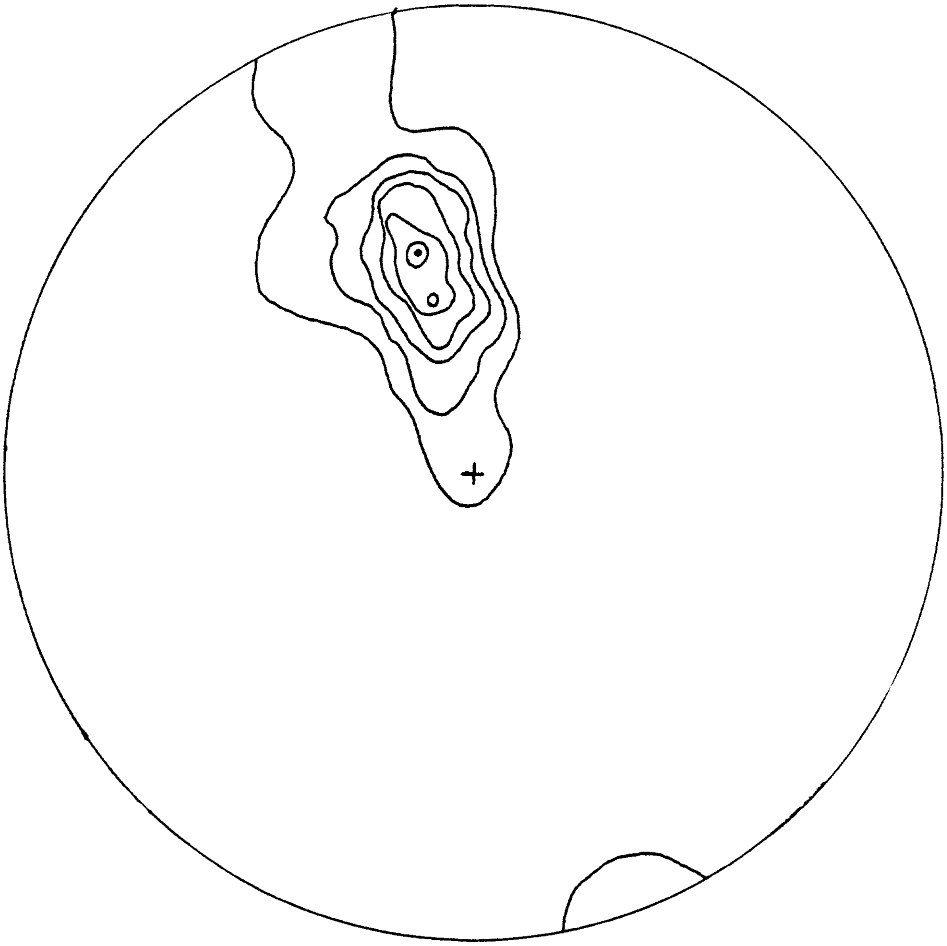


Figure 57: Equal area projection of poles to slaty cleavage in domain 2 of the New Tripoli quadrangle. Maximum-N.73°E.52°SE; n-23; Contour interval-7%/1% area;

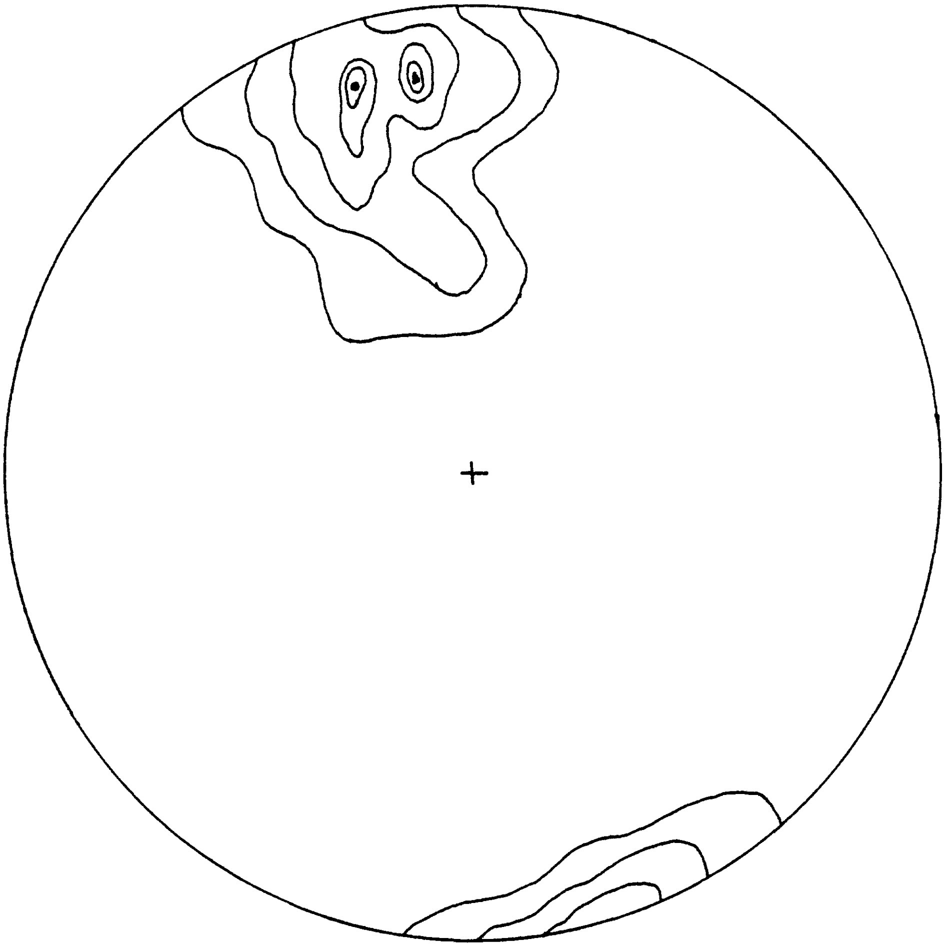


Figure 58: Equal area projection of poles to slaty cleavage in domain 3 of the New Tripoli and New Ringgold quadrangles. Maximum-primary (dot)-N.72°E. 83°SE., secondary (triangle)-N.81°E.83°SE.; n-20; Contour interval-0%, 10%, 20%, 30%, 35%;

5° to the north in the western part of the Slatedale quadrangle. This change in trend may be rotated to the formation of the Mosserville anticline. There is no change in the statistical strike of slaty cleavage from domain 1 to domain 2 in the New Tripoli quadrangle. As seen in figure 57 poles to slaty cleavage plot on a girdle suggesting the presence of the Eckville fault. In figure 58 (domain 3) there are two near equal maxima. The primary maximum is N.72°E.83°SE. and the secondary maximum is N.81°E.82°SE. The primary maximum suggests that no change in cleavage attitude has occurred in passing from domain 2 to domain 3 but the presence of the secondary maximum complicates this picture. There is no significant separation of the two maxima in the field or on selected fabric diagrams but it is suggested that as data were taken a short distance from the Eckville fault, strike-slip movement along the fault may have resulted in a regional kinking of the area. A girdle not as well defined as that in domain 2 is present. The other important feature of the diagram is the extreme dip of both maxima, 82°-83°SE. There is no flat-dipping cleavage here as in the other domains suggesting that the slaty cleavage has not been rotated. If this is so, the presence of the Eckville fault in this area could be questioned. The Eckville fault, however, is a high angle reverse fault and if the fault is parallel to the slaty cleavage in a particular area there would be little or no rotation of the slaty cleavage. Kink folds are the common deformatonal features in areas where the slaty cleavage parallels the fault such as in the Slateville and Mosserville areas. In domain 2 where the dip of the statistical slaty cleavage maximum is considerably less than the dip of the fault plane poles to cleavage plot on a large girdle suggesting rotation. The lack of a similar girdle in figure 58 suggests that the average dip of the Eckville fault is approximatley 80° to the southeast at the present level of erosion.

Figures 59 and 60 are equal area projections of poles to normal and inverted bedding, respectively, in the New Tripoli and New Ringgold quadrangles. The maximum for the normal beds is N.73°E.24°SE. and that for the inverted beds is N.71°E.62°SE. The calculated dihedral opening angle is 38° and the calculated attitude of the axial plane is N.73°E.44°SE., quite close to the slaty cleavage maximum, N.76°E.50°SE. As in the case of the Slatedale quadrangle bedding attitudes in the New Tripoli and New Ringgold quadrangles are undulose. They vary from N.76°E. in domain 1 to N.72°E. in domain 1 to N.72°E. in domain 2 and back to N.77°E. in domain 3. Attitude variations of the magnitude seen in the eastern part of the Slatedale quadrangle are lacking.

Figure 61 is an equal area projection of slaty

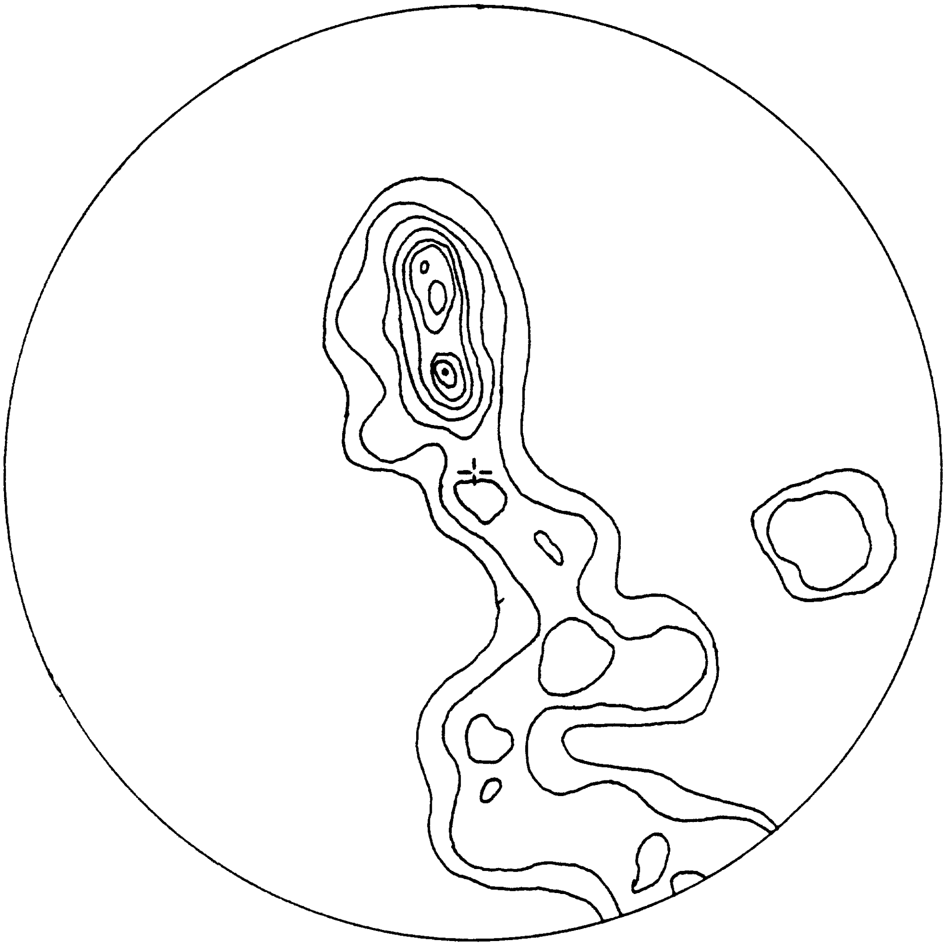


Figure 59: Equal area projection of poles to upright bedding in the New Tripoli and New Ringgold quadrangles. Maximum-N.73°E.24°SE.; n-32; Contour interval-3%/1% area;

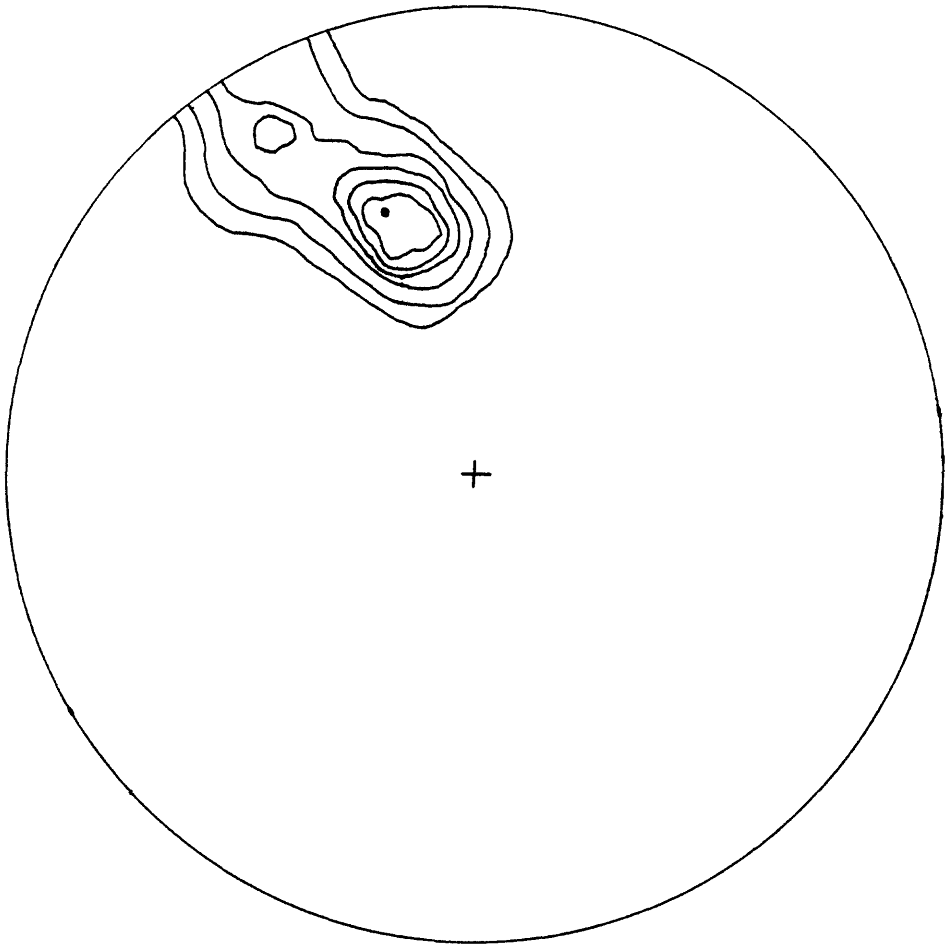


Figure 60: Equal area projection of poles to overturned bedding in the New Tripoli and New Ringgold quadrangles. Maximum-N.71°E.62°SE.; n-14; Contour interval-7%/1% area;

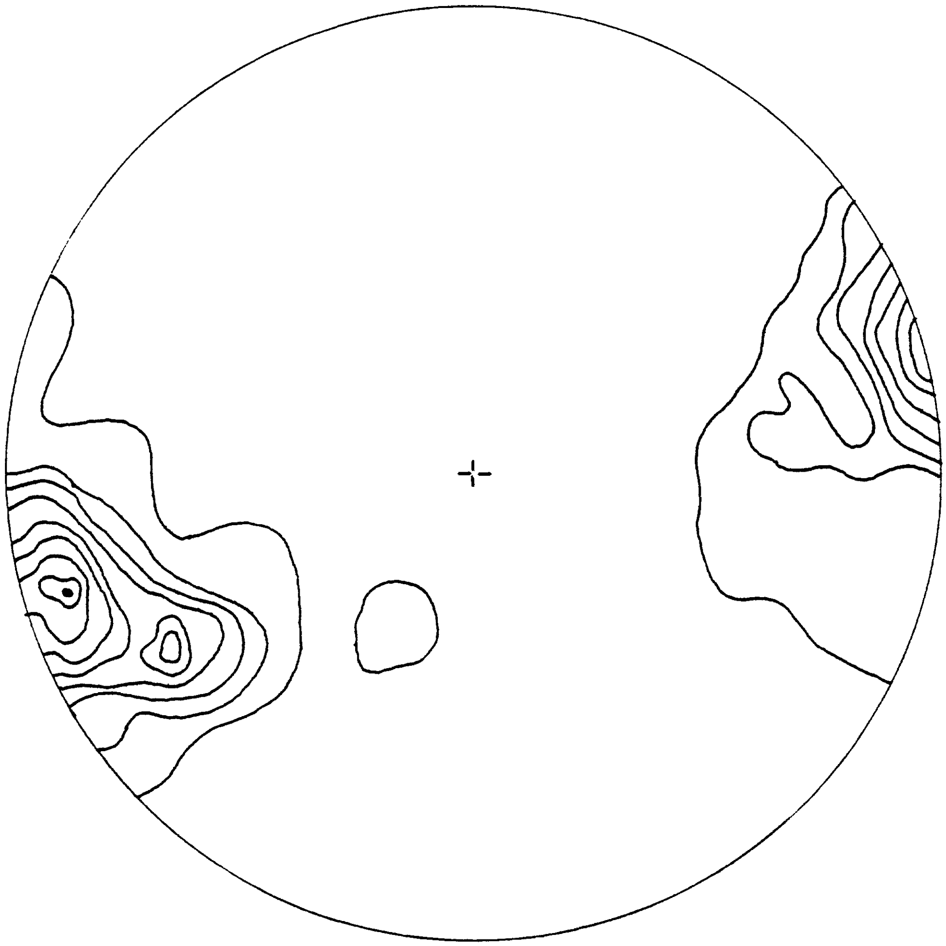


Figure 61: Equal area projection of slaty cleavage-bedding intersections in the New Tripoli and New Ringgold quadrangles. Maximum-6° S.75°W.; n-44; Contour interval-5%/1% area;

cleavage-bedding intersections within the New Tripoli and New Ringgold quadrangles. The maximum, 4° S.74°W., is almost identical to that of the Slatedale quadrangle, 6° S.75°W. Again, as in the case of the Slatedale quadrangle, a girdle indicative of rotation of the lineations is present and may be evidence of more than one period of folding. Figures 62, 63, and 64 are equal area projections of slaty cleavage-bedding intersections for domains 1, 2, and 3, respectively. Figure 62 shows an almost total lack of northeast plunging lineations in domain 1 lending support to the inferred presence of the southwest plunging Mosserville anticline. In domain 2 a maximum of 2° N.77°E. is present indicating a plunge depression between domain 1 (8° S.73°W.) and domain 2 whereas domain 3 shows a maximum of 2° S.71°W. indicating a plunge culmination between domains 2 and 3. Poorly developed girdles were noted in each of the plots. Variations in bedding attitudes are reflected in variations of the slaty cleavage-bedding intersections. The variations in both bedding and slaty cleavage-bedding intersections are not reflected in cleavage trends indicating that the Pen Argyl Member was folded prior to the formation of the slaty cleavage.

Although not as common as in the Slatedale quadrangle, strain-slip cleavage is present in the New Ringgold and New Tripoli quadrangles. Figure 65 is an equal area projection

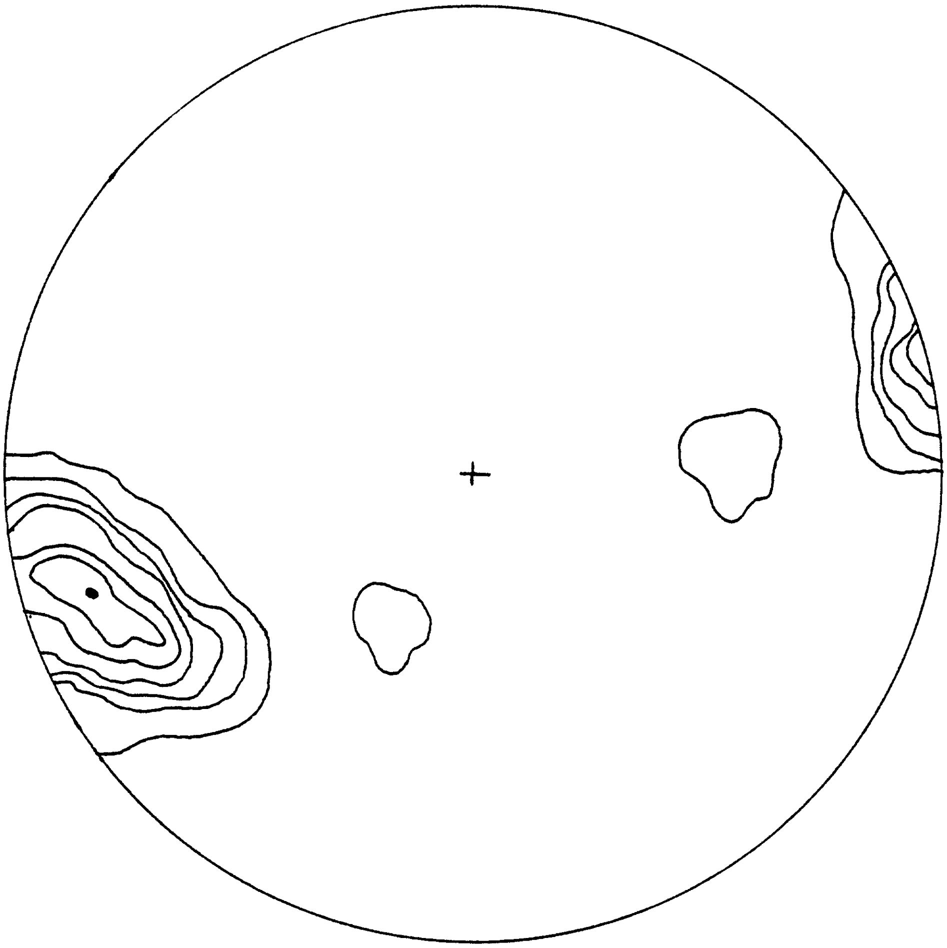


Figure 62: Equal area projection of slaty cleavage-bedding intersections in domain 1 of the New Tripoli quadrangle. Maximum-8° S.73°W.; n-15; Contour interval-7%/1% area;

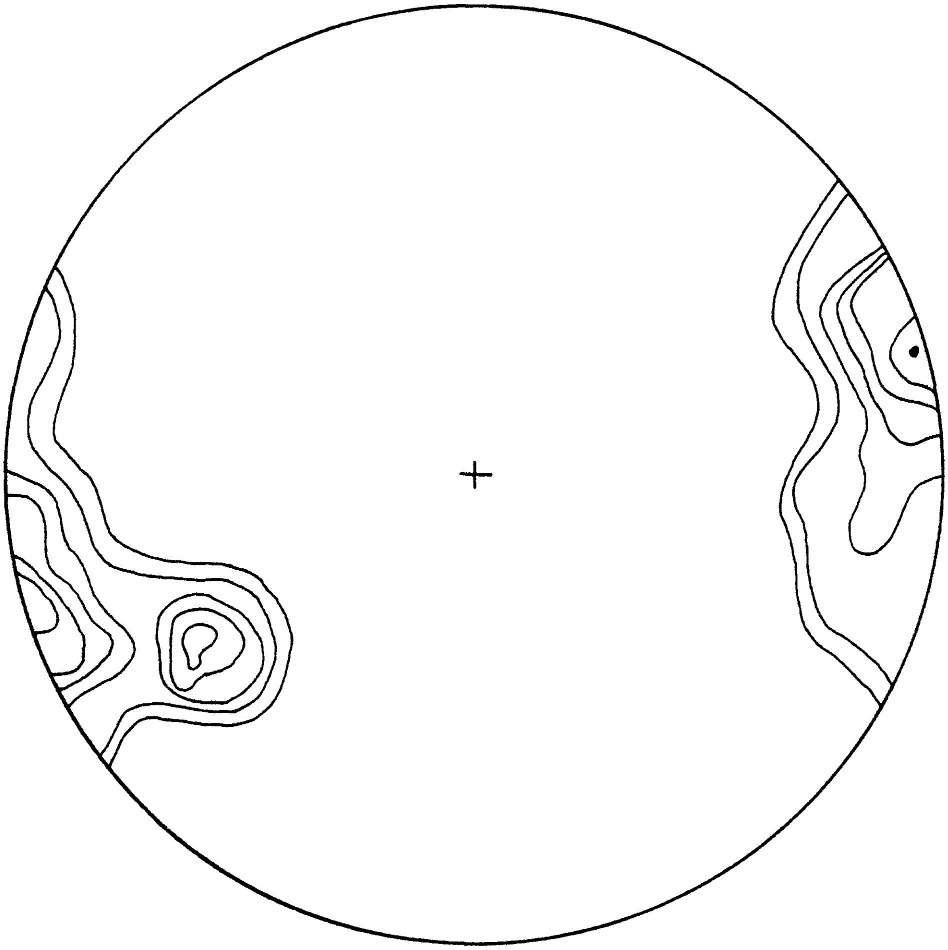


Figure 63: Equal area projection of slaty cleavage-bedding intersections in domain 2 of the New Tripoli quadrangle. Maximum-2° N.77°E.; n-13; Contour interval-7%/1% area;

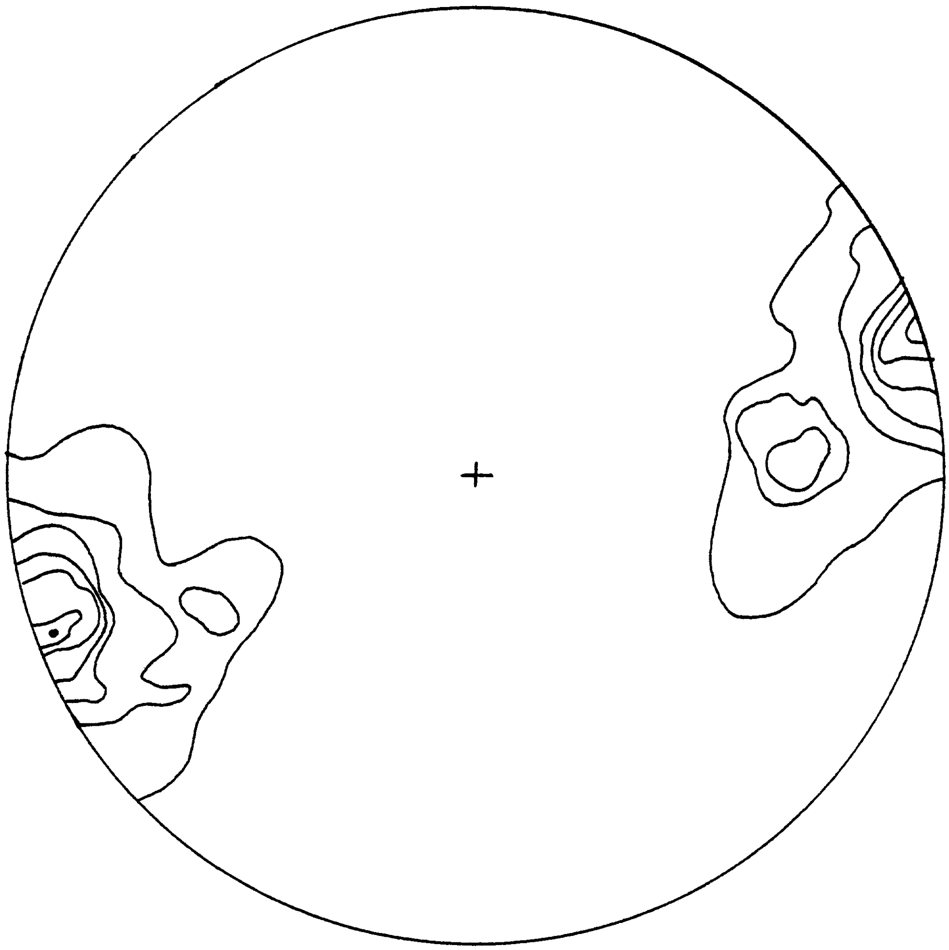


Figure 64: Equal area projection of slaty cleavage-bedding intersections in domain 3 of the New Tripoli and New Ringgold quadrangles. Maximum-2° S.71°W.; n-15; Contour interval-7%/1% area;

of slaty cleavage-strain-slip cleavage intersections within the New Tripoli and New Ringgold quadrangles. A maximum of 10° S.78°W. was noted which is quite close to the slaty cleavage-bedding intersection, 6° S.75°W. The maximum for this area is also quite similar to that of the Slatedale quadrangle, 2° S.83°W.

A girdle can be seen on figure 65 indicating either rotation or an early phase of strain-slip cleavage. This rotation may have been produced by movement along the Eckville fault as a similar girdle is lacking in the slaty cleavage-strain-slip cleavage intersection plot for the Slatedale quadrangle (figure 50). The data that plot on the girdle in figure 65 were taken from outcrops near the Eckville fault. This pattern indicates that the fault and associated strain-slip cleavage formed later than strain-slip cleavage within the main outcrop belt of the Pen Argyl Member. This is shown by the fact that the slaty cleavage-strain-slip cleavage intersections near the fault are oblique to similar lineations away from the fault. In addition, slaty cleavage-bedding intersections and slaty cleavage-strain-slip cleavage intersections away from the fault are essentially parallel indicating that they may have formed in close succession. Thus, as the Eckville fault truncates folds and all lineations associated with folding it is implied that any fault associated lineations are post folding features concomitant with faulting.

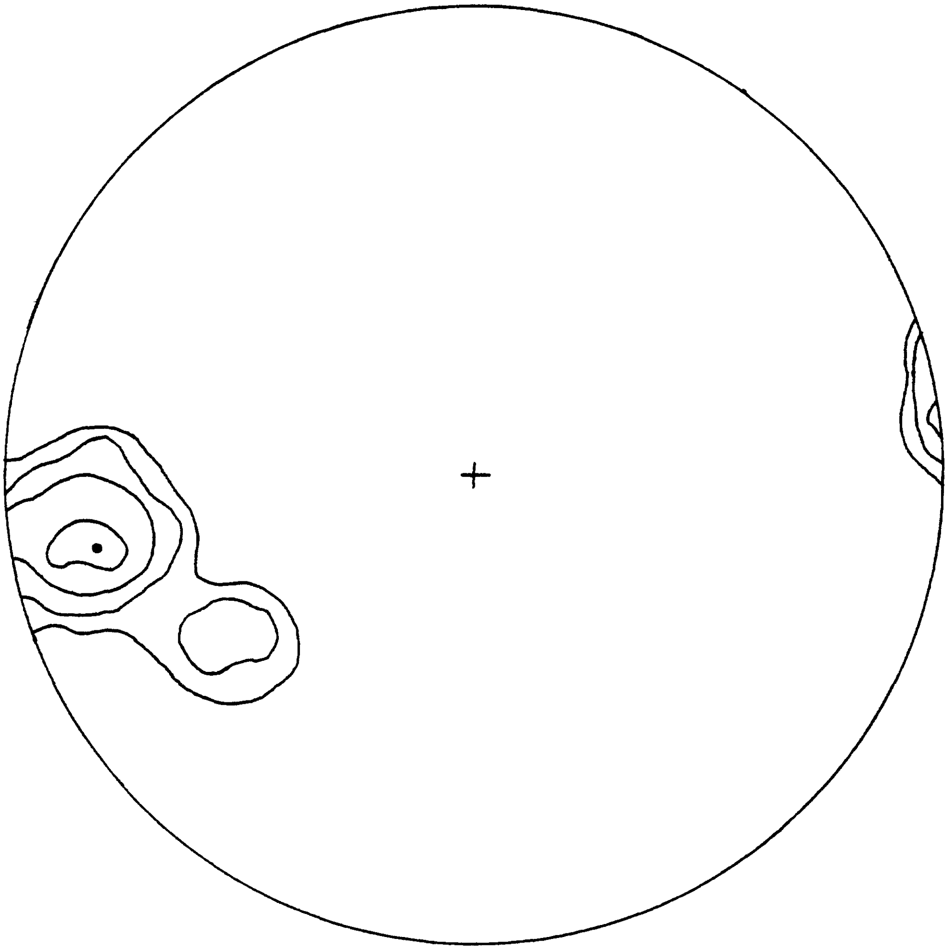


Figure 65: Equal area projection of slaty cleavage-strain-slip cleavage intersections in the New Tripoli and New Ringgold quadrangles. Maximum-10° S.78°W.; n-7; Contour interval-14%/1% area;

SUMMARY OF REGIONAL FABRIC:

The important points gained from the structural fabric analysis of the Pen Argyl Member in the Slatedale, New Tripoli, and New Ringgold quadrangles are listed below:

(1) Slaty cleavage shows very little variation in trend except in the area of the Mosserville anticline. The Mosserville anticline must be younger than the slaty cleavage and probably older than the Eckville fault.

The average dip of the slaty cleavage increases to the west from the Slatedale quadrangle indicating that the folds are becoming more upright to the west.

(2) Bedding shows undulose trends independent of the slaty cleavage suggesting that the variations formed prior to the development of the slaty cleavage. This is important in that it illustrates that the Pen Argyl Member was folded prior to the formation of the slaty cleavage and lends further support to the theory that the slaty cleavage is a post-Taconian deformational feature in these rocks.

(3) Slaty cleavage-bedding intersections are influenced by variations in bedding trends which lend further support to the idea that the Pen Argyl Member was folded prior to the development of the slaty cleavage. This interpretation is also supported by the presence of the conspicuous pi-

girdles on the lineation plots. The girdles indicate an early period of folding (F_2) independent of the slaty cleavage and a later period of folding (F_3) corresponding to the development of the slaty cleavage. Epstein (Epstein and others, 1974) found similar results for the Pen Argyl and Ramseyburg Members of the Palmerton and Lehighton quadrangles.

(4) On a regional scale the slaty cleavage-strain-slip cleavage intersections parallel the slaty cleavage-bedding intersections suggesting that the two lineations were formed in close succession. Two sets of crenulations are present in the area; (1) regional crenulations related to regional deformation and related stress and (2) crenulations located proximal to the Eckville fault with axes that trend in a more southerly direction than the regional crenulations. These crenulations are considered to be younger than the regional crenulations and are thought to be related to movement along the Eckville fault.

TIMING OF DEFORMATION:

Assignment of deformational effects to certian ages or orogenies has always attracted the attention of geologists not only in eastern Pennsylvania but in any other geologically complex terrain. Rogers (1838) maintained that the Appalachian orogeny was the greatest revolution of North America. Miller (1926) believed that slaty cleavage in the Martinsburg Formation had formed during the Taconic orogeny and was folded and faulted during the Appalachian (Alleghenian orogeny). Behre (1933) felt that the slaty cleavage, overturned folds, and thrust faults were the result of an intense Taconic deformation with distortion of the slaty cleavage attributable to the Appalachian or Alleghenian orogeny. Woodward (1957) maintained that the metamorphism of the slate belt or Pen Argyl Member resulted from the superposition of three periods of folding; Taconic, Acadian, and Alleghenian, each of which had different trends. Field support of this theory is lacking.

The arguement continued into the 1960's when Drake and others (1960), working in the Delaware Valley, proposed that the Taconic orogeny was far more intense than the Alleghenian orogeny and resulted in the slaty cleavage of the Martinsburg Formation but Arndt and Wood (1960), working in the Valley and Ridge province, concluded that the Alleghenian orogeny was much more intense than the Taconic orogeny. Maxwell (1962) in maintaining that the slaty cleavage had formed from soft sediment deformation believed that the Taconic orogeny was characterized by diagenetic deformation and the formation of the slaty cleavage.

As was mentioned earlier, field work in eastern Pennsylvania by members of the United States Geological Survey lead to the conclusion that the Great Valley in that area was underlain by a great nappe containing Ordovician and older rocks. The existence of nappes in Pennsylvania has been noted by Bird and Dewey (1970) in their plate tectonic modeling but they maintained that the "strong penetrative deformation of the Martinsburg occurred prior to the deposition of the Tuscarora."

Recently, Epstein and Epstein (1969) and Epstein (1971) have proposed that the Taconic orogeny was characterized by the emplacement of the Musconetcong nappe with associated warping of the nappe while asymmetric folding and associated slaty cleavage is Alleghenian in age. This view was challanged by Alterman (1972) working in the Great Valley between the Schuylkill and Delaware Rivers. She attributed folding and slaty cleavage development to the Taconic orogeny with later thrust and reverse faulting attributable to Alleghenian deformation.

Drake (1969) maintained that the nappe was emplaced in the Taconian and further stated that it may have been emplaced atectonically (no development of a tectonic fabric). He cited evidence from den Tex (1963) in which the author assigns this mechanism of emplacement to some of the nappes of the Caledonides and Alps. Despite this, Alterman maintains (written communication, 1978) that an early slaty cleavage, axial planar to the nappe can be seen in the field. She describes this cleavage as being parallel to bedding. Although it cannot be denied that a cleavage which is axial planar to the nappe is present in some areas field evidence supporting the presence of this cleavage is lacking in the Pen Argyl Member west of the Lehigh River.

In general, one's prejudice for either the diagenetic or metamorphic formation of the slaty cleavage will dictate the interpretation of the age of the slaty cleavage. If one maintains that the cleavage formed due to the rotation of minerals as a result of dewatering he would be required to place the age of the cleavage as Taconian. On the other hand, a metamorphic origin of the slaty cleavage with a minimum of rotation and a great deal of neocrystallization and pressure solution suggests an Alleghenian age for the cleavage. Based on the field and microscopic evidence discussed earlier it appears that the second choice is the more plausible choice.

In a previous section it was noted that bedding in the Pen Argyl Member had been folded prior to the development of the slaty cleavage. This was also noted to the northeast in the Stroudsburg quadrangle by Epstein (1971). In addition, he noted that all other structural features, including slaty cleavage, in the Martinsburg Formation and younger rocks were remarkably similar in strike. Field work in the Martinsburg Formation west of the Lehigh River yielded similar results suggesting that the Martinsburg and older rocks were folded and rotated prior to the Alleghenian deformation but that the slaty cleavage and associated folding was superimposed on the early folds in the Pen Argyl Member during the Alleghenian orogeny.

The relative intensities of the Alleghenian and Taconic orogenic events in eastern Pennsylvania remains an enigma. Assignment of deformational features to different orogenies without the use of isotopic dating is difficult. The absolute dates of events such as the Taconian and Alleghenian orogenies are poorly understood and vary from place to place along the strike of the Appalachian system. Also, deformational effects of the various orogenies are commonly lacking in certain areas. Based solely on field evidence gleaned from the study of the Pen Argyl Member it is concluded that (1) the Pen Argyl Member was deposited in the waning stages of flysch deposition in response to an uplifted land mass to the southeast during the Taconian event; (2) during the Taconic orogeny the outcrop belt of the Pen Argyl Member was folded and rotated as the large nappe was emplaced; (3) tight, asymmetric folding and associated slaty cleavage formed during a post-Silurian event, probably the Alleghenian orogeny; (4) the strain-slip cleavage formed towards the end of the stress continuum that had formed the asymmetric folds; (5) large scale folding (i.e., the Mosserville anticline) and high angle reverse faulting and associated strain-slip cleavage occurred late in the Alleghenian event. Table 3 provides a more detailed tectonic summary of the area. The reference to Taconic and Alleghenian is merely used to illustrate the relative timing of the deformation and its effects and is in no way intended to imply any absolute ages.

Bird and Dewey (1970) have offered a plate tectonic model for the formation of the Appalachians. The presence of ultramafic rocks in the Piedmont of the east coast of North America has been cited as evidence for subduction with nappe formation in the interarc basin to the northwest with the obduction of the ultramafics and their mélange. The obduction was probably quite instrumental in the formation of the Musconetcong nappe of southeast Pennsylvania. Further work is still needed to resolve this problem and understanding relations in the Piedmont is critical to resolution of this problem.

Table 3

DEFORMATION IN THE PEN ARGYL MEMBER

Deformation	Description	Resulting Structure	Remarks
D_1	nappe formation-Taconian	F_1-nappe	The emplacement of the nappe may or may not have been tectonic. No evidence of an axial plane cleavage to the nappe was observed in the area.
D_2	Taconian re-folding of the normal limb of the nappe	F_2-open folds	D_2 may be treated as an extension of D_1 as D_1 probably proceeded into D_2 without interruption.
D_3	Alleghenian tight, asymmetric passive-slip folds	F_3-asymmetric folds S_1-slaty cleavage	The slaty cleavage is axial planar to the folds. Small thrust and reverse faults are closely related to the folding. F_3 folds show a more east-west trend than the F_2 folds.
D_4	development of strain-slip	F_4-crenulations S_2-strain-slip cleavage	Strain-slip cleavage formed towards the end of the same Alleghenian stress continuum that had resulted in the F_3 folds and slaty cleavage.

Table 3 (cont'd)

Deformation	Description	Resulting Structure	Remarks
D_5	large scale folding	F_5-Mosserville anticline	This fold formed prior to movement along the Eckville fault and after the F_3 folding.
D_6	late Alleghenian high angle reverse faulting with associated strain-slip cleavage and kink folding	F_6-crenulations and kink folds associated with faulting	It should be noted that D_3 through D_6 form a continuum of deformational effects during the Alleghenian orogeny.

CONCLUSIONS:

The Pen Argyl Member is well suited to recording the effects of deformation. These have been described and summarized in the preceeding sections and will not be discussed here. It has been thoroughly demonstrated in the field that the Pen Argyl Member does in fact overlie the Ramseyburg Member in the normal sequence of the Martinsburg Formation. This supports the tripartite subdivision of the Martinsburg Formation. Proving the existence of the Mosserville anticline has been critical to this interpretation. The Ramseyburg Member occupies the core of this large, southwest plunging anticline. Graded bedding, crossbedding, and cleavage-bedding relationships at the contacts of the Ramseyburg and Pen Argyl Members further substantiate the tripartite subdivision.

The presence of a fault separating the slate belt from the rocks of Shochary Ridge was postulated by Behre (1933). Detailed mapping has substantiated the presence of the Eckville fault as existing between the Shochary sequence and Pen Argyl Member. In addition, it has been discovered that the fault is not a low angle thrust as proposed by Behre but a high angle reverse fault with a possible dip of 80° to 85° to the southeast. It is quite possible that the fault may flatten out with depth and may be a splay off a large décollement. At the present level of erosion this cannot be proven. The Eckville fault is located on the normal limb of the large, northward overturned syncline containing the Shochary sequence. The rocks to the south of the fault are thin bedded pelites and graywackes which are believed to represent the lower units of the Shochary sequence. The fault has been traced with difficulty eastward into the Slatedale quadrangle where it apparently separates the Ramseyburg Member from the interbedded pelite and graywacke. It may well extend into the Cementon quadrangle farther to the east. The Eckville fault formed late in the tectonic history of the area probably concomitant with a similar high angle reverse fault that separates the Shochary sequence from rocks of the Hamburg Klippe to the south (Peter Lyttle, personal communication, 1978).

Mapping of the Ramseyburg Member in the Slatedale quadrangle led to the conclusion that it is inverted. Mapping of the Pen Argyl Member in the Slatedale quadrangle and other quadrangles west of the Lehigh River indicates that these rocks are on the brow and normal limb of Muscontcong nappe. Thus a fault may be present in the Slatedale quadrangle that has juxtaposed the normal limb of the nappe, represented by the Pen Argyl Member, and the inverted limb, represented by the Ramseyburg Member. Another possibility is that the nose of the nappe may be located just to the south of the Pen Argyl Member thus exposing an inverted Ramseyburg sequence.

Analysis of the abundant structural fabric data obtained from the Pen Argyl Member indicates that the Pen Argyl Member and probably the rest of the Martinsburg Formation was folded prior to the development of the slaty cleavage. This phase of folding has been attributed to the Taconic orogeny with later tight folding and the development of the penetrative slaty cleavage resulting from Alleghenian deformation. Fold axes of the asymmetrical Alleghenian folds (F_3) closely parallel the axes of the strain-slip crenulations indicating that the strain-slip cleavage and crenulations (F_4) and the asymmetric (F_3) folds may have formed as part of the same stress continuum in the Alleghenian event. The last major tectonic event was high angle reverse faulting such as that characterized by the Eckville fault and the fault separating the Shochary sequence from the Hamburg Klippe. The Mosserville anticline formed before the reverse faulting but after the slaty cleavage formation.

Field and thin section studies have supported the interpretation that the slaty cleavage has a metamorphic origin. Porphyroblasts of chlorite and muscovite are clearly the result of metamorphism. They are not clastic grains. If the slaty cleavage is metamorphic in origin then an Alleghenian age of deformation is implied since the Pen Argyl Member is the highest stratigraphic unit during the Taconian time and could therefore not have been subjected to the great depth of burial. Mechanical rotation has not been very important in the formation of the slaty cleavage (Holleywell and Tullis, 1975) in the slate belt and it appears that pressure solution has played a significant role in the formation of the slaty cleavage (Groshong, 1976). Field and microscopic evidence indicates that; (1) the Pen Argyl Member was indurated prior to the development of the slaty cleavage, (2) pressure solution has played a great role in the formation of the slaty cleavage, and (3) neocrystallization in response to lower greenschist facies metamorphism was instrumental in the development of the slaty cleavage seen in the Martinsburg Member.

Placing the Pen Argyl Member and older rocks in a plate tectonic framework is not an easy task. It has been proposed that obduction was occurring to the southeast during the Taconic orogeny. The Martinsburg Formation was deposited as a flysch sequence in response to rising land masses to the south with the Pen Argyl Member being deposited in the late stages of the Taconic event. With the occurrence of subduction of the oceanic plate to the southeast the Appalachian geanticline began to rise in response to density contrasts. With formation of the geanticline and possible underthrusting of the Precambrian rocks (Drake, 1969) and obduction of the ultramafic rocks and their mélanges the large nappes present in the Great Valley resulted from the collapse of the system. In addition to nappe formation, gravitational sliding of slope, miogeosynclinal, eugeosynclinal, and basement rocks was occurring at this time and probably prior to the development of the nappes (Drake, 1969; written communication, 1978). Further regional studies in southeastern Pennsylvania may lead to a more complete picture of the interrelations of plate tectonics and orogeny in the Central Appalachians.

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APPENDIX A:

Slate Quarries of Lehigh and Berks Counties:

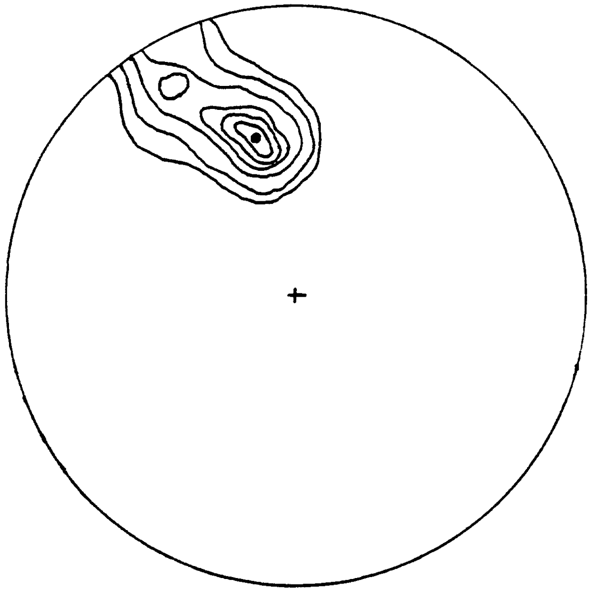
The Pen Argyl Member is best exposed in the many slate quarries of the area. It is here that the most structural and stratigraphic detail can be observed. The locations of locations of the slate quarries visited are given on Plates IV, V, and VI.

In general, most of the quarries are flooded. A rubber life raft was used to get into a number of them. The Manhattan quarry (#18) of the Penn Big Bed Slate Company is the only active quarry in the area. Some of the quarries have been described by Sanders (1883) and almost all were studied by Behre (1933). In spite of this, several of the quarries required different structural and stratigraphic interpretations.

The history of slate quarrying in Lehigh and Berks Counties is a long one. It is generally believed that quarrying began in the early 1800's. It continued until the early 1900's when it declined due to the production of synthetic products, high freight costs, and numerous other problems. The majority of the quarries visited have not been active for over 60 years.

Slate quarries in the Slatington and Lynnport slate districts were visited. The different methods of quarrying are immediately visible. Whereas the quarries of the Slatington district were worked to great depths (up to 500 feet) the quarries of the Lynnport district are much more shallow. Another difference can be seen in structural diagrams. Figure A1 shows the poles to normal and overturned bedding in the Lynnport slate district. Figure A2 shows the same information for the Slatington district. The plots indicate that the majority of the quarrying done in the Slatington district was done on the northern limb of northward overturned anticlines or the southern limb of overturned synclines. This is evident from the maxima indicating steeply dipping beds for both the normal and overturned beds. Figure A3 shows the positions of the quarrying on a fold. A secondary maximum for the upright beds shows a more gentle dip. The quarries of the Lynnport district have an upright maximum in the same general area on the diagram as the secondary maximum for the upright beds in the Slatington district. This maximum is taken to represent the true maximum for the normal limb of the folds in the Slatington district. Thus the data show that structural information (ie., bedding planes) from the Slatington slate district has been biased by the quarrying practices in that district.

Whereas most of the quarries of the Slatington district were confined to the steep limbs of the folds, operations in the Lynnport district were essentially evenly



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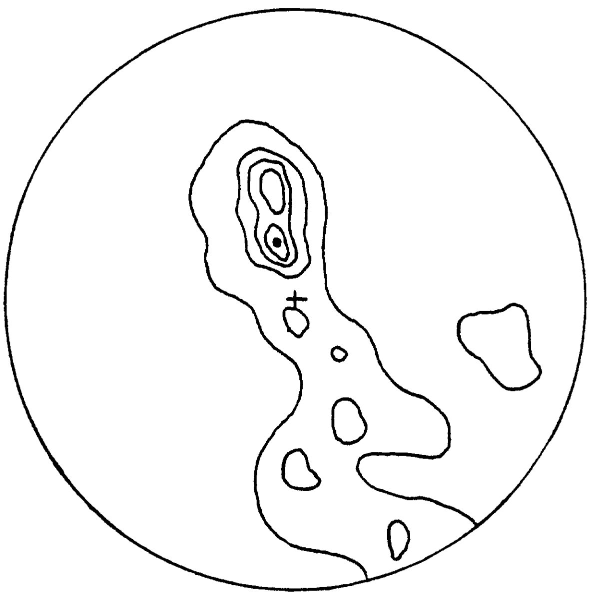
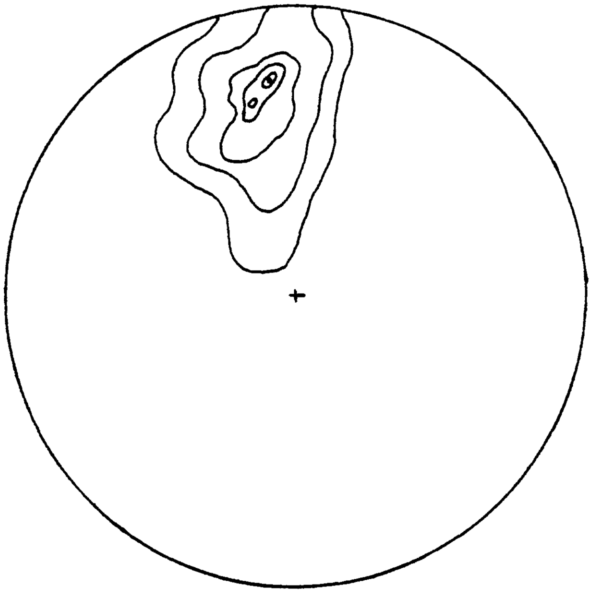
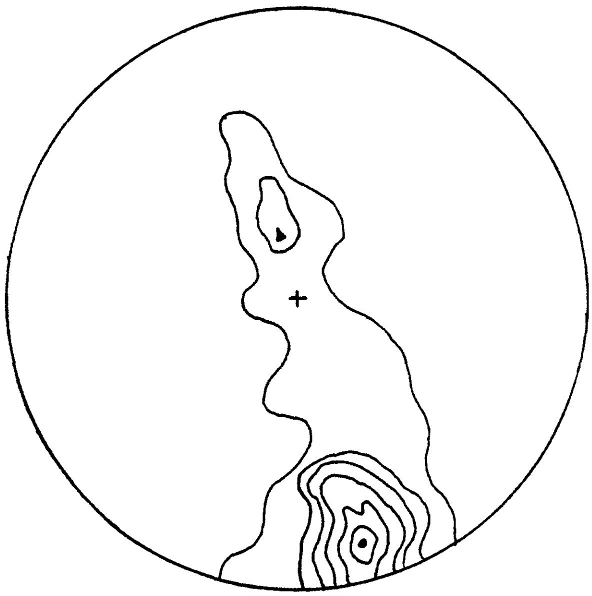


B

Figure A1: Poles to overturned (Max.-N.71°E.62°SE.) (A) and upright (Max.-N.73°E.24°SE.) beds (B) in the Lynnport slate district. Contour interval-10%/1% area.



A



B

Figure A2: A-Poles to overturned bedding in the Slatington slate district. Maximum-N.81°E.79°SE.
B-Poles to upright bedding in the Slatington slate district. Biased maximum (dot)-N.75°E.83°NW.; Unbiased maximum (triangle)-N.77°E.27°SE.;
The data indicates that the structural data for the Slatington slate district has been biased by quarrying operations. Contour interval-7%/1% area.

distributed between the steep or overturned limbs and the gently dipping normal limbs (figure A3).

Quarries will be discussed starting with those of the Slatington district. Most of the structural data was collected in the field but some of the data for inaccessible quarries was taken from Behre (1933). The reader may wish to refer to Plates IV, V, and VI for locations of the quarries.

Slatington Slate District (Slatedale Quadrangle)

Quarry (#1):

Two small, circular openings were visited. No exposed rock can be found in either of the openings. Dumps about 8 feet in height are associated with the openings. The slaty cleavage in small outcrops in a nearby stream dips 56° SE. but bedding cannot be determined.

Old Diamond Quarry (#2):

This quarry was described by Behre (1933, p. 283). The slaty cleavage dips 45° SE. and the beds dip 24° NW. indicating that the quarry was opened to the north of an anticlinal axis. Behre believed that this quarry was opened on the south limb of the Prudential syncline. One very thick bed (figure A4) was noted along with thin, highly carbonaceous beds commonly called "ribbon beds" or "ribbons".

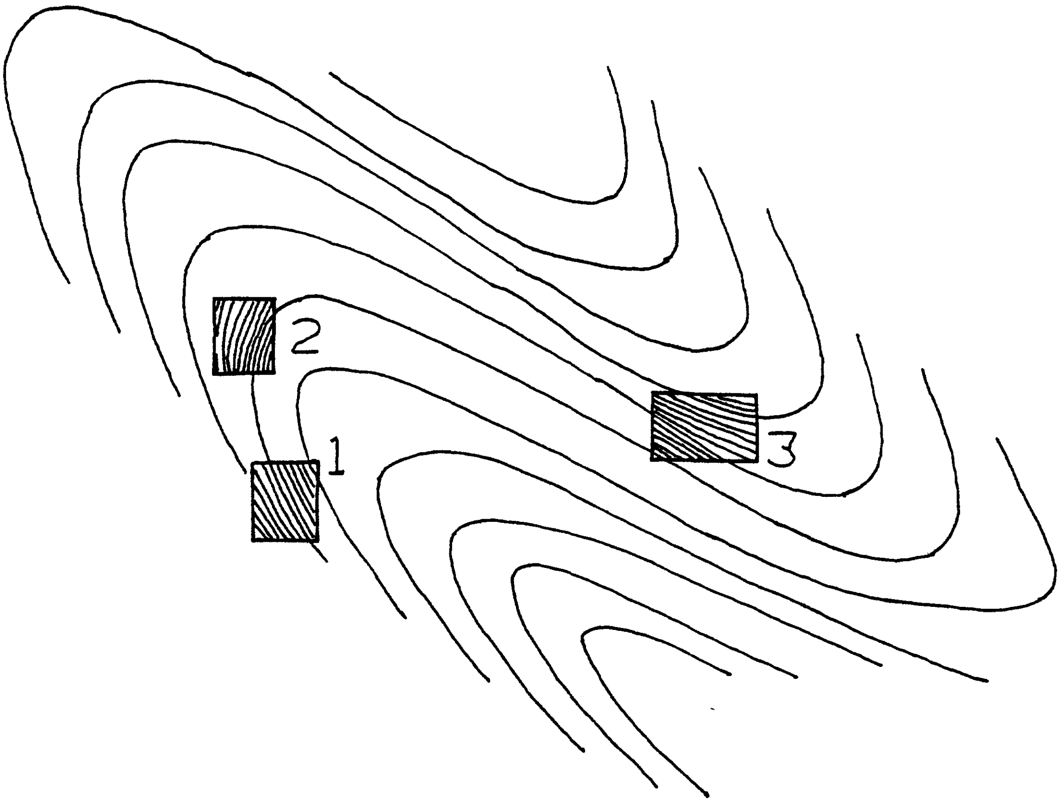


Figure A3: Diagram of quarrying operations on a fold in the Lynnport slate district (areas 1 and 3) and in Slatington slate district (areas 1 and 2). Areas 1 and 2 indicate the general location of quarry operations in the Slatington district that would result in the maxima seen in figure A2. Areas 1 and 3 indicate quarrying operations in the Lynnport district resulting in the maxima seen in figure A1.

Figure A4: East wall of the Old Diamond quarry located about 1 mile south of Lehigh Furnace. Beds dip to the north (left) and slaty cleavage dips to the south (right). Note the thick claystone slate bed in the center of the photograph. Slatedale quadrangle.

New Diamond Quarry (#3):

This quarry is about 500 feet east of the Old Diamond quarry (#2) and is filled with garbage and water. The beds here dip about 45°NW. indicating that it is structurally south of the Old Diamond quarry. It is located to the north of the anticlinal axis described in the discussion of the Old Diamond quarry above.

Quarry (#4):

This quarry is unnamed but was described by Behre (1933, p.283). The beds stand almost vertical dipping steeply north. It is very close to the crest of the anticline described in the above two quarries.

Quarry (#5):

Two small, unnamed openings were found, neither of which show any rock. Beds in outcrops in a nearby stream dip 20°SE. indicating a synclinal axis to the south.

Blumont Quarries (#6):

Very little slate was exposed in either of these two flooded quarries. Behre (1933, p. 285) described these openings as existing in the trough of the Eureka syncline. Beds dip 40°NE. and cleavage dips 50°SE.

Peach Bottom Quarry (#7):

This quarry was described by Behre (1933, p. 283). Beds dip 83°NW. but flatten out towards the top of the opening indicating an anticlinal axis to the immediate south.

Highland Quarries (#8):

The Highland quarries are made up of five openings on the side of a steep hill. The quarries are probably quite deep but are now filled with water. In general, bedding ranges from 70°NW. at the surface to horizontal at depth thus indicating a synclinal axis to the north. These quarries were described by Behre (1933, p. 285) as being opened along the strike of the beds in this area.

West Highland Quarry (#9):

This quarry was described by Behre (1933, p. 283). The beds dip steeply to the north indicating that the quarry was opened on then north limb of a northward overturned anticline and structurally south of the Highland quarries (#8).

Hope Quarry (#10):

This opening is about 500 feet in length and about 100 feet wide. It is completely filled with water. Slate is exposed at the west end of the quarry. Beds dip 74°SE. and cleavage dips 55°SE. Thus the inverted limb of a northward overturned fold has been exposed in this opening. Behre (1933, p. 285) described this opening as lying on the south limb of the Star syncline.

Saegersville Quarries (#11):

Three openings were visited. Bedding ranges from N.83°E.63°NW. in the easternmost quarry to N.87°E.83°SE. in the western quarry. Thus the structure seen in these quarries is essentially the same as that seen in the Hope quarry (#10) about 200 feet to the north.

Graded bedding and cross-bedding are well developed in some of the more silty beds. Much of the bedding in these quarries is of the "ribbon" type. Very thick beds (3 feet or greater) lacking. The openings were described by Behre (1933, p. 285).

Fenstermacher and Roth Quarry (#12):

This opening is completely filled with water and garbage and no slate is exposed. Behre (1933, p. 285) made similar observations.

Figure A5 shows a geological map and cross-section illustrating the relations of the Old Diamond, New Diamond, West Highland, Peach Bottom, Hope, and Saegersville quarries to the regional structural geology.

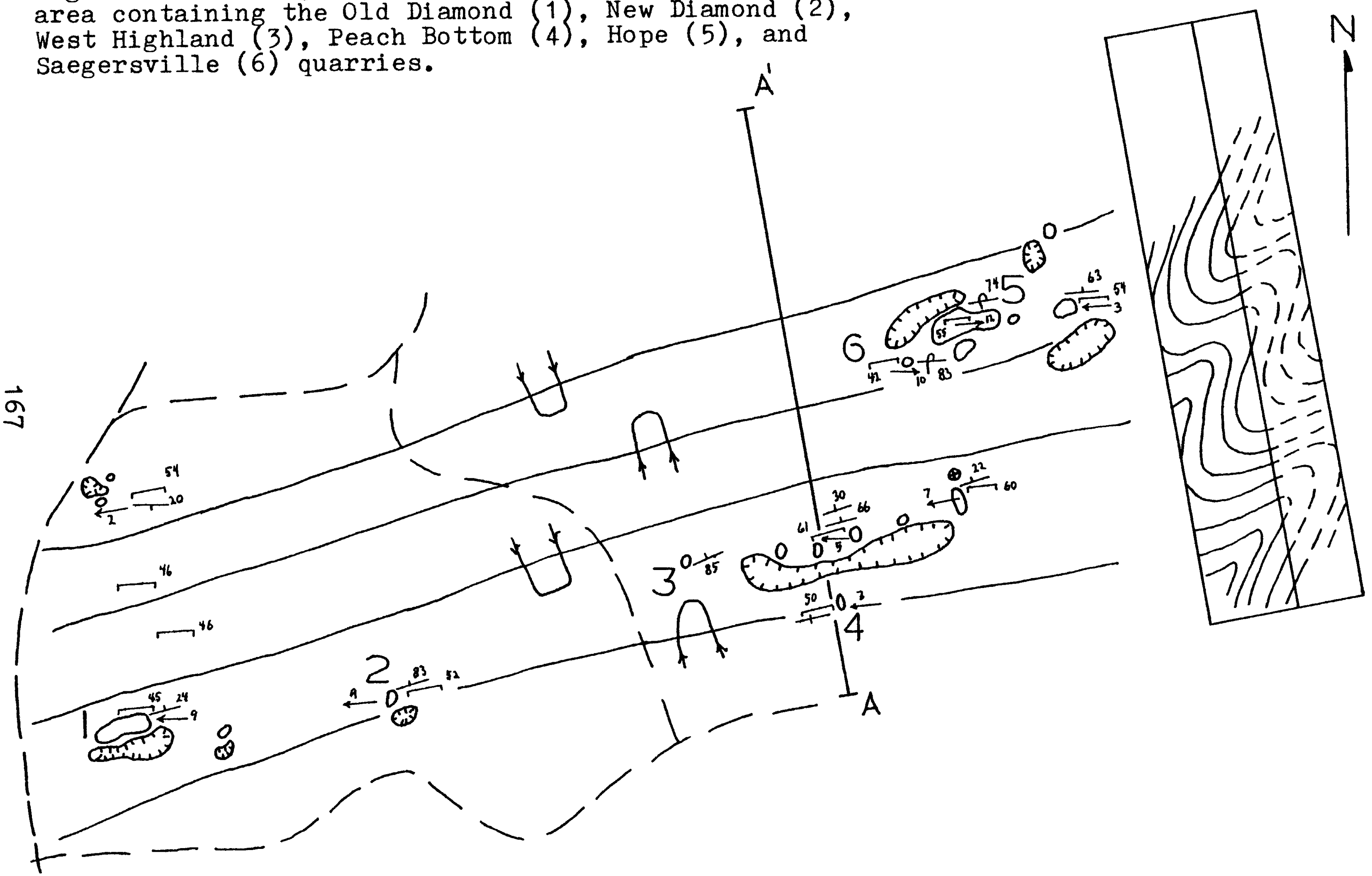
Royal Blue Quarries (#13):

This is actually three quarries which appear to be one due to flooding. There is no exposed slate. Behre (1933, p. 289) stated that the beds dipped 75°NW. but flattened "northward and downward." Thus an anticlinal axis to the south is indicated. This opening now serves as a dump for the Manhatten quarry (#18) to the north.

Locke Quarry (#14):

A good amount of slate is exposed on the west wall of this quarry. It is situated directly west of the Royal Blue quarries (#13). At the extreme northwest corner beds

Figure A5: Geological map and cross-section of the area containing the Old Diamond (1), New Diamond (2), West Highland (3), Peach Bottom (4), Hope (5), and Saegersville (6) quarries.



dip 38°NW. while farther to the south the beds dip 75°NW. Thus an anticlinal axis to the south and a synclinal axis to the north is indicated.

Figure A6 shows the west wall of the quarry. Here the beds can be seen dipping moderatley to the north. Bedding ranges from "ribbons" to beds 7 feet in thickness. Gentle north dipping joints are present and it appears that some movement has taken place along them.

Bloos Quarries (#15):

These two small openings lie to the south of the Locke (#14) and Royal Blue (#13) quarries. The northern quarry of the two, although flooded, exposes a small amount of slate in which the beds are essentially vertical. The southern quarry shows no slate but the structure in it is probably not much different than the one to the north.

Quarry (#16):

These quarries were unnamed. Behre (1933, p. 287) described four quarries. Beds dip 73°NW. but flatten downward indicating a synclinal axis to the immediate north. Behre felt that this quarry was in the Euraka syncline. Two beds, 10 to 15 feet in thickness, separated by about 40 feet of "ribbons" are present in the eastern quarry. Sedimentary structures such as graded bedding, cross-bedding, and convoluted beds are quite common.

These quarries are located along the strike of the Locke and Royal Blue quarries and thus show similar

Figure A6: West wall of the Locke quarry. Beds dip moderatly to the north. About 400 feet south of here the beds are vertical. Slatedale quadrangle.

structural relations.

Columbia Quarry (#17):

The Columbia quarry is the largest of three quarries in the general area. Two smaller quarries are located about 100 feet north of the Columbia quarry along the strike of the bedding.

Beds in the Columbia quarry dip about 80°NW. Behre (1933, p. 288) stated that beds in the southeast corner of the quarry dipped 10°NW. but became steeper to the north. The steep beds were noted in the present investigation but the gently dipping beds were not, presumably due to colluvium cover.

The two smaller quarries to the north show beds that are standing vertical. Thus the structural evidence found at these quarries and the Columbia quarry implies an anticlinal axis to the south.

Manhattan Quarry (#18):

This is the only active quarry in the area studied. It is located next to the old Manhattan quarry described by Behre (1933, p. 291). The quarry was opened on the hinge of the northward overturned anticline implied in the Columbia quarry (#17). Figure A7 shows the anticline. Cleavage fanning is quite evident from the picture. Bedding-plane slickensides, indicative of flexural slip folding, was also noted. Displacement of the slickensides along slaty cleavage planes indicates that passive folding

Figure A7: West wall of the Manhattan quarry showing the northward overturned anticline. Rough areas on the wall indicate where the slate has been blasted. Slatedale quadrangle.

has occurred. Quartz and calcite fracture fillings are common. Small sigmoidal tension gashes were found between two beds which is again indicative of buckling and flexural slip folding at some time. Numerous gentle, north-dipping joints were noted with most of them being confined to the normal limb of the fold. Cross-bedding and structures similar to ripple marks were also noted. Of special interest is the reverse fault found in the normal limb of the anticline. The fault shows relatively little displacement.

The Manhattan quarry has been described by Epstein and Epstein (1969) and Epstein and others (1974). It is approximately 400 feet by 300 feet in ground plan and about 250 feet deep at the present time. Figures A8 and A9 show the present opening and the part of the Manhattan quarry which is flooded and no longer being worked.

Kern Quarries (#19):

Three quarries were visited, two of which show no slate. Behre (1933, p. 291) described these openings at a time when they were still in operation. The easternmost quarry shows a small amount of slate in place. Here the beds dip 70°NW. at the northern edge and about 85°SE. at the south edge thus implying an anticlinal axis to the south. Behre stated that the southern quarry showed beds dipping about 83°SE. thus lending support to the above contention.

Figure A8: View of the present operation in the Manhattan quarry. At the present time the the depth of the quarry is about 250 feet. Slatedale quadrangle.

Figure A9: The east half of the Manhattan quarry which is, at the present time, not in operation. Slatedale quadrangle.

Standard Quarry (#20):

This quarry has been described by both Behre (1933, p. 292) and Epstein (Epstein and others, 1974). There are actually two Standard quarries; the West Standard quarry and the East Standard quarry. There is no exposed rock in the east quarry, a point noted by Behre, but a good amount is exposed in the west quarry. The beds dip 83°NW. at the surface but reverse themselves to 83°SE. near the bottom of the quarry. An anticlinal axis to the south is implied.

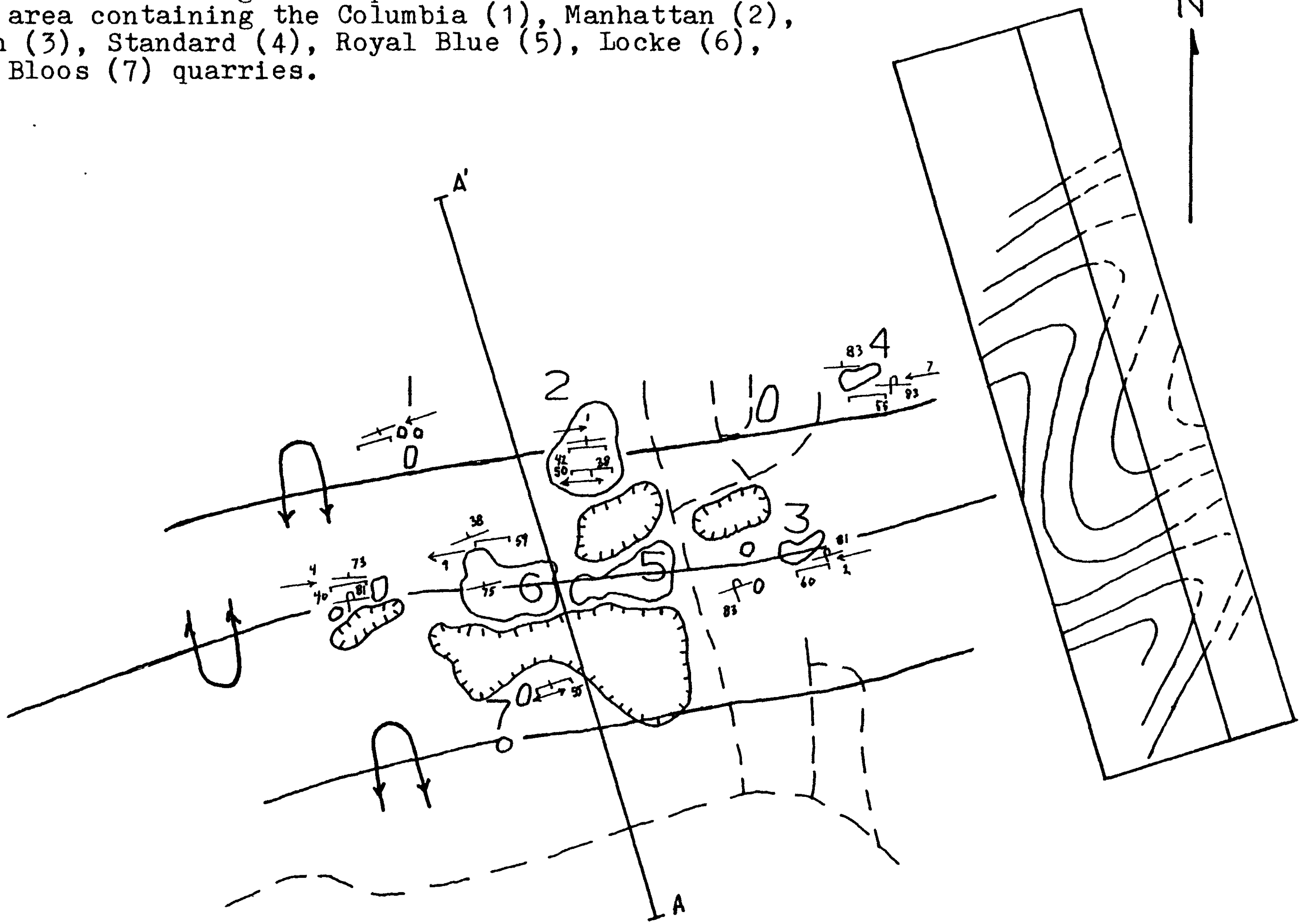
Another small, unnamed quarry west of the West Standard quarry was also noted. This opening is completely flooded with water rising to ground level. A good deal of the original equipment remains at the quarry.

Figure A10 shows a geological map and cross-section of the area containing the Royal Blue quarries (#13) to the Standard quarries (#20).

East Saegersville, Bittner, and Mack Quarries (#21):

More than 20 openings are concentrated in a ½ by 1 mile area about 3/4 of a mile south of Slatedale. The largest quarries are those of the East Saegersville group. They are continuous along the strike of the bedding from the Saegersville (#11) openings mentioned earlier. Behre (1933, p. 286) described these openings. The quarries are rectangular, the largest being about 70 by 250 feet. They are now completely filled with water. Slaty cleavage dips 47°SE. and beds dip steeply to the north. Thus these

Figure A10: Geological map and cross-section of the area containing the Columbia (1), Manhattan (2), Kern (3), Standard (4), Royal Blue (5), Locke (6), and Bloos (7) quarries.



quarries were opened on the crest of a northward overturned anticline. A great deal of "ribbon" beds were noted in these quarries. The same was noted for the Saegersville quarries (#11) to the west. Graywacke beds are common and display graded bedding and cross-bedding.

The Bittner quarries lie to the immediate east of the East Saegersville quarries. Behre (1933, p. 286) described ten openings but only seven were visited by myself. These openings are narrow and quite deep. Behre stated that some were connected by tunnels. They showed structural relations similar to the East Saegersville quarries with beds dipping to the north.

The Mack quarries and numerous unnamed quarries are located along the strike of the bedding immediately north of the Bittner quarries. The beds generally dip 80°NW. to vertical. A well developed strain-slip cleavage was noted in several of the quarries. The slaty cleavage-strain-slip cleavage intersection is 15° S.73°W. The Mack quarries, like the other quarries just described above, were opened on the crest and overturned limb of a northward overturned anticline.

Philadelphia Quarry (#22):

The Philadelphia quarry is found about 1,500 feet northeast of the East Saegersville quarries (#21) on the north side of the creek. This opening is completely flooded and shows no slate. Behre (1933, p. 286) made similar observations but stated that it "was said to have been opened in the Washington 'run', the beds standing vertical."

Figure A11 shows a geological map and cross-section showing the general area of the East Saegersville, Bittner, Mack, and Philadelphia quarries. Because of the proximity of the quarries to each other in this area and the area to the immediate west and east, the structure can be traced for long distances. This can be seen on the geological map of the Slatedale quadrangle (Plate III).

Myers Quarry (#23):

This quarry is one of about seven small but deep openings in the area. The Myers quarry was described by Behre (1933, p. 292). The beds dip 42°NW. while in the smaller quarries to the immediate south the beds dip about 80°NW. and steepen downward. Thus an anticlinal axis to the south is implied.

Blue Mountain Quarry (#24):

This quarry is quite large, measuring about 400 feet by 225 feet. Behre (1933, p. 292) described this quarry as did Dale (1914). A large syncline is exposed on the west wall of the quarry. Behre referred to this syncline as the Prudential syncline.

Beds at the north side of the quarry dip 6°SE. thus indicating an anticlinal axis to the north.

Strain-slip cleavage is quite prominant at the hinge

Figure A11: Geological map and cross-section of the area containing the East Saegersville (1), Bittner (2), Mack (3), and Philadelphia (4) quarries.

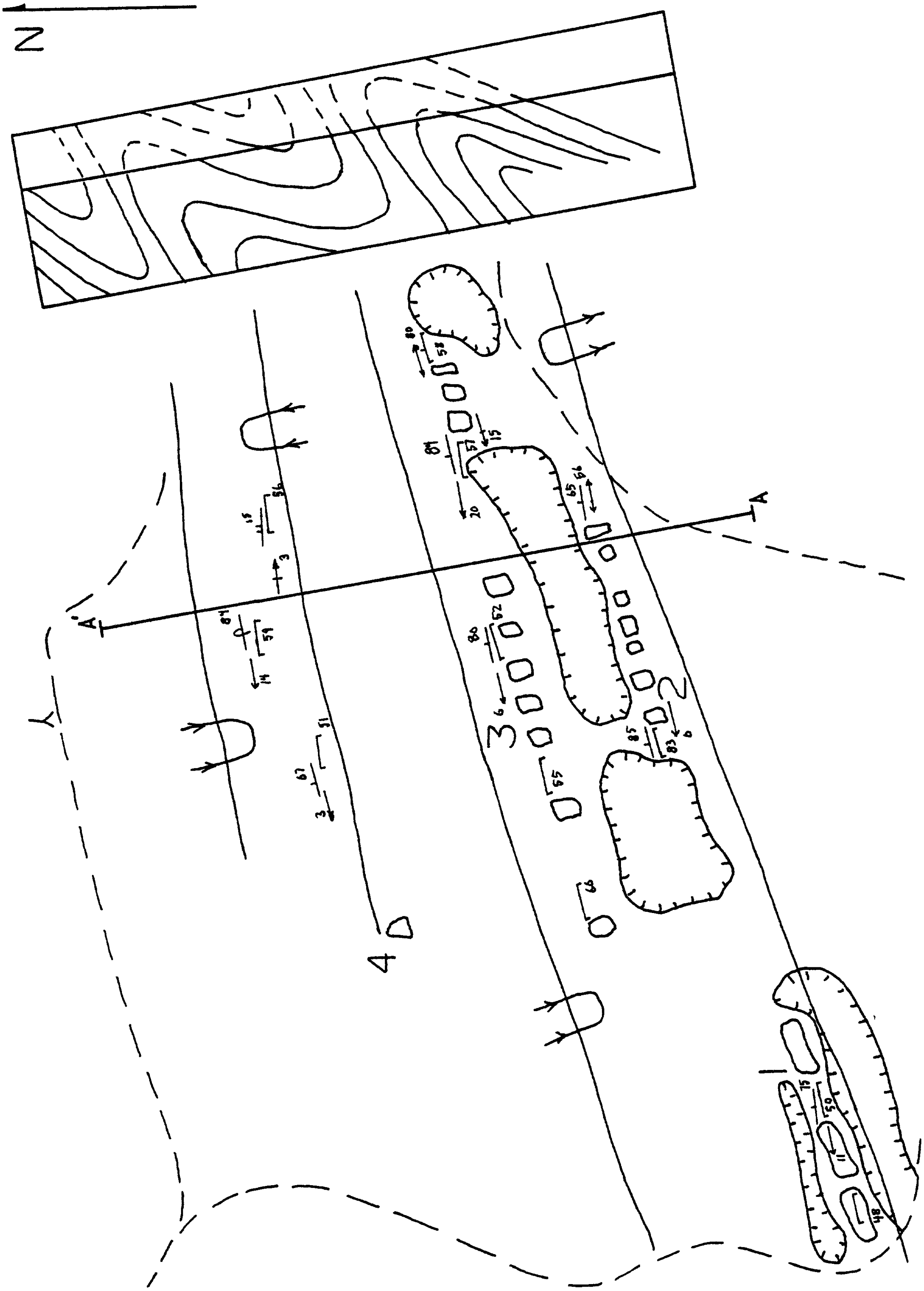

N
A
A'
1
2
3
4

Figure A12: Bedding in the Blue Mountain quarry on the north edge of the opening. The thick slate bed is 15 feet in thickness and is underlain by a 3-foot thick, massive graywacke bed. Beds dip to the south in the direction of the observer. Slatedale quadrangle.

of the syncline. This occurrence was also noted by Behre. The strain-slip planes dip about 40°NW., essentially perpendicular to the slaty cleavage at that part of the quarry. Cleavage fanning about the axial plane of the fold is also quite conspicuous.

Sedimentary structures such as cross-bedding and graded bedding are common in the graywacke and siltstone beds. One 3-foot thick, massive graywacke bed is present. A 15-foot slate bed was also noted. Behre mentioned this bed in his description of the quarry. Figure A12 shows the bedding on the north side of the quarry.

Bucktown (Dilliard) Quarry (#25):

This quarry is completely flooded and exposes no slate. Behre (1933, p. 294) noted that an "anticlinal crest emerges just north of the north corner of the opening, and here the beds strike N.72°E. and dip about 10°N." This anticline is the one inferred to lie to the north of the Blue Mountain quarry (#24).

Roberts and Peters Quarries (#26):

Six openings along the strike of the bedding were visited. Behre (1933, p. 294-295) described these openings as small but fairly deep quarries. All but two are flooded and therefore inaccessible. In general, beds dip 80°NW. at the surface to vertical at depth. Numerous gentle, north-dipping joints were noted.

Two thick beds are present and are separated by about 20 feet of "ribbons".

The structural data indicates that these quarries were opened on the hinge and steep limb of a northward overturned anticline.

Empire Quarry (#27):

Behre (1933, p. 295-297) described two quarries but due to subsequent flooding they will be treated as one. Very little bedrock is exposed. Behre described a syncline visible in the east wall of the eastern quarry. In the west quarry, originally called the Oplinger quarry, the beds dip 40°NW. at the southeast corner and 15°E. at the north corner. From this Behre was able to infer a syncline plunging to the east.

In addition, Behre also described heavy shattering that he felt indicated shearing movement along the bedding planes. As a result of flooding this could not be substantiated by the present study.

Owen Williams Quarry (#28):

Two openings along the strike of the bedding were visited. The western quarry is quite small while the quarry to the east is over 400 feet long. Behre (1933, p. 299) described these openings. The beds stand vertical and slaty cleavage dips to the south. One very thick bed was noted. The structure seen in this opening indicates that these quarries were opened on the south limb of the syncline mentioned in the discussion of the Empire quarry

(#27).

Custer Quarry (#29):

This quarry is partially flooded with water and filled with garbage. An anticlinal fold is visible in the northeast corner of the quarry. Slaty cleavage is quite steep and dips 73°SE. Slight folding of the slaty cleavage was noted and can be seen in figure A13. Strain-slip cleavage is typically conspicuous around the hinge of the fold. The slaty cleavage-strain-slip cleavage intersection is 16° S.78°W.

Ellis Owens Quarries (#30, #31):

Three openings were visited. The two eastern quarries labeled #30 on Plate VI are smaller and contain less exposed slate than the quarry labeled #31. Behre (1933, p. 298) stated that an anticlinal crest could be seen in the middle quarry. This was substantiated by this investigation. The easternmost quarry shows no slate above the water line.

The west quarry (#31) exposes a good amount of slate. This irregularly shaped quarry is flooded but accessible. A northward overturned anticline, probably the same one seen in quarry #30 is visible. The beds on the south limb strike N.65°E. and dip 32°SE. while beds on the north limb strike N.23°E. and dip 27°NW. thus indicating a plunge of the fold axis to the west.

One bed 15 to 20 feet thick was noted. Cross-bedding

Figure A13: Northwest side of the Custer quarry. Note the bending of the slaty cleavage which dips to the south (left). Slatedale quadrangle.

and graded bedding is present in some of the graywacke and siltstone beds. Figure A14 shows the bedding on the south limb of the fold.

Cleavage fanning about the axial plane of the fold is evident by cleavage measurements taken along the length of the fold. Strain-slip cleavage is quite conspicuous. The attitude of the slip cleavage planes is N.80°E.34°NW.

<u>Quarry (#32)</u>:

Two small openings on either side of the stream were noted. They are unnamed although described by Behre (1933, p. 298). No slate is visible in the south quarry. The northern quarry shows beds dipping about 70°SE. and slaty cleavage dipping 42°SE. Slaty cleavage-bedding relations indicate that the beds are inverted. Thus an anticlinal axis to the south is implied.

<u>Parry Quarry (#33)</u>:

This quarry, located about 200 feet east along the strike of the Owen Williams quarries (#28) is quite large with dimensions of about 450 by 300 feet. It is now the municipal dump for the town of Slatedale and therefore not accessible. It was described by Behre (1933, p. 299).

A good amount of slate is exposed on the north and east walls of the quarry. Two small folds of the flexural slip type can be seen on the east wall and are shown in

Figure A14: Bedding and slaty cleavage on the south limb of an anticline exposed in the Ellis Owens quarry. Beds dip to the south (left) less steeply than the slaty cleavage. Slatedale quadrangle.

figure A15. Strain-slip cleavage is common in the hinge area of the anticline. The strike of the slip cleavage planes is N.85°W. and they dip 27°NW. A small thrust fault is also exposed on the east wall.

Graded bedding and cross-bedding is well developed in some of the more silty beds.

Emerald Quarry (#34):

This quarry described by Behre (1933, p. 299-300) is located on the eastern edge of the town of Emerald. Its is flooded but accessible. At the north end of the quarry the beds dip about 35°NW. while beds at the south end are overturned. Thus an anticlinal axis to the south is inferred.

Big Franklin, Peters, Fairview, East Carbon, Hazel Dell, and Provident Quarries (#35):

All of these openings were visited and described by Behre (1933, p. 300-304). The Big Franklin quarry is about 700 feet east along the strike of the Parry quarry (#33). This opening is the largest in the Slatington district, measuring approximately 1,000 feet by 150 feet. As Behre mentioned, this opening is actually five separate openings with dividing walls which are no longer visible due to the high water level.

The strike of the bedding is generally N.75°E. and the dip varies from 60°NW. to 70°NW. Figure A16 shows bedding on the west wall of the opening. Slaty cleavage dips 52°SE.

Figure A15: Northeast wall of the Parry quarry exposing a small anticline. This quarry is the garbage dump for the town of Slatedale. The junk and weeds are floating on water. Slatedale quadrangle.

Figure A16: View of the west wall of the Big Franklin quarries. Beds dip to the north (right) and slaty cleavage dips to the south (left). Slatedale quadrangle.

Numerous north-dipping joints were noted. Some of these joints are horizontal. The structural data indicates that the quarries were opened just north of an anticlinal axis.

The waste dumps associated with the Big Franklin quarry are quite large and extend 80 to 100 feet above the water level.

The Peters quarries lie to the east of the Big Franklin quarry along the strike of the bedding. Two openings were visited. Beds dip to the north at the surface but steepen to vertical at depth indicating an anticlinal axis to the south. Figure A17 shows the westernmost of the two openings. North dipping joints are conspicuous in this opening. Behre (1933, p. 302), in his description of these openings made similar observations.

The Fairview quarries consist of three narrow but fairly deep openings located about 200 feet east along the strike of the bedding of the Peters quarries. The beds dip steeply north to vertical at depth. Thus the anticlinal axis implied to the south of the Big Franklin quarry and the Peters quarries is again implied here. Two big beds, both approximately 15 feet in thickness, are separated by about 10 feet of "ribbons".

The Old Columbia quarry is located about 100 feet east of the easternmost Fairview opening. It is rectangular, measuring about 250 feet by 50 feet, and flooded. Beds dip 60°NW. at the north edge of the quarry and 65°SE. at

Figure A17: East wall of the west Peters quarry. Beds are essentially vertical and slaty cleavage dips to the south. Note the presence of numerous north-dipping joints. Beds are slightly concave to the south (right) indicating an anticlinal axis to the south. Slatedale quadrangle.

the southern part thus indicating an anticlinal axis to the immediate south.

The East Carbon quarry, of irregular shape, is located south of the Fairview openings. Behre (1933, p. 303) described this once profitable opening as exposing a great deal of slate. As a result of flooding and sliding of the waste pile no slate is visible at present. Behre noted that beds dipped 58°NW. at the north edge and 70°SE. at the south edge. Again an anticlinal axis to the south is implied.

The Provident and Hazel Dell quarries lie to the immediate west of the East Carbon quarry. This group of quarries consists of seven closely spaced openings along the strike of the bedding. This type of quarrying has been termed "pigeonholing" by quarrymen and is absent from the Lynnport slate district to be discussed later. The western three openings of the group are the Hazel Dell quarries and the next three are the Provident quarries. The easternmost quarry is actually an extension of the East Carbon quarry and has a tunnel leading into the Provident quarries to the west. The beds in this small opening dip 65°NW. Quarries <u>d</u> and <u>e</u> (see figure A19) show beds dipping steeply north to vertical. Quarry <u>f</u> exposes an anticlinal fold in the east wall. The beds are horizontal at the south edge of the quarry and vertical on the north side. Figure A18 shows this overturned fold. In

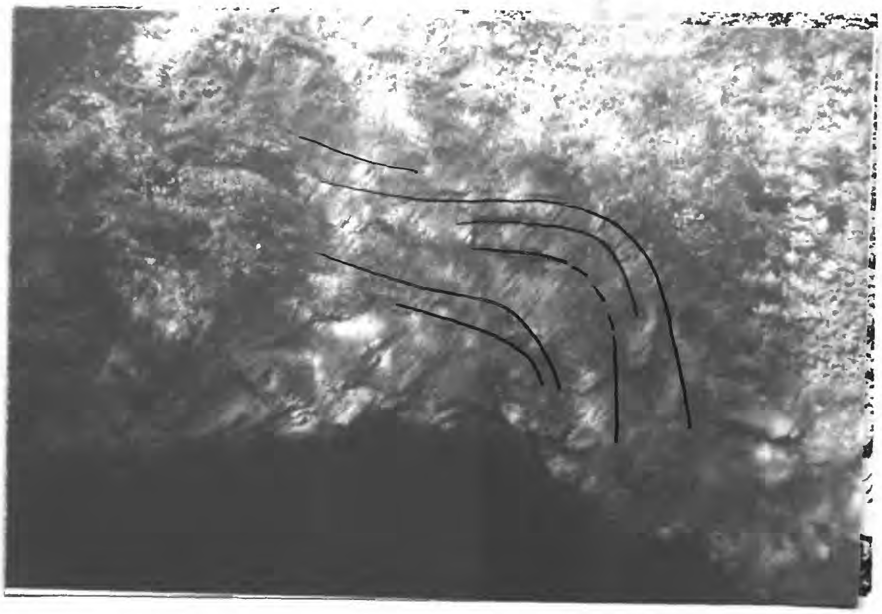


Figure A18: East wall of quarry *f* of the Hazel Dell quarries exposing an anticline. In the center of the photograph the beds dip slightly to the north (right) but at the right side of the photograph the beds are vertical. Slatedale quadrangle.

quarry g the beds dip steeply to the north at the south edge but flatten out to almost horizontal at the north end, a point not mentioned by Behre (1933, p. 301-302) in his description of the quarry. This indicates a synclinal axis to the north.

The Provident and Hazel Dell quarries were active during the "boom" years of slate quarrying and it is said that one of these quarries was worked to a depth of 430 feet.

Quarry h, located about 400 feet southwest of quarry g shows beds dipping 55°SE. and slaty cleavage dipping 45° SE. Thus this unnamed quarry was opened on the overturned limb of an overturned anticline.

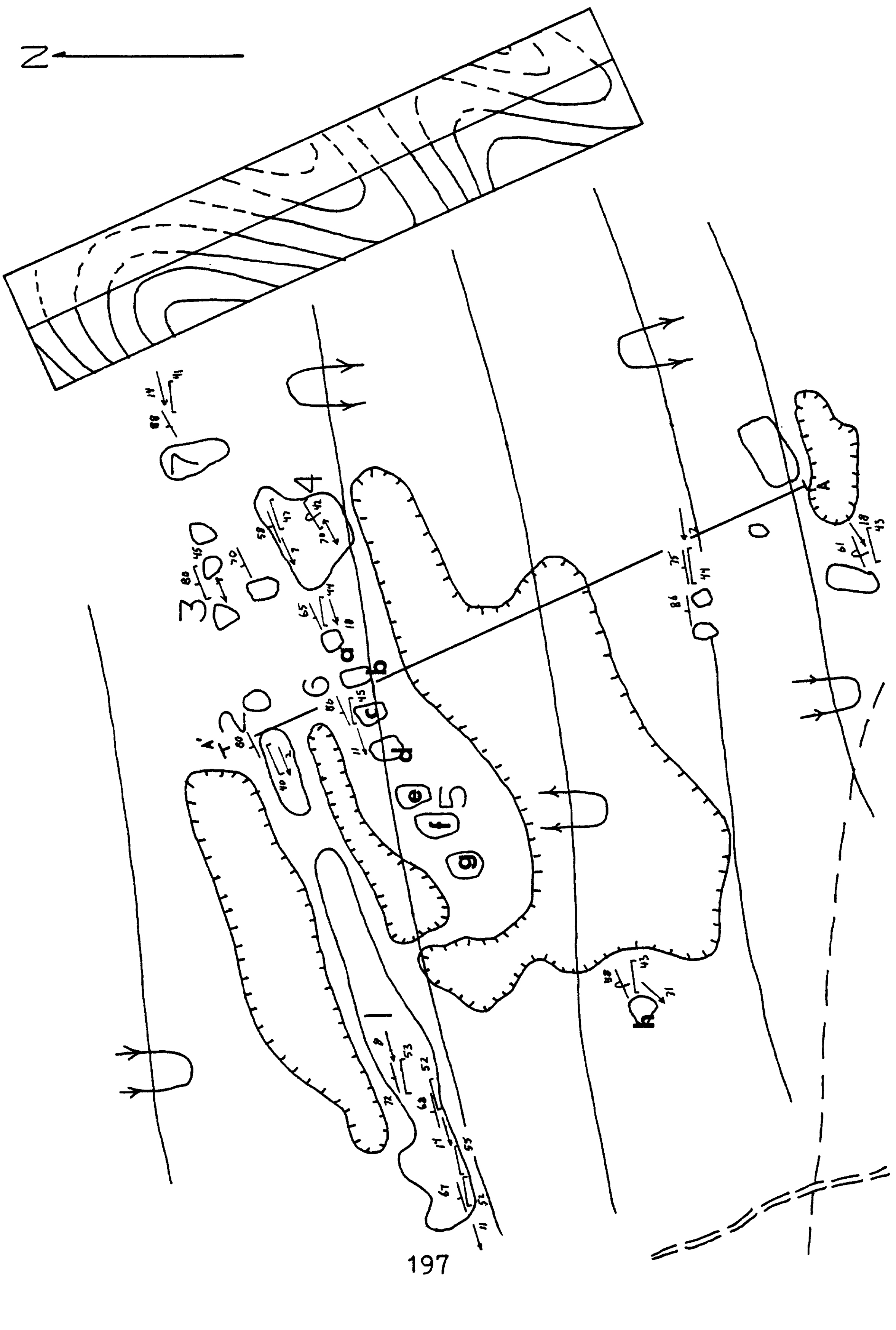
Figure A19 shows a geological map and cross-section of the area containing all of the quarries under the general heading of quarry (#35).

Williamstown and Unnamed Quarries (#36):

Two unnamed quarries on the north side of Trout Creek were visited. The larger of the two quarries had been dug into the hillside. Beds dip 70° to 80°NW. and slaty cleavage dips 45°SE. Very good cross-bedding indicates that the sequence is right-side-up. An anticlinal axis to the south is inferred. Conspicuous north-dipping joints similar to those seen in other openings are present here.

The Williamstown quarries, located about 200 feet north of the highway between Emerald and Slatington,

Figure A19: Geological map and cross-sections of the area containing the Big Franklin (1), Peters (2), Fairview (3), East Carbon (4), Hazel Dell (g-e) (5), Provident (d-b) (6), and Old Columbia (7) quarries.


N
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consist of three openings, two of which are completely flooded and expose no slate. The southernmost quarry of the three exposes a small amount of slate above the water line. Bedding can be seen to dip about 60°SE. while slaty cleavage dips 44°SE. Thus a synclinal axis to the north is inferred from the structural data. The Williamstown quarry, described by Behre (1933, p. 304), was last worked in 1910.

<u>Lynnport Slate District (New Tripoli and New Ringgold Quadrangles)</u>:

<u>Quarry (#1)</u>:

This quarry was cut into the hillside of the east bank of a tributary of the Ontelaunee Creek. Both slaty cleavage and bedding dip south but beds dip at a steeper angle than the cleavage indicating that the quarry was opened on the inverted limb of a northward overturned anticline. As Behre (1933, p. 347-348) noted in his description of this quarry its significance lies in the fact that it shows the upper slate member or Pen Argyl Member existing to the north of the belt of Ramseyburg Member (see geological map of the New Tripoli quadrangle, Plate II).

<u>Mosserville Quarries (#2)</u>:

Four openings along the road south of Mosserville were visited. These openings had been previously described by Behre (1933, p. 347). The openings are located south of the arm-like area of Ramseyburg outcrop mentioned in the description of quarry (#1).

Beginning at the north the quarries may be designated a through d. Quarry a was dug into the hillside. Beds dip 32°SE. Well developed graded bedding indicates that the beds are upright. A 3-foot thick graywacke bed was noted. Quarry b, located about 300 feet south of quarry a, shows beds dipping 21°SE. No conspicuous thick beds were noted. The thick graywacke bed in quarry a is stratigraphically lower than the beds in quarry b. Quarry c is located immediately south of quarry b. Beds here dip 27° NW. indicating a synclinal axis between quarry b and quarry c. Quarry d is located about 700 feet south of quarry c. This opening is the largest, measuring 300 feet by 100 feet and is flooded but accessible. The bedding in this opening is quite variable. At the south edge the beds are vertical at water level but flatten out and dip to the south at the top of the quarry and are thus the exposed inverted limb of the northward overturned syncline. This can be seen in figure A20. At the north edge of the quarry the beds strike N.16°E. and dip 70°NW. indicating that synclinal axis running through the quarry plunges to the west. An anticlinal axis can now be inferred between quarries c and d.

Slaty cleavage deformation is quite conspicuous in quarry d. Much of the cleavage is curved or displays well

Figure A20: Southwest wall of quarry d of the Mosserville quarries. The synclinal curvature of the beds is apparent. New Tripoli quadrangle.

developed kink folding. Crenulation cleavage or strain-slip cleavage is also quite common.

Siger and Kraus Quarry (#3):

This opening is located on the east side of the road, opposite quarry c of the Mosserville quarries (#2). It is flooded and shows no bed rock. Behre (1933, p. 347) in his description of this quarry made similar observations.

Kuntz Quarry (#4):

This rectangular quarry exposes very little slate above water level. Slaty cleavage dips about 60°SE. Strain-slip cleavage is quite common in material found in the waste pile. Bending of the slaty cleavage is also common. The fact that the angle between the cleavage and bedding is small may indicate that the quarry is located on the inverted limb of a northward overturned anticline.

Bauer Quarry (#5):

Two openings were visited. The larger of the two is situated topographically higher and south of the smaller one. It was this quarry that Behre (1933, p. 346) described in his report. The beds in this quarry dip 72°SE. and are concave to the south indicating that this quarry was opened on the inverted limb of an overturned anticline. Numerous north-dipping joints were noted. The rocks are badly deformed at the south edge of the quarry which may be the result of bedding-slip faults.

The smaller quarry exposes very little rock. Beds dip

48°NW. indicating a synclinal axis to the north.

Laurel Hill Quarry (#6):

This quarry located about 1,200 feet west of the Bauer quarry (#5) is completely flooded and exposes no slate. Slate outcrops in the nearby stream show beds dipping about 16°SE. Thus the quarry was opened south of the anticlinal crest mentioned in the description of the Bauer quarry. This quarry was described by both Sanders (1883) and Behre (1933, p. 346).

Hess (Ontelaunee) Quarry (#7):

The Hess quarry is about 300 feet by 200 feet in ground plan and, although filled with water, shows about 60 feet of slate in the walls. Beds measured on the northwest edge of the quarry dip 63°SE., about 5° steeper than the cleavage, indicating that the beds are overturned. Cleavage is conspicuously curved throughout the quarry (figure A21) but more so in the southwest part where it has been rotated to a near horizontal position (see figure 31 in the main text). Behre (1933, p. 345) felt that this rotation of the slaty cleavage was caused by movement along the Eckville fault, hypothesized to lie to the south of the opening. The presence of this fault has been established at this locality and outcrops to the east and west.

The relations between slaty cleavage and bedding are suggestive of isoclinal folding. Thus this quarry has been opened on the inverted limb of a large overturned anticline

Figure A21: Northwest corner of the Hess quarry northeast of Lynnport. Note the curvature of the slaty cleavage especially in the extreme right hand side of the photograph. New Tripoli quadrangle.

the axis of which may extend to the Kuntz quarry (#4). The Hess quarry was mentioned by Sanders (1883) thus indicating its age. At this time it was called the Ontelaunee quarry.

South Shenton Quarry (#8):

This small, flooded quarry lies about 1,200 feet north of the Hess quarry (#7). A small amount of slate is exposed but not enough to determine attitudes of bedding. Slaty cleavage dips 46°SE. and strikes N.75°E.

Shenton Quarries (#9):

Behre (1933, p. 344) described three openings but only two were found in the present study. The other is presumably filled with water and garbage. The southernmost of the two quarries was cut into the hillside. One very thick bed was noted, the rest being much thinner. At the south edge of the quarry the beds dip 7°NW. and the slaty cleavage dips 60°SE., however, at the north edge the beds dip 62°NW. and the slaty cleavage dips 45°SE. Cleavage fanning can easily be recognized. The northern quarry of the two, although almost totally flooded shows beds dipping 66°SE. and slaty cleavage dipping 37°SE. Thus the northern quarry was opened on the inverted limb of an overturned anticline, the axis of which lies just to the south of the first quarry described.

Quarry (#10):

This old quarry is about 40 feet square. No slate is exposed but good outcrops in a nearby stream bed show beds dipping about 61°SE. and slaty cleavage dipping 28°SE. The angle of dip of the cleavage is relatively low indicating that the folds are overturned more so in this area than others. The overturned limb of an anticline is exposed in cuts in the stream.

Quarry (#11):

This small quarry not mentioned by Behre was dug into the hillside. A small dump is associated with it. Several graywacke beds as thick as one foot were noted. These beds are highly calcareous. Beds dip 61°SE. and slaty cleavage dips 40°SE. thus indicating that the quarry was opened on the overturned limb of the same fold described in the discussion of quarry (#10).

Hermany Quarries (#12):

These quarries are presently under Leaser Lake and are therefore not available for inspection. Behre (1933, p. 343-344) described these openings and his observations and data will be used here. The beds dip 75°SE. in the northern quarry and 61°SE. in the southern quarry and slaty cleavage averaged 28°SE. to 30°SE. in both quarries. Thus, these quarries were opened on the north limb of a northward overturned anticline. Behre noted a great deal of aragonite, clacite, and quartz as joint fillings in the south end of the South Hermany quarry. This lends support to the inferred proximity of the Eckville fault to these quarries. The low angle of the slaty cleavage also implies the presence of this fault to the immediate south of these quarries.

Henry Quarry (#13):

This quarry, measuring 350 feet by 150 feet, is flooded but exposes a northward overturned syncline (figure A22) on the southwest wall. Well developed graded bedding indicates that the sequence is upright. Siltstone layers are quite common and one thick slate bed was noted in the east part of the quarry. Slaty cleavage is quite steep, with dips averaging 80°SE. to 84°SE.

Kistler Quarries (#14):

Two small openings, one of which is completely filled with water with no exposed bedrock, were visited. They are known individually as the North and South Kistler quarries. Small outcrops near the north and flooded quarry show beds dipping 51°SE. and slaty cleavage dipping 79°SE. It is inferred here that this quarry was opened on the north limb of the syncline mentioned in the above description of the Henry quarry (#13).

The South Kistler quarry, dug into the hillside along a stream shows beds dipping 60°SE. and slaty cleavage dipping 85°SE. The structure is thus the same as that of the North Kistler quarry.

Figure A22: Southwest wall of the Henry quarry. The hinge of a northward overturned syncline is visible. New Tripoli quadrangle.

Roberts Quarry (#15):

This quarry is filled with garbage and water and shows very little bedrock at present. Behre's (1933, p. 342) description of this quarry will be used here. The most interesting feature of this quarry is the small synclinal fold in the northeast wall which may be the same fold as that seen in the Henry quarry (#13) and the Kalbach quarry (#16). The fold is not visible at the present time but slaty cleavage was observed to be standing vertical.

Kalbach Quarry (#16):

This rectangular quarry, measuring about 200 feet by 50 feet in plan, is flooded but exposes slate in the east wall. A tight overturned syncline is exposed. Beds on the normal limb dip 38°SE. while those on the inverted limb dip 77°SE. Thus the openig angle of the fold is 39°. Slaty cleavage associated with the normal limb dips 47°SE. while that associated with the inverted limb dips 81°SE. indicating cleavage fanning about the axil plane. North-dipping joints are well developed. Strain-slip cleavage is common around the hinge area of the fold. The attitude of the strain-slip cleavage planes is N.81°E.56°NW. Thick beds are lacking and several cross-bedded siltstone and graywacke beds were noted. Behre (1933, p. 342) stated that this quarry was last operated in 1880.

Quarry (#17):

This large, flooded quarry measuring 250 feet by 150 feet exposes slate on the northwest edge. Beds dip 56°NW. while slaty cleavage dips 51°SE. indicating that the quarry was opened north of an anticlinal axis. Behre (1933, p. 341) described this unnamed quarry in his report.

<u>Quarry (#18)</u>:

This quarry is located about 600 feet west of quarry (#17). Behre (1933, p. 341) described this unnamed quarry as being 140 feet by 105 feet in ground plan. Very little slate is visible above the water level. Bedding was hard to distinguish but appeared to be dipping about 47°NW. with slaty cleavage dipping 67°SE. Thus the structural relations are the same as those seen in quarry (#17).

<u>Daniels Quarry (#19)</u>:

The Daniels quarry is located about 200 feet east of quarry (#18). It is flooded but slate is exposed on all sides of the quarry. It is roughly 300 feet by 150 feet in ground plan and probably over 100 feet in depth. The east wall exposes two folds slightly overturned to the north. The northernmost fold of the two is an anticline. The folds are much more symmetrical than other folds seen in the Pen Argyl Member. Slaty cleavage dips 74°SE. indicating that the axial planes of the folds are close to vertical and the folding is upright.

The effects of deformation are evident throughout the quarry. Strain-slip cleavage is common with an average attitude of N.76°E.53°NW. Bending of the slaty cleavage and kink folding is also common. Kink folds are especially prominant on the north side of the quarry where counter clockwise rotation is indicated. The majority of the deformational structures are probably the result of movement along the Eckville fault which is hypothesized to lie to the immediate south.

Behre (1933, p. 341) stated that this quarry was opened in 1872 and last operated about 1905. It is believed that the histories of quarries (#17) and (#18) are essentially the same as that of the Daniels quarry.

Pittsburgh Quarry (#20):

This quarry is long and narrow, extending about 200 feet in an east-west direction. Beds dip 76°NW. and the slaty cleavage dips 83°SE. Thus this quarry was opened to the north of an anticlinal axis. Graded bedding and cross-bedding are common. Thick beds are lacking. Strain-slip cleavage is common and its intersection with the slaty cleavage is, on the average, 10° S.78°W.

An interesting feature of this quarry is the well developed bedding plane slickensides. The bearing and plunge of the striations is 61° N.21°W. Northwest movement of the overriding beds is indicated by the microscarps.

Centennial Quarry (#21):

Three quarries in a north-south line were visited. One quarry is called the Centennial quarry and the other two were unnamed. The southern quarry is a small prospect pit with no exposed slate. The rock on the dump displays abundant slip cleavage. Cleavage-bedding relations of the material on the dump indicates that the quarry may have been opened on the south limb of a northward overturned anticline.

About 200 feet north of the above mentioned quarry another unnamed quarry was located. This one is considerably larger, measuring about 250 feet by 100 feet in size and was opened on the hinge of an anticline. Beds at the north side of the quarry dip about 5°NW. while beds at the south edge dip 20°SE. Slaty cleavage is quite steep, dipping 80° to 85° SE.

About 300 feet north of the above quarry is the Centennial quarry. It is separated into two openings by a narrow bridge of waste rock. A small amount of slate is visible in the east wall. Bedding, although hard to distinguish, dips about 80°NW. and slaty cleavage dips 65°SE to 70°SE. Thus the quarry was opened on the north limb of the above mentioned anticline.

Behre (1933, p. 341) stated that this quarry was opened in 1850 and ceased operations in 1905.

Quaker City Quarries (#22):

Two small openings and one opening measuring about 300 feet by 100 feet in plan lie to the west of the Centennial quarry (#21). There is no exposed slate in any of these openings. Behre (1933, p. 340) stated that bedding seemed to dip about 65°NW. thus indicating that these quarries lie to the north of the anticlinal axis of the fold described in the Centennial and associated quarries to the immediate east.

<u>Oswald Quarry (#23)</u>:

This small opening was found about 150 to 200 feet west of the Quaker City quarries (#24). The opening is completely flooded and bedrock could not be studied.

<u>Mammoth Quarry (#25)</u>:

This opening is located about 500 west of the Oswald quarry (#23). A small amount of bedrock is exposed. The slaty cleavage dips 79°SE. Beds in the stream to the immediate south of the quarry dip 53°SE.

<u>Hemerley Quarry (#26)</u>:

This quarry was cut into the hillside along the stream. Beds dip 57°SE. and the slaty cleavage dips 83°SE. This quarry was thus opened south of an anticlinal axis.

Vita

Gary George Lash was born in Allentown, Pennsylvania on August 3, 1954. He is the son of Mr. and Mrs. George Lash of Allentown. He attended Jackson Elementary School, Trexler Junior High School, and graduated from William Allen High School in June, 1972.

Mr. Lash graduated from Kutztown State College in May, 1976 with a Bachelor of Science degree in geology. In September, 1976 he began studies at Lehigh University towards a Master of Science in geology. He received a one-year appointment with the United States Geological Survey to work on the thesis. He received his Master of Science in geology in October, 1978.

Mr. Lash, a student member of the Geological Society of America and an associate member of Sigma Xi, will continue his studies at Lehigh University towards the Ph.D. degree and will continue working with the United States Geological Survey on a two-year appointment.

In August, 1977 Mr. Lash married Eileen P. McNamara of Bethlehem, Pennsylvania. They are residing in Bethlehem.