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STRUCTURAL GEOMETRIES AND CARBONATE DEFORMATION MECHANISMS IN THE BEAVER VALLEY - SALTVILLE TRANSFER ZONE

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Charles Talbott Lutz

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DEDICATION

This dissertation is dedicated to my parents,
George and Charlotte Lutz, with much appreciation and love.

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ABSTRACT

The Beaver Valley - Saltville transfer zone is a structurally complex area in the Valley and Ridge of east Tennessee, north and northeast of Knoxville, TN. Within this area, three regionally significant thrusts of the Southern Appalachians, the Copper Creek, the Beaver Valley, and the Saltville have deformed the rocks. The Beaver Valley thrust terminates within the area, but shortening remains constant.

This dissertation focuses on several problems related to the structures in this area. First, it examines the structural geometries in the area at both map (1:24,000) scale and at the mesoscopic scale. The geometries are interpreted on three balanced cross-sections. Second, a sequence of thrusting which explains the geometric evolution of the structures is presented. Finally, deformation mechanisms and twinning strains in limestones are examined and the contribution of the twinning and other features to the total strain is assessed.

The Copper Creek thrust sheet consists of four distinct areas: the Texas Valley anticline and syncline, an imbricate fan of Rome Formation and Conasauga Group lithologies, a uniformly dipping belt, and Clinch Mountain. The Beaver Valley thrust sheet is dominantly a set of folds in Middle and Upper Ordovician strata. The sheet also contains folded

pieces of the Knox and Conasauga groups, and the House Mountain syncline. The Saltville thrust sheet mainly contains uniformly southeast dipping beds of the Rome Formation, and the Conasauga and Knox groups. The leading edge of the thrust however is complexly imbricated.

Three balanced cross-sections record essentially uniform shortening across the area. Shortening values are 43 %, 48 %, and 49 %. The Copper Creek thrust is interpreted as being folded at its leading edge in this area. The interpretation is supported by both surface and well data. Towards its tip point, the Beaver Valley thrust changes the position of its branch line with the Saltville thrust. The interpretation is suggested by the structures in the footwall of the Saltville thrust and it accounts for the decrease in slip on the Beaver Valley thrust.

The Beaver Valley and Saltville thrusts are interpreted as having grown toward each other laterally during emplacement. The movement of the faults was intermittant, and the times during which the faults were being emplaced overlapped. This sequence of thrusting follows from the ideas of Jones (1971) and it suggests a local reversal and "break-back" relationship between the two thrusts. The Beaver Valley thrust terminated either due to an effect of the basement, or lateral stratigraphic change, or simply the inability of the thrust to continue propagation because the Saltville thrust had already shortened strata and the Beaver

Valley was no longer necessary to maintain shortening. There is no evidence for basement involvement so the stratigraphic theory combined with the thrusting sequence is favored. There are many lateral changes (especially in the Cambrian and Ordovician) in the stratigraphic column, which would argue for the stratigraphic theory. These lateral changes are of a regional scale and specific changes and their localities cannot be identified. The original stratigraphy may have strongly influenced the sequence of thrusting as well.

Deformational features recorded in limestones in the area include cleavage, stylolites and solution seams, fractures, veins, twins, breccia, and bedding slip surfaces. Strata within the thrust sheets (more than approximately 100 m from a thrust) record very low strains and appear virtually undeformed. Calculated twinning strain is low. Strains do not exceed 5 %, and most are less. No significant variation in either magnitude or orientation with structural position are observed.

A gap exists between total strain in the carbonates and total shortening indicated by the balanced cross-sections. This suggests that, although many deformational features are present in the carbonates, they contribute very little to the total strain at the scale of thrust sheets. Most of the strain occurred along fault planes or through buckling associated with map scale folds. The dominant mode of

deformation, therefore was brittle failure, at very low temperatures and pressures.

This study points out the need to integrate mesoscopic and microscopic studies with studies of macroscopic structure. Examination of the rocks out of context of the larger structures would either grossly underestimate total strain in the area or attribute greater significance to grain-scale and bed-scale features than is really warranted.

TABLE OF CONTENTS

CHAPTER		PAGE
1.	INTRODUCTION	1
	1. General Introduction	1
	2. Study Area and Purpose	3
	3. Previous Work in the Study Area	7
	4. Methods of Study	10
	5. Relationship of the Research to Oak Ridge National Laboratory	11
2.	STRUCTURAL GEOMETRIES IN THE BEAVER VALLEY - SALTVILLE TRANSFER ZONE	13
	1. Introduction	13
	2. Thrust Faults - General Considerations	14
	3. Description of the Study Area	17
	4. Geology of the Study Area	27
	5. Stratigraphic Separation Diagrams and Cutoff Lines	62
	6. Cross-sections	74
	7. Conclusions	96
3.	GEOMETRIC EVOLUTION OF THE BEAVER VALLEY - SALTVILLE TRANSFER ZONE	100
	1. Introduction and Purpose	100
	2. Assumptions and Techniques	101
	3. Interpretation of the Sequential Development of the Study Area	105
	4. Causes of the Termination of the Beaver Valley Thrust	119
	5. Conclusions	125
4.	STRAIN IN CARBONATES IN THE BEAVER VALLEY - SALTVILLE TRANSFER ZONE	129
	1. Introduction and Purpose	129
	2. Deformation Features	131
	3. Distribution of Deformation Features	167
	4. Strain in Twinned Calcites	176
	5. Discussion	189
	6. Conclusions	194
5.	SUMMARY AND CONCLUSIONS	198
LIST OF REFERENCES		204
APPENDICES		222
A.	STRATIGRAPHY	223

B. FIELD GUIDE 229

VITA 288

LIST OF FIGURES

FIGURE		PAGE
1.	Block diagram of a simple, idealized transfer zone	2
2.	Simplified map of the Beaver Valley - Saltville transfer zone	5
3.	Illustration of a thrust fault prior to (a) and after (b) movement	15
4.	An idealized imbricate fan and duplex, common components of thrust systems	18
5.	Map of the geologic provinces in East Tennessee and the major thrusts of the Valley and Ridge.	20
6.	Map of east Tennessee, showing the boundary between the belt of dominant faulting and the belt of dominant folding in the Valley and Ridge province	22
7.	Location map of the major structural subdivisions of the study area, discussed in the text	28
8.	Small scale folding in the middle Chickamauga Group, in the Copper Creek thrust footwall	31
9.	Structural subdivisions in the Copper Creek thrust sheet in the study area	33
10.	Stereographic projection showing the general trend of poles to bedding from the Texas Valley anticline and syncline	35
11.	Location of Fritz #1 Welch well	37
12.	Stereographic projection showing the general trend of poles to bedding from the Buffalo Ridge syncline	39
13.	Steeply dipping (southeast 85^{o}) beds of the Maryville Limestone on Route 370 in Texas Valley	43
14.	Downplunge projection of the Copper Creek thrust, projected from the axis of the Buffalo Ridge syncline	44

15. Anticlines and synclines developed at the southwest end of Clinch Mountain 49

16. Geologic cross-section showing the simple structure of beds within the Copper Creek thrust sheet under the Saltville thrust 50

17. Geologic map showing the inferred bend in the Middle Ordovician shelf edge 53

18. Stereographic projection showing the general trend of beds in the Corryton anticline 56

19. Geologic map showing the location of the Massengill syncline within the Saltville thrust sheet 61

20. Longitudinal stratigraphic separation diagram for the Copper Creek thrust 64

21. Longitudinal stratigraphic separation diagram for the Beaver Valley thrust 66

22. Longitudinal stratigraphic separation diagram for the Saltville thrust 68

23. Projected footwall cutoffs from the footwall of the Saltville thrust 72

24. Inferred length and position of the blind thrust under the Copper Creek thrust . . . 87

25. Diagrams from Jones (1971) showing the variation in thrusting sequence 103

26. Hangingwall sequence diagram showing the interpreted thrust development at T1 106

27. Hangingwall sequence diagram showing the interpreted thrust development at T2 109

28. Hangingwall sequence diagram showing the interpreted thrust development at T3 111

29. Hangingwall sequence diagram showing the interpreted thrust development at T4 113

30. Hangingwall sequence diagram showing the interpreted thrust development at T5 116

31. Trends of clastic ratios in the Conasauga Group plotted on a palinspastic base, from Simmons (1984) 122

32. Palinspastic map of Roeder and Witherspoon (1978), showing the approximate location of the bend in the interpreted position of the Middle Ordovician shelf edge (Walker, 1980) 124

33. Map of the study area, showing the location of cleaved strata 133

34. Diagram of the basic elements of cleavage classification, from Powell (1979) 133

35. Cleavage in the Moccasin Formation 135

36. Cleavage in the middle Chickamauga Group (Wardell Formation) 137

37. "Incipient" cleavage in the Moccasin Formation . . 139

38. Bedding parallel stylolites from a limestone bed in the Nolichucky Shale 143

39. Truncation of a vein by a "reactivated" bedding parallel stylolite 143

40. Slab photograph of tectonic stylolites in the Moccasin Formation 145

41. Photomicrographs of solution seams in carbonates . 146

42. Stereographic projection of poles to fractures in limestones in the study area 148

43. Outcrop photograph of the Maryville Limestone and overlying Nolichucky Shale in a quarry south of Paulette, TN along Tennessee Route 33 150

44 Veins in limestones in the study area 152

45. Twinning in calcite crystals 157

46. Photomicrographs of twinning in calcite 159

47. Map showing the location of exposures of breccia in the study area 160

48. Photographs of brecciated Mascot Formation from the Beaver Valley thrust sheet 162

49. Slab photograph of crush breccia from the Moccasin Formation 164

50. Bedding slip surface (the top surface of the large block of rock above the hammer) in the Maryville Formation 166

51. Cross-section A-A' and a table of deformation features showing the distribution of these features across the study area 168

52. Cross-section B-B' and a table of deformation features showing the distribution of these features across the study area 170

53. Cross-section C-C' and a table of deformation features showing the distribution of these features across the study area 172

54. Map showing the location of samples used to calculate strain from twinned calcite 182

55. Sketch showing the orientation of all thin-sections used in the strain analysis relative to bedding 183

56. Strain values calculated from twinned limestones in the study area 185

57. Stereonets showing the orientations of the principal strains calculated from the strain analysis of twinned limestone 187

58. Temperature and pressure estimates for several structurally important stratigraphic horizons . 192

59. Deformation mechanism maps for calcite 193

60. Generalized stratigraphic column of the study area 225

61. Summary of information concerning the stratigraphic units in the study area 226

62. Map showing the location of stops described in the road log 231

63. Photograph of Stop 1, looking north-northwest . . 235

64. Intraclasts in a limestone bed in the Nolichucky Shale, Stop 1 235

65. Stereographic projection of poles to bedding in the Nolichucky Shale, Stop 1 236

66. Geologic map of Stop 2 239

67. Folds in a gully at exposure A, Stop 2 241

68. Characteristic bedding and fracture orientation at exposure B, Stop 2 243

69. Geologic map of Stop 3 245

70. Small extension fault in the Rome Formation, 5 to 10 m above the Copper Creek thrust, Stop 3 . . . 248

71. Vein sets developed in the Moccasin Formation in the footwall of the Copper Creek thrust, Stop 3 250

72. Deformed chert nodules in the Moccasin Formation, Stop 3 250

73. An intensely pressure solved and cleaved bed in the Moccasin Formation, Stop 3 251

74. Tightly folded beds of the Moccasin Formation, Stop 3 253

75. Geologic map showing the location of Stop 4, with the three parts of the outcrop labelled . . 256

76. Sketch of the first part of Stop 4 257

77. Steeply dipping and folded beds of sandstone in the Rome Formation, Stop 4 259

78. Vertical beds of siltstone and shale in the Rome Formation, Stop 4 259

79. Small fold in the Rome Formation, Stop 4 261

80. Sketch of Stop 5 263

81. Histogram showing the distribution of fold trends in shale in the Rutledge Limestone, Stop 5 . . . 265

82. Two examples of folding in the Rutledge Limestone, Stop 5 267

83. Photograph of Stop 6 270

84. Stereographic projection of poles to bedding and cleavage from the Moccasin Formation, Stop 6 271

85. Planar and anastomosing solution selvages in the Moccasin Formation, Stop 6 273

86. A limestone bed telescoped by extensive pressure solution, in the Moccasin Formation, Stop 6 273

87. Two views of cleavage in the Moccasin Formation at Stop 6 274

88. Geologic map showing the location of Stop 7 . . . 278

89. Stereographic projection of poles to bedding and fractures from Stop 7 278

90. Tilted and fractured sandstone beds from the Rome Formation in Stop 7 279

91. Two views of folding in the Rome Formation at Stop 7 280

92. An asymmetric fold in limestones of the Martinsburg Formation at Stop 8 284

93. A close up view of a fold in a limestone bed of the Martinsburg Formation at Stop 8 . . . 284

94. A small faulted zone in the Martinsburg Formation at Stop 8 285

LIST OF PLATES

PLATE		PAGE
I.	Geologic map of the Beaver Valley - Saltville transfer zone	In pocket
II.	Cross-section A-A'	In pocket
III.	Cross-section B-B'	In pocket
IV.	Cross-section C-C'	In pocket

CHAPTER 1

INTRODUCTION

1. GENERAL INTRODUCTION

Thrust-faulted terranes are common components of orogenic belts, and they are commonly located along the external margin adjacent to the undeformed foreland. Good examples of this type of structural setting are the Canadian Rockies (Bally et al., 1966; Dahlstrom, 1970), the central and southern Appalachians (Rodgers, 1970), and the Idaho-Wyoming- Utah thrust belt (Armstong and Oriel, 1966; Royse et al., 1975).

Studies of structural geometries (e.g., Dahlstrom, 1970) indicate that, although many thrust faults persist along strike for great distances, some successively lose displacement along strike and finally terminate. At the termination of a thrust, an adjacent thrust typically increases in displacement, compensating for the loss of the other fault. These displacement "transfer" zones are a mechanism for maintaining total shortening across the thrust belt.

Dahlstrom (1969) originally defined transfer zones from examples in the Canadian Rockies (Fig. 1), however areas of

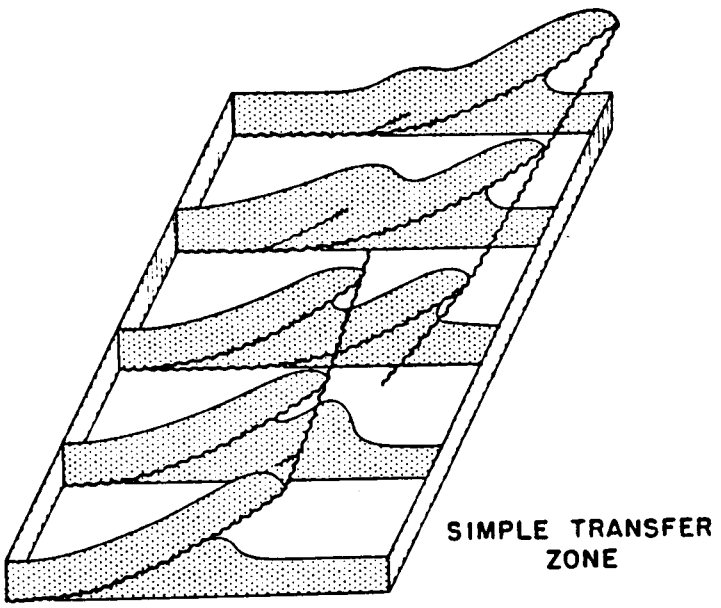


Figure 1. Block diagram of a simple, idealized transfer zone. From Dahlstrom (1970), based on examples from the Canadian Rockies.

this type had been described earlier (North and Henderson, 1954; Douglas, 1958). These features have been commonly described (From the Canadian Rockies: Brown and Spang, 1978; Langenberg, 1985, from the American Cordillera: O'Keefe and Stearns, 1982; Evans and Spang, 1984, and from the Appalachians: House and Gray, 1982). Gardner and Spang (1973) tried to clarify the transfer process through experimental modeling, based on field observations.

Despite the discussions and observations of these studies, a number of problems regarding transfer zones are not entirely resolved. First, how is the displacement transfer accomplished? Is it simply fault-to-fault, or is there a significant folding component? Second, what is the nature and significance of the structures adjacent to a thrust tip? How do these structures relate to the process of displacement transfer? Finally, what is the importance of the vertical and lateral packaging of the stratigraphy involved in a transfer zone? Does the stratigraphy itself cause fault termination?

2. STUDY AREA AND PURPOSE

An unstudied example of a transfer zone is found in the Southern Appalachians in the Valley and Ridge of East Tennessee, north and northeast of Knoxville. Components of the transfer zone are the Beaver Valley and Saltville

thrusts (Fig. 2). This dissertation focuses on several problems related to the Beaver Valley-Saltville transfer zone. It has three primary purposes. The first purpose is to examine and identify structural geometries within the Saltville, Beaver Valley, and Copper Creek thrust sheets in the transfer zone to understand the relationship between the faults. The geometries of the structures are presented on a geologic map (Plate I) and are interpreted on three balanced cross-sections (Plates II, III, IV). The relationship between stratigraphy and structural features is a part of this examination and analysis. The second purpose is to interpret the geometric evolution of the structures and probable sequence of thrusting. The third purpose is to study deformation mechanisms and deformation fabric development in carbonate units in the thrust sheets. This is accomplished using petrofabric techniques and microstructural strain analysis of twinned calcite grains.

From southwest to northeast within this area, the Saltville thrust takes up the slip which is lost as the Beaver Valley nears its end. The Beaver Valley terminates into folded Middle Ordovician carbonates and shales, approximately 22 km northeast of Knoxville. The Saltville thrust increases in stratigraphic separation adjacent to the Beaver Valley termination; in Knoxville the fault places Lower Cambrian strata upon Cambro-Ordovician rocks, whereas it thrusts the Lower Cambrian upon Mississippian units to

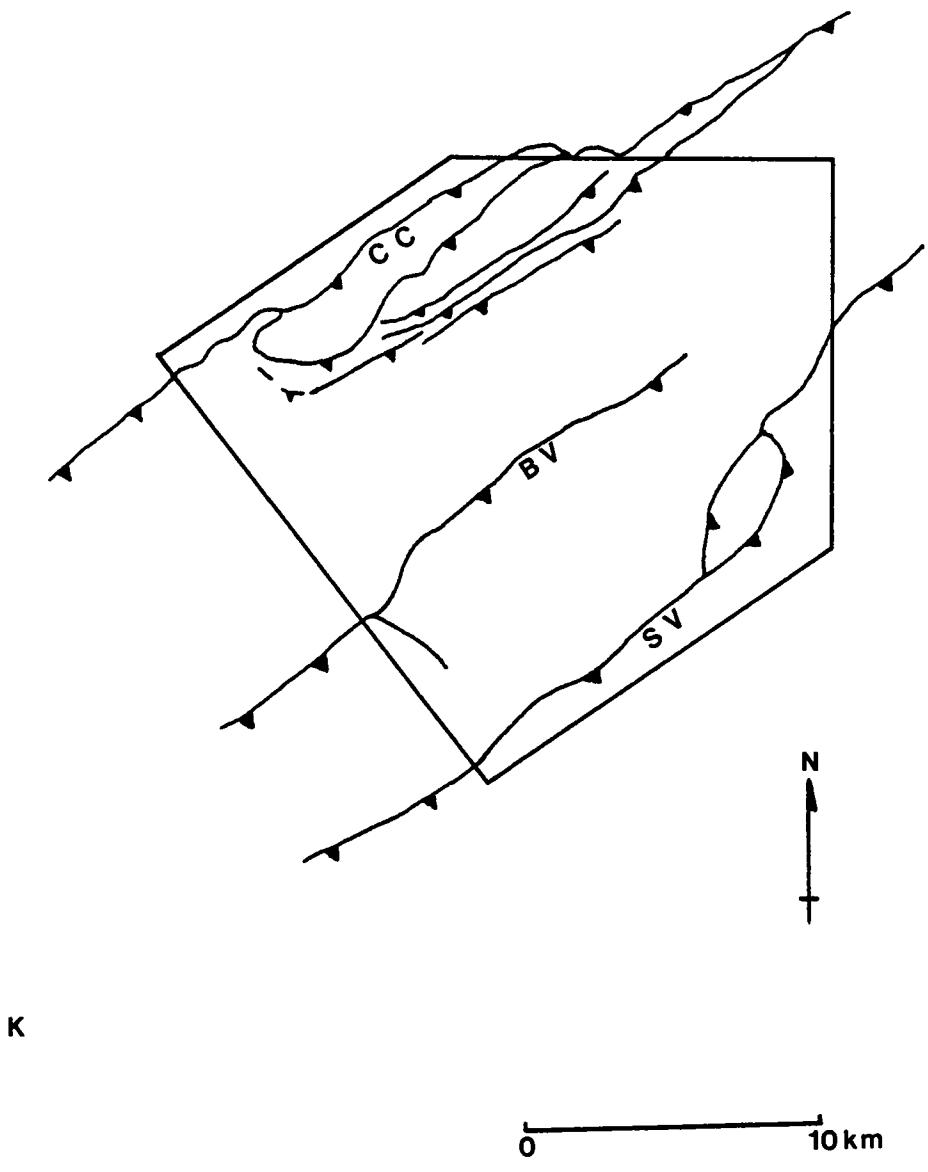


Figure 2. Simplified map of the Beaver Valley - Saltville transfer zone. The study area is outlined. C.C. = Copper Creek thrust, B.V. = Beaver Valley thrust, S. V. = Saltville thrust, K = Knoxville, TN.

the northeast. The more northwesterly Copper Creek thrust is also complex in the area, but this is probably unrelated to the Beaver Valley termination. The study area includes portions of five 7 1/2 minute quadrangles: John Sevier, Mascot, Luttrell, Graveston, and Big Ridge Park. The bulk of the area is in Graveston and Big Ridge Park quadrangles. These quadrangles are located in Knox, Union, Anderson, and Grainger counties.

The area is appropriate for this study for several reasons. First, the stratigraphy of the area is well understood, and this facilitates mapping structural geometries. Although the rocks in the area range in age from Cambrian to Mississippian, the formations are largely Ordovician and older. Sedimentologic and stratigraphic research in East Tennessee (particularly on the Middle Ordovician) by K. R. Walker and his associates at the University of Tennessee provides numerous measured sections, thin-sections, and documentation of three-dimensional geometries of stratigraphic units and their facies (e.g., Walker, 1977, 1980). There is also a growing body of data on the Conasauga Group, from work at the University of Tennessee, again by Walker and his associates (Simmons, 1984; Walker and Simmons, 1985; Kozar, 1986; Weber, in prep), and at Oak Ridge National Lab (Haase et al., 1985).

Second, the stratigraphic control on thrusting and attendant folding has long been recognized (Rich, 1934;

King, 1960; Price, 1967; Woodward, Walker, and Lutz, in press). Carbonates and shales of the Middle Cambrian Conasauga Group and the Middle Ordovician Chickamauga Group exhibit complex and variable facies relationships through a portion of the Valley and Ridge of east Tennessee which includes the study area. The complex stratigraphy provides an opportunity to examine the extent of its effect on the structures developed.

Lastly, because the bulk of the rocks which underlie the area are carbonates, samples are available to study carbonate deformation mechanisms. Examination of the samples may provide qualitative information on deformation, by identifying types of mechanisms responsible for strain accomodation. The samples may also be used to measure the strain through finite strain analysis. The deformation mechanisms present provide information which contributes to an understanding of conditions of deformation which can be inferred from deformation mechanism maps (Ashby, 1972). Such maps specify likely temperature, pressure, and strain rate values which existed during deformation, based on the mechanisms identified from the rocks.

3. PREVIOUS WORK IN THE STUDY AREA

A number of persons have worked in the study area; their efforts varied considerably in both purpose and

detail. Safford's (1869) work was the first systematic description of the geology of Tennessee, and his map indicates that the study area is underlain by "magnesian limestone and shale" and the "central limestone and shale group." His observations of the Valley and Ridge point out structural complexity: "In addition to the greater folds, multitudes of subordinate ones occur in the strata. Thus the formations are often extensively corrugated." Safford's work is comprehensive and, with the exception of its out-dated stratigraphic nomenclature, his map is accurate.

The work of the United States Geological Survey, which began in the 1890's, included the study area as part of the Maynardville Folio (Keith, 1901). This map reports more detail than the map of Safford because it is a larger scale (1:125,000), and the stratigraphic nomenclature is more similar to current usage.

Rodgers' (1953) fundamental work on east Tennessee is the starting point for any stratigraphic or structural study in this area. He included the study area on plate 2 (Maynardville), which is at a scale of 1:125,000. Rodgers was the first person to report the structural significance of the Beaver Valley - Saltville transfer zone and its associated complexity. He states: "Northeast from Knoxville remarkable changes appear. The Beaver Valley fault comes to an end in a few miles. . . the Saltville fault virtually doubles its stratigraphic throw. . . Indeed, the whole area

between Knoxville and Rogersville is notably more folded than any other in the belt dominated by the families of faults being described." In addition, Rodgers points out several unresolved problems in the area in his section on "future projects."

Mapping, by both the United States Geological Survey and the Tennessee Division of Geology, produced 1:24,000 maps of parts of the study area. The map by Cattermole (1966) covers the John Sevier quadrangle. Tennessee Division of Geology mapping includes the Luttrell quadrangle (Swingle et al., 1967). Unpublished mapping of parts of the Big Ridge Park and Graveston quadrangles by geologists of the Tennessee Division of Geology was provided to the author through the courtesy of the Tennessee Division of Geology.

Graduate research at the University of Tennessee had included some work in the study area as well. In general, the theses and dissertations fall into three categories. First, older work, which simply identified surficial geology and geography (Sawyer, 1947; Maher, 1948; Spangler, 1949). Second, theses which concentrated on small areas and attempted to unravel structural and stratigraphic relationships (King, 1960; Manus, 1960; Palmer, 1961; McReynolds, 1962; Benson, 1963). Finally, theses which are

stratigraphic and sedimentologic studies of the Middle Ordovician Chickamauga Group (Goldhaber, 1956; Breland, 1980; Ashworth, 1982).

4. METHODS OF STUDY

The first step in a study of thrust faults is the identification of structural geometries within the thrust sheets. To collect this information, all available maps, published and unpublished, were compiled. These were all field checked, with special attention to areas which seemed ambiguous. Previously unmapped portions of the study area were mapped at 1:24,000; individual outcrops deemed particularly important were studied at a larger scale. A map of the area was prepared at 1:24,000, along with three balanced cross-sections; two of the cross-sections depict only the area studied, while the third is a regional cross-section, drawn to the undeformed foreland, northwest of the study area.

Mesoscopic structural data were also collected. These include orientations of fractures, minor fold axes, stylolites, cleavages, and veins. These data are useful for both kinematic and dynamic interpretations (Price, 1967). Geometric constructions included a down-plunge projection, cutoff diagrams, stratigraphic separation diagrams, and hangingwall sequence diagrams.

Samples of carbonates were collected to identify strain features and for strain analysis. These samples are primarily from the Middle Cambrian Conasauga and Middle Ordovician Chickamauga Groups. The samples were slabbed for laboratory study, and selected samples were made into thin-sections for both microscopic examination of deformational features and strain analysis.

5. RELATIONSHIP OF THE RESEARCH TO OAK RIDGE NATIONAL LABORATORY

The Oak Ridge National Laboratory (ORNL) provided part of the financial support for this research. The laboratory is located approximately 43 km southwest of the study area. Haw Ridge, a continuation of Bull Run Ridge, passes through the ORNL reservation; it is held up by the Lower Cambrian Rome Formation, and is cut by the Copper Creek thrust. Additionally, the same stratigraphic units, for the most part, are present in the study area and at ORNL (McMaster, 1963; Haase et al., 1985). Therefore, one might reasonably expect similar structural characteristics and trends at the two locations.

A subject of on-going research at ORNL is low-level nuclear waste disposal. It is important to delimit the structural and stratigraphic characteristics, both on the surface and at depth, of a storage site. This dissertation

provides information which facilitates a better understanding of these characteristics. The information can, in some cases, be projected along strike, or, if not, it can at least be used to constrain a predictive model.

CHAPTER 2

STRUCTURAL GEOMETRIES IN THE BEAVER VALLEY - SALTVILLE TRANSFER ZONE

1. INTRODUCTION

This chapter examines structural geometries in the Beaver Valley - Saltville transfer zone and adjacent Copper Creek thrust sheet. A map (Plate I) of the area, drawn at a scale of 1:24,000, forms the basis of the chapter. Three balanced cross-sections (Plates II - IV), one of which is a "regional" cross-section, drawn to the undeformed foreland, accompany the map. Discussion here largely concerns macroscopic features; mesoscopic and microscopic features are discussed in chapter 4. Appendix A is a summary of the stratigraphy of the area. Structural data, taken from selected outcrops, along with a road log of the area, is in Appendix B.

The discussion of structural geometries in the chapter is organized into four parts. The first part is a brief summary of important aspects of thrust faults and thrust systems. The second part describes the geology of the study area. The third part discusses stratigraphic separation diagrams and a cut-off line diagram prepared for the thrusts

in the study area. Finally, the fourth part covers the cross-sections and their interpretation. Included in this section is a review of various aspects of balanced sections.

2. THRUST FAULTS - GENERAL CONSIDERATIONS

Thrusts are contractional faults of large dimension, commonly found in convergent orogenic belts. A thrust sheet is simply a volume of rock bounded below by a thrust fault. It is convenient to refer to the sheet because it may contain a characteristic stratigraphic sequence or degree of strain (Boyer and Elliott, 1982), which is useful in interpreting thrust emplacement.

Dahlstrom (1970) pointed out that thrusts telescope a package of rock by reducing area and increasing thickness, and this process generally follows two geometric rules:

1) Thrusts cut up-section in the direction of tectonic transport.

2) Thrusts parallel bedding in incompetent rocks and cut oblique to bedding in competent strata.

The second rule was first outlined by J. R. Rich (1934), using the Pine Mountain thrust sheet of Tennessee, Kentucky, and Virginia as the type example. The "stairstep" path of thrusts through a stratigraphic sequence is the ideal shape, and it consists of ramps through strong layers and flats through weak layers (Fig. 3). Thrusts also ramp up-section along strike; these are called lateral ramps

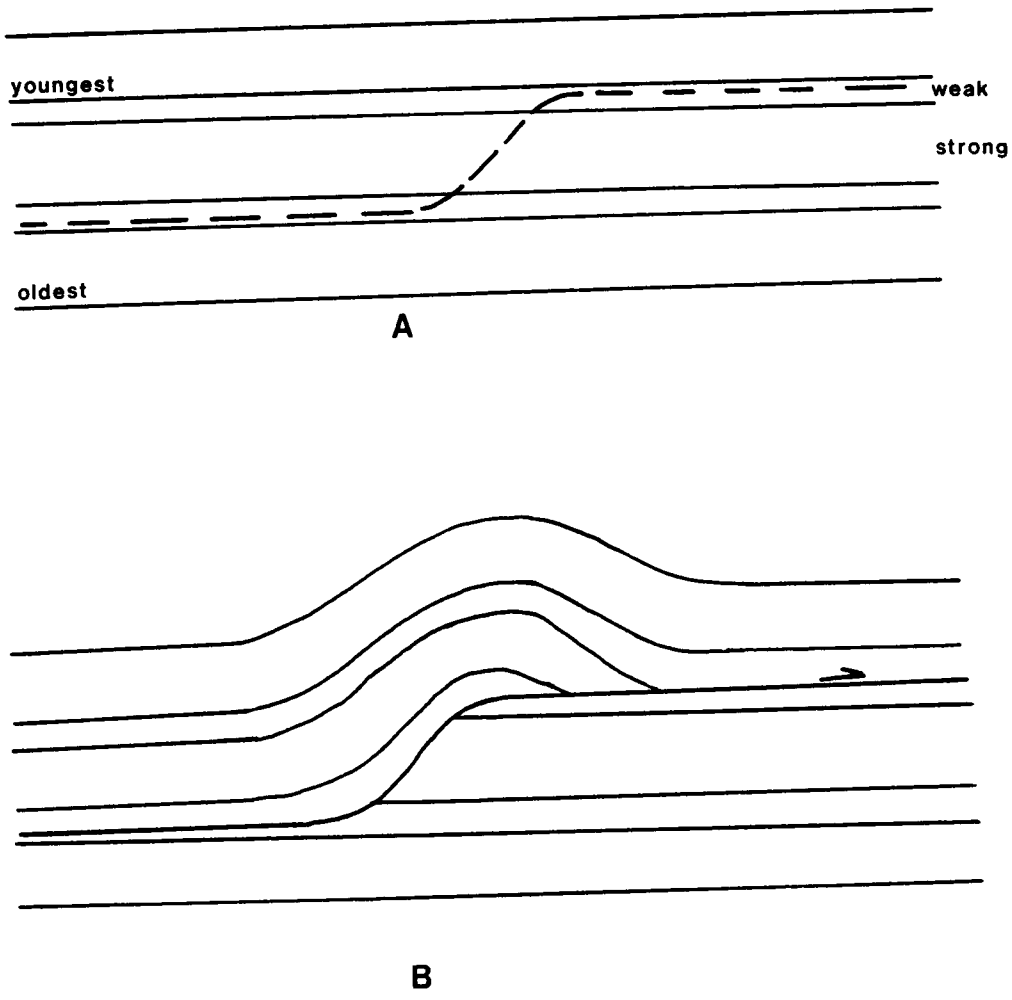


Figure 3. Illustration of a thrust fault prior to (a) and after (b) movement. The fault cuts the stratigraphy in a "stairstep" fashion due to varying strengths of the beds. Note that the thrust cuts up stratigraphic section in the transport direction.

(Dahlstrom, 1970; Harris, 1970), and they also affect the structures developed in a thrust sheet. Because thrust surfaces are non-planar, movement folds or tilts strata within each sheet. The folding of earlier faults by "piggy-back" movement on younger, structurally lower thrusts also contributes to the structures present in a thrust sheet.

Cooper and Trayner (1986) however, argue that the ideal stairstep thrust geometry may not always form. Instead, a range of thrust profiles are possible, which vary from a stairstep path to a smooth trajectory; most profiles fall somewhere between the extremes. The ranges of thrust profiles is a function of the stratigraphic sequence in a particular area. Cooper and Trayner (1986) point out that, despite ideal geometries often produced on balanced sections, the faults may not have propagated with this geometry. They stress the significance of deformation preceding thrust propogation, primarily through a ductile bead of deformation ahead of a thrust tip (Elliott, 1976). Cooper and Trayner (1986) also suggest that extensive footwall structures may provide evidence for this ductile bead.

Several adjacent faults can connect at depth to form an array termed a thrust system (Boyer and Elliott, 1982; also "family of faults," in Rodgers, 1953). Faults in a system are characteristically interleaved or imbricated, and dip in

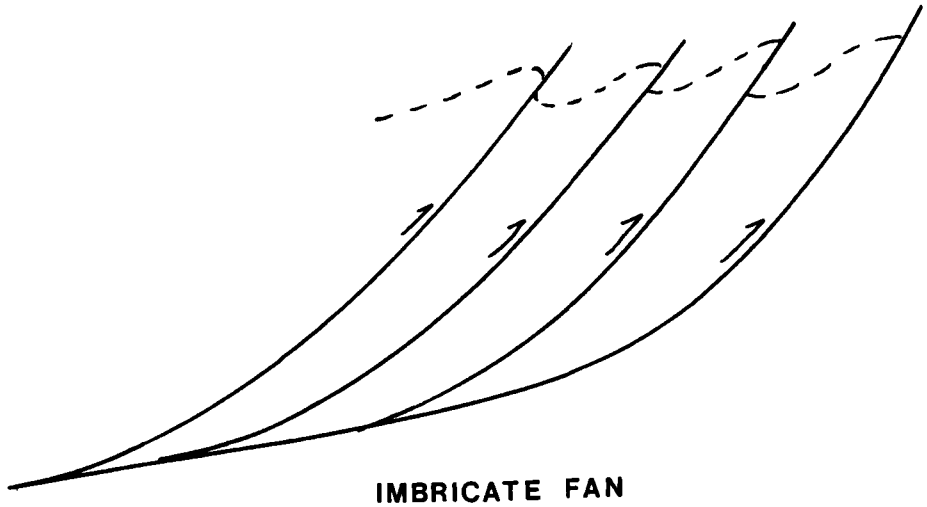
the same direction. It is useful to consider thrusts as developing as a system because several thrusts may interact during emplacement. The internal structure of a thrust sheet is commonly the result of movement on lower thrusts--blind or emergent--or imbricates within the sheet.

Two common elements of thrust systems are imbricate fans and duplexes (Fig. 4). Imbricate fans consist of a group of fault slices which dip in the same direction and merge asymptotically with a sole thrust. In some cases, a single imbricated slice will develop at the thrust's leading edge, rather than a group of them. A duplex is a group of horses--fault bound slices--which is composed of an upper "roof" thrust, a lower "floor" thrust, and subsidiary thrusts in between. Duplex formation and classification are discussed in Boyer and Elliott (1982) and Mitra and Boyer (1986).

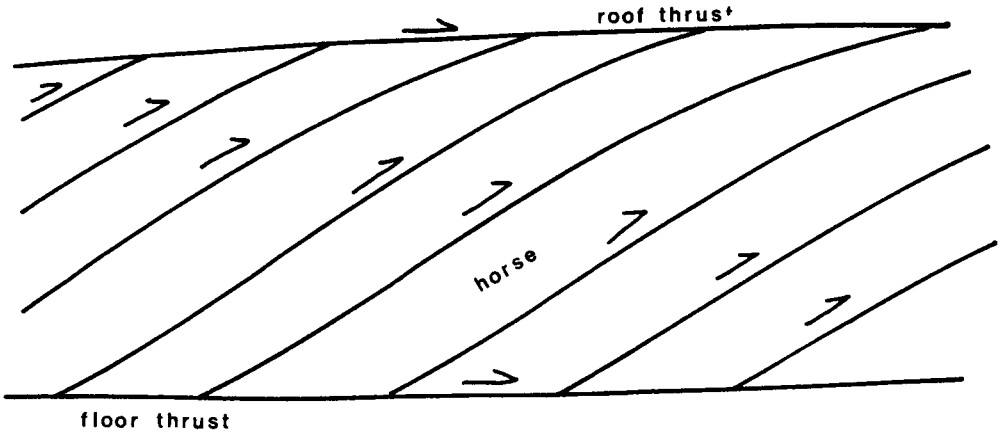
3. DESCRIPTION OF THE STUDY AREA

Regional Geologic Setting

The Valley and Ridge of east Tennessee is both a physiographic and geologic subdivision of the Southern Appalachians. Intensely deformed Lower Paleozoic and Precambrian metasedimentary and crystalline rocks of the Blue Ridge bound the Valley and Ridge to the southeast.



IMBRICATE FAN



DUPLEX

Figure 4. An idealized imbricate fan and duplex, common components of thrust systems. Note that individual faults merge asymptotically with the sole thrust in an imbricate fan. Also note the sigmoidal shape of horses in the duplex. These are diagnostic features of each.

Undeformed or mildly deformed Upper Paleozoic sedimentary strata of the Cumberland Plateau occur to the northwest.

The Valley and Ridge is characterized by parallel northeast-southwest trending ridges separated by valleys of varying dimension. In southwestern Virginia and Tennessee the structure is dominated by thrust faults with varying amounts of folding within the thrust sheets (Fig. 5).

The Valley and Ridge in east Tennessee is divisible into two belts: a belt of dominant faulting and a belt of dominant folding (Fig. 6). The belt of dominant faulting is 25 to 32 km wide and extends from the plateau southeast to the Knoxville thrust. This portion consists of southeast-dipping thrusts, between which are southeast-dipping beds; major folds are rare. The belt of dominant folding is as wide as the faulted belt (except near the Virginia state line), and does contain a few faults; however, it is dominated by folds, such as the Bays synclinorium and the complex folds in the Knoxville thrust sheet. The dividing line between the two belts to the northeast of the Knoxville area coincides with the Saltville thrust. The change in structural style is related to regional facies patterns of the stratigraphy, especially in the Middle and Late Cambrian Conasauga Group and the Middle Ordovician Chickamauga Group (Woodward, Walker, and Lutz, in press).

Figure 5. Map of geologic provinces in east Tennessee and the major thrusts of the Valley and Ridge. Study area is outlined. 1 = Pine Mountain, 2 = Jacksboro, 3 = Emory River, 4 = Cumberland Plateau, 5 = Sequatchie Valley, 6 = Rockwood, 7 = Chattanooga, 8 = Kingston, 9 = White Oak Mountain, 10 = Wallen Valley, 11 = Hunter Valley, 12 = Pine Hill, 13 = Copper Creek, 14 = Beaver Valley, 15 = Saltville, 16 = Knoxville, 17 = Rocky Valley, 18 = Carter Valley, 19 = Chestuee, 20 = Dumplin Valley, 21 = Great Smoky, 22 = Pulaski.

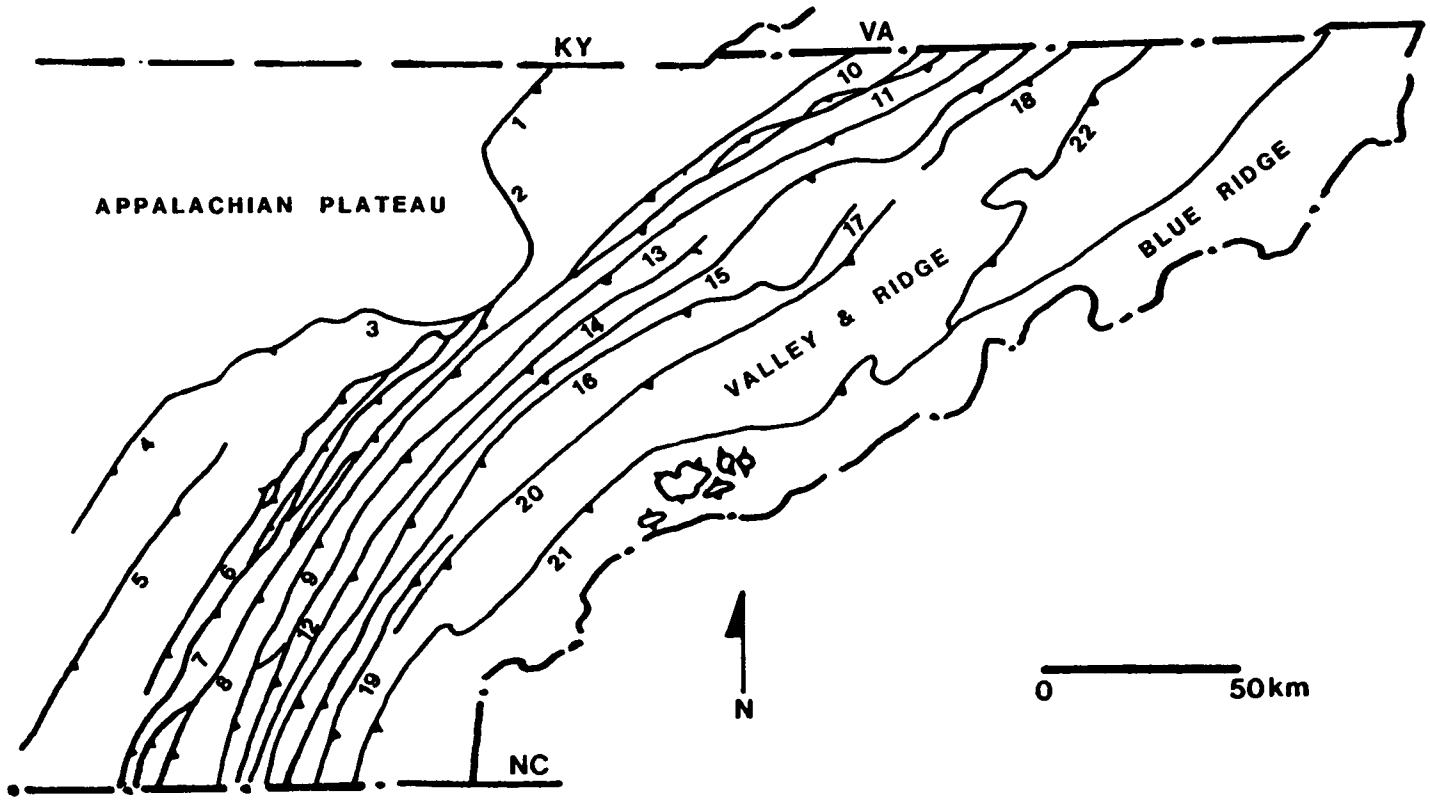
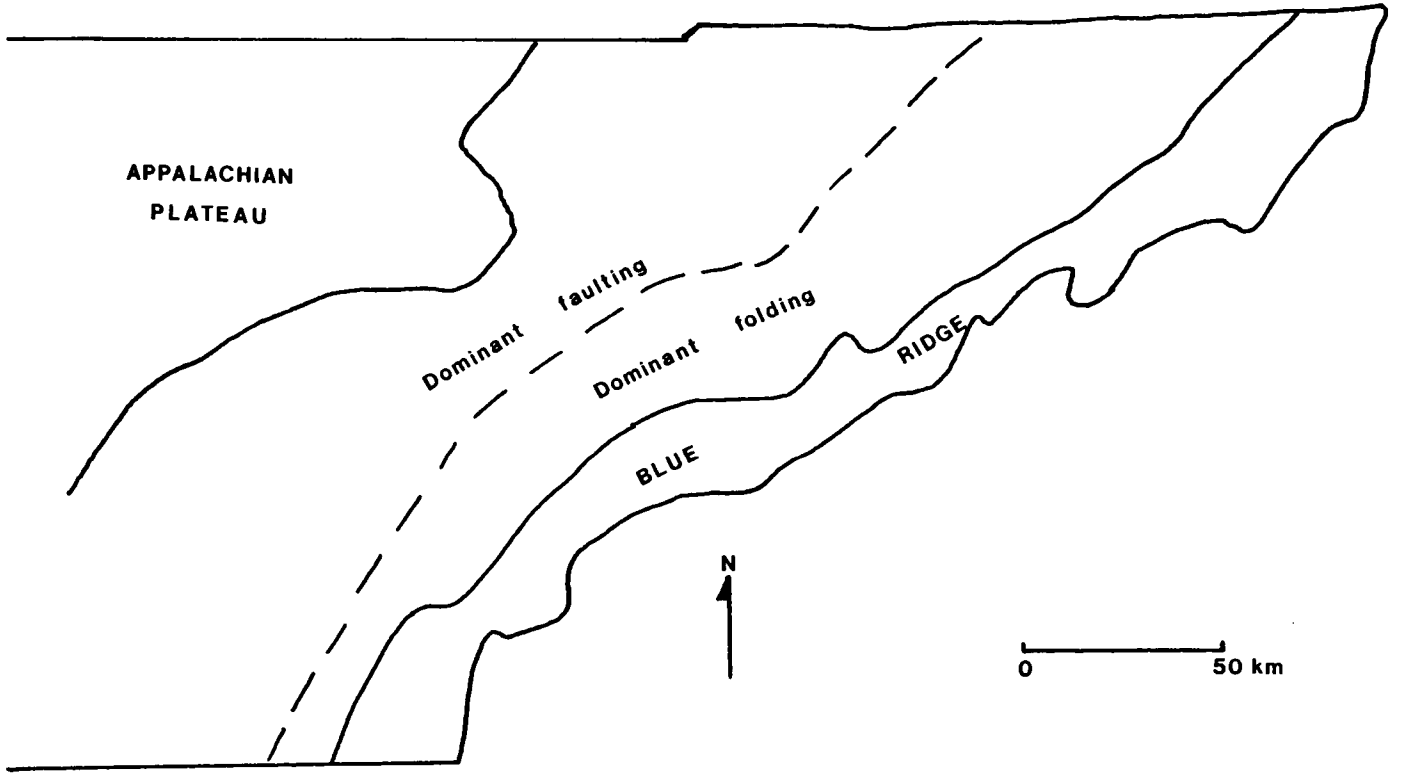

KY
VA
NC
APPALACHIAN PLATEAU
VALLEY & RIDGE
BLUE RIDGE
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
N
0
50km

Figure 6. Map of east Tennessee, showing the boundary between the belt of dominant faulting and the belt of dominant folding in the Valley and Ridge province. This boundary was first suggested by Rodgers (1953).


APPALACHIAN
PLATEAU
Dominant faulting
Dominant folding
BLUE
RIDGE
N
0
50 km

Deformation intensity also changes systematically across the thrust belt. Near the foreland, brittle failure dominates, and most of the intense deformation occurs in a zone close to a fault. Wojtal (1982, 1986) demonstrated that foreland thrust sheets deform in a brittle, inhomogeneous manner through growth of a population of discrete sliding surfaces. Fractures of varying orientation and type are common, as are extension veins, many of which trend parallel to the fractures. Cleavage is generally absent, and where developed it is confined to a zone extending only several meters from the fault. Cleavage which is penetrative at the scale of a thrust sheet is absent northwest of the Pulaski thrust. Although not preserved along all thrusts, cataclasite layers are common and vary in width from a thin coating on the fault surface to zones several meters thick (Wojtal, 1982; Paul and Woodward, 1985; Paul, 1986).

The three major thrusts which cut the study area are regionally significant Appalachian faults. The Copper Creek thrust extends southward to the Georgia state line, near which it merges into the White Oak Mountain thrust. Northward it also extends approximately 104 km into Virginia. The Beaver Valley and Saltville thrusts merge in northern Georgia to form the Rome thrust, which continues southwestward into Alabama as the Helena thrust. The Beaver Valley terminates in the study area, however the Saltville

extends 209 km into Virginia and disappears northwest of Roanoke in an anticline (House and Gray, 1982).

Sources of Data

The map is the result of fieldwork and compilation of published and unpublished data. Compiled data was checked in the field for accuracy and modified where necessary. Data for Big Ridge Park and Graveston quadrangles is from my own mapping and from master's theses done at the University of Tennessee by King (1960), Manus (1960), McReynolds (1962), and Benson (1963). Data for the Mascot quadrangle is from my mapping and a master's thesis by Palmer (1961). The map of the Luttrell quadrangle by Swingle et al. (1967a) was used without modification except for additional strike and dip measurements.

Cattermole's (1966) map of the John Sevier quadrangle is the primary source for this part of the study area, however his map was slightly modified. First, the Middle Ordovician nomenclature used on the map is now considered not to be applicable to this portion of the thrust belt. The subdivision of the Chickamauga into the Lenoir Limestone, the Holston Formation, and the Ottosee Shale is based on Rodgers' (1953, p. 68-72) "standard belt," which is defined from outcrop belts between the Saltville thrust and the Knoxville and Rocky Valley thrust to the southeast

of the study area. There is a marked change in the nature of Middle Ordovician strata across the Saltville thrust (McLaughlin, 1973). These strata are more appropriately subdivided using the nomenclature employed by Walker and his co-workers (e.g., Ruppel and Walker, 1984) for Middle Ordovician strata in strike belts northwest of the Saltville. This nomenclature is based on a modification of terms developed by Cooper and Prouty (1943) in southwestern Virginia. Second, the lower and middle Chickamauga - Moccasin contact is shifted to the southeast by a small amount near the northern margin of the quadrangle. This change conforms with field data from the adjacent Graveston quadrangle. Finally, strike and dip data are added from my fieldwork, particularly on and around House Mountain.

The Knox Group is shown on the map as "Knox Group, undivided." The Knox is not subdivided into constituent formations because the entire Knox Group behaved as a single structural lithic unit (Currie et al., 1962) during deformation. Strata within the group are uniformly tilted and fractured; complex structures are essentially absent. It is more appropriate for this study to represent the Knox Group as one block. The reader is referred to Manus (1960) or Swingle et al. (1967a) for a subdivision of the Knox in this area. Their contacts are determined largely by residuum because the Knox is deeply eroded. The various residua are distinguished using the "old" classification of

the Knox Group which includes the now abandoned Longview Dolostone (Milici, 1973, reviewed the characteristics of the Knox residua).

Likewise, all the Middle Ordovician formations are not shown on the map. An attempt was made to distinguish all the formations in the field, however the deep erosion level made this goal unattainable, except at isolated localities (e.g., the measured sections in Breland, 1980). The subdivision shown on the map splits the Chickamauga into two parts: the lower and middle Chickamauga (after usage in Walker, 1985), and the Moccasin Formation. The contact between the Moccasin and the underlyinig strata is an easily recognized break everywhere. The Moccasin's maroon argillaceous mudstones are distinct and easy to recognize in the field. The Moccasin is also a good structural lithic break because it exhibits deformational features not generally observed elsewhere in the Chickamauga.

4. GEOLOGY OF THE STUDY AREA

The area is subdivided into four parts for the purpose of discussion (Fig. 7). These are the footwall of the Copper Creek thrust, the Copper Creek thrust sheet, the Beaver Valley thrust sheet, and the Saltville thrust sheet.

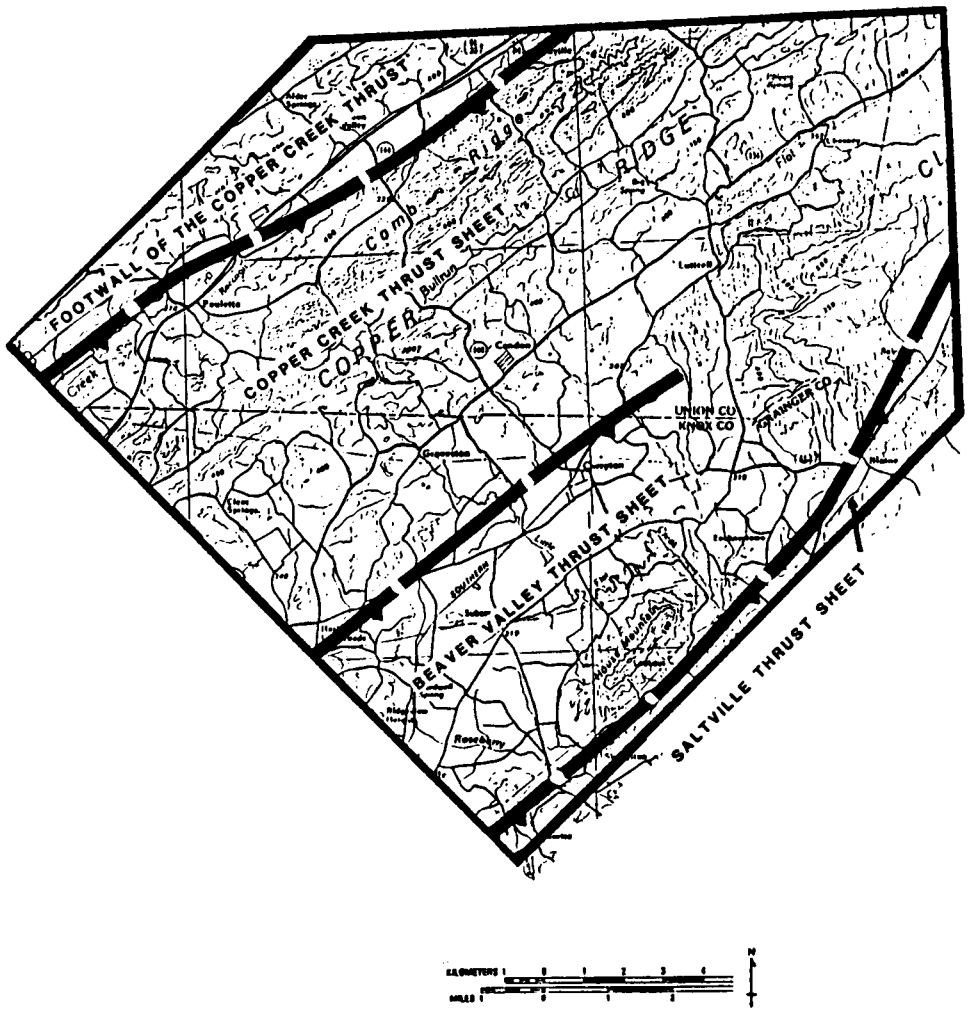


Figure 7. Location map of the major structural subdivisions of the study area, discussed in the text.

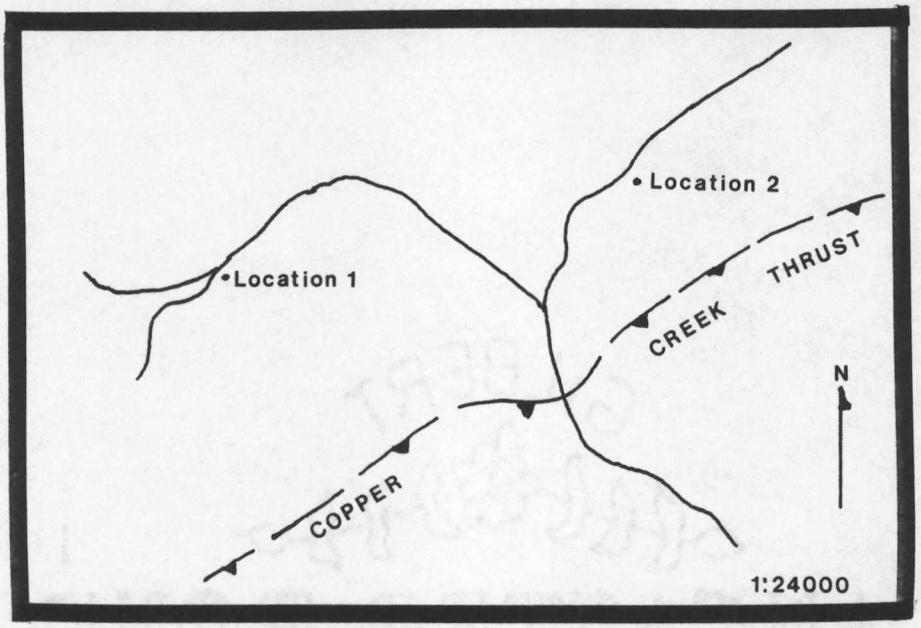
Footwall of the Copper Creek Thrust

This area consists of Cambro-Ordovician dolostones of the Knox Group which underlie Hinds Ridge, and Middle Ordovician limestones and shales of the Chickamauga Group which are exposed in Raccoon Valley and the northwest flank of Bull Run Ridge. The contact between the Knox and Chickamauga is approximated using topography and extrapolation from places where it is observable; the contact is usually not exposed. At two localities, the contact can be located with some precision. Along New Loyston Road, on the Stanley Farm, it is exposed (Ashworth, 1982), and near Alder Springs two closely-spaced outcrops contain upper Knox and lower Chickamauga lithologies, respectively.

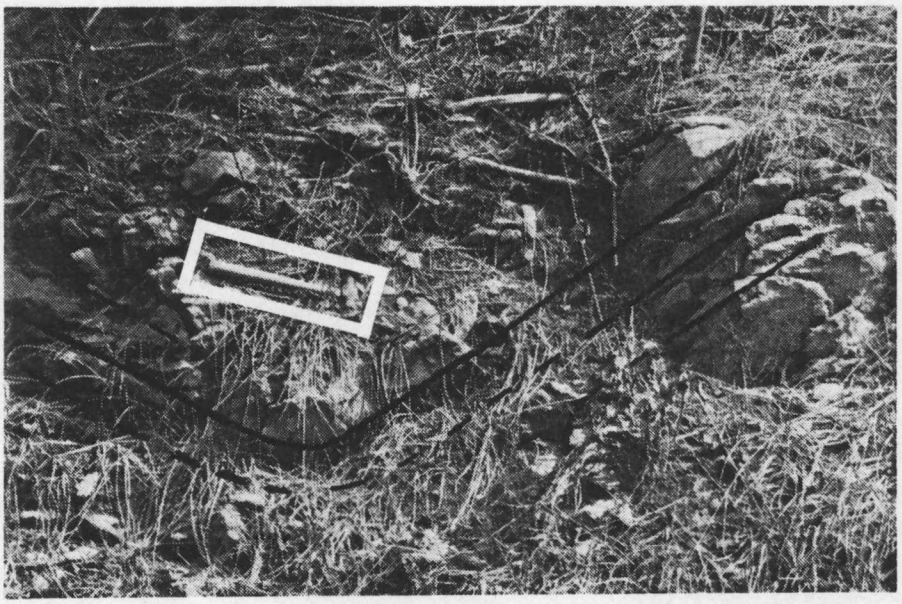
The gross structure is rather uniform; beds are tilted homoclinally, generally striking N40E to N50E, and dipping 25° to 45° southeast. Rocks adjacent to the thrust are more severely deformed. The Moccasin Formation is exposed along TN Route 61 (See Stop 3, Appendix B), and here beds vary in dip from 35° southeast to steeply overturned to the northwest, and strike direction rotates from northeast to northwest. The intensity of footwall deformation suggests that a blind or non-exposed detachment beneath the Copper Creek thrust affected these rocks.

At two locations, separated by 1.5 km (Fig. 8), small folds are exposed which are developed in Middle Ordovician strata. The folds are up to several meters wide. At the intersection of Raccoon Valley Road and Route 61, the Lincolnshire and Rockdell Formations are exposed on the road and in an adjacent field. The folds trend S50E to S70E, and plunge 20^0 southeast. More exposure of the Lincolnshire is found on Route 61, only 0.16 to 0.32 km away from the folds, and here its attitude is N43E, 34^o SE, and no folding is observable. The second locality is northeast of the first exposure and is also on Raccoon Valley Road, in farm fields. Here exposures of the Witten, Bowen, and Wardell formations are tilted and folded. The folds trend S20W to S55W, and plunge 25^o to 58^o southwest. At the northeast end of the fields, there is no evidence for folding, but the beds are inclined at various attitudes, ranging from north-northwest strike directions and vertical to more gently dipping beds (23^o to 40^o) striking northeast to northwest. The divergence of attitude at these localities and the localized nature of the folding in the footwall also suggests a blind or non-exposed detachment.

It is unclear whether the Moccasin and uppermost Chickamauga are present in the Copper Creek footwall throughout the study area, or if they are cutoff against the fault northeastward. The Moccasin is definitely present as far as the northeast end of Bull Run Ridge, however it is



A



B

Figure 8. Small scale folding in the middle Chickamauga Group, in the Copper Creek thrust footwall. A) Sketch map showing the locations and orientations of two well exposed sets of folds. B) Close-up view of location 1. Bedding is underlined. The hammer (outlined) is for scale.

impossible to determine its continuation farther northeast. Rodgers (1953) showed the Moccasin throughout the footwall of the Copper Creek thrust, however the more detailed map of the Maynardville quadrangle (Finlayson, 1964) does not. Exposures on Route 33/61 and Route 144, northeast of Bull Run Ridge, contain Middle Chickamauga Group strata, but no Moccasin. Outcrops on Miller Knobs, immediately to the southeast are of the Maryville Limestone in the Copper Creek thrust sheet. Therefore, the footwall cutoff of the Moccasin, shown on the map, is based on the last certain exposure of the Moccasin to the northeast. There are no other outcrops in this strike belt with which to confirm or refute the conclusion.

The Copper Creek Thrust Sheet

The Copper Creek thrust sheet contains four major structural subdivisions. These are: the Texas Valley anticline and syncline, the imbricate fan of Rome Formation and Conasauga Group lithologies, the uniformly dipping belt, and Clinch Mountain (Fig. 9; additional localities mentioned in the text are in this figure).

The Texas Valley anticline and syncline are composed of the Conasauga Group and the Copper Ridge Formation of the Knox Group, although the Knox is exposed only at the top of Potter and Mitchell Knobs, which are just southwest of the

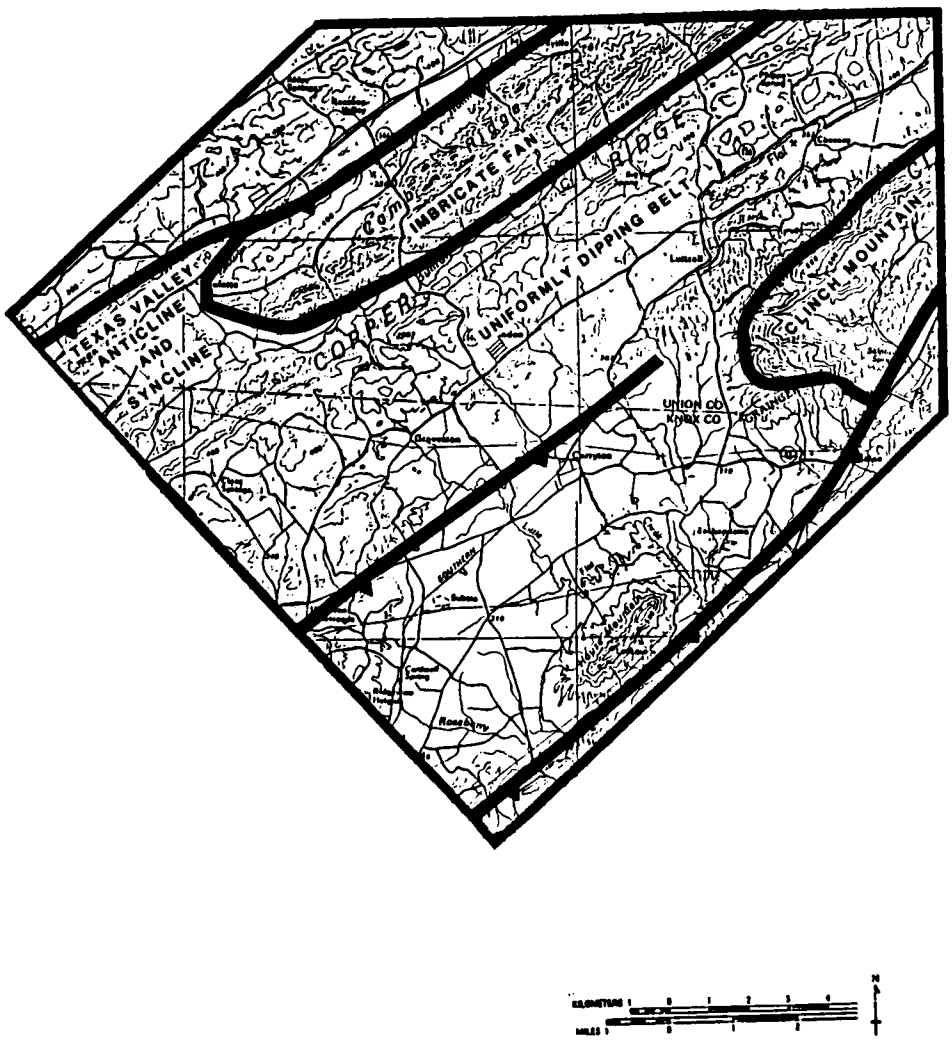


Figure 9. Structural subdivisions in the Copper Creek thrust sheet in the study area.

study area. The folds are symmetrical and are approximately 3.9 km wide and 7.8 km long. They terminate to the northeast at the southwest end of Comb Ridge, and die out to the southwest where the strata take on a homoclinal attitude, dipping to the southeast 10^{o} to 15^{o} (Fountain City quadrangle, Cattermole, 1966).

Beds strike northeasterly and vary in dip from 4^{o} to 78^{o}, however the average dip is approximately 20^{o}. Along the fold axes, beds are commonly horizontal or nearly so. For example, the Maryville Limestone is exposed along Route 33 on the Texas Valley anticline axis, dipping 5^{o} to horizontal. Similarly, nearly horizontal carbonate beds in the Nolichucky Shale are exposed on Route 33 on the axis of the Texas Valley syncline (Stop 1, Appendix B). The folds plunge gently to the southwest (Fig. 10). Benson (1963) reported that the plunge varies along the length of the folds, increasing southwestward along the anticline and decreasing southwestward along the syncline.

A small tear fault cuts the northwest limb of the syncline, near the northeast end of the folds. The fault was originally described by Benson (1963) based on bed offset and divergence of dip on either side of the fault. It is of limited extent and involves only beds of the Pumpkin Valley Shale, Rutledge Limestone, Rogersville Shale, and Maryville Limestone. Benson also described some small reverse and normal faults in the axial region of the folds,

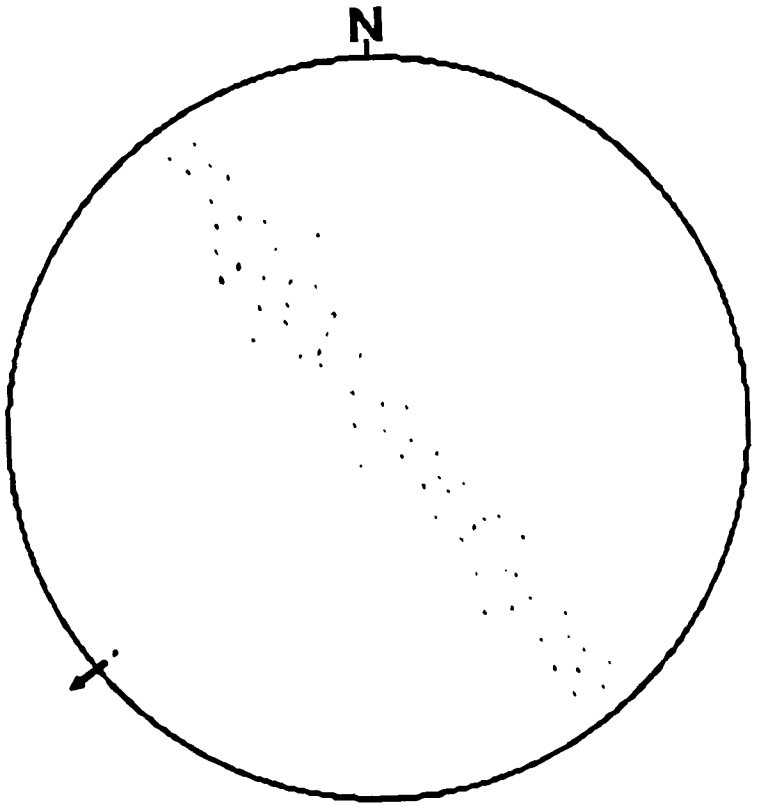
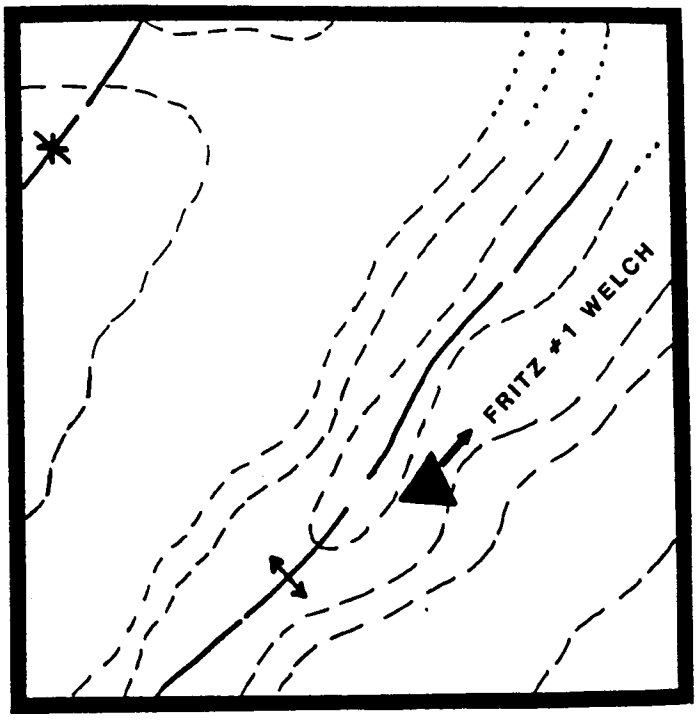


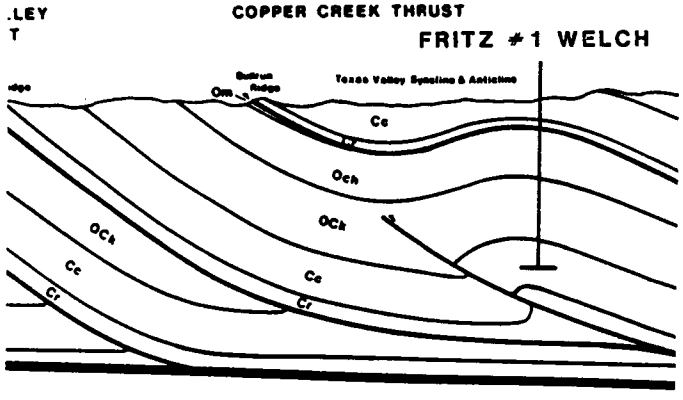
Figure 10. Stereographic projection showing the general trend of poles to bedding from the Texas Valley anticline and syncline. The folds plunge very gently to the southwest. Number of measurements = 60.

however these lie outside of the area studied. The northern margin of the folded area is a fault at the southwest end of Comb Ridge, which extends southeasterly from Paulette at the junction of Routes 33 and 61. This fault is not exposed; however, its presence is inferred from limited outcrops in road gullies of lower Conasauga strata juxtaposed along a zone which corresponds to the fault's trace. It apparently branches off of the folded portion of the Copper Creek. There may be strike-slip motion along this segment of the fault because it is parallel to the tectonic transport direction, but this is undeterminable, due to lack of exposure.

The Copper Creek thrust is folded under the Texas Valley anticline and syncline. Welch Unit #1 was drilled by Joseph F. Fritz Operating Company in 1982 on the southeast limb of the Texas Valley anticline, just south of the Union - Knox County line (Fig. 11). The well was spudded in the Rutledge Limestone, and has a total depth of 1929 m. The Copper Creek thrust is at a depth of 235 m which, when combined with the surface exposure of the fault in Bull Run Ridge, requires folding of the fault (Cross-section A-A'). The stratigraphic section, from Middle Ordovician down, is repeated beneath the thrust, and the well ends in the upper Conasauga. The folding is explained here by adding a blind thrust beneath the Copper Creek.



A



B

Figure 11. Location of Fritz #1 Welch well. A) Geologic map showing the location of the well in the Texas Valley anticline The map is taken from Plate I, therefore the scale is 1:24,000. B) Geologic cross-section showing the location of the well and its depth.

The imbricate fan of the Rome Formation and Conasauga Group is a set of thrust imbricates and associated folds within the Copper Creek thrust sheet. The rocks which comprise this area are the Rome Formation, the Conasauga Group, and the Copper Ridge Formation of the Knox Group. The Rome Formation and the lower half of the Conasauga Group constitute most of the domain.

The Buffalo Ridge area contains the upper Conasauga Group and Copper Ridge Formation of the Knox Group. The bounding fault on the northwest margin is the leading edge of the Copper Creek thrust sheet, but it was named the Miller Knobs fault by King (1960) for the knobby topography developed on the Maryville Formation. The name "Miller Knobs" is not used here because all the slices in this area are part of the Copper Creek thrust system. The southeastern boundary of the Buffalo Ridge area is the folded segment of the fault system.

The primary structure in the area is the Buffalo Ridge syncline, a slightly northwestward asymmetric fold which is approximately 1.9 km wide and 5.75 km long. Beds generally strike northeast and dip between 15° to 20° southeast on the northwest limb and between 30° to 55° northwest on the southeast limb. The axis trends to the southwest and plunges 10° in that direction (Fig. 12). A local anticlinal warp is present on the southern end of the sheet in Beard Valley. It contains steeply dipping beds of the

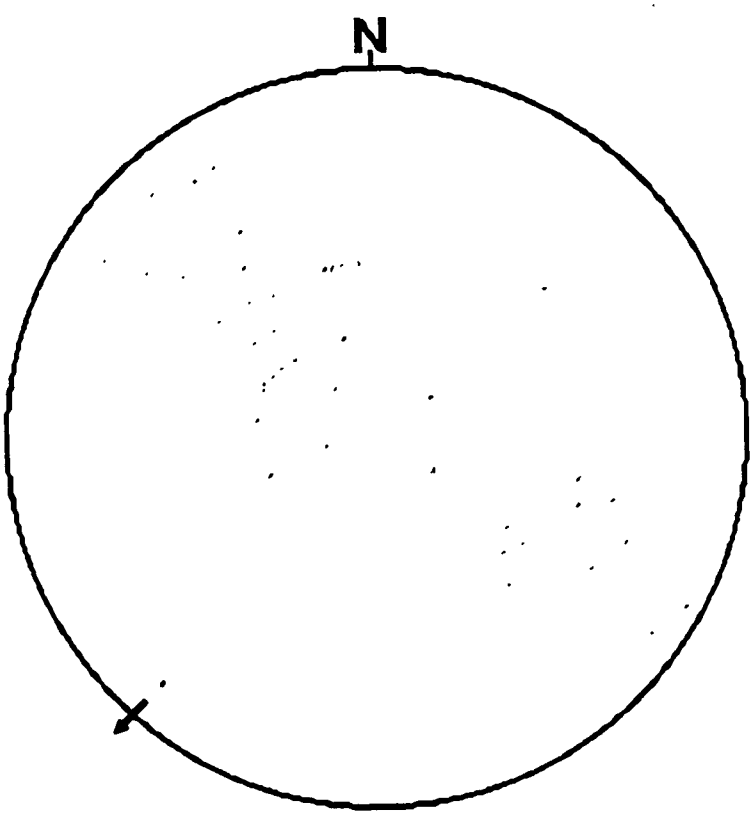


Figure 12. Stereographic projection showing the general trend of poles to bedding from the Buffalo Ridge syncline. The fold plunges 10^{o} southwest. Number of measurements = 40.

Nolichucky Shale and Maynardville Limestone. The Maryville Limestone is also folded just north of Route 144. The Buffalo Ridge syncline and the Beard Valley anticline lie approximately in line along strike from the Texas Valley structures, so it is inferred that the Copper Creek thrust is folded here as well (Cross-section B-B').

The thrust beneath the Buffalo Ridge slice is shown dashed because it is not actually exposed. Nolichucky Shale is present around Arick Hollow and the Rome Formation is visible on the adjacent ridge. The two small pieces of the Knox Group present along the Copper Creek fault were first observed by McReynolds (1962). He described "cemented breccia" along the fault plane, but all that is now exposed in this area is cherty residuum, which is characteristic of weathered Knox.

Comb Ridge consists of several slices of the Rome Formation and the lower Consauga Group and it makes up most of the imbricate fan in the Copper Creek thrust sheet. Bedding attitudes are highly variable, ranging from horizontal to vertical. Much of the area is rugged, heavily forested, terrain consequently it is difficult to locate precisely many of the stratigraphic and fault contacts. Five faults are identified (Plate I), and these were originally described by King (1960) and McReynolds (1962). King designated the faults A through D, and this usage is retained here. Fault E is McReynold's fault C (it is not

contiguous with King's fault C). The lettering does not imply a sequence of faulting.

Fault A places the Rome Formation against Rome Formation and extends northeastward to where it merges with the main trace of the Copper Creek thrust. The fault probably extends southward to the southeast boundary of the Buffalo Ridge slice because the thickness of the Rome here suggests that it is duplicated or folded or both. The fault however, is not traceable at this end of Comb Ridge. Fault B again only duplicates the Rome, except near Black Hollow where it places the Rome over the Pumpkin Valley Shale and Rutledge Limestone in its foot wall. The northeastern termination of the fault is uncertain because it is covered by vegatation. It is depicted on cross-section C-C' as being non-emergent.

Fault C extends northeast from Stover Gap to beyond the northern margin of the map. The fault juxtaposes Rome and lower Conasauga Group rocks. Fault D branches southwestward off of fault C and the Rome and lower Conasauga Group are thrust onto the Rutledge Limestone. An excellent exposure of the footwall of fault D is on the (unnamed) road which branches off of Route 144 to Pleasant Grove School (Stop 5, Appendix B). At this locality, the foot wall consists of interbedded shale and limestone of the Rutledge, which is intensely folded. Fault E branches off of fault C as a splay at the south end of Potato Valley. It extends only a

short distance and repeats the lower Conasauga Group, dying out in the Rome Formation. Texas and Potato Valleys form the southeastern margin of the imbricate fan in the Copper Creek thrust sheet and consist of rocks of the upper half of the Conasauga Group. The structure is simple, with beds striking northeast, and dipping to the southeast between 30° and 60°. Locally, dips increase to 85° (Fig. 13).

The Buffalo and Comb Ridge area together represent either an imbricate fan or an eroded duplex. The key factor which would distinguish the two possibilites is whether or not the faults connected with one another during deformation, isolating a group of horses. A down-plunge view of the domain, projected from the axis of the Buffalo Ridge syncline (Fig. 14), suggests a duplex geometry. However, the interpretation is based on the inferred branch points, and is somewhat distorted because the Copper Creek thrust is folded and the Buffalo Ridge slice contains several folds, therefore a projection down one fold axis approximates the shape. I favor the imbricate fan interpretation because individual slices lack sigmoidal anticlines and synclines, which are characteristic of horses in a duplex. The imbricate geometry is also the simplest balanceable interpretation which matches the surface geology (Cross-sections B-B', C-C'). Either geometry reflects the influence of the Rome - Conasauga stratigraphy on the structure formed. The alternation of weak and strong layers

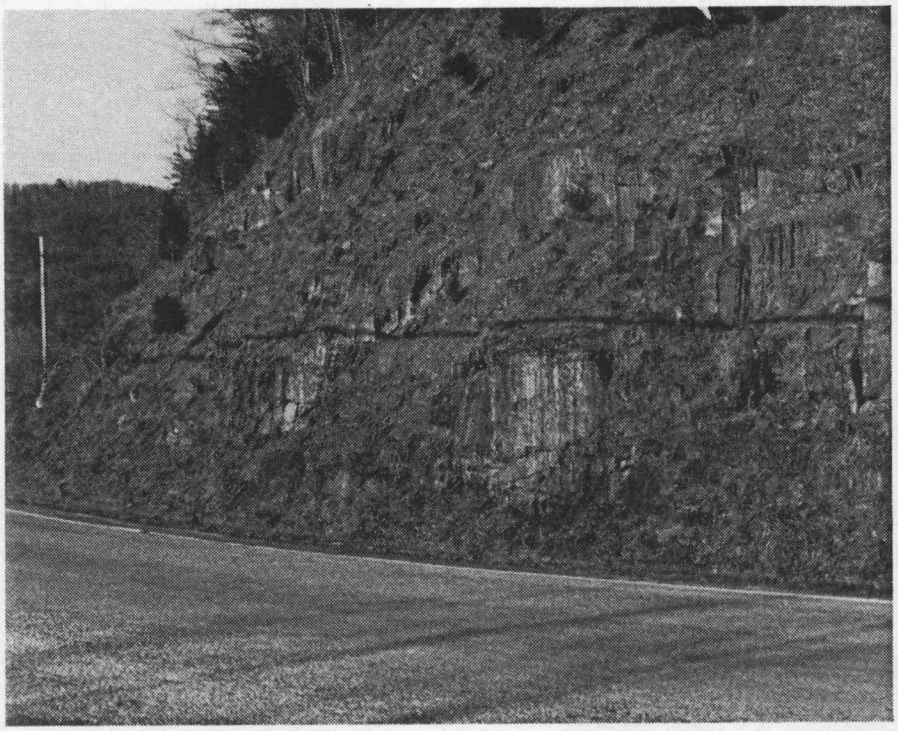
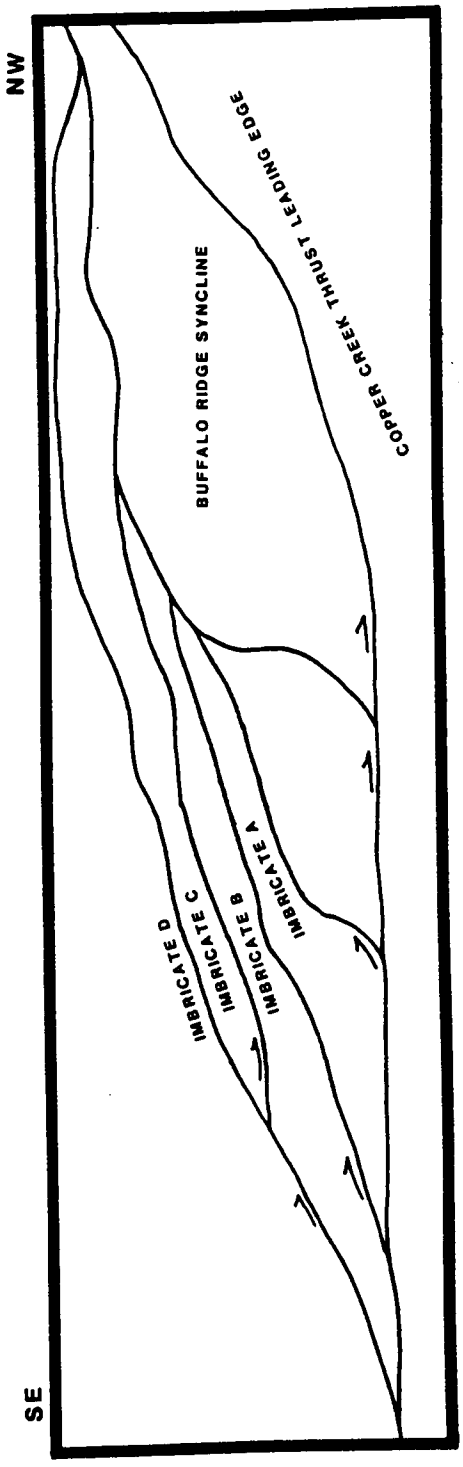


Figure 13. Steeply dipping (southeast 85°) beds of the Maryville Limestone on Route 370 in Texas Valley. The steep dips appear to be confined to this locality; elsewhere in the valley, dip does not exceed 50°.

Figure 14. Downplunge projection of the Copper Creek thrust, projected from the axis of the Buffalo Ridge syncline. Because of extensive folding, the shape is distorted, but it shows the imbricated nature of this portion of the thrust.


NW
SE
BUFFALO RIDGE SYNCLINE
COPPER CREEK THRUST LEADING EDGE
IMBRICATE D
IMBRICATE C
IMBRICATE B
IMBRICATE A

promotes imbrication with folded strata between the faults (Woodward et al., in press).

The uniformly dipping belt includes strata from the Knox Group, the Chickamauga Group, the Moccasin Formation, and the Martinsburg Formation. The structure of this domain is, for the most part, simple and uniform. Beds strike northeasterly and dip to the southeast betweeen 17° and 45°. Rocks in this belt do not exhibit evidence of much deformation. Fractures are well developed, commonly striking northeast and dipping steeply to the northwest. Determining the contacts at the southwest end of the domain is complicated by deep weathering and, in places, by alluvial cover. The contacts from the Fountain City quadrangle (Cattermole, 1966) and from the Graveston and Condon areas.

Three structural features are present within the uniformly dipping belt. An overturned syncline is developed in the footwall of the Beaver Valley thrust at the southwest end of the belt. The syncline involves part of the Chickamauga Group, the Moccasin Formation, and the Martinsburg Formation; the hinge is in the Martinsburg and trends approximately N45E. Overturned beds dip moderately (30° to 40°) to the southeast. The syncline is adjacent to complexly faulted pieces of the Conasauga and Knox Group in the Beaver Valley thrust zone.

A tear fault occurs at the northeast end of the belt in the Luttrell quadrangle. The fault was first described by Skinner (1961), who named it the Chesney fault for the community of Chesney through which it passes. It strikes N70W, is approximately 3.5 km long, and it affects the stratigraphy from the lower Knox Group (upper Copper Ridge Formation - lower Chepultepec Formation) through the lower Martinsburg Formation. The sense of shear is dextral, and the horizontal displacement is small, less than 61 m. Skinner also reported two small faults which trend oblique to the Chesney fault, however these were not observed.

Two small folds, an anticline and a syncline, are developed in the Moccasin and Martinsburg Formations just over a kilometer south of the Chesney fault. The folds are 180 m wide and 788 m long; fold axes trend approximately N60E. The folds may be related to movement on the Chesney fault, or perhaps to another small fault which is not seen.

Clinch Mountain is a prominent feature in the Copper Creek thrust sheet which rises to an elevation of over 600 m and extends from Luttrell northeastward into southwest Virginia. The rocks which comprise Clinch Mountain include the only post-Silurian formations in the study area. The strata include the Mississippian Grainger and Newman formations, the Mississippian - Devonian Chattanooga Shale,

the Silurian Clinch Formation, and the Upper Ordovician Juniata and Martinsburg formations.

Strike and dip values are from the map of the Luttrell quadrangle (Swingle et al, 1967). Along Clinch Mountain, beds strike northeasterly and dip to the southeast between 20^{o} and 70^{o}. However, at the end of the mountain, beds of the Martinsburg, Juniata, and Clinch are folded into a set of a dozen or so small anticlines and synclines (Fig. 15). Beds dip from 10^{o} to 80^{o}, and the folds all trend and plunge to the northeast. The folds may be cored at depth by thrusts of very small displacement within Martinsburg shales adjacent to the end of the Beaver Valley sheet, but there are no faults at exposed at the surface. Earlier workers (e.g., Swingle, 1973) referred to Clinch Mountain as the "Clinch Mountain syncline," which implied that the southeast limb lay under the Saltville thrust and therefore that folding preceded faulting. This interpretation is actually more complex than necessary because the beds merely dip homoclinally and the mountain ends in a lateral ramp beneath the Saltville thrust (Fig. 16). The footwall has stepped down stratigraphically through the area where the Beaver Valley thrust ends.

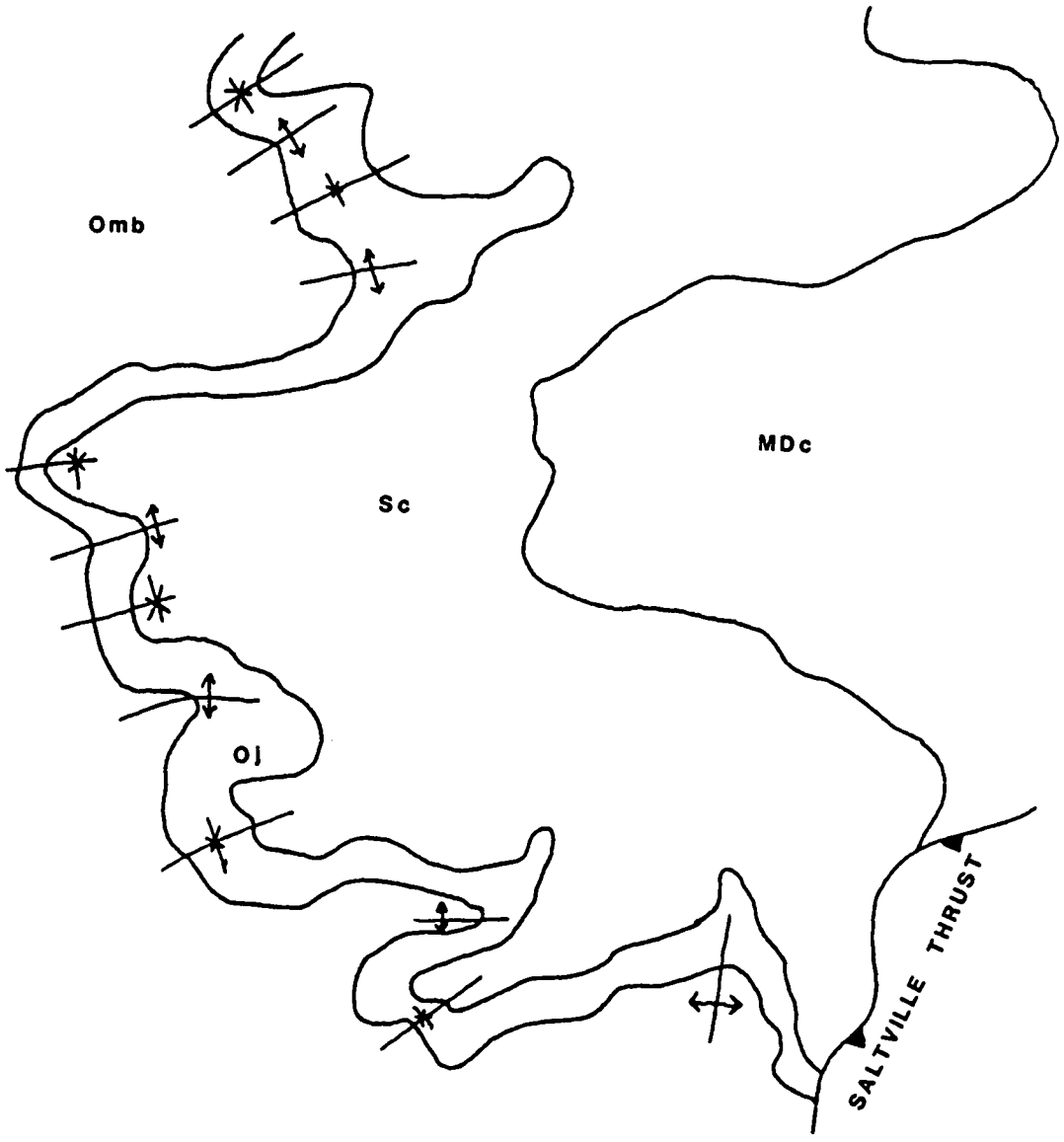
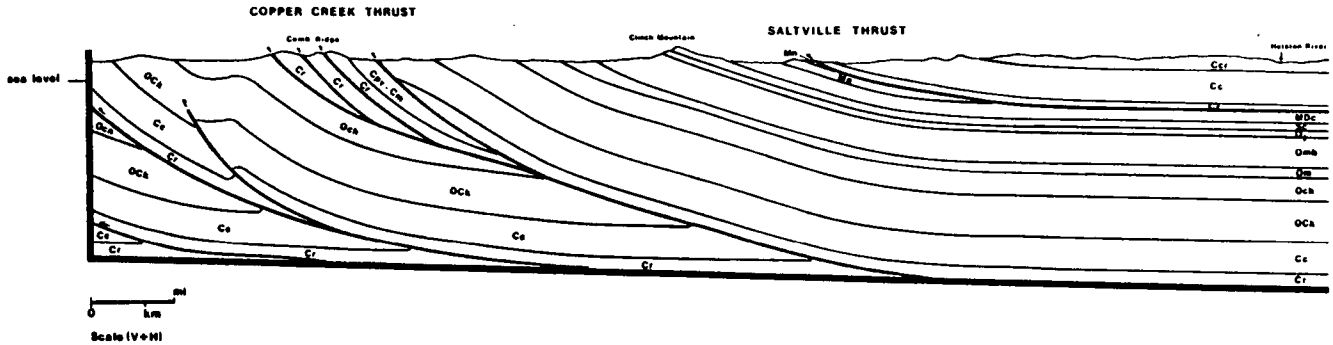


Figure 15. Anticlines and synclines developed at the southwest end of Clinch Mountain. Axial trend varies from north-south to east-west. The folds are probably cored by detachments at depth. The map is taken from Plate I, therefore the scale is 1:24,000.

Figure 16. Geologic cross-section showing the simple structure of beds within the Copper Creek thrust sheet under the Saltville thrust. Note that the beds which hold up Clinch Mountain do not fold under the Saltville thrust into a syncline but rather dip homoclinally and flatten at depth. This interpretation is suggested by the dominance of horizontal strata in the Saltville thrust sheet in this area which suggest that the thrust is horizontal

CROSS SECTION C-C'

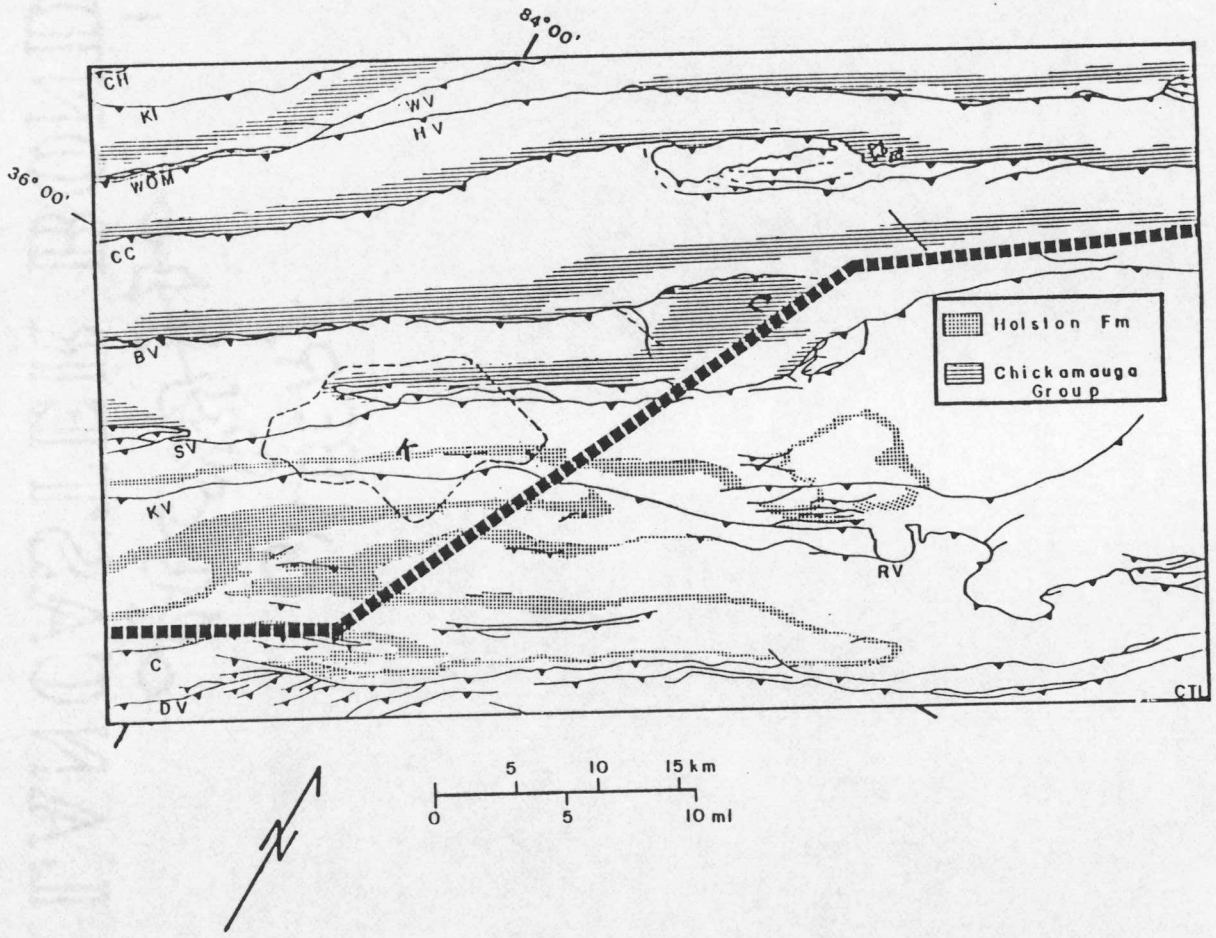


The Beaver Valley Thrust Sheet

The rocks exposed in this thrust sheet are dominantly Middle and Upper Ordovician carbonates and shales, with Conasauga Group and Knox Group strata at the southern end of the area, and the Juniata Formation and Clinch Sandstone on House Mountain. The structure is complex, yet is generally poorly exposed. With the exception of House Mountain, the area has extremely low topographic relief, and most of the land is forested or farmed. The carbonates are deeply eroded and, as a result, outcrop is not plentiful. The Middle Ordovician stratigraphy in this area is also a problem. The inferred position of the Middle Ordovician shelf edge makes a sharp turn through this area (Breland, 1980; Walker, 1980) from northeast - southwest to roughly north - south. The kink makes its turn near Corryton (Fig. 17), and the stratigraphy is an interfingering of lithotypes, some of which resemble shelf lithologies, some of which resemble shelf-edge lithologies. The mixed lithologic package makes it difficult to determine what part of the Middle Ordovician is present from one outcrop to the next.

The structure is dominated by a set of folds in Middle and Upper Ordovician strata that, taken together, comprise the Corryton anticline (Manus, 1963). The folds trend approximately N60^{O}E and plunge gently to the northeast (Fig.

Figure 17. Geologic map showing the inferred bend in the Middle Ordovician shelf edge. The dashed line is the inferred position of the Middle Ordovician shelf edge. Its position is inferred based on detailed study of the stratigraphy in the area and the palinspastic base map of Roeder and Witherspoon (1978). See Walker (1980) for additional discussion. K = Knoxville, TN. C = Corryton, TN.


84°00'
36°00'
CH
KI
WV
HV
WOM
CC
BV
SV
KV
RV
C
DV
CTI
Holston Fm
Chickamauga Group
5 10 15 km
0 5 10 mi

18). Some of the folds are overturned to the southeast. Outcrop scale folds generally conform with the trend of the major structure. Overturned beds of the Moccasin Formation are exposed near the approximate location of the Beaver Valley thrust along Route 144 in gullies and in fields just northwest of Corryton - Luttrell Road. Cleavage is developed in the Moccasin, although it is rarely visible in outcrop. The cleavage is axial planar to minor folds (Stop 6, Appendix B). The folds are inferred to be cored at depth by a blind imbricate or imbricates off of the Beaver Valley thrust. This is a necessity for a geometrically reasonable and balanceable interpretation (Dahlstrom, 1970, his "front-fold" detachment).

Southwest of the Corryton anticline are faulted pieces of Conasauga and Knox Group units. The Conasauga rocks are caught in two tear-fault bound pieces at the end of Beaver Ridge. The tear faults die out eastward in the Chickamauga, as mapped by Cattermole (1966). The state geologic map (Hardeman and others, 1966) shows this splay turning northeast and continuing to cut Middle Ordovician strata. It is omitted from this map because it was not observed anywhere in the field, and its presence was judged unnecessary for the reasonable interpretation of exposed structures.

The Knox Group (excluding the Copper Ridge Formation) is caught between the tear faults and a splay off of the

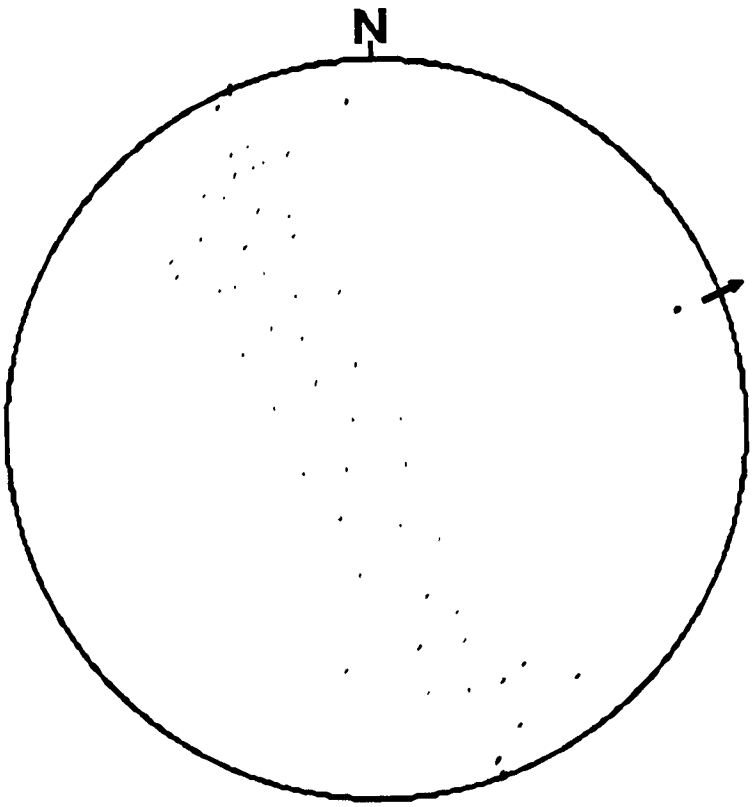


Figure 18. Stereographic projection showing the general trend of beds in the Corryton anticline. The fold trends approximately N60^{O}E and plunges gently to the northeast. Number of measurements = 50.

Beaver Valley thrust. These rocks are exposed in only three or four places. The faults are not observed, but their presence is inferred from two lines of evidence. First, the Knox strikes abruptly into middle Chickamauga Group and Moccasin Formation strata just north of Emory Road. Also the estimated Knox contacts trend obliquely to the strike of the Chickamauga. This suggests the beds are cut-off against a fault. Second, an exposure of the Mascot Formation on Emory Road exhibits beds striking N45^{o}E and dipping 33^{o} southeast. The rocks are highly jointed, with three fracture sets observable striking N20^{o}E, N70^{o}E, and S70^{o}E. The rock is a protocataclasite (see Chapter 4). The occurrence of these brecciated rocks also suggests the presence of a fault.

House Mountain is a prominent topographic feature which rises abruptly to an elevation of nearly 640 m west of the town of Blaine. It sits in the foot wall of the Saltville thrust, adjacent to the Middle Ordovician folds in the Beaver Valley sheet. The mountain consists of the Martinsburg Formation, the Juniata Formation, and the Clinch Sandstone. Structurally, House Mountain is a syncline which trends N45^{o}E to N60^{o}E, and beds on the southeast limb are overturned to the northwest. The axis of the syncline does not correspond to the topographic crest of the mountain; rather, it cuts the southeastern slope through the Martinsburg. The location of the axis was fixed at the

southern end using data from Cattermole (1966), and farther north by two traverses across the structure. One traverse was up the mountain, and poorly exposed but identifiable Martinsburg beds crop out along the trail, dipping to the southeast. The beds probably correspond to the mixed-carbonate and shale facies described by Walker and Diehl (1985) because beds of shale and shale chips are regularly interbedded with limestone float and residuum. The other location actually exposes the axis along Idumea Road (Plate I). The overturned attitude of the beds on the southeast limb was confirmed by slabbed samples, which revealed the graded limestone beds of the Martinsburg in an overturned orientation.

Beds of the Juniata and Clinch on top of the mountain vary considerably in both strike and dip. At the northeast end of the mountain, the Clinch is horizontal, but to the southwest it is folded into several small folds of varying orientation. Clinch beds at the southwest end strike northeast and dip gently southeastward. The Juniata generally strikes to the northeast, and dips steeply southeast (65^{o} to vertical). The shales in the Martinsburg are tightly crumpled and folded. None of the small folds on House Mountain are depicted on the cross-section because they are smaller than map scale. The thickness of the Martinsburg was estimated for the cross-section because of the extent to which it is folded and faulted.

The Saltville Thrust Sheet

The rocks in the Saltville sheet here include the Rome Formation, and the Conasauga and Knox Groups. At the southern end of the area, the Saltville consists of the main trace, which places the Rome on the Martinsburg Formation, and a hanging wall imbricate which places the Rome and Pumpkin Valley Shale on units of the Conasauga Group. The imbricate continues to the southwest, where additional imbricates are added so that an imbricate fan produced which extends to Knoxville (Cattermole, 1966; Paul, 1986). The three imbricated slices in the study area contain the Rome Formation and Pumpkin Valley Shale, overturned Maryville Limestone and Nolichucky Shale, and Knox Group strata, respectively.

To the northeast in the vicinity of Blaine, the Saltville is more complex, and includes a wide slice of faulted and folded Rome Formation and Conasauga Group (Plate I). Beds generally strike northeast, and dip in widely varying orientations. An anticline consisting of beds of the Maryville Limestone, Rogersville Shale, and Rutledge Limestone trends approximately N40E and is bounded by faults at its southwest end. South of the anticline, beds of the same formations plus the Pumpkin Valley Shale are steeply overturned to the northwest and also bound by

small faults. North of the anticline, the Nolichucky Shale is tightly folded and probably faulted. Palmer (1961) who did the first detailed mapping in this area, pointed out that the lack of good outcrop masks the true complexity of the folding and faulting in the Nolichucky. Several pieces of Knox are caught along the lower-most fault (called the Blaine fault by Palmer), and they are distinguished from the Conasauga by cherty residuum and scattered outcrops.

Immediately to the northeast, structural complexity decreases and the Saltville is a single fault trace, with Clinch Mountain in the footwall. Rome and Conasauga units in the hanging wall dip gently southeast and are thrust on Middle Ordovician and younger strata. Foot wall rocks decrease in age northeastward; the Mississippian Newman Limestone is the youngest exposed formation. The Knox Group in the hanging wall generally dips gently southeast, however the upper Knox and Middle Ordovician strata are folded. The rocks are folded into a syncline (Fig. 19) which was named the Massengill syncline by Palmer (1961; the structure was called the Strawberry Plains basin by Bridge, 1956). The fold is cut by the Holston River and truncated to the southeast by the Knoxville - Rocky Valley thrust system.

Beds in the syncline strike between N33^{o}E and N61^{o}E and dip 20^{o} to 40^{o} southeast on the northwest limb, and on the northeast limb strike between N56^{o}W and N71^{o}W, dipping between 15^{o} and 25^{o} southwest. The syncline trends

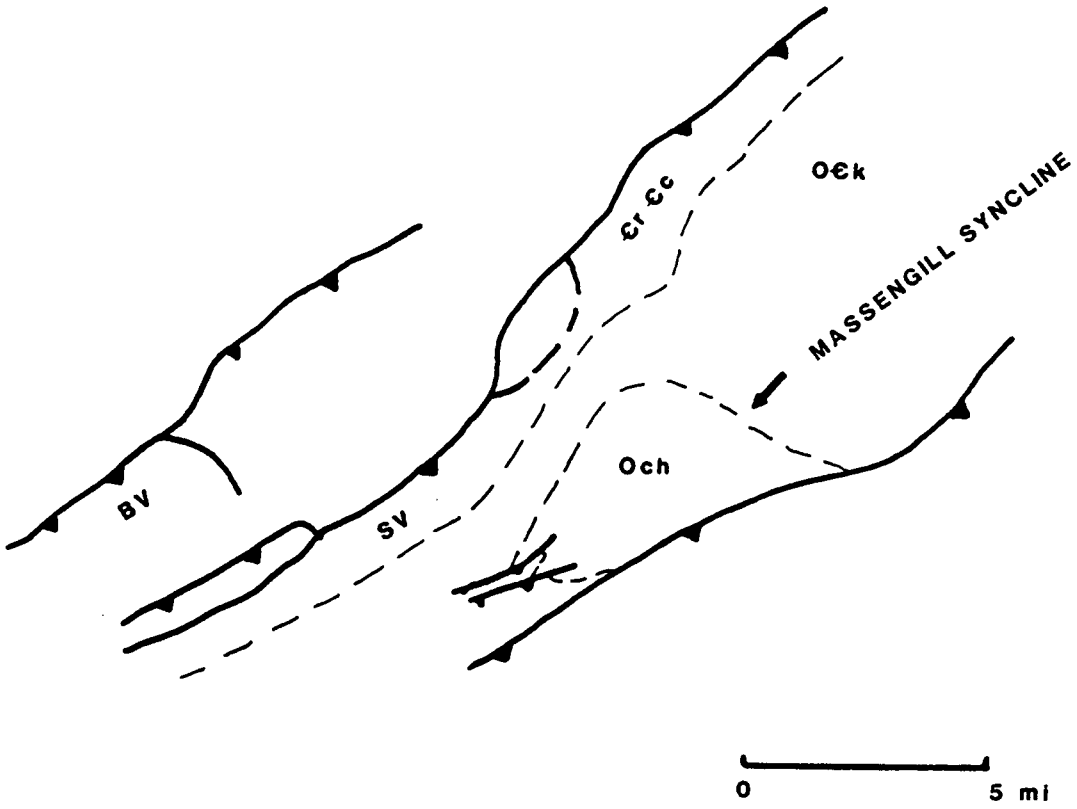


Figure 19. Geologic map showing the location of the Massengill syncline within the Saltville thrust sheet. Lithologic symbols are the standard symbols used on Plate I. BV = Beaver Valley thrust. SV = Saltville thrust.

approximately S10°E and plunges to the southeast very gently. The trend of the fold axis is oblique to the transport direction of the thrust. The Massengill syncline and the folded and faulted slice of the Rome Formation and Conasauga Group in Blaine support the interpretation of a lateral footwall ramp along the Saltville thrust as indicated by the map pattern. The structures are of limited size and extent and their development was promoted by the change in the shape of the fault along strike in this area.

5. STRATIGRAPHIC SEPARATION DIAGRAMS AND CUTOFF LINES

It is possible to interpret the three-dimensional shape of structures from map patterns. Three techniques are commonly used to clarify the geometry of structures: down-plunge projections, stratigraphic separation diagrams, and cutoff line maps. A down-plunge projection was made to study the Comb Ridge structure in the Copper Creek thrust sheet (see p. 42), and it is not discussed here. Stratigraphic separation diagrams for each of the thrusts in the study area and a cutoff line diagram for the Saltville thrust are covered in this section.

Stratigraphic separation diagrams plot the stratigraphic position of the hangingwall and footwall on the ordinate versus geographic location of the fault on the abscissa. Separation diagrams may be drawn either in the

tectonic transport direction or longitudinally to the fault. Together these two types provide at least a first approximation of fault shape because relative distances travelled in each horizon specify the position of ramps and flats (Woodward et al., 1985). Therefore, it is useful to construct these diagrams prior to the construction of cross-sections. Stratigraphic separation diagrams have been used in a number of thrust studies, including Rubey (1973), Woodward (1981), House and Gray (1982), and Rutherford (1985).

A direct relationship does not necessarily exist between stratigraphic separation and fault slip. If one considers a thrust fault as a planar surface, slip and stratigraphic separation can easily be calculated from a simple block diagram (Billings, 1972, p. 189-190). However, the relationship is not so simple for the cases of stairstep and listric thrust geometries. Woodward et al. (1985) illustrate how stratigraphic separation changes when a fault rides over a stepped surface. The "displacement diagram" of Pfiffner (1982) is another way to understand slip and fault shape.

Longitudinal stratigraphic separation diagrams were constructed for the Copper Creek, Beaver Valley, and Saltville thrusts (Figs. 20 - 22). Transport direction diagrams are not presented because their construction requires a level of exposure not found in this part of the

Figure 20. Longitudinal stratigraphic separation diagram for the Copper Creek thrust. Note that stratigraphic separation is nearly constant. The Rome Formation is typically the hangingwall formation with the Moccasin Formation generally in the footwall. Stratigraphic separation decreases slightly between Paulette, TN and Maynardville, TN but this is not considered to reflect a lateral ramp because there is no evidence from the structures in the area to suggest ramping. Stratigraphic symbols are standard symbols used on Plate I.

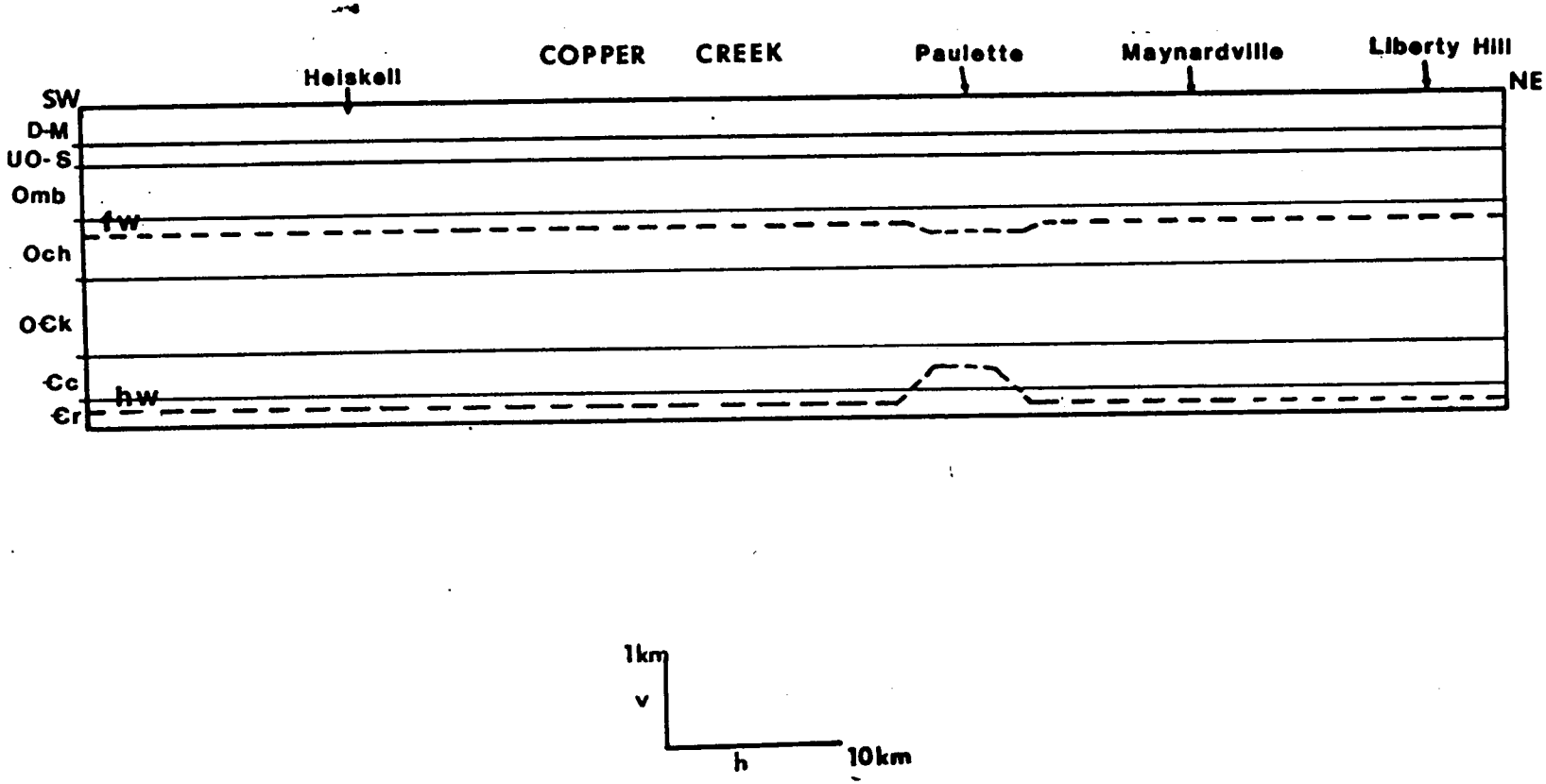

COPPER CREEK
Helskell
Paulette
Maynardville
Liberty Hill
SW
NE
D-M
UO-S
Omb
fw
Och
OCk
Cc
hw
Cr
1km
v
h
10km

Figure 21. Longitudinal stratigraphic separation diagram for the Beaver Valley thrust. Variable stratigraphic separation characterizes the thrust in this area, and this is mostly attributable to footwall imbricates, which create a variation in the amount of separation on the thrust. In general, the Rome Formation has been thrust against either the Knox Group or Middle Ordovician strata. Near the thrust's tip, stratigraphic separation greatly decreases and the fault terminates in folds in the Martinsburg Formation. Here, the stratigraphic separation is zero. Stratigraphic symbols are standard symbols used on Plate I.

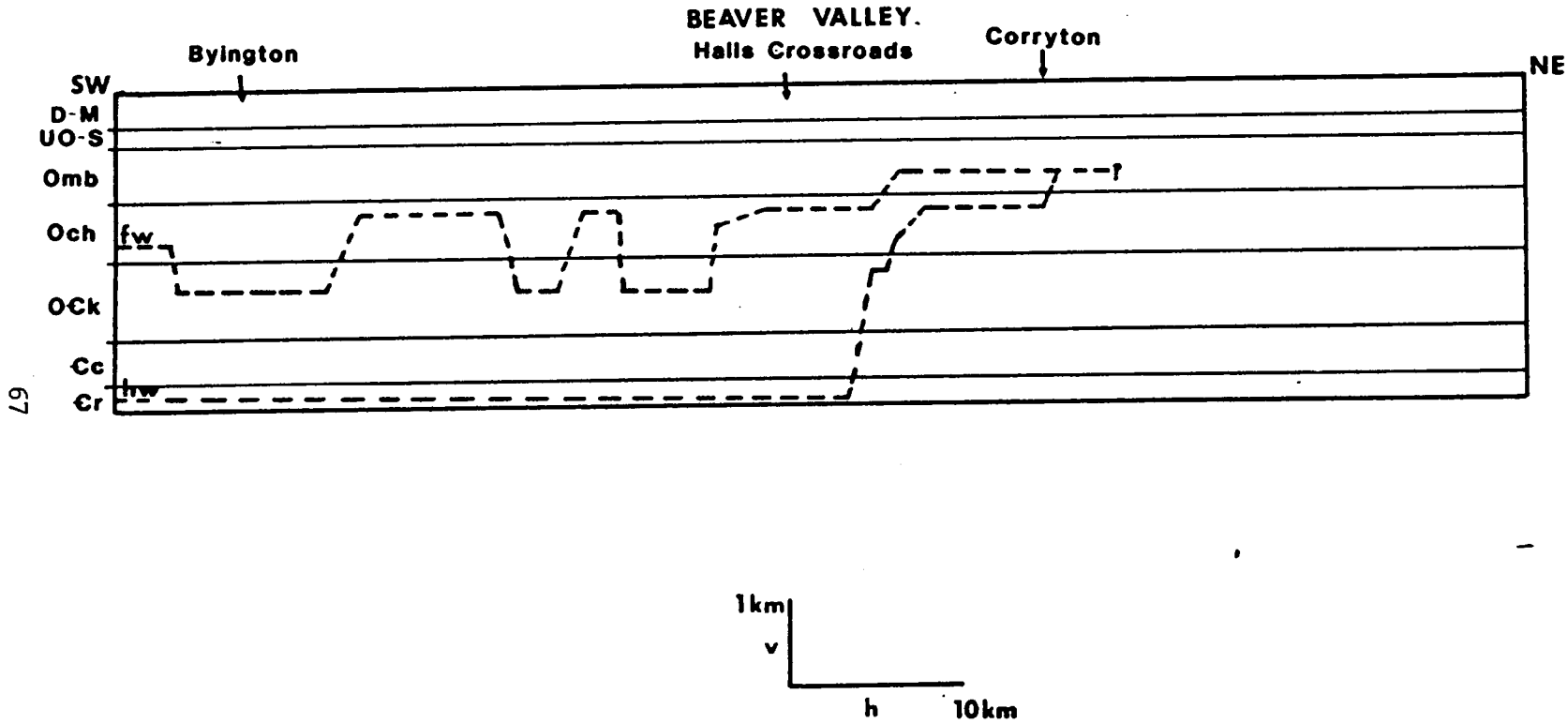
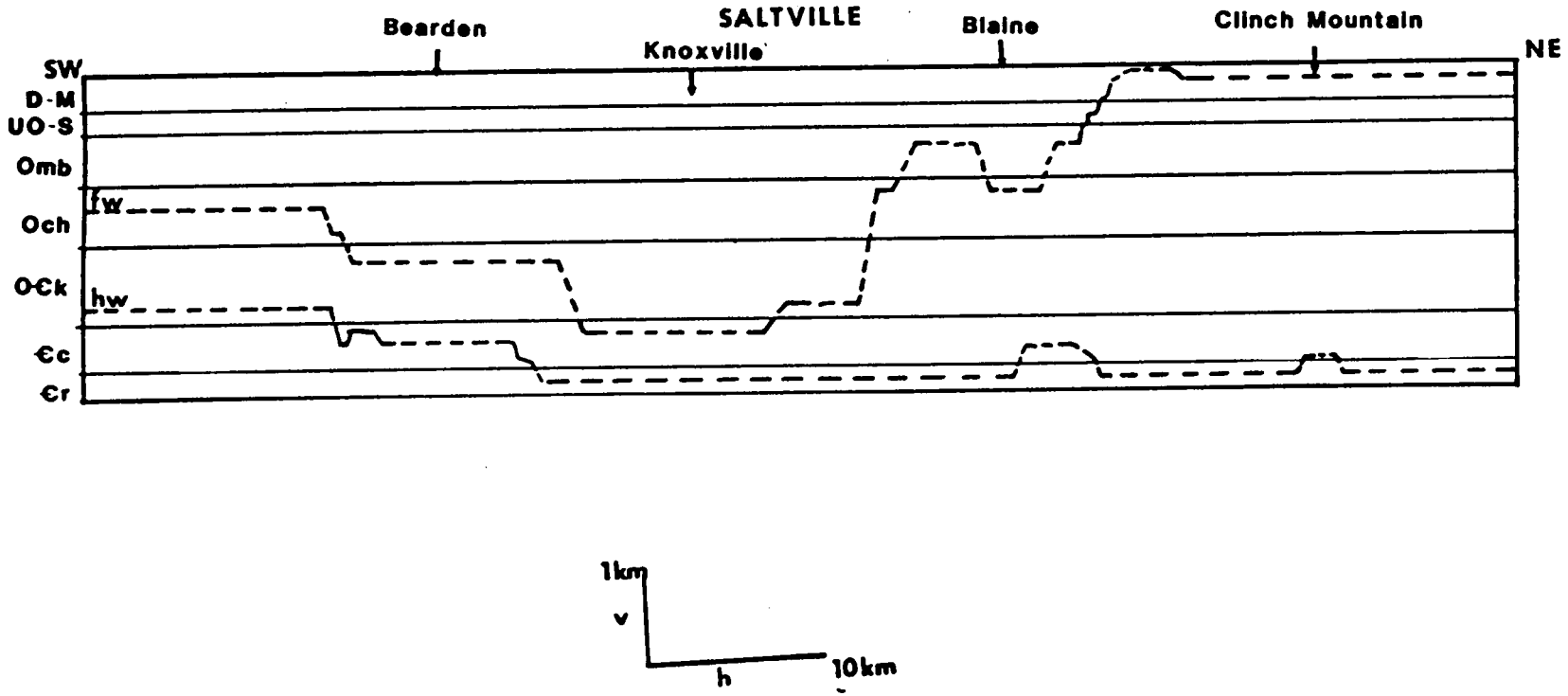

BEAVER VALLEY.
Halls Crossroads
Byington
Corryton
SW
NE
D-M
UO-S
Omb
Och
fw
OCk
Cc
Cr
hw
f
1km
v
h
10km

Figure 22. Longitudinal stratigraphic separation diagram for the Saltville thrust. From the southwest end of the diagram to the Knoxville area, both the hangingwall and the footwall step down section. Northeast of Knoxville, the hangingwall generally remains in the Rome Formation, while the footwall steps up section. Stratigraphic separation is greatest along Clinch Mountain, where Mississippian strata are in the footwall, with the Rome Formation in the hangingwall. Stratigraphic symbols are standard symbols used on Plate I.


Bearden
SALTVILLE
Knoxville
Blaine
Clinch Mountain
SW
NE
D-M
UO-S
Omb
Och
O-Ck
Cc
Cr
lw
hw
1km
v
h
10km

Valley and Ridge. The diagrams extend beyond the study area to both the northeast and southwest to better depict changes along the faults in this area. The base map used to construct the diagrams is from Rodgers (1953). This map was used because its smaller scale and size (compared to the 1:24,000 map) allows for diagrams of a manageable size. In addition, a stratigraphic separation diagram constructed from the larger scale map would be virtually identical.

A comparison of the three diagrams indicates that the Copper Creek thrust has a fairly uniform stratigraphic separation throughout the area, while the Beaver Valley and Saltville exhibit variable stratigraphic separation. Change in stratigraphic separation along the Saltville thrust suggests a footwall lateral ramp, an inference supported by structural geometries in this area. The greatly increased stratigraphic separation along the Saltville thrust northeastward contrasts with the greatly decreased stratigraphic separation along the Beaver Valley thrust in the same area. Stratigraphic separation is essentially zero at the Beaver Valley tip, where the fault has Martinsburg strata in both hangingwall and footwall. The Copper Creek thrust apparently includes no lateral changes in shape through this area. Although the stratigraphic separation diagrams are not directly applicable to constructing fault shapes for the cross-sections, the information provided about lateral change in shape is useful in interpreting

related structures, because the diagrams suggest which possibilities are and are not likely.

A cutoff line is the intersection of a stratigraphic horizon with a thrust surface. Cutoff lines were first used in structural interpretation by Douglas (1958), and are discussed by Diegel (1986) and Woodward (1986). Any thrust has a hangingwall and footwall cutoff for each stratigraphic unit. A single footwall or hangingwall cutoff cannot form a closed loop because the thrust cuts up section in the transport direction. Diegel (1986) points out that a hangingwall cutoff either joins the corresponding footwall cutoff at a tip line, or joins the footwall cutoff of the next higher thrust at the branch line. Cutoff line diagrams show the trajectories of cutoffs, and these diagrams are based on cutoff line "rules," which fix the buried portion of the cutoff (see Diegel, 1986). In the case of hinterland dipping thrusts, the buried part of the cutoff is on the younger side of the cutoff contact on the map. For foreland dipping thrusts, the buried part of the cutoff lies on the older side of the cutoff contact; dashed lines mark buried or eroded parts. Narrow spacing between the top and bottom cutoffs of a stratigraphic unit indicate the fault ramps through the unit, whereas wide spacing indicates a flat.

The footwall of the Saltville thrust northeast of the tip of the Beaver Valley thrust is interpreted with the aid of a cutoff line diagram (Fig. 23). Similar diagrams for

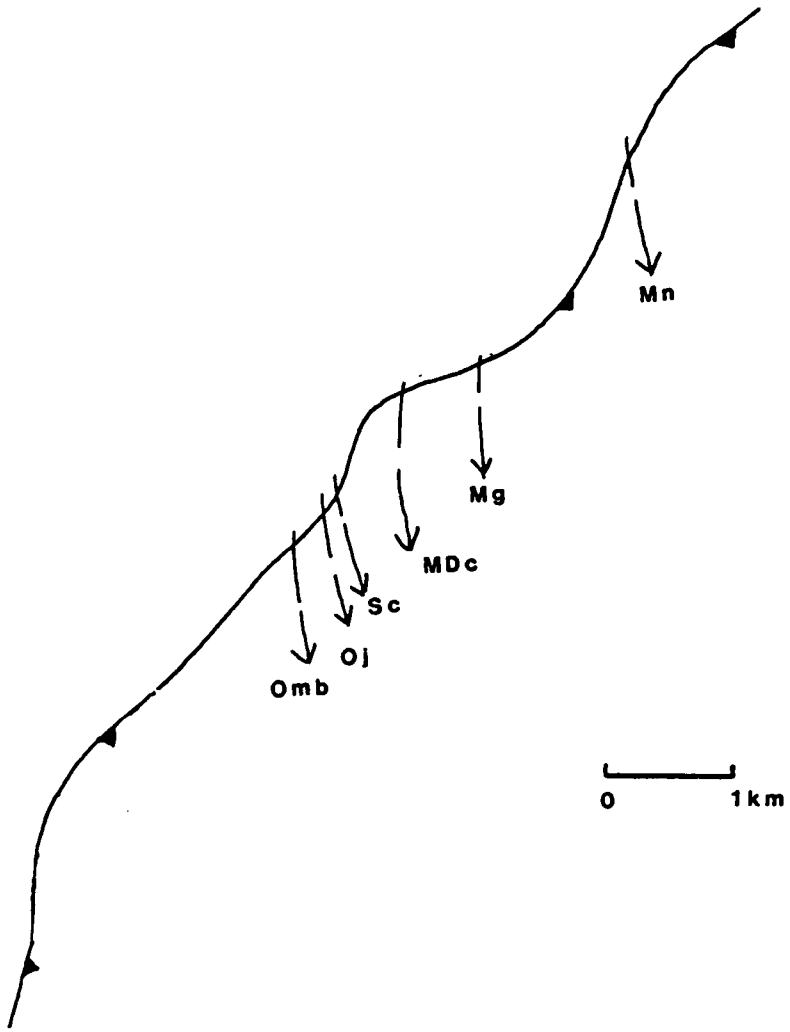


Figure 23. Projected footwall cutoffs from the footwall of the Saltville thrust; the trends suggest a lateral ramp in the thrust's footwall.

other portions of the study area were prepared but are not shown here because the structures are not significantly clarified by the diagrams. The spacing of the cutoffs decreases toward the southwest end of Clinch Mountain, suggesting a lateral ramp, as older units are exposed in the footwall. The steepest part of the ramp is through the competent Juniata and Clinch formations, and the ramp may be gentler through the overlying Mississippian strata.

The stratigraphic separation diagrams and the cutoff line diagram for the footwall of the Saltville thrust suggest that the shape of the Saltville thrust changes along strike from southwest of Knoxville to the northeast along Clinch Mountain. The Beaver Valley loses stratigraphic separation at its tip, and this loss of separation coincides with the increased separation recorded for the Saltville thrust. This may indicate that a change in shape along the Beaver Valley thrust near its tip may have caused the lateral step in the Saltville's footwall. Conversely, the lateral step in the footwall of the Saltville thrust may have caused the change in shape along the Beaver Valley thrust.

CROSS SECTIONS

Introduction

Balanced cross-sections provide the most reasonable solution to a structural interpretation because they are constrained by a number of geometric "rules." They first gained widespread use in the oil industry of Canada in the 1950's and 1960's, but the underlying philosophy of pulling apart a cross-section is seen in work done earlier in the century. Woodward et al., (1985) reviewed the historical development of balanced sections. Dahlstrom (1969) presented the first formal discussion of balanced cross-sections. By definition, a balanced section is a cross-section which is both viable and admissable (Elliott, 1983). The section is viable in that it can be restored to the undeformed state. The section is admissable in that the structures shown on the section are the same types as those seen in the field.

Dahlstrom (1969) discussed the technique of balancing sections. The first step is to identify "families" of structural type or structural association present in the area. Next, it is necessary to make two assumptions. First, there is no volume lost during deformation. This requirement is probably never strictly met, because solution processes may remove material, but in the outer sheets of a

thrust belt, the material lost is such a small percentage of the total volume, the assumption is valid. Woodward et al. (1986) presented a strategy for balancing more highly strained rocks, where volume loss is potentially more significant. Second, the deformation occurred by plane strain; in other words, no movement occurred into or out of the section line. This assumption implies that the intermediate axis of the strain ellipsoid is normal to the section line. The requirement is also not entirely met. For example, Groshong's (1975) strain study of limestones in the Pennsylvania Valley and Ridge demonstrated that a portion of the strain is non-plane. McClay and Insley (1986) described out of the plane movement from duplexes in the Lewis thrust sheet of Canada. Lateral ramps on thrusts may also produce structures with non-plane strain. Despite the exceptions to these assumptions, they are a reasonable first approximation.

The actual process of balancing may be accomplished by several different methods. These include the sinuous bed method, the key bed method, and the equal area method (all summarized in Woodward et al., 1985). A more quantitative approach to balancing sections is from Suppe (1983). This technique is largely derived from his theories of fault-bend and fault-propogation folding.

A restored cross-section is useful beyond its obvious function of demonstrating geometric viability in a

cross-section. The restored section can be used to calculate shortening, either on individual sheets or for a group of thrusts (Hossack, 1979). The calculated shortening is obviously a minumum, because erosion erases many cut-offs, but even a minimum calculation is valuable.

It is important to remember that a balanced section is not necessarily the truth; it is a model which is a geometric possibility for a given set of assumptions and identifiable structural style (Woodward et al., 1985).

Roeder et al. (1978) and Woodward (1985) calculated shortening across the Southern Appalachians, using serial balanced sections. A restored cross-section may also be used to prepare a palinspastic map (Kay, 1944) of the area, which also has applications in stratigraphic and sedimentologic studies. Roeder and Witherspoon (1978) prepared a palinspastic map of east Tennessee, using their balanced sections. Their work provided a framework for reconstruction of Middle Ordovician paleo-environments (Walker, 1980).

Location of the cross-sections

Three cross-sections accompany the geologic map. The locations are shown on Plate I. These section lines were chosen to illustrate the changing structures in the three thrust sheets across the area. The deformed and restored

cross-sections provide a basis for the interpretation of the geometric evolution presented in the next chapter. The cross-sections were drawn at 1:24,000 and restored at 1:48,000. The deformed and restored sections are reproduced for the dissertation (Plates II - IV) at 1:48,000 and 1:96,000 respectively.

Cross-section A-A' extends to the foreland beyond the Pine Mountain thrust. The cross-section stretches through ten 7 1/2 minute quadrangles. These are: Pioneer, Ivydell, Jacksboro, Demory, White Hollow, Big Ridge Park, Graveston, John Sevier, Mascot, and Boyd`s Creek. The cross-section is bent in the Mascot Quadrangle to accomodate a change in strike direction.

Cross-section B-B' extends from the footwall of the Copper Creek thrust southeastward through the Beaver Valley and Saltville sheets. It goes through five 7 1/2 minute quadrangles: Big Ridge Park, Graveston, Mascot, New Market, and Douglas Dam. Cross-section C-C' extends from the footwall of the Copper Creek thrust southeastward through the Saltville sheet. It is located approximately 5.5 km northeast of the tip of the Beaver Valley thrust. The cross-section goes through six 7 1/2 minute quadrangles: Maynardville, Graveston, Luttrell, Joppa, Talbott, and Jefferson City. The bend in the cross-section adjusts for the change in strike along Clinch Mountain.

The restored section of B-B' and C-C' are tied to the restored positions of the Pine Mountain, Wallen Valley, and Hunter Valley thrusts on cross-section A-A'. The assumption in doing this is that the shortening between the Copper Creek and the Pine Mountain thrust is nearly constant along strike (significant differences do not occur from one cross-section to the next). This assumption is valid because the distance between successive sections is small relative to the size of the thrust sheets. The restored Wallen Valley sheet is larger on both of the local sections because the sheet contains more stratigraphy to the northeast, away from its intersection with the Hunter Valley thrust (Hardeman and others, 1966).

Data for the cross-sections

Depth to basement for the cross-section is primarily constrained from three sources: Watkins (1964), Burgess (1982), and Mitra (1986 and in press). Several other publications include depth to basement and these are briefly discussed below. The justification for not using the other sources is given as well.

Watkins (1964) discussed a regional gravity and magnetic survey of east Tennessee and southern Kentucky, which is used to determine basement depth (see Fig. 8 in Watkins). This is most useful for the foreland end of the

cross-section. Harris (1976) interpreted depth to basement from a seismic line in east Tennessee. The nearest the line is to the study area is 53 km southwest. Similarly, Tegland (1978) presented depth to basement from three seismic lines; the nearest of the lines is 23 km northeast of the study area. Neither of these sources were used, because depth values are available from more accurate seismic lines closer to the study area, and the values from these lines appear to be too deep.

Roeder et al (1978) includes a contoured map of the depth to the "base of deformation." They cited Watkins and stratigraphic information as the basis for their interpretation, point out that if the map is in error, it is probably too shallow rather than too deep. Although I tried using their values for depth, a gap was present between the basement and the bottom of the Rome Formation in the footwall of the Pine Mountain thrust sheet and between the basement and the base of the thrust sheets to the southeast. Because this gap widened southeastward, I concluded that the dip of the basement used in their study was too steep.

Burgess (1982) presented a group of cross-sections in the Valley and Ridge of Georgia and Tennessee. His depth to basement calculations are based on three sources of data: 1) Stratigraphic thicknesses; 2) Seismic data; 3) T. J. Kemmer #1 well (Ladd Petroleum Company) which penetrated the basement. Burgess' basement values closely match my

stratigraphic and structural data. Rutherford (1985) compiled a depth to basement diagram for the Wartburg Basin and adjacent Pine Mountain sheet. These values are therefore not applicable for the study area.

Mitra (1986 and in press) studied the Pine Mountain thrust sheet and included a cross-section which runs 8 km southwest of the study area. His depth to basement was based on high resolution seismic lines. The values from Burgess appear to match the basement depths on Mitra's cross-section. Depth to basement values given in Harris (1976), Tegland (1978), and Roeder et al (1978) are all deeper than the values from Mitra. Because the cross-sections in this study were drawn at a large scale and use stratigraphic values from measured sections, they are assumed to be more accurate than the cross-sections shown in Harris (1976), Tegland (1978), and Roeder et al (1978). The cross-sections in these reports are drawn at a smaller scale and therefore gloss over some detail. Mitra's values match the cross-sections in this study, are closer to the study area than the lines in the other reports, and are based on high resolution seismic lines. The Mitra values are used here.

Two assumptions accompany the depth to basement values used here. First, the basement dips uniformly toward the hinterland at a very gentle angle, probably no more than one or two degrees. This was first clearly shown for thrust

belts by Bally et al. (1966). Second, no significant change exists in basement depth between the cross-section lines. Given the inexact nature of geophysical data, deviation from these assumptions is possible.

Stratigraphic thicknesses for the cross-sections, taken from measured sections and mapping, were in general fairly accurate. The thickness of the Rome Formation however was a problem because it is the basal decollement of the thrust sheets and therefore it exhibits a wide range of thicknesses. Reported values range from 90 to 518 m across the Valley and Ridge. In thrust sheets within the study area, the Rome is of variable thickness because of varying amounts of imbrication and/or folding. No "uniform" value for thickness applies.

The thicknesses of the Conasauga, Knox, and Chickamauga Groups over the area are nearly uniform. Therefore, an average value was calculated for these strata. Conasauga and Chickamauga thicknesses suggested for the footwall of the Pine Mountain thrust (Englund, 1968) were changed to conform with values in other thrust sheets. These units are not exposed in the area studied by Englund, so he estimated or approximated their thicknesses, Post-Ordovician rocks are not abundant in the study area, and thicknesses for these formations are from Swingle et al (1967), Englund (1968), and Walker (1985).

Each of the cross-sections extends beyond the boundaries of the study area. Thus, it was necessary to use mapping by other workers for these areas. Sources for this include: Bridge (1956), Swingle (1960), Jones (1962), Finlayson (1965a, 1965b), Finlayson et al. (1965), Cattermole (1966), Hardeman (1966), Englund (1968), Bridge and Hatcher (1973), and Hatcher (1973).

An appropriate simplification of the Conasauga Group on the cross sections appears necessary. The Conasauga Group is shown as one undivided block where the Conasauga is a homoclinally dipping panel. This is done for clarity and to reduce "clutter" on the cross-sections. In locations where the Conasauga is folded and/or faulted, individual formations are shown.

Cross-section A-A'

The Pine Mountain thrust is the most external thrust on the cross-section and in the Valley and Ridge. It is the type example of a stepped thrust surface (Rich, 1934). The sheet contains two structures, the Middlesboro syncline and the Powell Valley anticline. The Middlesboro syncline is a flat and broad structure which overlies the upper decollement of the thrust, where the fault flats in the Chattanooga Shale and the Rockwood Formation (Englund, 1968). The syncline is approximately 14 km wide, and is

composed of Carboniferous units. Beds on the northwest limb dip to the southeast at 15° to 20°, while beds on the southeast limb dip steeply northeast or are vertical.

The Powell Valley anticline is a structure developed over a footwall ramp in the thrust surface. Here, the fault cuts up section from the Rome Formation to the Rockwood - Chattanooga interval. Boyer (1985) refers to this type of structure as a "trailing edge ramp anticline," and points out that these folds form as hangingwall cutoffs conform to the thrust surface. The anticline is approximately 20 km wide and is composed of Cambrian and Ordovician strata. Beds on either limb dip 10° to 20°, and the broad core consists of horizontal beds overlying the upper level flat.

In this area, the Bales thrust is apparently not present beneath the Pine Mountain thrust (Harris, 1970; Mitra, 1986 and in press). I made several attempts to draw a balanceable section including the Bales, but these were unsuccessful. The extremely broad and flat core of the anticline also suggests the absence of the Bales. Horizontal Knox Group strata are exposed in the core of the anticline, with only a small band of the uppermost Conasauga present at the surface (just southeast of the Clinch River, Demory quadrangle). This is in marked contrast with areas to the northeast where the Bales has bowed the anticline upward and brought lower stratigraphy to the surface (see Woodward, 1985, cross-sections 21 and 22). If the Bales is

present, it is probably only a small imbricate or horse at the base of the footwall ramp.

The Pine Mountain thrust has moved approximately 17.3 km to the northwest in this area. Englund (1968) calculated movement on the Jacksboro fault using the stratigraphic interval between the top of the Chattanooga Shale and a coal bed in the Hance Formation; the interval thickens to the southeast. He calculated 17 km of sinistral movement, which matches the value from this cross-section. Movement on the Pine Mountain calculated from cross-sections to the northeast (Woodward, 1985, cross-sections 21 and 22) is 8.4 km and 8.85 km. These values are low, but if slip in the underlying Bales thrust is added, the amount of slip is 18.6 km and 17.9 km. These values match cross-section A-A'. This may imply the displacement is transferred in part to the Bales from the Pine Mountain northeastward.

The Wallen Valley thrust cuts Bluebird Ridge and is approximately 25 km northeast of its junction with the Hunter Valley thrust. This juncture is another type of transfer zone (Beets, 1985), and southwest of it the merged faults are renamed the White Oak Mountain thrust. Stratigraphic separation on the Wallen Valley thrust decreases to the southwest, as beds are successively cut off in the footwall. Only the Rome Formation, Conasauga Group, and Knox Group are present within the Wallen Valley thrust sheet in this area. The structure of the sheet is

relatively simple; beds generally dip southeastward at 30° to 35 °. Locally, beds dip more gently or steeply. The Conasauga Group here is the same thickness as it is in thrust sheets to the southeast, however it is mostly shaley (northwest phase of Rodgers, 1953). Jones (1962) mapped it as Conasauga Shale and Maynardville Limestone, however he noted the presence of thin limestone beds in the shale portion; the limestones may suggest the proximity of the central phase. On this cross-section, the six formations of the central phase first appear in the adjacent Hunter Valley sheet.

The Hunter Valley thrust cuts Pine Ridge, and extends southeastward under the Copper Creek thrust. Rocks in the sheet here include the Rome Formation, and the Conasauga, Knox, and Chickamauga Groups. In general, the structure of the sheet is rather simple. Beds dip 30° to 40° southeastward, except at its leading edge, where beds dip steeply and are folded, and at its trailing edge in Raccoon Valley where the Chickamauga Group is folded.

The Copper Creek thrust is folded in this area, and the folding is explained on the cross-section by a blind thrust which curves upward from the basal detachment near the trailing edge of the Hunter Valley thrust. Folded thrusts are usually interpreted in two ways: to have originated by compression of the orogenic belt following thrusting or from folding by lower thrusts as deformation proceeds

progessively (Bally et al., 1966; Jones, 1971). Because compression of the orogenic belt would have affected several of the thrusts, folding by a lower thrust is the more likely interpretation. The Copper Creek was first shown as folded in this area on the cross-sections of Benson (1963), and additional data from Welch Unit #1, drilled on the southeast limb of the Texas Valley anticline, confirm the interpretation. Roeder et al. (1978) termed this a "folded-fault structure, domal type," and point out that one or several slices may actually underlie the folded thrust. The blind thrust explains the geometry of the Copper Creek on cross-sections B-B' and C-C' also. An examination of the map pattern of the thrust (Fig. 24) indicates that the sheet widens over a segment of the thrust which is 41 km long. This may approximately correlate with the length of the blind thrust.

The Copper Creek thrust sheet contains several structures. The Texas Valley anticline and syncline overlie the folded portion of the thrust and are approximately 3.9 km wide. At the base of the sheet is the Rome Formation, which here is rather thin. Exposures on Bull Run Ridge indicate it is only 100 to 150 m thick. Uniformly dipping Knox and Chickamauga Group rocks are adjacent to the Texas Valley structures. These strata are poorly exposed, but indicate very gentle dips (15^{o} to 30^{o}) where measurable. The strata maintain nearly uniform dip as the fault ramps

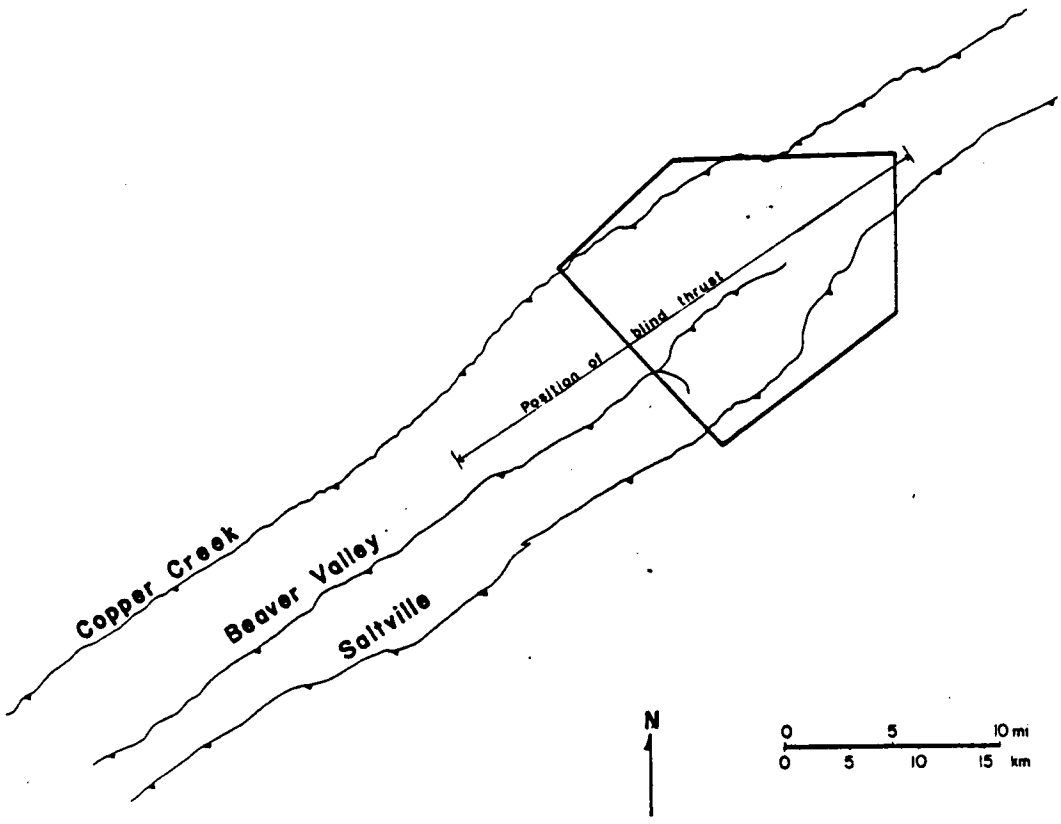


Figure 24. Inferred length and position of the blind thrust under the Copper Creek thrust.

down to the basement. Adjacent to the Beaver Valley thrust is an overturned syncline, cored by the Martinsburg Formation. Overturned Moccasin Formation beds are poorly exposed and dip southeastward at approximately 30^{o} on the southeast limb of the fold.

The Beaver Valley thrust, as interpreted here, is a shallow sheet which contains strata from the Rome Formation through the Moccasin Formation. The fault is nowhere exposed northeast of the end of Beaver Ridge, so its dip is estimated. The folds at the surface primarily involve the middle Chickamauga Group and the Moccasin Formation, and are cored by a detachment. The presence of the detachment is not based on direct evidence, but is inferred and justified because it is a geometric necessity for balancing (Dahlstrom, 1970); there may actually be several detachments. The beds flatten at depth in the trailing edge of the sheet. The geometries in the Beaver Valley sheet here differ from geometries in the sheet to the southwest. There, the beds dip uniformly to the southeast. The differing areas are separated by the tear faults at the end of Beaver Ridge. The relationship the tear faults have to the differing geometries is unclear.

The trailing edge of the Beaver Valley thrust on this cross-section merges with the Saltville thrust and sits on top of the trailing edge of the Copper Creek sheet. This interpretation has implications bearing on the sequence of

thrusting which will be discussed in the next chapter. In addition, the Beaver Valley thrust shape differs on cross-section B-B' nearer to the fault termination. The change in shape accomodates for loss of slip toward the tip and is also suggested by the lateral ramp and complex structures in the footwall of the Saltville thrust.

The Saltville thrust cuts McAnnally Ridge, which is an extension of Sharp Ridge which passes through Knoxville. The fault includes a small frontal imbricate of the Rome Formation, which generally dips gently to the southeast, with minor small-scale folds (see Appendix B, Stop 7). The thrust sheet contains the Rome Formation, and the Conasauga and Knox Groups; structure within the sheet is rather simple. The Knoxville thrust overlies the Saltville and contains complexly folded Knox and Middle Ordovician rocks (Bridge, 1956). The trailing edge position of the Saltville is estimated and is based on regional sections (Roeder et al, 1978; Woodward, 1985). The leading edge of the Saltville sheet is much more complex to the southwest in Knoxville where an imbricate fan is developed involving the Rome Formation in the hangingwall and the Knox and Chickamauga Groups in the footwall (Cattermole, 1960; Paul, 1986).

Cross-section B-B'

The Copper Creek is the most external thrust on this cross-section, and it is folded as on cross-section A-A'. The structure however is a bit more complex than it is to the southwest. The fault's leading edge is an imbricate fan of Rome and Conasauga lithologies as discussed previously (p. 38). The lowest slice sits above the blind thrust and is folded. It contains the Buffalo Ridge syncline and the Beard Valley anticline. This slice places the Maryville Limestone on middle Chickamauga Group rocks. The lower Conasauga Group and the Rome Formation are folded into an anticline and do not reach the surface. Roeder et al. (1978) termed this type of structure a "folded-fault structure, frontal type." Adjacent to the folded area is a slice containing the Rome Formation and a slice containing the Rome Formation, Pumpkin Valley Shale, and Rutledge Limestone. The remainder of the Copper Creek sheet has a rather simple structure. The sheet carries strata from the Rome Formation through the Martinsburg Formation, and beds dip uniformly southeastward 30° to 40°. The small trailing edge footwall syncline, which is present to the southwest, as shown on cross-section A-A' apparently dies out along strike.

The imbricate fan at the leading edge of the Copper Creek thrust reflects the packaging of weak and strong layers in the Rome Formation - Conasauga Group portion of

the stratigraphic column. This stratigraphic interval is a structural lithic unit (Currie et al., 1962) and it is particularly distinct within the central phase of the Conasauga Group. Its effect on structures is evident along the leading edge of several major thrusts which pass through the three phases of the Conasauga Group (Woodward et al., in press). The limited geographic extent of the imbricate fan in the Copper Creek sheet may be related to the original distribution of the lithologies or localized stratigraphic variation encountered during deformation.

The Beaver Valley thrust here is only 4.2 km from its termination and the sheet contains strata from the Rome Formation through the Clinch Sandstone, most of which is extensively folded. The two major structures are the Corryton anticline and the House Mountain syncline. The Corryton anticline trends approximately N60^{o}E, and consists of several smaller (second order) anticlines and synclines, all of which trend with the major structure (see Appendix B, Stop 6). The fold is cored by a detachment as shown on cross-section A-A'.

The House Mountain syncline includes Middle Ordovician through Silurian rocks and is adjacent to the Saltville thrust. The fold axis is located along the base of the mountain on the southeast side; Martinsburg beds southeast of the axis are overturned. At the top of the mountain, the Clinch Sandstone exhibits small-scale folds (several meters

in wavelength), but these folds are smaller than map scale and they are not included on the cross-section. The structure of the beds on the southeast limb beneath the Saltville thrust is not clear. The Martinsburg Formation, in particular, is extensively folded and may be cut by numerous small faults and detachments, therefore it is thickened on the cross-section.

The Beaver Valley thrust is extended to the basement on this cross-section. This interpretation shows the thrust's branch line in the trailing edge of the Copper Creek thrust rather than at the leading edge of the Saltville thrust as drawn in cross-section A-A' where the fault sits on top of the Copper Creek sheet. The change in shape accounts for the loss of slip along the Beaver Valley near its tip. The fault "stands up" toward its tip, changing the position of the branch line and losing slip.

The Saltville thrust here places the Rome on the Martinsburg, and dips gently to the southeast with a rather simple structure in the sheet. The sheet contains the Rome, the Conasauga and Knox Groups, and a small part of the Middle Ordovician. The small slice at the front of the sheet contains the Rome and Pumpkin Valley Shale. The Knoxville thrust sheet overlies the Saltville and it contains complexly folded and faulted Knox Group and Middle Ordovician strata. This cross-section is located near the termination of the Knoxville thrust. Displacement was taken

up to the northeast by the Rocky Valley thrust, so that the Knoxville and Rocky Valley thrusts are components of another transfer zone. The Knoxville - Rocky Valley trailing edge merges with the Dumplin Valley thrust.

Cross-section C-C'

The most external thrust on this cross-section is also the Copper Creek, and the structure along this cross-section is relatively simple. Chickamauga Group strata are folded in the Copper Creek footwall, as indicated on the Maynardville quadrangle map (Finlayson, 1964). This folding is interpreted as being related to the blind imbricate responsible for the folding of the Copper Creek thrust. Here, the folded footwall beneath the Copper Creek is exposed because the fault's trace changes from approximately N60^{o}E to E-W along the border between the Graveston and Maynardville quadrangles. The trend of the blind imbricate northeastward from the other cross-sections projects into this folded area.

The frontal imbricate fan in the Copper Creek is present, and consists of slices of Rome and Conasauga strata. Comb Ridge is composed of two stacked slices of the Rome. One of the faults shown cannot be mapped along the section line, but is projected into the section from the southwest. The third imbricate slice includes the Rome and

the Pumpkin Valley Shale, the Rutledge Limestone, the Rogersville Shale, and the Maryville Limestone. The highest imbricate of the thrust sheet places the Rutledge - Rogersville interval on the Maryville; the Rome and Pumpkin Valley are cut off in the subsurface. The depth to which the imbricate fan extends on this cross-section and B-B' is estimated.

The Copper Creek sheet includes a complete stratigraphic section from the Rome Formation through the Newman Limestone. The beds generally dip uniformly to the southeast, 20° to 40°. The Moccasin and Martinsburg Formations both exhibit small-scale folds but no faults at the surface. I have extended the beds under the Saltville and Rocky Valley thrusts, as in Roeder et al. (1978, cross-section 5). Lower Knox Group beds in the overlying Saltville sheet are horizontal in the Joppa quadrangle, suggesting that the thrust and beds under it are flat.

The Saltville thrust sheet is a thin slice in this area, sitting on top of the Copper Creek sheet. The thrust has placed the Rome on the Mississippian Newman Limestone. The Rome is rather thin at the surface; Swingle et al. (1967a) report a maximum thickness in this area of 122 m. The sheet carries the Rome Formation through the lower half of the Knox Group. Most of the exposed Knox strata is the Copper Ridge Dolostone. Its attitude is horizontal and constitutes an outcrop band 10.5 km wide. The overlying

Chepultepec Dolostone is exposed in the trailing edge of the sheet beneath the Rocky Valley thrust.

The shape of the Saltville is related to the Upper Ordovician and younger stratigraphy present in its footwall in this area. The fault ramped through the more competent sandstones and siltstones of the Juniata Formation and the Clinch Sandstone. Next, the Chattanooga Shale acted as an "upper level" flat, underlying the flat portion of the fault. The interpreted shape of the fault correlates well with projection of surface strikes and dips.

The trailing edge of the Saltville thrust merges with the Rocky Valley thrust. The Rocky Valley sheet contains a group of several thrusts which complexly fold and fault Cambrian through Middle Ordovician rocks. The Rocky Valley thrust's trailing edge merges with the Dumplin Valley thrust (Roeder et al., 1978; Woodward, 1985), and at depth the Copper Creek thrust merges with the Dumplin Valley thrust.

Shortening, calculated from the restored cross-sections, is essentially uniform: 43 % for A-A', 48 % for B-B', and 49 % for C-C'. The total shortening is constant despite the lowering of slip on and loss of the Beaver Valley thrust northeastward.

7. CONCLUSIONS

1) The study area is cut by three major thrusts of the Southern Appalachians, the Copper Creek, the Beaver Valley, and the Saltville. The thrusts are regionally significant. This area is best subdivided into four parts: the foot wall of the Copper Creek thrust, the Copper Creek thrust sheet, the Beaver Valley thrust sheet, and the Saltville thrust sheet.

2) The footwall of the Copper Creek thrust mostly contains homoclinally dipping strata which are Middle Ordovician and older in age. Locally, small scale folding is present in the lower and middle Chickamauga Group. The trend of the smaller folds is generally oblique to transport direction.

3) The Copper Creek thrust sheet consists of four distinct areas: the Texas Valley anticline and syncline, an imbricate fan of Rome Formation and Conasauga Group lithologies, a uniformly dipping belt, and Clinch Mountain.

4) The Texas Valley structures are interpreted here as being underlain by a blind thrust under the Copper Creek thrust. The imbricate fan contains five faults and consists of the Buffalo Ridge syncline at the leading edge of the thrust sheet, and Comb Ridge which is held up by slices of

the Rome Formation. The uniformly dipping belt contains homoclinally southeast dipping strata from the Conasauga Group through the Martinsburg Formation. Clinch Mountain contains the only post-Silurian formations in the study area; beds dip fairly uniformly to the southeast, and a group of folds are present at the southwest end of the mountain.

5) The Beaver Valley thrust sheet is dominantly a set of folds in Middle and Upper Ordovician strata. The sheet also contains faulted pieces of the Knox and Conasauga groups, and House Mountain, which is a syncline containing the Martinsburg and Juniata formations, and the Clinch Sandstone.

6) The Saltville thrust sheet contains the Rome Formation and the Conasauga and Knox groups. At the southwestern end of the study area, the leading edge is imbricated. In the vicinity of Blaine, TN the leading edge is a wide slice of folded and faulted Rome Formation and Conasauga Group strata. Northeast of the folded and faulted slice, the Saltville is a single trace, and beds in the sheet dip uniformly southeast.

7) Longitudinal stratigraphic separation diagrams contructed for the three thrusts indicate that separation is

highly variable on both the Beaver Valley and Saltville thrusts, while it is uniform along the Copper Creek.

8) Regional cross section A-A' extends to the foreland beyond the Pine Mountain thrust. The interpretation of the three thrusts northwest of the study area--the Pine Mountain, the Wallen Valley, and the Hunter Valley--generally conforms with other published interpretations, however the Bales thrust is not shown beneath the Pine Mountain thrust. The Bales is omitted because the shape of the Powell Valley anticline does not require a lower thrust. It was impossible to balance the cross-section with the Bales thrust present.

9) The Copper Creek thrust sheet is interpreted as being folded at its leading edge on all three cross-sections. The interpretation is supported by both surface data--the Texas Valley anticline and syncline, the Buffalo Ridge syncline, and folded Middle Ordovician strata--and a well drilled in the Texas Valley structures.

10) The Beaver Valley thrust is present on two of the cross-sections (A-A', B-B'). The folds in the thrust sheet are shown as being cored by a detachment. The location of the detachment is approximate, and more than one may actually exist. Towards its tip point, the fault's branch

line with the Saltville sheet changes position. This inferred change is suggested by the structures in the foot wall of the Saltville thrust and by the decrease in slip on the Beaver Valley thrust.

11) The Saltville thrust sheet possesses fairly simple structures on all of the cross-sections. Strata from the Rome Formation and the Conasauga, Knox, and Chickamauga groups dip uniformly southeast. Towards the northeast the fault dips at progressively gentler angles. On cross-section C-C', the thrust is essentially flat. This interpretation is supported by a wide band of horizontal Conasauga and Knox beds at the surface.

12) The three cross-sections depict geometrically reasonable interpretations of the structures in the study area. The cross-sections show uniform shortening: 43% for A-A', 48% for B-B', and 49% for C-C'.

CHAPTER 3

GEOMETRIC EVOLUTION OF THE BEAVER VALLEY - SALTVILLE TRANSFER ZONE

1. INTRODUCTION AND PURPOSE

The three balanced cross-sections depict a viable interpretation of the surface geometries, given the available data and the assumptions and rules of thrust faults. The evolution of these structures should be modelled to investigate further the viability of the interpretation. The purpose of this chapter is to interpret the geometric evolution and probable thrusting sequence of the structures in the study area. The first section of the chapter is a brief introduction and statement of purpose. The second part of the chapter is a discussion of the assumptions necessary for the interpretation and the techniques by which the interpretation is made. The third part presents the interpretation. The fourth part considers the cause or causes of the termination of the Beaver Valley thrust. The final section lists the conclusions drawn from the analysis.

2. ASSUMPTIONS AND TECHNIQUES

The underlying assumption of thrust analysis is that faults in a thrust belt generally follow an orderly and systematic sequence of emplacement. This sequence is commonly from the higher-grade terrane or hinterland to the undeformed margin of the craton or foreland (in the Appalachians, southeast to northwest). This suggests that in the Valley and Ridge of east Tennessee the Pine Mountain thrust is the "youngest" fault. This sense of timing is confirmed in the Cordillera by syntectonic conglomerates (Armstrong and Oriel, 1965; Wiltschko and Dorr, 1983), and by analogy fits the older thrusts of the Appalachians. Such deposits in the Appalachians are now eroded. Some workers however, favor a "break-back," foreland to hinterland sequence (Milici, 1975, 1986; Harris and Milici, 1977).

Jones (1971) studied thrust timing in a complex area of folded thrusts in the Canadian Rockies and observed paradoxical age relationships. He stressed that understanding sequential thrust development is commonly hindered by use of map patterns and cross-sections because these represent relationships at the <u>end</u> of thrusting. The final configuration does not unravel the path of deformation. The key to understanding the structural geometries lies in reconstructing the sequence of thrusting. He developed an explanation based on three assumptions.

First, faults develop as an initial break and then grow along strike while being emplaced. Wiltschko and Dorr (1983) similarly point out that thrusts may nucleate at facies changes, in fold cores, or at basement highs and then propogate along strike. Elliott (1976) noted that while thrusts grow laterally during emplacement, the rate of lateral growth is generally up to several orders of magnitude faster than the rate of slip. Second, the amount of thrust slip is proportional (more or less) to duration of movement. Third, the time between the initiation of successive faults is greater than the time required to emplace a single fault completely.

Jones proposed that faults may exhibit changing age relationships as individual faults propagate towards one another, stopping and starting movement at various times during emplacement. He showed (Fig. 25) that the sequence of thrusting may be complex and could be interpreted as out-of-sequence where several faults initiate, grow, and are emplaced in an overlapping sequence. The regional thrust sequence in his sequence generally propagates towards the foreland. Local, "out-of-sequence" thrusting explains the anomolous relationships. The problem in clarifying the sequence of thrusting is in the scale of observation.

Childers (1963) discussed a similar timing sequence as that proposed by Jones (1971) of thrusts in the northern Rocky Mountains of Montana. There, the earliest major

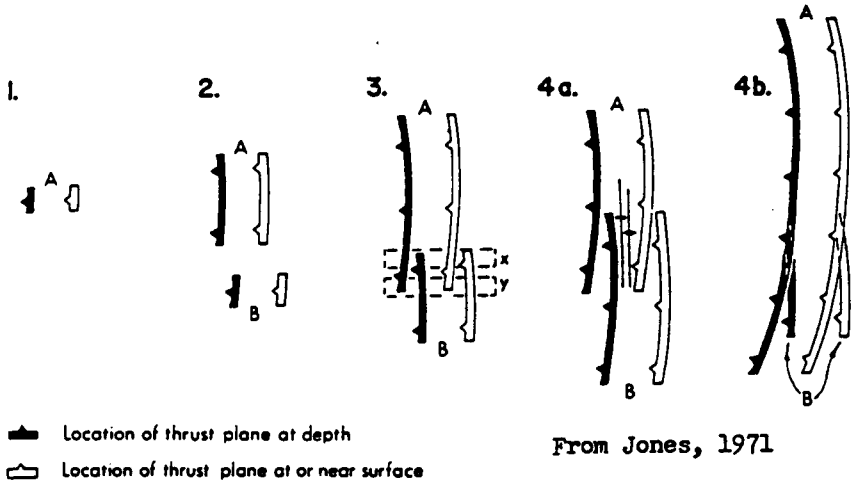


Figure 25. Diagrams from Jones (1971) showing the variation in thrusting sequence. Because individual faults start and stop movement through time, and because younger faults initiate movement while earlier faults are not moving, paradoxical age relationships in thrust timing result.

thrust initiated first and developed several imbricates, starting and stopping its movement with time. During periods of quiescence on the first thrust, other faults initiated movement, and these faults were modified in turn by reactivation of the earlier thrust. Overlapping movement on the various faults in the area were responsible for the structures present.

The structural geometries in the Beaver Valley and Saltville sheets imply timing relationships between the faults which are not entirely clear. The broad southeastward reentrant in the Saltville sheet suggests this fault was carried "piggy-back" and folded by the lower Beaver Valley thrust as part of a "normal" hinterland to foreland progression. On the other hand, the decreased stratigraphic separation and lateral footwall ramp southwestward along the Saltville thrust suggests the fault responded to the presence of the Beaver Valley thrust. This implies a reversed sequence in which the Beaver Valley had formed prior to the Saltville in this area. A model for structural evolution must account for the apparent discrepency.

The analysis used by Jones (1971) is considered to be applicable to the structural development and sequence of thrusting in the study area. The analysis is presented on hanging wall sequence diagrams. Hanging wall sequence diagrams are a convenient way to illustrate the development

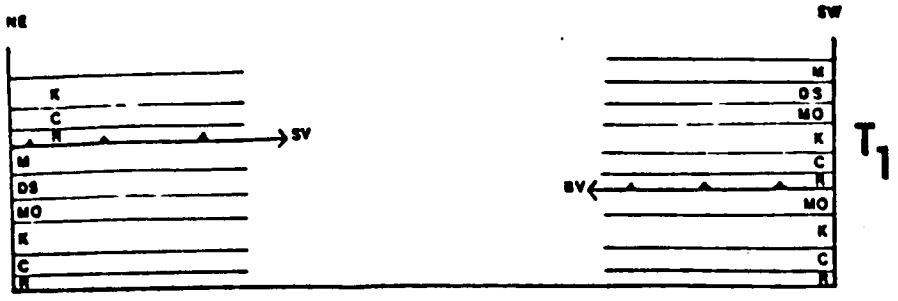
of thrust sheet geometries through time. Drawn parallel to strike, the diagrams depict the inferred sequence of deformation and thrust emplacement. These diagrams have been used in studies of the Appalachians (Harris, 1970) and the Moine thrust of Scotland (Elliott and Johnson, 1980). Jones' (1971) arguments, combined with hanging wall sequence diagrams illustrate my proposed geometric evolution of the study area.

3. INTERPRETATION OF THE SEQUENTIAL DEVELOPMENT OF THE STUDY AREA

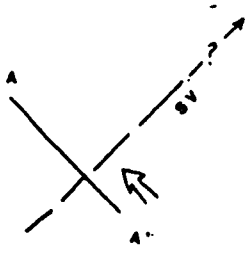
The interpretation of the sequential development of the Beaver Valley - Saltville transfer zone and adjacent Copper Creek thrust is presented below. The time depicted on each diagram (e.g., T1, T2, etc.) is arbitrarily chosen and does not represent absolute time; these diagrams show the relative sequence of events suggested by the structures in the area. All geographic coordinates (i.e., southwest, northeast, Knoxville, etc.) are with respect to current position for clarity.

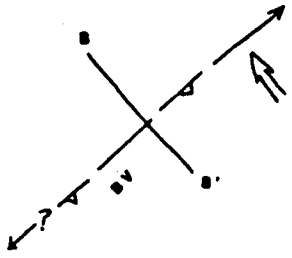
At T1 (Fig. 26), both faults had initiated and were moving to the northwest. The Beaver Valley was imbricating strata southwest of Knoxville while the Saltville was moving northeast of Knoxville. The faults were growing towards each other along strike, and it is unclear how much farther

Figure 26. Hangingwall sequence diagram showing the interpreted thrust development at T1. The Beaver Valley and Saltville thrusts are moving and also propagating laterally. Hypothetical sketches of map and cross-sectional views are below the sequence diagram.

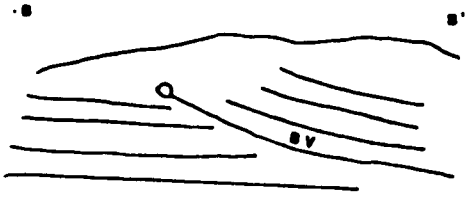

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MAP VIEW


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A
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SV


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BV

to the southwest or northeast they had developed. By T2 (Fig. 27), the Beaver Valley and Saltville were continuing to move and grow. It is not likely that both the faults were moving at the same time; movement was intermittant, and may have been of variable rate. For example, Wiltschko and Dorr (1983) determined that thrust rate in the Idaho-Wyoming thrust belt varied from 0.2 cm/yr to 1.0 cm/yr. By this stage in the thrust emplacement, the Saltville and Beaver Valley were essentially acting as one fault, accomodating shortening at different places along strike.

The Beaver Valley had terminated its growth by T3 (Fig. 28). Its lateral tip must have been pinned and folds were developing to take up the stress which was still being imposed. The cause of the thrust's lateral termination is not clear-cut (see the next section of this chapter). The Saltville may have reached the duplicated strata at the northeast end of the Beaver Valley sheet and started to step downward in the footwall to maintain a planar shape. The Copper Creek thrust had probably initiated movement by this time. It is shown as having developed several of its imbricates already, but this is speculative.

By T4 (Fig. 29), the Beaver Valley had completed folding at its tip and the Saltville had grown southwestward. Therefore, the Saltville is inferred to be a younger fault in this area southwest of the Beaver Valley termination. The sense of timing is relative, and various

Figure 27. Hangingwall sequence diagram showing the interpreted thrust development at T2. The Beaver Valley and Saltville thrusts are moving and continuing lateral propagation. Hypothetical sketches of map and cross-sectional views are below the sequence diagram.

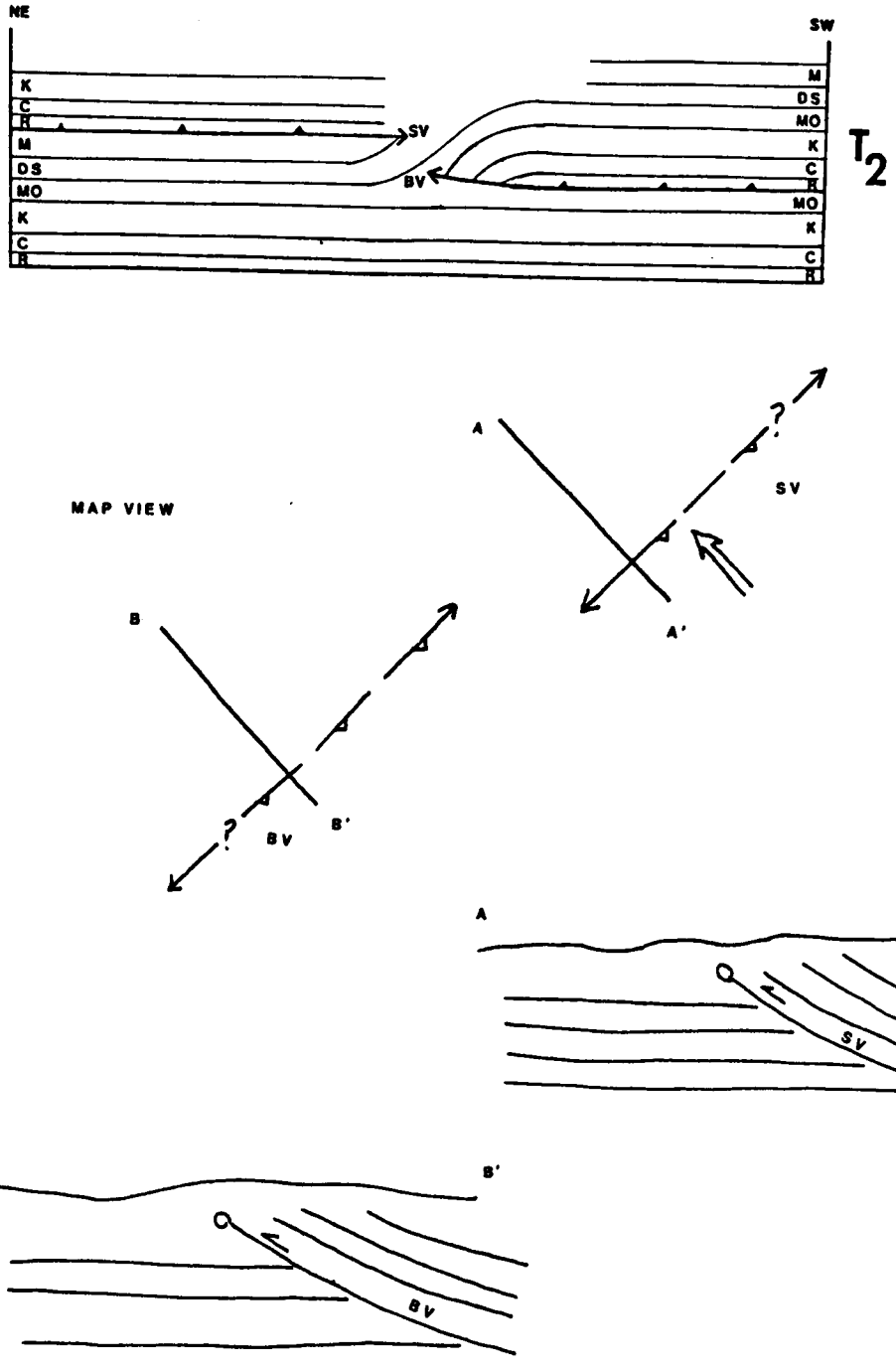
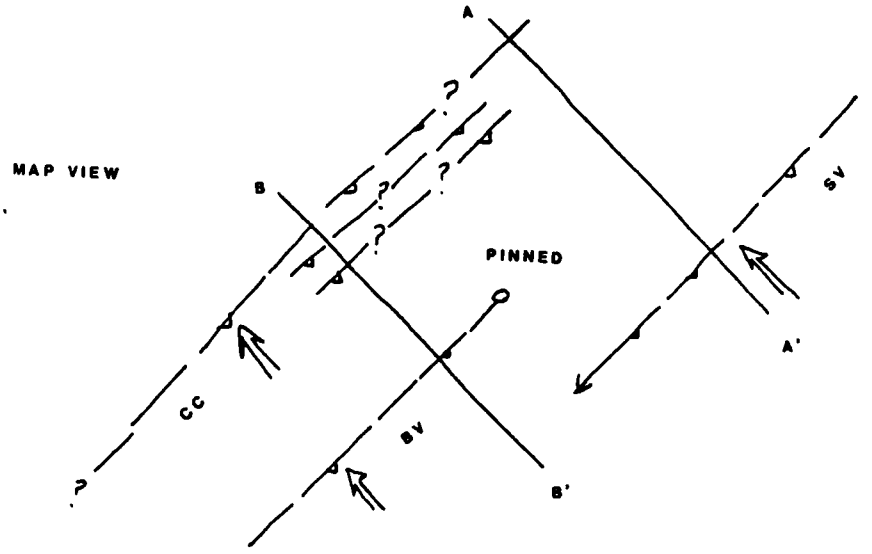

NE
SW
K
C
R
M
DS
MO
K
C
R
SV
BV
M
DS
MO
K
C
R
MO
K
C
R
T2
MAP VIEW
A
A'
SV
?
B
B'
BV
?
A
A'
SV
B
B'
BV

Figure 28. Hangingwall sequence diagram showing the interpreted thrust development at T3. The Beaver Valley thrust's northeastern tip is pinned and strata at this end of the thrust sheet are folding. The Saltville continues lateral propagation to the southwest. the younger Copper Creek thrust has begun emplacement. Hypothetical sketches of map and cross-sectional views are below the sequence diagram.


NE
SW
C
R
M
DS
MO
K
C
R
MO
C
S.V
BV
C.C
MO
K
C
R
MO
K
C
R
MO
C
T3


MAP VIEW
A
A'
B
B'
PINNED
S.V
CC
BV
?

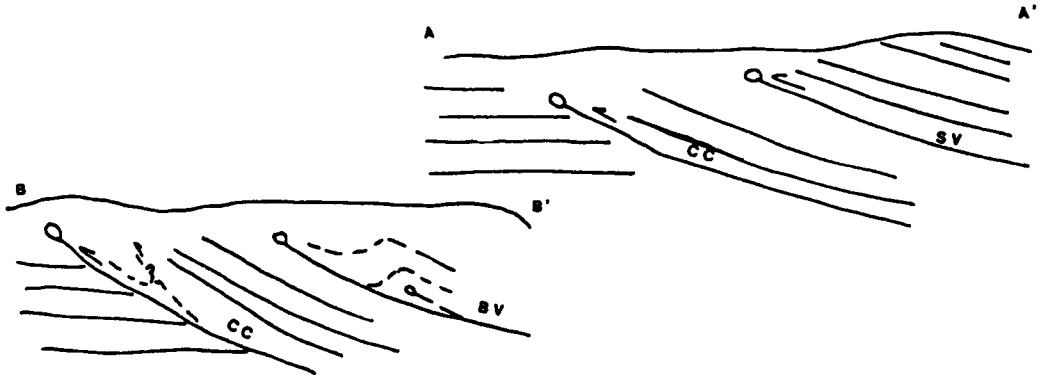
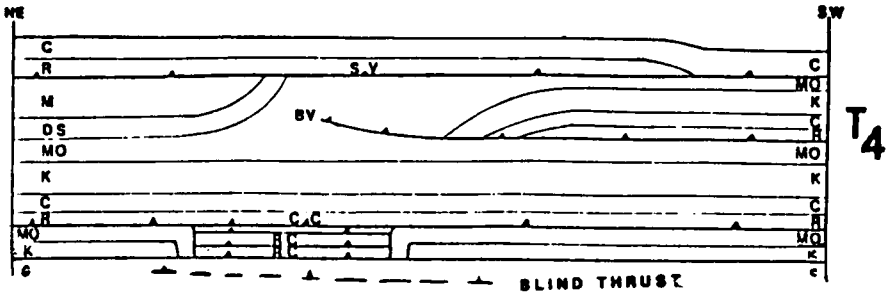
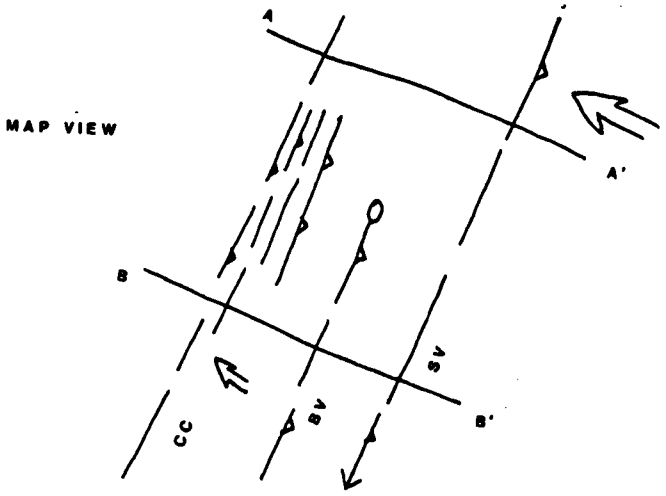
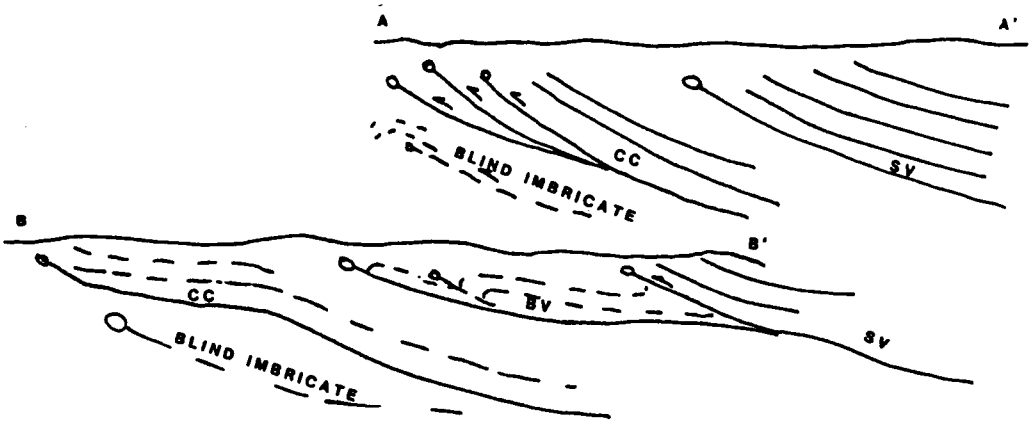

A
A'
B
B'
CC
S.V
BV

Figure 29. Hangingwall sequence diagram showing the interpreted thrust development at T4. The Saltville has propogated southwest beyond the area, and the Beaver Valley has completed its folding. The Copper Creek may have still been moving. Hypothetical sketches of map and cross-sectional views are below the sequence diagram.


NE
SW
C
R
S.V
M
DS
MO
K
BV
MQ
BLIND THRUST
T4


MAP VIEW
A
A'
B
B'
SV
BV
CC

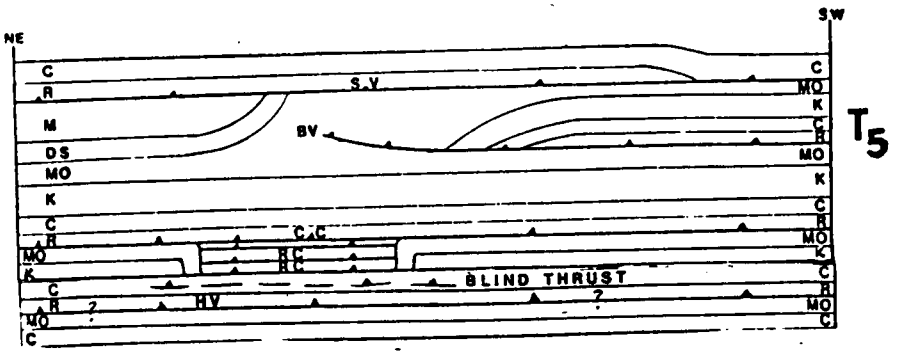

A
A'
B
B'
CC
SV
BV
BLIND IMBRICATE

events in this scenario were probably nearly contemporaneous with large amounts of overlap. The Copper Creek continued to develop its imbricate fan and folds, and the younger Hunter Valley and Wallen Valley thrusts may have initiated movement also. Diagram T5 (Fig. 30) represents the configuration of the faults at the end of all movement in the area, and prior to erosion. Note that the cross-section sketches match the balanced sections from the map, so that the proposed sequence of events actually produces the structures observed in the field.

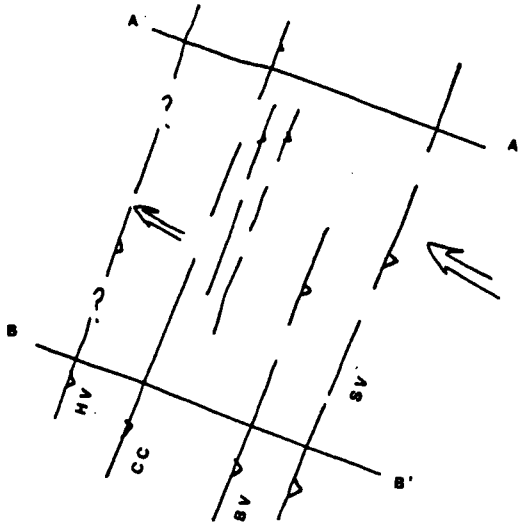
This interpretation of the sequence of thrusting points out the necessity of considering the interaction of the faults during emplacement. Each fault probably did not develop and propogate individually; they acted as a system. The process was on-going and overlapping. One might envision a "network" of faults, growing and emplacing, with each fault's movement overlapping the others. An entire thrust, as seen today, was probably not completely developed and moving at one specific time.

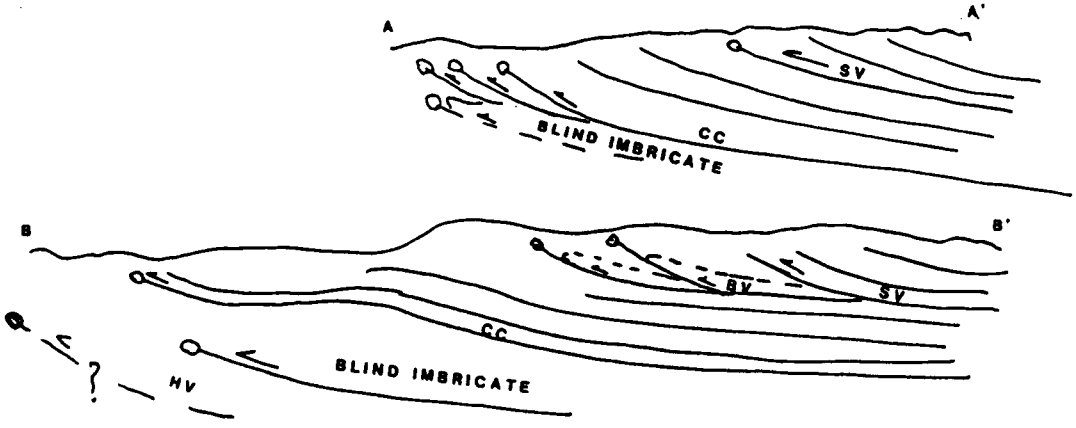
This is a significant conclusion because it argues that a "single" thrust as seen today may not have moved as one fault during its development. Various segments merged and coalesced into "single" thrusts through time. Therefore, the "paradox of overthrusting," (Hubbert and Rubey, 1959) so widely discussed in the past may be irrelevant for the reason outlined in Jones (1971): Map patterns and

Figure 30. Hangingwall sequence diagram showing the interpreted thrust development at T5. This diagram shows the relationships at the end of deformation, prior to erosion. Hypothetical sketches of map and cross-sectional views are below the sequence. Note that the cross-sections match those constructed from the geologic map of the study area.


NE
SW
C
R
M
DS
MO
K
S.V
BV
C.C
H.C
BLIND THRUST
HV
?
T5

MAP VIEW


A
A'
B
B'
?
HV
CC
BV
SV


A
A'
SV
CC
BLIND IMBRICATE
B
B'
BV
SV
CC
?
HV
BLIND IMBRICATE

cross-sections depict relationships at the end of thrusting, and do not directly unravel the path of deformation. This cannot be a paradox because at any one time only a segment of each thrust was moving.

It is also significant that the Saltville may actually be younger than the Beaver Valley for a portion of its length. To the northeast, the Beaver Valley thrust is absent and the Saltville sits directly on top of the lower Copper Creek sheet. To the southwest, south of the Georgia - Tennessee state line, the two faults merge into one (Rodgers, 1953). Thus, in a part of Tennessee, the two thrusts may be considered as components of one larger thrust system. This larger thrust fits the hinterland to foreland propogation sequence. Locally, however there is a reversal of the thrust sequence. This interpretation is important because it suggests that the thrust sequence does not necessarily propagate in one direction or the other. Therefore it may be misleading to strictly adhere to one direction of propagation. The thrusting sequence was much more complex although the over-all or "averaged" sequence is apparently hinterland to foreland.

4. CAUSES OF THE TERMINATION OF THE BEAVER VALLEY THRUST

Why did the Beaver Valley thrust end? This is both a significant and difficult question to answer. It is interesting to note that the Copper Creek thrust was generally unaffected as it passed through the same general area where the Beaver Valley thrust's growth was impeded. The imbrication along the front of the Copper Creek thrust is believed to be related to the mixed weak and strong layers of the Rome Formation and Conasauga Group and was not a response to the Beaver Valley's termination (see Chapter 2). The Saltville thrust changed its stratigraphic position in response to the pinning of the Beaver Valley. The behavior of the the Copper Creek and Saltville thrusts in this area suggests that the cause of the Beaver Valley termination was a localized feature.

Three possible causes can be inferred. The first is an irregularity in the basement which acted as a buttress for continued development to the northeast. The assumption that the basement dips uniformly to the southeast is justified (Bally et al., 1966), but local irregularities do exist. Geophysical evidence may indicate a local high in the basement northeast of Knoxville. Watkins (1964, his Fig. 8) inferred a basement high, inferred from magnetic data, but he based this on only two data points. In addition, if this

supposed basement high affected the Beaver Valley but not other thrusts, it would mean it was extremely small, perhaps smaller than any feature detectible by geophysical means.

A greater problem with this "basement" feature hypothesis is that such a feature, if real, exists beneath the basement under the present-day location of the Beaver Valley. This is certainly not the same part of the basement encountered by the fault as it was emplaced. In addition, the restored positions of the thrusts from the balanced sections do not suggest a basement high. The role of basement in thrust development has been discussed (Wiltschko and Eastman, 1983) but in this area evidence for basement interaction is not compelling.

A second explanation is a localized stratigraphic change which prevented the thrust from growing northeastward. The specific change would now be masked by deformation and erosion, but the characteristics of portions of the stratigraphic column in this area suggest two possible intervals: the Conasauga Group and the Middle Ordovician.

The regional facies pattern of the Conasauga Group consists of a northwestern shale phase, a central phase of carbonates and shale and southeastern phase of carbonates (Rodgers, 1953). The boundaries between the three phases are complex and interfinger. The shale and limestone distributions within the central phase are similarly

complex. Woodward et al. (in press) discuss the complexity found in the Saltville sheet northeast of the study area in the Bean Station, TN area, where duplex geometries occur. Complexity at the Saltville's leading edge diminishes southwestward as the fault passes into the western shaley phase. Similarly the imbricate fan in the Copper Creek thrust sheet in this area represents the complex nature of the phase.

Studies on the Conasauga at the University of Tennessee (Simmons, 1984; Kozar, 1986; Weber, in prep) have documented the stratigraphy of the Conasauga at several localities in the central phase. A plot of clastic ratios on a palinspastic base show trends cut oblique to structural trend (Fig. 31) suggesting lateral stratigraphic change and potentially related structural change. Hasson and Haase (in press) plotted stratigraphic thicknesses of the Conasauga on a palinspastic base, and they noted a trend grossly similar to the trend of the Middle Ordovician Chickamauga Group.

Several thrusts in east Tennessee exhibit changes in structural style related to the facies changes in the Conasauga Group. Within the study area however, the only noticeable changes are thicknesses of the six formations of the central phase. The changes are not drastic enough to have significantly affected the thrusts. The marked changes in the Conasauga Group are found northeast of Thorn Hill, Tn

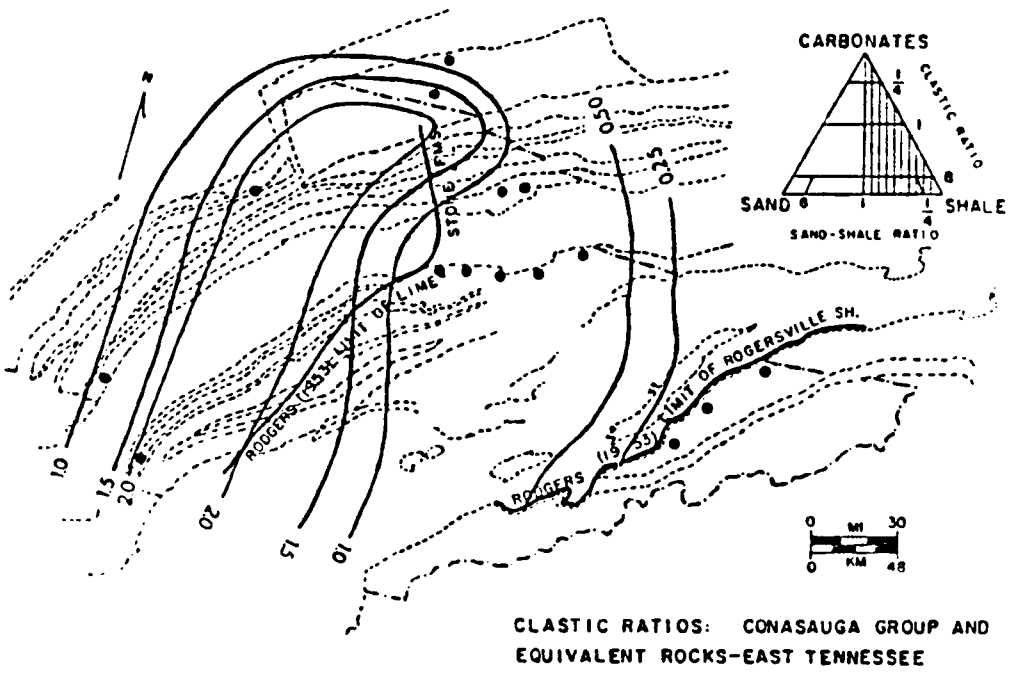


Figure 31. Trends of clastic ratios in the Conasauga Group plotted on a palinspastic base, from Simmons (1984). Palinspastic base is from Roeder and Witherspoon (1978). Note that the trends are oblique to structural grain.

and southwest of the study area towards Oak Ridge, TN (Walker, pers. comm. 1987)

The stratigraphic framework ot the Middle Ordovician in east Tennessee is well-understood (Walker, 1977, 1980). Interpretations of Middle Ordovician paleoenvironments plotted on a palinspastic base led Walker (1980) to propose a change in the shelf-edge trend between present-day Knoxville and Luttrell, TN. This bend roughly coincides with the restored position of the Beaver Valley thrust (Fig. 32). This suggests that differing Middle Ordovician lithotypes on either side of the bend--shelf carbonates vs. slope and basinal limestones and clastics--might have possessed a marked mechanical difference which affected northeastward growth of the Beaver Valley thrust.

This interpretation suggests that the faults propagated in carbonates and died out in shales. The shale, being weaker, failed more easily than the thicker and stronger carbonates. Tight folds, cored by detachments, would have formed. Thus, the fault would not have continued to propagate and emplace because the slip was "transferred" to folds in the shale.

The third potential explanation follows from the proposed sequence of thrusting. To the northeast, the Saltville is interpreted as being the older of the two thrusts. It was growing southwestward as it emplaced.

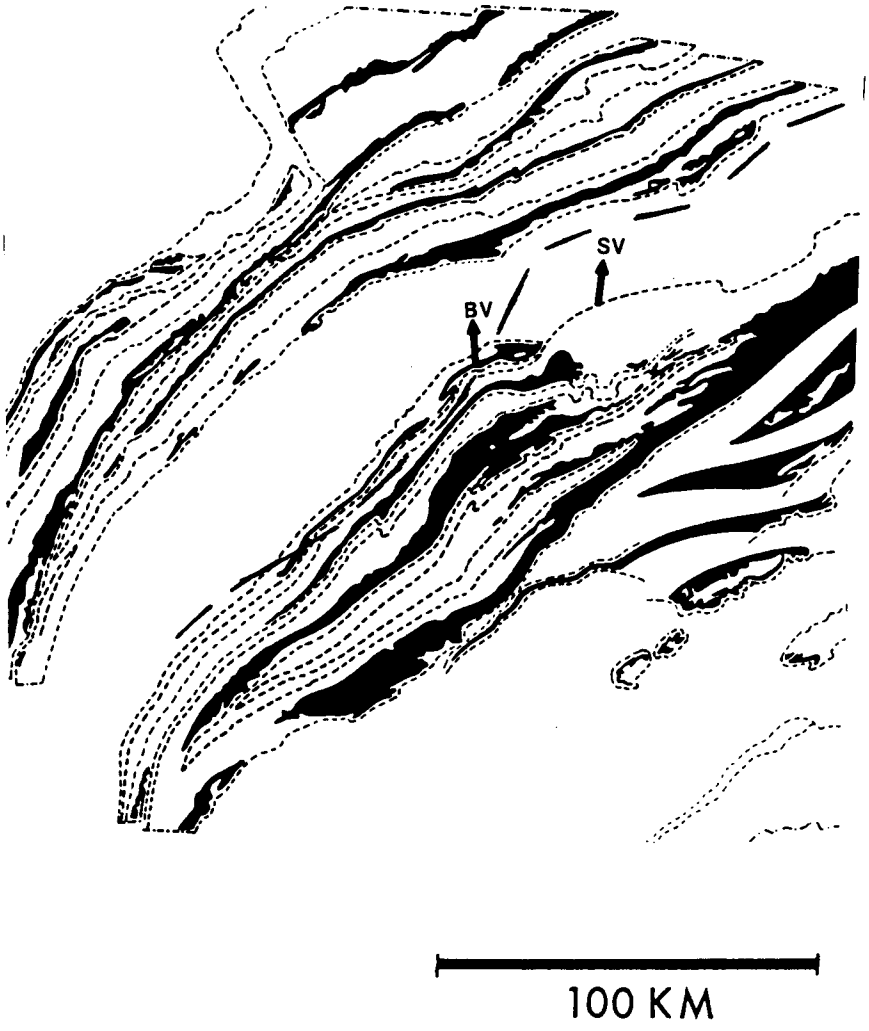


Figure 32. Palinspastic map of Roeder and Witherspoon (1978), showing the approximate location of the bend in the interpreted position of the Middle Ordovician shelf edge (Walker, 1980). BV = Beaver Valley thrust; SV = Saltville thrust.

Thus, as the Beaver Valley thrust was growing laterally, it terminated because it had nowhere to go. The Saltville thrust had displaced the strata already, therefore the Beaver Valley lost slip and terminated because the shortening had been accomplished solely by the Saltville thrust.

The second and third explanations are favored as the likely causes of the termination of the Beaver Valley thrust. The influence of basement is rejected not only because the evidence is scarce, but also because there is no evidence for it from the restored position of the thrusts. In contrast, the Conasauga Group and the Middle Ordovician, with the Rome Formation to a much smaller degree, are known to undergo lateral change in their stratigraphy in a direction coincident with the termination of the Beaver Valley. Specific stratigraphic changes and the locations of these changes cannot, however, be identified. The proposed sequence of thrusting, which itself may have been controlled by the stratigraphy, also would have prevented continued lateral growth of the Beaver Valley thrust.

5. CONCLUSIONS

1) The proposed sequence of thrusting in the study area, presented here on hanging wall sequence diagrams, is based

on the application of ideas outlined by Jones (1971) in his study of thrusts in the Canadian Rockies.

2) The Beaver Valley and Saltville thrusts are interpreted as having grown toward each other laterally during emplacement. The movement of the faults was intermittant, and the times during which the faults were emplacing overlapped.

3) At some point in the thrust emplacement, the lateral tip of the Beaver Valley thrust was pinned and could no longer propogate. As a result, a series of folds developed at its tip.

4) The Saltville thrust continued its growth southwestward despite the presence of the Beaver Valley thrust. Locally, it is the younger thrust.

5) The Copper Creek thrust, despite the imbricate fan along its leading edge was apparently unaffected by the termination of the Beaver Valley thrust. The imbrication is related to the mixed weak and strong layers in Rome - Conasauga portion of the stratigraphic column.

6) The interpretation of the thrust sequence suggests a local reversal and "break-back" relationship between the

Saltville and Beaver Valley thrusts in this portion of the Valley and Ridge. This only applies to these two thrusts. The interpretation suggests a much more complex thrusting sequence for the Valley and Ridge than a purely "foreland-breaking" or a purely "break-back" explanation.

7) This thrust sequence implies that during deformation "single" thrusts were not present, but rather shortening was accomplished by a "network" of smaller segments moving in different locations, all within the same general time interval. Ultimately, the segments coalesced and comprise the single faults presently observable.

8) The Beaver Valley thrust terminated either due to an effect of the basement, or lateral stratigraphic change, or the inability of the thrust to continue to propagate because the Saltville had already shortened the strata. The basement theory is rejected, because evidence for it is scarce, and because it is not suggested by the restored positions of the thrusts. The stratigraphic theory combined with the interpreted sequence of thrusting is favored because a known amount of stratigraphic variation--especially in the Conasauga Group and the Middle Ordovician--occurs in the direction of the thrust's termination. These stratigraphic changes may be responsible for the thrust sequence. The changes are broadly defined

however, and specific changes and the locations of these changes cannot be identified.

CHAPTER 4

STRAIN IN CARBONATES
IN THE BEAVER VALLEY - SALTVILLE TRANSFER ZONE

1. INTRODUCTION AND PURPOSE

The purpose of this chapter is to discuss strain and examine microscopic and mesoscopic features in carbonates in the study area. Most of the samples examined are limestones. A few dolostones of the Knox Group are also included. Much of the study area which is underlain by dolostone is deeply eroded, and most of the exposed dolostones lack appreciable deformation features other than fractures. The discussion includes four parts. Deformation features present in the carbonates are described in the first part. The second part describes the distribution of the deformation features. The third part concerns strain recorded in the limestones in twinned calcite. The final section is a discussion of inferences about temperature and pressure ranges during deformation, along with a comparison of strain in the carbonates with total shortening indicated by balanced cross-sections.

Data for this chapter comes from mesoscopic (outcrop scale) features and slabs and thin-sections of samples collected throughout the study area. From the samples

collected, 103 thin-sections were prepared; these are both the 2" x 3" and 1" x 1 3/4" size. The initial plan was to collect samples along transects parallel or nearly parallel to cross-section lines. The lack of consistent outcrop, vegetative cover, and limited access to some properties precluded this approach. Samples amassed for examination are taken from available outcrops where bedding orientation was distinct and the rocks were not appreciably weathered.

The processes involved in deformation generally combine to impart a fabric to the rocks involved. Fabric refers to the internal arrangement of the particles or grains which comprise the rock (Suppe, 1985). Fabrics which develop vary with both lithology and conditions during deformation. Common examples of fabrics include preferred orientation of elongate grains, or crystallographic axes, or planar features such as fractures, cleavage, or schistosity. In rocks deformed at fairly low temperatures and pressures however, fabrics are commonly not penetrative, and may largely consist of fractures and veins (Price, 1967; Hancock, 1985). This is true of carbonates in the study area. Fault zone rocks do exhibit fairly intense cataclastic deformation, whereas those in most of the area are only mildly deformed.

Lithology exerts a control on fabric development and style of deformation because differing lithologies accomodate strain with different deformation mechanisms.

Deformation mechanisms are the processes by which strain is accomodated during deformation. The scale implied by the term "deformation mechanism" can be confusing. In some cases, it is confined to the scale of a grain (or less), whereas in other cases bed-scale or larger processes are included as well. In this chapter, both bed and grain scale features will be considered as deformation mechanisms.

The deformation mechanism which operates at any given time will be a function of mineralogy, temperature, pressure, strain rate, and grain size. Generally, strain is divided among several competing mechanisms. Strain partitioning is the subdivision of total strain into components driven by different deformation mechanisms (Groshong et al., 1984). An examination of strain partitioning is a useful way to identify the presence and relative significance of various deformational processes in an area being studied.

2. DEFORMATION FEATURES

McClay (1977) and Rutter (1983) pointed out three fundamental types of processes that deform rocks: cataclasis, intracrystalline plasticity, and flow by diffusive mass transfer. These three processes are all evident in carbonates in the study area to varying degrees. The deformation features which are present and comprise the

total strain in the carbonates are: cleavage, stylolites and solution seams, fractures, veins, twin lamellae, brecciated rock, and bedding slip surfaces.

Cleavage

Cleavage in the study area is not extensively developed. The primary reason for its poor development is that the area is located in the external portion of the thrust belt, where there was little penetrative deformation at the scale of the thrust sheet. In this area, deformation conditions were also inappropriate (low T, low P) for a sheet-wide cleavage to form. Cleavage is confined to location adjacent to several thrust faults where strains are highest. Cleavage is observable at three outcrops (Fig. 33), but it is probable that cleavage developed elsewhere at localities which are now eroded or are still buried.

Powell's (1979) cleavage classification is employed here (Fig. 34). The scheme is descriptive and non-genetic, and is based on the two components of a cleaved rock: cleavage domains and microlithons. Cleavage domains are the areas of preferred mineral orientation or seams which correspond to the cleavage planes, and microlithons are the areas of rock between domains. Powell considered four aspects of these two components in the classification: spacing of cleavage domains, shape of cleavage domains,

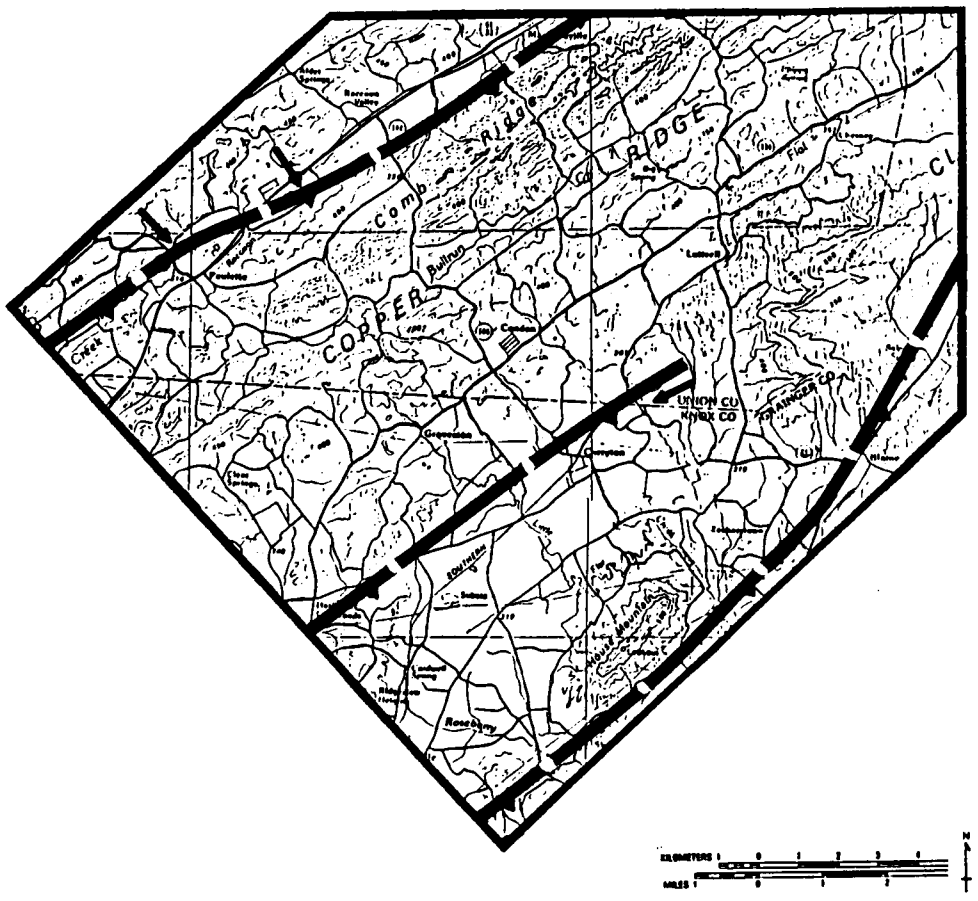


Figure 33. Map of the study area, showing the location of cleaved strata. Note the proximity of the outcrops to major thrusts.

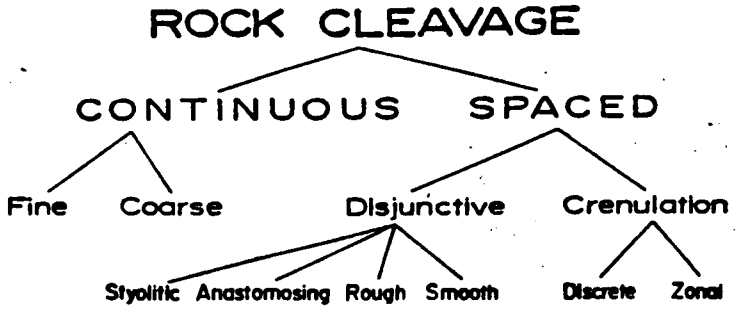


Figure 34. Diagram of the basic elements of cleavage classification, from Powell (1979).

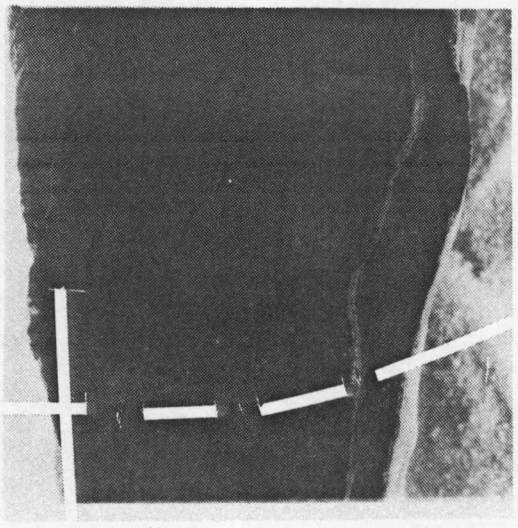
microlithon fabric, and proportion of rock occupied by cleavage domains.

Cleavage at two of the three exposures occurs in the Moccasin Formation (Fig. 35); the cleavage is generally perpendicular to bedding and is axial planar to folds. Cleavage domains are spaced from 1 to 3 cm apart suggesting cleavage of moderate intensity (Alvarez et al., 1978; Fig. 35a). The cleavage is an anastomosing and rough disjunctive cleavage with dark seams of argillaceous material corresponding to the cleavage domains. There is a gradational increase in carbonate material away from the cleavage domain. This is evident in thin-section; material adjacent to the vein is entirely quartz silt and opaque clays. Carbonate allochems appear and increase in abundance away from the cleavage domain.

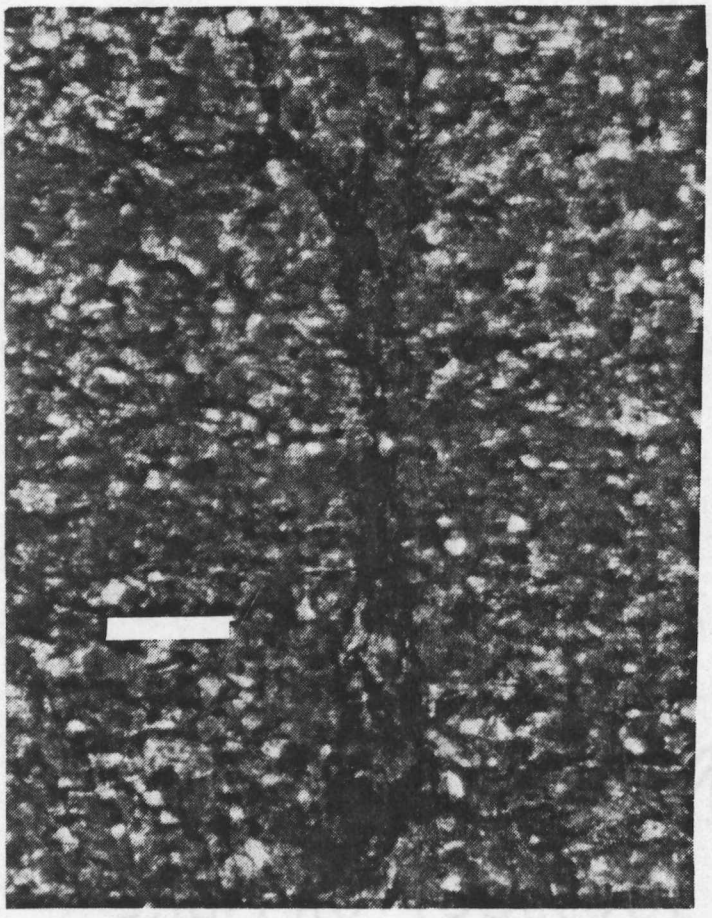
Middle Chickamauga Group strata, (probably in the Wardell Formation, (based on the location of the outcrop with respect to a nearby exposure of the overlying Bowen Formation) also show some cleavage. The beds are not folded, but the cleavage is essentially perpendicular to bedding, as it is at the other outcrops. Here, the cleavage domains are spaced up to several cm apart as well, and the cleavage is largely an anastomosing disjunctive cleavage (Fig. 36). In contrast to the Moccasin however, some of the cleavage here is also stylolitic. Thin-sections of the Moccasin from several localities within the Beaver Valley

Figure 35. Cleavage in the Moccasin Formation. Sample location is near the tip of the Beaver Valley thrust, approximately 1.8 km northeast of Corryton, TN (see Stop 6, Appendix B). A) Slab photograph of cleavage. Note that the cleavage domains are identified by dark seams of insoluble material. B) Photomicrograph of the cleavage. The black seam is the cleavage domain and consists of insolubles. The rock is a peloidal packstone. Scale bar = 20 μm .

A



B



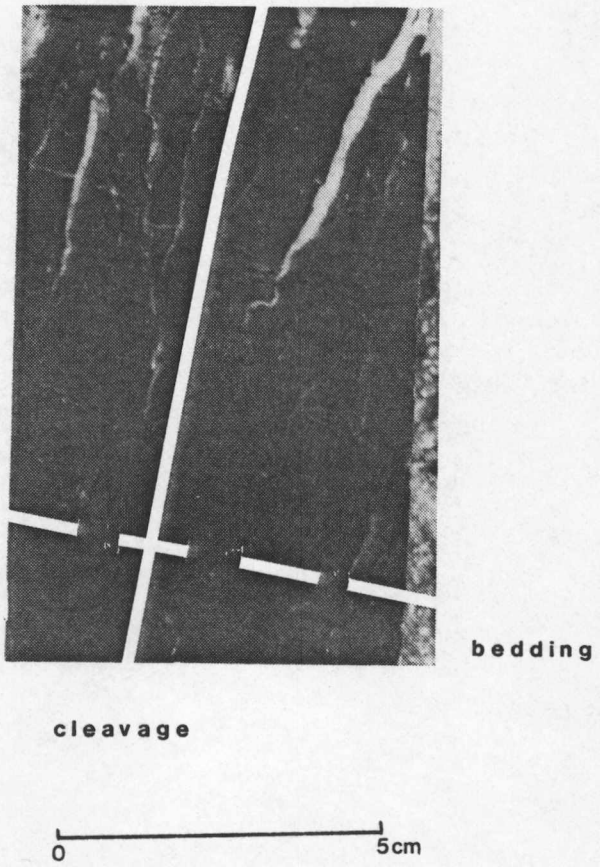


Figure 36. Cleavage in the middle Chickamauga Group (Wardell Formation). Sample location is on Tennessee Route 33 in the footwall of the Copper Creek thrust, approximately 7.9 km southwest of Maynardville, TN. The slab photograph illustrates the stylolitic nature of the cleavage in this rock. These strata consist of fossiliferous packstones and wackestones. The veins which are subparallel or parallel to cleavage planes both cut through cleavage domains and are offset by cleavage domains.

thrust sheet exhibit small, discrete pressure solved "segments" cutting bedding at a steep angle (Fig. 37). These may represent "incipient" cleavage which did not develop into a penetrative feature.

Veins are parallel or sub-parallel to the cleavage planes in the exposure of the cleaved Wardell Formation. Close examination of the veins indicates that some cut through the cleavage domains, while others are offset by the stylolitic cleavage. Several workers have argued that cleavage may form in limestones relatively early during deformation and is subsequently rotated or modified (Mitra and Yonkee, 1983, Marshak and Engelder, 1985). The cleavage here therefore probably formed early in the deformation due to layer parallel shortening, and the fractures formed later as the rocks were extended during thrust transport or fold tightening. The veins offset along stylolites indicate either continued or re-initiated pressure solution after vein formation, or slip along early solution surfaces.

In all cases, the cleavage is a pressure solution cleavage. The cleavage domains are composed of insoluble residue including quartz and clays. Apparent offset of beds and stylolites also indicates that pressure solution acted strongly upon the rocks (see Appendix 2, stop 6). Alvarez et al. (1976) and Mitra and Yonkee (1983) reported similar cleavage in limestones in other fold-and-thrust belts. They termed this type of cleavage "spaced cleavage," suggesting

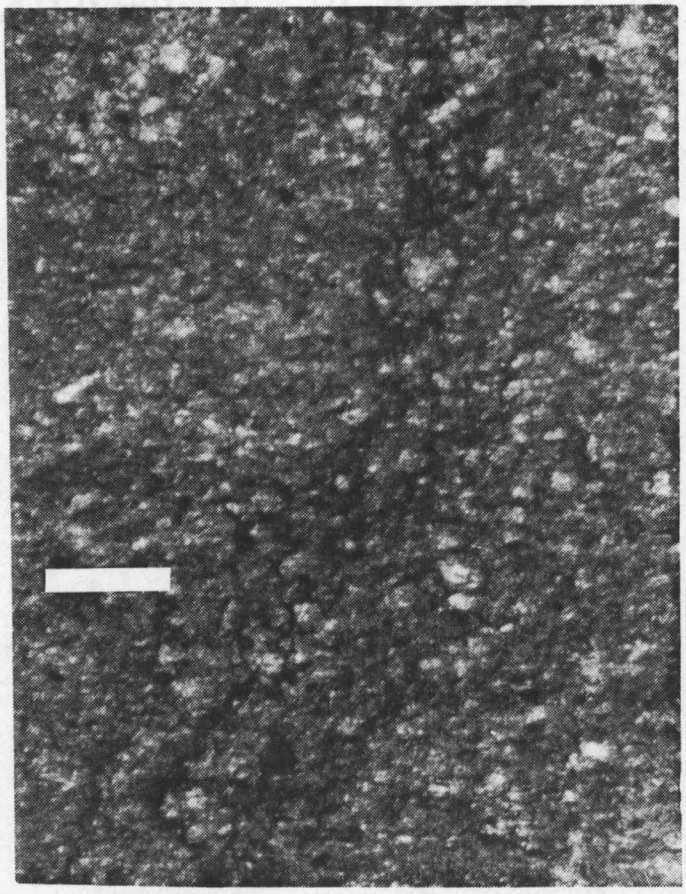


Figure 37. "Incipient" cleavage in the Moccasin Formation. Sample location is in the Beaver Valley thrust sheet on Corryton Road, 1.8 southeast of Corryton, TN. Notice that the pressure solved segment is somewhat diffuse and not as strongly defined as the cleavage domains in Fig. 35. Segments like this one are only visible in thin-section. Scale bar = 20 μm .

surfaces of discontinuity separating undeformed microlithons of rock.

Cleavage is best developed in the Moccasin Formation for two reasons: structural position and lithology. The Moccasin is positioned near or adjacent to the thrusts in many instances. Thus, the beds suffered relatively higher strains compared to beds farther within the sheet. Exposures of the Moccasin within the Copper Creek sheet exhibit no cleavage. Therefore, because strata of the same lithologies do not possess cleavage within the sheets, one can conclude that structural position is a significant factor.

Cleavage is generally not found in limestones with less than 10 % of a clay-quartz component (Wanless, 1979). Marshak and Engelder (1985) investigated cleavage formation in limestones and determined that at 10 % or greater quartz-clay matrix, a "network" of matrix exists that is interconnected between grains. The clay provides interconnectivity between dissolution sites on grain boundaries and the fluid system associated with pressure solution, thus enhancing the solution process.

The Moccasin illustrates this relationship. Most of the Moccasin is an argillaceous peloidal packstone. Simonson (1985) processed 114 samples for insoluble residue. The values he reported range from 5.9 to 82.7 weight per cent with a mean value of 31.5 %. X-ray diffraction

analysis showed that the insolubles are mostly quartz and illite, with some chlorite, kaolinite and vermiculite. Cleavage is preferentially developed in the impure carbonates, whereas in purer beds of the Moccasin (e.g., unit "B" of Simonson, 1985) pressure solution features, such as stylolites are present, but cleavage is absent. Cleavage in the Wardell Formation is morphologically different from that in the Moccasin because it is a purer limestone (mostly fossiliferous packstones and wackestones). The cleavage domains are not tectonic stylolites, but they do possess a more stylolitic and sutured morphology.

Stylolites and solution seams

Stylolites are pressure solution seams of relatively unsoluble material left behind in a rock which has been subjected to stresses from loading or deformation (see Stockdale, 1922 and Bathurst, 1975 for a thorough discussion). Stylolites characteristically possess a sutured, "saw-tooth" morphology and rock on either side of the stylolites appears interlocked. Pressure solution however commonly creates layers of insoluble residue which do not have the sutured morphology of stylolites and these are best termed solution seams (see Wanless, 1979 for a discussion of the distinction).

Carbonates in the study area contain stylolites and solution seams resulting from both post-depostional burial and deformation. Bedding parallel stylolites are probably non-deformational, while those which are perpendicular or oblique to bedding are probably attributable to deformation.

Bedding parallel stylolites are widely developed across the study area in all the limestones. The stylolites are commonly visible in outcrop, and vary in amount of spacing between each layer (Fig. 38). These features are certainly from burial or loading after deposition and pre-date deformation; however the stylolites record a volume loss strain suffered by the rocks. In several cases, these bedding parallel stylolites appear to have been kinematically active during deformation as well. Veins, which cut bedding at a steep angle are cut and offset by bedding parallel stylolites (Fig. 39). This relationship suggests two possibilites: First, the stylolites were reactivated during deformation, producing "offset" of the veins (see Groshong, 1975). Second, the stylolites were planes of weakness which acted as very small slip surfaces during deformation. Hancock (1985) points out that cross-cutting relationships suggest that stylolite development may be a multiphase process. In the absence of additional evidence, the reactivation of stylolitic surfaces seems more likely.

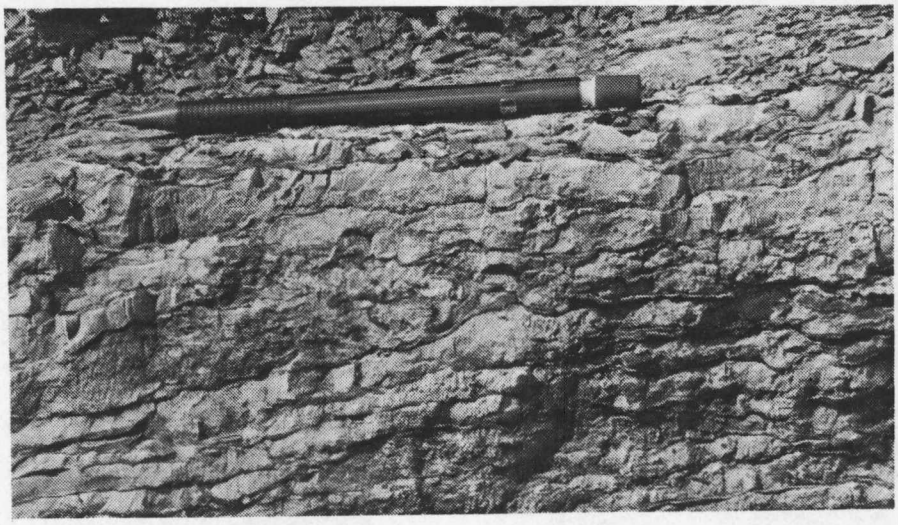


Figure 38. Bedding parallel stylolites from a limestone bed in the Nolichucky Shale. Sample location is along Tennessee Route 33, 2.1 km southwest of Paulette, TN in the Texas Valley syncline (see Stop 1, Appendix B). the pencil is 14 cm long.

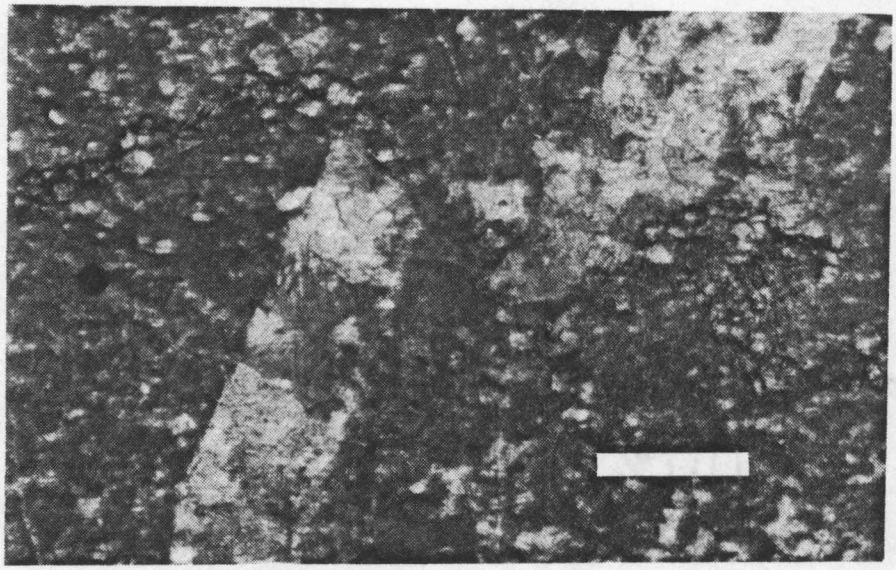


Figure 39. Truncation of a vein by a "reactivated" bedding parallel stylolite. Sample location is the foot wall of the Copper Creek thrust on Tennessee Route 61 (see Stop 3, Appendix B). Note that the stylolite clearly offsets veins which are perpendicular to bedding. Scale bar = 10 μm .

Tectonic stylolites are developed in the study area, but are not widely distributed. In general, these are found in localities near one of the thrust faults (usually within 100 m). The tectonic stylolites are visible in both slabs and thin-sections, although they are more evident in slabs where it is easier to see the relationship to bedding (Fig. 40). These stylolites are perpendicular to bedding or cut it at a steep angle. These stylolites are best exhibited in the Moccasin Formation. The tectonic stylolites are useful kinematic indicators (Price, 1967), and suggest a significant amount of layer parallel shortening. They may also represent an "early" stage in the development of cleavage, which did become penetrative because of lithology. The tectonic stylolites in the Moccasin are found in the purer carbonate layers, whereas the cleavage is developed in more argillaceous portions.

The third type of pressure solution features are termed solution seams because they do not possess the sutured morphology of stylolites, they are not throughgoing, or both; that is, they do not cut the sample over a large distance. These range from several mm to a cm in length. The seams have various orientations with respect to bedding and commonly truncate or wrap around allochems (Fig. 41). These seams and the other stylolites represent a form of grain boundary accomodation; stresses were highest at the grain boundaries and this drove the pressure solution.

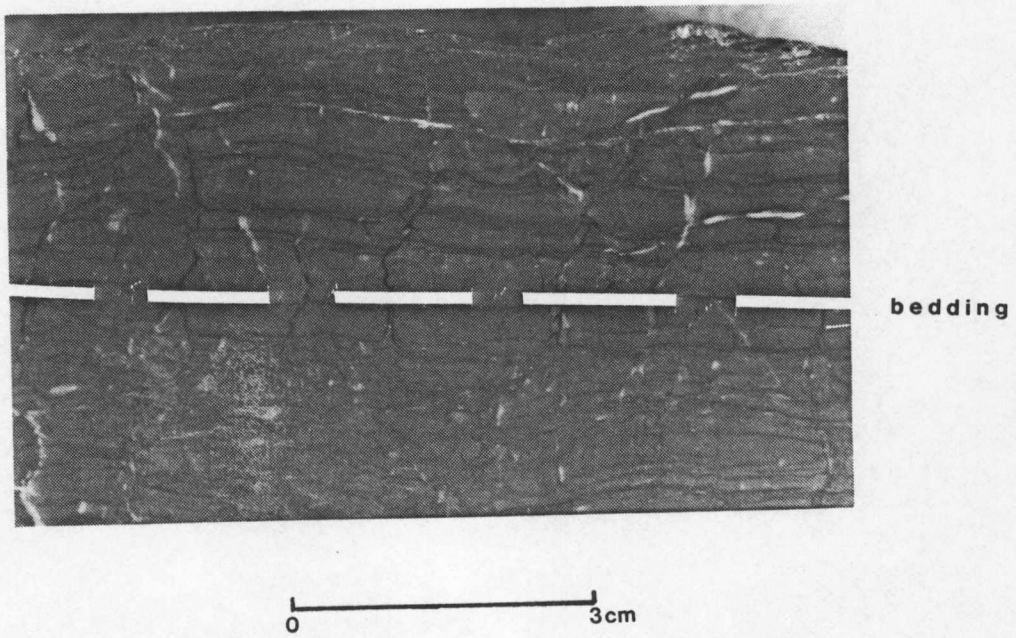
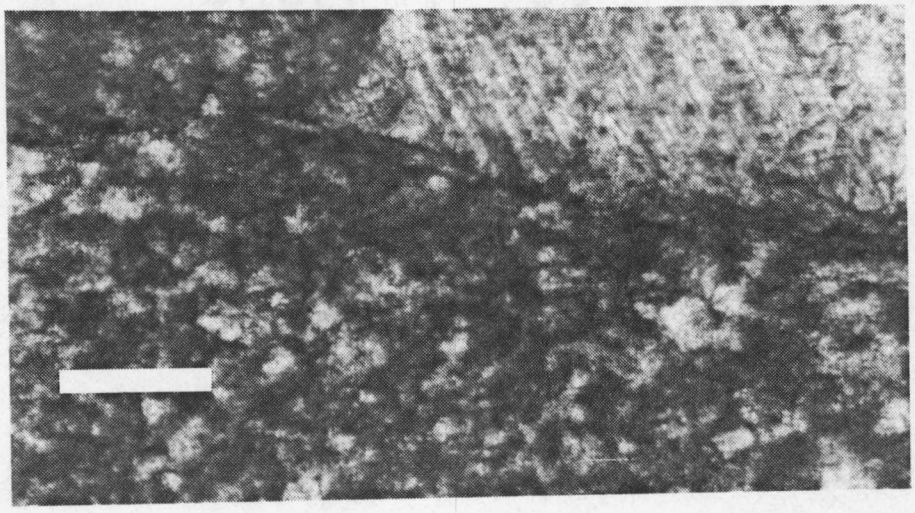
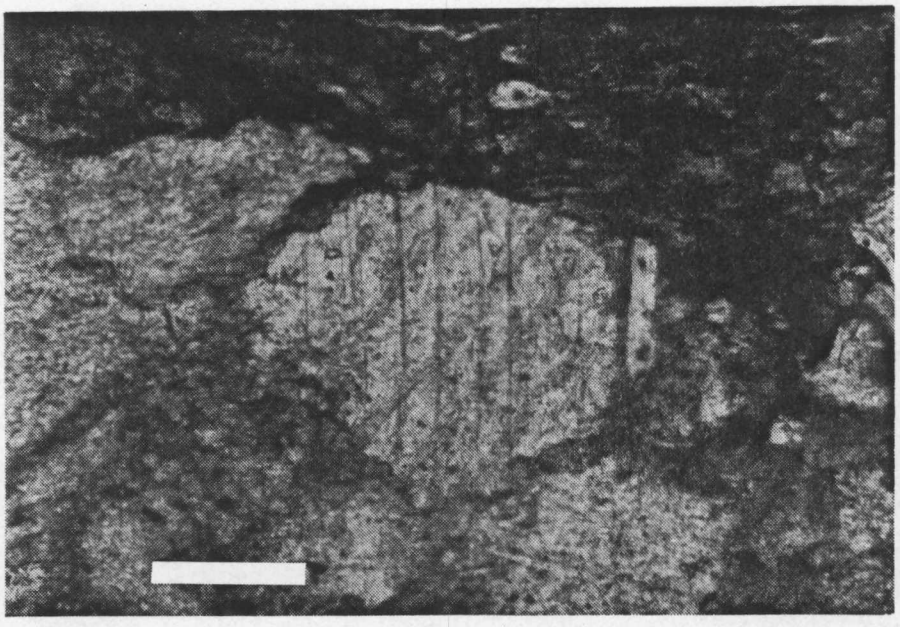


Figure 40. Slab photograph of tectonic stylolites in the Moccasin Formation. Sample location is the foot wall of the Copper Creek thrust on Tennessee Route 61 (see Stop 3, Appendix B).



A



B

Figure 41. Photomicrographs of solution seams in carbonates. A) Moccasin Formation. B) Middle Chickamauga Group (Lincolnshire Formation). Scale bar in each photomicrograph = 10 μm .

Fractures

Fractures are present in all stratigraphic units in the study area. These are the best and most consistently developed deformational feature. Most are steeply inclined or perpendicular to bedding. Although there is some scatter in orientation, two concentrations are indicated (Fig. 42). This suggests a conjugate relationship. Based on pole concentrations, the "mean" orientations of the sets are N to N1^{o}W and N45^{o}E.

Hancock (1985) points out that although fractures are widespread in deformed rocks, determining their kinematic significance is not always clear-cut. Additionally, they account for only a small amount of strain. Hancock cites a study which concluded that fractures accounted for only 0.01 % elongation. Nevertheless, it is important to record the presence and orientation of fractures. In general, three types of fractures may develop: extension, shear, and hybrid. Hancock presents 10 criteria which may used to determine the type of fractures which are present; of these, determining the dihedral angle between conjugate fractures is particularly useful for identifying fracture type.

The fractures in the study area are interpreted as being dominantly of the hybrid type. This conclusion is based on three lines of evidence. First, the dihedral angle

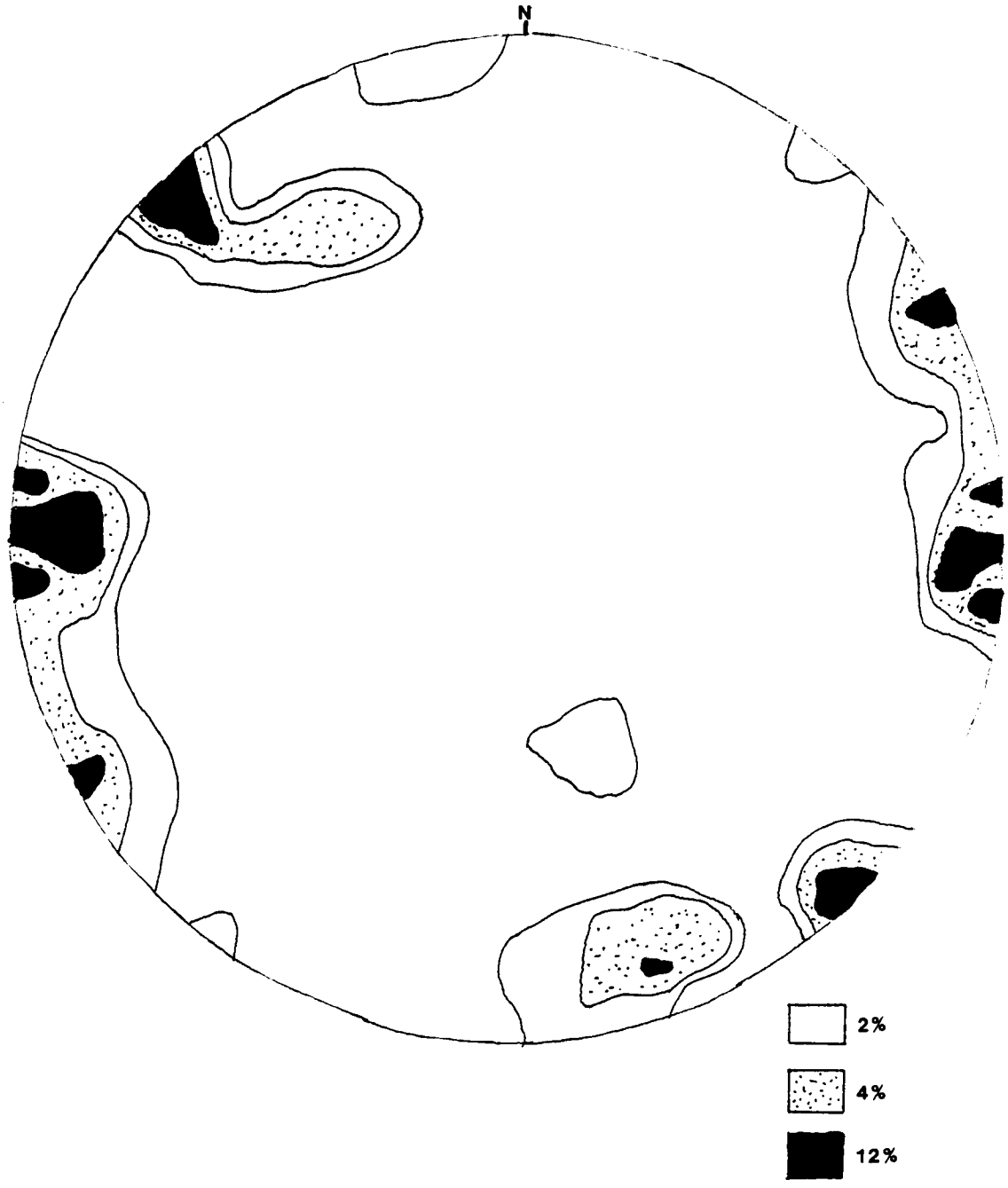


Figure 42. Stereographic projection of poles to fractures in limestones in the study area. Note the two well-defined maxima, suggesting the presence of a conjugate set throughout the area. These fracture sets are oriented N to N1°W and N45°E, with a dihedral angle of 46°. Number of measurements = 213.

between the two fracture sets is 46°. Hancock (1985) pointed out that conjugate hybrid fractures enclose a small dihedral angle, generally 10° to 50°. Second, if the principal stress direction (σ_1) corresponded (in general) to transport direction, one would expect a set of conjugate shear fractures to form at 30° on either side of σ_1 (Friedman and Sowers, 1970). An estimation of the orientation of (generally perpendicular to strike of the thrusts) relative to "mean" fracture orientations indicates that the angle is not exactly 30° but is within 10°. Finally, Hancock points out that, as a general observation, many steeply inclined or vertical fractures are hybrid or extensional.

The fractures are ubiquitous and evident in outcrop (Fig. 43). No systematic increase in fracture density and spacing with distance from the thrusts was observed. Some of the fracture surfaces are coated with calcite grains (c.f. "ornamented surfaces" of Wiltschko et al., 1985), which may indicate that the surfaces were kinematically active during deformation. In most cases, however, these coated surfaces are simply veins which are now exposed because a block of rock has fallen out of the outcrop. In general, the distribution of the fractures resembles the observations of Price (1967) who noted the dominance of fractures, mostly steeply inclined to bedding, in a layered sequence which failed in a brittle manner.



Figure 43. Outcrop photograph of the Maryville Limestone and overlying Nolichucky Shale in a quarry south of Paulette, TN along Tennessee Route 33. Beds dip at 5^{o} or less. The development of fractures is evident and the orientation of the fractures with respect to bedding is typical of fracture orientation in carbonates throughout the study area.

Veins

Veins are widely distributed across the study area; their orientation is commonly identical or close to fracture orientation. The similarity between vein and fracture distributions is not coincidental. In most cases, the veins probably represent mineral filled "healed" fractures. The veins may be characterized in several ways:

1) The veins are commonly at a high angle or perpendicular to bedding.

2) The veins range in width from 0.2 mm to nearly 1 cm, with most less than 5 mm wide.

3) The veins are filled with sparry calcite which is commonly twinned.

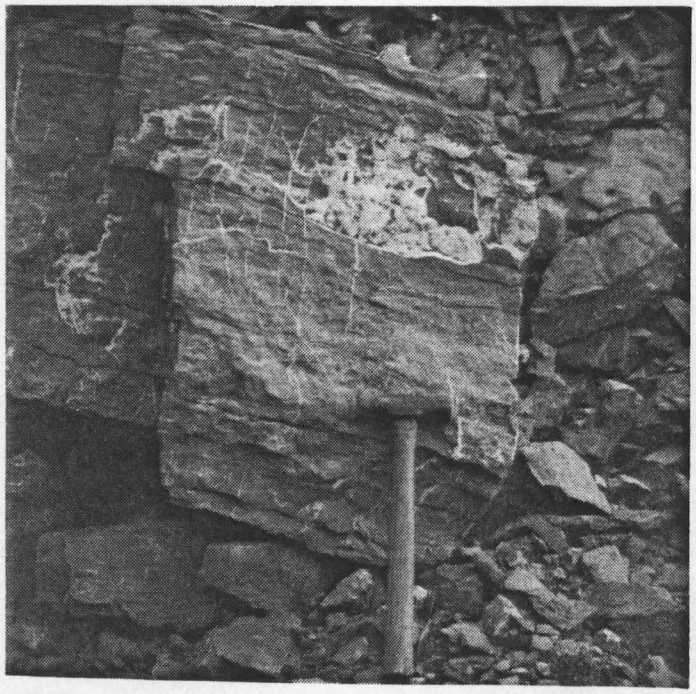
Figure 44 illustrates veins at various scales. No more than three sets of veins were observed in any samples, with one or two sets the general rule. No curved or sigmoidal veins, suggesting rotation, were observed. Where two sets are developed, one set is generally perpendicular to bedding, and the other is oblique to bedding but at a steep angle to it.

In rare cases, veins occur parallel to bedding (Fig. 44e). The width of these veins is identical to the others, but they are are not very long. Most of the bedding parallel veins do not exceed 5 cm in length. Veins are also found in cleaved samples and may represent areas of redeposition approximately aligned with the least

Figure 44. Veins in limestones in the study area. A) Veins perpendicular to bedding in the Maryville Limestone. B) Veins in the Maryville Limestone. C) Photomicrograph of veins filled with twinned calcite in the middle Chickamauga Group. Scale bar = 20 μm . D) Slab photograph of veins in the Rutledge Limestone. E) Slab photograph of bedding parallel veins in the Moccasin Formation.



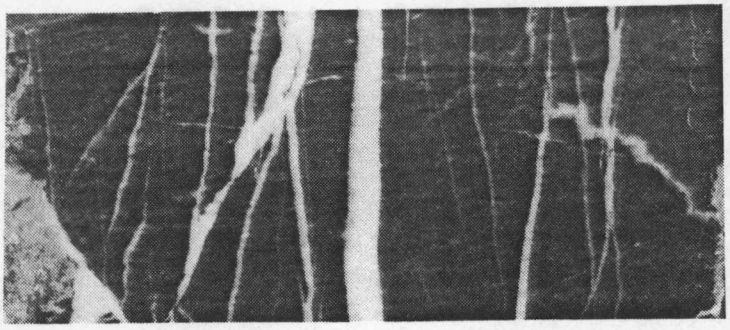
A



B

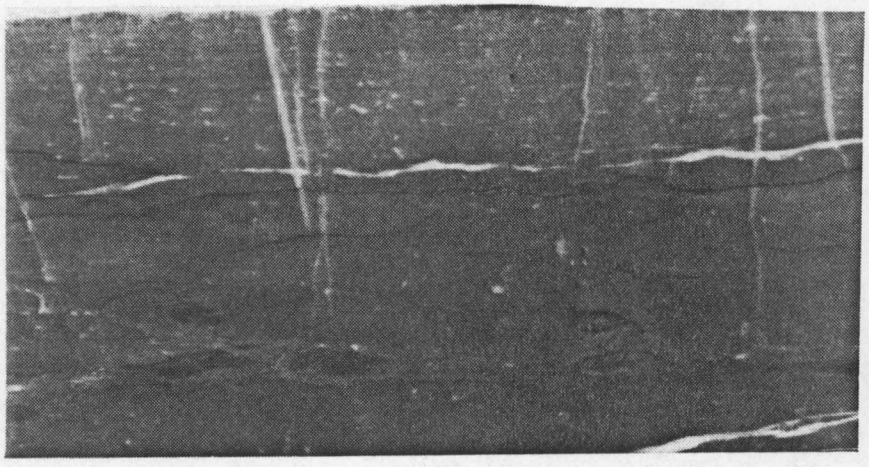


C



D

0 3cm



E

0 3cm

compressive stress. Thus, they represent a "sink" for the material removed during cleavage formation.

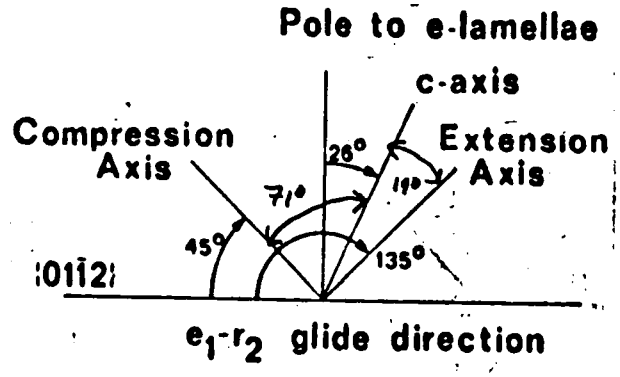
Another case of a non-characteristic vein occurs in one sample of the Moccasin Formation. The vein is filled with twinned calcite, but the calcite is grown around a nucleus of silt-sized quartz in the middle of the vein. Misik (1971) mentioned similar veins in limestones from eastern Europe. This is the only example of this type of vein filling which was observed. Its meaning is somewhat unclear. However, Ramsay and Huber (1983) discuss veins in which the material making up the veins has a different composition from the vein walls; these are termed antitaxial veins. They point out that the source of the differing vein filling is generally nearby. Because the Moccasin Formation is an impure limestone which contains quartz and also chert nodules, it is not difficult to identify a probable source for the vein nucleus.

The development of veins appears to be more pronounced in exposures which are folded or near faults. At these localities, the density of the veins is greater, and the number of vein sets is generally higher. Price (1967) noted that veins are unique kinematic indicators because they represent a locus of dilation and a direction of extension. In addition to this observation, the veins at least imply a large amount of pressure solution in the carbonates because there must be a process to account for the source of the vein filling minerals.

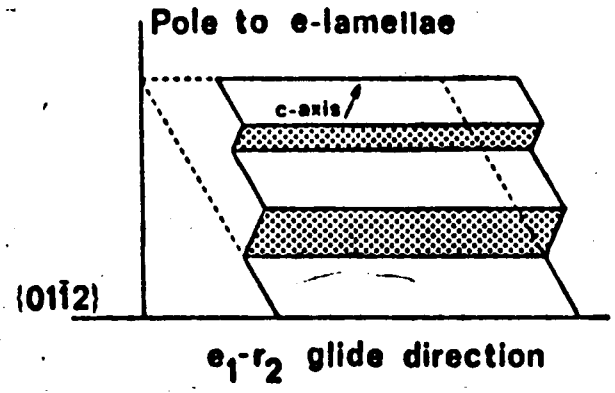
Calcite twins

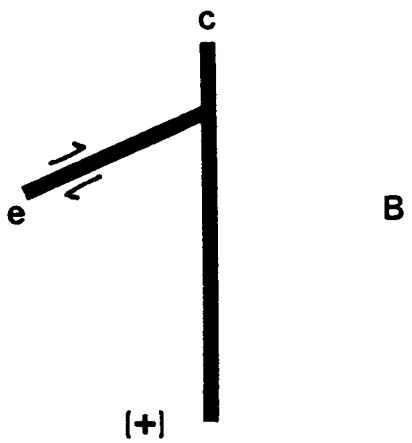
The coarser-grained limestones and the veins in the study area contain calcite grains which exhibit twin lamellae that are visible in thin-section. The lamellae are the result of twin gliding during deformation. Twinning is a type of simple shear which occurs on a given twin plane in a particular glide direction (Bell, 1941; Groshong, 1972). The directions are crystallographically controlled; for calcite the twin plane (e) is the {0112} direction, and the glide direction (g) is the intersection of e and r, where r is the {1011} direction. The crystal structure of calcite indicates that there are three e planes, hence three potential sets of twins (Turner and Weiss, 1963). The presence of twinning is identified by the twin lamellae, dark bands which are optically distinct under crossed nicols (see Groshong, 1974 and Appendix C).

Twinning can be visualized as a process of moving layers of atoms fixed fractions of integral atomic distances (Fig. 45a). The distance through which layers move is proportional to their distance from the twin plane, so shear strain is constant (Carter and Raleigh, 1969). Twinning in calcite is said to be in a positive sense because layers of the lattice are displaced upward toward the c-axis (Fig. 45b and Turner et al., 1954).



A





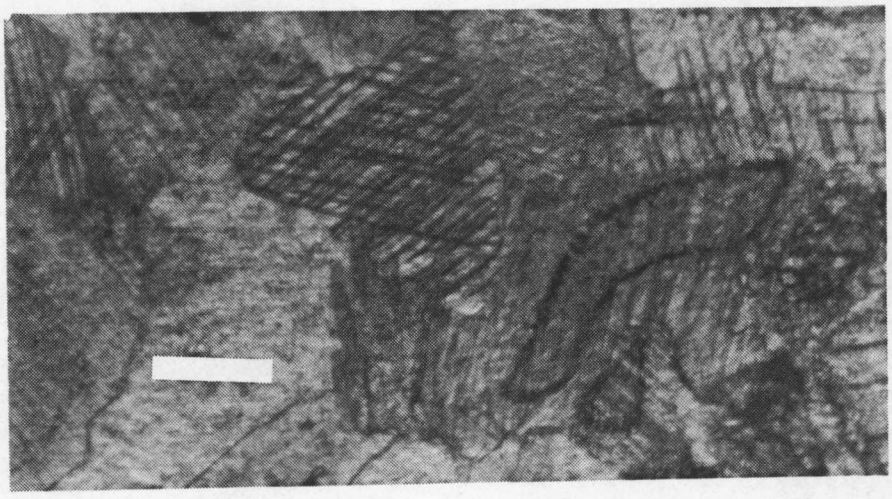
B

Figure 45. Twinning in calcite crystals. A) Drawing showing the angular relationships of crystallographic directions and the effect of twinning on the crystal. From Spang (1972). B) Sketch of positive shear sense in calcite twinning. Layers are sheared upward towards the optic axis.

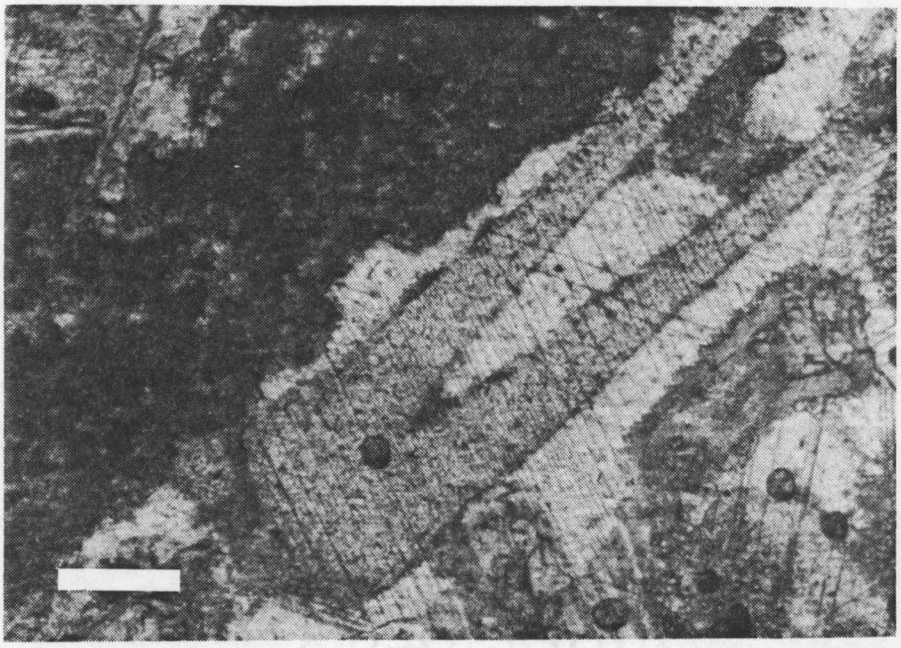
The twin lamellae from samples in the study area are usually found as two sets per grain (Fig. 46). Only in rare cases are one or three sets found. For example, in the nearly 100 twinned samples examined, one grain contained one set and two grains contained three sets. Curved twins were not observed; these are generally attributed to translation gliding in a crystallographic direction other than the twinning direction. Some samples were examined to determine finite strain from twinning; this will be discussed in another section of the chapter.

Breccia

Cataclasis is a deformation mechanism involving fracture and rigid-body rotation (Engelder, 1974), which contributes to faulting in the brittle regime. Its products are cataclasites and brecciated rocks. Brecciated carbonates are only found at two localities within the study area (Fig. 47); the rare occurrence is probably a function of erosion and not of absence. For example, brecciated Knox Group carbonates are exposed in the footwall of the Beaver Valley thrust in Crippen Gap, approximately 8.5 to 9.0 km southwest of the study area. Their presence suggests that cataclasis was an important part of the emplacement process along the Beaver Valley thrust, although it is not evident in the study area. Paul's (1986) work demonstrates the



A



B

Figure 46. Photomicrographs of twinning in calcite. A) Twinned grains from the Chickamauga Group. B) Twinned echinoderm fragment from the Rockdell Formation of the Chickamauga Group. The scale bar in each photomicrograph = 20 μm .

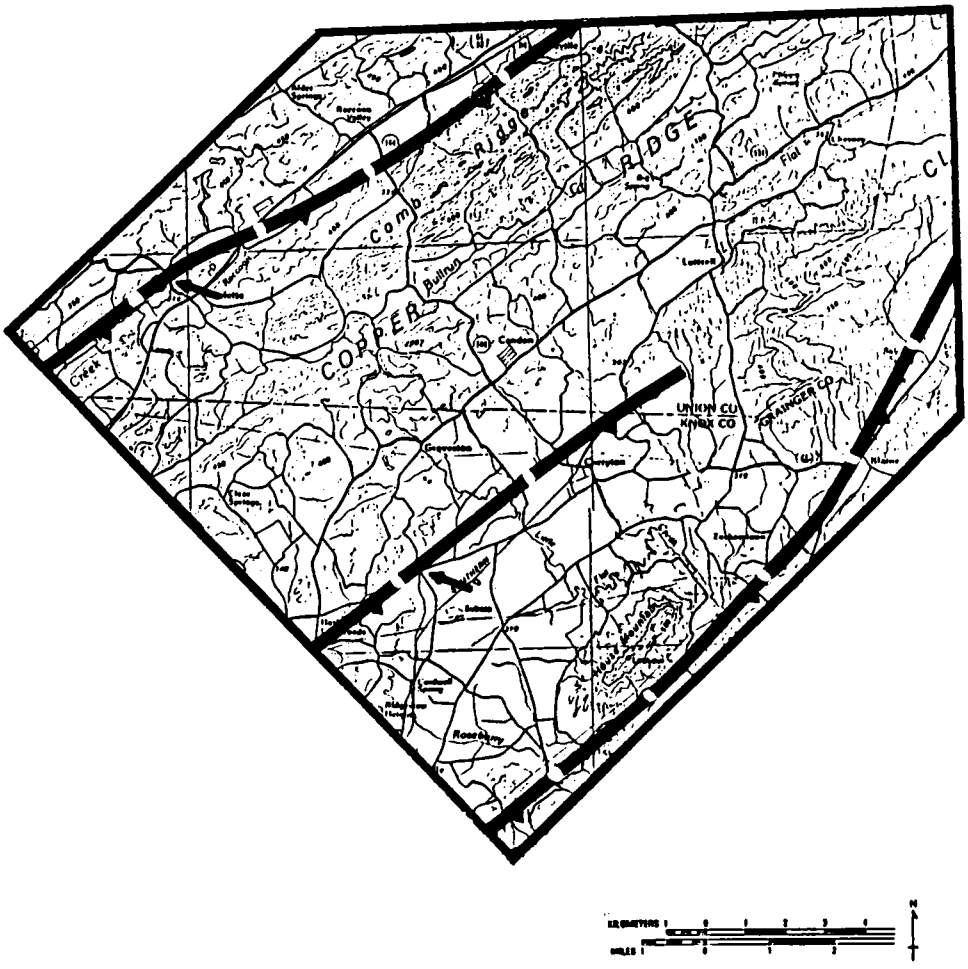
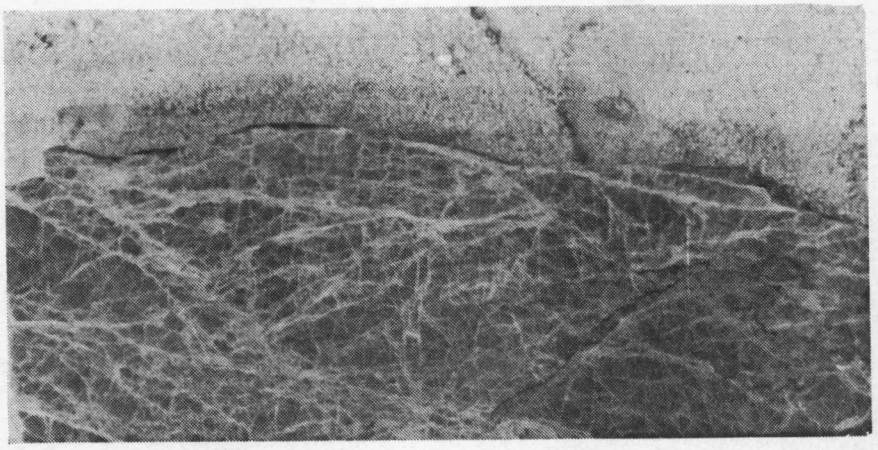


Figure 47. Map showing the location of exposures of breccia in the study area.

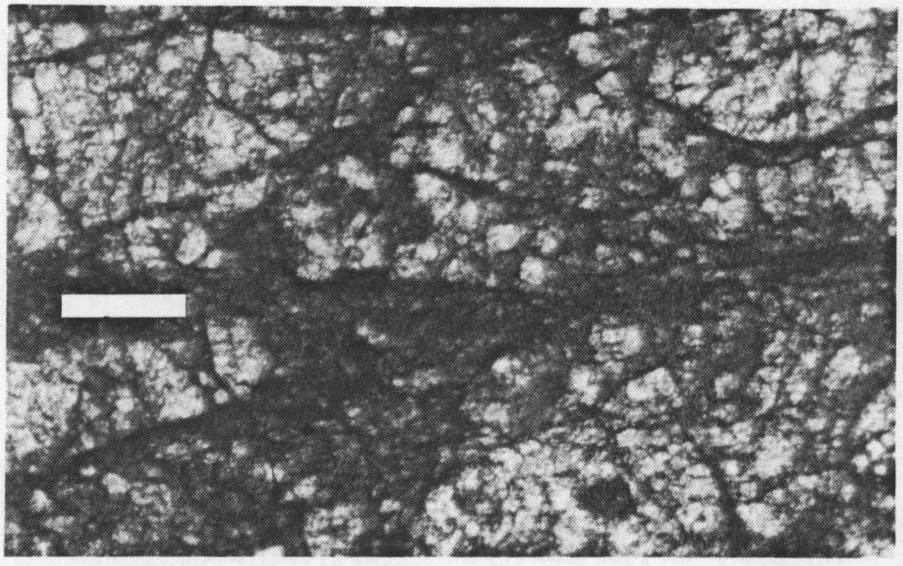
presence of cataclasites and brecciated rock along the Saltville thrust also, although none are exposed in the study area.

An exposure of the upper part of the Knox Group on Emory Road contains brecciated strata (Fig 48). The outcrop is assigned to the Mascot Dolostone because it is a light gray, fine-grained dolostone observed in complete exposures of the Mascot Dolostone along strike (Lutz, 1985). The rocks are highly fractured, with three fracture sets observable. The sets trend N20^{o}E, N70^{o}E, and N20^{o}W. The rocks from the outcrop also show a random fabric, consisting of particles which range in size from several mm to 1.5 cm (Fig. 48a). Stylolites cut the rock in an anastomosing and random manner and are up to 7 cm long. The amount of matrix reaches approximately 10% to 20%, making the rock a protocataclasite according to the fault rock classification of Sibson (1977; Fig. 48b). It appears that all clasts are from the Mascot and no other lithologies are incorporated; staining with alizurin red indicates that the interstices are filled with calcite. Sibson suggested that this type of fault rock suggests elastico-frictional behavior, with a "crush melange" developing as a result of faulting.

The Moccasin Formation is exposed in the footwall of the Copper Creek thrust along Route 61 near Paulette, Tennessee (see Appendix B, Stop 3). The fault plane is not exposed, but its location can be approximated within several



A



B

Figure 48. Photographs of brecciated Mascot Formation from the Beaver Valley thrust sheet. The rock is a protocataclasite. A) Slab photograph. B) Photomicrograph. Scale bar = 20 μm .

meters, based on foot wall and hanging wall pieces which are preserved. Samples of the Rome Formation clastics in the hanging wall are heavily fractured and contain microfaults and brecciation. The Moccasin from the footwall likewise shows brecciation (Fig. 49). The footwall carbonates are highly fractured, but are not broken up into small pieces; the clasts are generally large and are separated by solution seams. Faults, showing offsets of mm, are also developed. Several patches of white calcite, which may have originally been veins appear broken and rotated. A few narrow veins (less than 1 mm wide) are truncated and offset by solution seams. The amount of matrix is less than 10 %, therefore the rock is a crush breccia (Sibson, 1977). This type of rock is also suggestive of elastico-frictional behavior (Sibson, 1977).

Despite the scarcity of outcrops which contain brecciated carbonates, the two exposures suggest cataclasis was an important deformation mechanism during fault emplacement. Many other exposures outside the study area exhibit the development of cataclasites and brecciated rocks in carbonates including: the Saltville thrust at Sharp Gap (Paul, 1986), the Beaver Valley thrust in Crippen Gap, and the Copper Creek thrust in Diggs Gap (Wojtal, 1986). It seems certain that with better exposures in the study area similar pronounced zones of cataclasis would be observed. In addition, it is possible that within some

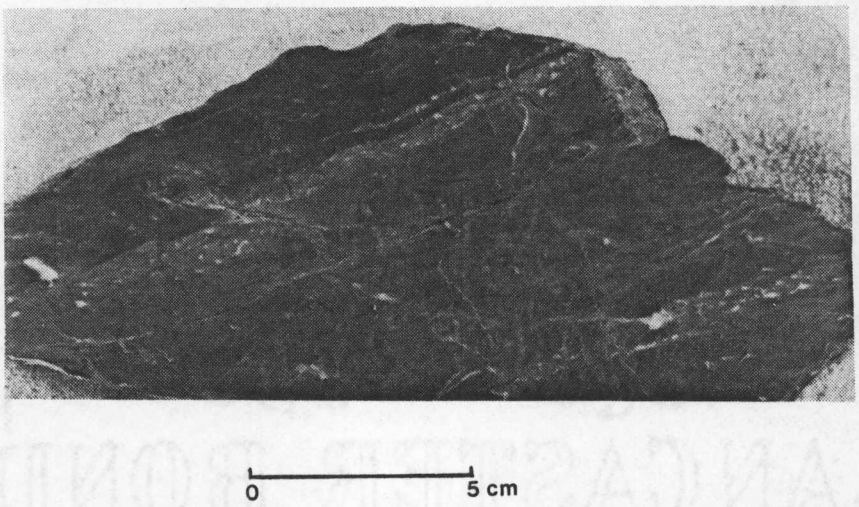


Figure 49. Slab photograph of crush breccia from the Moccasin Formation. Sample is from the fault zone of the Copper Creek thrust along Tennessee Route 61 (see Stop 3, Appendix B).

areas on the thrust plane, cataclasites never form.

Bedding slip surfaces

Polished and slickensided bedding surfaces are indicators of bedding plane slip. Although not widely found across the study area, these features, particularly polished surfaces are found. The best exposure of these is in a quarry at Paulette, Tennessee. The quarry is in the Maryville Limestone, although the overlying Nolichucky Shale is exposed at the surface and visible at the top of the quarry. Structurally, the quarry is situated in the axial region of the Texas Valley syncline, and the beds are dipping very gently (up to 5 ^{o}) to the south-southwest. Within the quarry bedding surfaces both in and out of place reveal polishing (Fig. 50). The bedding planes are quite smooth and dark gray to black in color.

Other localities within the study area show polishing, particularly in the Texas Valley anticline and syncline. Bedding slip is characteristic of flexural slip as the mechanism of folding (Donath and Parker, 1964). The presence of polished bedding surfaces supports the interpretation that the Texas Valley folds formed by flexural slip folding. The Copper Creek thrust was a passive marker and folded similarly.

An exposure of folds in the Rutledge Formation



Figure 50. Bedding slip surface (the top surface of the large block of rock above the hammer) in the Maryville Formation. The surface is dark gray and black in color and very smooth, indicating that it was an active slip surface during folding. Sample locality is a quarry just south of Paulette, TN on Tennessee Route 33.

(Appendix B, Stop 5) also exhibits polishing and fibers on bedding surfaces suggestive of flexural slip folding. In portions of the study area where the rocks are uniformly tilted, polished bedding surfaces are not observed. Likewise, they are not seen in the Middle Ordovician carbonates near the tip of the Beaver Valley thrust. Nevertheless, bedding plane slip was an active deformation mechanism in at least a part of the area.

3. DISTRIBUTION OF DEFORMATION FEATURES

The deformation features present in the study area appear to vary in abundance and distribution across the study area. The distribution suggests a subdivision into two strain domains: strata in a thrust zone or within several tens of m of it, and strata within the thrust sheet. To clarify this subdivision and to depict variation in abundance, the deformational features are plotted from locations along the cross-sections (Figs. 51 - 53). The locations are either outcrop coincident with the cross-section lines, or are outcrops projected from nearby. Deformation features in the Rome Formation are shown for several localities for comparison with the carbonates and for completeness.

Figure 51. Cross-section A-A' and a table of deformation features showing the distribution of these features across the study area. a = abundant, c = common, r = rare, - = absent.

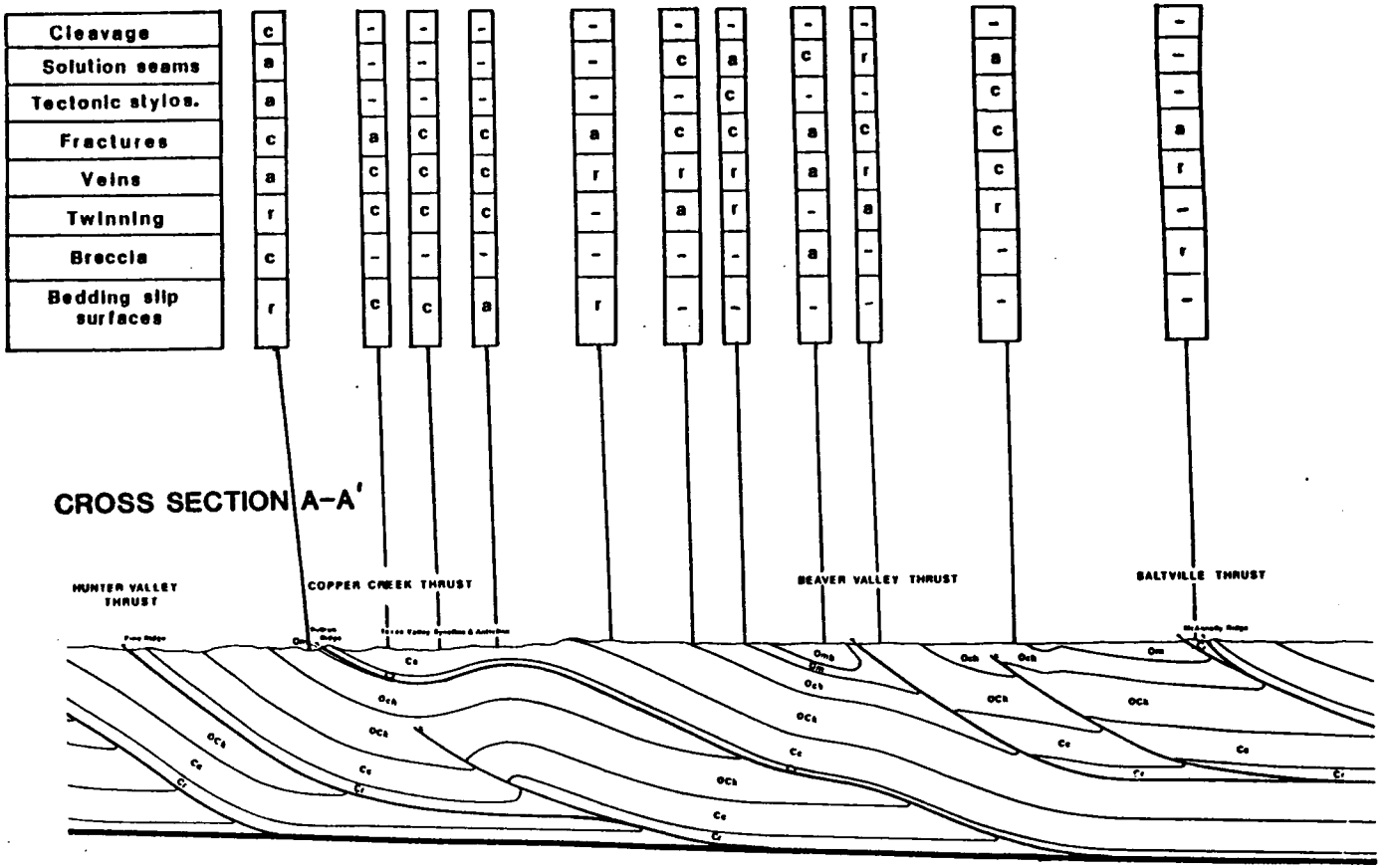

Cleavage
Solution seams
Tectonic stylos.
Fractures
Veins
Twinning
Breccia
Bedding slip surfaces
CROSS SECTION A-A'
HUNTER VALLEY THRUST
COPPER CREEK THRUST
BEAVER VALLEY THRUST
SALTVILLE THRUST

Figure 52. Cross-section B-B' and a table of deformation features showing the distribution of these features across the study area. a = abundant, c = common, r = rare, - = absent.

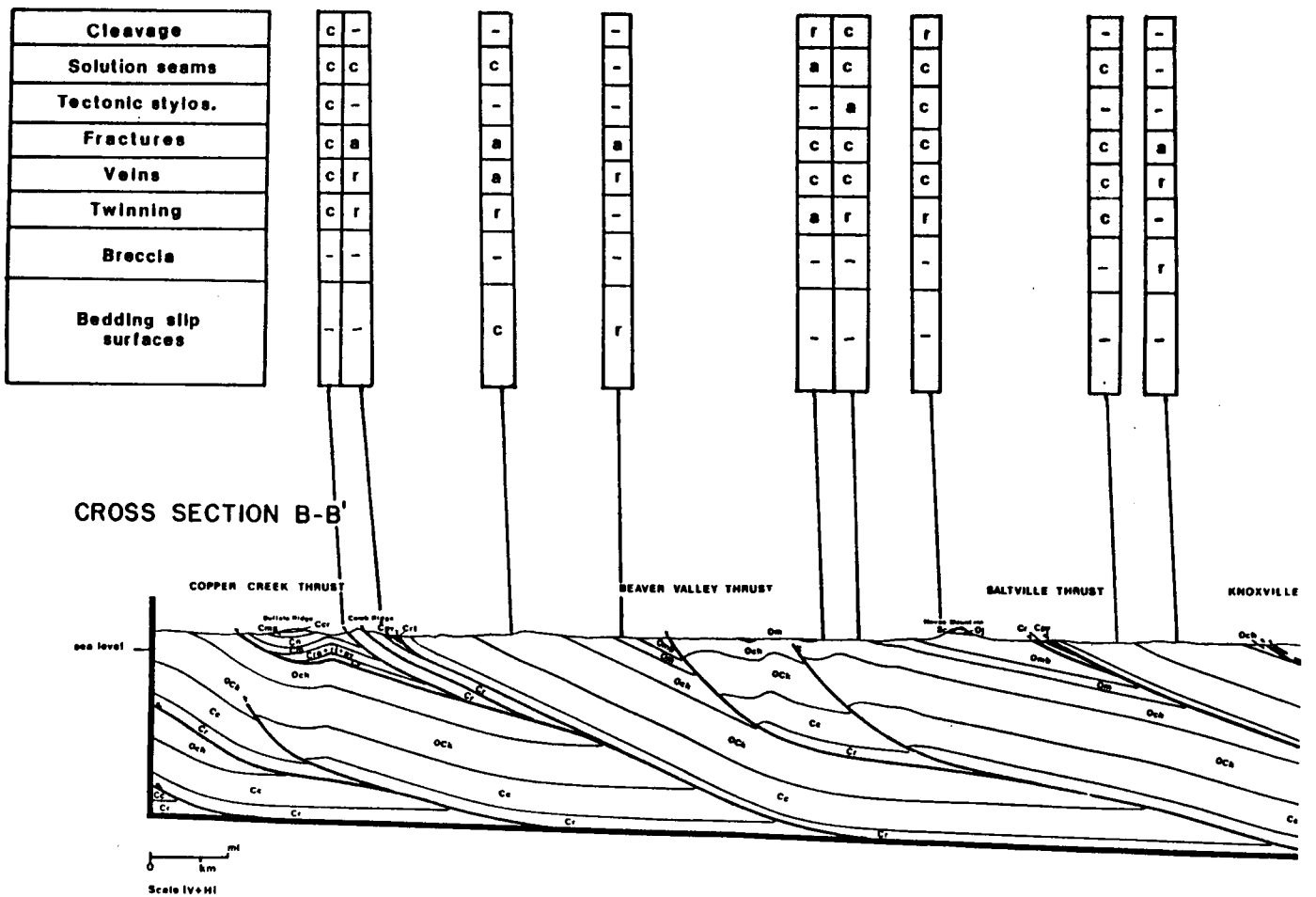
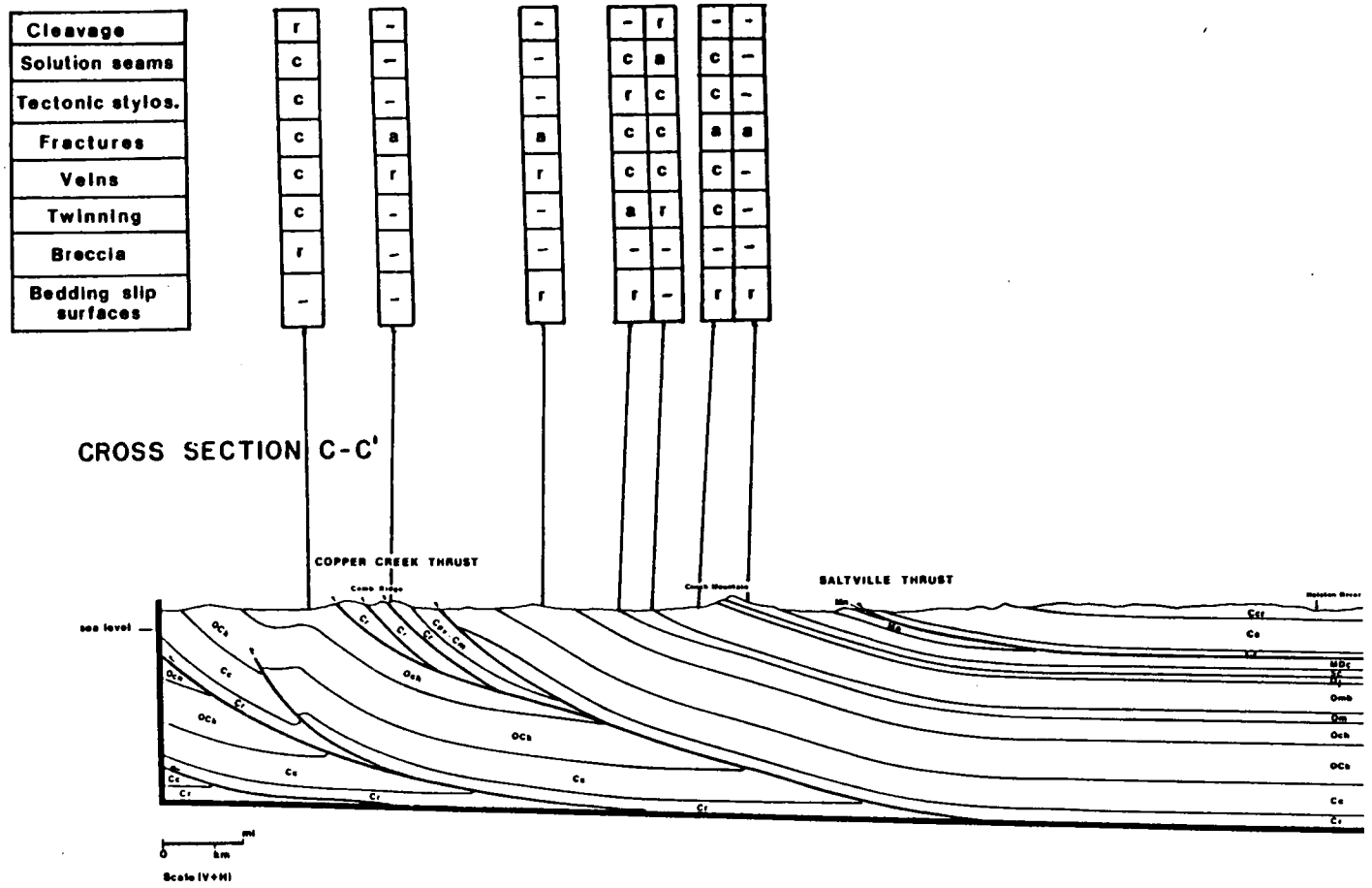

Cleavage
Solution seams
Tectonic stylos.
Fractures
Veins
Twinning
Breccia
Bedding slip surfaces
CROSS SECTION B-B'
COPPER CREEK THRUST
BEAVER VALLEY THRUST
SALTVILLE THRUST
KNOXVILLE
sea level
mi
km
Scale IV=HI

Figure 53. Cross-section C-C' and a table of deformation features showing the distribution of these features across the study area. a = abundant, c = common, r = rare, - = absent.


Cleavage
Solution seams
Tectonic stylos.
Fractures
Veins
Twinning
Breccia
Bedding slip surfaces
CROSS SECTION C-C'
COPPER CREEK THRUST
SALTVILLE THRUST
sea level
Scale (V=H)

The distinction between "rare," "common," and "abundant" is not quantitative and is based on outcrop, slab, and thin-section examination. Rare indicates that the feature is found in approximately 10 % or less of the exposure. Common indicates that the feature is uniformly developed across the exposure and is moderately intense. Finally, abundant indicates that the feature is found throughout the exposure and is intensely developed.

Examination of the diagrams indicates several characteristics of the distribution of the deformation features. In both domains, brittle deformation dominates, but the thrust zone rocks exhibit much more severe deformation. This observation supports Wojtal's (1982, 1986) argument that the bulk of the strain necessary to emplace a thrust sheet occurs in brecciated and faulted zones adjacent to the main thrust. Cataclasis, at both a microscopic and mesoscopic scale, is found at several localities and includes both carbonates--generally from the footwall--and non-carbonates derived from the Rome Formation. Near fault, locations at which breccia is absent are believed to result from non-preservation, rather than lack of development.

Cleavage is also found either near faults or in the intensely folded strata of the Beaver Valley thrust sheet. Carbonate lithology, as well as structural position, control its development. For example, cleavage is best developed in

the argillaceous Moccasin Formation and is either poorly developed or "incipient" in the lower and middle Chickamauga Group beds which are purer carbonates. Solution seams are at least common in all the limestones at all localities, and these are more abundant closer to faults and in the Moccasin Formation. Tectonic sylolites show approximately the same distribution as cleavage.

Fractures and veins are ubiquitous (except for one location in the Clinch Sandstone on Clinch Mountain; no veins were observed) but there does not appear to be any systematic trend related to structural position. It is interesting to note that fractures are the most abundant feature in the dolostones of the Knox Group. Exposures of these strata show very few features.

Intracrystalline plasticity, in the form of twinning, is ubitquitous in limestones. Its abundance, however is controlled by carbonate lithology. In coarse grained, pure carbonates it is found in all sparry grains. In argillaceous limestones, sparry grains which fill veins are commonly twinned, as are sparry grains scattered throughout the rock. Some dolostones of the Knox Group probably exhibit dolomite twinning but samples of these were not examined.

Bedding slip surfaces are not widely exposed and were only found in the Copper Creek thrust sheet. The absence of these surfaces is probably due to non-preservation rather

than original absence. Given the fairly low temperatures and pressures during deformation in this area (discussed later in the chapter) flexural slip folding and layer parallel shortening are probably the processes responsible for folding and tilting beds within the thrust sheets. Bedding slip would be expected (Price, 1967). In the study area, bedding slip surfaces are best developed in the Texas Valley anticline and syncline.

4. STRAIN IN TWINNED CALCITES

Calculation of finite strain requires markers of known initial shape, length, or angle. Fossils or initially spherical objects such as ooids are particularly useful. Cloos' (1947) study of deformed ooids from South Mountain, Maryland was the first thorough and systematic regional strain analysis, and set the stage for the developments of the past several decades. Ramsay (1967) and Ramsay and Huber (1983) review the most commonly employed techniques and document many of the important studies.

A significant shortcoming of strain analysis is that many rocks do not contain markers of known initial shape, length, or angle. In many cases, one can document the various mechanisms responsible for total strain, but not its value. Thus, nothing more than an qualitative examination of strain is possible in numerous deformed zones.

A solution to this problem exists for many marbles and limestone. Calcite has long been known to deform by intracrystalline twinning at very low temperatures and pressures; the critical shearing stress necessary is quite low (Carter, 1976). These mechanical twins are not to be confused with growth twins or traces of cleavage planes; laboratory experiments of clearly untwinned specimens indicate twinning results from deformation. Universal stage analyses of naturally deformed rocks indicate that natural deformation twinning is crystallographically identical to the twins in experimentally deformed rocks.

The first significant work on calcite crystals was by Griggs (1938). He concluded that the direction of twinning must be those of highest resolved shear stress. Additional work on single calcite crystals (Turner et al., 1954) demonstrated the presence of other deformation mechanisms, but twinning was deemed dominant, at least over the temperature range 20° C to 300° C. Experimental deformation of calcite aggregates, most notably Yule Marble and Solenhofen Limestone, also indicated the dominance of twinning as a deformation mechanism, even up to 600° C (Griggs and Miller, 1951; Turner and Ch'ih, 1951; Griggs et al., 1951; Griggs et al., 1953; Turner et al., 1956; Barber and Wenk, 1973; Wenk et al., 1973). At higher temperatures (600° C to 1000° C) twinning is less dominant or absent, and

the rocks commonly exhibit "superplastic" behavior (Heard and Raleigh, 1972; Schmid, 1976; Schmid et al., 1977).

Sets of twin lamellae cannot extend beyond grain boundaries. Therefore, because twins end at grain boundaries, they only accomodate strain within the interior of a grain (Schmid, 1972a). Each grain is restricted by neighboring grains, so every grain suffers the same strain as the surrounding material, resulting in a "homogeneous" deformation (Handin and Griggs, 1951). Thus, twinned calcite is an excellent strain marker of the limestone or marble in which it is found; initial shape is known from calcite crystal structure and the deformed shape is measured.

The use of twinned limestones and marbles to infer stresses and strains associated with deformation started with the "dynamic analysis" of Turner (1953). His technique involved determination of the axes of compression and extension from known angular and crystallographic relationships. Orientations came from stereonet plots of universal stage data, which could then be related to bedding. Subsequent to Turner's work, several other approaches to inferring stress were developed (e.g., Spang, 1972; Friedman and Heard, 1974; Jamison and Spang, 1976). The use of twins to determine finite strain was not addressed in detail until the work of Conel (1962). Groshong (1972) investigated the problem farther, and

formalized a technique of strain analysis using calcite twins. Spang (1974) and Chapple and Spang (1974) presented an extension of Spang's (1972) dynamic analysis which included strain calculation also.

The strain gage technique of Groshong is an expansion of the earlier work by Conel, and it follows from the idea that a twinned calcite grain is interpretable as an internal strain gage. The basis of the calculation is the equation (from Conel):

$$\Gamma_{eg} = \frac{0.347}{t} \sum_{i=1}^{n} t_i$$

where Γ_{eg} is the tensor shear strain of originally perpendicular lines parallel to the e and g directions, t is the width of the grain perpendicular to the twin plane, t_i is the thickness of an individual lamella, and n is the total number of twin lamellae. The value 0.347 is from 1/2 tan Ψ where Ψ is the angular shear for calcite twinning, fixed at 38^{o} 17'. The equation shows that the magnitude of the tensor shear strain is a function of the thickness of the twinned portion of the grain. Each twin set yields an equation for tensor shear strain in six unknowns, which are components of the finite strain tensor. Calcite twinning is volume constant, so the ε_z component of the strain tensor is dropped. leaving five unknowns. A least-squares solution of at least five strain gage equations gives the value of total strain. Groshong pointed out that strain analysis by the

technique is appropriate for rocks strain from < 1 % to approximately 17 %. The upper limit is based on the assumption that each grain is no more than half twinned (this is explained in detail in Groshong, 1972).

Spang (1972, 1974) presented a numerical version of the dynamic analysis of calcite twin lamellae originally proposed by Turner (1953). Spang (1972) assumed that each twin set represented the same amount of strain. He calculated stress tensors, one for each twin set which were then added together and divided by the number of twin sets to form the "bulk stress tensor." The principal axes of the stress ellipsoid and their orientations are determined by taking eigenvectors and eigenvalues of this tensor. the axes of extension (E) and compression (C) are then rotated into thin-section coordinates. Spang (1974) pointed out that the E and C axes from the dynamic analysis are equivalent to the principal axes of infintesimal strain for simple shear represented by a twin set. He took the tensor shear strain, $\gamma = \frac{1}{2}\tan\Psi$, from each twin set and transformed it into principal axes of infintesimal strain.

Strains are determined here using Spang's technique. The principal stress axes are used as principal strain axes because they are parallel to the principal strain axes within error for the numerical dynamic calculation (Spang, 1974; Groshong, pers. comm. 1987). The amount of strain from a sample is an average of the ten highest values of the

tensor shear strain (minus any unusually high values) from each thin section. This is the same way Spang calculated strain, but the transformation into principal axes of infintesimal strain is omitted. According to Groshong (pers. comm., 1987), this value is an acceptable measure of twinning strain. He mentioned that his unpublished work verifies this.

Groshong's strain gage technique was tried also. The University of Tennessee computer, however, would not calculate the strain matrix or principal strain magnitudes and orientations correctly. Extensive trouble shooting and a double-precision version of the program failed to resolve the problem.

Nine thin-sections were used for strain calculations; these are taken from five samples, which are from localities both within thrust sheets and near thrusts (Fig. 54). From these thin-sections, 306 twin sets and 7708 individual twin lamellae were recorded. Standard universal stage techniques were employed in the analysis. A thorough treatment of the universal stage and techniques for its use are found in Emmons (1943), Turner and Weiss (1963, p. 197-199; p. 237-244), and Kerr (1977).

Two additional comments must be made. With respect to sample orientation, samples labelled "A" are parallel to strike direction and samples labelled "B" are parallel to dip direction (Fig. 55). In all cases, the top of the

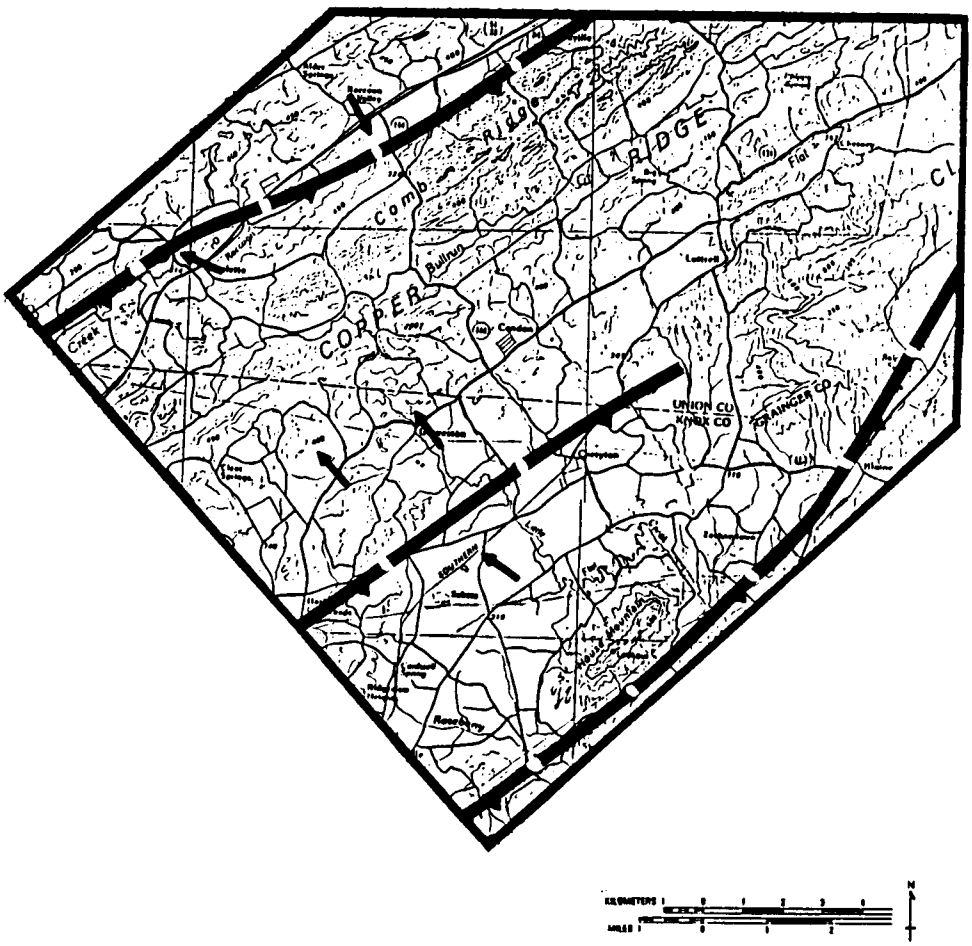


Figure 54. Map showing the location of samples used to calculate strain from twinned calcite.

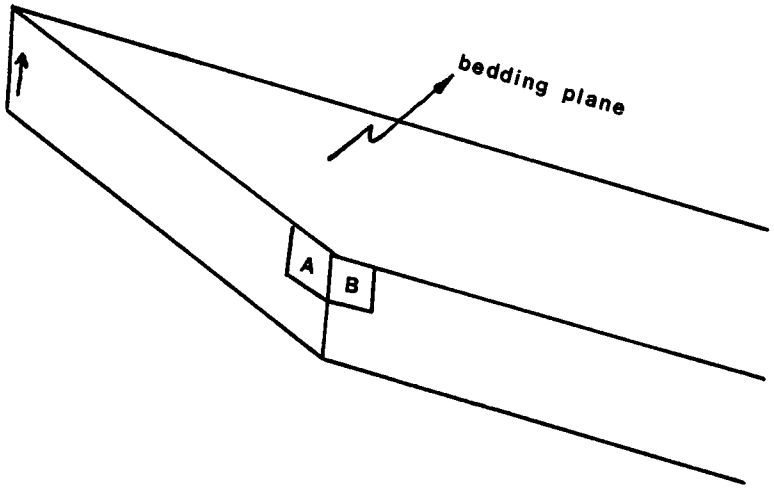


Figure 55. Sketch showing the orientation of all thin-sections used in the strain analysis, relative to bedding. "A" is the strike section and "B" is the dip section.

slide is the stratigraphic up orientation. The stereonets showing principal directions are in the "B' plane, therefore bedding is the horizontal line because the top and bottom of the thin-section is parallel to bedding. This depiction of the principal strains with respect to bedding is similar to that used by Spang and Groshong (1981). All orientation data was measured on a Leitz four-axis universal stage. Information on universal stage procedure and a copy of the computer program used in the study are in Appendix C.

The strains calculated from the samples ranges from 0.8 % to 4.7 %, however, most of the samples range from 2.2 % to 3.9 % (Fig. 56). The extreme high and low values may be inaccurate. The low value is not fully accurate because an inadequate number of twin lamellae were measured in this sample. The high value is not a useful number because several of the top ten shear strains were unusually high. Ommission of the high values lowers the strain to 3.4 %. The high and low values may also be the result of non-systematic variations larger than observational error such as have been found in other twin studies (Chapple and Spang, 1974).

Two observations concerning the strains are important. First, for thin-sections from the same sample, a low degree of strain variation exists between the two sections. The difference in magnitude is within one percent. This suggests that the twinning strain affected the rocks

THIN-SECTION	STRAIN
D2A	2.3%
D2B	2.9%
11A	3.9%
11B	3.2%
16A	3.7%
16B	3.7%
GR131A	2.9%
GR131B	3.4%
D3A	0.8%

Figure 56. Strain values calculated from twinned limestones in the study area.

uniformly in three dimensions. Second, the strain from samples near faults and samples within the thrust sheets are not significantly different. For example, sample 11 is from a footwall exposure of the Moccasin Formation, less than 100 m from the Copper Creek thrust. Twinning strain is 3.2 % and 3.9 %. On the other hand, sample D2 is from the Rockdell Formation (Middle Chickamauga Group) in the middle of the Copper Creek thrust sheet. The stratigraphic position of the Rockdell Formation is approximately 1.8 km above the Copper Creek fault plane. Twinning strain from this sample is 2.3 % and 2.9 %, a difference of one per cent or less compared to sample 11. This is an insignificant difference compared to the very different structural positions of the two localities.

Principal strain orientations are taken from the Spang calculation of principal stress directions. A direction of compression in or close to bedding, and extension at a high angle to bedding are indicated (c.f. Groshong, 1975; Spang and Groshong, 1981) (Fig. 57). The orientations generally conform to most twinning strain studies. Sample D3 is an exception, and this may again be related to the small number of grains measured. Orientations of principal directions are shown for both the "A" and for these values rotated into the "B" plane. The orientations of strain do not appear to change their relationship to bedding with structural position. Compression is in bedding and

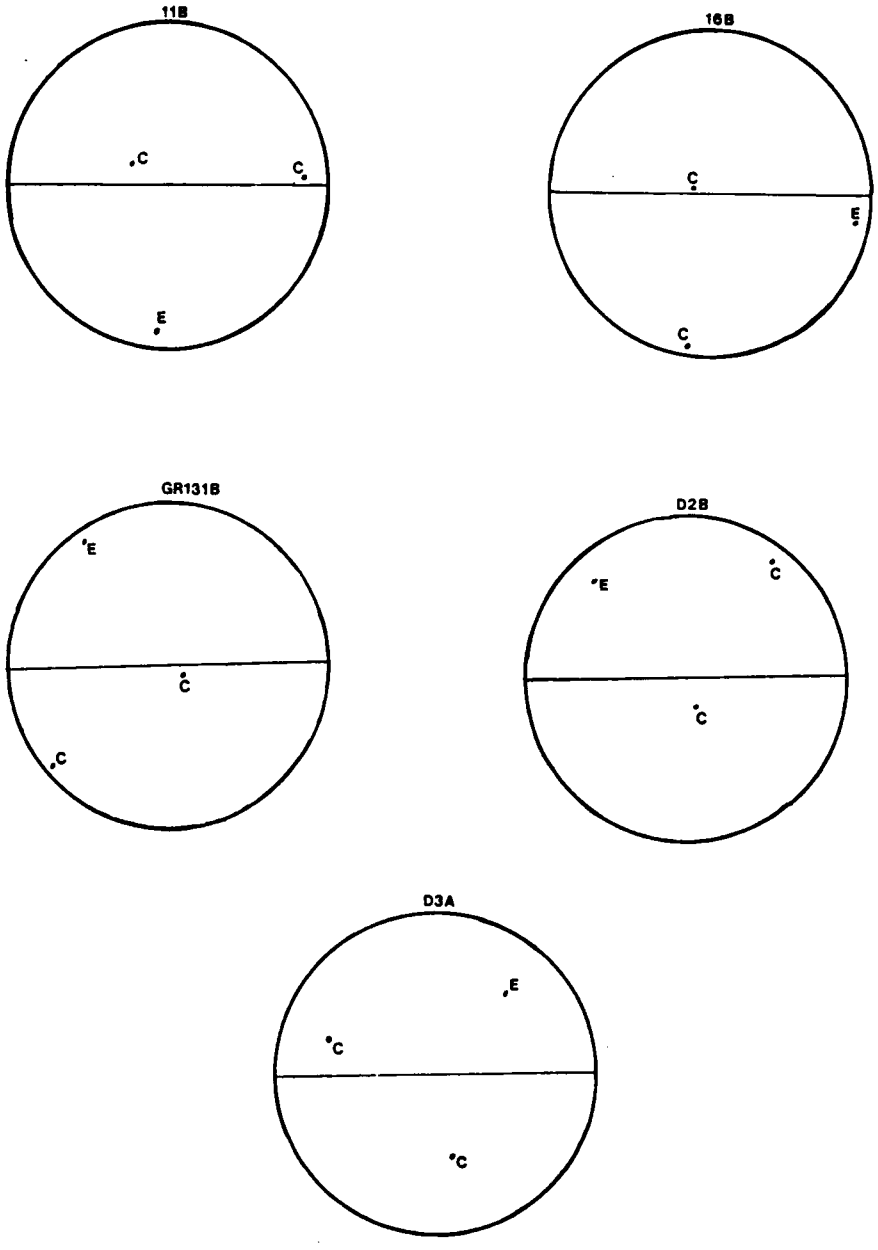


Figure 57. Stereonets showing the orientations of the principal strains calculated the strain analysis of twinned limestone. Note that the trends are similar for nearly all the samples: compression in bedding or close to it, and extension at a high angle to bedding.

therefore down the dip of the strata. A comparison of sample 11 with sample GR131 illustrates this well.

The critical resolved shear stress necessary for twinning is low, and the twinning probably occurs early in the deformation and a value of "finite strain" is locked into the grain. Thus, the likelihood that the twinning strains will show significant changes in either orientation or value with position in the thrust sheets is highly unlikely. The strains are small enough and occur early enough that it is virtually independant of structural position. The results from strain calculations confirm this.

The twinning strains appear to be areally consistent and uniform with respect to both their magnitudes and orientations. Structural position does not seem to affect either aspect of the strain. It can be concluded therefore, that twinning is a noticeable component of the strain but is an early and small contributor to the total strain. The twinning probably occurred in an initial stage of deformation, consisting of layer parallel shortening or buckling.

This conclusion contrasts with several other studies of twinning strain which attribute a greater degree of importance to it as a deformation mechanism (Chapple and Spang, 1974; Groshong, 1975; Engelder, 1979; Spang and Groshong, 1981; Wiltschko et al., 1985). The conclusion here does not suggest that these studies are wrong. Rather,

there is a problem of scale involved (Schwerdtner, 1973). In contrast with this study area, the locations examined in the other studies were either an outcrop, a fold smaller than map scale, or the relatively undeformed foreland. Groshong et al. (1984) studied localities across a rather large and complexly deformed area in the Alps, however the twinning strain was viewed as a component of strain in the carbonates, with an emphasis on changing deformation mechanisms rather than on its importance as part of total strain across the structures.

In the context of an outcrop or fold, twinning strain is important. At the scale of a bed or at grain-scale, twinning is an obvious and noticeable part of the total strain. This "finite" strain however is only a small percentage of the total strain in the thrust sheets.

5. DISCUSSION

Deformation features in the carbonates in the study area include cleavage, stylolites and solution seams, fractures, veins, twinning, brecciated rocks, and polished surfaces. Penetrative fabric is essentially absent; many of the rocks are practically undeformed sedimentary strata. Price (1967) noted that the principal fabric elements in the Southern Rocky Mountains of Canada were fractures, and a similar conclusion is drawn from the rocks in the study

area; at many outcrops, fractures and bedding parallel stylolites are the only features. The features can roughly be divided into two domains: areas within the thrust sheets and areas in or near to fault zones. Despite the wide array of deformation features, the total strain recorded in the carbonates is generally small, probably less than 10 %. Strata adjacent to faults may record somewhat higher strains, but this is only locally observed.

In general, these features are reflective of "low" temperatures and pressures during deformation. A way of estimating probable temperatures and pressures during deformation is to reconstruct the eroded stratigraphy assumed to be present at the time of deformation, and, using a "normal" gradient calculate temperature and pressure. Roeder et al (1978) suggest a temperature gradient of 25 ^{o} C/km; they do not give a gradient for pressure. Groshong (1975) used Gulf Coast temperature and pressure gradients, taken from the literature. The pressure gradient assumes water saturated sediment. Extrapolation from his estimates suggests a pressure gradient of 120 bars/km. Temperatures and pressures are calculated for three stratigaphic horizons: the Moccasin Formation, the lower and middle Chickamauga Group, and the Conasauga Group; these are the horizons from which the samples came. Maximum stratigraphic thicknesses for strata above the Newman Limestone are from Hardeman (1966).

Estimated temperatures range from approximately 77° C to 130° C, and pressures from 372 to 624 bars (Fig. 58). Neither range contains particularly high values. Temperatures inferred from conodont studies likewise suggest low temperatures. Epstein et al (1977) present conodont alteration index (CAI) values of 2 (northwest) to 3 (southeast) from the Valley and Ridge (their figure 15), around the study area. This corresponds to a maximum temperature range of 60° to 200° C, with the values overlapping in the range 110° to 140° c. The temperature and pressure effects of loading from thrust sheets was not calculated.

Deformation mechanism maps (Ashby, 1972) are another means by which conditions of deformation can be estimated. Assuming geologic strain rates of 10^{-10} to 10^{-15} per second (Schmid, 1982b) for the range of temperatures estimated, pressure solution, Coble creep, or some form of dislocation movement is predicted (Fig. 59). The twinning and various pressure solution features confirm this. Other deformational features, particularly brecciation and fracturing, would not appear on the map because these are not thermally activated, therefore they are not dependant on temperature or strain rate (Schmid, 1982b). However Pfiffner and Ramsay (1983) argue that fault rocks, such as mylonite zones are simply reflective of strain rates faster

TEMPERATURE (°C)	PRESSURE (BARS)	STRATIGRAPHIC HORIZON
77.5	372	Top of the Moccasin Formation
82.5	396	Bottom of the Moccasin Formation
82.5	396	Top of the Chickamauga Group
92.5	444	Bottom of the Chickamauga Group
112	540	Top of the Conasauga Group
130	624	Bottom of the Conasauga Group

Figure 58. Temperature and pressure estimates for several structurally important stratigraphic horizons. The range of values indicates deformation under very low temperature, low pressure conditions. The gradients used are explained in the text.

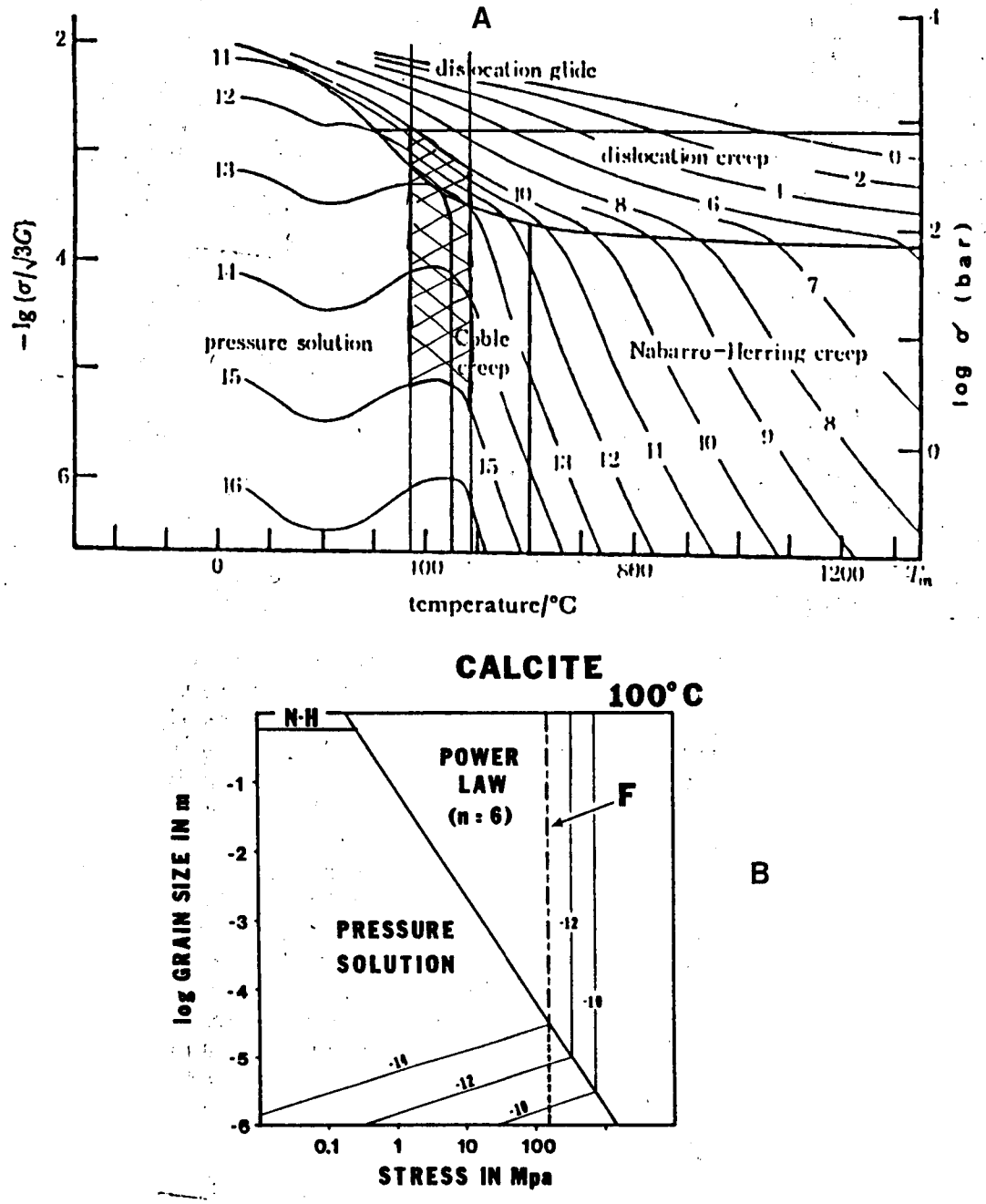


Figure 59. Deformation mechanism maps for calcite. A) Map from Rutter (1976). Hatched area includes estimated temperatures from the study area. B) Map from Wojtal and Mitra (1986) at 100° C. This map illustrates the deformation mechanisms seen in the study area for various grain sizes.

than 10^{-13} , with most moderate strains corresponding to strain rates in the interval 10^{-13} to 10^{-15}.

In contrast to strain indicated by the carbonates, the balanced cross-sections constructed for the area (Chapter 2) indicate 40 % to 50 % shortening. Obviously, there is a gap between the strain in the carbonates and the total strain across the area. Shortening values of 40 % to 50 % do not necessarily suggest that high a percentage of strain, but they do suggest more than is recorded in the carbonates. This gap means that the major mechanism of strain probably was macro-scale faulting and the buckling associated with map-scale folds. The rocks dominantly suffered brittle deformation at the scale of the thrust sheets. Movement along the fault planes and associated shortening accounts for most of the strain. The buckling of the Texas Valley anticline and syncline when folded by a lower thrust and the folding at the end of the Beaver Valley sheet also record major strains.

The deformational features in the carbonates are important because they demonstrate how the strain was accomodated during deformation. They also provide evidence from which conditions of deformation may be inferred. With the possible exception of the brecciated rocks however, the contribution these features made to the development of major structures in the study area was small. This conclusion

points out the need to integrate studies of meso- and/or microstructures with macrostructures.

6. CONCLUSIONS

1) The deformation features recorded in carbonates in the study area include cleavage, stylolites and solution seams, fractures, veins, twins, breccia, bedding slip surfaces.

2) Cleavage and brecciated/cataclastic rocks are only present in areas in or within several 10's of m of a fault zone.

3) Fractures are the most commonly developed feature. They are ubiquitous and generally at a high angle to bedding. The trend of the fractures indicates some scatter and a well-defined conjugate set. The dihedral angle between the "mean" orientation of the two sets is 46^{o}. Based on criteria outlined in Hancock (1985), the fractures are probably hybrid, containing an extension and shear component.

4) Veins vaary in intensity of development, but the trend of veins appears to coincide with fracture trends. Therefore, these features likely represent "healed" fractures. The veins commonly cut bedding at a steep angle, are commonly

filled with twinned sparry calcite, and are generally less than 1 cm wide.

5) Two domains are suggested by the distribution of deformational features: areas within the thrust sheet, and areas within 100 m of a thrust. Although seemingly simplistic, this bipartate subdivision is the only one which appropriately characterizes the rocks. Within each domain, the abundance of features is additionally controlled by carbonate lithology.

5) Twinning strains, calculated by a combination of the Spang (1972, 1974) and Groshong (1972) techniques are low. Strains do not exceed 5 %, and most are less. No significant variation in either magnitude or orientation with structural position are observed.

6) Temperatures and pressures of deformation are estimated by calculating effects of overburden, values of conodont alteration index (CAI) from the study area, and deformation mechanism maps. In general temperatures probably were between 100^{o} and 150^{o} C, with possible ranges of 60^{o} to 200^{o} C. Estimated pressures range from 0.37 to 0.62 kb.

7) Deformation mechanism maps for calcite indicate good agreement between the deformational features observed in the

study area and the temperatures and pressures estimated from overburden and conodont alteration index (CAI).

8) The deformational features and strain data suggest that the total strain recorded in the carbonates generally does not exceed 10 %, except for local variation seen in fault rocks.

9) A gap exists between total strain in the carbonates and total shortening indicated by balanced cross-sections across the study area. The interpretation of this is that, although many deformational features are present in the carbonates, they contribute very little to the total strain at the scale of the thrust sheets. Most of the strain occurred along fault planes or through buckling associated with map scale folds (e.g., the Texas Valley anticline and syncline). The dominant mode of deformation, therefore was brittle failure, at fairly low temperatures and pressures.

CHAPTER 5

SUMMARY AND CONCLUSIONS

The Beaver Valley - Saltville transfer zone is located in the Valley and Ridge of East Tennessee, immediately north and northeast of Knoxville, TN. Within this area, three regionally significant thrusts of the Southern Appalachians, the Copper Creek, the Beaver Valley, and the Saltville have deformed the rocks. The Beaver Valley thrust terminates within the area, but shortening remains constant across the area.

This disseration has focused on structural problems related to this area. It has examined the structural geometries at both map scale and at the mesoscopic scale to understand the structures present in the area. The geometries are interpreted on three cross-sections. A sequence of thrusting which explains the geometric evolution of the structures is presented. Finally, deformation mechanisms and twinning strains in limestones are examined and the contribution of the twinning and other features to the total strain is assessed.

The principal conclusions of the dissertation are:

1) The Copper Creek thrust sheet consists of four distinct areas: the Texas Valley anticline and syncline, the imbricate fan of Rome Formation and Conasauga Group lithologies, the uniformly dipping belt, and Clinch Mountain.

2) The Beaver Valley thrust sheet is dominantly a set of folds in Middle and Upper Ordovician strata. The sheet also contains folded pieces of the Knox and Conasauga Groups, and House Mountain, which is a syncline that contains the Martinsburg and Juniata formations, and the Clinch Sandstone.

3) The Saltville thrust sheet contains the Rome Formation and the Conasauga and Knox groups. At the southwestern end of the study area, the leading edge is imbricated. In the vicinity of Blaine, TN the leading edge is a wide slice of folded and faulted Rome Formation and Conasauga Group strata. Northeast of the folded and faulted slice, the Saltville is a single trace, and beds in the sheet dip uniformly southeast.

4) The Copper Creek thrust is interpreted as being folded at its leading edge on all three cross-sections. The interpretation is supported by surface and well data.

5) The Beaver Valley thrust changes the position of its branch line with the Saltville thrust towards its tip point. This inferred change is suggested by the structures in the foot wall of the Saltville thrust and the by the decrease in slip on the Beaver Valley thrust.

6) The Saltville thrust sheet possesses fairly simple structures. Strata from the Rome Formation and the Conasauga, Knox, and Chickamauga groups dip uniformaly southeast. Towards the northeast the fault dips at progressively gentler angles.

7) The cross-sections record essentially uniform shortening across the area. Cross-section A-A' shows 43%, cross-section B-B' shows 48%, and cross-section C-C' shows 49%.

8)The Beaver Valley and Saltville thrusts are interpreted as having grown toward each other laterally during emplacement. The movement of the faults was intermittant, and the times during which the faults were emplacing overlapped.

9) At some point during the emplacement, the Beaver Valley thrust was pinned and could no longer grow laterally. As a result a series of folds developed at the fault's tip. The Saltville thrust continued its growth southwestward despite the presence of the Beaver Valley thrust. Locally, it is the younger fault.

10) The interpretation of the sequence of thrusting suggests a local reversal in order of thrusting and a "break-back" relationship between the two thrusts. The Beaver Valley thrust terminated either due to an effect of the basement, or lateral stratigraphic change, or simply the inability of the the thrust to continue propagation because the Saltville thrust had already shortened strata and the Beaver Valley was no longer necessary to maintain shortening. There is no evidence for basement involvement, so the stratigraphic theory combined with the thrusting sequence is favored. Lateral stratigraphic changes which may be responsible are of a regional scale and specific changes and their localities cannot be identified.

11) The deformation features recorded in carbonates in the study area include cleavage, stylolites and solution seams, fractures, veins, twins, breccia, and bedding slip surfaces.

12) Two domains are suggested by the distribution of deformational features: areas within the thrust sheet, and areas within 100 m of a thrust. Although seemingly simplistic, this bipartate subdivision is the only one which appropriately characterizes the rocks. Within each domain, the abundance of features is additionally controlled by carbonate lithology.

13) Calculated twinning strains are low. Strains do not exceed 5 %, and most are less. No significant variation in either magnitude or orientation with structural position are observed.

14) Temperatures and pressures of deformation are estimated by calculating the effects of overburden (assuming a gradient), values of conodont alteration index (CAI), and deformation mechanism maps. In general, temperatures did not exceed 150^{o} C, and pressures were less than 0.6 kb.

15)The deformational features and strain data suggest that the total strain recorded in the carbonates generally does not exceed 10 %, except for local variation which is seen in fault rocks.

16) An order-of-magnitude gap exists between total strain in the carbonates and total shortening indicated by balanced

cross-sections. Although many deformational features are present in the carbonates, they contribute very little to the total strain at the scale of the thrust sheets. Most of the strain occurred along fault planes or through buckling associated with map scale folds. The dominant mode of deformation, therefore was brittle failure, at very low temperatures and pressures.

LIST OF REFERENCES

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Alvarez, W., Engelder, T., and Lowrie, W., 1976, Formation of spaced cleavage in brittle limestone by dissolution: Geology, v. 4, p. 698-701.

Alvarez, W., Engelder, T., and Geiser, P., 1978, Classification of solution cleavage in pelagic limestones: Geology, v. 6, p. 263-266.

Armstrong, F. C. and Oriel, S. S., 1965, Tectonic development of Idaho-Wyoming thrust belt: AAPG Bull., v. 49, p. 1847-1866.

Ashby, M. F., 1972, A first report on deformation-mechanism maps: Acta Metallurgica, v. 20, p. 887-897.

Ashworth, J. K., 1982, Depositional environments and paleoecology of Middle Ordovician rocks in Union County, Tennessee: unpubl. M.S. thesis, University of Tennessee, 176 p.

Bally, A. W., Gordy, P. L., and Stewart, G. A., 1966, Structure, seismic data, and orogenic evolution of the southern Canadian Rocky Mountains: Bull. Canadian Petroleum Geology, v. 14, p. 337-381.

Barber, D. J. and Wenk, H. R., 1973, The microstructure of experimentally deformed limestones: Jour. Mat. Sci., v. 8, p. 500-508.

Bathurst, R. C. G., 1975, Carbonate sediments and their diagenesis (second ed.): New York, Elsevier Pub. Co., 658 p.

Beets, J. W., 1985, Structural analysis of the Hunter Valley, Wallen Valley, and Whiteoak Mountain fault intersection, northeastern Tennessee: unpubl. M. S. thesis, University of Tennessee, 111 p.

Bell, J. F., 1941, Morphology of mechanical twinning in crystals: American Min., v. 26, p. 247-261.

Benedict, G. L. and Walker, K. R., 1978, Paleobathymetric analysis in Paleozoic sequences and its geodynamic significance: Amer. Jour. Sci., v. 278, p. 579-607.

Benson, L. I., 1963, Geology of the Texas Valley area, Knox and Union Counties, Tennessee: unpubl. M.S. thesis, University of Tennessee, 26 p.

Billings, M. P., 1972, Structural Geology (third edition): Englewood Cliffs, NJ, Prentice-Hall, Inc., 606 p.

Boyer, S. E., 1985, Hydrocarbon trap styles in fold-and-thrust belts and related terranes: 17th offshore Technology Conference, OTC 4873, p. 297-302.

Boyer, S. E. and Elliott, D., 1982, Thrust systems: AAPG Bull., v. 66, p. 1196-1230.

Breland, F. C., 1980, Stratigraphic, paleoenvironmental, and echinoderm distributional patterns in an unfaulted Middle Ordovician (Chickamauga Group) shelf-edge to on-shelf transect in East Tennessee: unpubl. Ph.D. dissertation, University of Tennessee, 217 p.

Bridge, J., 1956, Stratigraphy of the Mascot-Jefferson City zinc district, Tennessee: U. S. Geol. Surv. Prof. Paper 277, 76 p.

Bridge, J. and Hatcher, R. D., 1973, Geologic map of the New Market quadrangle, Tennessee: Tennessee Div. of Geol., GM 155-SE

Brown, S. P. and Spang, J. H., 1978, Geometry and mechanical relationship of folds to thrust fault propogation using a minor thrust in the Front Ranges of the Canadian Rocky Mountains: Bull. Canadian Petroleum Geology, v. 26, p. 551-571.

Burgess, L. B., 1982, The structure and stratigraphy of the Valley and Ridge province of Georgia and Tennessee: unpubl. M. S. thesis, University of South Carolina, 88 p.

Campbell, M. R., 1893, Geology of the Big Stone Gap coal field of Virginia and Kentucky: U. S. Geol. Surv. Bull. 111.

----------, 1894, U. S. Geol. Surv. Geol. Atlas, Estillville folio, no. 12.

Carter, N. L., 1976, Steady state fow of rocks: Rev. Geophys. Space Phys., v. 14, p. 301-360.

Carter, N. L. and Raleigh, C. B., 1969, Principal stress directions from plastic flow in crystals: Geol. Soc. America Bull., v. 80, p. 1231-1264.

Cattermole, J. M., 1966a, Geologic map of the Fountain City quadrangle, Knox County, Tennessee: U. S. Geol. Surv. Map GQ-513.

----------, 1966b, Geologic map of the John Sevier quadrangle, Knox County, Tennessee: U. S. Geol. Surv. Map GQ-514.

Childers, M. O., 1963, Structure and stratigraphy of the southwest Marias Pass area, Flathead County, Montana: Geol. Soc. America Bull., v. 74, p. 141-164.

Churnet, H. G., 1979, The relationships between dolomitization and sphalerite mineralization in the Lower Ordovician upper Knox carbonate rocks of the Copper Ridge district, East Tennessee: unpubl. Ph.D. dissertation, University of Tennessee, 237 p.

Churnet, H. G., Misra K. C., and Walker, K. R., 1982, Deposition and dolomitization of upper Knox carbonate sediments, Copper Ridge district, East Tennessee: Geol. Soc. America Bull., v. 93, p. 76-86.

Cloos, E., 1964, Wedging, bedding plane slips, and gravity tectonics in the Appalachians: in Lowry, W. D., ed., Tectonics of the southern Appalachians: Virginia Polytechnic Institute, Dept. Geol. Sci., Mem. 1, p. 63-70.

Conel, J. E., 1962, Studies of the development of fabrics in some naturally deformed limestones: unpubl. Ph.D. thesis, California Institute of Technology, 257 p.

Cooper, B. N. and Prouty, C. E., 1943, Stratigraphy of the lower Middle Ordovician of Tazewell County, Virginia: Geol. Soc. America Bull., V. 54, p. 819-886.

Cooper, M. A. and Trayner, P. M., 1986, Thrust-surface geometry: implications for thrust-belt evolution and section-balancing techniques: Jour. Structural Geology, v. 8, p. 305-312.

Coward, M. P., 1984, The strain and textural history of thin-skinned tectonic zones: examples from the Assynt region of the Moine thrust zone, northwest Scotland: Jour. Structural Geol., v. 6, p. 89-99.

Currie, J. B., Patnode, H. W., and Trump, R. P., 1962, Development of folds in sedimentary strata: Geol. Soc. America Bull., v. 73, p. 655-673.

Dahlstrom, C. D. A., 1969, Balanced cross-sections: Canadian Jour. Earth Sci., v. 6, p. 743-757.

----------, 1970, Structural geology in the eastern margin of the Canadian Rocky Mountains: Bull. Canadian Petroluem Geology, v. 18, p. 332-406.

Darton, N. H. and Taff, J. A., 1896, U. S. Geol. Surv. Geol. Atlas, Piedmont folio, no. 28.

Davis, G. H., 1984, Structural geology of rocks and regions: New York, John Wiley and Sons, 492 p.

Diegel, F. A., 1986, Topological constraints on imbricate thrust networks, examples from the Mountain City window, Tennessee, U. S. A.: Jour. Structural Geol., v. 8, p. 269-279.

Diehl, W. W., 1982, Depositional environments and paleoecology of the Middle and Upper Ordovician Martinsburg Formation of Grainger County, Tennessee: unpubl. M. S. thesis, University of Tennessee, 242 p.

Donath, F. A. and Parker, R. B., 1964, Folds and folding: Geol. Soc. America Bull., v. 75, p. 45-62.

Douglas, R. J. W., 1958, Mount Head map area, Alberta: Canada Geol. Survey, Mem. 291, 241 p.

Durney, D. W., 1976, Pressure-solution and crystallization deformation: Phil. Trans. Royal Soc. Lond., ser. A, v. 283, p. 229-240.

Elliott, D., 1976a, The energy balance and deformation mechanisms of thrust sheets: Phil. Trans. Royal Soc. London, Ser. a, v. 283, p. 289-312.

----------, 1976b, The motion of thrust sheets: Jour. of Geophysical Research, v. 81, p. 949-963.

----------, 1983, The construction of balanced cross-sections: Jour. Structural Geology, v. 5, p. 101.

Elliott, D. and Johnson, M. R. W., 1980, Structural evolution in the northern part of the Moine thrust belt, northwest Scotland: Trans. Royal Soc. Edin., v. 71, p. 69-96.

Emmons, R. C., 1943, The Universal Stage: Geol. Soc. America Mem. 8, 205 p.

Engelder, J. T., 1974, Cataclasis and the generation of fault gouge: Geol. Soc. America Bull., v. 85, p. 1515-1522.

Englund, K. J., 1968, Geology and coal resources of the Elk Valley area, Tennessee and Kentucky: U. S. Geol. Surv. Prof. Paper 572, 59 p.

Evans, J. P. and Spang, J. H., 1984, The northern termination of the Crawford thrust, western Wyoming: Contributions to Geol., University of Wyoming, v. 23, p. 15-31.

Finlayson, C. P., 1964, Geologic map and mineral resources summary of the Maynardville quadrangle, Tennessee: Tennessee Div. of Geol., GM 145-SE and MRS 145-SE.

----------, 1965a, Geologic map and mineral resources summary of the Joppa quadrangle, Tennessee: Tennessee Div. of Geol., GM 155-NE and MRS 155-NE.

----------, 1965b, Geologic map and mineral resources summary of the White Hollow quadrangle, Tennessee: Tennessee Div. of Geol., GM 145-SW and MRS 145-SW.

Finlayson, C. P., Oder, C. R. L., and Coker, A. E., 1965, Geologic map of the Talbott quadrangle, Tennessee: Tennessee Div. of Geol., GM 163-NW.

Friedman, M. and Heard, H. C., 1974, Principal stress ratios in Cretaceous limestones from Texas Gulf Coast: AAPG Bull., v. 58, p. 71-78.

Friedman, M. and Sowers, G. M., 1970, Petrofabrics: A critical review: Canadian Jour. of Earth Sci., v. 7, p. 477-497.

Friedman, M., Teufel, L. W., and Morse, J. D., 1976, Strain and stress analyses from calcite twin lamellae in experimental buckles and faulted drape-folds: Phil. Trans. Royal Soc. London, ser. A, v. 283, p. 87-107.

Gardner, D. A. C. and Spang, J. H., 1973, Model studies of the displacement transfer associated with overthrust faulting: Bull. Canadian Petroleum Geology, v. 21, p. 534-552.

Geiger, H. R. and Keith, A., 1891, The structure of the Blue Ridge near Harpers Ferry: Geol. Soc. America Bull., v. 2, p. 155-163.

Goldhaber, M. M., 1956, The Chickamauga rocks of the Beaver Valley belt from Halls Crossroads, Knox County, to the Union County line, Tennessee: unpubl. M.S. thesis, University of Tennessee, 38 p.

Griggs, D., 1938, Deformation of single calcite crystals under high confining pressure: American Min., v. 23, p. 28-33.

Griggs, D. and Miller, W. B., 1951, Deformation of Yule Marble: Part I-Compression and extension experiments on dry Yule Marble at 10,000 atmospheres confining pressure, room temperature: Geol. Soc. America Bull., v. 62, p. 853-862.

Griggs, D., Turner, F. J., Borg, I., and Sosoka, J., 1951, Deformation of Yule Marble: Part IV-Effects at 150° C.: Geol. Soc. America Bull., v. 62, p. 1385-1406.

Griggs, D., Turner, F. J., Borg, I., and Sosoka, J., 1953, Deformation of Yule Marble: Part V-Effects at 300° C.: Geol. Soc. America Bull., v. 64, p. 1327-1342.

Groshong, R. H., 1972, Strain calculated from twinning in calcite: Geol. Soc. America Bull., v. 83, p. 2025-2038.

----------, 1974, Experimental test of least-squares strain gage calculation technique using twinned calcite: Geol. Soc. America Bull., v. 85, p. 1855-1864.

----------, 1975a, "Slip" cleavage caused by pressure solution in a buckle fold: Geology, v. 3, p. 411-413.

----------, 1975b, Strain, fractures, and pressure solution in natural single-layer folds: Geol. Soc. America Bull., v. 86, p. 1363-1376.

Groshong, R. H., Pfiffner, O. A., and Pringle, L. R., 1984, Strain partitioning in the Helvetic thrust belt of eastern Switzerland from the leading edge to the internal zone: Jour. Structural Geol., v. 6, p. 5-18.

Groshong, R. H., Teufel, L. W., Gasteiger, C., 1984, Precision and accuracy of the calcite strain-gage technique: Geol. Soc. America Bull., v. 95, p. 357-363.

Haase, C. S., Walls, E. C., and Farmer, C. D., 1985, Stratigraphic and structural data for the Conasauga Group and the Rome Formation on the Copper Creek fault block near Oak Ridge, Tennessee: Preliminary results from test borehole ORNL-JOY No. 2: ORNL/TM-9159, Oak Ridge National Laboratory, 111p.

Hancock, P. L., 1985, Brittle microtectonics: principles and practice: Jour. Structural Geol., v. 7, p. 437-457.

Handin, J. W. and Griggs, D., 1951, Deformation of Yule Marble: Part II-Predicted fabric changes: Geol. Soc. America Bull., v. 62, p. 863-886.

Hardeman, W. D., 1966, Geologic map of Tennessee (East Sheet): Tennessee Div. of Geol.

Harris, L. D., 1969, Kingsport Formation and Mascot Dolomite (Lower Ordovician) of East Tennessee: in Papers on the stratigraphy and mine geology of the Kingsport and Mascot formations, Tennessee Div. of Geol., Rept. Investig. 23, p. 1-39.

----------, 1970, Details of thin-skinned tectonics in parts of of the Valley and Ridge and Cumberland plateau provinces of the Southern Appalachians: in Fisher, G. W., Pettijohn, F. J., Read, J. C., and Weaver, K. N., eds., Studies of Appalachian Geology: Central and Southern, New York, Interscience, p. 161-173.

----------, 1976, Thin-skinned tectonics and potential hydrocarbon traps - illustrated by a seismic profile in the Valley and Ridge province of Tennessee: Jour. Research U. S. Geol. Surv., v. 4, p. 379-386.

Harris, L. D. and Milici, R. C., 1977, Characteristics of thin-skinned style of deformation in the southern Appalachians and potential hydrocarbon traps: U. S. Geol. Surv. Prof. Paper 1018, 40 p.

Hatcher, R. D., 1973, Geologic map of the Jefferson City quadrangle, Tennessee: Tennessee Div. of Geol., GM 163-SW.

Hayes, C. W., 1891, The overthrust faults of the southern Appalachians: Geol. Soc. America Bull., v. 2, p. 141-152.

Heard, H. C. and Raleigh, C. B., 1972, Steady-state flow in marble at 500° to 800° C: Geol. Soc. America Bull., v. 83, p. 935-956.

Hossack, J. R., 1979, The use of balanced cross-sections in the calculation of orogenic contraction: a review: Jour. Geological Soc. (London). v. 136, p. 705-711.

House, W. M. and Gray, D. R., 1982, Displacement transfer at a thrust termination in the Southern Appalachians - Saltville thrust as an example: AAPG Bull., v. 66, p. 830-842.

Hubbert, M. K. and Rubey, W. W., 1959, Role of fluid pressure in overthrust faulting, I.: Geol. Soc. America Bull., v. 70, p. 115-166.

Jamison, W. R. and Spang, J. H., 1976, Use of calcite twin lamellae to infer differential stress: Geol. Soc. America Bull., v. 87, p. 868-872.

Jones, C., 1962, The geology of the New Loyston area, Union and Anderson counties, Tennessee: unpubl. M. S. thesis, University of Tennessee, 31 p.

Jones, P. B., 1971, Folded faults and sequences of thrusting in the Alberta foothills: AAPG Bull., v. 55, p. 292-306.

Kay. M., 1945, Paleogeographic and palinspastic maps: AAPG Bull., v. 29, p. 426-450.

Kerr, P. F., 1977, Optical Mineralogy (fourth edition): New York, McGraw-Hill Book Company, 492 p.

Keith, A., 1895, U. S. Geol. Surv. Geol. Atlas, Knoxville folio, no. 16.

---------, 1896, U. S. Geol. Surv. Geol. Atlas, Morristown folio, no. 27.

---------, 1901, U. S. Geol. Surv. Geol. Atlas, Maynardville folio, no. 75.

King, J. S., 1960, The Geology of the Buffalo Ridge area, Union County, Tennessee: unpubl. M. S. thesis, University of Tennessee, 34 p.

King, P. B., 1960, The anatomy and habitat of low-angle thrust faults: American Jour. Sci., v. 258A, p. 115-125.

Kozar, M. G., 1986, The stratigraphy, petrology, and depositional environments of the Maryville Limestone (Middle Cambrian) in the vicinity of Powell and Oak Ridge, Tennessee: unpubl. M. S. thesis, University of Tennessee, 242 p.

Langenberg, W., 1985, The geometry of folded and thrusted rocks in the Rocky Mountain foothills near Grand Cache, Alberta: Canadian Jour. Earth Sci., v. 22, p. 1711-1719.

Lutz, C. T., 1985, The Kingsport and Mascot formations of the Knox Group: in Walker, K. R., ed., The geologic history of the Thorn Hill Paleozoic section (Cambrian - Mississippian), Eastern Tennessee: University of Tennessee, Dept. Geol. Sci., Studies in Geol. no. 10, p. 43-50.

Maher, S., 1948, The geology of the John Sevier quadrangle, Knox County, Tennessee: unpubl. M. S. thesis, University of Tennessee, 71 p.

Manus, R. W., 1963, The Geology of the Condon area, Union County, Tennessee: unpubl. M. S. thesis, University of Tennessee, 43 p.

Marshak, S. and Engelder, T., 1985, Development of cleavage in limestones of a fold-and-thrust belt in eastern New York: Jour. Structural Geology, v. 7, p. 345-359.

McClay, K. R., 1977, Pressure solution and Coble creep in rocks and minerals: a review: Jour. Geol. Soc. (London), v. 134, p. 57-70.

McClay, K. R. and Insley, M. W., 1986, Duplex structures in the Lewis thrust sheet, Crowsnest Pass, Rocky Mountains, Alberta: Jour. Structural Geology, v. 8, p. 911-922.

McLaughlin, R. E., 1973, Observations on the biostratigraphy and stratigraphy of Knox County, Tennessee and vicinity: in Geology of Knox County, Tennessee Div. of Geol. Bull. 70, p. 25-62.

McMaster, W. M., 1963, Geologic map of the Oak Ridge reservation, Tennessee: ORNL/TM-713, Oak Ridge National Laboratory.

McReynolds, J. L., 1962, The geology of the Maynardville area, Union County, Tennessee: unpubl. M. S. thesis, University of Tennessee, 38 p.

Milici, R. C., 1973, Stratigraphy of Knox County: in Geology of Knox County, Tennessee Div. of Geol. Bull. 70, p. 9-24.

----------, 1975, Structural patterns in the Southern Appalachians - Evidence for a gravity slide mechanism for Alleghenian deformation: Geol. Soc. America Bull., v. 86, p. 1316-1320.

----------, 1986, West-to-east (break-back) imbrication of the Alleghenian allochthon: Tennessee Div. of Geol., Inf. Circ. no. 19, 13 p.

Misik, M., 1971, Observations concerning calcite veinlets in carbonate rocks: Jour. Sed. Pet., v. 41, p. 450-460.

Mitra, G. and Boyer, S. E., 1986, Energy balance and deformation mechansms of duplexes: Jour. Structural Geol., v. 8, p. 291-304.

Mitra, G. and Yonkee, W. A., 1985, Relationships of spaced cleavage to folds and thrusts in the Idaho-Utah-Wyoming thrust belt: Jour. Structural Geol., v. 7, p. 361-373.

North, F. K. and Henderson, G. G. L., 1954, Summary of the geology of the Southern Rocky Mountains of Canada: in 4th Annual Field Conf. Guide Book: Alberta Soc. Petroleum Geologists, p. 15-81.

Oder, C. R. L., 1934, Preliminary subdivision of the Knox dolomite in East Tennessee: Jour. Geology, v. 42, p. 469-497.

Oder, C. R. L. and Miller, H. W., 1945, Stratigraphy of the Mascot-Jefferson City zinc district: Am. Inst. Min. Met. Eng. Tech Pub. 1818.

O'Keefe, F. X. and Stearns, D. W., 1982, Characteristics of displacement transfer zones associated with thrust faults: Rocky Mountain Assoc.of Geol., p. 219-233.

Palmer, R. A., 1961, The geology of the Blaine Valley area, Grainger, Knox, and Union Counties, Tennessee: unpubl. M. S. thesis, University of Tennessee, 51 p.

Paul, J. B., 1986, The Saltville fault at Sharp Gap: geometries, mesofabrics, and microfabrics associated with a major thrust: unpubl. M. S. thesis, University of Tennessee, 140 p.

Paul, J. B. and Woodward, N. B., 1985, Brittle and ductile evolution of a thrust zone: thin and thick cataclasites along the Saltville fault: Geol. Soc. America abs. with prog., v. 17. p. 685-686.

Pfiffner, O. A. and Ramsay, J. G., 1982, Constraints on geological strain rates: Arguments from finite strain states of naturally deformed rocks: Jour. Geophys. Res., v. 87, p. 311-321.

Powell, C. McA., 1979, A morphological classification of rock cleavage: Tectonophysics, v. 58, p. 21-34.

Price, R. A., 1967, The tectonic significance of mesoscopic subfabrics in the Southern Rocky Mountains of Alberta and British Colombia: Canadian Jour. Earth Sci., v.4, p. 39-70.

Quick, K., 1960, The geology of the southern portion of the Maynardville quadrangle, Union County, Tennessee: unpubl. M. S. thesis, University of Tennessee, 58 p.

Ramsay, J. G., 1967, Folding and fracturing of rocks: New York, McGraw-Hill Book Company, 568 p.

----------, 1969, The measurement of strain and displacement in orogenic belts: in Time and Place in Orogeny, Geol. Soc. London, p. 43-79.

Ramsay, J. G. and Huber, M. I., 1983, The techniques of modern structural geology, volume 1: Strain Analysis: New York, Academic Press, 307 p.

Rich, J. L., 1934, Mechanics of low-angle overthrust faulting illustrated by Cumberland thrust block, Virginia, Kentucky, and Tennessee: AAPG Bull., v. 18, p. 1584-1596.

Rodgers, J., 1953, Geologic map of East Tennessee with explanatory text: Tennessee Div. of Geol. Bull 58, Part II, 168 p.

----------, 1970, The tectonics of the Appalachians: New York, Interscience Publishers, 271 p.

Rodgers, J. and Kent, D. F., 1948, Stratigraphic section at Lee Valley, Hawkins County, Tennessee: Tennessee Div. of Geol. Bull 55.

Roeder, D., Gilbert, O. E., and Witherspoon, W. D., 1978, Evolution and macroscopic structure of the Valley and Ridge province thrust belt, Tennessee and Virginia: University of Tennessee, Dept. Geol. Sci., Studies in Geology, no. 2, 25 p.

Roeder, D. and Witherspoon, W. D., 1978, Palinspastic map of East Tennessee: American Jour. Sci., v. 278, p. 543-550.

Royse, F., Warner, M. A., and Reese, D. L., 1975, Thrust belt structural geometry and related stratigraphic problems, Wyoming-Idaho-Northern Utah: in Rocky Mountain Assoc. of Geol., Symposium on Deep Drilling FRontiers in the central Rocky Mountains, p. 4-54.

Ruppel, S. C. and Walker, K. R., 1982, Sedimentology and distinction of carbonate buildups: Jour. Sed. Pet., v. 52, p. 1055-1071

----------, 1984, Petrology and depositional history of a Middle Ordovician carbonate platform: Chickamauga Group, northeastern Tennessee: Geol. Soc. America Bull., v. 95, p. 568-583.

Rutherford, E., 1985, Stratigraphic controls of thrust faulting and the structural evolution of the Wartburg Basin, Tennessee: unpubl. M. S. thesis, University of Tennessee, 145 p.

Rutter, E. H., 1976, The kinetics of rock deformation by pressure solution: Phil. Trans. Royal Soc. Lond., ser. A, v. 283, p. 203-219.

----------, 1983, Pressure solution in nature, theory, and experiment: Jour. Geol. Soc. (London), v. 140, p. 725-740.

Safford, J. M., 1856, A geological reconnaissance of the state of Tennessee: State Geologist 1st bienn. rept., Nashville.

----------, 1869, Geology of Tennessee: Nashville, State of Tennessee, 550 p.

Samman, N. F., 1975, Sedimentation and stratigraphy of the Rome Formation in East Tennessee: unpubl. Ph.D. dissertation, University of Tennessee, 337 p.

Sawyer, N. G., 1947, The geology of the Big Ridge Park quadrangle, Knox, Union, and Anderson Counties, Tennessee: unpubl. M. S. thesis, University of Tennessee, 46 p.

Schmid, S. M., 1976, Rheological evidence for changes in the deformation mechanism of Solnhofen limestone towards low stresses: Tectonophysics, v. 31, p. T21-T28.

----------, 1982a, Laboratory experiments on rheology and deformation mechanisms in calcite rocks and their application to studies in the field: Mitteilungen aus dem Geologischen Institut der Eidg. Technischen Hochschule und der Universitat Zurich, no. 241, 106 p.

----------, 1982b, Microfabric studies as indicators of deformation mechanisms and flow laws operative in mountain building: in Hsu, K. J., ed., Mountain Building Processes: London, Academic Press, p. 95-110.

Schmid, S. M., Boland, J. N., and Paterson, M. S., 1977, Superplastic fow in fine-grained limestone: Tectonophysics, v. 43, p. 257-291.

Schoner, A. K., 1985, The Clinch Sandstone (Lower Silurian) along 25E at Beans Gap: in Walker, K. R., ed., The geologic history of the Thorn Hill Paleozoic section (Cambrian - Mississippian), Eastern Tennessee: University of Tennessee, Dept. Geol. Sci., Studies in Geology, no. 10, p. 100-110.

Schwerdtner, W. M., 1973, A scale problem in paleo-strain analysis: Tectonophysics, v. 16, p. 47-54.

Sibson, R. H., 1977, Fault rocks and fault mechanisms: Jour.Geol. Soc. (London), v. 133, p. 191-213.

Simmons, W. A., 1984, Stratigraphy, facies, petrology, and depositional environments of the Middle Cambrian Maryville Limestone (Conasauga Group) near Thorn Hill, Tennessee: unpubl. M. S. thesis, University of Tennessee, 258 p.

Simonson, J. C. B., 1985, The stratigraphy, carbonate petrology, depositional environments, and paleoecology of the Middle Ordovician Moccasin Formation near Thorn Hill, Tennessee: unpubl. M. S. thesis, University of Tennessee, 279 p.

Skinner, R. B., 1961, The geology of the Luttrell area, Union and Grainger Counties, Tennessee: unpubl. M. S. thesis, University of Tennessee, 38 p.

Spang, J. H., 1972, Numerical method for dynamic analysis of calcite twin lamellae: Geol. Soc. America Bull., v. 83, p. 467-472.

Spang, J. H. and Groshong, R. H., 1981, Deformation mechanisms and strain history of a minor fold from the Appalachian Valley and Ridge province: Tectonophysics, v. 72, p. 323-342.

Spangler, J. F., 1949, The geology of the Graveston quadrangle, Union and Knox Counties, Tennessee: unpubl. M. S. thesis, University of Tennesssee, 67 p.

Staub, W. P. and Johnson, V. C., 1973, Gravity survey of Knox County, Tennessee: in Geology of Knox County, Tennessee, Tennessee Div. of Geol. Bull. 70, p. 74-75.

Stockdale, P. B., 1922, Stylolites: their nature and origin: Indiana University Studies, n. 55, 97 p.

Suppe, J., 1983, Geometry and kinematics of fault-bend folding: American Jour. Sci., v. 283, p. 684-721.

---------, 1985, Principles of Structural Geology: Englewood Cliffs, NJ, Prentice Hall, 537 p.

Swingle, G. D., 1960, Geologic map of the Jacksboro quadrangle, Tennessee: Tennessee Div. of Geol., GM 136-SW.

--------------, 1973, Structural geology of Knox County, Tennessee: in Geology of Knox County, Tennessee Div. of Geol., Bull. 70, p. 63-73.

Swingle, G. D., Palmer, R. A., Skinner, R. O., Hawkins, J. O., and McReynolds, J. L., 1967a, Geologic map and mineral resources summary of the Luttrell quadrangle, Tennessee: Tennessee Div. of Geol., GM 155-NW and MRS 155-NW.

Swingle, G. D., Harper, D. D., Palmer, R. A., and Milici, R. C., 1967b, Geologic map of the Boyd's Creek quadrangle, Tennessee: Tennessee Div. of Geol., GM 156-NW.

Tegland, E. R., 1978, Seismic investigations in eastern Tennessee: Tennessee Div. of Geol., Bull. 78, 68 p.

Teufel, L. W., 1980, Strain analysis of experimental superposed deformation using calcite twin lamellae: Tectonophysics, v. 65, p. 291-309.

Turner, F. J., 1953, Nature and dynamic interpretation of deformation lamellae in calcite of three marbles: American Jour. Sci., v. 251, p. 276-298.

Turner, F. J. and Ch'ih, C. S., 1951, Deformation of Yule Marble: Part III-Observed fabric changes due to deformation at 10,000 atmospheres confining pressure, room temperature, dry: Geol. Soc. America Bull., v. 62, p. 887-906.

Turner, F. J., Griggs, D., Clark, R. H., and Dixon, R. H., 1956, Deformation of Yule Marble, Part VII: Development of oriented fabrics at 300° C-500° C: Geol. Soc. America Bull., v. 67, p. 1259-1294.

Turner, F. J. and Weiss, L. E., 1963, Structural analysis of metamorphic tectonites: New York, McGraw-Hill Book Company, 545 p.

Twombly, G. L. and Spang, J. H., 1982, Experimental test of the calcite strain gage technique at low confining pressure: Tectonophysics, v. 89, p. T17-T26.

Ulrich, E. O., 1911, Revision of the Paleozoic systems: Geol. Soc. America Bull., v. 22, p. 281-680.

Walker, K. R., 1977, A brief introduction to the ecostratigraphy of the Middle Ordovician of Tennessee (Southern Appalachians, U. S. A.): in Ruppel, S. C. and Walker, K. R., eds., The ecostratigraphy of the Middle Ordovician of the Southern Appalachians (Kentucky, Tennessee, and Virginia), U. S. A.: A field excursion, University of Tennessee, Studies in Geology, no. 1, p. 12-17.

----------, 1980, Introduction to the stratigraphy and paleoenvironments of the Middle Ordovician of Tennessee (Southern Appalachians, U. S. A.): in Walker, K. R., Broadhead, T. W., and Keller, F. B., eds., Middle Ordovician Carbonate shelf to deep water basin deposition in the Southern Appalachians, University of Tennessee, Studies in Geology, no. 4, p. 4-12.

Walker, K. R. and Diehl, W. W., 1985, Upper Ordovician "Martinsburg" Formation, a deep-water to shallow-water sequence: in Walker, K. R., ed., The geologic history of the Thorn Hill Paleozoic section (Cambrian - Mississippian), Eastern Tennessee, University of Tennessee, Studies in geology, no. 10, p. 86-92.

Walker, K. R. and Ferrigno, K. F., 1973, Major Middle Ordovician reef tract in east Tennessee: American Jour. Sci., v. 273A, p. 294-325.

Walker, K. R. and Simmons, W. A., 1985, The Middle Cambrian Conasauga Group in the Thorn Hill section: an intracratonic platform/basin complex: in Walker, K. R., ed., The geologic history of the Thorn Hill Paleozoic section (Cambrian - Mississippian), Eastern Tennessee, University of Tennessee, Studies in Geology, no. 10, p. 14-24.

Wanless, H. R., 1979, Limestone response to stress: pressure solution and dolomitization: Jour. Sed. Pet., v. 49, p. 437-462.

Watkins, J. S., 1964, Regional geological implications of the gravity and magnetic fields of a part of Eastern Tennessee and Southern Kentucky: U. S. Geol. surv. Prof. Paper 572, 59 p.

Weber, L. J., 1985, Stratigraphy and depositional environments of the lower Knox Group (Copper Ridge Dolomite and Chepultepec Dolomite) along U. S. Route 25E: in Walker, K. R., ed., The geologic history of the Thorn Hill Paleozoic section (Cambrian - Mississippian), Eastern Tennessee, University of Tennessee, Studies in Geology, no. 10, p. 32-42.

----------, in prep, Depositional environments and post-depositional alteration of the upper Conasauga Group (Nolichucky Shale and Maynardville Limestone) along Copper Ridge and nearby strike belts, East Tennessee: Ph.D. dissertation, University of Tennessee.

Wenk, H. R., Venkitasubramanyan, C. S., and Baker, D. W. (Appendix by F. J. Turner), 1973, Preferred orientation in experimentally deformed limestone: Contrib. Min. Petr., v. 38, p. 81-114.

Wiltschko, D. V. and Dorr, J. A., 1983, Timing of deformation in overthrust belt and foreland of Idaho, Wyoming, and Utah: AAPG Bull., v. 67, p. 1304-1322.

Wiltschko, D. V. and Eastman, D., 1983, Role of basement warps and faults in localizing thrust fault ramps: GSA Mem. 158, p. 177-190.

Wiltschko, D. V., Medeweff, D. A., and Millson, H. E., 1985, Distribution and mechanisms of strain within rocks on the northwest ramp of the Pine Mountain block, Southern Appalachian foreland: Geol. Soc. America Bull., v. 96, p. 426-435.

Wojtal, S. F., 1982, Finite deformation in thrust sheets and their material properties: unpubl. Ph.D. dissertation, Johns Hopkins University, 285 p.

----------, 1986, Deformation within foreland thrust sheets by populations of minor faults: Jour. Structural Geology, v. 8, p. 341-360.

Woodward, N. B., ed., 1985, Valley and Ridge thrust belt: balanced structural sections, Pennsylvania to Alabama: University of Tennesee, Studies in Geology, no. 12, 64 p.

Woodward, N. B., Boyer, S. E., and Suppe J., 1985, An outline of balanced sections (second edition): University of Tennessee, Studies in Geology, no. 11, 170 p.

Woodward, N. B., Gray, D. R., and Spears, D. B., 1986, Including strain data in balanced cross-sections: Jour. Structural Geology, v. 8, p. 313-324.

Woodward, N. B., Walker, K. R., and Lutz, C. T., in press, Relationships between Lower Paleozoic facies patterns and structural trends in the Tennessee Valley and Ridge: submitted to Geol. Soc. America Bull.

APPENDICES

APPENDIX A

STRATIGRAPHY

APPENDIX A

STRATIGRAPHY

This appendix is a summary of the stratigraphy in the study area. The summary concentrates on thicknesses and lithologies, rather than environments of deposition; it is intended as an overview, and not a comprehensive description Figure 60 is a generalized stratigraphic column. More detailed information and discussion are found in the references shown on Figure 61.

The stratigraphic units in the area range in age from Cambrian to Mississippian, and are a mixture of terrigenous clastic and carbonate deposits. Most of the area is underlain by strata which are Ordovician and older; post-Ordovician rocks are found only on Clinch Mountain and House Mountain. The section is approximately 3.2 to 3.7 km thick, averaging 3.5 km.

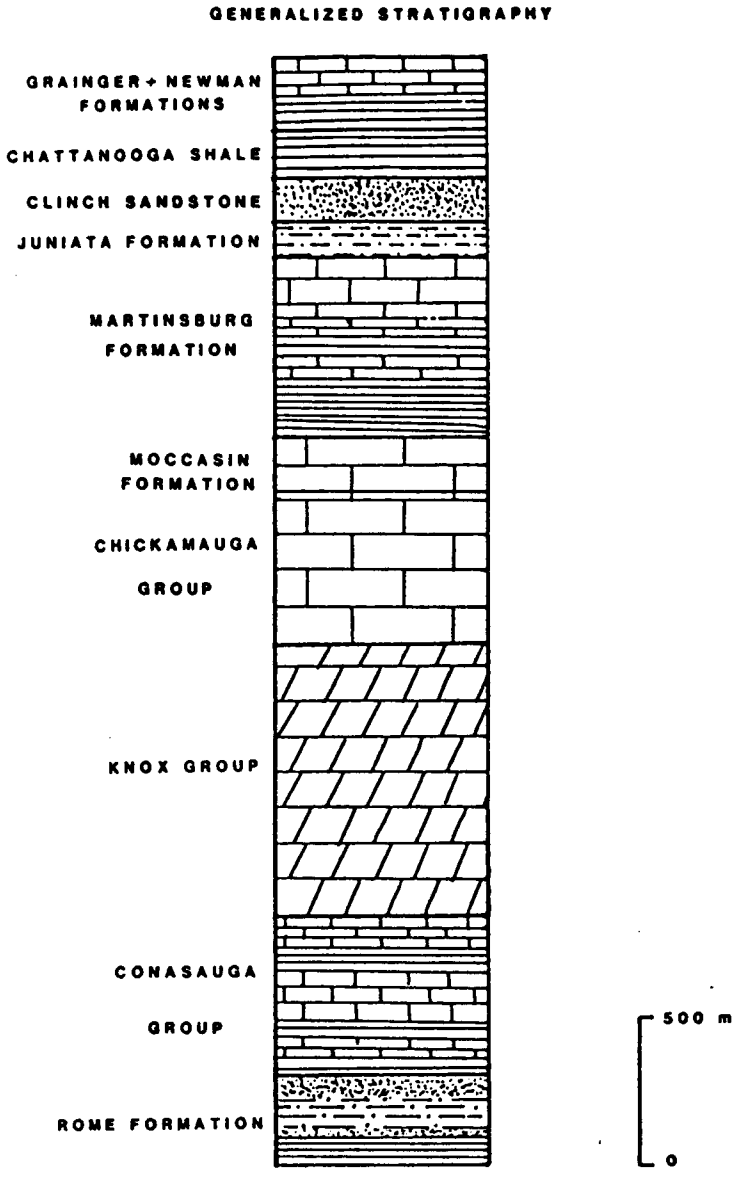


Figure 60. Generalized stratigraphic column of the study area. Note that most of the strata are Ordovician and older and most are carbonates.

Figure 61. Summary of information concerning the stratigraphic units in the study area

Mississippian	Grainger Formation	Siltstone, shale, and limestone approx. 196 m thick.	Campbell (1893); Keith (1895, 1896); Swingle et al. (1967)
Mississipppian - Devonian	Chattanooga Shale	Black shale, 267 m thick.	Hayes (1891); Rodgers (1953); Harris and Milici (1977).
Silurian	Clinch Sandstone	Quartz sandstone, 71 to 152 m thick.	Safford (1856); Schoner (1985)
Upper Ordovician	Juniata Formation	Shale, siltstone, and sandstone, 120 m thick.	Darton and Taff (1896)
Upper Ordovician	Martinsburg Formation	Limestone and shale, 600 m thick.	Geiger and Keith (1891); Diehl (1982); Walker and Diehl (1985)
Middle Ordovician	Moccasin Formation	Argillaceous limestone with shale, 191 m thick.	Campbell (1894); Rodgers (1953); Simsonson (1985)
Middle Ordovician	Chickamauga Group	Limestone, with varying amounts of interbedded shale, 400 to 450 m thick.	Rodgers (1953); Walker (1977, 1980); Walker and Ferrigno (1973); Ruppel and Walker (1982, 1984)

Lower Ordovician and Upper Cambrian	Knox Group Mascot Dolostone Kingsport Formation Chepultepec Dolostone Copper Ridge Dolostone	Dolostone, with limestone interbedded in the upper half. Thickness is generally 700 to 800 m.	Safford (1869); Ulrich (1911); Oder and Miller (1945); Rodgers (1953); Bridge (1956); Quick (1960); Harris (1969); Milici (1973); Churnet (1979); Churnet et al. (1982); Lutz (1985) Weber (1985).
Upper Cambrian and Middle Cambrian	Conasauga Group Maynardville Limestone Nolichucky Shale Maryville Limestone Rogersville Shale Rutledge Limestone Pumpkin Valley Shale	Limestone and shale with subordinate dolostone, especially in the Maynard-ville Limestone. Thickness is generally 550 to 650 m.	Hayes (1891); Campbell (1894); Oder (1934); Rodgers and Kent (1948); Rodgers (1953); King (1960); Finlayson (1964); Simmons (1984); Haase et al. (1985); Walker and Simmons (1985); Kozar (1986); Weber (in prep.).
Lower Cambrian	Rome Formation	Interbedded sandstone, shale, and siltstone, with carbonate beds locally present. Thickness ranges from 90 to 400 meters; the average thickness in the study area is 150 m.	Hayes (1891); Rodgers (1953); Cattermole (1966); Samman (1975); Beets (1985).

APPENDIX B

FIELD GUIDE

APPENDIX B

FIELD GUIDE

This appendix contains a road log of several traverses across the area studied, and a description of eight stops. Figure 62 shows the road log route and the location of the stops.

ROAD LOG

Miles	Cum. miles	
0.0	0.0	The Geology and Geography Building on "the Hill," University of Tennessee. Proceed down the hill.
0.2	0.2	Traffic light at the intersection with Cumberland Avenue. Turn left.
0.3	0.5	Proceed on Cumberland Avenue to 17th Street (3rd traffic light. Turn right.
0.5	1.0	Continue on 17th Street to Dale Avenue (3rd traffic light). Turn right. Seventeenth Street is underlain by the Copper Ridge and Chepultepec Formations of the Knox Group; the Knoxville thrust crosses the street just north of Forest Avenue.
0.3	1.3	Traffic light. Follow the sign and proceed north on I-275.
2.8	4.1	Sharp Gap, exposing the Saltville thrust. Here, the fault places the Rome Formation on the Mascot

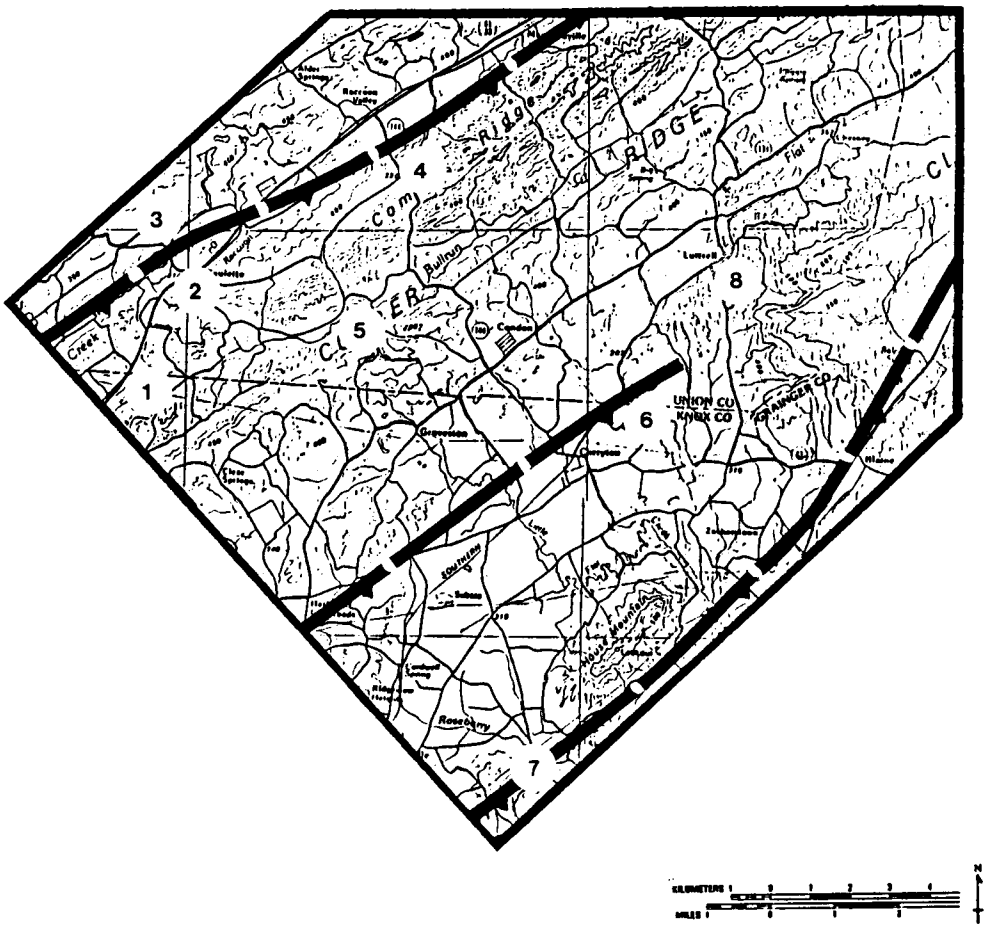


Figure 62. Map showing the location of the stops described in the road log.

		Formation of the Knox Group. In Knoxville, the Saltville system includes several imbricates, and at this exposure a three meter thick cataclasite is developed on the fault (Paul, 1986).
0.1	4.2	Exit I-275 at the intersection with I-640. Follow I-640 east.
2.3	6.5	Southest dipping beds of the Rome Formation and Pumpkin Valley Shale visible to the northwest of the highway on a hill slope. These beds are in a frontal imbricate slice of the Saltville.
0.4	6.9	Exit I-640 at the Broadway exit. Follow Broadway north.
0.3	7.2	Tazewell Pike exit. On the right-hand (east) side of the road, the Saltville thrust is exposed; fault attitude is N60^{o}E, 55^{o} SE, with the Rome Formation thrust on the Mascot Formation. Unlike the Sharp Gap exposure, the fault surface is knife-sharp (Paul, 1986). For the next 2.7 miles, Broadway is underlain by carbonates of the Chickamauga and Knox Groups.
2.4	9.6	Blackoak Ridge, which is held up by the Copper Ridge Formation and Maynardville Limestone.
0.6	10.2	Hines Valley. This valley is underlain by carbonates and shales of the Conasauga Group.
0.4	10.6	Crippen Gap in Beaver Ridge. This gap exposes the Beaver Valley thrust which places the Rome Formation on overturned beds of the Mascot Formation of the Knox Group and the

		lower Chickamauga Group (Lenoir and Holston formations). Mascot Formation strata are well exposed; bedding is indistinct and the rocks are quite brecciated. Middle Ordovician rocks are not well exposed. The overturned beds in the footwall sit within a frontal slice. A cataclasite is developed on the fault plane that is 4 to 5 m thick.
1.2	11.8	Middle Ordovician carbonates exposed on the south side of the road dipping southeast.
0.2	12.0	Halls Crossroads and the intersection with Emory Road. Continue north on Broadway (name changes to Maynardville Pike), TN Route 33.
2.1	14.1	Exposure of upper Knox Group strata to the right-hand (east) side of the road. Attitude is N55^{o}E, 15^{o} SE.
1.8	15.9	Copper Ridge, which is held up by the Copper Ridge Formation and the Maynardville Limestone.
0.5	16.4	Beech Grove, Tennessee. Southeast dipping beds of the Nolichucky Shale and Maynardville Limestone are exposed on the right-hand (east) side of the road. These strata are on the southeast limb of the Texas Valley anticline. Texas Valley is immediately north of the outcrop, and is underlain by the Nolichucky Shale.
0.4	16.8	Exposures of the Maryville Limestone; attitude N60^{o}E, 10^{o} SE.

0.3	17.1	Approximate location of the axis of the Texas Valley anticline. Note the beds of Maryville Limestone exposed on the left-hand (west) side of the road which are essentially horizontal.
1.8	18.9	Exposure of carbonate beds in the Nolichucky Shale to the left-hand (west) side of the road. STOP 1 (Proceed north on Route 33 to continue the road log).

STOP 1

MILDLY DEFORMED BEDS OF THE NOLICHUCKY SHALE

Gently dipping shale and limestone beds of the Nolichucky Shale are exposed on Route 33 in southern Union County (Fig. 63). Limestone constitutes approximately 75 % of the outcrop, and beds are 5 to 60 cm thick. Some beds are oolitic, and several possess the intraclastic bases (Fig. 64) commonly described from the Nolichucky (e.g., Walker and Simmons, 1985). Bedding parallel stylolites are also well-developed.

The outcrop is adjacent to the axis of the Texas Valley syncline. Beds strike nearly east-west, dipping gently southeast, with some variation (Fig. 65). Two deformation features are found: fractures, which are generally perpendicular to bedding, and veins. Some fracture surfaces are coated with calcite, and the coated fractures

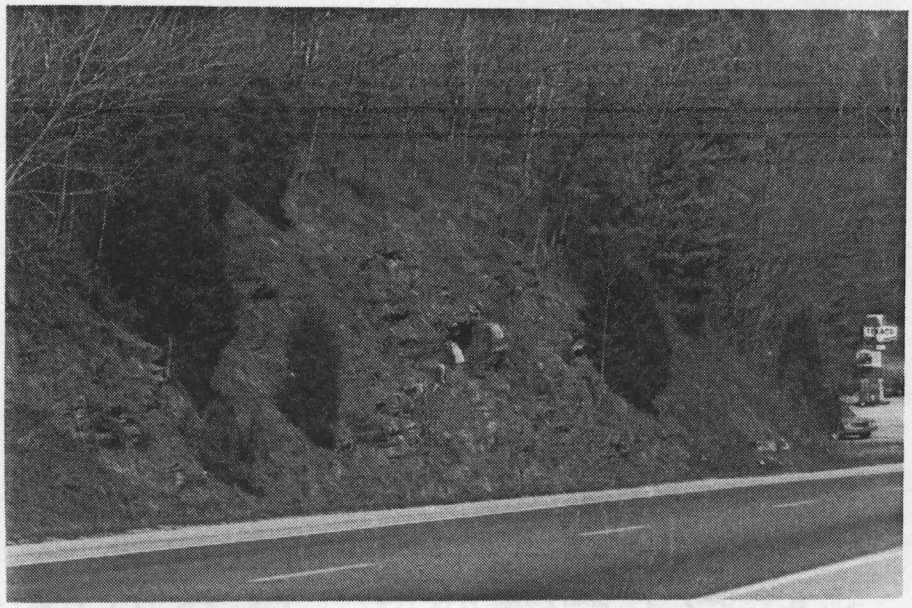


Figure 63. Photograph of Stop 1, looking north-northwest. Interbedded limestones and shales of the Nolichucky Shale are dipping very gently southeast. The road is Tennessee Route 33.



Figure 64. Intraclasts in a limestone bed in the Nolichucky Shale, Stop 1.

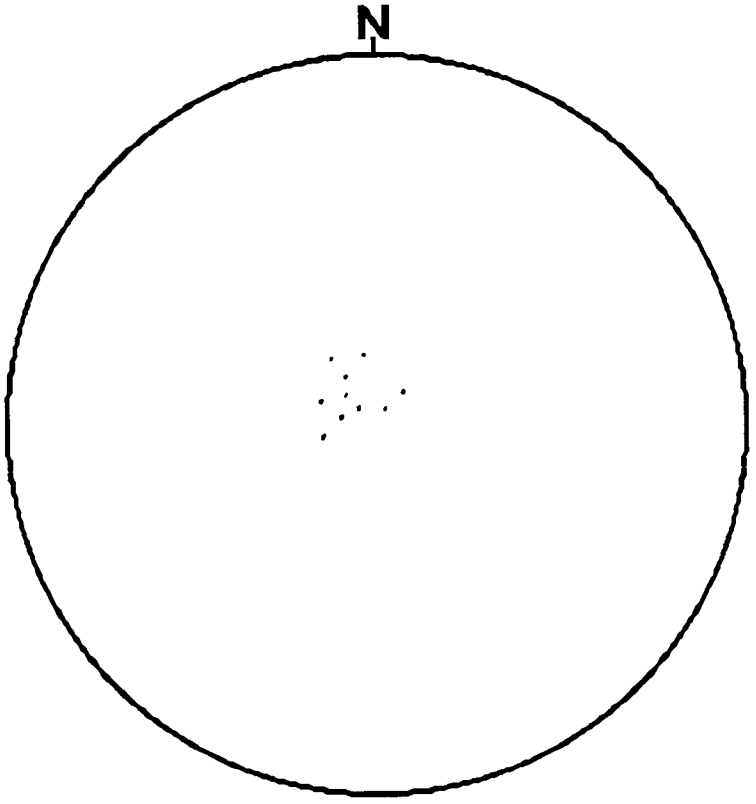


Figure 65. Stereographic projection of poles to bedding in the Nolichucky Shale, Stop 1. The beds dip gently southeast, and strike nearly east-west.

resemble the "ornamented surfaces" described by Wiltschko et al. (1985) in that calcite fibers show no preferred orientation. Veins are poorly developed and in general have the same orientation as the fractures. Thus, these may represent "healed" fracture surfaces. The veins are filled with white calcite and are about 2 to 4 mm wide.

This exposure exhibits several of the brittle deformation features common in foreland thrust sheets (Price, 1967). It also shows the low deformation intensity found in carbonates within the thrust sheets in the study area.

0.4	19.3	Quarry exposing the Maryville on the right-hand (east) side of the road. The Maryville - Nolichucky contact is visible at the top of the quarry. Beds in the quarry are nearly horizontal, with dips up to 5 ^{O} SE.
0.35	19.65	Exposure of a shaly portion of the Maryville on the left-hand (west) side of the road. Bedding attitude is N60^{O}E, 45^{O} SE.
0.85	20.5	Paulette, Tennessee. Turn left onto TN Route 61, and pull off the road adjacent to the Union County Coon Hunting Association Building. STOP 2 (Turn left back onto Route 61 to continue road log).

STOP 2

FOLDED BEDS OF THE PUMPKIN VALLEY SHALE

The Pumpkin Valley Shale is exposed in two outcrops at this stop (Fig. 66). Although it superficially resembles the Rome Formation, the Pumpkin Valley differs by the absence of thick quartz sandstone beds. Monotonously interbedded shales and siltstones generally comprise the formation. Siltstone beds are up to 5 or 6 cm thick (see Rodgers and Kent, 1948 and Walker and Simmons, 1985).

This locality is on the northwest limb of the Texas Valley syncline, near its northeast termination. One exposure is located in the gully at the junction of Route 33 and Route 61, at the northwest corner of the intersection. A group of folds are exposed, which are several tens of cm wide (Fig. 67). The fold axes trend S10^{o}E to S45^{o}E. The fold trending S45^{o}E is approximately parallel to transport direction of the Copper Creek thrust; the folds are essentially plunging down the dip direction of the thrust. The other folds are oblique to transport direction. Veins are present, both perpendicular and oblique to bedding; some of these contain calcite grains. Dark seams are present along some bedding planes, and these are probably solution selvages.

Figure 66. Geologic map of Stop 2. "A" indicates the exposure at the junction of Tennessee Routes 33 and 61. "B" indicates the exposure adjacent to the Union County Coon Hunting Association building.

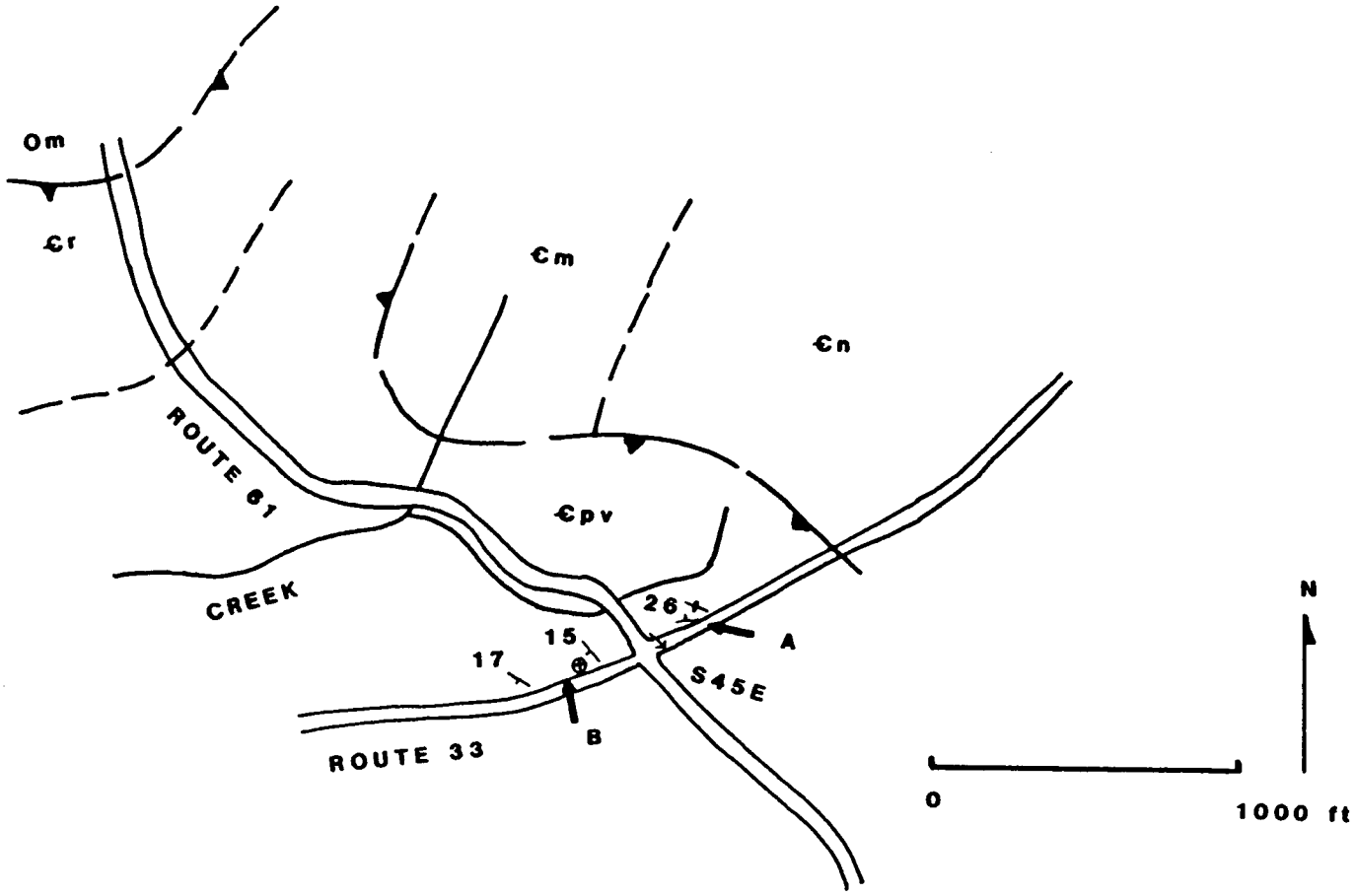

Om
€r
€m
€n
ROUTE 61
€pv
CREEK
26
15
17
A
B
S45E
ROUTE 33
N
0
1000 ft



Figure 67. Folds in the gully at exposure A, Stop 2. Interbedded shales and siltstones of the Pumpkin Valley Shale are tighly folded. This fold trends S45 ^{o}E.

The other exposure is located southwest of the Union County Coon Hunting Association building, on the (unnamed) road which parallels Route 33. Bedding strikes N41°W to N75°W, and dips southwest 8° to 20°, or 30° northeast, or is horizontal. The fold axis which is exposed trends S5°E. Fractures strike N40°W to N70°W or N8°E to N25°E; all are perpendicular to bedding (Fig. 68).

The folding at these outcrops reflects the proximity to the Copper Creek thrust and the incompetent behavior of the Pumpkin Valley. Between this stop and stop 3, Route 61 cuts through more Pumpkin Valley Shale, then crosses the fault into the Maryville Limestone and across the fault back into the Pumpkin Valley. The Maryville is poorly exposed and only found in a creek bed on the south side of the road, and on the southwest end of Miller Knobs, north of the road.

0.2	20.7	Exposures of the Pumpkin Valley Shale; attitude of beds is N80°E, 70° SE.
0.2	20.9	The Copper Creek thrust. Hangingwall rocks are the Rome Formation, and those in the footwall are the Moccasin Formation of the Chickamauga Group. Hangingwall and footwall strata are exposed for approximately 400 m along the road.

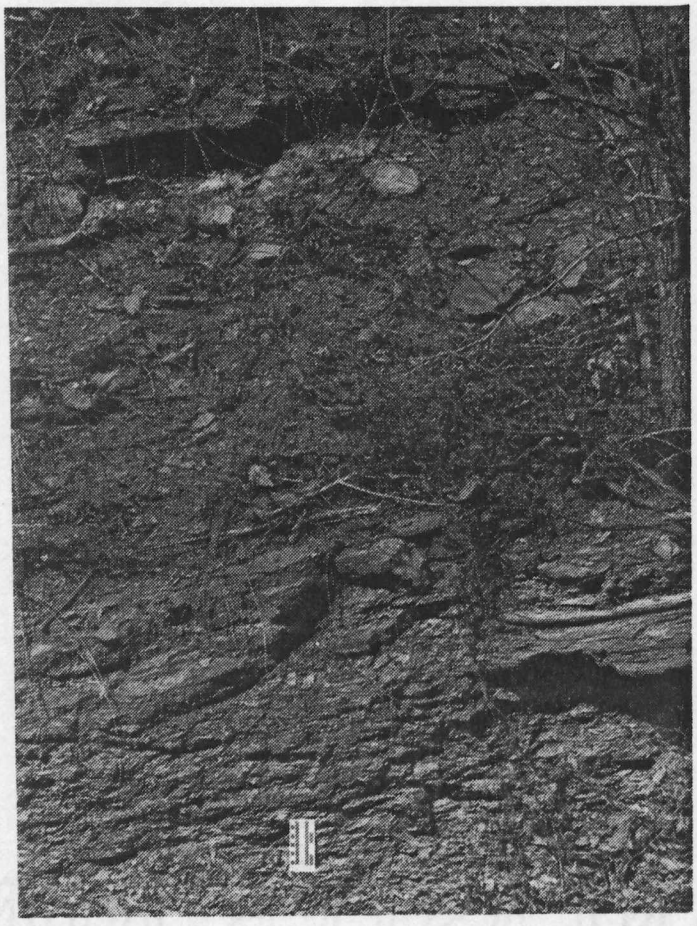


Figure 68. Characteristic bedding and fracture orientation at exposure B, Stop 2. Bedding dip at this exposure is gentle and generally does not exceed 20°. A fold in this exposure trends S15°E, but is not as tight as the folds at exposure A. Fractures are perpendicular to or steeply inclined to bedding.

0.1	21.0	Junction with Raccoon Valley Road. Stay on Route 61 (take the left fork in the road) Pull off the road at the building on the left-hand (southwest) side of the road. STOP 3. Continue northwest on Route 61 after examining the rocks at this stop.

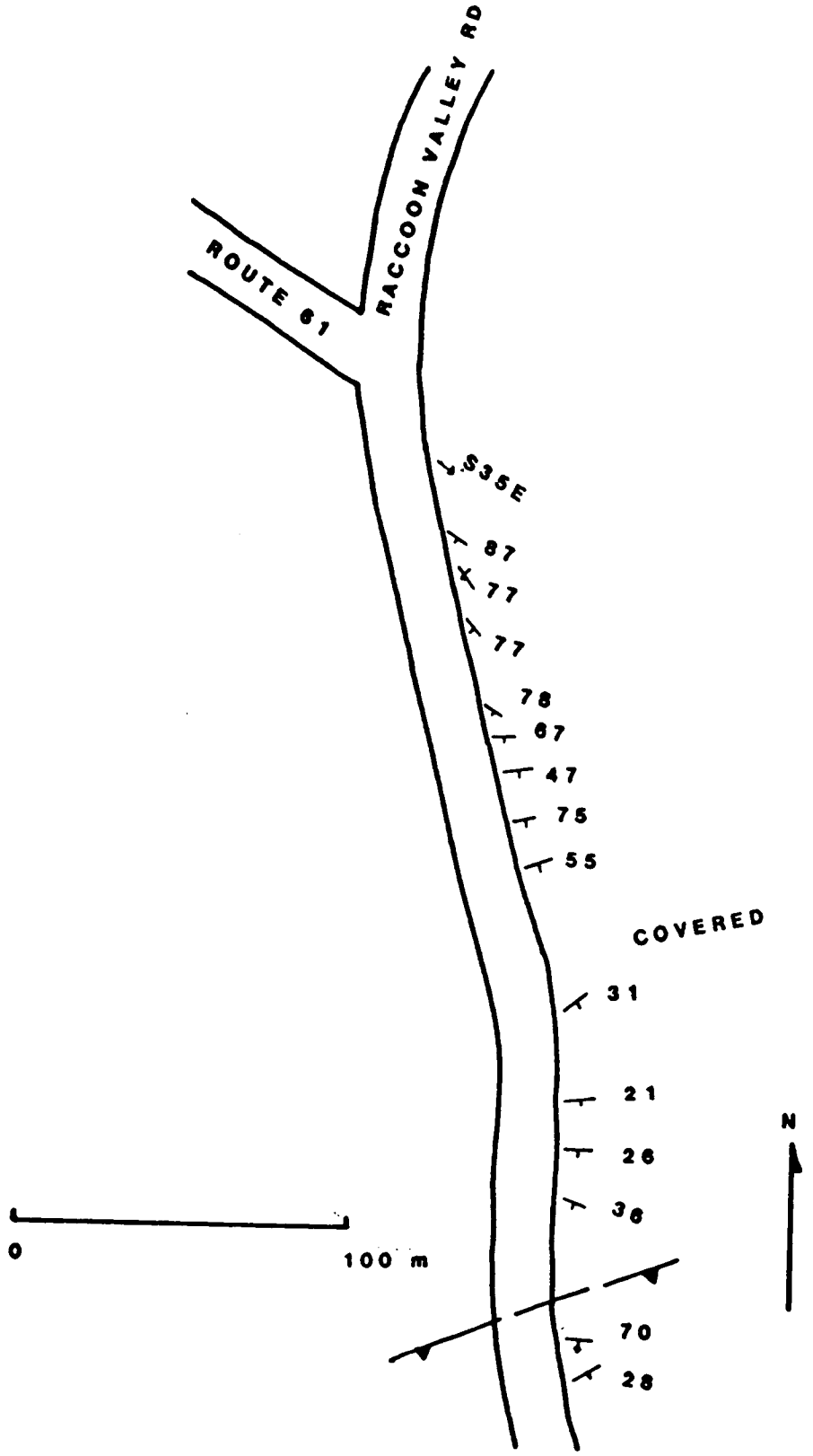
STOP 3

THE COPPER CREEK THRUST

This stop examines the Copper Creek thrust along Route 61, immediately west of Paulette, TN (Fig. 69). The fault places the Rome Formation on the Moccasin Formation. Although the fault plane is not exposed, hangingwall and footwall rocks are quite accessible. This exposure of the Copper Creek thrust is very different from the well-studied exposure approximately 18 km to the southwest at Diggs Gap (Harris and Milici, 1977; Wojtal, 1982, 1986). At that exposure, the hangingwall exhibits the most intense deformation; in contrast, the foot wall of this exposure is more intensely deformed.

The stop location is at the northwest end of the outcrop at the junction of Route 61 and Raccoon Valley Road. Examination of the exposure begins in the Pumpkin Valley Shale in the hangingwall. Walk back south-southeast along Route 61 to the Rome/ Pumpkin Valley contact. This contact

Figure 69. Geologic map of Stop 3. Map scale is 1:1000.


ROUTE 61
RACCOON VALLEY RD
S35E
87
77
77
78
67
47
75
55
COVERED
31
21
26
36
70
28
N
0
100 m

is placed at the top of the uppermost thick-bedded sandstone in the Rome. The overlying Pumpkin Valley is moderately deformed. At the bottom of the formation, beds dip southeast 35°. Some small (several cm wide) folds are developed, which trend N65°E to N70°E. Just up section from the folds, there is a partially covered area in which there is a divergence of dip about a narrow zone: 70° to 85° versus 30° to 50°. I interpret this as a small contraction fault, based on inferred direction of movement on either side of the zone. From this fault to the southeast end of the outcrop, beds dip uniformly 30° to 40° southeast.

The Rome dips southeast 25° to 35° and exhibits a small amount of deformation. The massive sandstone at the top is approximately 10 m thick, with individual beds up to 70 cm thick. The sandstone is fractured, and fractures strike N35°E to N60°E, dipping 50° to 65° northwest. The sandstone is underlain by thinly bedded sandstone and siltstone, interbedded with thin shale laminae. Beds are 2 to 10 cm thick, and fractures trend with those in the overlying thick sandstone. A small extension fault (Fig. 70) is evident 5 to 10 m above the thrust. The fault dips steeply to the southwest and has about 0.5 m displacement.

The thrust is not exposed, however carbonates in the footwall are easily distinguished from the terrigenous clastics of the hangingwall, so its location is easy to estimate. Rocks on either side of the thrust show marked

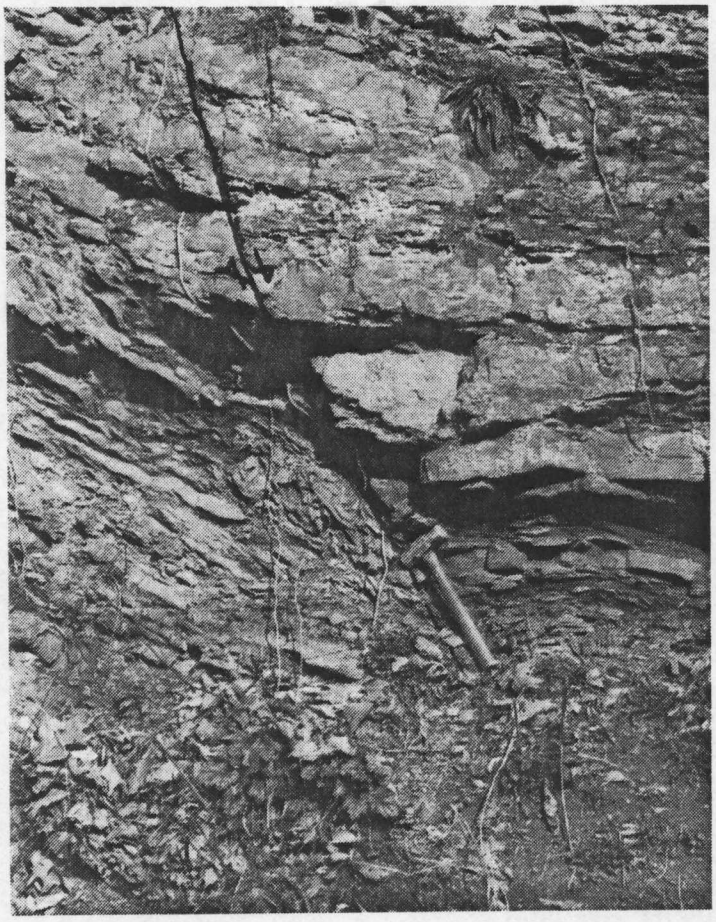


Figure 70. Small extension fault in the Rome Formation, 5 to 10 m above the Copper Creek thrust, Stop 3. Slip on the fault is approximately 50 cm. Hammer is for scale.

brecciation and intense deformation(see Chapter 4). It is not possible to measure total thickness of the zone of cataclasis because so much of this part of the outcrop is covered.

The first exposures of the Moccasin in the footwall are tan and gray limestone dipping 21° to 30° southeast. The rocks show extensive dissolution and a weakly developed cleavage. These beds are underlain by gently dipping maroon limestone with a more pronounced cleavage. A covered interval separates these strata from the underlying beds.

The underlying rocks are gray limestones which dip southeast 50° to 75°. These limestones are less argillaceous and do not exhibit cleavage. Vein arrays are well-developed (Fig. 71). The veins are perpendicular to bedding, few mm wide, and filled with white calcite. Spacing between veins is up to several cm. Two sets usually cut the beds, however 3 sets are present in some cases. Surfaces coated with calcite fibers are present, but are not extensively developed. Deformed chert nodules are also conspicuous (Fig. 72). Individual nodules are 5 to 15 cm long, and they are extended and/or pressure solved.

The gray limestones are underlain by maroon and gray argillaceous limestones which are steeply dipping to overturned. Strike direction rotates from northeast to northwest down section. Cleavage is developed, as well as extensive dissolution (Fig. 73). Chert is absent and veins



Figure 71. Veins sets developed in the Moccasin Formation in the foot wall of the Copper Creek thrust, Stop 3. The view is looking down on bedding. The white circle is a quarter for scale.

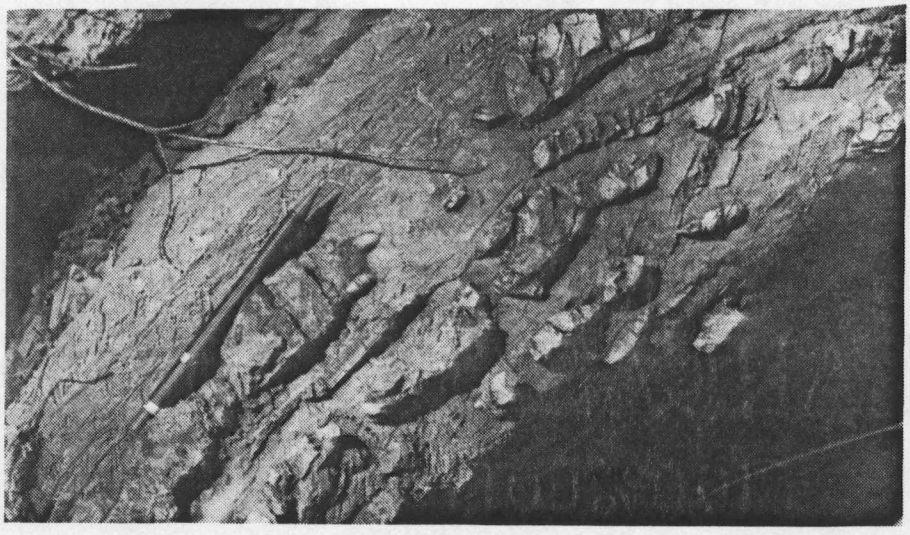


Figure 72. Deformed chert nodules in the Moccasin Formation, Stop 3. The pencil is for scale and is 14 cm long.

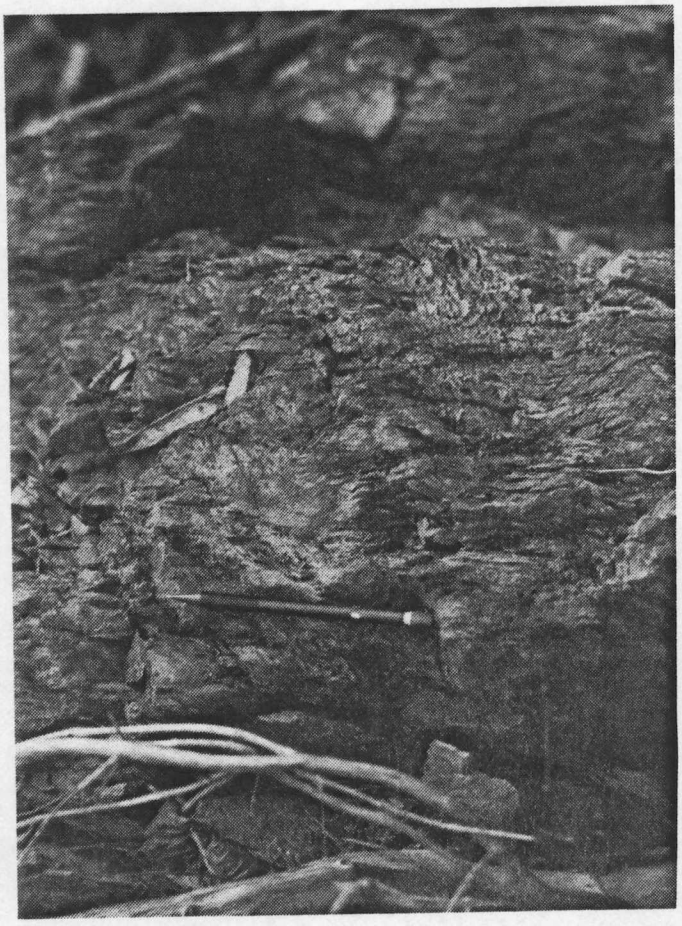


Figure 73. An intensely pressure solved and cleaved bed in the Moccasin Formation, Stop 3. Bedding is nearly parallel to the pencil, and the cleavage is steeply inclined and nearly perpendicular to bedding. The pencil is for scale and is 14 cm long.

are not as prominent. At the north end of the outcrop, intensely folded and pressure solved limestone beds are exposed (Fig. 74); the folding trends S35°E.

The deformation features of the Moccasin correlate with its variable carbonate composition. The more argillaceous portions show extensive solution, and weak to moderately intense (Alvarez et al., 1978) cleavage. The purer limestones exhibit vein sets and twinned calcite. Dissolutional features are present but not as prominent. The pronounced footwall deformation suggests a blind thrust beneath the Copper Creek thrust (see the cross-sections).

0.8	21.8	Exposure of folded Lincolnshire and Rockdell Formations of the Chickamauga Group. These folds trend S50°E to S70°E. Turn around where Raccoon Valley Road branches off of Route 61, adjacent to the outcrop, and go back towards stop 3.
0.8	22.6	Turn left off of Route 61 onto Raccoon Valley Road.
0.7	23.3	Exposures of the Wardell, Bowen, and Witten Formations of the Chickamauga Group on the right-hand (east) side of the road. Rocks are exposed around the barn and in the fields; bedding attitude varies widely, and some beds are folded. Fold axes trend S20°W to S55°W.



Figure 74. Tightly folded beds of the Moccasin Formation, Stop 3. Notice the pervasive pressure solution indicated by the anastomosing selvages which cut the beds.

0.8	24.1	Junction with TN Route 33. Turn left. Exposed across the road behind the house are beds of the Maryville Limestone in the hangingwall of the Copper Creek thrust.
1.1	25.2	Exposures of the upper Chickamauga Group to the right-hand (east) side of the road; bedding attitude is N45°E, 20° SE. Continue north to Maynardville.
1.5	26.7	Junction of TN Route 144. Turn right.
0.1	26.8	Approximate location of the Copper Creek thrust (fault is not exposed). On the property on the right-hand (south) side of the road, Chickamauga carbonates, especially the Bowen Formation, are exposed (rather poorly) around the barn and other buildings, and the Maryville Limestone is exposed on the hillside. Attitude of the Maryville is N60°E, 77° SE. For the next mile, the road cuts through the northeast end of the Buffalo Ridge syncline.
1.0	27.8	Turn left off Route 144, and immediately pull off the road. Walk east on Route 144 approximately 0.1 mile to Comb Ridge. STOP 4 (Proceed east on Route 144 to continue road log).

STOP 4

THE ROME FORMATION AT AILOR GAP

The Rome Formation is exposed along Route 144 in Ailor Gap of Comb Ridge. The Rome is in the hangingwall of an imbricate thrust which is part of the imbricate fan along the larger Copper Creek thrust in this area. Vertical beds of the Rome are visible in Bull Run Creek, adjacent to the outcrop. The Nolichucky Shale is in the footwall, but it is not exposed. The outcrop consists of three parts each separated by a covered interval (Fig. 75).

The first outcrop (Fig. 76) contains maroon and tan sandstones, siltstones, and shales. At the northwest end, the rocks are entirely sandstones, with most beds 20 to 35 cm thick; maximum bed thickness is 1 m. The beds dip steeply northwest or southeast, and are folded and faulted (Fig. 77). folds trend N35^{o} E to N60^{o}E. Faults dip to the southeast, and several appear to be wedge faults (Cloos, 1964). Fractures are well-developed, and strike N30^{o}E to N60^{o}E, dipping gently and steeply northwest and southeast.

The southeast end of the outcrop contains beds striking N40^{o}E to N45^{o}E and dipping southeast 85^{o} to vertical (Fig. 78). It consists of two parts: one, tan and maroon sandstone beds, up to 80 cm thick and two, interbedded

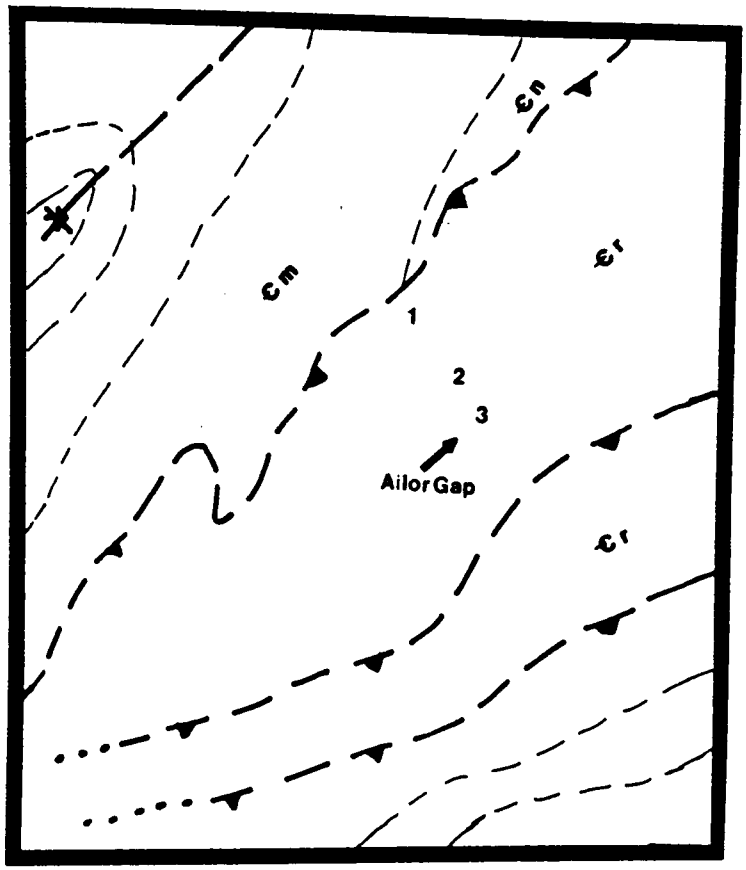
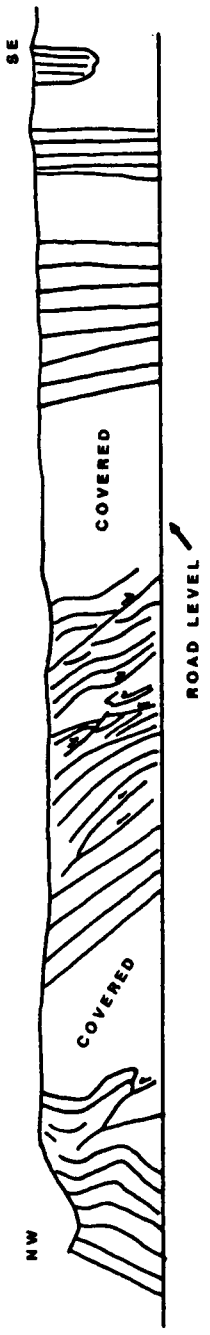


Figure 75. Geologic map showing the location of Stop 4, with the three parts of the outcrop labelled. The map is copied from Plate I, therefore the scale is 1:24,000.

Figure 76. Sketch of the first part of Stop 4. This first part is located at the northwest end of the stop, and is adjacent to the imbricate thrust which is part of the imbricate fan along the leading edge of the larger Copper Creek thrust.


SE
COVERED
ROAD LEVEL
COVERED
NW

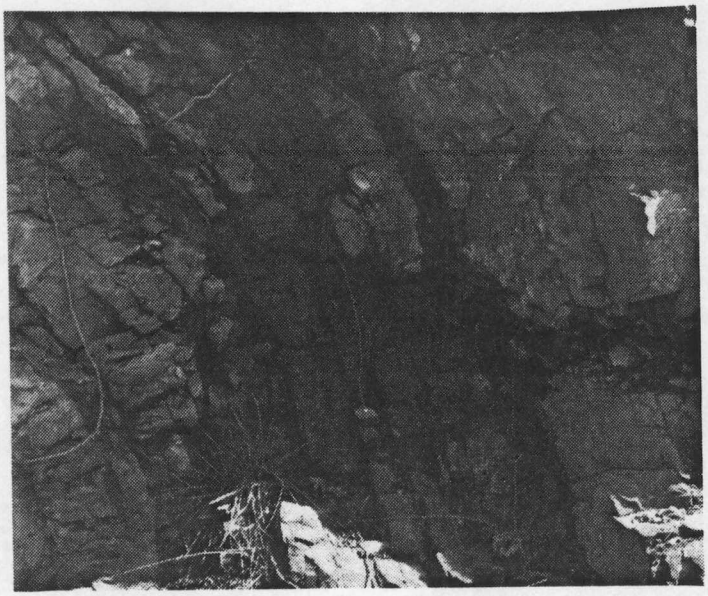


Figure 77. Steeply dipping and folded beds of sandstone in the Rome Formation, Stop 4. The beds are located in the first part of Stop 4.

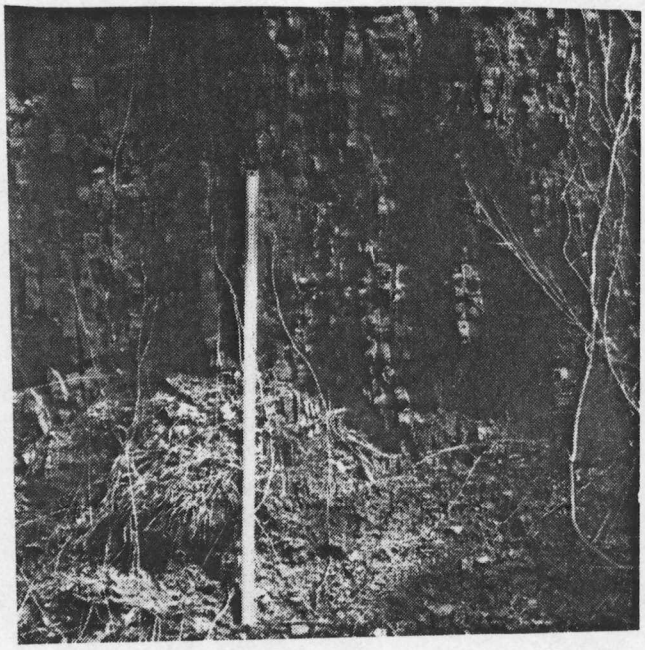


Figure 78. Vertical beds of siltstone and shale in the Rome Formation, Stop 4. The beds are located in the first part of Stop 4. The stick is one m long.

siltstone and shales, containing ripple marks and trace fossils. Here, individual beds are up to 6 or 7 cm. Both parts are extensively fractured, and fractures are horizontal or dip up to 15° northwest.

The second outcrop consists of dark gray carbonates and olive gray and maroon sandstone, siltstone, and shale. A N60°E fold of carbonate beds, 4 to 4.5 m across, is exposed at the northwest end (Fig. 79). The fold passes into a covered area, adjacent to which sandstone and siltstone beds are exposed, dipping 50° southeast. These beds are up to 30 cm thick and interbedded with shale. They are overlain by folded siltstones and shales; fold axes trend N20°E. Individual folds are up to 10 cm across, but most are 5 cm wide or less. The folds are overlain by thick-bedded dark gray dolostone dipping 25° southeast.

The third outcrop contains thick bedded dark gray dolostone at the northwest end which grades into interbedded siltstone and shale. Beds are generally 6 to 7 cm thick, with a few thicker beds up to 20 cm. Attitude is rather uniform, N35°E, 30° southeast. Some folds are developed in shale beds; these are 3 to 4 cm wide, and they trend with strike. Fractures are well developed, and dip northwest up to 70°.

0.5	28.3	Ailor Gap, with outcrops of the Rome Formation on the right-hand (west) side of the road.

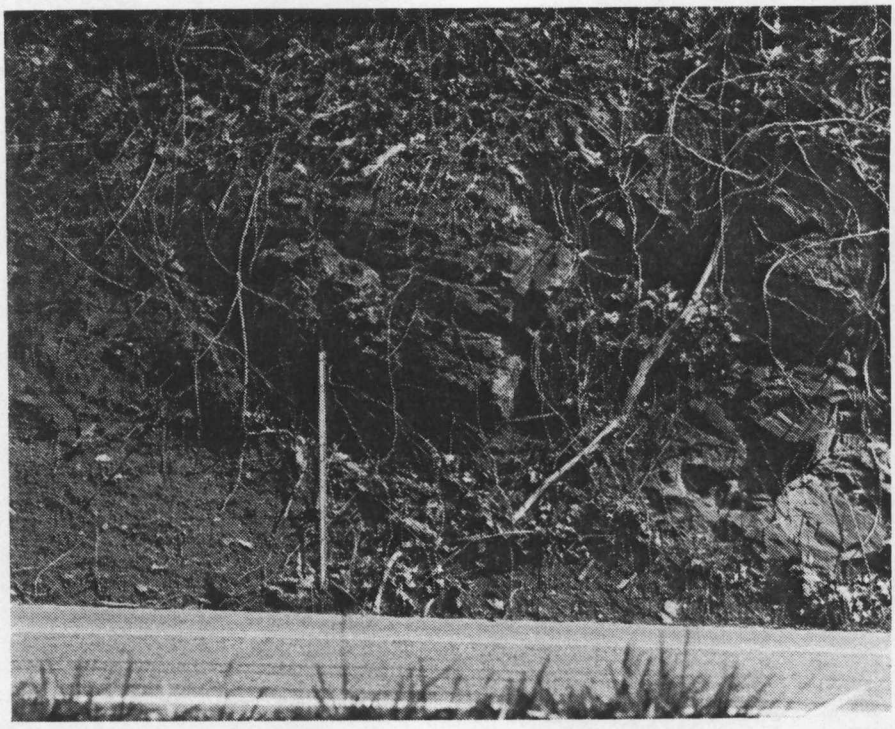


Figure 79. Small fold in the Rome Formation, Stop 4. The fold is located in the second part of Stop 4. The stick is one m long.

1.1	29.4	Road to Pleasant Grove School. Turn right. The road cuts through the Pumpkin Valley Shale and Rutledge Limestone, which are striking approximately N60°E and dipping 20° to 80° SE.
1.4	30.8	Outcrop of the Rutledge Limestone on the left-hand (east) side of the road. Pull off the road. STOP 5

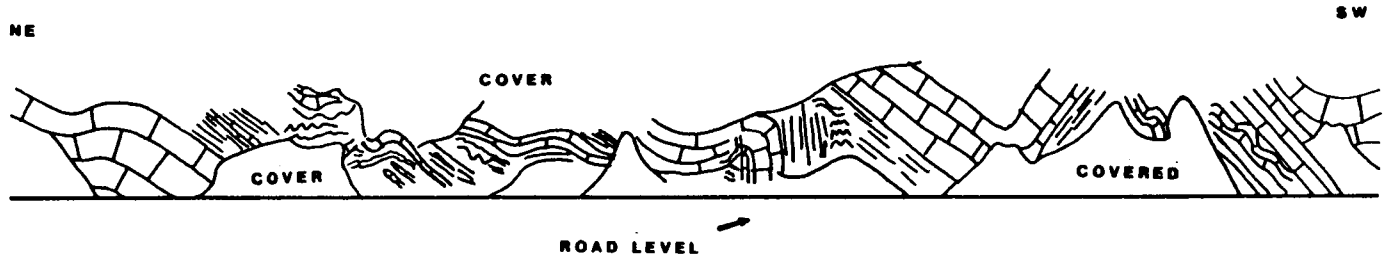
STOP 5

FOLDS IN THE RUTLEDGE LIMESTONE

This stop is an exposure of limestones and shales of the Rutledge Formation (Fig. 80) in the footwall of an imbricate in the Copper Creek thrust zone. The outcrop consists of broad, concentric folds in the limestone beds, which trend N70°E to N80°E. Folding in the shale is generally chevron-style, and fold axes fall into two groupings of orientations (Fig. 81). Most of the folds however trend N70°E to N85°E, mimicking the folds in the limestone.

Limestone beds are cut by veins filled with white calcite, which are generally 3 mm wide. Most veins are perpendicular to bedding, and strike of the veins varies between northeast and northwest. Surfaces coated with

Figure 80. Sketch of Stop 5. This sketch shows the folded nature of the limestones and interbedded shales in the Rutledge Limestone. The beds are located in the footwall of an imbricate thrust in the imbricate fan of the larger Copper Creek thrust.


NE
SW
COVER
COVER
COVERED
ROAD LEVEL

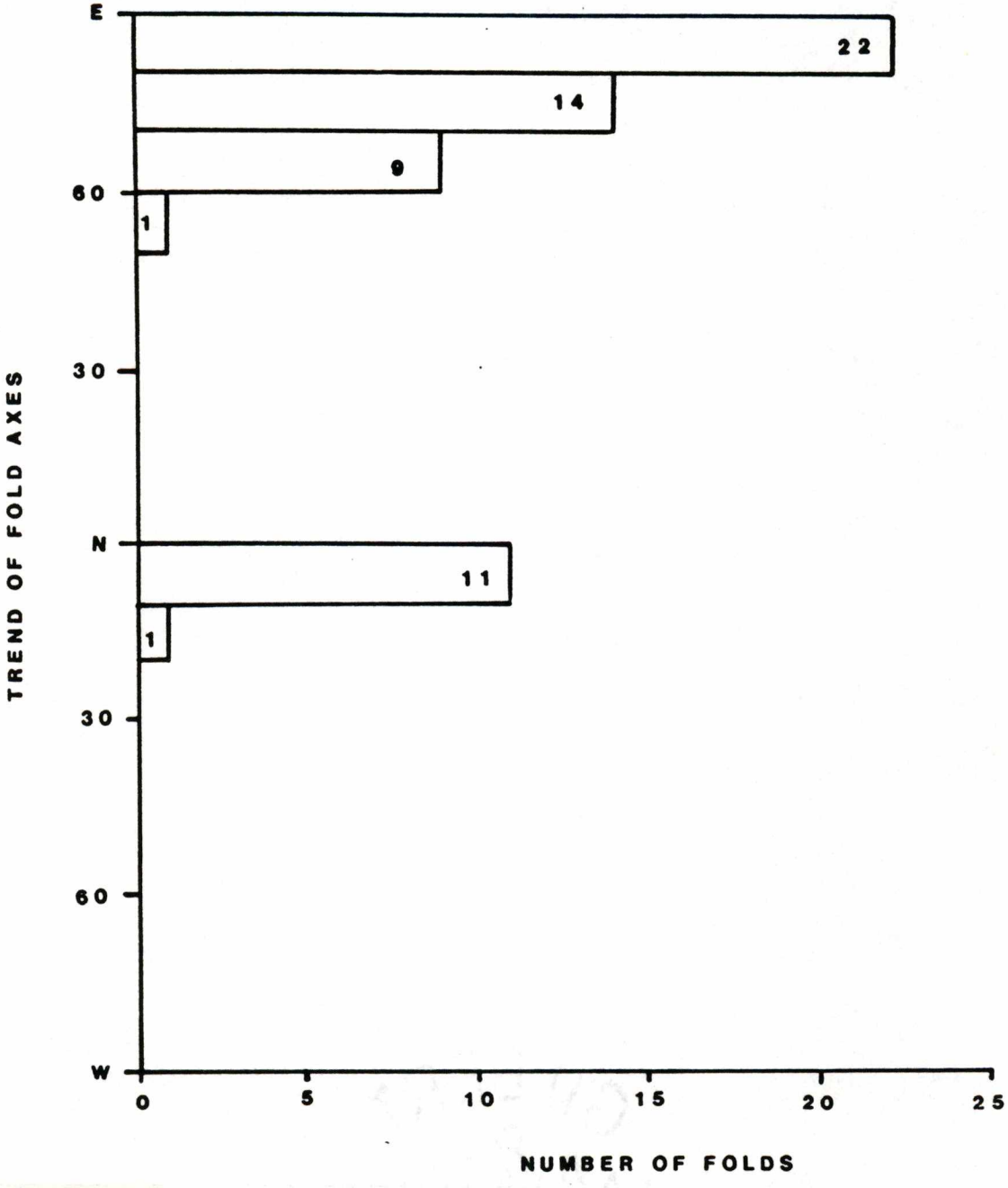


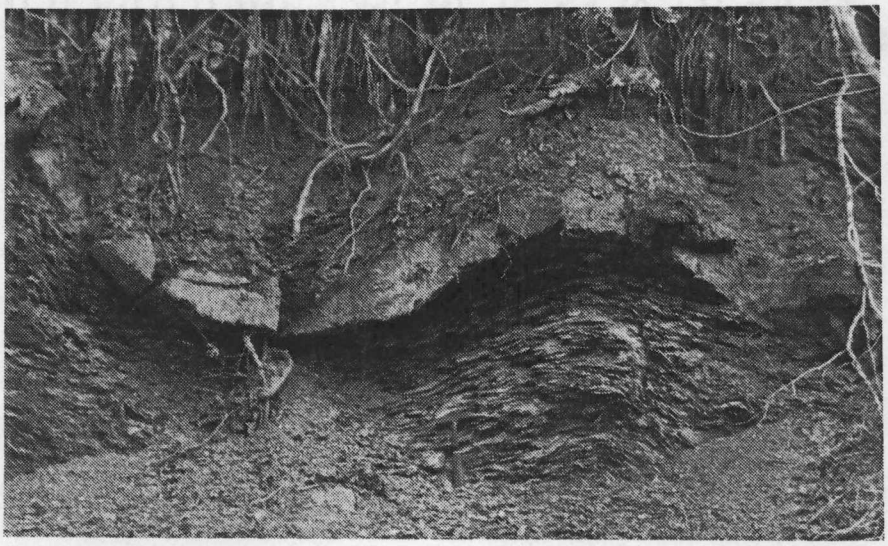
Figure 81. Histogram showing the distribution of fold trends in shale in the Rutledge Limestone, Stop 5.

calcite and surfaces with oriented fibers are present, but neither are well-developed.

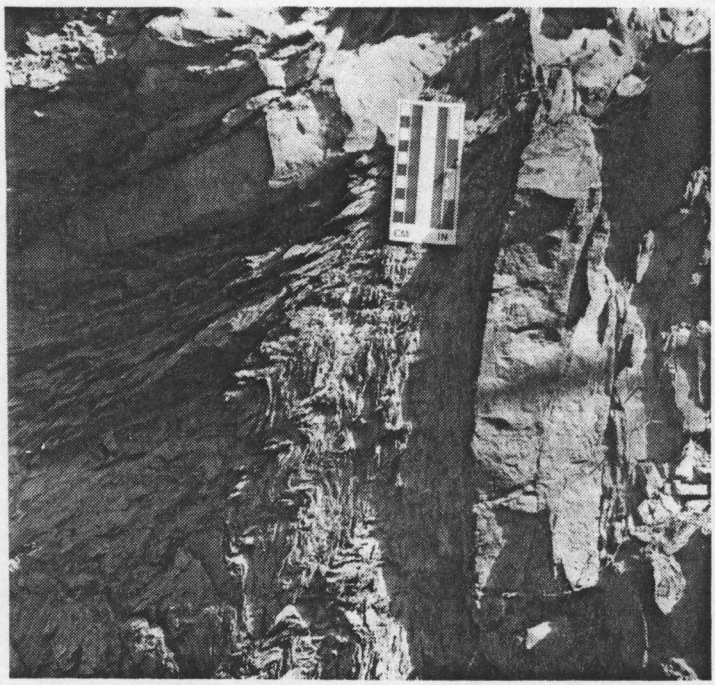
King (1960) described a "fracture cleavage" at this locality, which is evident in the shale folds. Fracture planes strike between N40°E and N82°E, and most dip steeply to the southeast. This fracture set may not actually be a cleavage, but simply a set of joints which developed due to brittle failure during or prior to folding. Davis (1984) suggested that fracture cleavage be referred to as spaced cleavage, and he points out that it is common in tightly folded sedimentary rocks.

Hangingwall rocks are visible at the end of the outcrop, and the strata are from the Rome Formation. The sandstones and shales strike approximately N60°E to N70°E, and dip moderately to the southeast. A conspicuous joint set strikes N80°E and dips 32° northwest. Surfaces with oriented fibers are present, but rare. A small fold is exposed, and its trend and plunge are E-W, 10° east.

The outcrop is a good example of the types of structures that develop in a stratigraphic unit which contains interbedded competent and incompetent beds. The folds in the shales and limestones of the Rutledge trend similarly, but the limestones folded concentrically (Fig. 82a), whereas the shales folded in a chevron-style (Fig. 82b).



A



B

Figure 82. Two examples of folding in the Rutledge Limestone, Stop 5. A) Concentric folding of limestone with interbedded shale. The rock hammer is for scale. B) Tight, "chevron" folding of shales. The overlying limestone bed is also tighly folded and conforms with the underlying shales.

1.4	32.2	Turn around and go back to Route 144. At the junction of Route 144, turn right.
0.8	33.0	Junction with Route 370. Exposed at the junction are southeast dipping beds of the Nolichucky Shale. Approximately 2.0 miles northeast on Route 370 are outcrops of the Maryville Limestone. The strata strike N50°E and vary in dip from 35° to 85° SE (see Fig. 13). Fractures and extension veins are well-developed.
1.0	34.0	Copper Ridge, which is held up by the Copper Ridge Dolostone and the Maynardville Limestone. Beds dip 20° to 23° southeast.
1.3	35.3	Junction with Route 131 (Tazewell Pike).
1.0	36.3	Approximate location of the Beaver Valley thrust (fault is not exposed). This point is only about 4.5 km from the tip of the fault, and stratigraphic separation is small--the Moccasin Formation sits on the Martinsburg Formation. The fault location is approximated by a couple of small, partially covered exposures, and a change in residuum and soil type.
0.4	36.7	A few beds exposed in the gully on the left-hand (east) side of the road. Bed attitude is N55°E, 75° southeast, overturned.
0.3	37.0	Exposures of Chickamauga Group carbonates; bedding attitude is N70°E, 41° southeast.

0.25	37.25	Corryton, TN; junction with Corryton-Luttrell Road (the road is adjacent to the railroad tracks). Turn left
0.6	37.85	Exposure of Chickamauga Group carbonates. Bedding attitude is difficult to measure because of vegatation and blocks of float.
0.6	38.45	Turn left onto Eva Road and pull off the road. STOP 6 is the outcrop of the Moccasin Formation across the railroad tracks. WARNING: Trains come through this area very rapidly.

STOP 6

THE MOCCASIN FORMATION

Folded beds of the Moccasin Formation are exposed in a railroad cut adjacent to Corryton-Luttrell Road, approximately 1.8 km northeast of Corryton (Fig. 83). The outcrop is several hundred meters from the Beaver Valley thrust, near its tip. Folds trend northeast and are generally upright (Fig. 84); beds dip between 30° and 65°. Moccasin beds on the west side of the road, only tens of meters from this outcrop, bear little relationship to these folds. There, the strata strike west-northwest (N80°W to N85°W) or east-northeast (N74°E to N80°E) and dip southeast and northeast.



Figure 83. Photograph of Stop 6. The view is towards the east-northeast.

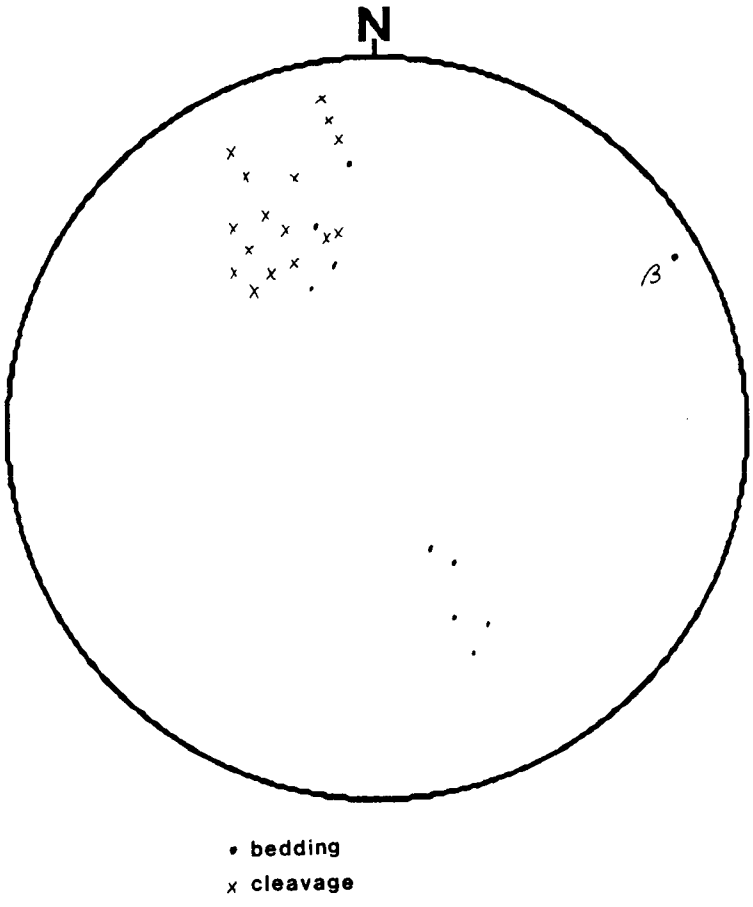


Figure 84. Stereographic projection of poles to bedding and cleavage from the Moccasin Formation, Stop 6. Number of measurements = 25.

Pressure solution or dissolution is the most obvious deformation mechanism in these rocks. It is evident in two ways. First, planar and anastomosing selvages cut the beds at various orientations (Fig. 85). Some more resistant beds appear offset or telescoped by the solution (Fig. 86). Second, solution cleavage is well-developed and is approximately axial planar to the folds (Fig. 87). Cleavage planes dip between 39^{o} and 71^{o}. Slabbed samples and thin-sections demonstrate that solution selvages coincide with cleavage (see chapter 4). Spacing between cleavage planes is 1 to 3 cm. Using the classification of Alvarez et al. (1978), the cleavage is of moderate intensity. They estimate shortening accomodated by cleavage of moderate intensity to be 4 to 25 %, however this is based on restoration of shortened chert beds in the area they studied.

Veins are present at the outcrop, but they are not extensively developed. All veins are perpendicular to bedding or cut it at a steep angle. Sparry calcite fills the veins, and it is commonly twinned. The veins are up to a cm wide. Vein-filling calcite may represent redeposition from solution surfaces.

The Moccasin Formation averages approximately 30% terrigenous clastic material (Simonson, 1985), and this promotes extensive dissolution and cleavage seen in folded and faulted road cuts. Marshak and Engelder (1985)

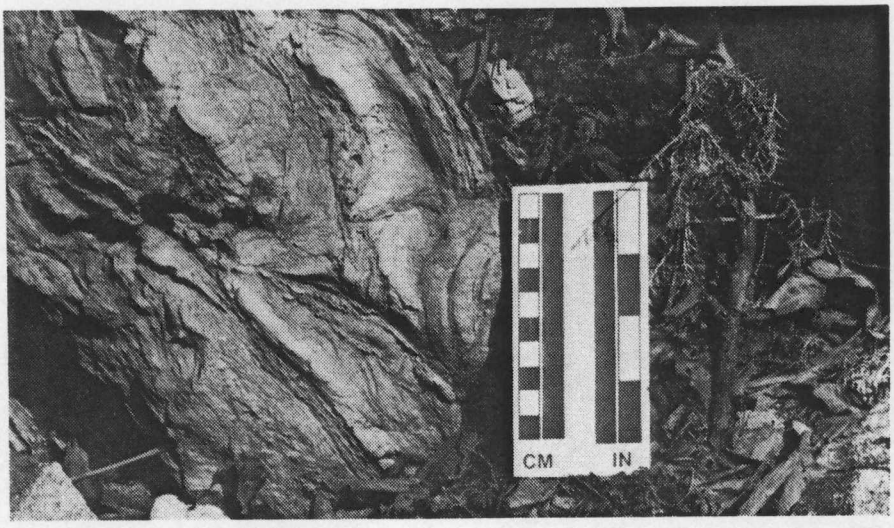


Figure 85. Planar and anastomosing solution selvages in the Moccasin Formation, Stop 6.

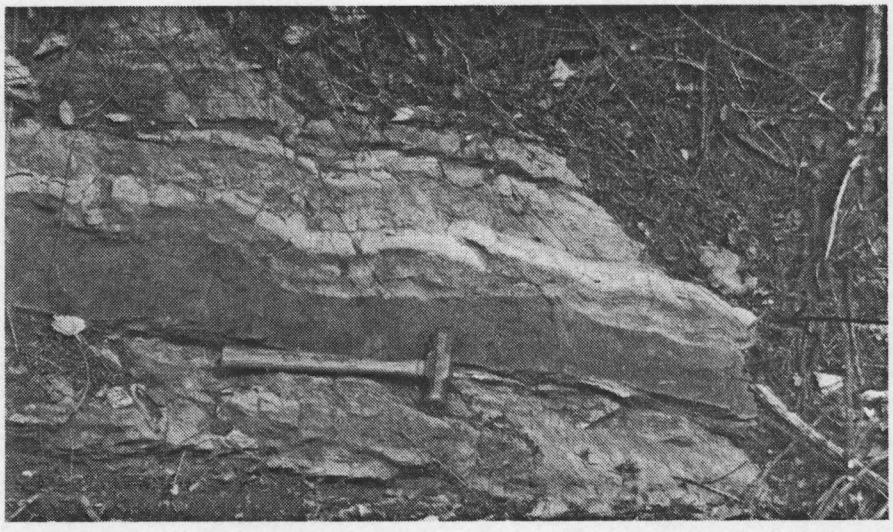


Figure 86. A limestone bed telescoped by extensive pressure solution, in the Moccasin Formation, Stop 6.

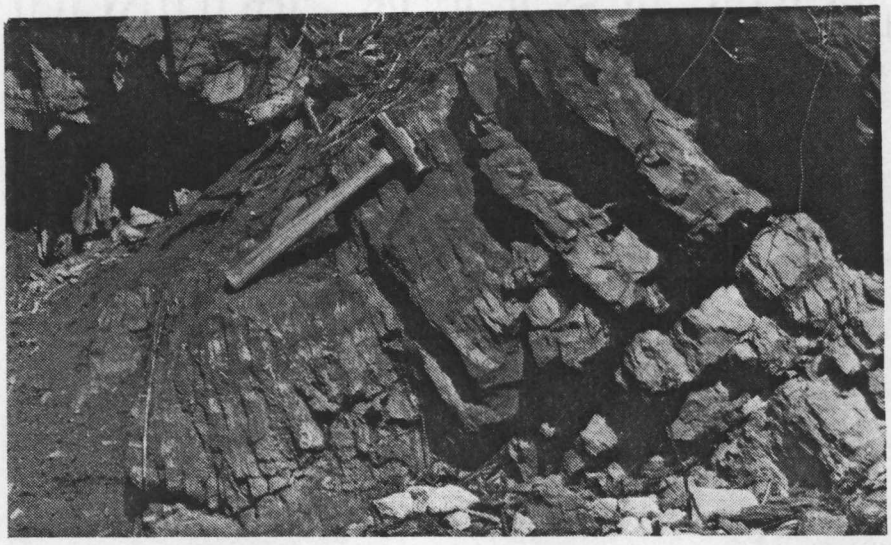




Figure 87. Two views of cleavage in the Moccasin Formation at Stop 6. In each case, the hammer is parallel to bedding. The cleavage is a solution cleavage and is steeply inclined with respect to bedding.

discussed the relationship between carbonate lithology and the development of solution cleavage, and they found that at 10% and greater terrigenous clastic components, cleavage is more likely to develop. The Moccasin appears to confirm their findings.

1.2	39.65	Return to Corryton. At the junction with Corryton Road, <u>turn left</u>
0.4	40.05	Intersection with Emory Road.
0.2	40.25	Exposure on the right-hand (west) side of the road of the Moccasin Formation. Attitude of bedding is N55°E, 50° southeast.
0.2	40.45	House Mountain is on the horizon facing south-southeast.
0.3	40.75	Outcrop of folded Moccasin Formation. Fold axes at the outcrop trend N50°E to N60°E. Beds strike between N40°E and N60° E, dipping 40° to 45° southeast, or 72° to 76° northwest. Fractures and veins are well developed. Veins are typically filled with sparry calcite.
0.2	40.95	Junction with Washington Pike. <u>Turn right</u>
0.2	41.15	Junction with Childs Road. <u>Turn left</u>
0.6	41.75	Junction with Walker Road. <u>Bear left</u> and stay on Childs Road.
1.0	42.75	Junction with Idumea Road. <u>Bear right</u> onto Idumea Road.

0.4	43.15	The Martinsburg Formation is exposed on the right-hand (southwest) side of the road. An overturned syncline is found at this outcrop which may coincide with the axis of the House Mountain syncline. Beds dip between 40° and 83° southeast. Shale beds are tightly folded and heavily fractured. Several small faults cut the outcrop.
0.2	43.35	Exposure of the Martinsburg Formation, right-hand (southwest) side of the road. The outcrop consists of thin- to medium-bedded limestone interbedded with thin shales. Attitude of beds is uniform at N60°E, 29° southeast, overturned. The limestone beds exhibit a set of fractures which are perpendicular to bedding. Veins are common, filled with sparry calcite, and are up to 1 cm wide. Pressure solution selvages are abundant.
1.4	44.75	McAnnally Ridge. The ridge is held up by massive sandstones in the Rome Formation, and it is cut by the Saltville thrust. The fault is not exposed. The Martinsburg Formation constitutes the footwall.
0.4	45.15	Junction with Rutledge Pike. Turn right.
1.3	46.45	Junction with Millertown Pike. Turn right. Millertown Pike is underlain by the Rutledge Limestone, which is only exposed as weathered blocks along the road.
1.3	47.75	Junction with Roberts Road. Turn right.

0.3	48.05	Junction of Roberts Road and Sunrise Road. Pull off onto Sunrise Road. STOP 7(Turn left back onto Roberts Road to continue the road log).

STOP 7

THE ROME FORMATION IN THE SALTVILLE THRUST SHEET

The Rome Formation is exposed along Roberts Road at its junction with Sunrise Road (Fig. 88). The Saltville thrust, which is not exposed, lies approximately 100 to 200 m west of the outcrop. In this area, the Saltville includes the main fault and a small imbricate of Rome in front of it.

The west end of the outcrop consists of tan to brown and maroon sandstone beds, 10 to 80 cm thick. The beds dip to the southeast at 45° to 53°, and are cut by fractures of moderate dip (Figs. 89 and 90). The sandstones are overlain by siltstone and sandstone beds up to 7 or 8 cm thick interbedded with very thin shale laminae. Some of these beds are folded; individual folds are up to 10 cm wide and trend N50°E to N60°E (Fig. 91a). These beds are overlain by tan to brown siltstone beds which are up to 4 cm thick interbedded with gray and maroon shale beds, 1 to 2 cm thick. These beds are folded and folds also trend N50° to N60°E (Fig. 91b).

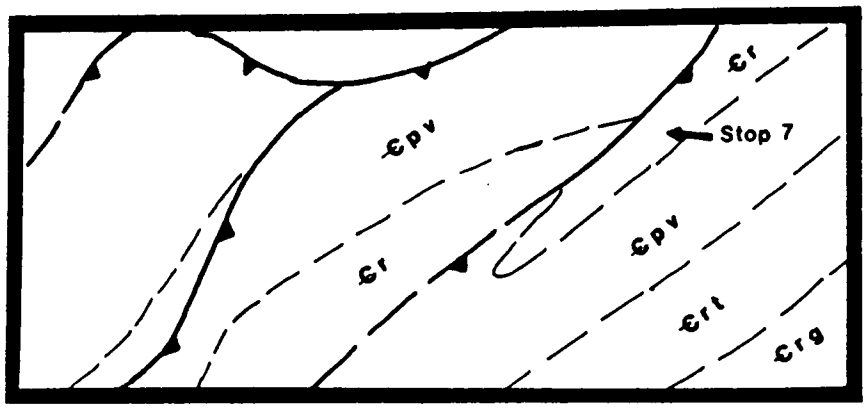


Figure 88. Geologic map showing the location of Stop 7. The map is copied from Plate I, therefore the scale is 1:24,000.

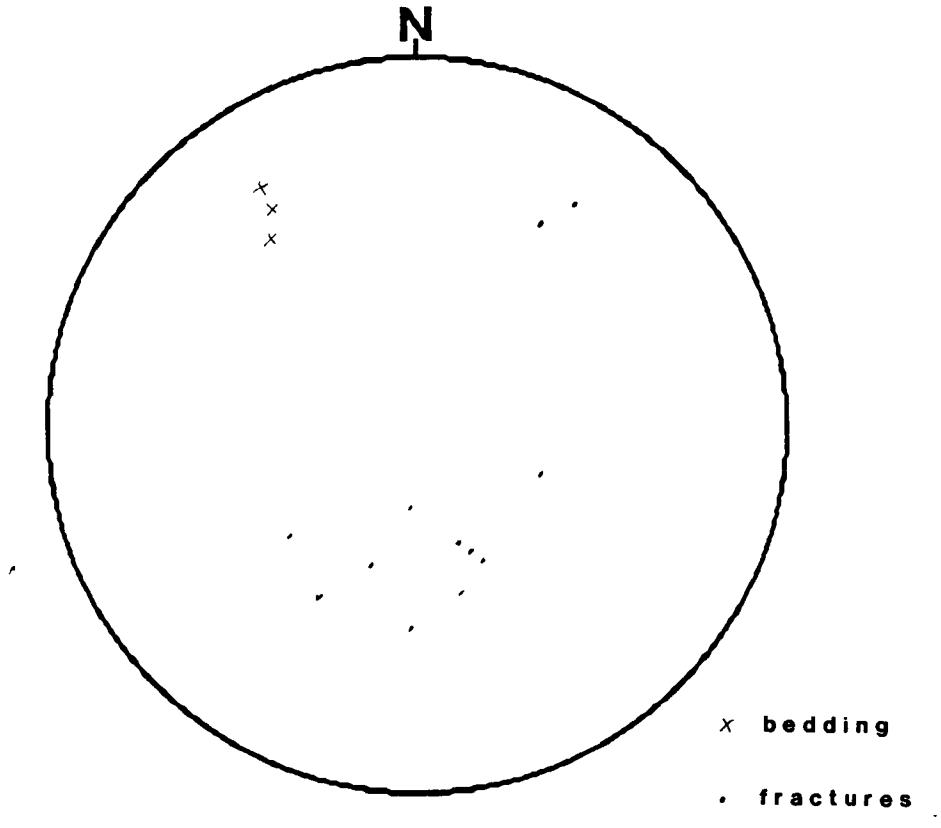


Figure 89. Stereographic projection of poles to bedding and fractures from Stop 7.

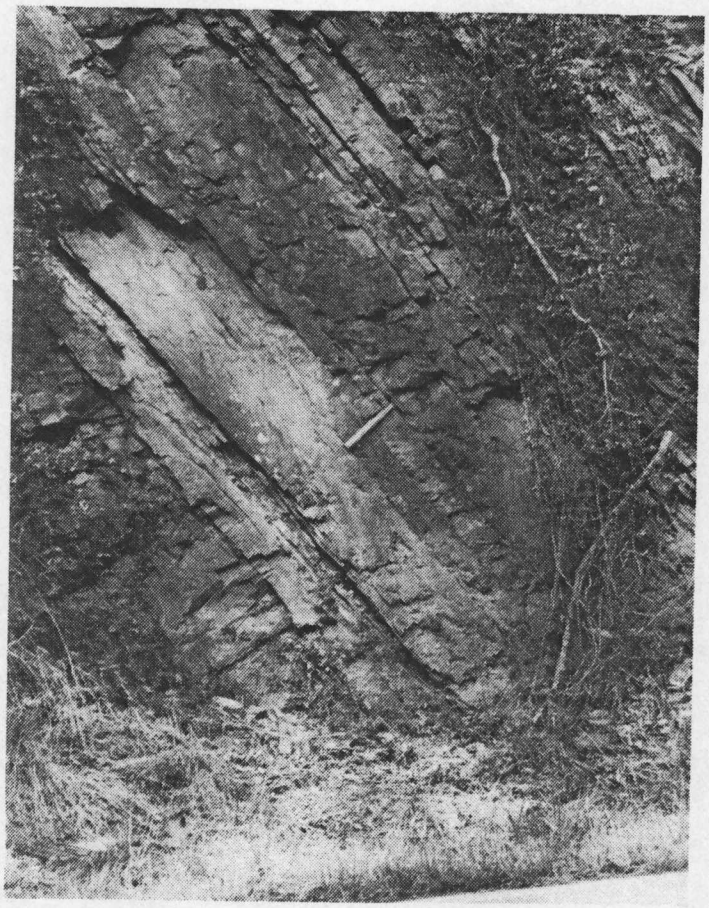
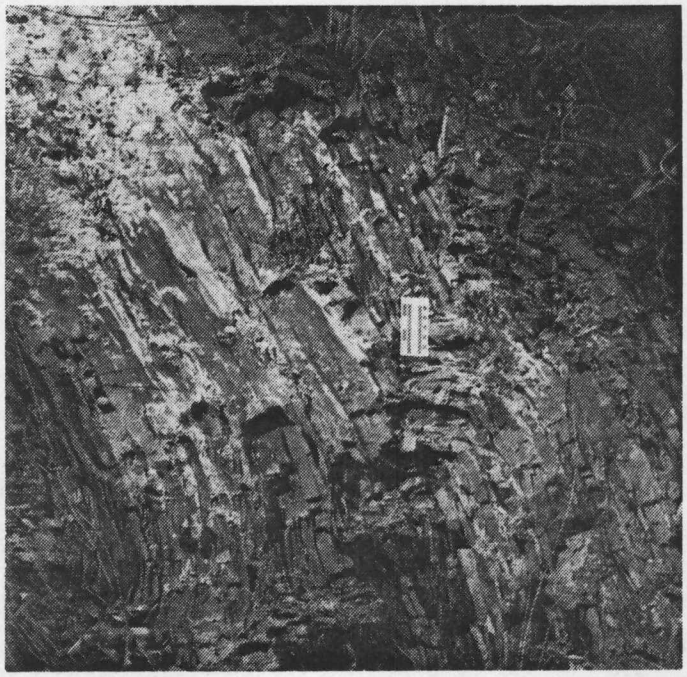


Figure 90. Tilted and fractured sandstone beds from the Rome Formation in Stop 7.



A



B

Figure 91. Two views of folding in the Rome Formation at Stop 7. A) Folds in interbedded siltstone and sandstone. B) Folds in interbedded siltstone and shale.

This outcrop demonstrates the effect of varying rock strength and bed thickness on deformational style. The thick and stronger sandstones are tilted and noticeably fractured. The weaker and thinner siltstones and shales are folded and appear somewhat less fractured. The outcrop also demonstrates how deformation intensity drops greatly only a short distance from the thrust in the study area. Despite the proximity to the fault, deformation at the outcrop is not striking.

0.2	48.25	Outcrop of the Rome Formation on the right-hand (north) side of the road. Beds dip 30° to 40° southeast. Continue on Roberts Road. The road cuts through the Martinsburg and Moccasin formations and Chickamauga Group carbonates; all of these are largely covered by vegatation.
2.5	50.75	Intersection with Washington Pike. Turn right, then turn left to continue on Roberts Road.
1.2	51.95	Intersection with railroad tracks. Along the railroad tracks are exposures of Chickamauga Group carbonates.
0.2	52.15	Junction with Emory Road. Turn right
0.5	52.65	Chickamauga Group carbonates on the left-hand (north) side of the road. Beds are dipping 20° southeast.
1.3	53.95	Intersection with Corryton Road.

0.15	54.1	Moccasin Formation on the right-hand (south) side of the road; beds are dipping 65° southeast.
0.45	54.55	Dan McBee Road branches off to the left.
1.6	56.15	Intersection with Route 61. Turn left onto Route 61. The southwest end of Clinch Mountain is on the horizon. Exposures of the Clinch Sandstone are visible through the trees. The road is underlain by the Martinsburg Formation.
2.5	58.65	Pull off Route 61 onto the (unnamed) side road STOP 8 (Turn right back onto Route 61 to continue the road log).

STOP 8

THE MARTINSBURG FORMATION

The Martinsburg Formation is exposed in an outcrop on Route 61, approximately 1.5 km south-southeast of Luttrell. The folding and faulting exhibited in this outcrop reflects its proximity to the southwest end of Clinch Mountain and the northeast end of the Beaver Valley thrust.

The poorly exposed northwest end of the outcrop is mostly gray to olive shale with limestone interbeds. Exposed limestone beds strike N60°E and dip 65° southeast. Many of the beds contain the graded bedding described by Walker and Diehl (1985). The beds are fractured but not



Figure 92. An asymmetric fold in limestones of the Martinsburg Formation at Stop 8. The hammer is for scale.



Figure 93. A close up view of a fold in a limestone bed of the Martinsburg Formation at Stop 8. The fold is cut by calcite veins. The pencil is approximately 14 cm long.

heavily; fractures are generally perpendicular to bedding. This portion of the outcrop passes into limestone beds up to 7 cm thick interbedded with shale. Solution selvages are obvious. Veins filled with white calcite are steeply inclined (70° to 90 °) to bedding and up to 3 mm wide. Several asymmetrical folds are developed, with fold axes trending N60°E (Fig. 92). Beds on fold limbs dip between 47° and 85°. Veins of calcite are developed, and, in one fold, become narrower from outer to inner arc of the fold (Fig. 93).

Adjacent to the folds is a mostly covered area. Several limestone beds are visible, and these dip between 60° southeast and vertical. The remainder of the outcrop consists of limestone beds steeply dipping to the southeast. A small thrust fault cuts the beds (Fig. 94), and its presence is marked by a zone of chaotic bedding, wedging, and pulverized rock. Veins are well developed and are generally perpendicular to bedding. The veins are filled with white calcite and are up to 4 or 5 mm wide. The southeast end of the outcrop is partially covered and contains limestone beds dipping between 80° southeast and vertical.

0.7	59.35	Junction with Corryton - Luttrell Road. Bear right, and remain on Route 61. The exposure at the junction is weathered shale of the Martinsburg Formation. Bedding is indistinct.



Figure 94. A small faulted zone in the Martinsburg Formation at Stop 8. Position of the thrust is indicated on the photograph. The hammer is for scale.

0.3	59.65	Luttrell, TN; remain on Route 61.
0.6	60.25	Junction with Route 131. Stay on Route 61.
0.7	60.95	Exposure of the Mascot Formation; attitude of the beds is N65°E, 40° southeast.
0.3	61.25	Turn left and stay on Route 61 north. The road cuts downsection through the Chickamauga and Knox Groups, which dip 30° to 60° southeast.
1.7	62.95	Exposure of the Maryville Limestone on the right-hand (north) side of the road. Bedding attitude is N50°E, 35° southeast. Fractures are developed which strike northeast (N40° - 45°E), and dip steeply (60° to 75°) northwest. Bedding thins up-section.
0.4	63.35	Exposure of the Pumpkin Valley Shale, dipping steeply to the southeast left-hand (south) side of the road.
0.1	63.45	Exposure of the Rome Formation, adjacent to a fault of the Copper Creek thrust system.
0.3	63.75	Exposure of the Rome Formation on the right-hand (north) side of the road. This exposure is northeast of the approximate termination of fault B of the Copper Creek thrust system. Note that some beds are horizontal.
2.3	66.05	Junction with Route 33. Turn left. Follow the road back to Knoxville.

3.2	69.25	Southeast dipping beds of the Benbolt Formation (Chickamauga Group) on the right-hand (west) side of the road.
4.6	73.85	Junction with Route 61, Paulette, TN. Continue south on Route 33.
8.2	82.05	Halls Crossroads, junction with Emory Road. Continue on Route 33.
4.9	86.95	Fountain City, junction with I-640. End of the road log.

VITA

Charles Talbott Lutz was born on September 14, 1959 in Washington, D. C.. He attended public schools in Fairfax County, Virginia and graduated from Thomas Jefferson High School, Alexandria, Virginia in June of 1977. In September of 1977 he entered the College of William and Mary in Williamsburg, Virginia. He received a Bachelor of Science degree from the College in May of 1981.

Charlie entered the University of Tennessee, Knoxville in September of 1981 and began work on a Master of Science in geology. In January of 1982 he accepted an offer to bypass the master's program and work on a doctorate. He completed the Ph.D. degree in the Fall of 1987.

Charlie is currently employed by Oak Ridge Associated Universities as a post-doctoral research fellow, and works at Oak Ridge National Laboratory in the Environmental Sciences Division. He is a member of the Geological Society of America, the American Association of Petroleum Geologists, the American Geophysical Union, and Sigma Xi. Charlie and his wife Kris live in relative obscurity in Karns, Tennessee along with their cats, Randle and Elvis.