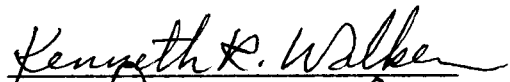
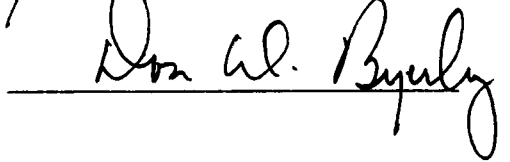


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STRATIGRAPHIC CONTROLS OF THRUST FAULTING
AND THE STRUCTURAL EVOLUTION OF THE
WARTBURG BASIN, TENNESSEE

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Everett Rutherford, Jr.

March 1985

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ABSTRACT

The Wartburg Basin is a broad area of little deformed rocks which protrudes into structurally disturbed portions of the Cumberland Plateau and northwestern Valley and Ridge. Northeast of the protrusion the Pine Mountain fault system is characterized by a classic staircase geometry. Southeast of the Wartburg Basin the Chattanooga thrust segment of the Pine Mountain system assumed a more listric thrust shape and cut up-section to a higher stratigraphic position above the presently preserved Wartburg Basin. The two contrasting thrust shapes are joined laterally by a suite of transitional structures, including a major lateral ramp, which is surficially expressed as the Jacksboro tear fault. Subsequent erosion has exposed the Wartburg Basin as the undeformed footwall to the Pine Mountain thrust system.

Classically, the evolution of lateral structures has been attributed to "along strike" changes in the distribution of structural units within a sedimentary succession. An evaluation of the stratigraphic units encountered by the Pine Mountain thrust system led to the distinction of five structural units. Unit 1 is the basal weak layer and consists of the Rome Formation and the Conasauga Shale. Unit 2 is dominant strong layer in the sedimentary wedge and is composed of the Maynardville Limestone, the Knox Group, and the Chickamauga Group. Unit 3 is the primary upper-level weak unit and includes the Reedsville Shale, Sequatchie Formation, Chattanooga Shale, and the Grainger Formation. Unit 4 is a strong layer whose members are from

the Mississippian carbonate section. Finally, unit 5 behaved as a weak unit during deformation and consists of the Pennington Shale and the lower portion of the Crab Orchard Mountain Group.

The pronounced lateral change in structural geometries of the Pine Mountain thrust system occurred in response to the loss of the Grainger Formation, and much of the Chattanooga Shale, from structural unit 3 due to southwesterly thinning of the two shale sections. This change in the character of structural unit 3 is paralleled by a progressive change in modes of upper-level detachment. Along the central portion of the Pine Mountain fault trace extensive detachment is by sole thrusting or duplexing in the upper parts of unit 3. As the Grainger and Chattanooga thin to the southwest, duplexing becomes more prominent and the floor thrust to the detachment lowers in stratigraphic position. Southwest of the Jacksboro fault, detachment is by blind imbrication off of a poorly developed flat in the Reedsville Shale. The lack of an extensive upper-level detachment southwest of the Jacksboro fault resulted in increased fault angles, thus prompting the development of a more listric fault shape.

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CHAPTER 1

INTRODUCTION

A major concern in structural geology is the problem of what factors control the evolution of structures. The geometric evolution of thrust faults is considered to be closely associated with the physical properties of rocks through which they propagate. John L. Rich (1934), in reference to the Cumberland over thrust block (Pine Mountain thrust sheet) of Tennessee, Kentucky, and Virginia, suggested that thrust faults tend to lie parallel to bedding while in weak rocks that provide planes of "easy gliding," and they "break diagonally across more brittle rocks" (Rich, 1934, p. 1589). With the modification that thrusts climb slowly up-section through weak rocks and rapidly up-section through strong rocks, Rich's hypothesis has been considered a fundamental geometric rule for thrust faulted terrains (Dahlstrom, 1970, 1977). Additionally, Dahlstrom (1970) points out that the three dimensional distribution of lithologies within a sedimentary succession will dictate the three dimensional stratigraphic position of a thrust fault, and changes in the position of a fault may occur perpendicular, parallel, or obliquely to the direction of tectonic transport. Consequently, any attempt to describe and explain structural geometries should include an analysis of the distribution of weak and strong rocks in the undeformed sedimentary wedge. A major problem, however, is that while stratigraphic controls of structural development is a popular concept, documentations of changes in

structural style resulting from stratigraphic changes are few. Thus, the objective of this study is to further investigate macroscopic deformation and changes in geometric expression with respect to the distribution of rock properties in the Pine Mountain thrust system of Tennessee.

The Area of the Study

The area chosen for this investigation lies in the western margin of the Valley and Ridge thrust belt of Tennessee. The primary area of interest falls in Anderson, Campbell, and Scott Counties of Tennessee; however, portions of adjacent Tennessee counties as well as parts of southeastern Kentucky and southwestern Virginia are addressed (Plate 1, in pocket).

The unusual structural configuration of this area makes it ideal for attempting to judge the amount of control which was exerted on propagating thrusts by the stratigraphic array. The most intriguing aspect of this region is the conspicuous protrusion of a broad area of little disturbed rocks into structurally disrupted portions of the Cumberland Plateau and northwestern Valley and Ridge. This relatively undisturbed area is known as the Wartburg Basin and is defined as being bound on the northeast by the Jacksboro tear fault and Pine Mountain thrust sheet, on the southeast by the Chattanooga fault, and on the southwest by the Emory River fault and Cumberland Mountain overthrust sheet. The structures of primary concern in this report are the Jacksboro, Pine Mountain, and Chattanooga faults.

The projected cutoff line (line marking the truncation of a horizon by a fault) for the top of the Rome Formation in the Pine Mountain system indicates that a part of the Pine Mountain thrust sheet once covered the southeastern edge of the Wartburg Basin (Fig. 1), but to the northeast the fault lies at a lower stratigraphic position. In the immediate study area three major faults are named at the surface, the Pine Mountain thrust, the Jacksboro tear fault, and the Chattanooga thrust; however, only one thrust system exists in the area. Since the Pine Mountain and Chattanooga plates are continuous along strike, they must belong to the same thrust sheet. Thus, the Jacksboro fault lies in a transitional area between two areas of differing fault-stratigraphic positions in the Pine Mountain thrust system, and therefore, is a lateral ramp. Strictly speaking, the entire length of the fault trace from south of Harriman, Tennessee, including the Jacksboro fault, to its termination in Virginia, should be called the Pine Mountain thrust, and the name "Chattanooga" thrust should be reserved for a fault system which occurs from south of Harriman southward through the Chattanooga, Tennessee area, reaching a terminus in Alabama.

Previous Investigations

Previous investigations in the vicinity of the study area are numerous. Modern geologic cross sections through the area have been offered by many workers (Englund, 1968; Harris, 1970; Harris and Milici, 1977; Horton, 1977; Milici, 1979; Miller, 1973; Roeder et al., 1978; Woodward, 1983). Of these, however, only the detailed sections

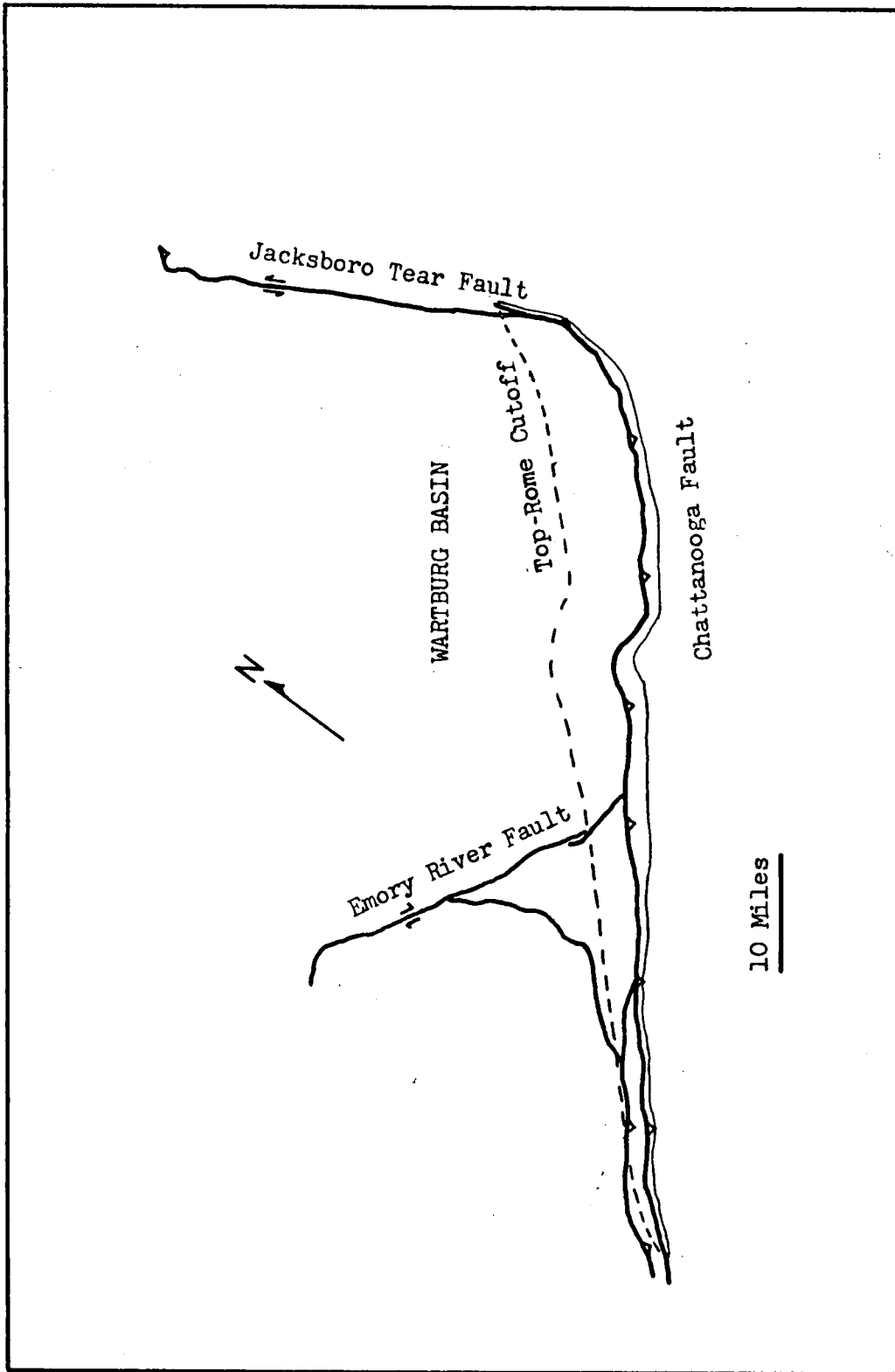


Figure 1. Projection of top-Rome-Formation cutoff-line from along the Jacksboro fault to the southern extent of the Pine Mountain thrust indicates that a portion of the thrust sheet once covered the southeast margin of the Wartburg Basin.

of Englund (1968) and Horton (1977) were constructed at a sufficiently large scale to adequately show geometric relationships. Additionally, Horton studied mesoscopic fabric data from the area of the Jacksboro reentrant, and Masuoka (1981) and Slusarski (1979) presented fracture studies for portions of the Wartburg Basin and the Cumberland Plateau northwest of the frontal area of the Pine Mountain fault. Earlier cross sections of Byerly (1957), Jackson (1956), and McCallum (1958) were used as aids in establishing near surface structural relationships, but the depth of interpretation on these sections is limited to 2,000 feet below mean sea level. References to stratigraphic studies in the area are numerous as well (Appendix B).

Three studies conducted in the region are of particular importance. These are Harris (1970), Milici (1979), and Miller (1973). Harris was the first to document the Jacksboro faults role as a lateral ramp in the Pine Mountain thrust system and the importance of other lateral structures in the outer margin of the Valley and Ridge (i.e., the Russell Fork fault and the Emory River fault zone; also see Wilson and Stearns, 1958). The key conclusions of Harris's paper are that tear faults associated with lateral ramps reflect the shapes of thrust fault surfaces rather than different amounts of shortening within the fault systems, and that faults commonly change stratigraphic positions both in the direction of tectonic transport and longitudinally.

Miller (1973) offered another attempt at explaining the geometry of the Pine Mountain thrust sheet. In this study, the pore pressure theory of Hubbert and Rubey (1959) was used to explain the extensive

flat that underlies the Middlesboro synclinorium, as well as the basal detachment to the southeast. The important points of pore pressure theory for thrust belt geology are that lithostatic or tectonic loading of water saturated, porous, but relatively impermeable rocks can result in abnormal fluid pressures within those rocks. Once developed, these high fluid pressures may exist for long periods of time, depending on the clay content of the overpressured zone, the thickness of the overpressured sequence, and the ability of the underlying and overlying rocks to accept the escaping fluids. With increasing pore pressures, the overpressured unit becomes less resistant to shear failure, whereas the weight of the overburden is partially supported by the pore fluids. At such times less lateral stress is required to initiate motion of the upper plate. Miller pointed out that lithologies of the Chattanooga Shale, the Rockwood Formation, the Conasauga Group, and the Rome Formation are appropriate for the development of abnormally high fluid pressures, and that such high pore pressures caused the units to fail as low-angle detachments. Miller also noted that the detachment beneath the Middlesboro synclinorium drops in stratigraphic position from the Chattanooga Shale to the Rockwood and Sequatchie Formations as the Jacksboro fault is approached from the northeast. He attributes this to a thinner section of Chattanooga which is less capable of sustaining high pore pressures. Wiltschko (1977) has pointed out, however, that documentation of high pore pressures is difficult, and he sees no evidence of the mechanism being of great significance in the development of the Pine Mountain thrust system.

Milici attempted to relate the development of structures in the region to weak and strong units in the sedimentary succession; however, he employed the construction of structural cross sections as the only technique for distinguishing lithotectonic units (structural units by the terminology of this study). Milici's study pointed out gross relationships between stratigraphy and structure, it did not include an in depth explanation of contrasting structural styles within the thrust belt.

A major advantage of the study area is that detailed geologic maps have been compiled for most quadrangles at 1:24,000 and 1:31,680 scales. These maps, along with my supplemental field investigation, are the primary data base for the analysis of structural geometries presented with this report. Additionally, larger scale maps of Butts (1933), Froelich (1973), Rodgers (1953), Hardeman (1966), and McDowell et al., (1981) were useful in establishing regional structural and stratigraphic relationships.

Studies of Structural Units

Previous studies of interactions between stratigraphy and evolving thrust belt structures are uncommon. The idea that the interlayering of different rock types can be an effective stress guide was given initial credibility when Rich (1934) noticed that angles of fault-bedding intersection change as a function of the strength of the rocks being faulted. His hypothesis was simply that fault-bedding angles decrease with decreased material strength; thus, the stacking of weak and

strong lithologies is a major factor in controlling the development of fault paths. Rich's hypothesis was later tested by Douglas (1950) and Bally et al. (1966) and is currently considered a fundamental aspect of thrust belt geology (Dahlstrom, 1969, 1970).

Stacking orders do not, however, remain constant areally. Sedimentary sequences are often characterized by complex three dimensional arrangements of lithologies. If a lateral reorganization of lithologies occurs, it is probable that the arrangement of weak and strong units will change as well. It would be expected that such lithologic variations would have an effect on thrust geometries. Cook (1975) has pointed out that facies changes in the Cambrian section of British Columbia and Alberta resulted in a major change in structural style. He noted that Cambrian rocks in the western Main Ranges are dominated by shaly lithologies, and their counterparts to the east are typically more massive carbonates. The shaly section commonly deformed as a weak unit, and the carbonates usually acted as strong rocks. The area containing the approximate facies boundary is characterized by a zone of extensive imbrication. The implication is that the facies transition provided a stress guide which deflected thrusting upwards.

The example of stratigraphic controls of structural style given by Cook involves a setting for which a facies boundary is crossed in the direction of tectonic transport. Thompson (1981) has further illustrated that longitudinal variations in lithologies and unit thicknesses also affect geometries in Canada. He indicates that shortening in the

northern Canadian Rockies was taken up along flats in Devonian and Mississippian shales. This shale section thins significantly to the south, and in the southern Canadian Rockies, carbonate rocks become the major lithologic element of the Mississippian section. Thompson implies that the section becomes increasingly strong to the south, and that the resulting restacking of weak and strong units is recorded by a change in structural style. Where the structures of the northern Canadian Rockies are typically flat and blind thrusts with associated fold complexes, structures of the southern part of the thrust belt tend to be dominated by imbricate thrusts. The important result of Thompson's study is that both thickness and facies variations are important influences of structural style.

Wiltschko and Chapple (1977) have given additional documentation of thickness-structural style relationships by showing that increases in fold wavelengths and amplitudes are directly related to increases of Silurian evaporite thicknesses in the intraplateau fold belt of Pennsylvania. They also note, however, that large wavelengths can indicate that a major competent unit is present in the stratigraphic section. Similar correlations of structural style and lithologic character have been conducted by Wood and Bergin (1970) for the Anthracite region of Pennsylvania.

As previously stated, a major goal of this study is to describe how the distribution of physical properties interacted with developing thrust geometries. By noting how individual units of a sedimentary sequence deform, stratigraphic units can be reorganized into new

packages based on how the rocks comprising them deform. A unit of this type is referred to as a structural unit (Johnson, 1980) or structural lithic unit (Currie et al., 1962). Distinguishing structural units is an important step in structural analysis, because it allows better correlation of geometric development with the mechanical character of the stratigraphic sequence.

The role of structural units and layered sequences has been extensively investigated in relation to folding (Biot, 1957, 1961; Currie et al., 1962). Currie et al. pointed out that the wave length of a fold will be equal to 27 times the thickness of the dominant member. Johnson (1980) has further noted that a sedimentary sequence which is composed primarily of strong units will tend to fault instead of fold, but when interlayering of weak and strong rocks is considered, the relationship of Currie et al. holds true. Johnson states, however, that adequate development of an analogous concept for explaining thrust geometries is lacking. Thus, the study of structural unit distributions and thrust sheet geometries is a logical course for further understanding the role of distinct layers in thrust belt mechanics.

There are, however, some problems with attempting to associate strength distributions within a sedimentary sequence with the development of a particular structural style. Spencer (1972, p. 40) points out that, "Changes in the physical properties which are important in the structural behavior of layered rocks do not generally coincide with recognized stratigraphic boundaries." Deciding on how structural

units are distributed, therefore, requires careful consideration of stratigraphy, structural geometries, and any relation between the two. Further explaining why a unit behaves in a certain manner is difficult and sometimes impossible; this is in part due to a relatively poor understanding of what criteria determine whether a rock will respond in a weak or strong manner when subjected to stress. This discussion limits the usages of the terms "weak" and "strong" to describing qualitative observations of the mode of unit deformation.

CHAPTER 2

METHODS AND ASSUMPTIONS

Structural Techniques

Methods and assumptions used in the analysis of structures in foreland fold and thrust belts are primarily a product of field studies and petroleum exploration in the Canadian Rockies. Fundamental geometric rules and analytical techniques for thrust terrains are drawn from several key studies. A summary of the methods and rules used in this report, as taken from Bally et al. (1966), Boyer and Elliott (1982), Dahlstrom (1969; 1970; 1977), Dixon (1982), Elliott (1981), Elliott and Johnson (1980), Price (1981), Royce et al. (1975), and Woodward (1981).

1. Cross sections constructed for this study are balanced cross sections. Balanced cross sections provide a logical method for restoring a deformed belt to its predeformational configuration by correcting for minimum and documentable amounts of shortening (see Dahlstrom, 1969; Woodward, 1981). Balanced structural sections should ideally be constructed so that they lie in the direction of tectonic transport, and further they should be positioned so that the amount of out of plane plunge is minimal (Royce et al., 1975). Price (1981) points out that lines of section may deviate slightly from true tectonic transport direction and still be considered valid. Price indicates that a deviation of 15 degrees will induce only about 4 percent length error into the system.

2. For the purpose of constructing the balanced sections, it was assumed that deformation progressed by plane strain. Under the condition of plane strain, no material movement would occur into or out of the plane of the cross section.

3. Thrust faults cut up-section in the direction of tectonic transport.

4. Thrust faults bring stratigraphically older rocks upward into higher structural levels where they are placed into fault contact with younger rocks.

5. Deformation features in foreland fold and thrust belts fall within a typical family of structures. These typical structures are: (1) concentric folds, (2) decollement (flat horizons), (3) thrusts, (4) tear faults, and (5) late listric normal faults (Dahlstrom, 1969, p. 744).

6. A structure shown in cross section must be observed in map pattern within the general region. Additionally, map pattern data may be directly extrapolated to the cross section by down-plunge projection (see Mackin, 1950). Elliott and Johnson (1980) point out that information projected down plunge should be within a kilometer or so of the line of section. Errors induced by projection of data are usually low. Elliott and Johnson further note that a 10 degree misalignment of projection of data from 2 kilometers along strike results in only about a 35 meter error at 1:250,000 scale.

7. Thrusts tend to cut steeply up-section while in strong rocks, and they cut gently up-section while in weak rocks. This

behavior gives a staircase trajectory in which steep portions of the fault plane are termed ramps, and the gently sloping portions of the fault plane are called flats. Decollements are the basal detachment surfaces.

8. Major thrusts flatten at depth and merge with a basal detachment (basal decollement), which occurs above the basement-cover contact.

9. Deformation is assumed to have progressed toward the fore-land. Thus, thrusts become progressively older toward the inner portion of the thrust belt, and older, higher thrusts are carried in piggy-back fashion above the lower, younger faults. Also, older thrusts are commonly folded above the younger thrusts (Jones, 1971), or where listric fault shapes dominate, they may be oversteepened toward the hinterland.

10. The amount of shortening between adjacent cross sections is similar.

11. Structures are relatively continuous along strike.

12. Where a younger thrust cuts up-section to a point of intersection with a higher and older thrust, the two faults merge to a single surface of displacement (Boyer and Elliott, 1982). The reuse of an older surface of displacement requires less work than cutting up through an already duplicated section, and thus is the preferred route. This isolates a horse along the fault; a group of horses stacked together is called a duplex.

13. Thrusts may cut up- or down-section longitudinally. Such lateral or oblique ramping commonly results in the development of tear faults or hanging-wall drop faults (Butler, 1982).

14. Stratigraphic separation diagrams, fault preference diagrams, and map-view dimensions of horses were employed to aid in deciding on the stratigraphic positions of ramps and flats for cross section construction.

The balanced structural cross sections constructed for this study, along with several taken from Woodward (in prep.), were used to construct a palinspastic map of the area. These maps are constructed by laterally connecting several parallel restored cross sections. Palinspastic maps are an excellent way of making sure that adjacent cross sections are geometrically compatible. Lateral changes in amounts of shortening should be gradual, and discontinuities in shortening between adjacent sections would indicate that further work in interpretation is needed unless the discrepancy can be shown to have a sound structural explanation. Additionally, data plotted on palinspastic maps will appear in their predeformational positions; thus, thickness and lithofacies information will conform to the original configuration of a sedimentary body.

Depths to basement for the study area were arrived at by four methods: (1) use of wells penetrating basement or near basement rocks, (2) use of down-section extrapolation to basement for shallower wells (Appendix A list all well data), (3) building section downward with map thicknesses in the construction of cross sections (Roeder

et al., 1978), and (4), application of half-slope methods to aeromagnetic data. Values for individual data points were then plotted on a 1:250,000 scale base and contoured employing a contour interval of 1000 feet. Basement depths taken from this map were used along lines of cross section. The map generally agrees in form with the depth to base of deformation map presented by Roeder et al. (1978), showing a generally southeastward dipping irregular basement surface (Fig. 2); however, since the depth map of this report gives depths to basement instead of depth to the basal detachment, corresponding contour values vary between the two maps.

Description of Detachments

Historically, Valley and Ridge detachments have been represented on cross sections as being almost knife sharp surfaces contained within single stratigraphic units. Recent workers (Boyer and Elliott, 1982; Wiltschko and Chapple, 1979; Woodward, 1982; Wojtal, 1981) have noted that in many cases, a single detachment surface is very much an oversimplification. In this report several detachment types are distinguished to allow for better description of structural relationships within fault zones (Fig. 3). Also, the usage of the term detachment in this study is in the same context as the term flat.

Methods for Identifying Structural Units

The recognition of structural units involves applying several techniques. First, much can be learned about thick stratigraphic

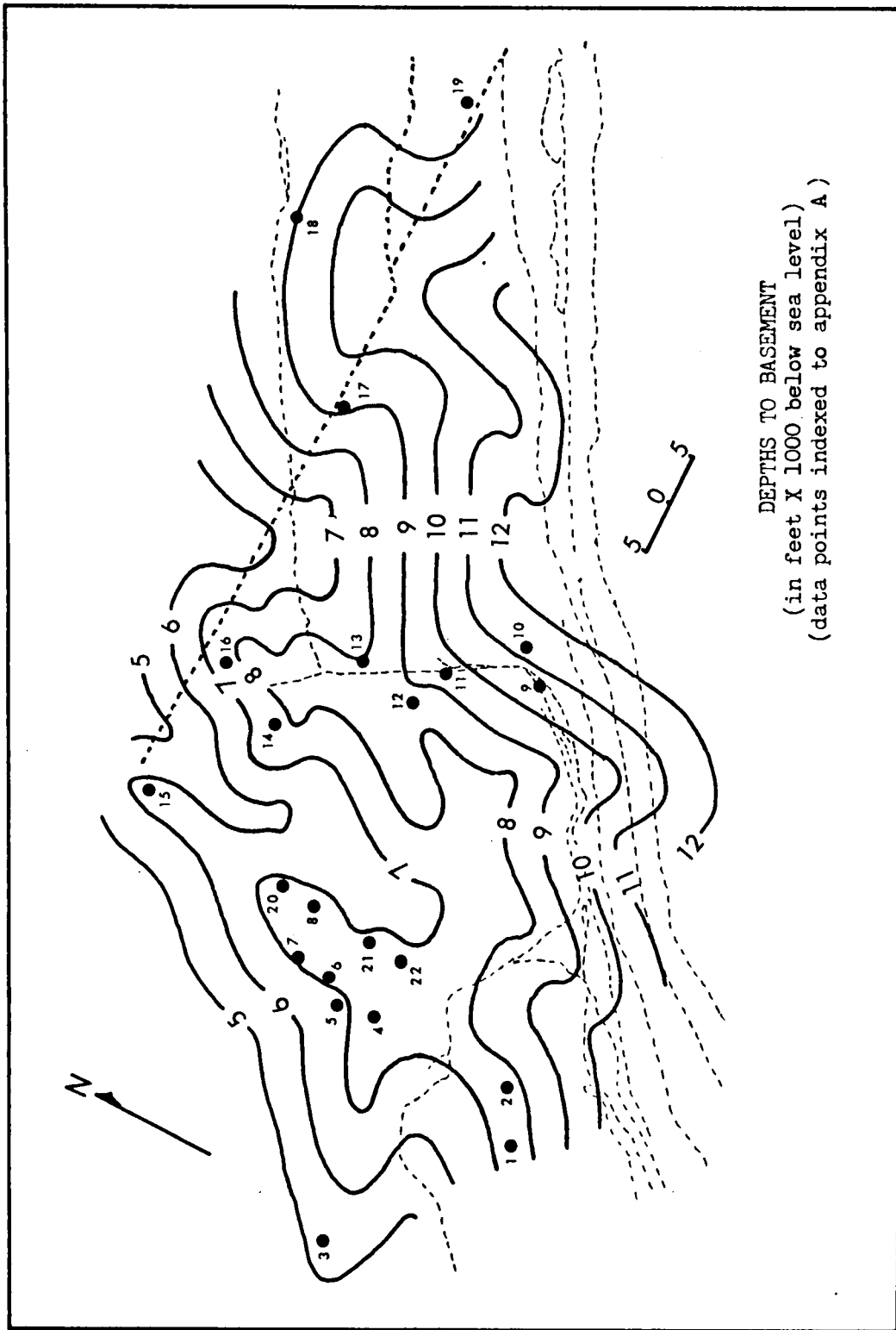


Figure 2. Basement surface slopes gently to the interior of the thrust belt. Contour form generally agrees with that of Roeder et al. (1978), but since their depths were to base of deformation, some differences are expected.

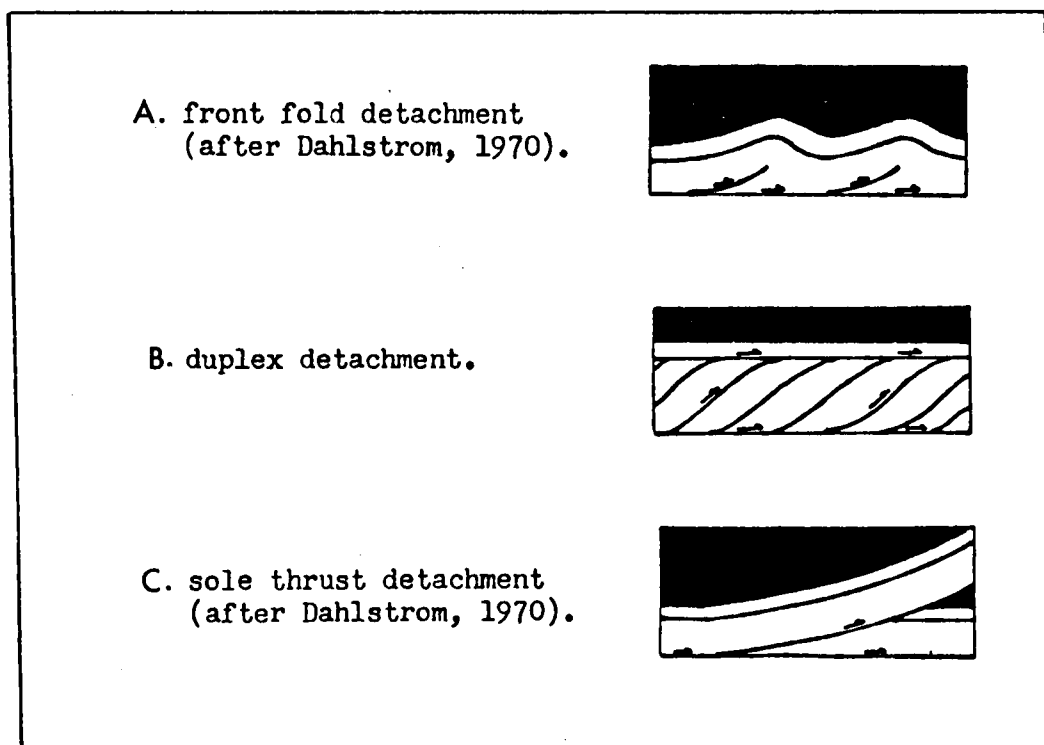


Figure 3. Three detachment types were used to describe modes of detachment: (A) front fold type, (B) duplex type, and (C) sole thrust type (Dahlstrom, 1970).

units simply from the construction of balanced structural cross sections. For a given set of structural parameters (strikes, dips, thicknesses of sections, and basement configuration), only a limited number of geometrically acceptable cross sections can be drawn. Generally, the thicker units will behave similarly for all interpretations of a given cross section. Balanced sections do not, however, allow for adequate representation of thin units, where a small misplacement of a formational contact, or fault, may represent a major thickness change, or a significant change in structural behavior. Balanced sections alone are, for the most part, too subjective to give an accurate picture of the distribution of structural units for an entire sedimentary package.

Another method involves the construction of fault preference diagrams (Dahlstrom, 1970). Fault preference diagrams are histograms that plot stratigraphic position against the distance a fault trace is in contact with individual units. Dahlstrom describes the technique as showing a relative measure of the tendency for faults to gather preferentially in specific units. Ramp-forming sections would typically show low fault-preference values, and flat forming sections would be associated with high fault-preferences. Dahlstrom's construction method for fault preference diagrams is described in Appendix C.

Fault preference diagrams have several shortcomings. First, since they summarize data from all portions of a fault trace to a single histogram, they make no allowance for the distance that a fault is in contact with individual units; thus, they give no indication of the geographic aspect of fault shape. Second, preference for an

individual unit may only be applicable for a part of the fault trace. Structural units may change in distribution along strike, and an individual units behavior may change drastically. Fault preference diagrams effectively mask such changes. Thus, they should be used for only relatively small segments of fault traces. Third, Woodward (1981) points out that fault preference histograms give different relative preferences between areas of high topographic relief and areas of less relief. This problem can be solved by projecting cutoff positions to a straight line trending parallel to the longitudinal direction of the fault, and using data taken from the straight line projection to calculate fault preference; this correction is described by Elliott and Johnson (1980) for constructing stratigraphic separation diagrams. Finally, fault preference diagrams make no distinction between hanging-wall preferences and footwall preferences; separate diagrams should ideally be constructed for both the hanging-wall and footwall.

Fault preference calculations given in this study use data from straight line projection stratigraphic separation diagrams (discussed below). Further, all fault preference diagrams are thickness corrected to the thickest unit in the stratigraphic section, and preferences are given in terms of percentages (Appendix C); this was done to facilitate the comparison of individual units with respect to relative unit strengths.

Stratigraphic separation diagrams offer perhaps a more comprehensive method for distinguishing structural units. This technique

has been successfully used by a number of workers (Elliott and Johnson, 1980; Froidevaux, 1968; Rubey, 1973; Woodward, 1982). There are two major advantages to stratigraphic separation diagrams: (1) they can provide indication of both angles and geographic positions of fault penetrations through units, thus aiding in locating the stratigraphic positions of ramps and flats, and (2) since the axes of the diagrams are stratigraphy and distance, rock property data can be plotted directly on them. Stratigraphic separation diagrams give stratigraphic positions for both the hanging-wall and footwall along a fault trace. A single fault trace will be represented by two lines on the diagram, and the distance between them represents the amount of section duplicated by thrusting. Woodward (1981) has additionally shown that fault shape information gained from stratigraphic separation diagrams is directly applicable in the construction of balanced cross sections.

Cutoff lines mapped on a palinspastic base provide a tool for showing the areal distribution of ramps and flats with respect to stratigraphy, and thus, aid in grouping stratigraphic units into structural units. For a single unit of a given thickness, the horizontal spacing between the unit base and unit top cutoff lines will reflect the angle at which the fault passes through the layer. A narrow spacing indicates a steep angle of penetration, and a wide spacing indicates a lower angle of penetration. If a unit changes from a flat forming section to a ramp forming section, the change will be recorded by a narrowing of the spacing between base and top cutoff

lines. When comparing the behavior of multiple units, thickness differences between the units should be kept in mind.

Outcrop scale observations offer direct evidence for deformational behavior. Weak units should exhibit more intensely developed deformation features than strong units (Spencer, 1972), and the style of deformation features should additionally differ between the two. In outer portions of thrust belts, temperatures and pressures are too low to lead to the development of penetrative fabrics. Where an abundance of outcrop scale structures are found, it can be assumed that either the occurrence is near a major fault, or that the unit served to concentrate deformation (Spencer, 1972).

A final method for distinguishing structural units involves noting the dimensions of horse blocks. Currie et al. (1962) have demonstrated that fold wavelengths are controlled by the thickness of the major strong unit within a sedimentary succession. Where a sequence contains a thick strong unit, folding will be characterized by long wavelengths; a lack of a thick strong unit in a section will yield short wavelength folds. Similarly, horses composed of weak material should be smaller in dimension than strong blocks. A major strong unit is referred to as a tectonic strut, that is, a strong unit capable of transmitting stresses without buckling (Wood and Bergin, 1970). Weak units cannot transmit large stresses and imbricate much more quickly, thus they should show a greater density of fault slices. A commonly given example of such a strut is the Knox Group of the east Tennessee Valley and Ridge (Smith, 1979). Although this relationship

is most commonly pointed out in major thrust sheets, the concept should hold true for outcrop scale faulting and duplexes. Placed in context with ramp and flat geometries, a duplex type of detachment in a weak zone would be composed of numerous small horses, and duplexes containing a significant strong member should be larger in dimension due to a greater ability of the strong member to transmit stress without faulting. Helton (1979) has pointed out that large single horses along Valley and Ridge thrusts are typically composed of ramp section rocks, mostly carbonates of the Knox and Chickamauga Groups. In contrast, horses derived from sections of weak rocks are smaller in size. Englund (1968) notes the occurrence of numerous small fault slices in the Devonian shales along the Pine Mountain thrust. Where imbricates propagated off of the main trace of the Pine Mountain fault and penetrated the carbonate section of the Mississippian, the dimensions of the fault slices are larger. Harris and Milici (1977) additionally note that zones of decollement within weak rocks are composed of numerous anastomosing faults, which result in abundant small horses.

Quantitative description of the mechanical nature of the sedimentary wedge can be accomplished by applying vertical variability calculations (Krumbein and Libby, 1957) to individual stratigraphic sections. The methods for calculating aspects of vertical variability are discussed in Appendix D. Values from these calculations are then contoured over the area of interest. Application of this technique allows the description of average center of occurrence and dispersion

around that center for a particular type of unit. In the case of this study, the method is applied to positions of weak rocks in the sedimentary sequence. Elsewhere, the technique has been proven effective for expressing vertical distributions of sandstones and shales (Krumbein and Libby, 1957; Doveton et al., 1984).

CHAPTER 3

STRATIGRAPHY AND STRUCTURAL UNITS

Introduction

The most complete section of Paleozoic rocks exposed in Tennessee is found within the region encompassing the Jacksboro fault. Units range in age from Cambrian to Pennsylvanian at the surface, with a maximum preserved thickness of approximately 12,000 feet occurring in the Lake City and Jacksboro Quadrangles. A detailed account of all stratigraphic units of the area is beyond the scope of this study. Instead, emphasis is placed on larger scale distributions of thicknesses and lithologies. For reference a generalized stratigraphic correlation diagram is given in Fig. 4.

Formation thicknesses and descriptions presented in this report are of three forms. Detailed descriptions are compiled from field observations and accounts of stratigraphy given by previous workers. References to regional thickness and lithologic distributions are mostly taken from the literature. As an additional source of information, well data were incorporated into the study where they are available; however, since detailed descriptions of borehole data are rare, the use of well data is primarily limited to regional studies. Wells used in this study are listed in Appendix A.

Synthesis of stratigraphic information was accomplished by way of composite stratigraphic sections (indexed in Fig. 5). Each section

SYSTEM	SOUTHWEST PORTION PINE MOUNTAIN SHEET	CENTRAL PORTION PINE MOUNTAIN SHEET	Gen. lith.
Pennsylvanian	Pcm	Pb	
	Pvm		
	Pvm		
	Pvg		
	Pib		
	Ps		
	Pcf		
Miss.	Pcg	Pl	
	Mp	Mp	
	Mn	Mn	
	Mfp	Mfp	
Dev.	Mc	Mc	
	Ss	Ss	
	Sr	Sr	
	Os	Os	
Silurian	Or	Or	
	Och	Och	
	Ok	Ok	
	Ccr	Ccr	
Ordovician	Qm	Qm	
	Ccl	Ccl	
	Cr	Cr	

Pcm = Cross Mountain Fm.
 Pvm = Vowell Mountain Fm.
 Pvm = Redoak Mountain Fm.
 Pvg = Graves Gap Fm.
 Pib = Indian Bluff Fm.
 Ps = Slatestone Fm.
 Pcf = Crooked Fork Group
 Pcg = Crab Orchard Mtn. and Gizzard Groups
 Pl = Lee Fm.
 Mp = Pennington Fm.
 Mn = Newman Limestone
 Mfp = Fort Payne Fm.
 Mg = Grainger Fm.
 Mc = Chattanooga Shale
 Ss = Rockwood Fm.
 Sr = Sequatchie Fm.
 Or = Reedsville Shale
 Och = Chickamauga Group
 Ok = Knox Group (undevided)
 Ccr = Upper Knox
 Ccr = Copper Ridge Dolomite
 Cc = Conasauga Group (undevided)
 Qm = Maynardville Limestone
 Ccl = Conasauga Shales
 Cr = Rome Fm.

Pb = Breathitt Group
 Pl = Lee Fm.

Ss = Seelsville Limestone
 Sh = Hancock Dolomite
 Scl = Clinton Fm.
 Sc = Clinch Fm.

EXPLANATION OF SYMBOLS

Figure 4. Stratigraphic correlation diagram shows nomenclature and common lithologies for the southern portion of the Pine Mountain thrust system. Formational symbols shown are used on maps and cross sections.

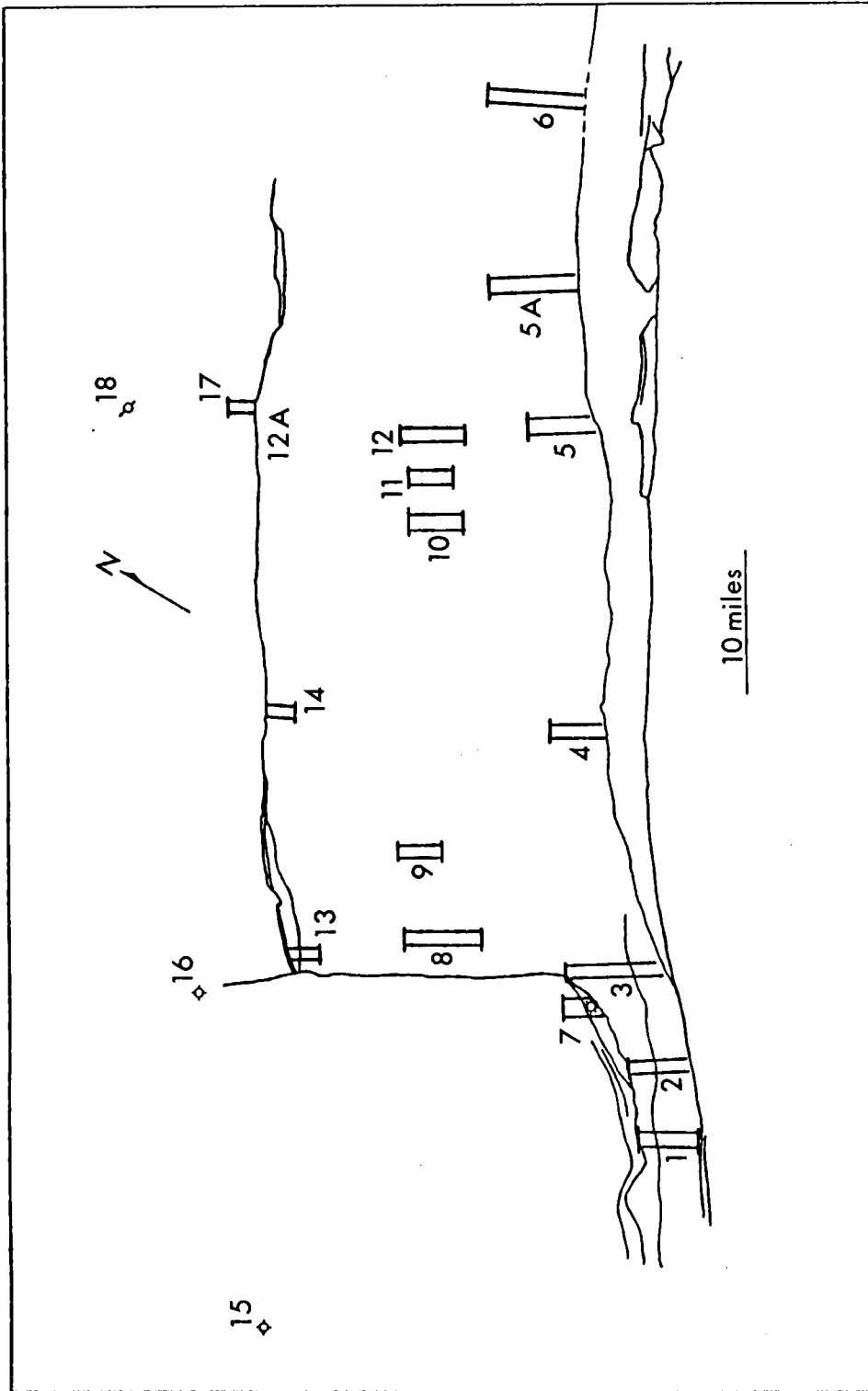


Figure 5. Eighteen primary areas of stratigraphic description were used to develop composite stratigraphic sections. Each of the eighteen points represents data compiled from field observations for this study and information taken from literature (Appendix B).

summarizes data for a portion of a single thrust sheet from an area generally limited to the size of a single quadrangle. References for each composite stratigraphic section are given in Appendix B. The balanced structural cross sections presented in this report, and those taken from Woodward (1984), were used to construct the palinspastic map shown in Fig. 6. The composite stratigraphic sections were plotted on the palinspastic base and used to construct regional restored stratigraphic cross sections (Figs. 7 through 12). Restored isopach maps were also constructed for all units except for those that were not significantly involved with deformation, or where the data were unreliable. Stratigraphic data plotted on palinspastic maps appear in their predeformational positions; thus, thickness and lithofacies information will roughly conform to the original configuration of a sedimentary body.

The discussion of unit lithologies, thicknesses, and groupings of units into structural units as presented below applies primarily to the eastern margin of the Wartburg basin, the southern extent of the Pine Mountain thrust sheet, and to the Kingston thrust sheet (composite stratigraphic sections 1, 2, 3, 7, 8, 9, 13, and 16); however, regional relationships are briefly discussed. Unit descriptions are purposely kept brief and are intended to set the stage for the presentation of structural analyses. Where detailed knowledge of a unit is required for understanding structural relationships, more extensive descriptions are provided. Additionally, a structural unit correlation is given in Fig. 13.

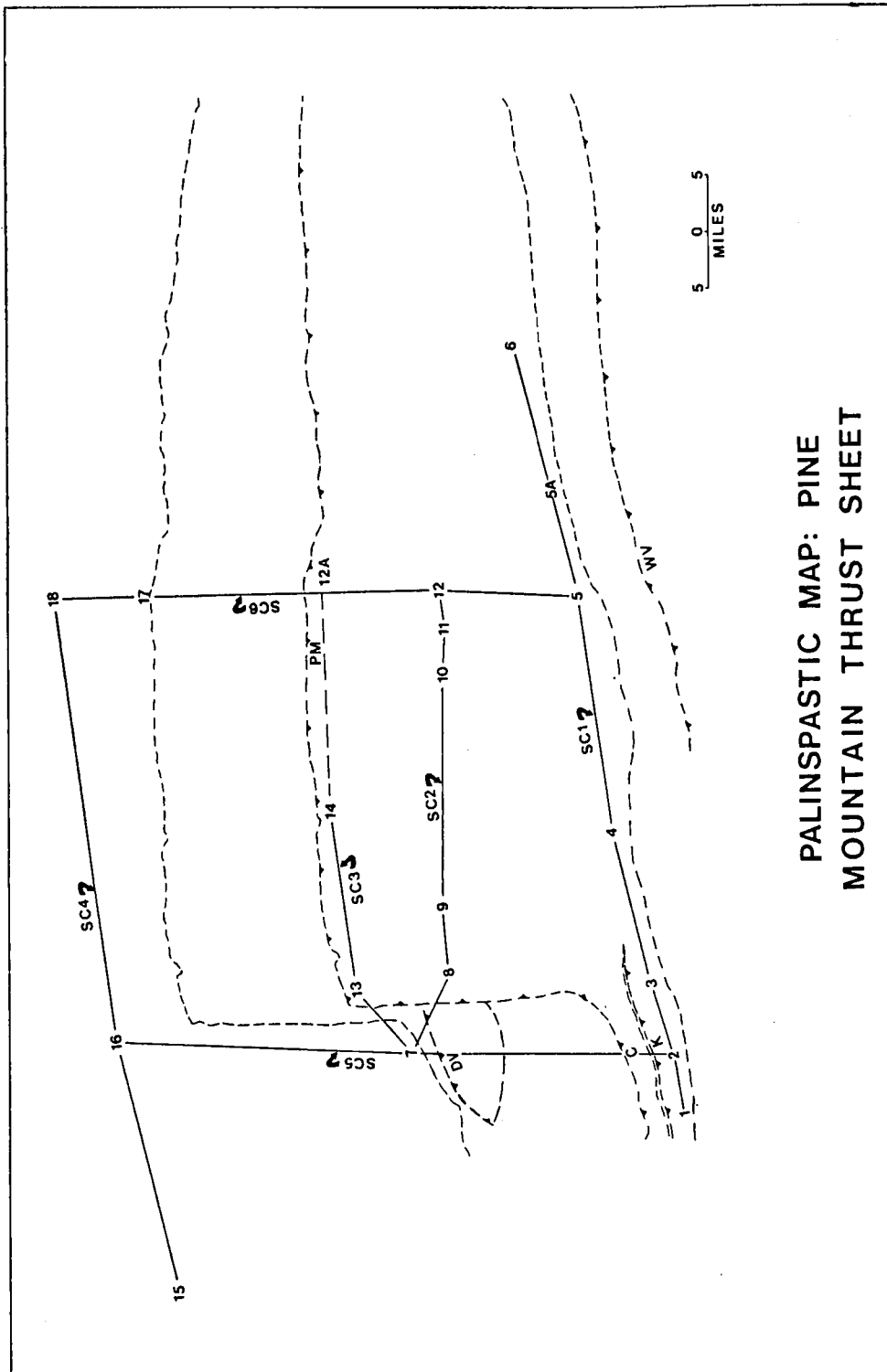


Figure 6. Palinspastic map of the Pine Mountain and adjacent thrust systems, with lines of stratigraphic cross sections. Restoration of the area is based on the balanced structural cross sections of this study and several taken from Woodward (in prep.).

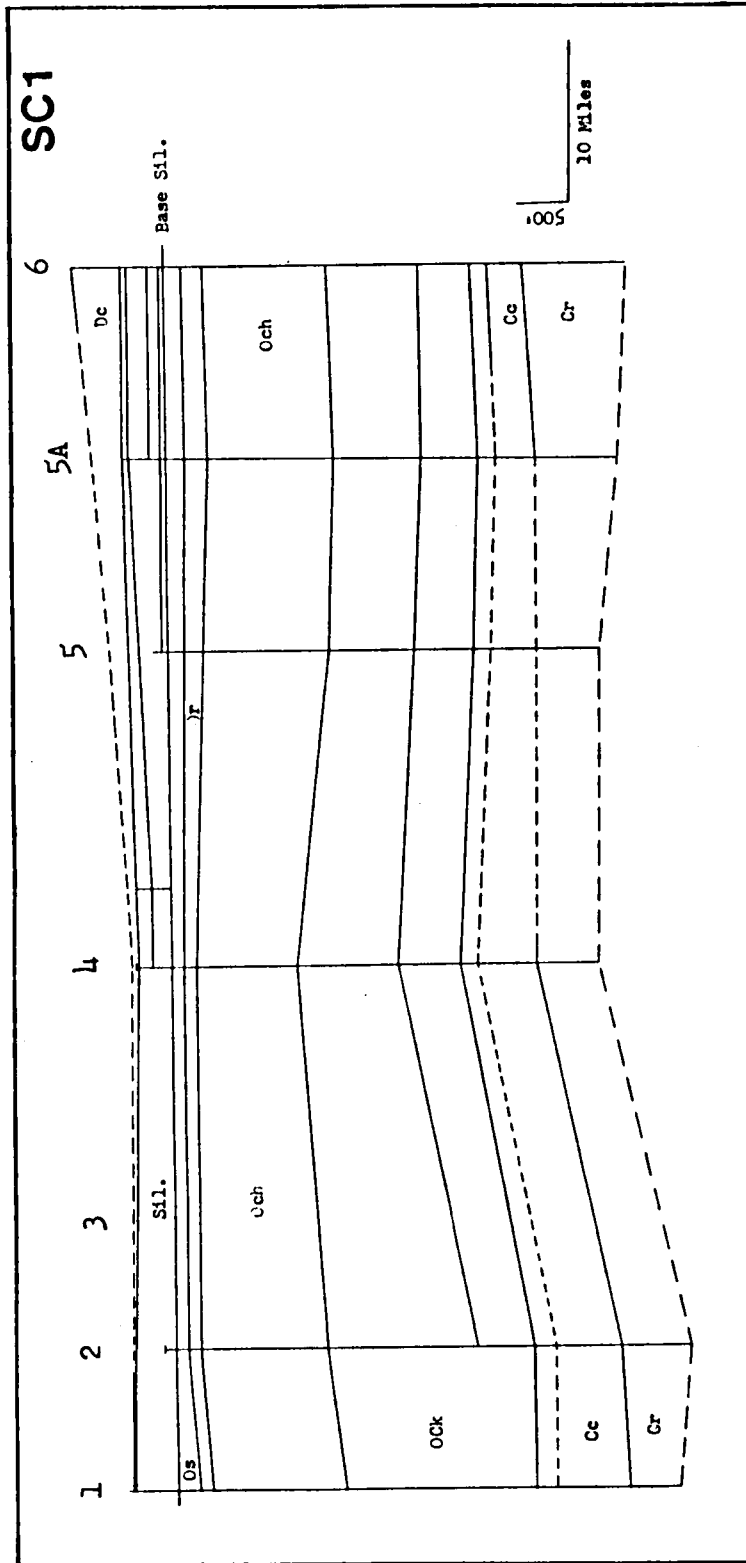


Figure 7. Restored stratigraphic cross section constructed along the southeast limb of the Powell Valley anticline. Datum is the base of the Silurian. Line of section is indexed to Figure 6, p. 29.

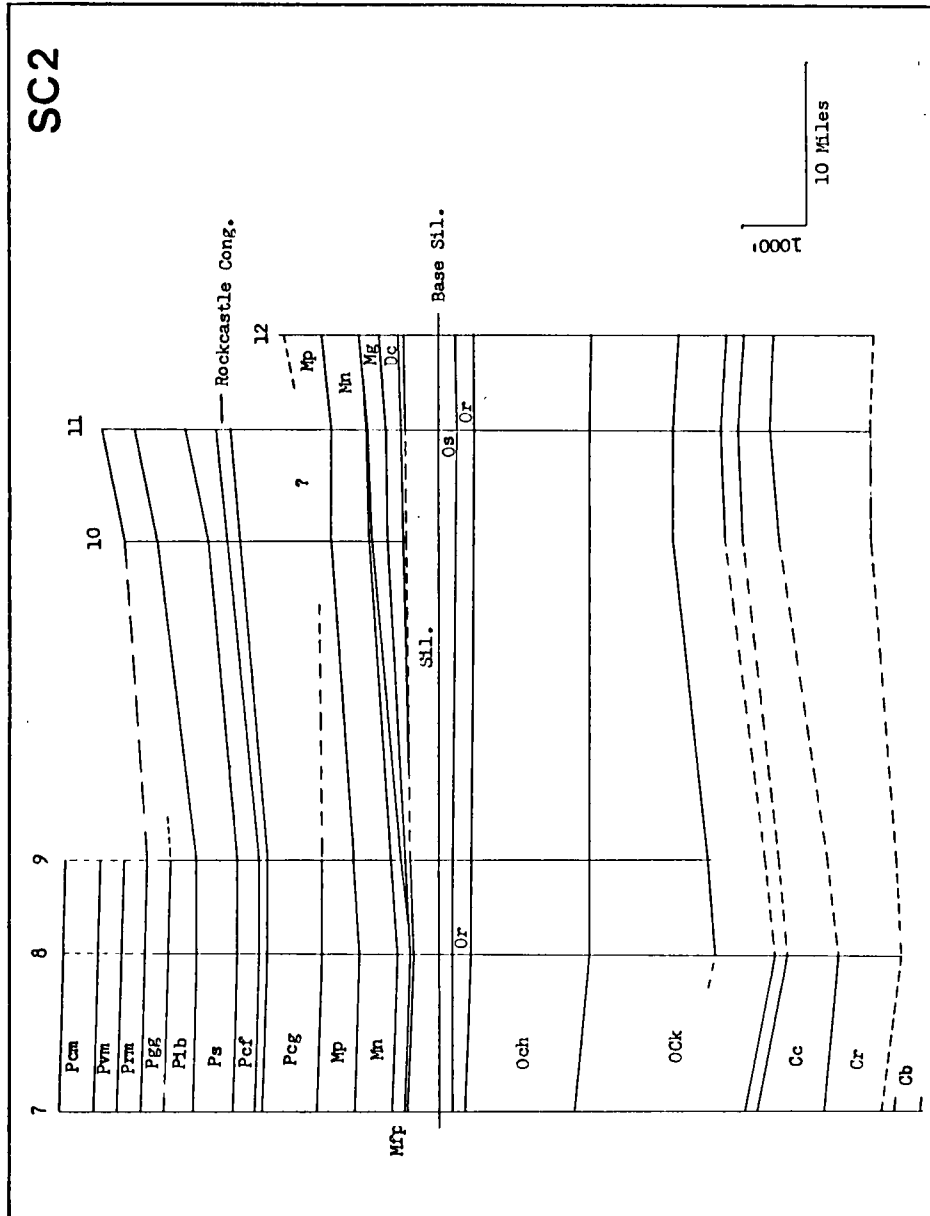


Figure 8. Restored stratigraphic cross section constructed along the northwest limb of the Powell Valley anticline. Datum is the base of the Silurian. Line of section is indexed to Figure 6, p. 29.

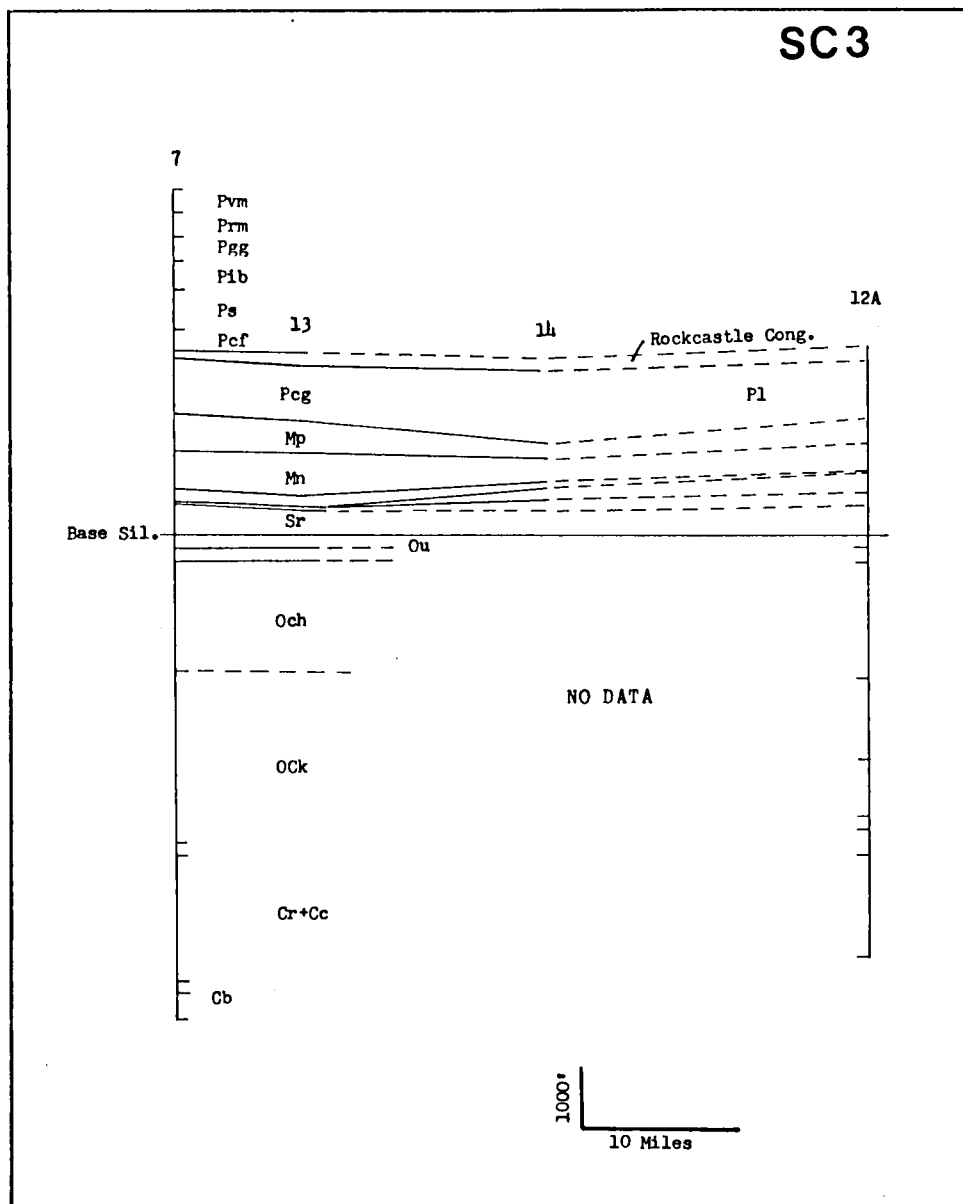


Figure 9. Restored stratigraphic cross section constructed along the trace of the Pine Mountain thrust fault. Datum is the base of the Silurian. Line of section is indexed to Figure 6; p. 29.

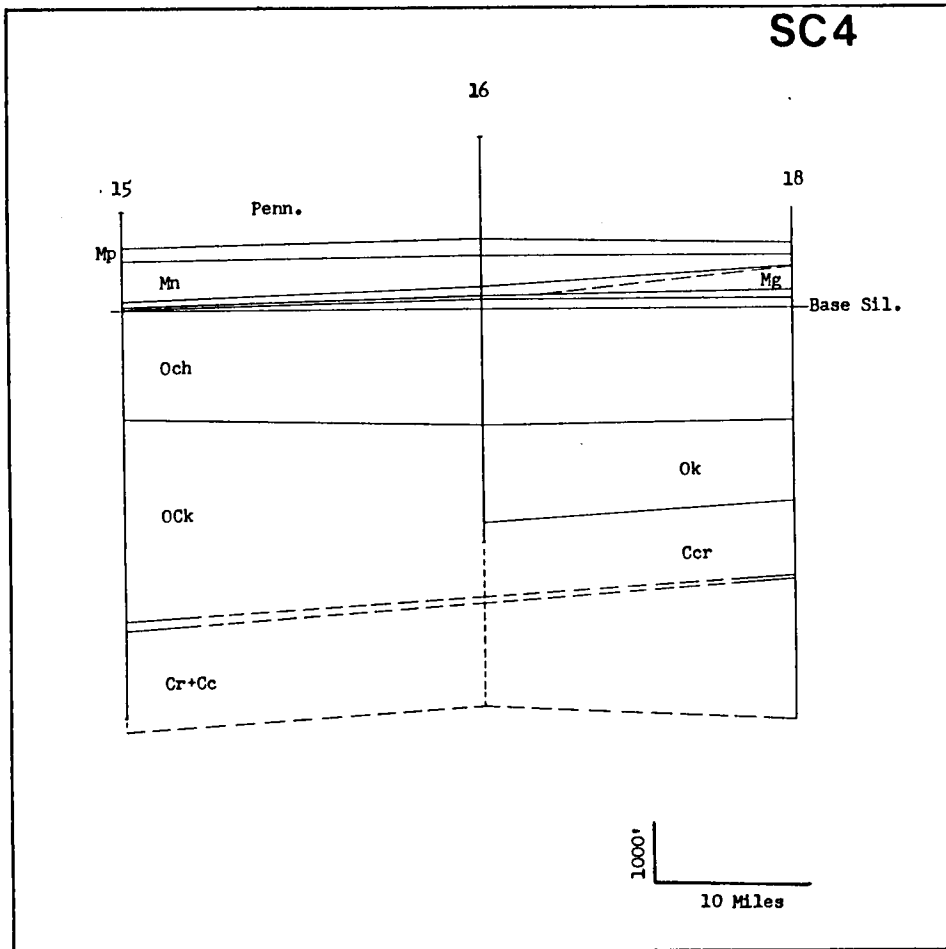


Figure 10. Stratigraphic cross section constructed within the Cumberland Plateau, parallel to the regional strike of the thrust belt. Datum is the base of the Silurian. Line of section is indexed to Figure 6, p. 29.

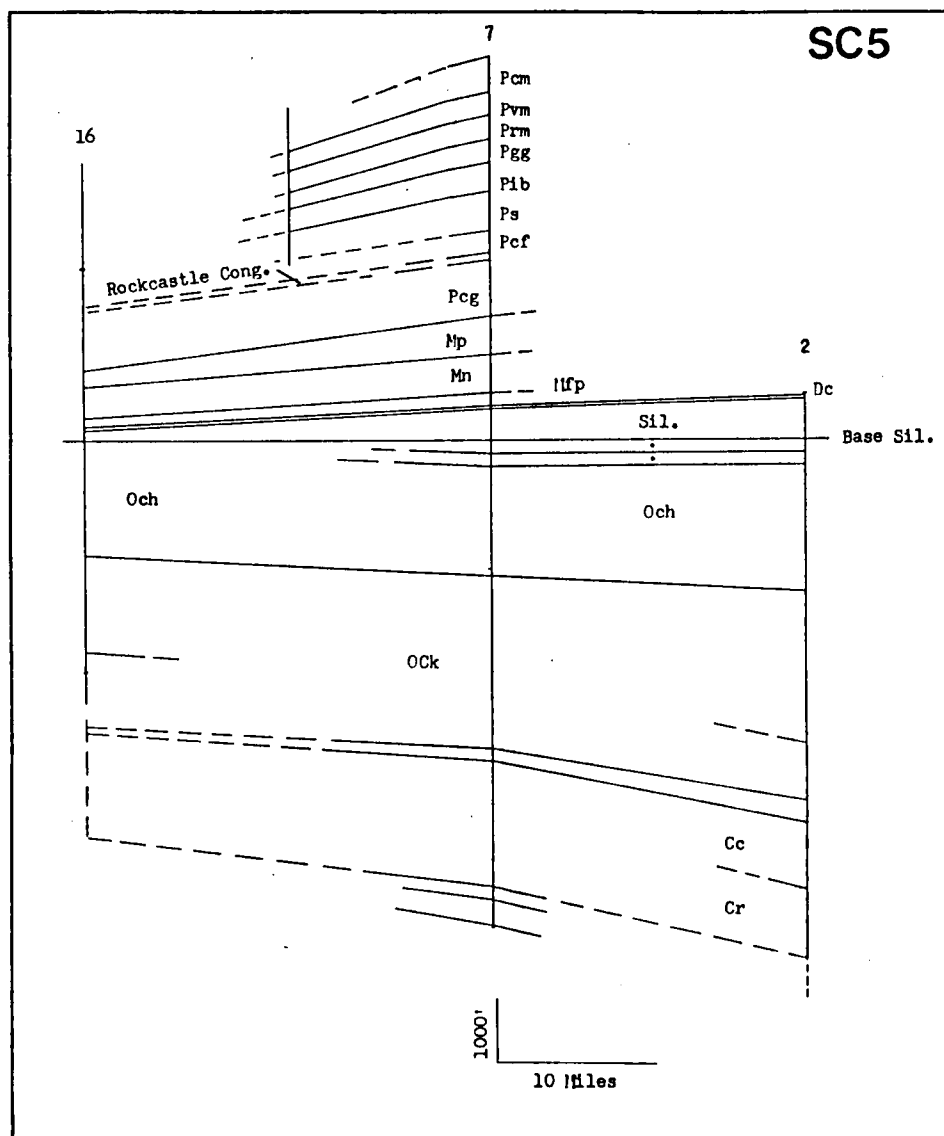


Figure 11. Restored stratigraphic cross section constructed parallel to the Jacksboro fault. This section is constructed across structural strike and represents the configuration of the undeformed sedimentary wedge for the southwestern portion of the Pine Mountain thrust sheet. Datum is the base of the Silurian. Line of section is shown in Figure 6, p. 29.

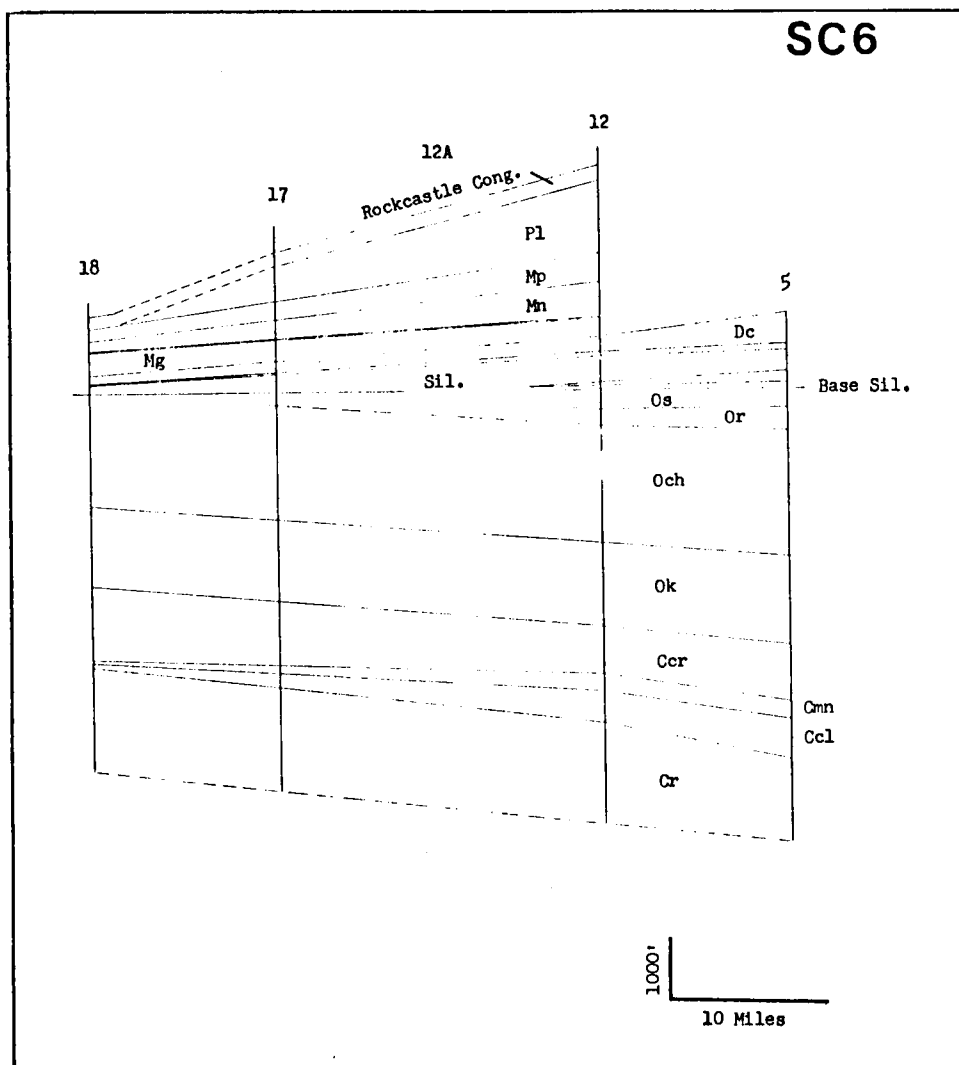


Figure 12. Restored stratigraphic cross section constructed for the central portion of the Pine Mountain thrust sheet. This section represents the shape of the undisturbed sedimentary wedge for that portion of the Pine Mountain thrust system. Datum is base of the Silurian. Line of section is shown in Figure 6, p. 29.

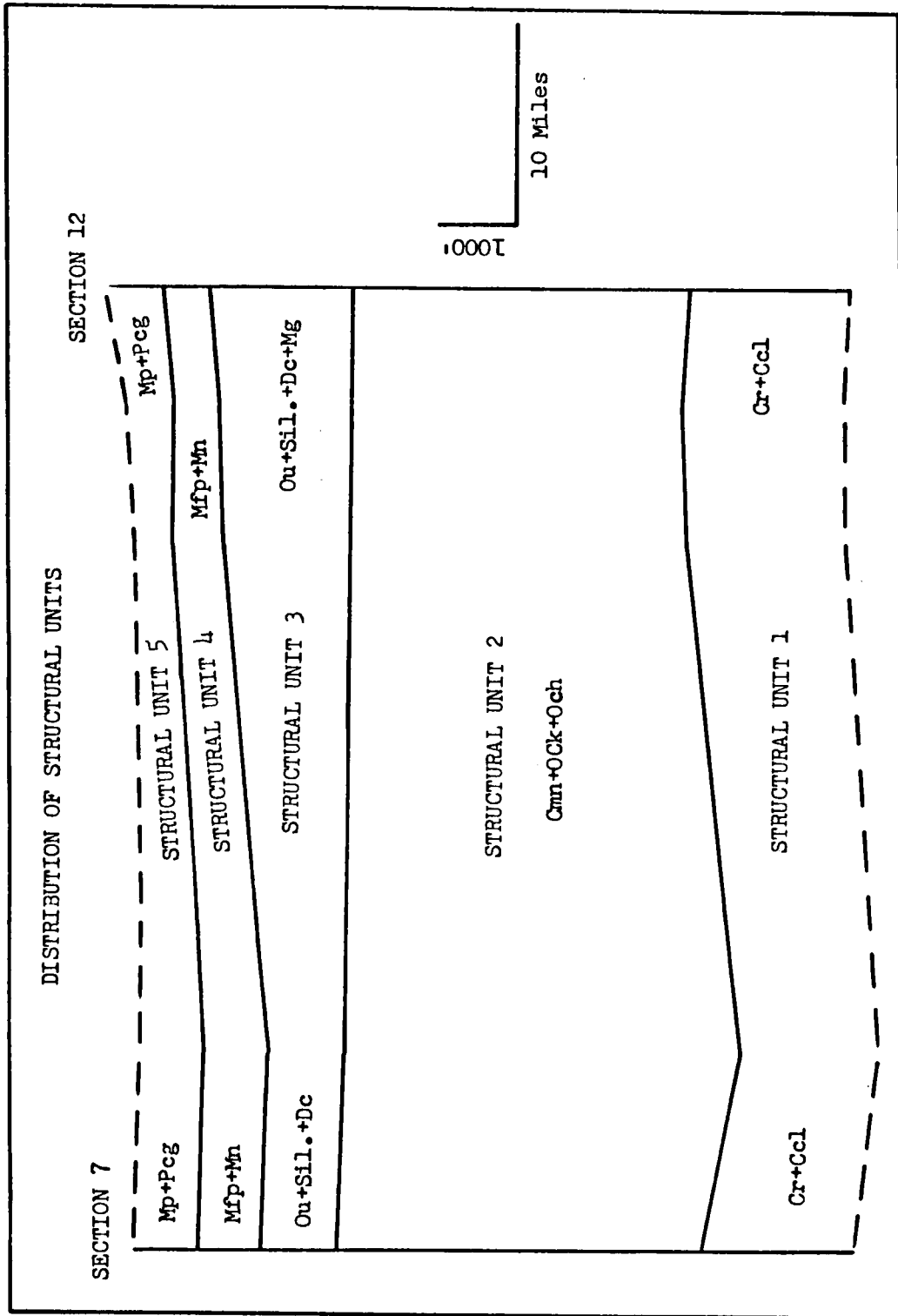


Figure 13. Structural unit correlation diagram illustrates the distribution of structural units with respect to stratigraphic divisions.

The Lower Cambrian Basal Sequence

The Lower Cambrian basal sequence is not exposed within the study area. However, the Arco/Oxy, 1 Sanford Heirs in Dutch Valley encountered 180 feet of dolostone and 410 feet of sandstone before penetrating basement. Although thickness distributions for this unit are not known, Harris (1975) speculated that local thickness patterns are controlled by basement topography. A similar basal sequence has been recorded in wells further onto the craton, especially in Kentucky (Wilson and Sutton, 1976; Sutton, 1981), but no other points of control are available in the region encompassed by this report. Dipmeter data from the Heirs well indicate that this section is not involved with deformation and it is not carried to present surface by any of the thrust faults in the area; thus, it was not assigned to a structural unit.

Structural Unit 1

Structural unit 1 lies just above the Cambrian basal sequence and is composed of the Rome Formation and the lower part of the Conasauga Group. This unit contains the basal detachment at depth and is consistently an important lower level hanging-wall flat for major thrust sheets. The Rome has long been described as the basal weak layer in Valley and Ridge thin-skinned deformation. In the area of study the Rome-Conasauga contact is difficult to distinguish and these two stratigraphic units together form the weak basal layer.

Stratigraphic separation diagrams for the Kingston, Chattanooga, and Jacksboro faults (Figs. 14, 15, and 16) were constructed from geologic maps of Hardeman et al. (1966), Lessig (1949), McMaster (1962), and Swingle (1960a, 1964). Hanging-wall positions indicate that thrusts cut through both the Rome and Conasauga at low angles. Additionally, high fault preference values are associated with both units (Figs. 17 and 18), which further indicates that the two units behaved similarly under deformation. This relationship is readily apparent in both map pattern (Plate 2, in pocket) and outcrop. Major imbricates along the northeast end of the Chattanooga thrust and southeast end of the Jacksboro fault branch from the main hanging-wall trace and penetrate both the Rome and Conasauga at low angles. There are no observed locations where the Knox Group was truncated by these imbricates, thus implying that unit 1 effectively contained the deformation in either duplex or blind imbrication (front fold detachment of Dahlstrom, 1970) style of detachment. Several exposures illustrate the deformational structures that resulted from the intra-unit faulting and are characteristic of unit 1 (Appendix E).

Lithologies within unit 1 are diverse. The Rome consists of intercalated sandstones and shales with a few dolostone beds low in the section; shales are typically more abundant in upper portions of the Rome. The lower part of the Conasauga Group is predominantly a shale section with interbeds of sandstone and limestone; limestone interbeds typically occur higher in the section, and the sandstones occur in the lower reaches. Completing the Conasauga section is the

Figure 14. Stratigraphic separation diagram for the northeast portion of the Kingston thrust indicates that the Conasauga Group is an important flat forming unit. The majority of the Knox Group acted as a ramp section. The Chickamauga Group was not sufficiently involved with thrusting at this level of exposure to adequately judge its behavior.

Figure 15. Stratigraphic separation diagram along the Chattanooga fault shows the dominance of the Rome Formation as a lower level hanging-wall flat. The footwall trace indicates that the Pennington Shale and a portion of the Lower Pennsylvanian behaved as weak rocks. The horse shown at the northeast end of the diagram is the Dutch Valley structure.

Kingston Thrust

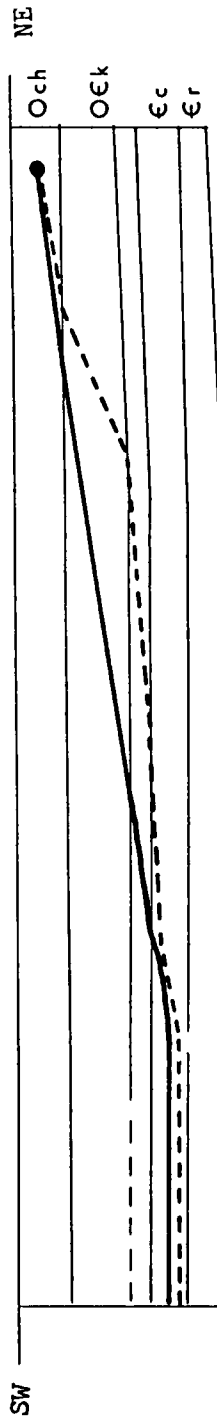


Figure 14

VERTICAL EXAGGERATION 2X

0 200 400 Feet

Chattanooga Thrust

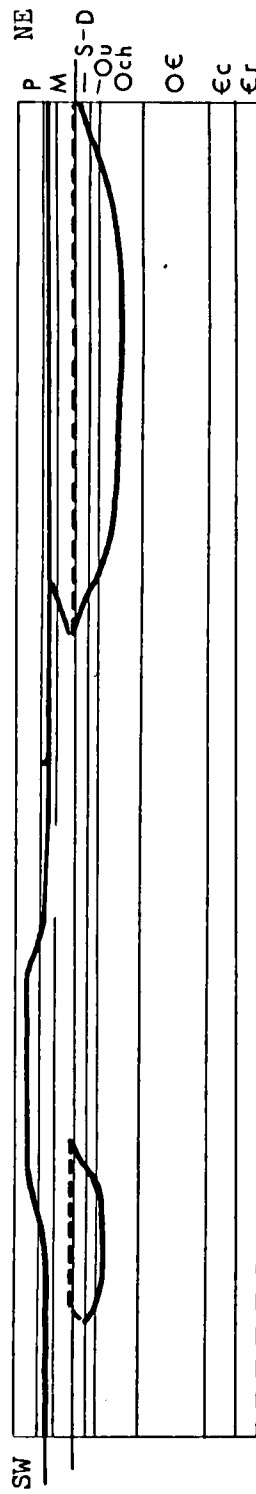


Figure 15

Figure 16. Stratigraphic separation diagram along the trace of the Jacksboro fault represent transport direction relationships for the Pine Mountain thrust system. The important aspects of this diagram are: (1) the Rome and Conasauga are major lower level flat units, (2) the Knox and Chickamauga Groups are major ramp forming units, (3) Upper Ordovician through Mississippian rocks exhibit smaller scale weak and strong relationships, and (4) stratigraphic separation decreases significantly going into the Middlesboro synclinorium.

Figure 17. Fault preference diagram constructed for the Kingston thrust shows the importance of the Conasauga Group as a weak layer. The Knox Group exhibits a low fault preference, thus indicating that it acted as a strong layer. Uncorrected values are quite different in that they partially reflect inherently greater fault contact for thicker stratigraphic units. The high fault preference for the upper Conasauga (Maynardville Limestone) and lower Knox may indicate that the interface between the Conasauga and Knox was mechanically important.

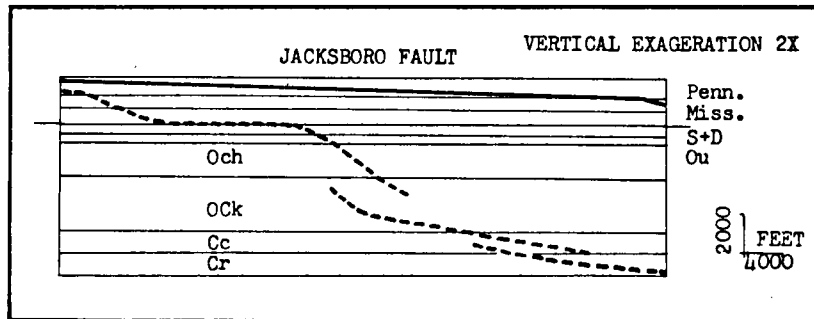


Figure 16

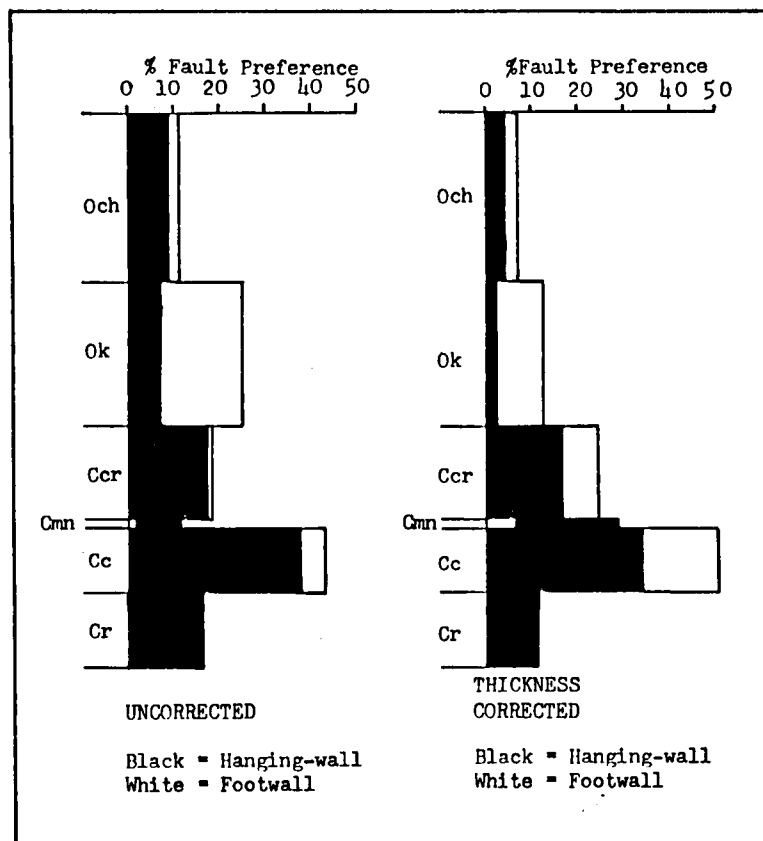
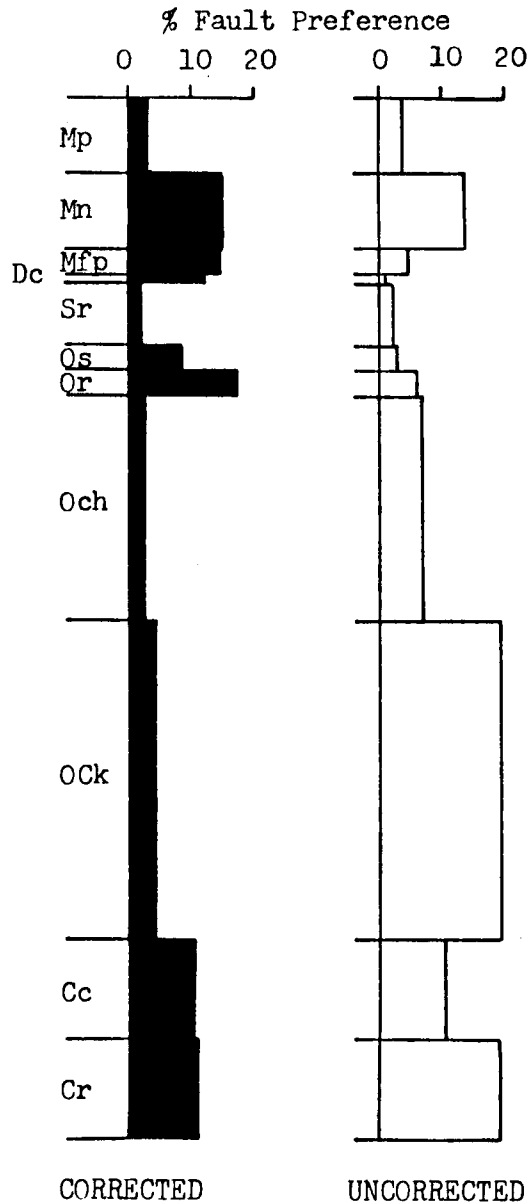


Figure 17



FAULT PREFERENCES
ALONG JACKSBORO HANGING-WALL

Figure 18. Fault preference diagram constructed for the hanging-wall trace of the Jacksboro fault. Thickness corrected values indicate that the Rome and Conasauga acted in approximately the same manner in deformation, and together formed the lowest weak layer. The Knox and Chickamauga acted as the ramp section and are interpreted as being composed of strong rocks. High preference values for the Upper Ordovician rocks indicate that, although thin, they acted as an important upper-level weak layer. High preferences associated with the Mississippian carbonates (Fort Payne and Newman) are unclear as to their meaning.

Maynardville Limestone, which consists of limestones, dolostones, and lesser shales. For reasons discussed later, the Maynardville is, however, included in structural unit 2.

Regionally, unit 1 thins westward onto the craton (Fig. 11, p. 34). Harris (1975) indicated that the thickness of the Rome-Conasauga sequence was in part controlled by the locations of basement normal faults, but he showed an overall westward thinning. It is important to note that sections of both the Rome and Conasauga are usually tectonically thickened. The most reliable thickness for the Rome-Conasauga sequence is probably that taken from the Oxy-Arco, 1 Sanford Heirs well, where approximately 2000 feet of combined section was penetrated. Here dipmeter data indicate a relatively flat-lying section. If a fault is present in the Heirs well, it is flat-lying also and has little stratigraphic duplication associated with it. Tectonic thickness for unit 1 reaches approximately 3000 feet in the Pine Mountain thrust sheet near Lake City, Tennessee; this is 150 percent of the thickness from the nearby Sanford Heirs well; however, palinspastically the thicknesses are not significantly different for the two data sources. The extensive overthickening precluded isopach mapping of the Rome and Conasauga.

Structural Unit 2

Structural unit 2 is composed of the Maynardville Limestone, and the Knox and Chickamauga Groups and is the dominant strong unit of the sedimentary sequence. Unit 2 is consistently a ramp forming

section in the Pine Mountain thrust system. Fault preference values for both the Knox and Chickamauga are typically quite low (Figs. 17 and 18). Correspondingly, stratigraphic separation diagrams show relatively steep angles of fault penetrations for the sections (Fig. 14, p. 39), although faults are generally a bit steeper through the Knox than the Chickamauga. Large horse blocks of unit 2 commonly "decorate" the traces of major thrusts (note traces of the Chattanooga and Whiteoak Mountain thrusts in Plate 1, in pocket); the large size of these horses further suggests that the unit behaved as a strong layer.

Structural unit 2 is dominated by carbonate lithologies. The Maynardville Limestone consists of limestone, dolostone, and shale. Over the study area it averages 200 feet in thickness. The contact between the Maynardville and underlying shales of the Conasauga is gradational, and shale content steadily decreases up-section. The Maynardville exhibits a higher fault preference than the other constituents of unit 2 (Fig. 17), but field examination indicates that the formation is not extensively involved with detachment formation (Appendix E). Instead, faulting often reaches to the gradational zone between the Conasauga shales and the Maynardville before dying out. On structural cross sections, the Maynardville is not separated from the Conasauga Group. Additionally, its thickness is included in that of the Knox Group for isopach map construction (see below).

The Knox Group is the thickest map unit in the study area, ranging from about 2600 to 3500 feet. It is also the most lithologically

homogeneous map unit, with rock types being almost exclusively dolomites with lesser limestones. The Knox Group is usually shown in structural cross sections as being a single unit; however, in stratigraphic illustrations, it is given as two units, the Copper Ridge Dolomite and the upper Knox. Restored isopachs for the Knox Group indicate that the unit thickens to the south, and is characterized by roughly northeast-southwest thickness trends (Fig. 19).

The Chickamauga Group ranges from about 1700 to 2000 feet in thickness and primarily consists of limestones with lesser shales. No subdivisions of the Chickamauga are addressed in this study, but it is commonly divided into 6 units in the western Valley and Ridge and is composed of the Stones River Group and Trenton Limestone in the Cumberland Plateau subsurface. On a regional scale the Chickamauga thickens to the southeast, with a superposed northwest to southeast trending series of thick-thin belts (Fig. 20). In the study area, the lower two-thirds of the Chickamauga section generally consists of more thinly bedded to shaly limestones than the upper third. Thin shale units are common throughout the section.

As with most of the other stratigraphic units of the Pine Mountain region, constituents of structural unit 2 thicken roughly to the southeast in wedge fashion (Fig. 21). The most conspicuous aspect of the thickness pattern for unit 2 is a roughly northwest-southeast trending anomalously thick area that occurs just northeast of the restored hanging-wall trace of the Jacksboro fault. Cutoff lines for the Knox and Chickamauga Groups do not change in conjunction with

Figure 19. Restored isopach map of the Knox Group. Data points correspond with those of Figure 6, p. 29 and Appendix B.

Figure 20. Restored isopach map of the Chickamauga Group. Data points are given in Figure 6 and Appendix B.

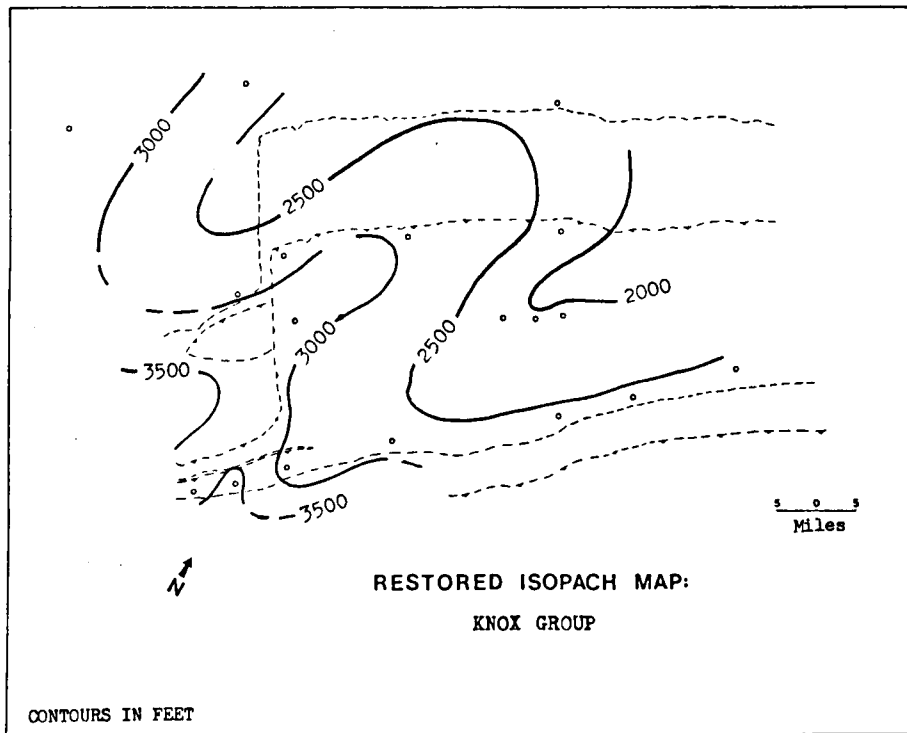


Figure 19

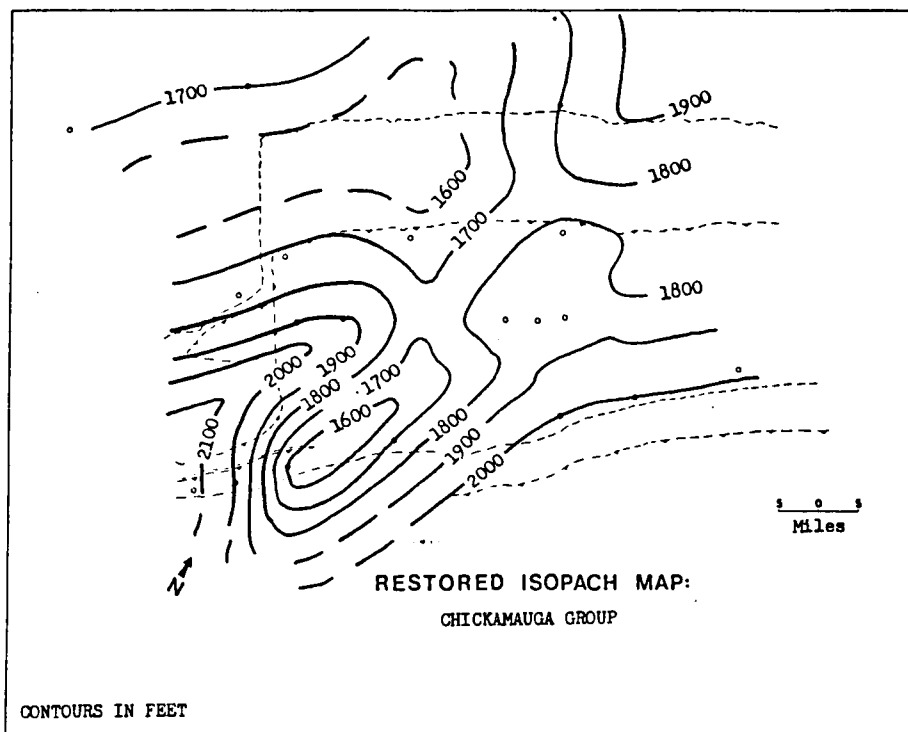


Figure 20

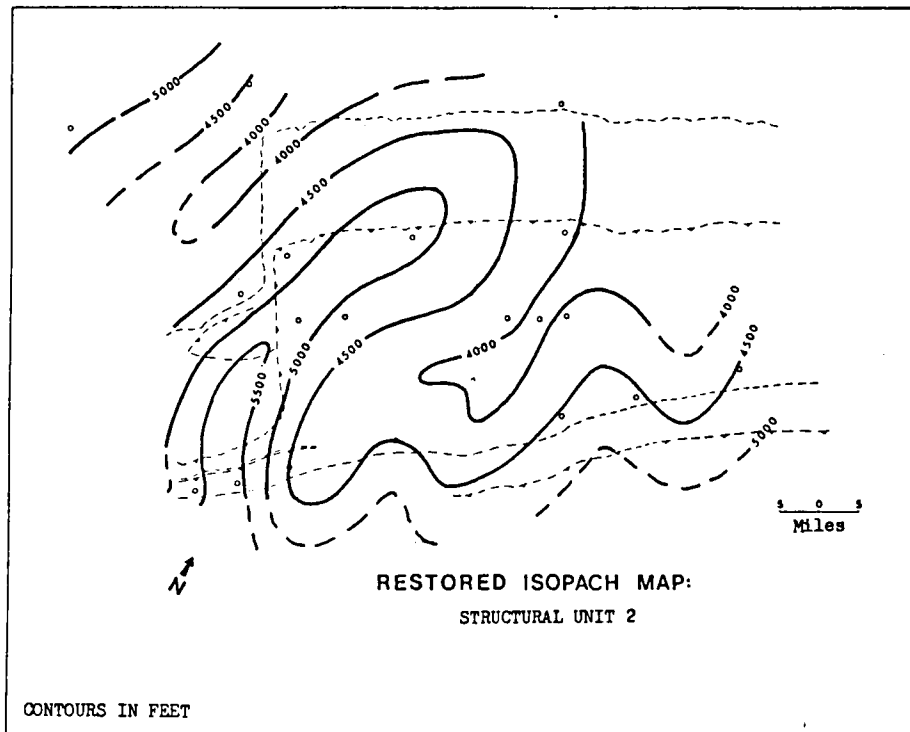


Figure 21. Restored isopach map for structural unit 2 (combined Knox and Chickamauga Groups) depicts the unit as thickening to the southeast.

this area. Thus, it apparently does not constitute an increase of sufficient magnitude as to affect the lower level transport-direction length of the Pine Mountain thrust sheet.

Structural Unit 3

Structural unit 3 is the dominant upper-level weak layer in the Pine Mountain system. The constituent stratigraphic units of unit 3 are the Reedsville Shale, Sequatchie Formation, Rockwood Formation, Chattanooga Shale, and where present, the Grainger Formation. Mechanically, unit 3 is the most complex structural unit present. From northeast to southwest there is a repartitioning of weak and strong rocks within the unit. This is a result of the southwestward thinning of the Devonian and Lower Mississippian shales; the thinning of the shales both thinned and strengthened the entire unit. There is a change in behavior which accompanies the rearrangement of mechanical properties.

Northeast of the Jacksboro fault, the rocks together have the characteristics of a weak layer. Along the Pine Mountain fault trace, all stratigraphic units of the sequence exhibit high fault preferences (Fig. 22). This relationship is also found along the Jacksboro trace. Northeast of the Jacksboro trace, all units show wide separations between their top and base cutoff lines (Fig. 23). In outcrop, the weak behavior of the unit is expressed by numerous small scale imbricates that penetrate the section; an example of such structures is shown in Fig. 24.



Figure 22. Fault preference diagram along the southeast portion of the Pine Mountain fault trace shows high fault preferences associated with the Rockwood Formation, Chattanooga Shale, Grainger Formation, and Fort Payne Formation. This indicates that these units acted as weak layers in the system. The exception is the Fort Payne; with this carbonate unit, the high preference is due to a roof thrust which occurs near the base of the unit. The Sequatchie Formation and Pennington Shale were not sufficiently involved at this level of exposure to allow for proper evaluation.

Figure 23. Cutoff line map shows lines of truncation for the tops of the major stratigraphic units of the Pine Mountain thrust system. Note that cutoff line separations for the upper stratigraphic units narrow to the southeast, indicating that the Pine Mountain fault penetrated the units at a higher angle in the southwest than in the northeast.

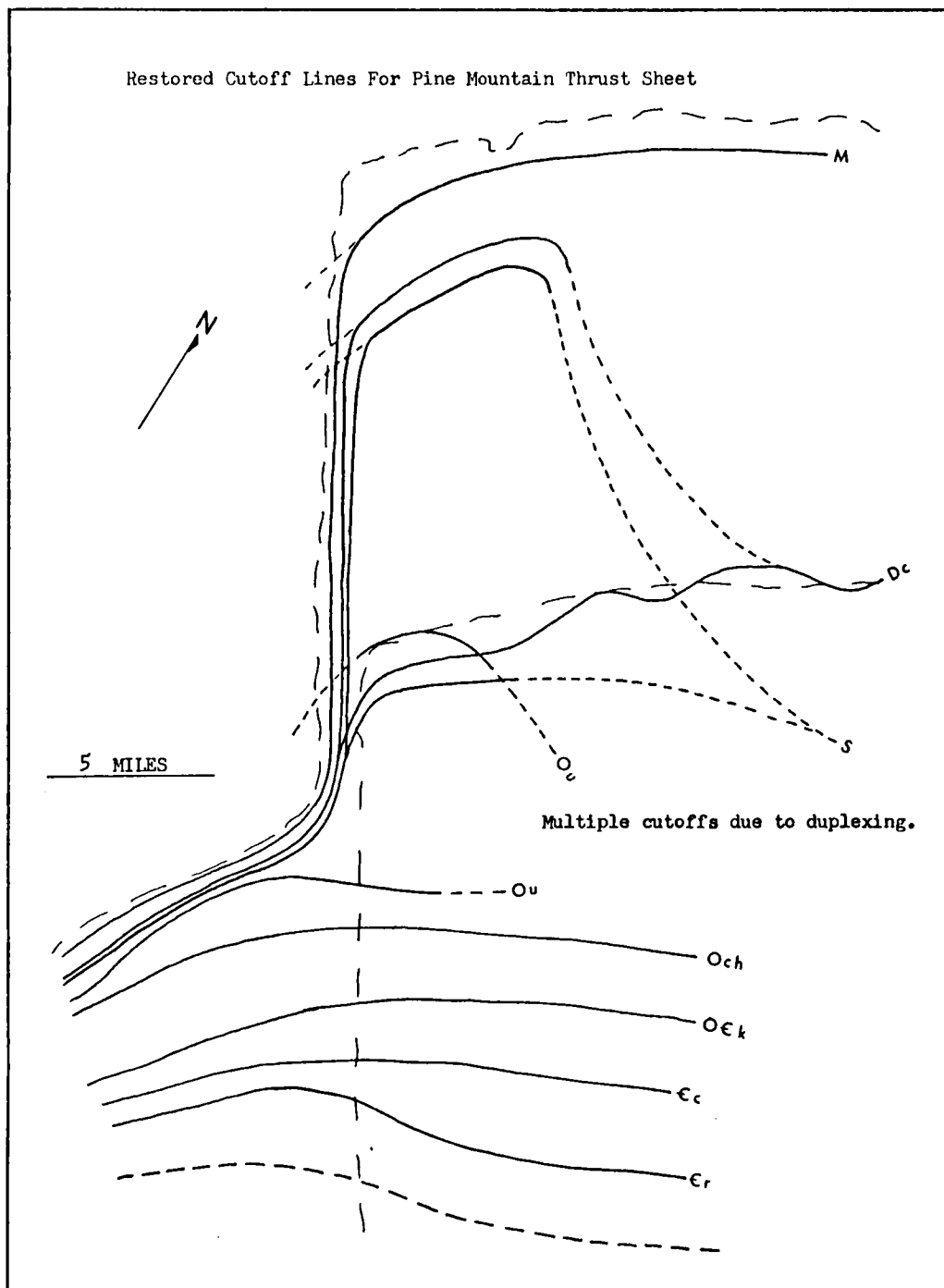


Figure 23

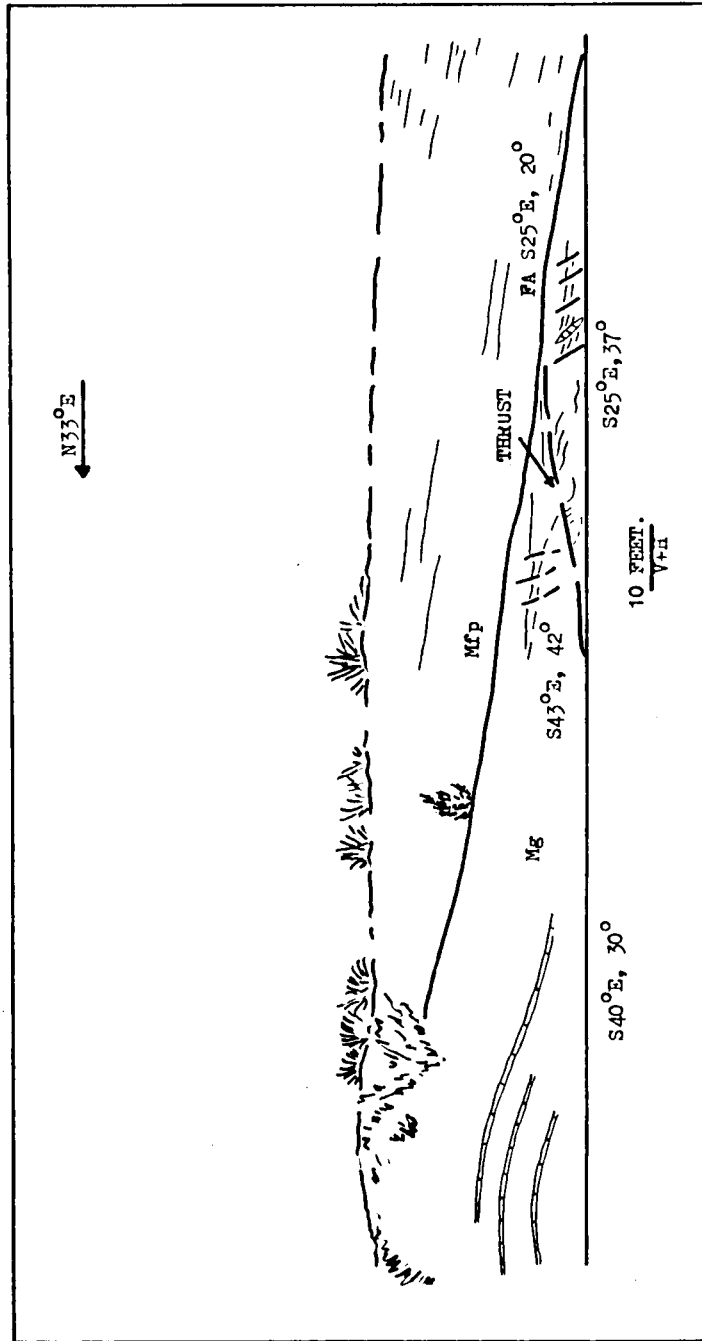


Figure 24. Outcrop sketch of the Grainger and Fort Payne Formations 1.9 miles southwest of the Jellico exit on Interstate 75. Several very small thrusts are present in the shales of the Grainger, but the Fort Payne is undeformed (see Appendix E).

Southwest of the Jacksboro fault the same age rocks behaved quite differently. Fault preference data from along the footwall of the Chattanooga fault suggests that only the Upper Ordovician rocks (Reedsville Shale and Sequatchie Formation) acted as weak rocks (Fig. 25). Stratigraphic separations, given in Fig. 14, p. 39, for the same area show that fault penetrations through the Rockwood Formation and Chattanooga Shale are steeper than to the northeast.

Lithologies of formations that constitute structural unit 3 are typically uniform within the immediate study area. The Reedsville Shale is primarily composed of calcareous shales and thin limestone beds; it averages 200 feet in thickness. The Sequatchie is mostly argillaceous limestones with lesser shale. The Sequatchie Formation is also about 200 feet in thickness within the immediate study area. A restored state isopach map of combined Reedsville and Sequatchie thicknesses indicates that the Upper Ordovician sequence thickens to the east (Fig. 26).

The Rockwood Formation is Silurian in age and consists of interbedded sandstones and shales. Occasional carbonate beds occur in the upper parts of the Rockwood, but they do not constitute a major percentage of the section. The Rockwood is variable in thickness, ranging from approximately 500 to 700 feet thick. Additionally, restored isopachs for the Rockwood show a set of thick-thin relationships that trend roughly northwest-southeast (Fig. 27); however, since the formation in the northwest portion of the study area is only found in the subsurface, these thick-thin trends may be artifacts of

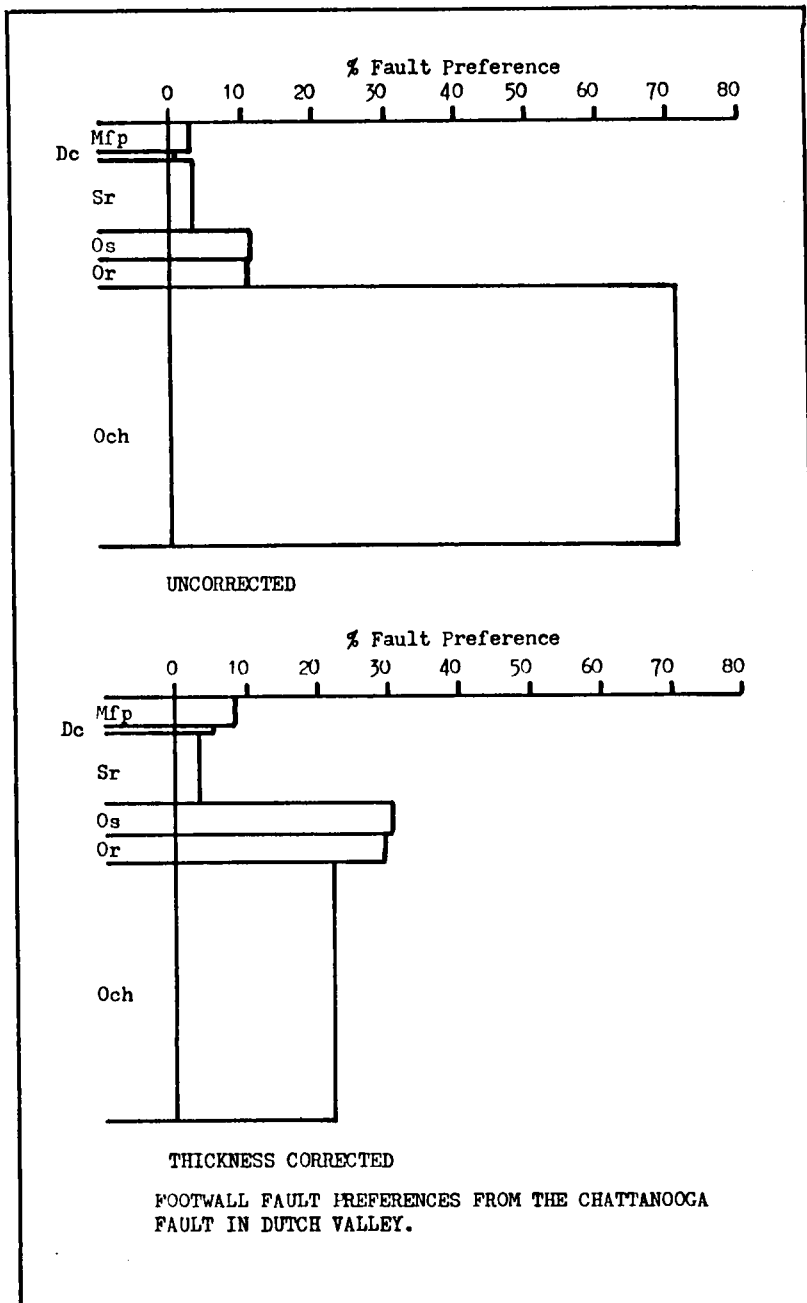


Figure 25. Fault preference data from the footwall of the Chattanooga fault in Dutch Valley shows that the Upper Ordovician rocks are the important upper-level weak rocks southwest of the Jacksboro fault. The Silurian and Devonian rocks are less important here than to the northeast.

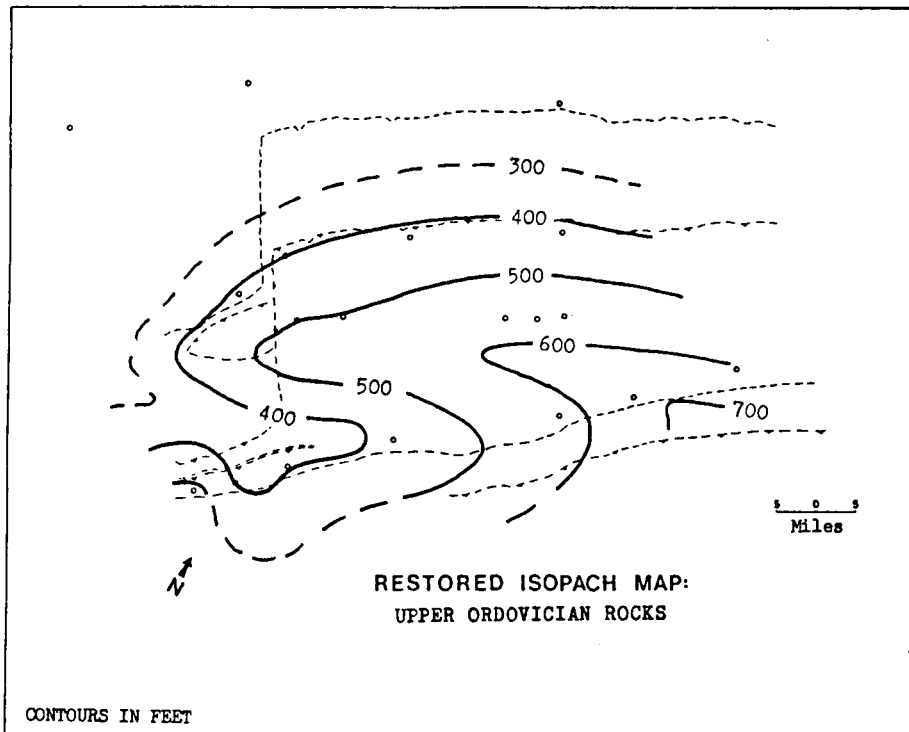


Figure 26. Restored isopach map for Upper Ordovician rocks (Reedsville Shale and Sequatchie Formation) indicates an eastward thickening trend.

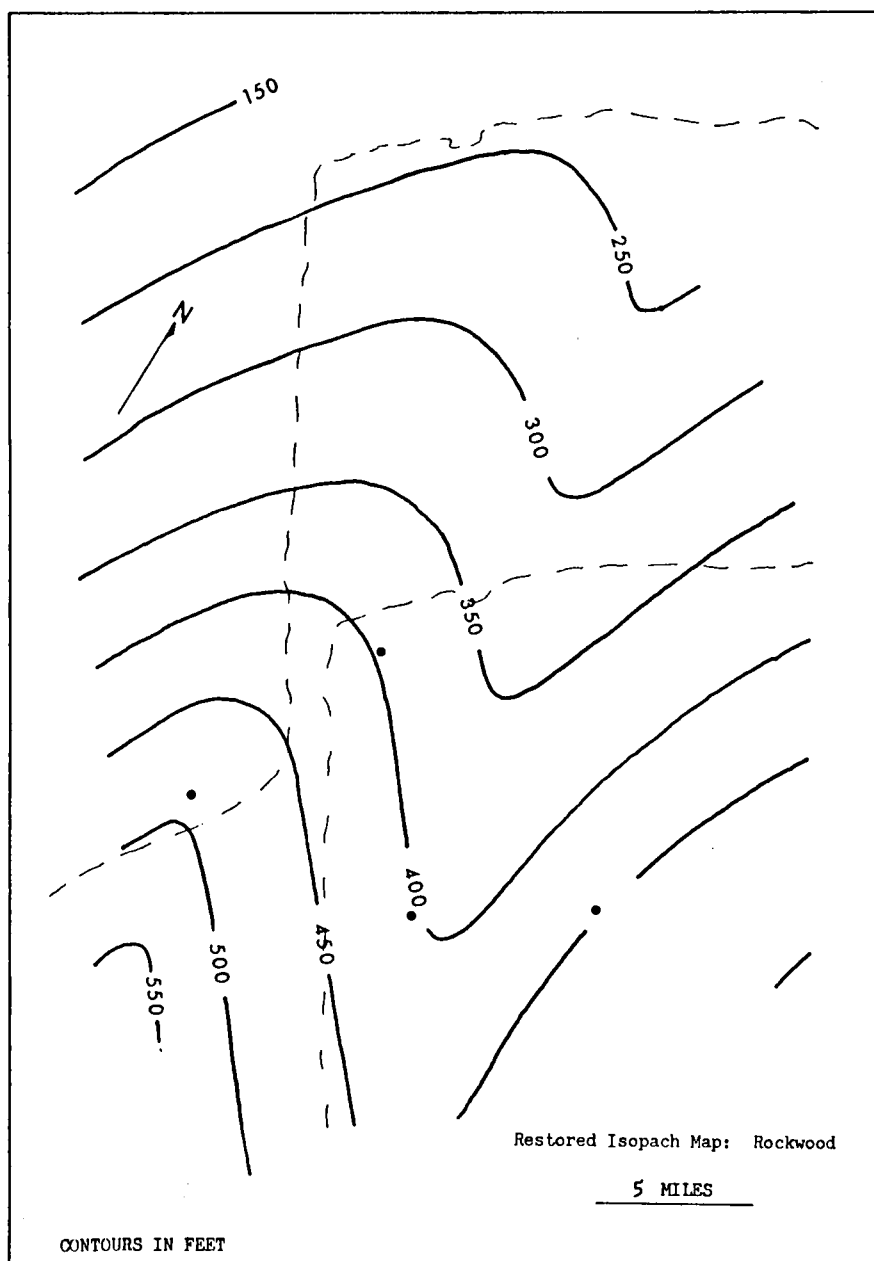


Figure 27. Restored isopach map for the Silurian Rockwood Formation in the vicinity of the Jacksboro fault shows an area of thinning just to the northeast of the fault trace. It is important to note, however, that this thin may be an artifact of contouring, since thicknesses of the Rockwood are rather poorly constrained.

contouring. To the northwest, the Rockwood, and correlatives, thin, and the distribution is probably erratic.

Within the immediate study area, the Chattanooga Shale consists exclusively of black shale. Generally, its thickness is between 30 and 100 feet; however, it is uncertain as to how much apparent thickness is added due to deformation. Over the length of the Pine Mountain thrust sheet the Chattanooga Shale changes drastically in thickness. In southwestern Virginia, the Chattanooga ranges to over 700 feet in thickness. By contrast, the southern portion of the thrust system has generally less than 40 or 50 feet of Devonian shales. Figure 28 further illustrates that restored isopachs generally trend across structural strike, with the direction of maximum thickening being northeast. As previously noted, the Chattanooga is commonly tectonically overthickened; thus, the isopach map presented here is probably most useful for simple illustrating that a thickening to the northeast does exist, though definite amounts of change are not known.

Fault preferences for the Chattanooga decrease across the Jacksboro fault. Here the Chattanooga was not as important in controlling fault paths. Dahlstrom (1970) noted that it is not unusual for thrusts, especially large ones, to bypass thin weak layers.

Grainger lithologies are dominated by shales, although limestones and occasional thin sandstones occur in the section. This unit is quite variable in thickness distribution in the study area, but it ranges in thickness to approximately 80 feet. Like the Chattanooga Shale, the Grainger thickens considerably to the northeast, with restored isopachs trending roughly parallel to the Jacksboro fault (Fig. 29).

Figure 28. Restored isopach map for the Chattanooga Shale shows the unit thinning dramatically from northeast to southwest. Southwest of the Jacksboro fault the Chattanooga is quite thin and varies between 30 and 50 feet in thickness.

Figure 29. Restored isopach map of the Grainger Formation indicates a southwestward thinning. The unit pinches out just to the northeast of the Jacksboro fault, and its stratigraphic position is occupied by carbonates of the Fort Payne.

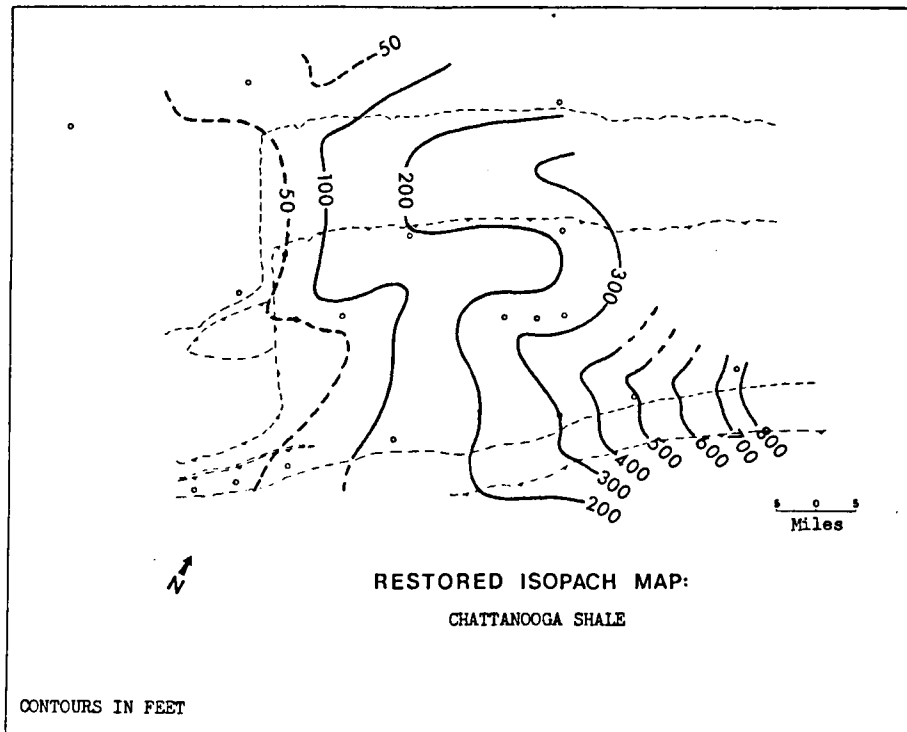


Figure 28

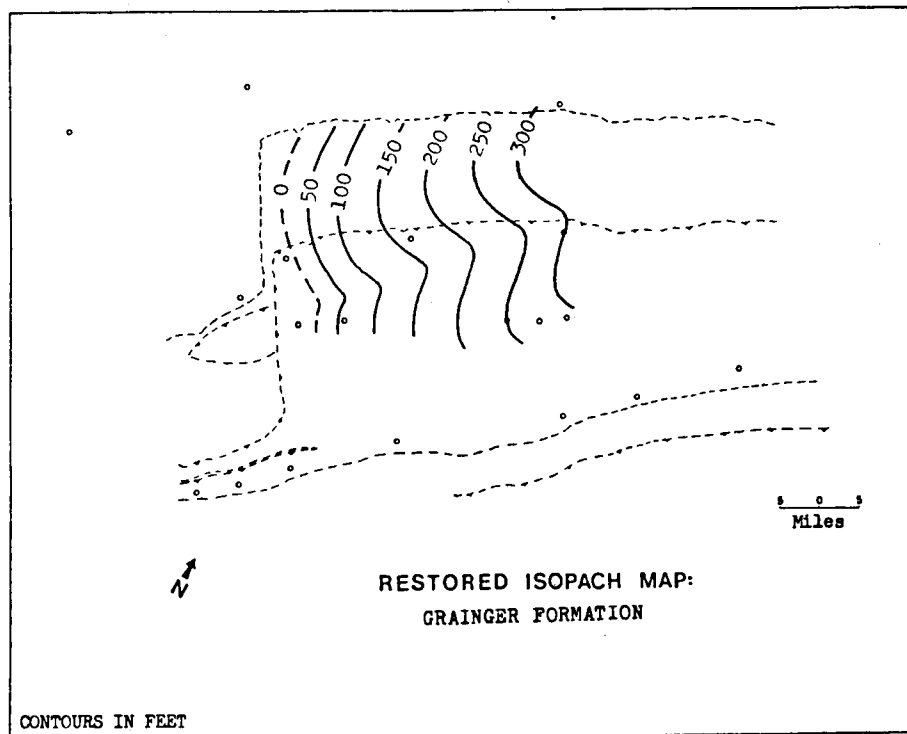


Figure 29

Structural Unit 4

Structural unit 4 is an important upper-level strong unit. The two constituent stratigraphic units of unit 4 are the Fort Payne Formation and the Newman Group. In contrast with the thickness distribution of unit 3, unit 4 thins to the northeast; this is primarily due to the transition of the shales of the Grainger Formation to carbonates of the Fort Payne. An interesting point pertaining to this unit is the high fault preference values associated with the base of the unit along the Pine Mountain and Jacksboro fault traces. These high preference values, along with occurrences of fault zones near the Fort Payne-Grainger contact along the Pine Mountain indicate that the interface between units 3 and 4 was an important stress guide in the system (Appendix E); like the Maynardville Limestone of unit 2, the Fort Payne was not extensively involved in low angle thrusting.

The Fort Payne Formation consists primarily of cherty dolostones, limestones, and lesser shales. This unit is replaced by the Grainger Formation to the northeast with restored isopachs trending roughly subparallel to the trace of the Jacksboro fault (Fig. 30).

The Newman Group consists of the Warsaw, St. Louis, Monteagle, Hartselle, and Bangor Formations as described by Vail (1959) and Stearns (1963). For simplicity, however, the constituent formations will not be addressed individually in this study. The Newman ranges between 500 and 700 feet in thickness and is composed of carbonates (mostly limestone) and lesser shale. The Newman is relatively consistent both in lithology and thickness over the entire extent of the Pine

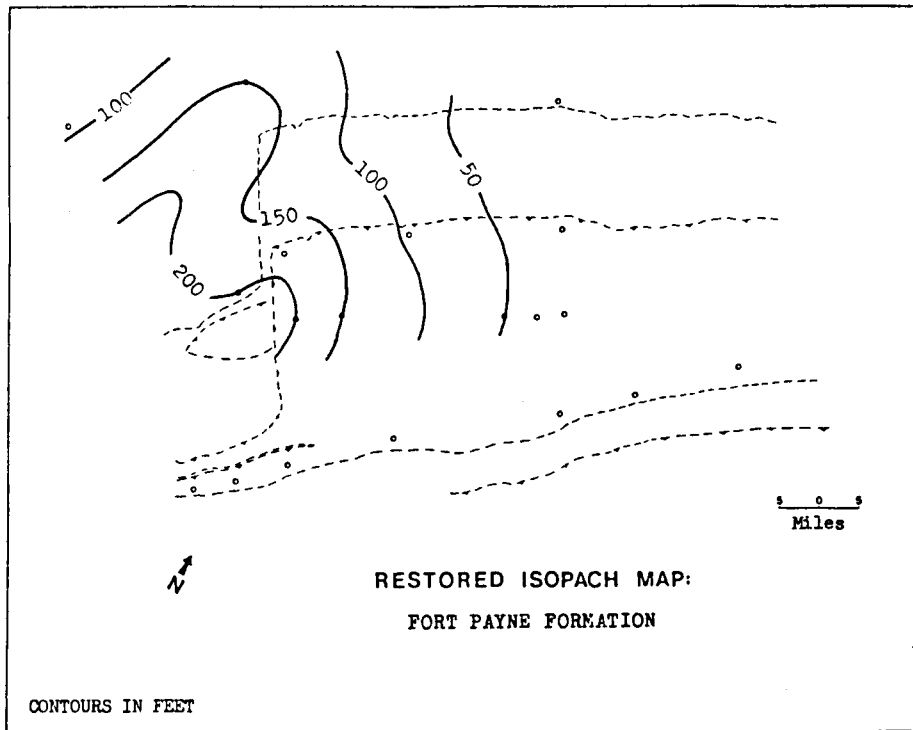


Figure 30. Restored isopach map of the Fort Payne shows a marked thinning to the northeast.

Mountain thrust sheet; however, regionally it thins gradually to the north (Fig. 31).

Structural Unit 5

The highest structural unit identified in this report is composed of the Mississippian Pennington Shale and a poorly defined and apparently quite variable portion of the Lower Pennsylvanian Gizzard Group. The Pennington averages 600 feet in thickness over the study area and primarily consists of shales, although thin limestone beds occur throughout the section. The upper parts of the Pennington usually contain sandstone beds up to a foot or so thick. In the Wartburg Basin area the Pennington is gradational with the overlying rocks of the Gizzard Group. To the northeast, especially in Virginia and Kentucky, the Pennington becomes gradational with the overlying Lee Formation of Pennsylvanian age. At this point, the Pennington consists of shales, sandstones, and occasional conglomerates, and its thickness becomes quite variable (Fig. 8, p. 31).

Unit 5 acted as an important high level weak unit. This is best seen in the stratigraphic separation diagram constructed along the Chattanooga fault (Fig. 15, p. 39), where unit 5 occupies 100 percent of the main footwall trace of the fault. Along the Pine Mountain trace the unit does not occupy a significant percentage of fault contact; however, proper evaluation of the unit was not possible due to a lack of exposure and the eroded hanging-wall.

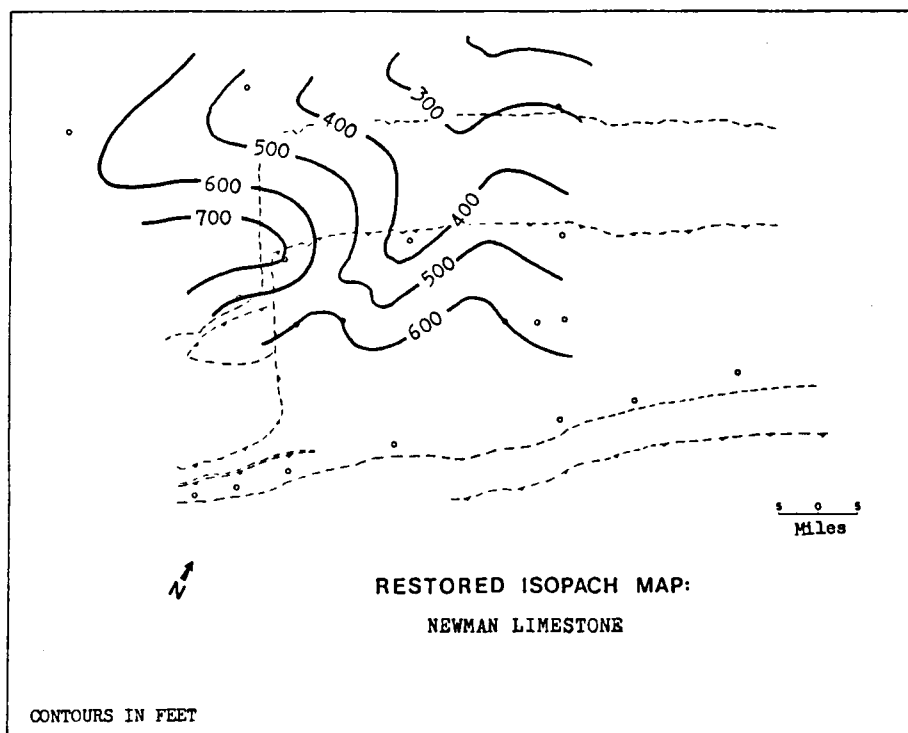


Figure 31. Restored isopach map for the Newman Limestone shows the formation thinning to the north.

The deformational behavior of unit 5 was probably consistent over the entire area. Likewise, the unit changes little in thickness or lithologic character over the area. Although the distribution of unit 5 is only known for the plateau areas and Middlesboro synclinorium, the unit generally thins to the northwest, north, and northeast. In the Wartburg Basin, the top of the unit is not distinguishable due to lack of exposure of deformed zones and the often gradational lithologic boundaries between the Pennington and Lower Pennsylvanian rocks. In the northeastern portions of the Pine Mountain thrust system, the top of unit 5 is placed at the contact with the overlying Lee Formation. This boundary marks a major contrast in rock strengths between the weak Pennington and a very strong Lee (Wiltschko, 1979).

Role of Rocks Above Unit 5

The role of rocks of the Pennsylvanian System during deformation cannot be determined from available data within the study area. Southwest of the Wartburg Basin, Pennsylvanian rocks are extensively involved in deformation. The detachment beneath the Cumberland Plateau overthrust is completely contained within Pennsylvanian rocks (Wilson and Stearns, 1958; Harris and Milici, 1977). On the northeast end of the Cumberland Plateau sheet, the thrust cuts up-section laterally in a well developed step shape and finally is expressed at the surface by the Emory River fault (Harris, 1970).

Along the Pine Mountain trace there is indication that the Slatestone Formation acted as an important weak unit. Here the Slatestone

occupies 100 percent of the main footwall trace of the Pine Mountain fault. The footwall position on a stratigraphic separation diagram would be a straight line, thus indicating that the unit serve as a detachment zone. Such extensive involvement beneath the Wartburg Basin is not apparent, and any major detachment that might have existed would have been higher in the section and is now eroded.

Stratigraphic units above unit 5 include the Gizzard Group (to some extent), Crooked Fork Group, Slatestone Formation, Indian Bluff Formation, Graves Gap Formation, Redoak Mountain Formation, Vowell Mountain Formation, and the Cross Mountain Formation. Correlatives of these units for areas near Kentucky and Virginia are given in Fig. 4, p. 26. These groups and formations consist of alternating shales, siltstones, sandstones, conglomerates, and coals, in varying proportions. Individual formation descriptions are not given in the text; however, diagramatic representations of their distributions are shown in Figs. 7 through 12, pp. 30-35.

CHAPTER 4

DEVELOPMENT OF PINE MOUNTAIN STRUCTURES

The Lower Structural Levels

The Pine Mountain thrust originated beneath the older Whiteoak Mountain-Wallen Valley-Hunter Valley fault system, as a flat fault within the Rome Formation, thus extending the basal decollement westward (Fig. 32). Within the study area, the fault remained flat in the Rome and Conasauga for approximately 10 miles before ramping up-section through the Knox and Chickamauga Groups. Basement and the Cambrian basal sequence were not involved with deformation, and basement surface dips gently toward the interior of the thrust belt (Fig. 2, p. 17). The basal detachment in the study area is described as occurring near the base of the Rome Formation (Harris and Milici, 1977; Roeder et al., 1978; Horton, 1977). A more accurate characterization of the detachment is to describe it as being either a duplex or front fold type of detachment contained within structural unit 1.

Down-plunge projection of the southwest end of the Powell Valley anticline (Fig. 33) shows numerous northwest facing folds in the Conasauga-Knox contact above the Pine Mountain fault. The presence of these folds indicates that imbricates branching from the main trace of the Pine Mountain thrust are significant geometric elements throughout structural unit 1. Numerous such imbricate thrusts are observed branching from the main thrust surface and penetrating into the upper parts of structural unit 1 (Appendix E). Several of these faults are

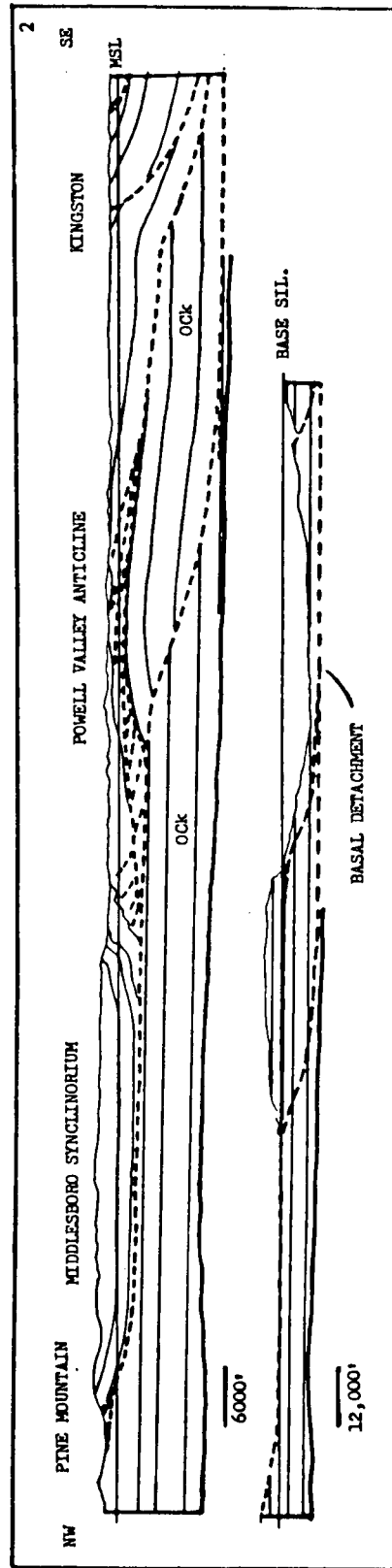


Figure 32. Balanced structural cross section across the Pine Mountain thrust sheet shows the classic staircase geometry that characterizes that portion of the thrust system. The extensive upper-level detachment occurs in structural unit 3. The line of section is shown in Plate 1, in pocket.

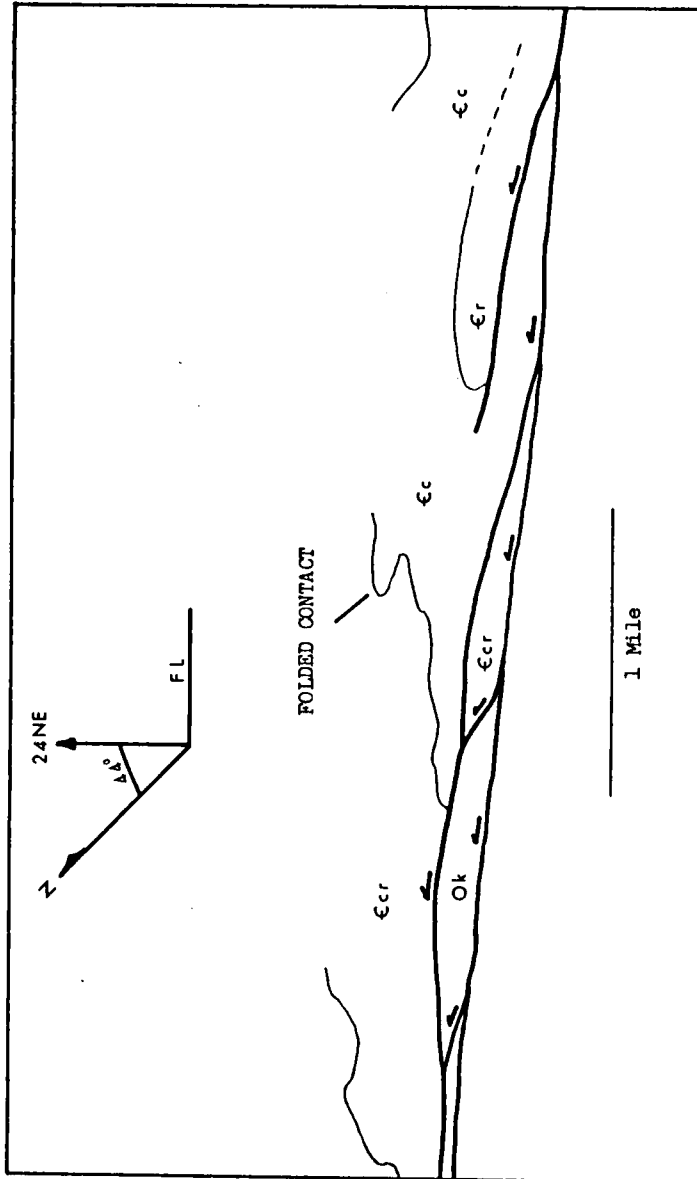


Figure 33. Down-plunge projection of the Powell Valley anticline along the Jacksboro fault shows the folding of the Pine Mountain fault by horses beneath the fault. Numerous folds occur in the Knox-Conasauga contact. These folds probably reflect faulting and stratigraphic duplication within structural unit 1. Rome and Conasauga outcrops are riddled with small faults and folds, but deformation does not extend across the Knox-Conasauga contact.

large enough to show in map pattern (Plate 2, in pocket); most, however, are too small to be mapped individually at 1:24,000 scale. Extensive deformation within the Conasauga Group was noted by Rodgers (1953), Swingle (1960a, 1960b, 1964), and Horton (1977). Duplication of section from these imbricates tectonically thickened unit 1 to approximately 150 percent of its normal thickness (Fig. 34). The Knox is not truncated by these imbricates, and in the Lake City area, intra-unit 1 deformation is observed throughout the middle and upper parts of the shaly portion of the Conasauga Group; however, a further distinction between front fold and duplex types of detachment is not possible due to lack of sufficient exposure. Cutoff-line positions (Fig. 23, p. 52), outcrop relationships, and geometric considerations indicate that these lower level structural relationships are consistent over the entire study area.

Assuming that the basal detachment is either of the duplex or front fold type, the unit 1-unit 2 interface, due to the large contrast in rock strengths and large thickness of unit 2, would be a likely place for a roof thrust to form. A similar relationship exists at the base of the Maryville Limestone elsewhere in the Valley and Ridge (Woodward and Walker, 1983). Imbricates propagated off of the floor thrust at closely spaced intervals, but major truncations of unit 2 occurred only at the leading and trailing bounding surfaces of the thrust sheet.

Where on the Pine Mountain fault cuts structural unit 2, penetration angles range between 25 and 30 degrees, as reconstructed in

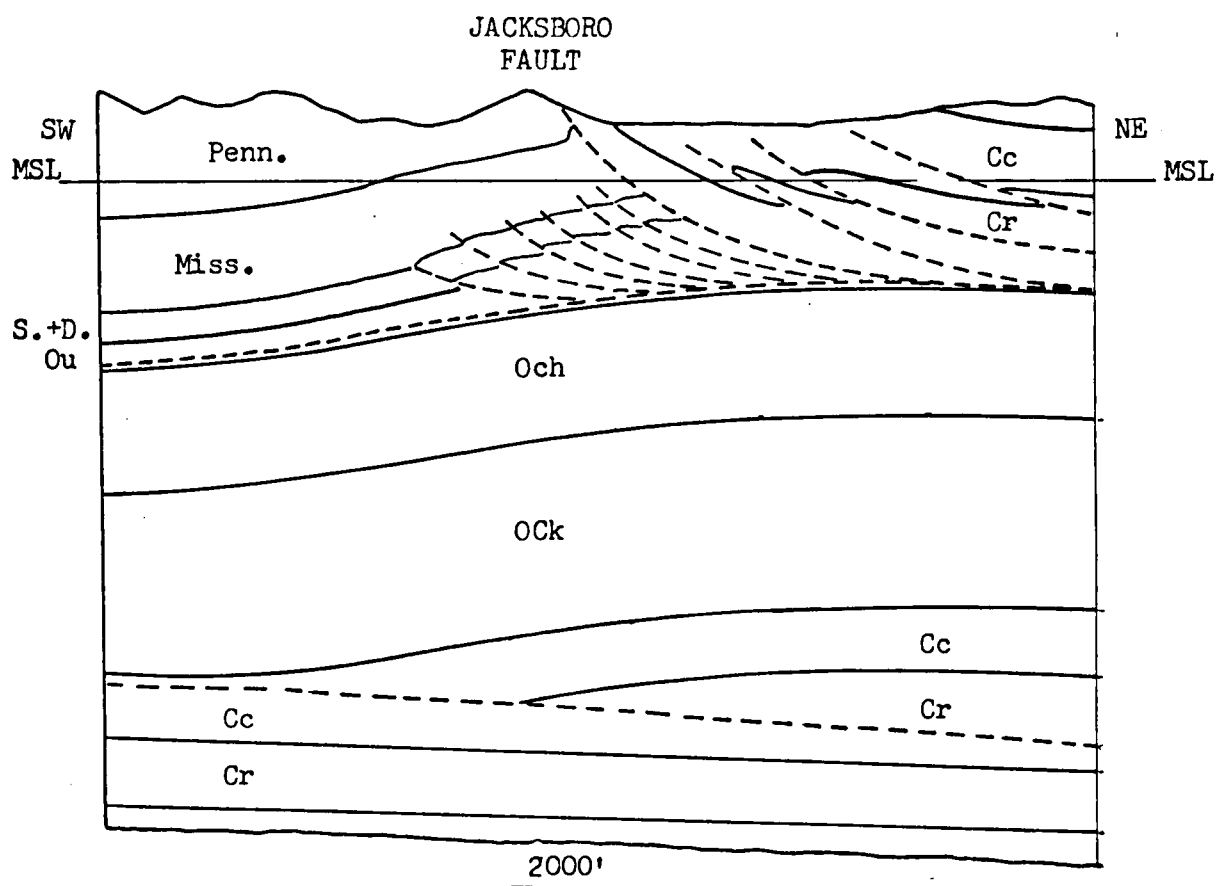


Figure 34. Longitudinal structural cross section across the Jacksboro tear fault near Lake City. Note that the Pine Mountain fault is flat in Upper Ordovician rocks to the northeast of the tear fault and cuts steeply up-section along a northeast-dipping lateral ramp, thus resulting in the tear fault. The Rome and Conasauga are tectonically thickened to approximately 150 percent of their combined normal stratigraphic thickness. The footwall contains numerous blind imbricates above the Upper Ordovician Projection of units upwards indicates that the thrust sheet once covered a portion of the Wartburg Basin.

balanced cross sections. The break, however, did not occur cleanly. As the fault propagated through unit 2 imbrication of the ramp section occurred. This resulted in the generation of a complex horse system, part of which is known as the Dutch Valley anticline (Fig. 35), and the remainder of the system is exposed along the trace of the Jacksboro fault. The evolution of these horses can be explained in the context of high strain and imbrication of the overturned limb associated with a developing ramp fold. The mode of development for the Dutch Valley system is illustrated in Fig. 36. Longitudinally, the horse was imbricated along the Jacksboro tear fault and the northeast part of the structure was carried to the northwest along the major footwall flat underlying the Pine Mountain sheet. Further northwestward translation of the southwestern part of the horse system was impeded by the much steeper angle of thrusting along the main footwall trace of the Chattanooga fault.

Alternative interpretations for the Dutch Valley structure are given by Horton (1977) and Roeder and Witherspoon (1978). Horton indicates that the Dutch Valley anticline is continuous with a Bales thrust equivalent which extends under the Pine Mountain thrust sheet to the northeast. Roeder and Witherspoon indicate that the Dutch Valley anticline is part of a minor thrust sheet that underlies the Chattanooga thrust, but does not extend to the northeast under the Powell Valley anticline. The similarity between the Dutch Valley structure and horses that occur along the trace of the Jacksboro fault indicates that the systems are related. Trailing-edge cutoff

Figure 35. Balanced cross sections across the Chattanooga fault illustrate that this segment of the Pine Mountain thrust system developed a more listric shape. Only a weakly developed flat exists beneath the Wartburg Basin. Blind imbrication off of this flat completes requirements for a front fold type of detachment. The Dutch Valley anticline is shown as a horse that imbricated from the ramp section during thrust emplacement. Line of section are given in Plate 1, in pocket.

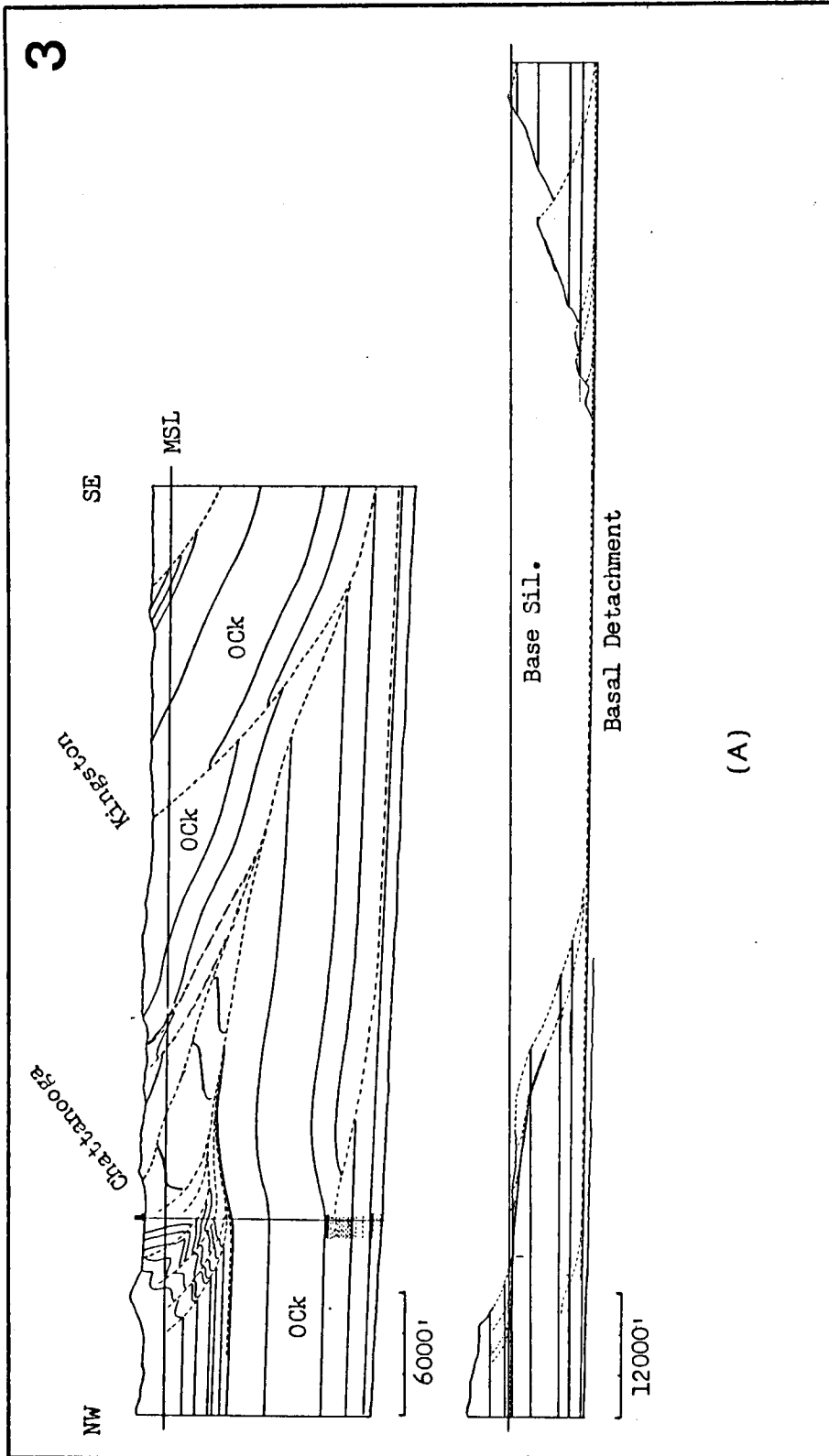


Figure 35

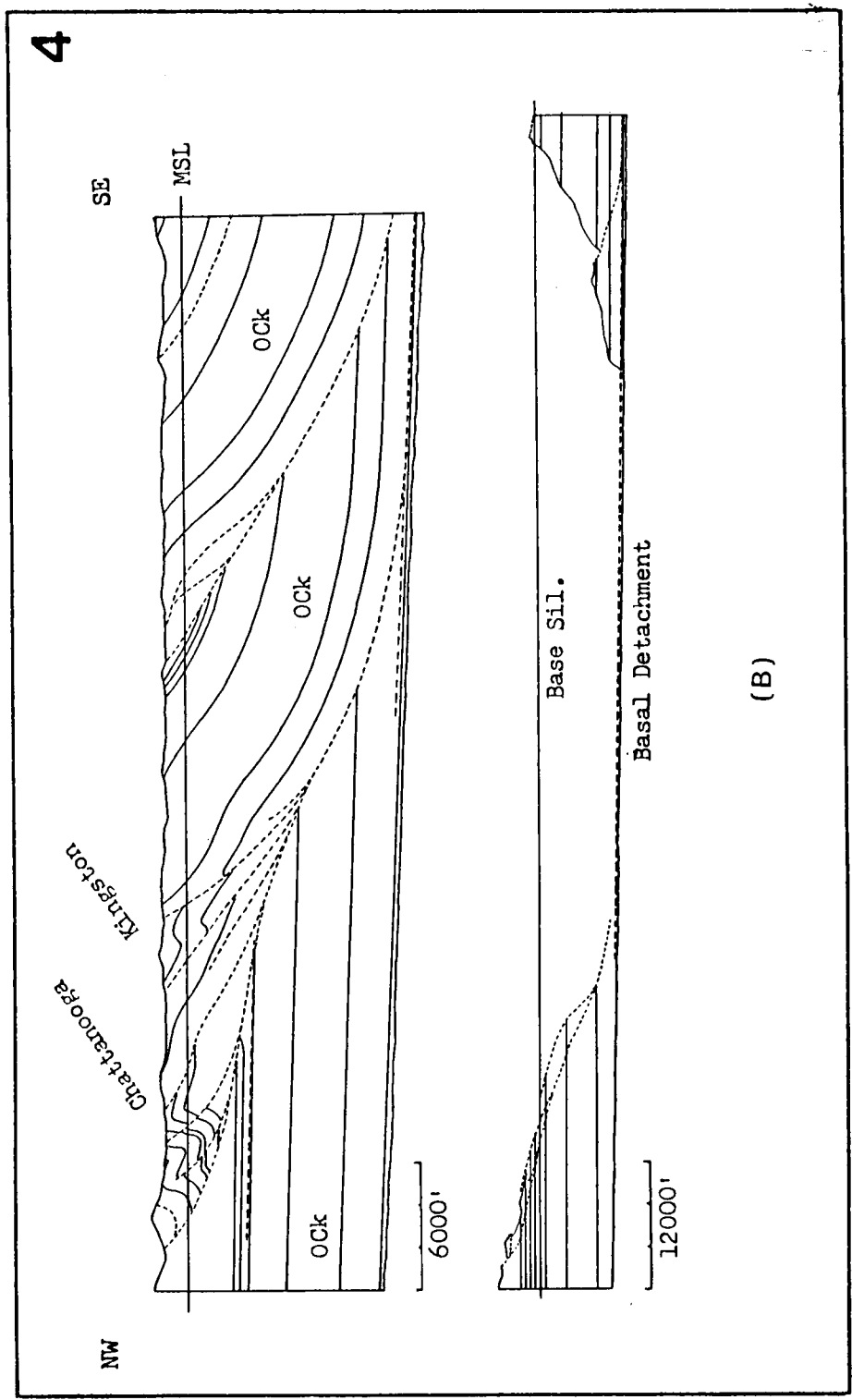


Figure 35 (continued)

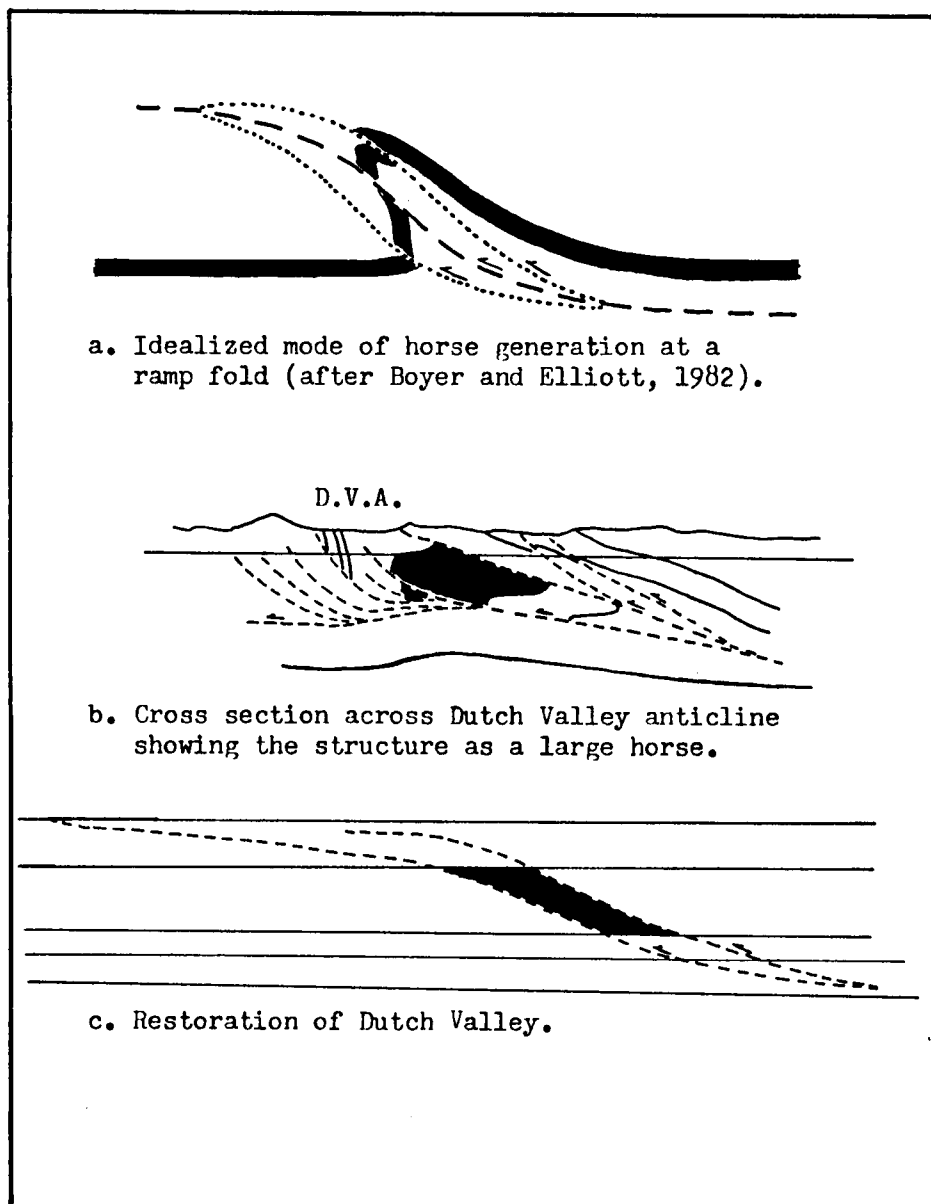


Figure 36. Boyer and Elliott (1982) noted that horses are commonly generated in association with developing ramp folds (a). The evolution of the Dutch Valley structure probably took place in that manner (b and c). As the Chattanooga segment propagated through structural unit 2, imbrication took place, and a large horse system was transported for a short distance along the fault.

relationships between the Dutch Valley structure and Jacksboro fault indicate that the structure is tapering to the northeast and probably terminates approximately 5 miles in the same direction.

Further indication of how unit 2 controlled deformation, as well as how it responded to deformation, are observed in geometric relations of the Powell Valley anticline. The Powell Valley anticline is the hanging wall ramp anticline to the Pine Mountain thrust, resulting from duplication of section above the Pine Mountain fault. The anticline is slightly asymmetrical to the northwest due to folding of the hanging wall ramp as it was placed on the upper level footwall flat, thus changing the original configuration of the cutoffs in the hanging wall ramp (Suppe, 1983). Dips on the southeast limb of the anticline are typically shallow, reflecting the shape of the footwall ramp underlying the thrust sheet. At its southwest end, the Powell Valley anticline apparently truncates against the Jacksboro fault. However, reconstruction of the eroded hanging-wall of the Chattanooga fault and down-plunge projection of the Powell Valley anticline along the Jacksboro fault indicates that a single hanging-wall was folded above a lateral ramp bordering the northeast margin of the Wartburg Basin, which is now expressed as the Jacksboro fault. The hanging-wall continued above the Wartburg Basin to a position just southwest of the Harriman area.

The hanging-wall ramp section in the northwest limb of the Powell Valley anticline has an increased density of contractional deformation features associated with it. The majority of these features occurs just

to the southeast of Cumberland Mountain. In this area, southeast dipping imbricates, with associated folding, and folds related to blind thrusts, are numerous (Fig. 37). There are two plausible explanations for this area of high strain. First, the increased strain could be related to the imbrication of the hanging-wall ramp as it was moved over the footwall flat; this type of situation has been documented experimentally by Morse (1977). The second explanation is that the features developed in association with the propagation of the Pine Mountain fault through the structural unit 2 ramp. When ramping occurs, the outer limb becomes overturned and is subjected to unusually high strains (Mitra, 1978; Boyer and Elliott, 1982; House and Grey, 1982). Of course, it is also plausible that both mechanisms combined to produce the high strain features.

Added structural relief was given to the Powell Valley anticline by a lower thrust sheet which is interpreted as being a Bales thrust equivalent. The name, Bales thrust refers to a relatively small fault and thrust sheet below the Pine Mountain thrust sheet in Virginia and a portion of the Pine Mountain sheet in Tennessee (Harris, 1967). Several factors support the interpretation of a Bales thrust equivalent for the southern portion of the Powell Valley anticline. First, without the Bales equivalent, there was a material void of about 2000 feet between the hanging-wall trace and footwall trace of the Pine Mountain thrust. Additional support for a Bales equivalent comes from well data. Dipmeter data from the 1 Sanford Heirs well indicate a northwesterly dip in the lower footwall levels of the Chattanooga fault; thus

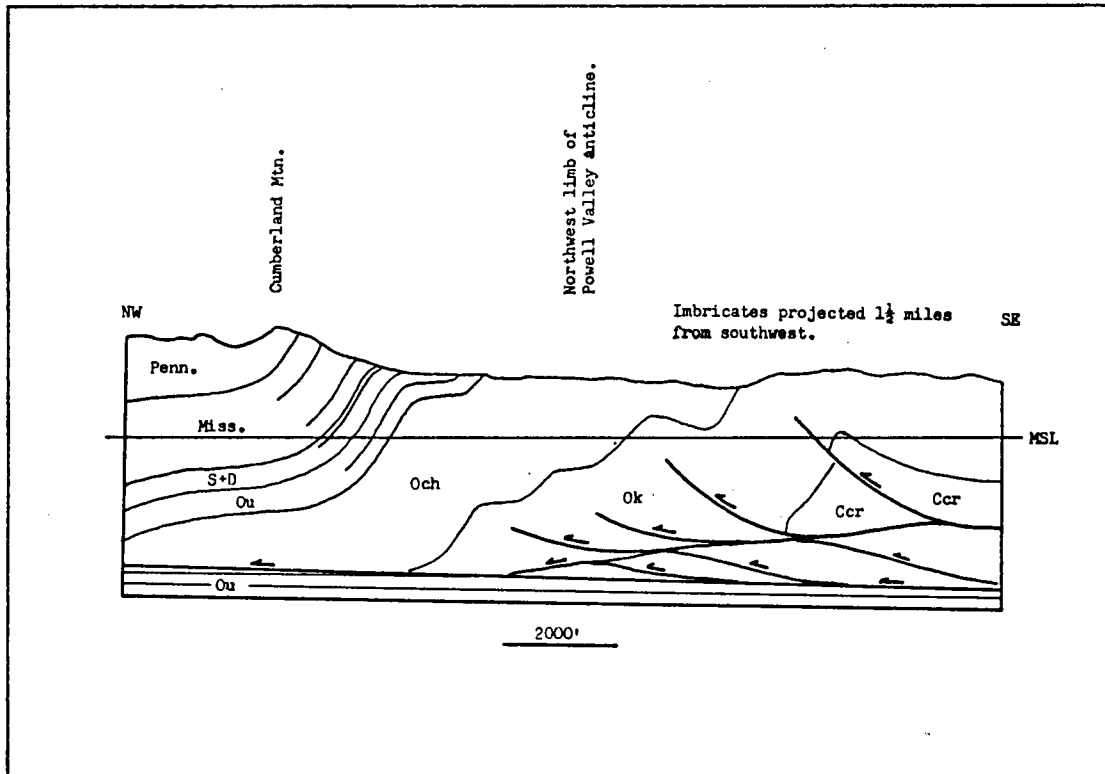


Figure 37. The northwest limb of the Powell Valley anticline exhibits numerous imbricates (mostly blind) and associated folds. These features probably resulted from high strain on the outer limb of the hanging-wall ramp anticline.

the well was drilled on the northwest limb of a subcropping structure. The northeast extent of the thrust sheet is placed at approximately 20 miles northeast of the Jacksboro fault where a pronounced change in the width of the Powell Valley anticline occurs.

The Upper Structural Levels

Propagation of the Pine Mountain fault through structural unit 2 and into unit 3 led to the development of a diverse suite of upper level structures. Northeast of the Jacksboro fault the Pine Mountain propagated as a flat fault within structural unit 3 (Fig. 32, p. 69). This is reflected geometrically in the Middlesboro synclinorium by relatively flat lying strata, although a few low relief folds occur in the structure (Froelich, 1973; Harris and Milici, 1977). Southwest of the Jacksboro fault, the Chattanooga segment of the Pine Mountain system took on a more listric shape, and only a weakly developed flat formed in unit 3 (Figs. 35 and 36). The two areas of different fault shape are connected by an area of transitional structural style, which includes the Jacksboro lateral ramp.

An outstanding aspect of upper level geometries is the marked change in types of upper level detachments from northeast to southwest. As shown in Fig. 38, the northeast to southwest transition is a narrow duplex or sole thrust, to a well developed duplex, and finally to a poorly developed sole thrust or a poorly developed front fold detachment in the vicinity of the Jacksboro fault. Finally southwest of the Jacksboro fault and northwest of the Dutch Valley structure, little displacement occurred along upper level detachments.

Figure 38. Diagrammatic representation of upper-level detachment types in restored states shows a northeast to southwest transition. North of the major duplex a narrow duplex detachment is contained within the Devonian and Lower Mississippian shale section. At approximately 10 miles northeast of the Jacksboro the duplex detachment widens in the amount of stratigraphic section it incorporates. The roof thrust remains in the Chattanooga and Grainger shales, but the floor thrust cuts down into the Rockwood Formation; occasional imbricates cut the Mississippian carbonate section. This trend continues to the southwest, but upon crossing the Jacksboro fault, the system loses the roof thrust and becomes a front fold type of detachment.

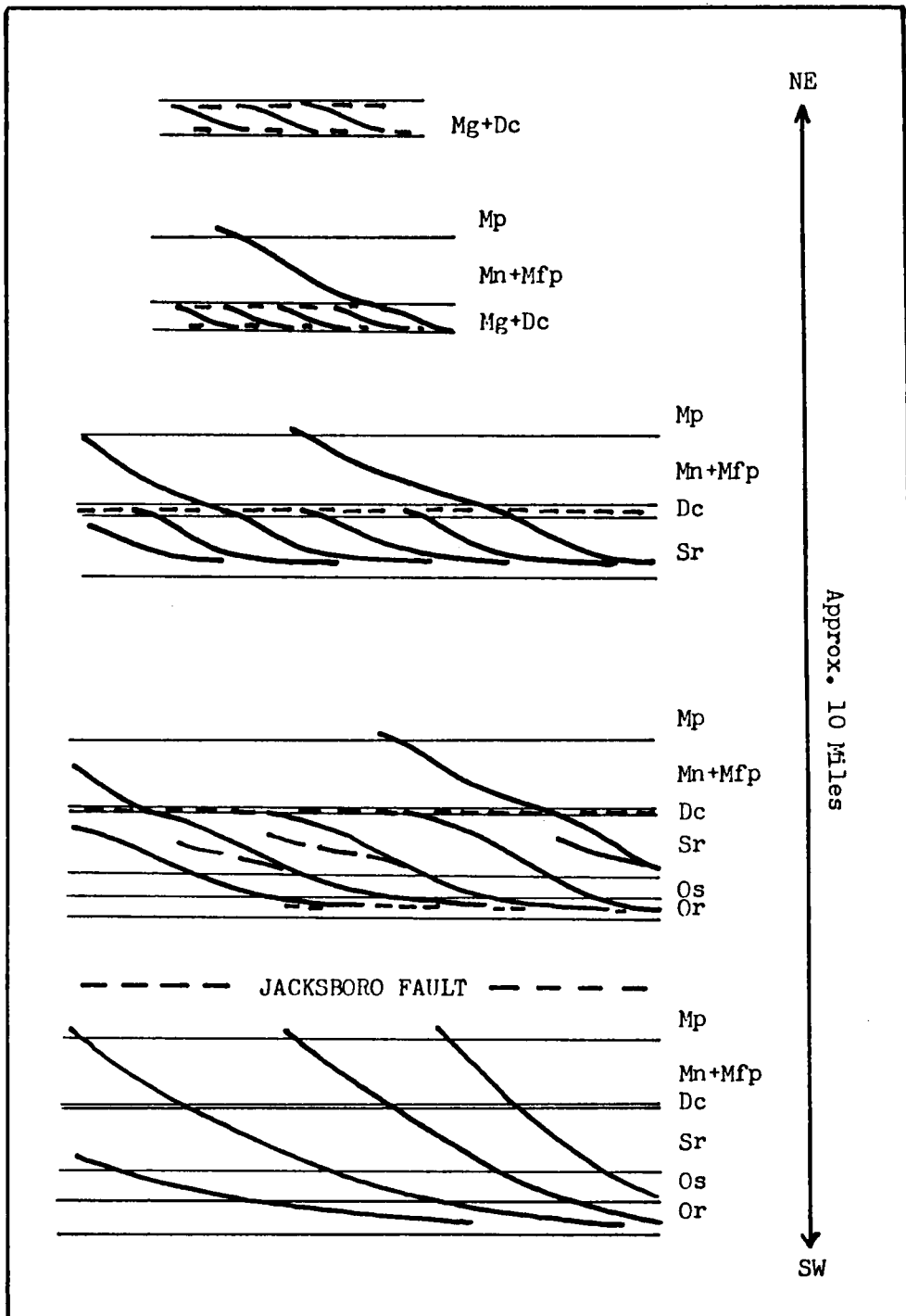


Figure 38

The transition of style begins approximately 10 miles northeast of the Jacksboro fault. Northeast of the major duplex the detachment is contained within the Chattanooga and Grainger shales section. Here the style of detachment is seemingly simple; however, Harris (1970) noted that there is approximately 1000 feet of stratigraphic duplication in the Devonian and Lower Mississippian shales just above the Pine Mountain fault. Additionally, in outcrop the shales contain numerous small imbricates. Many of these imbricates apparently merge near the base of the Mississippian carbonate section to form a roof thrust, thus completing requirements for a duplex type of detachment. Such fault occurrences are difficult to locate due to difficulties of mapping faults in shales. The poor resistance of shales to weathering does not make for extensive outcroppings. Thus, while the mode of detachment in this area is probably one of duplexing, documentation is often difficult.

In the northeast parts of the duplex, imbrication within the Mississippian and Devonian shales continues to be important, but imbricates begin to break from the main detachment and propagate upward into the overlying carbonates. Down-structure projection of the major faults of the duplex area (Fig. 39) illustrates that numerous low-amplitude culminations resulted from the stacking of horse blocks. Transport-direction cross sections (Fig. 40) further show complexities related to duplexing. The more extensive imbrication shown in the cross sections is based on field relationships given in Appendix E. The behavior of the small thrusts above structural unit 4 is not

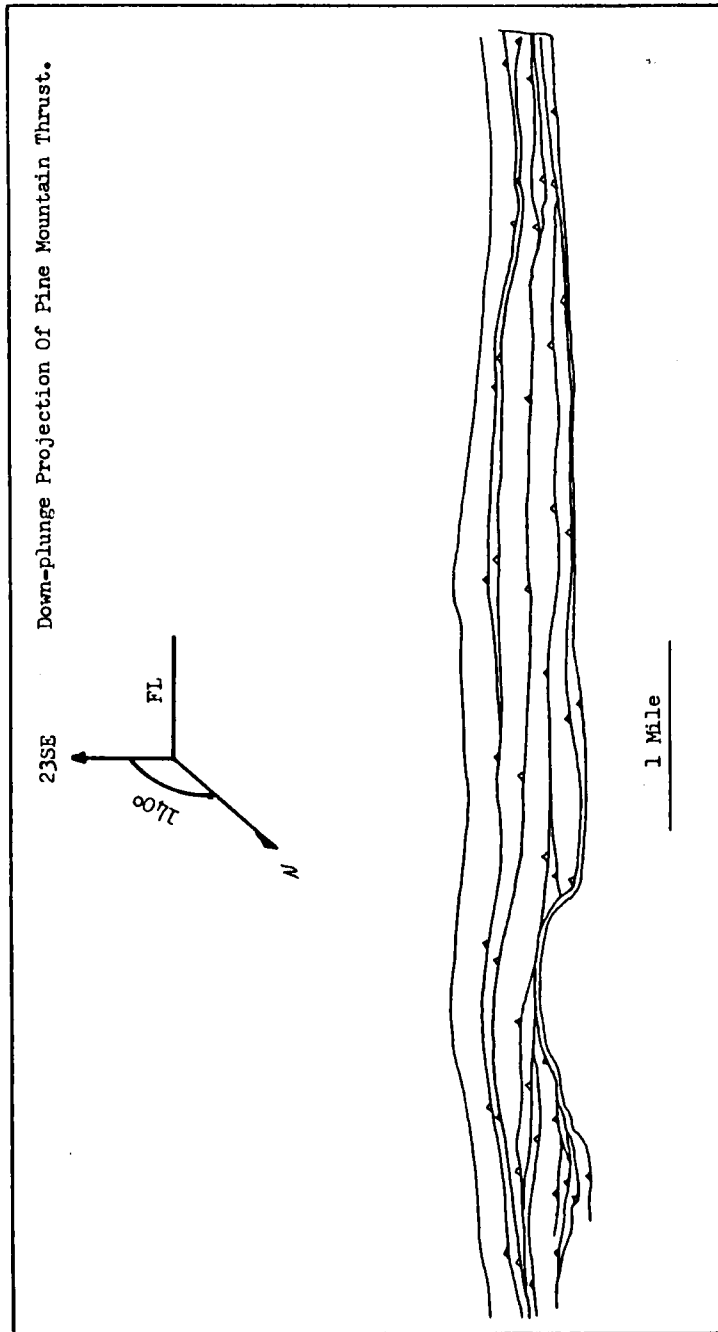


Figure 39. Down-structure view of the Pine Mountain duplex shows the lateral geometries of the major faults in the system. Note that the zone of imbrication widens to the southwest.

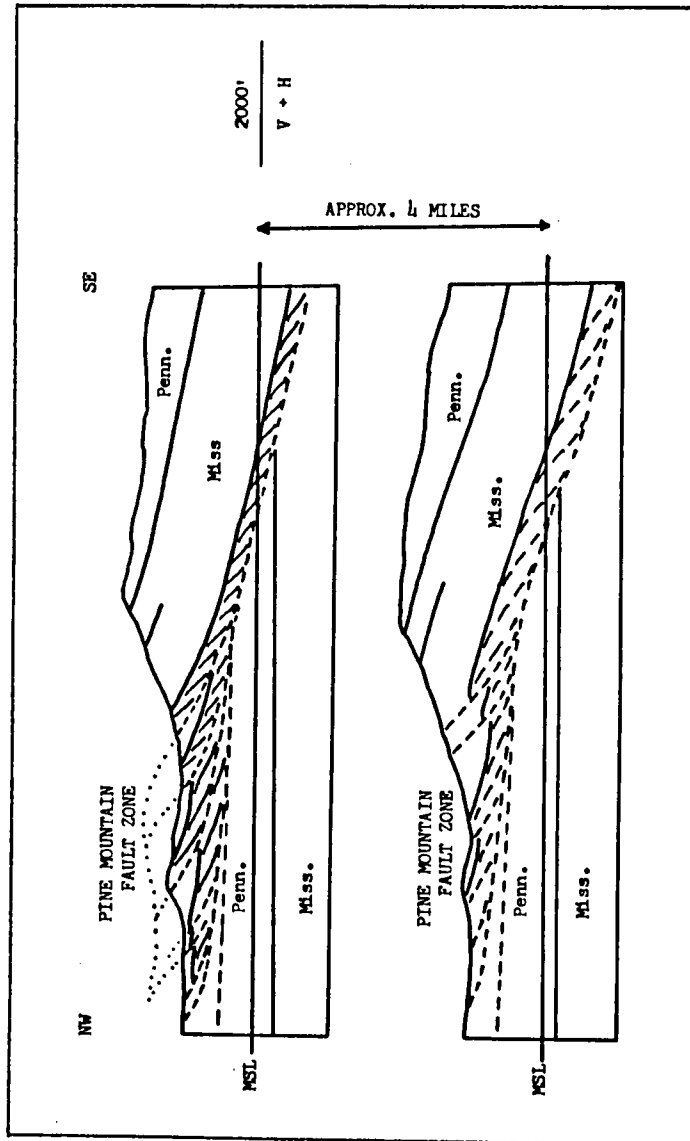


Figure 40. Cross sections across the Pine Mountain fault trace show the complexity of the fault zone. The distance that the duplex extends beneath the Middlesboro synclinorium is not known.

known; however, based on high fault preferences for structural unit 5 from the southwest parts of the study area, the Pennington may have served as a higher level flat.

Approximately 6 miles northeast of the Jacksboro fault the map pattern indicates the first major involvement of the Rockwood Formation in the duplex. At this point the floor thrust drops into the Rockwood Formation, but the roof thrust rides in the Chattanooga and Grainger shale section. The first appearance of Rockwood on the fault occurs in the area where the Grainger Formation is becoming thin and sporadic in distribution. Additionally, the Chattanooga Shale has thinned to an average of 100 feet in this area, and much of this may be tectonic rather than stratigraphic thickness. Imbricates continue to propagate through the overlying Mississippian carbonates.

Near the Jacksboro fault, Upper Ordovician rocks comprise the lowest hanging-wall unit, indicating that the floor thrust continued to drop to the southwest (Miller, 1973). The roof thrust continues to occur in the Chattanooga Shale, which has thinned to a thickness of about 50 feet. The imbrication of Mississippian carbonates is still significant. In this area the Grainger Formation is absent.

Southwest of the Jacksboro fault, geometric considerations and data from the 1 Sanford Heirs well indicate that the roof thrust is lost from the upper level detachment system and a single bedding-subparallel detachment lies in the Reedsville Shale. Thrusts branching from the Upper Ordovician flat are in the form of blind imbricates, and detachment is of the front fold type. Prospects for a roof zone

above the Devonian Shales are doubtful for the eastern margin of the Wartburg Basin. Southwest of the study area Pennsylvanian rocks are extensively involved with deformation. On the northwest end of the Cumberland Plateau sheet, the thrust cuts up-section laterally in a well developed step-shape and finally is expressed at the surface by the Emory River fault (Harris, 1970). The presence of several small anticlines in the southwestern part of the Wartburg Basin indicates that this area is underlain by a detachment, but it was not significantly displaced. There are no indications of an analogous detachment beneath the remainder of the Wartburg Basin, and deformation of Pennsylvanian rocks is limited to imbricate thrusting proximal to the major fault boundaries. Any major detachment that existed would have been higher in the section and is now eroded.

The dominant lateral structure in the upper levels of the Pine Mountain thrust system is the Jacksboro lateral ramp, which is mapped at surface as the Jacksboro tear fault. On the northeast side, where structural unit 3 is thick, the Pine Mountain thrust sheet rides on an extensive footwall flat. Southwest of the structure, unit 3 is thinner and the Chattanooga segment of the Pine Mountain fault propagated up-section to a higher stratigraphic level. The tear fault developed to serve as a connecting surface between the adjacent, differing fault levels. The longitudinal stepping across the lateral ramp resulted in a footwall protrusion, which is now expressed as the Wartburg Basin.

The Jacksboro fault dips approximately 20 to 45 degrees to the northeast where it bounds the Powell Valley anticline (Figs. 41 and 42), but as the northwest extent of the fault is approached, the fault

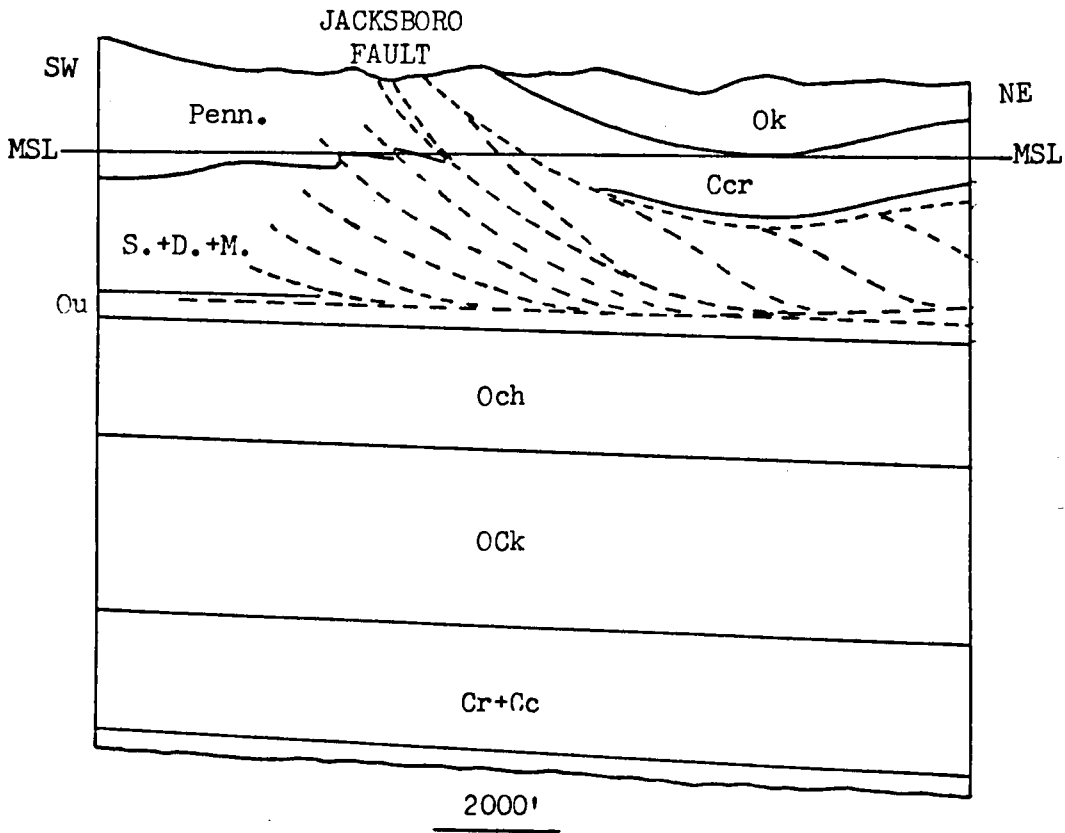


Figure 41. Longitudinal cross section across the Jacksboro fault shows the fault dipping to the northeast and flattening into Upper Ordovician rocks in the footwall. Thus, although the fault is mapped as the Jacksboro fault, it is actually the Pine Mountain thrust exposed along a reentrant. Horses wedged in the system are interpreted as being the northeast end of the Dutch Valley horse system which was imbricated above the lateral ramp and carried further to the northwest above the major footwall flat. To the southeast, further displacement of the horse system was impeded by steeper fault angles.

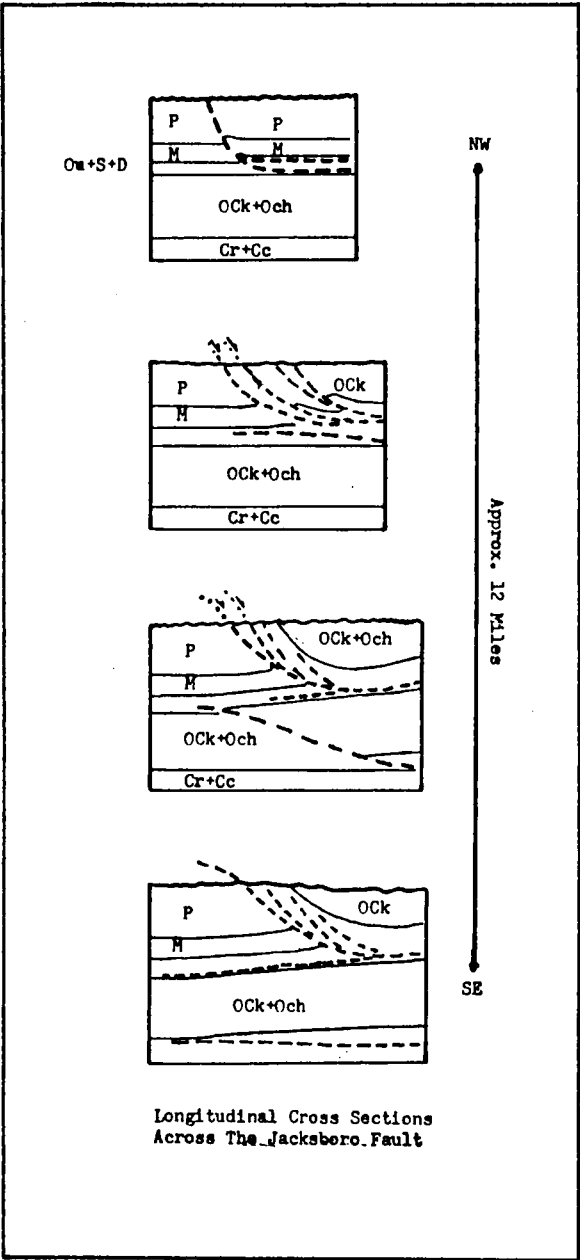


Figure 42. A series of idealized longitudinal cross sections across the Jacksboro fault illustrates the progressive loss of stratigraphic separation to the northwest. Dips on the fault also increase somewhat in that direction.

dips very steeply to the northeast (Fig. 43). Commonly, when a lateral ramp develops, the hanging-wall is subject to both extension and tear faulting above the ramp fault (Elliott and Johnson, 1980; Butler, 1982) and normal displacement will occur on the down-dip side of the structure. Presently, it is unclear whether or not the Jacksboro fault has been subjected to normal displacement.

Calculations of displacement along the Jacksboro fault have been offered by several workers. Englund (1968) estimated displacement to be 11 miles, Harris (1970) proposed 10 to 12 miles, and Elliott (1981) calculated 12.5 miles of displacement along the trace of the Jacksboro fault. Based on the restoration of preserved cutoffs from along the trace of the Jacksboro fault, the displacement offered in this report is about 13.5 miles.

The surficially exposed deformation zone thickens in terms of the amount of section which it incorporates as the Jacksboro fault is approached from the northeast. This thickening trend parallels the thinning direction of the Devonian and Lower Mississippian shales. Coincidentally, the size of individual fault slices within the duplex increases to the southwest; indicating the transition from unit 3 domination to the northeast and unit 4 domination to the southwest. The key aspect of the transitional system is that the roof thrust for the duplex attempts to migrate to higher stratigraphic levels to the southwest, while the floor thrust drops to lower levels (Fig. 44). The implication is that the Jacksboro structure began evolving north of its

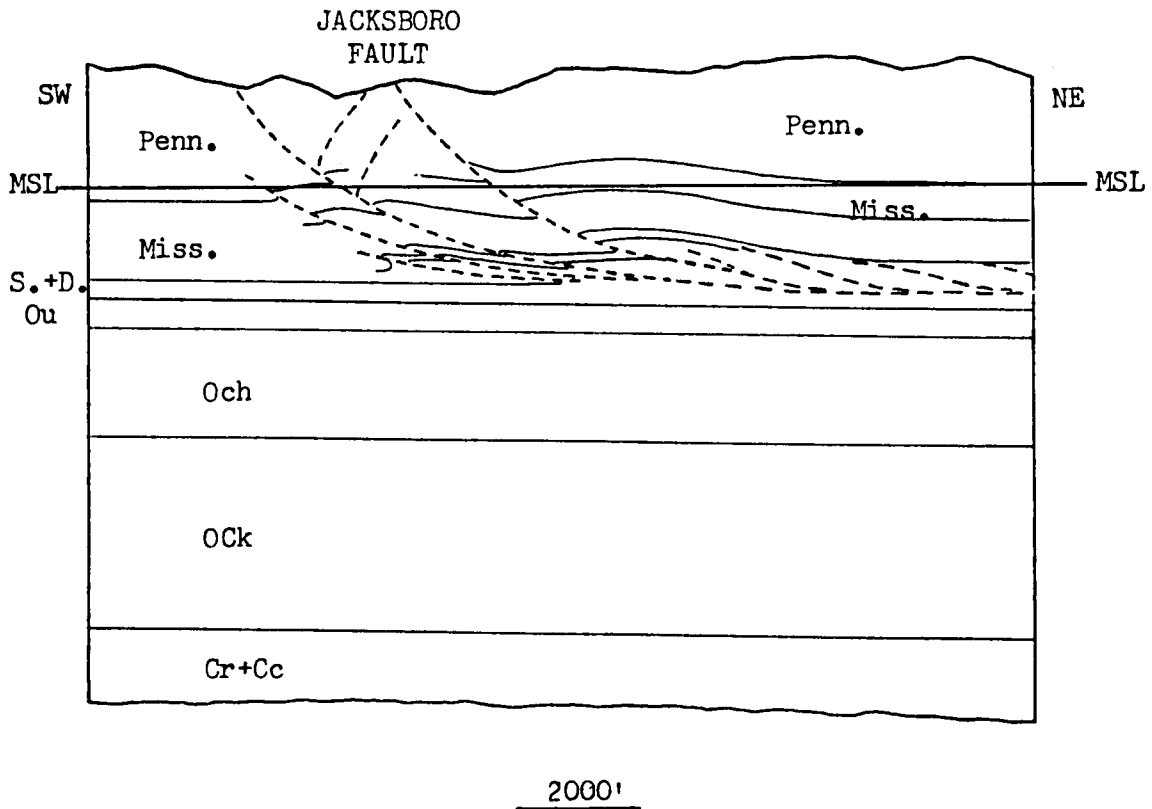


Figure 43. Near the Pine Mountain trace the Jacksboro fault does not show major stratigraphic separation. Little should be expected since the Pine Mountain fault beneath the Middlesboro synclinorium has little stratigraphic separation associated with it.

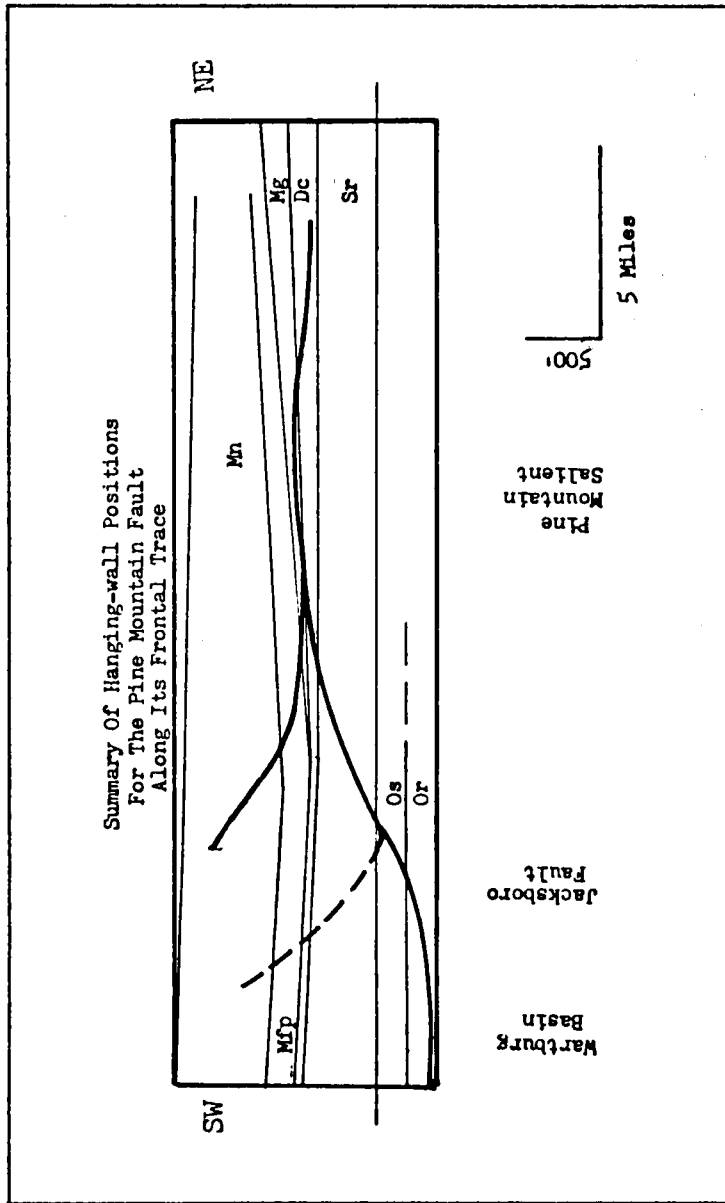


Figure 44. A plot of restored hanging-wall positions for the upper structural levels of the southwestern portion of the Pine Mountain thrust system shows that at distances greater than about 10 miles northeast of the Jacksboro fault the hanging-wall rides exclusively in the Chattanooga and Grainger shales. As the Jacksboro fault is approached from the northeast, a duplex develops. Within the duplex, the floor thrust cuts down-section to the southwest, and finally stabilizes in Upper Ordovician rocks. The roof thrust remains constant or climbs up-section to the southwest.

present position and represents the major upwards break off of the roof thrust. The weakly developed flat beneath the Wartburg Basin would then represent the southwestward projection of the floor thrust.

The distribution of detachment types and lateral structures in the upper levels of the Pine Mountain thrust system is directly related to the distributions of structural units 3 and 4. The important aspects of units 3 and 4 in this respect are: (1) the southwestward thinning of the Grainger Formation and Chattanooga Shale, (2) the strike of the Jacksboro fault parallels Chattanooga and Grainger isopachs, (3) the Silurian thins in the vicinity of the Jacksboro fault, (4) the coincidence of the above three aspects with a zone of structural style transition which is bound on the southwest by the area of front fold detachment type and on the northeast by deformation being largely contained within the Chattanooga-Grainger Shale section, (5) the loss of the Rockwood and Chattanooga as extensive flat forming units beneath the Wartburg Basin, and (6) little variation in individual unit lithologies are observed across the zone of structural transition; this implies that thickness variations and changes in gross unit character are the important causes of change in structural style.

Effects of Gross Stacking of Structural Units

The importance of demonstrating the nature of the mechanical layering of a system is pointed out by Johnson (1980). Johnson has shown that the number of structural units can determine whether a sequence will fault or fold when stressed. He determined that when 2

or fewer structural units are present in a mechanical system faulting will be the dominant response to deformation. When more than 2 structural units are present folding will dominate structural style. A similar relationship generally exists for thrust shapes relative to the stacking arrangement of weak and strong structural units within a sedimentary succession. Based on the distribution of weak and strong layers previously discussed, there is a decrease in stacking complexity from northeast to southwest for the Pine Mountain fault system. The northern parts of the Pine Mountain system involve an extensive inter-layering of weak and strong structural units, or is multilayered. Structural unit 3 is of considerable thickness in the northern areas and exerted a major influence on thrusting. In the southwest, unit 3 is comparatively thin and is less important as a structural influence; at this point, units 2 and 4 can almost be considered continuous. The net result of the loss of unit 3 to the southwest is that, with the exception of the basal weak unit, the section below the base of unit 5 is dominated by strong rocks.

Calculations of Centers of Gravity and Dispersions

Using the method described in Appendix D, relative centers of gravity and standard deviations of weak units were calculated for each of the composite stratigraphic sections shown in Fig. 5, p. 27. The relative center of gravity reflects the mean vertical position of a specified type of unit within a stratigraphic section, and standard deviation represents the degree of dispersion of the type unit about

the center of gravity. Both values are expressed as a percentage of the total section thickness, and center of gravity is measured from the top of the highest unit used in a calculation; thus, a high center of gravity value would correspond to a point low in the stratigraphic section.

Calculations were completed only for portions of the sections lying below the top of structural unit 4. Unit 5 was not treated due to a lack of adequate data. Additionally, stratigraphic sections of Fig. 6, p. 29, were not used because of lack of control over unit 4. Values were contoured on a palinspastic base map to allow comparison of stacking in the predeformational state with the evolution of structures.

Figure 45 shows the relative center of gravity for all potential weak units below the top of the Newman Limestone (top structural unit 4); the assumption here is that a unit that behaved weakly anywhere in the region could possibly behave in a like manner in any other part of the area. Contouring of calculated values shows that the center of gravity values for all potential weak layers increase toward the southwest portion of the Pine Mountain system. This indicates that weak layers (measured in percent of section from the top of unit 4) tend to occur lower in the section for the southwest as compared to the northeast. Accompanying the increase in center of gravity is a decrease in relative standard deviation (again measured in percent of section). Since standard deviation reflects dispersion of a unit type around a center of gravity, the lower standard deviation for the southwestern portion of the Pine Mountain thrust system indicates

Figure 45. Relative centers of gravity and standard deviations for all possible weak units were calculated for each composite stratigraphic section and contoured on a palinspastic base map. The highest unit used in the calculations was the Newman Limestone. Contours indicate that the weak fraction of the sedimentary wedge tends to be concentrated lower in the section to the southwest, whereas in the northeast, weak units are more widely dispersed through the section.

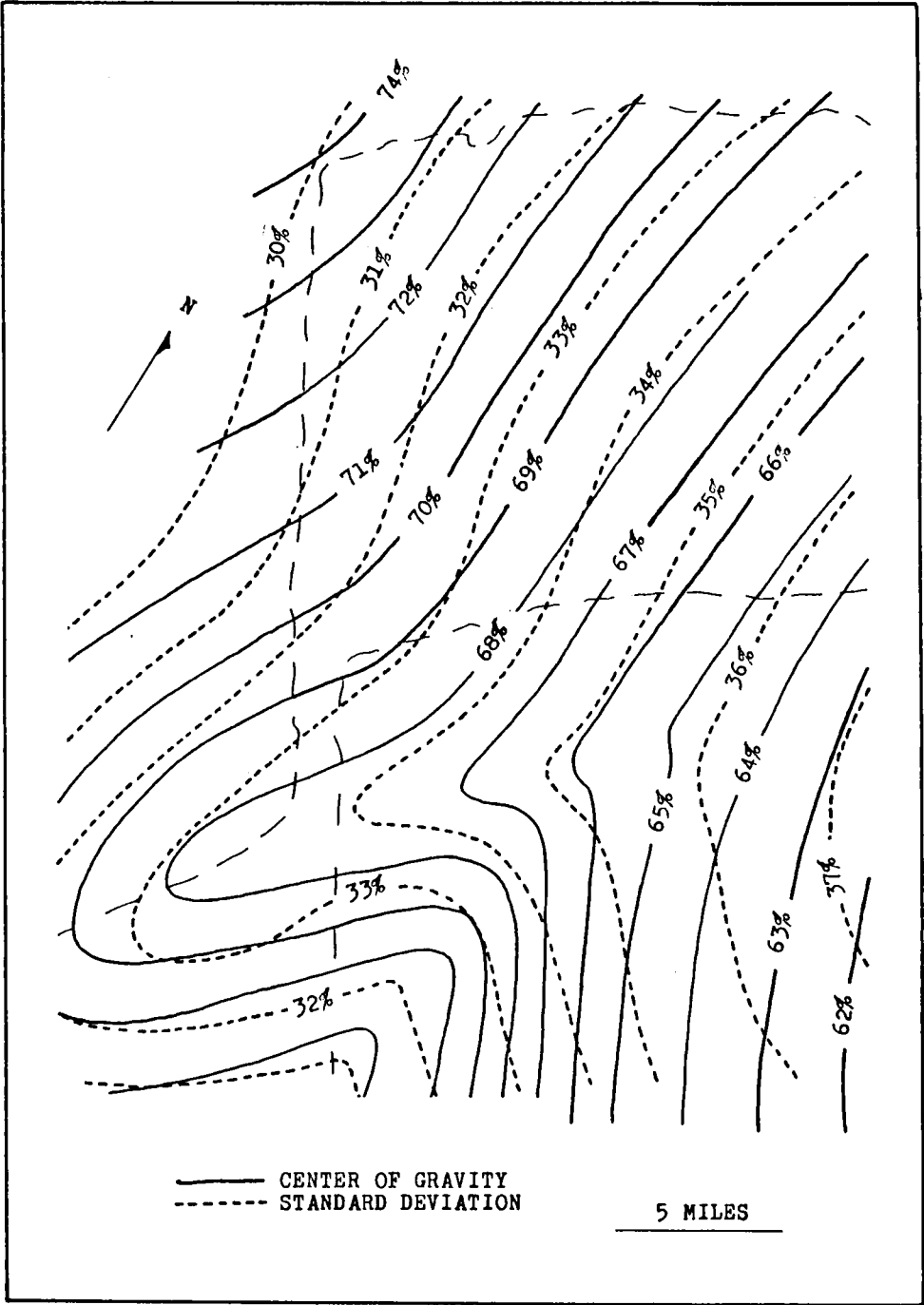


Figure 45

that the weak portion of the sequence is less dispersed about the center of gravity. In terms of mechanical layering, areas northeast of the Jacksboro fault can be considered multilayered. Southwest of the Jacksboro fault, the sedimentary wedge tends to more closely approximate a two layer mechanical-layer system, with the constituents being a basal weak layer and a higher, thick strong layer.

The southwestward trend of concentrating weak units toward the base of the section is even more pronounced when only units that are known to behave as weak units in the proximity of each composite section are taken into consideration. This probably gives a more realistic representation of the mechanical layering. Figure 46 shows a comparison of centers of gravity and dispersions for composite sections 7 and 12. The highest structural unit used in the calculations is again unit 4. The upper weak layer for section 12 includes Upper Ordovician through Lower Mississippian rocks, while the upper weak layer section 7 consists only of the Reedsville Shale. Here the center of gravity is approximately 1800 feet lower for the southwesternmost section (6 percent difference), and the relative standard deviation decreases by about 4 percent. For comparison, calculations using all potential weak units are also plotted on this diagram.

Thrust Shapes and Mechanical Layering

The shape of thrust faults varies between two endmembers: stepped and listric (Fig. 47). Subsequent deformation often masks the true geometries of thrusts, as they may be folded or oversteepened

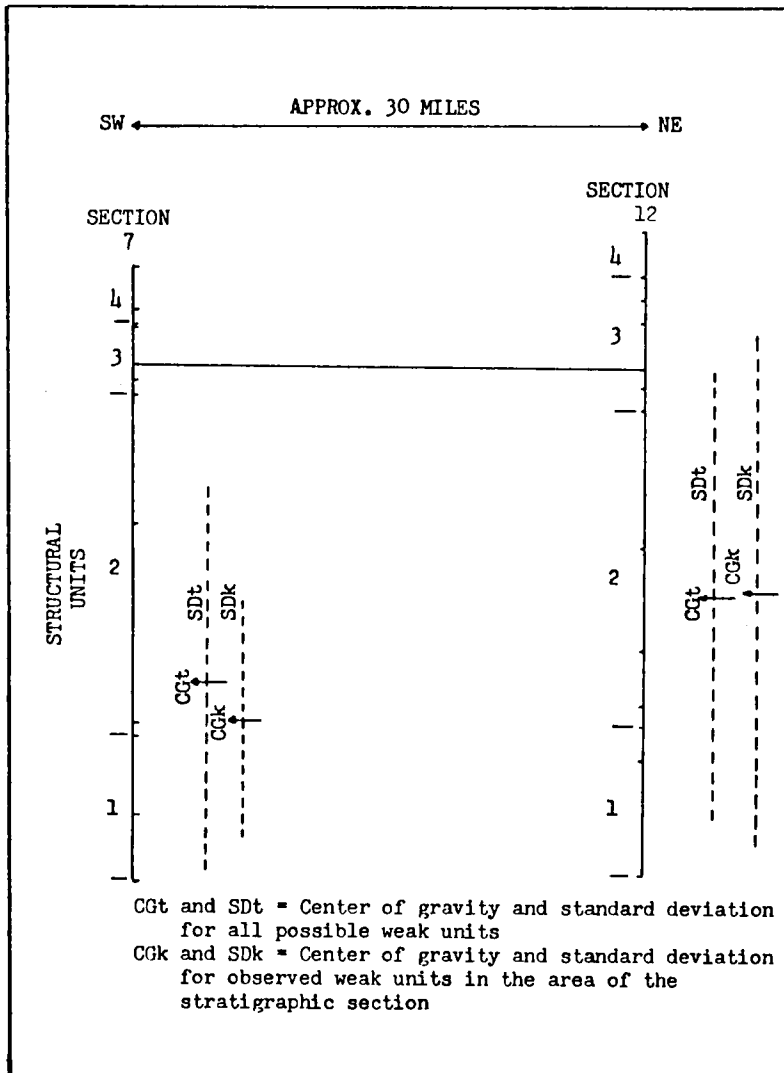


Figure 46. Recalculation of centers of gravities and standard deviations on the basis of units known to have led to the development of significant flats in a specific area shows that the difference from northeast to southwest is even greater than for all possible weak units. Calculations here are for composite sections 7 and 12. Both calculations (for known and all possible) are shown for comparison.

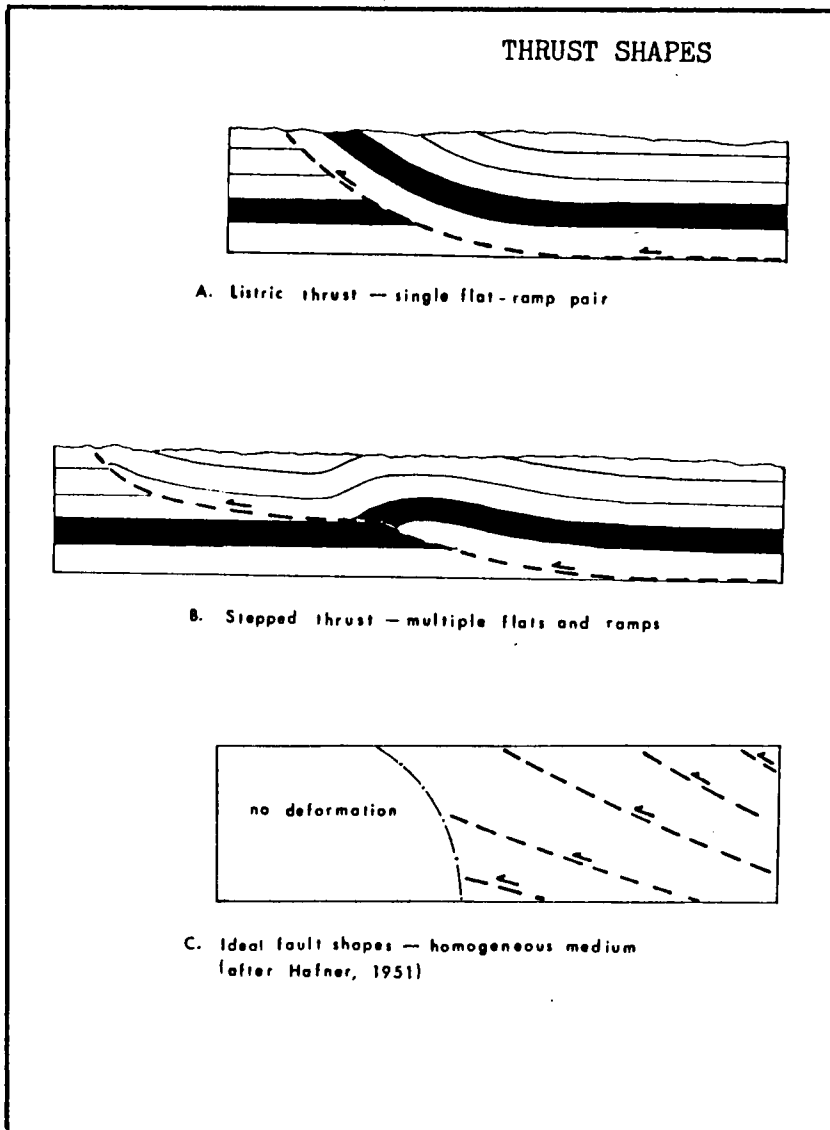


Figure 47. Thrust shapes tend to range between two endmembers: listric and stepped. Stepped thrusts develop where an upper level detachment surface can be propagated (b). Propagation of a thrust through a homogenous medium will yield a listric shape (c). Thus, where no upper level unit is weak to the point of allowing a detachment to propagate, a more listric shape will dominate fault shapes (a).

above lower, younger thrusts. The two basic shapes, however, have been verified by numerous workers through studies of palinspastic cross sections (Douglas, 1950; Bally et al., 1966; Dahlstrom, 1970; Roeder et al., 1978). Bally et al. (1966), Elliott and Johnson (1980), and Woodward (1981) have additionally shown that since thrusts may cut either up- or down-section longitudinally, the basic shapes occur both frontally and longitudinally.

The obvious question is what determines which of the endmembers will dominate. First, we can consider the case of listric geometries. This shape is quite common in preserved thrust sheets of the Valley and Ridge of Tennessee (Roeder et al., 1978). Results of experiments with stress distributions and fault propagation conducted by Hafner (1951) indicate that fault shapes trend toward listric in homogeneous media. Where a sedimentary prism is composed of similar rock types, thrusts propagated through the section would ideally tend to be listric.

Stepped thrusts are considered classic thrust belt structures. They involve a multiple flat-ramp system, which leads to the development of a staircase geometry. The explanation for stepped thrusts is that they respond to an interlayering of weak and strong rocks in the stratigraphic succession. Where weak rocks are encountered, a thrust will tend to cut slowly up the stratigraphic sequence; when strong rocks are met, a thrust will cut steeply up-section. The Pine Mountain thrust of this study is perhaps the best known stepped thrust in thrust belt geology.

The dramatic stepped-thrust to more listric-thrust that resulted in the major lateral ramp expressed in the Jacksboro fault and the unusual configuration of the Pine Mountain thrust sheet is the direct result of the southwestward strengthening of the section. Southwest of the Jacksboro fault, the Pine Mountain fault (Chattanooga fault) broke from the basal detachment and was confronted with approximately 6000 feet of strong to relatively strong rocks; except for a poorly developed flat in the drastically thinned section of unit 3, the fault cut through in listric fashion. Northeast of the Jacksboro fault, the Pine Mountain fault cut through structural unit 2 and encountered another major weak unit in unit 3. Upon encountering unit 3, the fault propagated as a relatively flat lying system. A lateral ramp was required to develop between the Pine Mountain and Chattanooga segments to maintain continuity along the fault surface (Fig. 48).

The transitional area between the two layer and multilayer regions is characterized by structures that reflect the change in mechanical layering. First, the extensive duplex exposed along the southwestern end of the Pine Mountain frontal region formed in response to Chattanooga Shale thinning and the loss of the Grainger shale section. The thrust cut lower into the unit 3 section in an attempt to maintain geometric continuity along strike. Second, the Jacksboro lateral ramp formed in response to southwestward thinning of unit 3, but also, the formation of this structure indicates that unit 3, without the thick Devonian and Lower Mississippian shales, was less capable of supporting an extensive detachment.

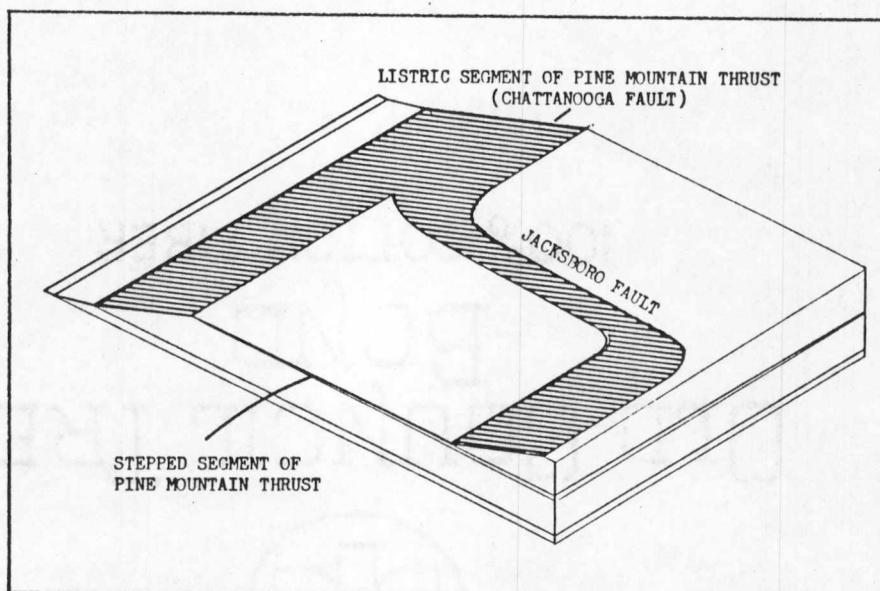


Figure 48. Block diagram illustrates an idealized Pine Mountain footwall. The northeast portions of the system are characterized by a staircase geometry, and the portions of the fault southwest of the Jacksboro fault tend to be more listric in shape. The Jacksboro fault serves as a connecting surface between the two different fault shapes.

Based on comparisons of known geometries and contoured values of centers of gravities and standard deviations, several relationships have been identified. Listric fault shapes occur where center of gravity exceeds 71 percent and standard deviation is less than 31 percent. A staircase geometry developed in areas that have centers of gravity less than 67 percent and standard deviations greater than 34 percent. The range of values that correspond to areas of transitional structural style are 67 to 71 percent for center of gravity and 31 to 34 percent for standard deviation. Southwest of the Jacksboro fault values quickly surpass the limits of the transitional range, indicating that only a more listric shape is stable as the dominant style of thrusting.

CHAPTER 5

SUMMARY AND CONCLUSIONS

Summary

The Pine Mountain thrust sheet is considered a premier example of a stepped thrust, but more accurately the Pine Mountain thrust system has a stepped geometry in its northeastern extent and a more listric geometry in its southwestern extent, which is mapped as the Chattanooga fault. The two contrasting styles meet in a lateral ramp system which is expressed as the Jacksboro fault.

The fault system developed in a setting typical of foreland fold and thrust belts. The basement dips gently to the southeast, or toward the interior of the thrust belt. The original configuration of the sedimentary cover was a wedge shape which generally thickened to the southeast. Deformation shortened the cover rocks by approximately 50 percent.

An evaluation of the stratigraphic succession for its behavior when stressed resulted in an organization of stratigraphic units into five distinct structural units. Unit 1 consists of the Rome Formation and Conasauga Group. Unit 2 includes the Knox and Chickamauga Groups. Unit 3 consists of Reedsville Shale through the Grainger Formation. Unit 4 members are the Mississippian carbonates. Unit 5 is composed of the Pennington Shale and the lower portion of the Crab Orchard Mountain Group of the Pennsylvanian System.

Placed in context of developmental stages, the Pine Mountain fault first propagated as a westward extension of the basal detachment beneath the older Kingston and Wallen Valley faults. The westward flat propagated for about 10 miles as a zone of blind imbrication or duplex type of detachment within the weak rocks of structural unit 1. When the fault penetrated unit 2, it cut steeply up-section. Fault preference calculations show high values associated with the Maynardville Limestone, which lies at the unit 1-unit 2 interface. This seems to indicate that the thick, strong unit 2 played a major role in containing the basal detachment, and thus, was an important stress guide. Structural units 1 and 2 behaved consistently across the entire study area.

Along the southeast margin of the Wartburg Basin, the fault propagated up-section at a relatively steep angle, with only a slight flattening at the top of unit 2 (within a thin unit 3). To the northeast, the fault encountered a thick unit 3 and propagated as a duplex type of detachment within it, with occasional imbricates propagating up-section through unit 4. Finally, unit 4 was crossed at an increased angle. As with the unit 1-unit 2 interface, the high fault preference values for the base of unit 4 along the Pine Mountain trace probably indicates that the interface between weak rocks of unit 3 and stronger rocks of unit 4 was an important stress guide, and served as a roof for the detachment. Above unit 4, the nature of stratigraphy-structure interactions is poorly constrained, but the presence of a major roof thrust within unit 5 in the frontal exposure

of the Pine Mountain fault suggest that unit 5 may have been a significant detachment.

The occurrence of the Jacksboro tear fault and associated lateral ramp shows an excellent correlation with the distribution of weak and strong units in Upper Ordovician through the Lower Mississippian rocks (structural unit 3). The Jacksboro fault, while the most prominent cross strike structure, is simply part of a suite of lateral transitional structures. The lateral system started forming as a duplex at least 10 miles northeast of the major lateral ramp. At this point the Pine Mountain system branched laterally, cutting both up- and down-section longitudinally.

The most important factor in the evolution of the lateral system was the loss of the Lower Mississippian shales and drastic thinning of the Devonian shales to the southwest. With the thick shale section intact, detachment was contained within the sequence. Where the shales are thinner, but still significant, such as in the northeastern portion of the duplex, the Rockwood Formation became involved with the detachment, with a floor thrust occurring within the Rockwood and a roof thrust in the overlying shale section. From this point southwestward, the floor thrust progressively dropped to lower stratigraphic levels and finally stabilized in the Reedsville Shale. Coincidentally, higher imbricates become more numerous. The Jacksboro fault initiated from this type of imbrication at the point where the upper level detachment was incapable of sustaining large displacements. In the immediate vicinity of the Jacksboro fault, and the area

where the floor thrust cuts down to the Reedsville, the Chattanooga Shale is only about 50 feet thick and the Grainger is absent; in contrast, north of the duplex, in the central portions of the Middlesboro synclinorium, the combined Chattanooga-Grainger thickness exceeds 350 feet. In this context the cross strike structural system, which includes the Jacksboro fault resulted from the Pine Mountain faults attempt to find a stratigraphic position of similar mechanical property to the Devonian and Mississippian shales farther northeast.

Lithologies of rocks involved with upper level detachment do not vary significantly over the area. Additionally, the duplex, where it involves all rocks from Upper Ordovician through the Devonian-Lower Mississippian sequence, is interpreted as existing for a considerable distance beneath the Middlesboro synclinorium in the direction of tectonic transport. Where the thick shale section is too thin to support a roof thrust, detachment is in the form of blind imbrication (front fold detachment type of Dahlstrom, 1970), with the floor thrust occurring in the Reedsville Shale. To the northeast, where the Devonian and Mississippian shales are extremely thick, they comprise the dominant section of weak rocks. Thus, there is a good correlation between low angle detachment and shales. However, ultimately, thickness is the dominant control. No matter how "weak" a section is, it must be of significant thickness before it can act as a major stress guide in a major thrust system.

The reorganization of weak and strong rocks in the Upper Ordovician through Lower Mississippian interval resulted in an overall

stronger section in the vicinity of the Jacksboro fault and southwestward. Northeast of lateral structure the mechanically multilayered sedimentary sequence allowed for the development of a classic stepped thrust. Southwest of the Jacksboro fault vicinity the preserved portion of the succession exhibits essentially a two layer stacking, with a basal weak layer and an overlying strong layer; this resulted in a more listric thrust shape, with only a minor flat occurring at the top of the Knox-Chickamauga ramp section (structural unit 2). Thus, geometrically, the Jacksboro fault is simply the connecting surface between the two fault levels.

Conclusions

From the investigation of structural geometries, arrangements of lithologies and thicknesses within the sedimentary wedge, and distribution of structural units within the Pine Mountain fault system, several conclusions are drawn.

1. The Pine Mountain fault system exhibits a pronounced along strike change in structural style. The northeastern portion of the fault system has a staircase geometry, and the southwestern portion of the system has a more listric shape. The two areas of contrasting style are joined by a lateral ramp, the tear fault component of which is mapped at the surface as the Jacksboro fault.

2. Deformation of the system is in many ways typical of foreland thrust and fold belts. The basement surface dips gently toward the interior of the belt and the stratigraphic succession thickens to the interior as well.

3. By applying several structural and stratigraphic techniques, the stratigraphic succession can be reorganized into structural units. Five major structural units are present in the Pine Mountain thrust system. The two lowest units are very consistent over the entire area, but the upper units are characterized by areal changes.

4. The transition in structural style in the Pine Mountain system shows a good correlation with the loss of a major weak structural unit from the mechanical system. A thick section of Devonian and Mississippian shales promoted the development of an extensive upper level detachment for the northeast parts of the Pine Mountain thrust. Southwest of the Jacksboro fault, the shale section is quite thin, and upper level detachments are poorly developed.

5. The area of transition between the thick shale section and thin shale section is characterized by structures that reflect the change. The most prominent of these structures is the Jacksboro tear fault; however, transitional structures first appear approximately 10 miles north of the Jacksboro fault in the form of extensive duplexing. The area of transition is marked to the southwest by the eastern corner of the Wartburg Basin, where front folding is the primary detachment mode.

6. Reorganizations of weak and strong rocks in the sedimentary wedge resulted in a northeast to southwest strengthening of the sequence. Southwest of the Jacksboro fault the sedimentary sequence approximates a two mechanical-layer system, thus, it yielded a more listric shape when propagated by the Chattanooga segment of the Pine

Mountain thrust. The northeastern areas approximated a multilayer mechanical system, and yielded a staircase geometry. The two layer to multilayer transitional zone encompasses the Jacksboro fault. The critical number of structural layers in the transition is probably three; if less than three are present, a listric shape will occur and if more than three are represented, a stepped shape will be the stable fault shape. This is similar to the transition of fold dominated deformation to fault domination described by Johnson (1980).

7. The evolution of lateral structures (lateral ramps) is classically attributed to thickness and/or lithologic variations in the sedimentary wedge. - The lateral structures in the Pine Mountain system, however, are directly related to thickness changes and restacking of weak and strong rocks, since lithologic changes in individual units are not pronounced across the area.

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APPENDICES

APPENDIX A

WELL DATA

Map # Operator, Farm; TD; Basement Ele.

1	Shell, 1 Peterson; 5,404, Ccr; 07,500*
2	Ladd Pet., 1 Kemmer et al.; 10,141 pC; -7,772
3	Miller, 1 Carey Kenneth; 3, 260, OCK; -5,300*
4	COPCO, 3 Adkins; 4,000 OCK; -7,400*
5	Western & Collins, 1 Self Arnold; 2,524 Osr; -6,800*
6	COPCO, 1 Overton-Olmstead; 4,015, OCK; -7,100*
7	Riley Oil, 1 Lanham; 8,021, CR; -7,100*
8	Tate, 1 Baker-Pemberton; 5,517, OCK; -8,100*
9	Arco/Oxy, 1 Sanford Heirs; 11,540 pC; -10,549
10	Stoll, 1 Maples; 3,480 Cr; ----
11	Geo inc., 5 Lindsay Land, 3,395 Sr; -9,500*
12	PDC, 7 Koppers; 6,636 OCK; -8,500*
13	PDC, 8 Koppers, 6,128 OCK; -8,100*
14	Shurin, 6 West; 7,000 OCK; -7,600*
15	Trans-Tennessee, 1 Rivermont Farms; 3,425 OCK; -6,500*
16	Redman Oil, 1 Ketchen Coal; 7,555, C; -7,500*
17	Allegheny, AT-2 Huber; 3,973, Ot; -9,100*
18	United Fuel Gas, 2 Knuckles; 10,034, Cr; -9,000*
19	Shell, 1 L. S. Bales; ----; -8,700*
20	Cauble, 2 Riseden; 2,602, Osr; -7,100*
21	Rogers, 4A Garrett; 2,788, Osr; -7,200*
22	Tartan Oil, 1 Howard; 1,977, Ot; -7,200*
23	Allegheny, AT-1 Huber; 8,503, Cc; -8,600*

Map numbers indexed to Figure 2, p. 17.

*denotes estimated basement elevation.

APPENDIX B

REFERENCES TO COMPOSITE STRATIGRAPHIC SECTIONS

Section 1--McMaster, 1962; Swingle, 1964.

Section 2--Borowski, 1982; Jackson, 1956; Sniegocki, 1949; Swingle, 1964.

Section 3--Cathey, 1950; Byerly, 1957; Jackson, 1956; Lessig, 1949; Swingle, 1960a; Berry Stoll, 1 Maples well.

Section 4--Finlayson, 1964a, 1964b.

Section 5--Harris, 1965b; Tegland, 1978.

Section 5A--Harris, Stephens, and Miller, 1962; Tegland, 1978.

Section 6--Harris, 1967; Harris and Miller, 1963; Harris, Miller, and Stephens, 1962; Miller, 1965; Miller and Brosge, 1954; Miller and Fuller, 1954.

Section 7--Arco/Oxy, 1 Sanford Heirs well; Geo inc., 5 Lindsay Land co. well; Byerly, 1957; Jackson, 1956; Milici et al., 1979; Milici and Roen, 1981; Swingle, 1960a.

Section 8--Englund, 1968; Glen, 1925; Luther, 1967; McCallum, 1958; Milhous, 1959; Swingle, 1960b; Berry Stoll, 1 Shoun well.

Section 9--Englund, 1968; Glenn, 1925.

Section 10--Englund, 1964; Milici et al., 1979.

Section 11--Harris, 1965a; Milici et al., 1979.

Section 12--Harris, 1965a; Milici et al., 1979.

Section 12A--Englund, 1968; Milici et al., 1979; Froelich, 1973.

Section 13--Englund, 1968; Glenn, 1925; Milici et al., 1979.

Section 14--Englund, 1968; Milici et al., 1979.

Section 15--Riley Oil Co., 1 Louise Lanham well; Coker, 1966; Harris, 1975; Jewell, 1972.

Section 16--Martin Shurin, 6 West well; Luther and Avery, 1970; Glenn, 1925.

Section 17--Englund, 1968; Pomerene, 1964; Milici et al., 1979;
Wilson et al., 1956.

Section 18--Sutton, 1981; Wilson and Sutton, 1976.

Table B-1. Thicknesses used for construction of composite stratigraphic sections and isopach maps (in feet).

Section	Cr+Cc	OCk+Cmn	Och	Ou	Sil.	Dev.	Mg	Mfp	Mn	Mp
1	1,970	3,350	2,120	550	690	30	*	*	*	*
2	2,140	3,650	2,000	400	620	40	*	*	*	*
3	1,920	2,880	1,600	400	510	100	*	*	*	*
4	1,860	2,800	1,700	440	550	135	*	*	*	*
5	1,720	2,580	2,000	560	620	300	*	*	*	*
5A	1,940	2,590	2,000	660	690	490	*	*	*	*
6	2,210	2,560	1,975	610	695	770	*	*	*	*
7	1,970	2,910	1,750	420	490	50	0	200	600	600
8	1,800	3,150	1,900	500	400	50	0	200	600	600
9	1,850	3,000	1,900	510	450	80	70	150	600	500
10	2,020	2,440	1,860	550	560	245	250	50	600	?
11	2,100	2,080	1,850	560	590	250	275	30	550	450
12	2,090	2,360	1,850	565	595	245	285	20	550	450
12A	2,010	2,390	1,830	420	490	210	300	25	450	400
13	**	**	**	400	400	50	0	185	700	500
14	**	**	**	**	400	180	180	95	340	250
15	1,600	3,320	1,710	0?	20	40	0	85	640	210
16	1,625	2,800	1,700	105	150	60	0	150	485	257
17	1,850	2,390	1,800	200	305	175	340	20	300	300
18	2,210	2,480	1,780	0	150	130	350	10	160	180

*Eroded section.

**No data--rocks in subsurface.

? No data--rocks in surface.

APPENDIX C

FAULT PREFERENCE DIAGRAMS

Fault preference diagrams, as described by Dahlstrom (1970, p. 344), show a relative measure of the tendency of faults to gather preferentially in specific units. Dahlstrom's method for calculating fault preference is given as:

$$\text{F.P.} = \frac{\text{length along fault}}{\text{unit thickness}} \times C.$$

where F.P. = fault preference, and

C = an arbitrary constant.

The numerical value is then plotted against the stratigraphic section to produce a histogram. Fault preference is taken to be a measure of how a fault reacted when it cut into a unit. High fault preferences may indicate that faults tend to lie at low angles to bedding in the unit, and low fault preferences may indicate that faults tend to cut the unit at higher angles.

A problem with fault preference values is that while they reflect the behavior of individual units, they do not allow for direct numerical comparison of behaviors for multiple units. This problem can be readily overcome by calculating fault preferences as percentages of the total length of fault under investigation. Additionally, since differing unit thicknesses will bias fault preferences toward the thick units, unit thicknesses are normalized to the thickness of one of the units of

the sequence (as a convention, either the thickest or thinnest). As with Dahlstrom's method, percent fault preferences are plotted in histogram form, with the stratigraphic sequence being shown on the vertical axis. The method of calculation is as follows:

$$\text{F.P.} = \frac{[K]L_x}{\text{SLk}} \times 100$$

where F.P. = % fault preference,

K = thickness of thickest unit/thickness of unit x,

Lx = sum of lengths of unit x fault contact,

SLk = sum of corrected lengths ([K]Lx) for all units.

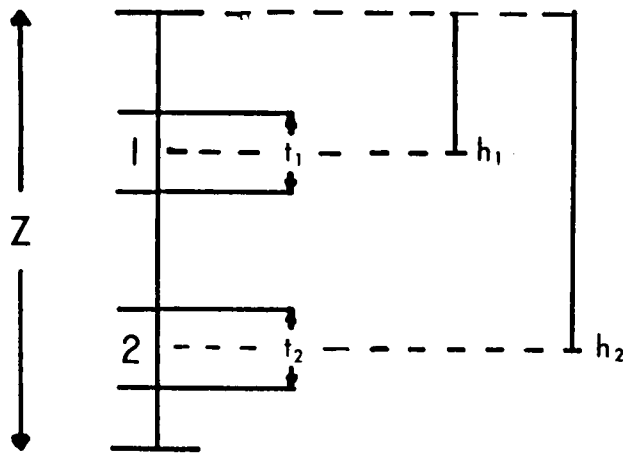
APPENDIX D

VERTICAL VARIABILITY MAPS

Vertical variability maps are essentially facies maps that show how a specific type of unit is arranged within a sedimentary body. The technique was formally introduced by Krumbein and Libby (1957) and involves calculating statistical moments of vertical distribution from well logs or measured sections. The utility of variability maps was demonstrated by Krumbein and Libby in their study of mean vertical occurrence and degree of dispersion of sandstone units for a portion of the Cretaceous section of north-central Wyoming. Doveton et al. (1984) have additionally applied the technique, in conjunction with conventional facies maps, in a study of shale distribution patterns in the Ordovician Simpson Group in south-central Kansas.

The construction of variability maps first requires that a series of calculations be performed for a number of stratigraphic sections. The desired results of these operations are the first and second moments, which correspond to the center of gravity and standard deviation. The first two moments are particularly important because they define the weighted mean vertical position and degree of dispersion. Higher moments can be used to indicate skewness (third moment) and kurtosis (fourth moment). Krumbein and Libby and Doveton et al. point out, however, that the calculations are cumbersome and are extremely susceptible to operator error.

The method for calculating center of gravity and standard deviation is given in Figure D-1. Both values are converted to



UNIT#	h_i	t_i	$h_i t_i$	$h_i^2 t_i$
1	h_1	t_1	$h_1 t_1$	$h_1^2 t_1$
2	h_2	t_2	$h_2 t_2$	$h_2^2 t_2$
SUMS	—	A	B	C

$$\text{Center of Gravity} = B/A$$

$$\text{Relative C.G.} = (\text{C.G.}/Z)(100)$$

$$\text{Approx. Std. Deviation} = \sqrt{\frac{C - (B^2/A)}{A}}$$

$$\text{Relative S.D.} = (\text{Approx. S.D.}/Z)(100)$$

Figure D-1. The method for calculating relative center of gravities and standard deviations (redrawn from Krumbein and Libby, 1957).

relative terms by dividing each by the total section thickness; this allows expression of the terms as percentages of the total section thickness. Additionally, converting the values to percentages facilitates direct comparisons between multiple sections, thus allowing the data to be presented in contour map form. In the cases of the examples given in Figures 46, p. 100, and D-1, relative center of gravity is in percent of section below the top of the highest unit used in the calculation. Once establishing the weighted mean occurrence of the specified type of unit through the relative center of gravity calculation, the relative standard deviation will define the radius of vertical distribution about the center of gravity. Values greater than 50 percent for relative center of gravity indicate that the weighted mean position of the unit type lies in the lower portion of the section, and values less than 50 percent indicate that the mean position lies in the upper portion of the section. Additionally, small relative standard deviations indicate small degrees of dispersion about the relative center of gravity; large relative standard deviations represent large dispersions about the center of gravity.

APPENDIX E

OUTCROP STUDIES

Study Area 1. The Rome Formation

Study area 1 lies in the Lake City quadrangle along the north-bound lane of Interstate 75 just north of the Lake City exit. Here the upper portion of the Rome is exposed in over one-eighth mile of road cut. The main plane of the Pine Mountain thrust lies approximately 1000 feet below this outcrop, and rocks of this exposure are in the hanging-wall of a major imbricate which branches from the Pine Mountain fault. This exposure is of particular importance because it illustrates minor structures associated with the basal detachment zone. These structures, as well as orientation data, are summarized in Figure E-1.

The Rome consists of interbedded maroon to brown shales, siltstones, and sandstones. Individual sandstone beds range to about a foot in thickness, but generally are on the order of six or fewer inches in thickness. Shales occupy approximately 60 percent of the outcrops lithologies. Several small thrusts are present. At the outcrop face, strikes of these faults vary from north 25 degrees east to north 5 degrees west. Fault dips are typically steep to the northeast or southeast. One pronounced backthrust is also present, trending north 55 degrees east and dipping approximately 30 degrees

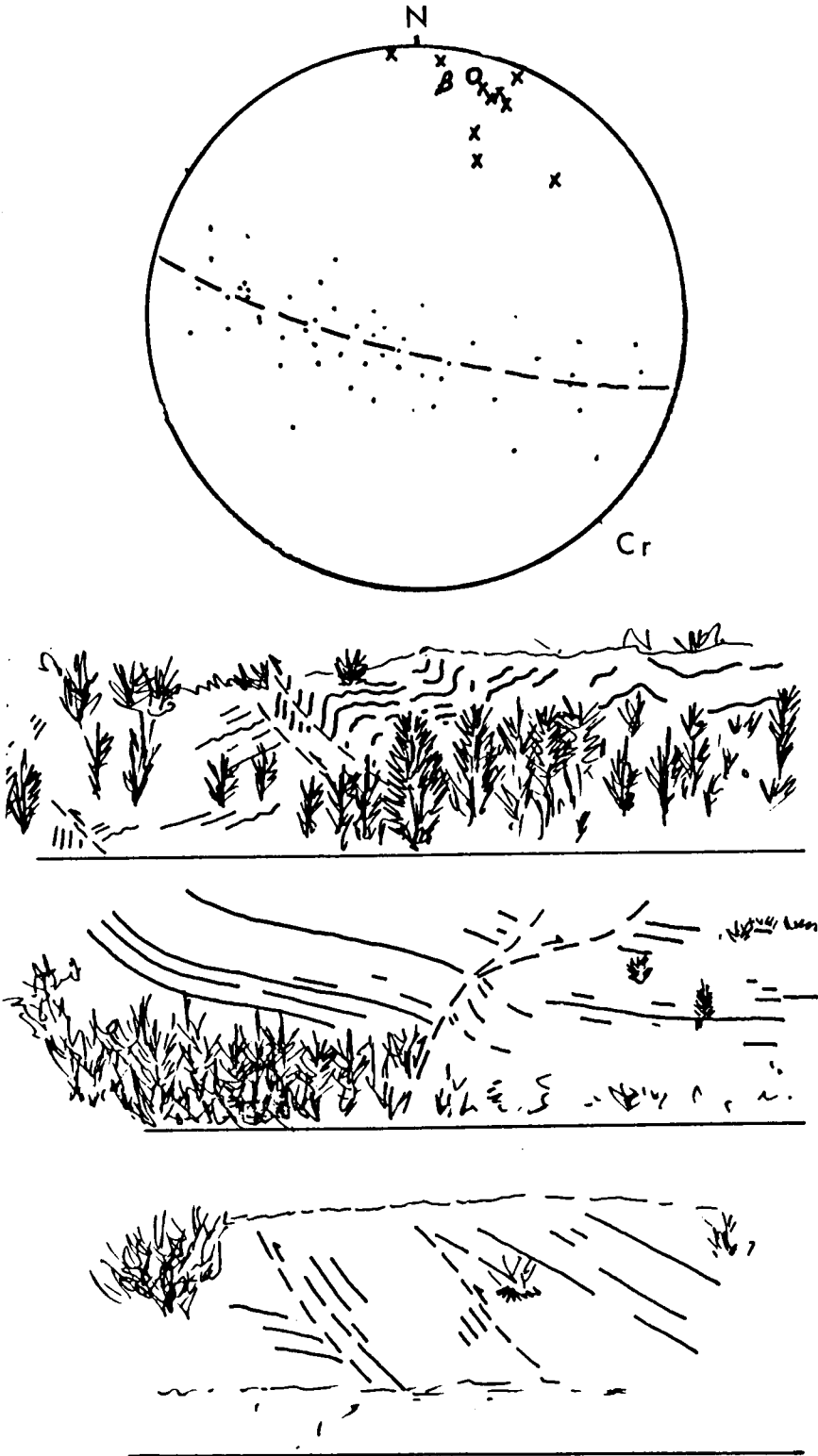


Figure E-1. Summary of structures occurring in the Rome Formation along Interstate 75 near Lake City.

to the northwest. The numerous minor folds in the outcrop are for the most part related to faulting by either duplication of stratigraphic section or drag at the fault surface. Trends of fold axes range from north 5 degrees west to north 45 degrees east. All folds plunge to the northeast or northwest (away from the Jacksboro fault) by amounts of 5 to 30 degrees. The beta axis for the area trends 14 degrees east of north and plunges 10 degrees to the northeast.

Study Area 2. The Conasauga Group

Study area 2 contains numerous small outcrops of the Conasauga Group, and encompasses the U. S. highway 441-Interstate 75 interchange at Lake City. The full suite of Conasauga lithologies occur in the area. The lower parts of the section are dominated by shales with limestone interbeds. Generally, the carbonate interbeds are less than 6 inches in thickness, and they increase steadily in number upward through the section. A few thin sandstone beds also occur low in the Conasauga section; however, they are absent in the middle and upper parts of the Group.

On the northeast side of area 2, rocks of the uppermost unit of the Conasauga Group, the Maynardville Limestone, crop out. This outcrop exposes approximately 90 feet of limestones and dolostones, with interbeds of shale. Individual limestone beds of the Maynardville range to about 6 inches in thickness, but packages of carbonate beds

range to almost 20 feet. The highest percentage of shale in the outcrop occurs near its base, and below that point shales are the predominant lithologic constituent; thus, the base of the outcrop probably marks the contact between the Lower Conasauga and the Maynardville.

The Conasauga also exhibits a gradation of degree of deformation through the section. Outcrops near the Rome-Conasauga contact are typically marked by numerous small scale thrusts and folds (Fig. E-2). Often shales contain the small thrusts at low angles to bedding, while the limestone and sandstone interbeds are faulted at higher angles. Fold axes trend from north 20 degrees west to north 10 degrees east. Plunge is northwest or northeast at angles ranging to 30 degrees. Axial trends of folds correlate well with the beta axis extrapolated from bedding; the beta axis trends 11 degrees east of north and plunges 12 degrees to the northeast (Fig. E-3). Many of the folds are slightly asymmetrical to the northwest. Calcite filled fractures occur in the limestone interbeds both parallel and perpendicular to the fold axes. Additionally, shear fractures occur, with axial trends roughly bisecting the obtuse angles of the shear sets. Minor thrusts generally trend just east of north and dip to the southeast. The highest minor structures occur approximately 100 feet below the base of the Maynardville Limestone, and within the Maynardville, minor structures are absent. Unfortunately, due to insufficient exposure, it is not known whether deformation simply dies out near the contact, or if a roof thrust exists.

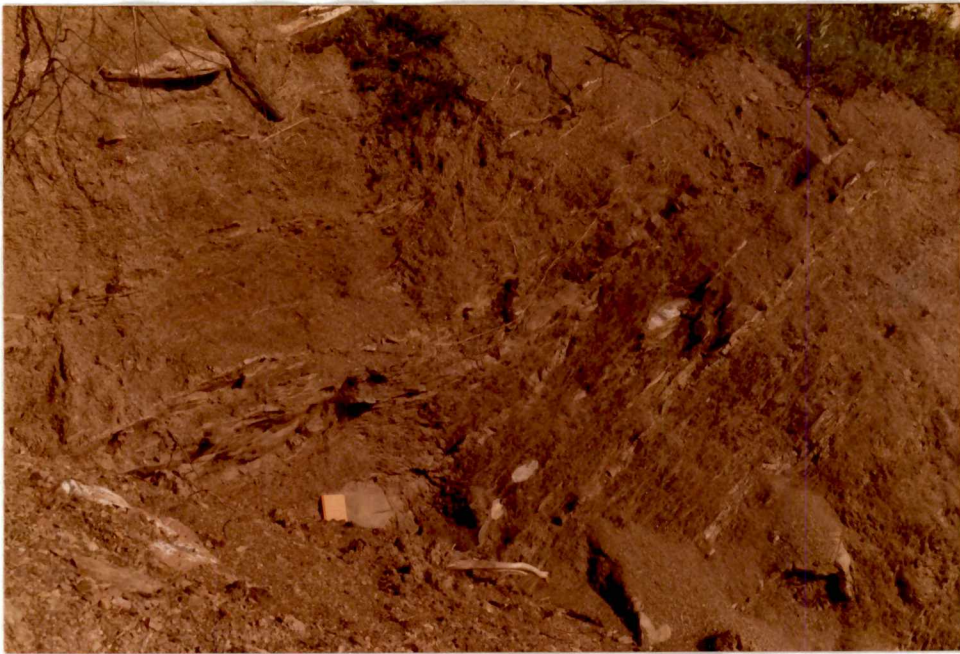


Figure E-2. Photograph illustrating features typical of the Conasauga Shale near Lake City. The folds shown plunge 20 degrees toward north 18 degrees east.

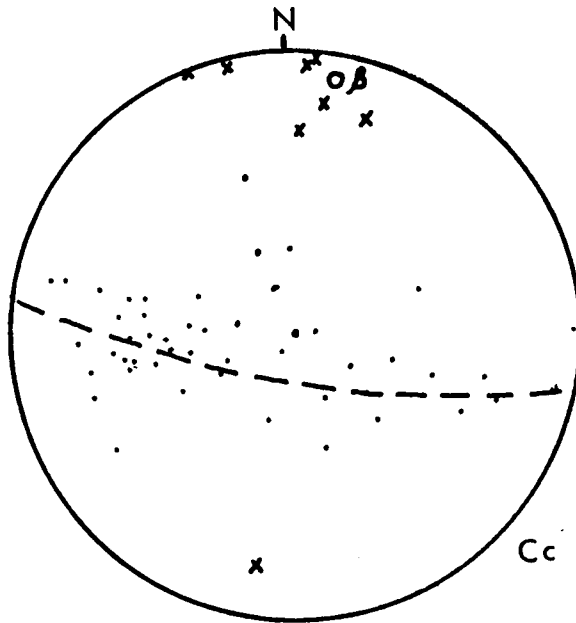


Figure E-3. Stereonet summary of attitudes from Conasauga outcrops near Lake City.

Study Area 3. Devonian and Mississippian Shales and Mississippian Carbonates

Study area 3 is located along the northbound lane of Interstate 75, 1.9 miles southwest of the Jellico exit, and is immediately above the Pine Mountain fault. Outcropping rocks belong to the Newman Limestone, Fort Payne Formation, Grainger Formation, and Chattanooga Shale. The Newman consists of thin to thick bedded limestone and lesser dolostone, with common thin shale beds. Fort Payne lithologies include limestones, in beds ranging to 11 inches in thickness, and a few interbeds of shale occurring in the upper 5 feet of the formation. At this location the Fort Payne is 31 feet in thickness. The Grainger is mostly medium to dark gray shale. Several limestone interbeds occur in this Grainger section. A few are as much as 5 inches thick, but most occur as very thin lens-like beds less than one half inch in thickness. The Chattanooga consists of black sulfidic shale, with rare thin sandstone interbeds.

The Fort Payne is not involved with deformation at this location; however, the Grainger and Chattanooga are extensively deformed. The outcrop sketch in Fig. 24, p. 54, shows the larger scale relationships in the outcrop. Dip directions throughout the outcrop range between north 25 and 45 degrees east, but dip amounts vary widely (18 to 61 degrees). Numerous small faults are present in the Grainger. Many of these faults, however, are implied on the basis of dip variations of thin limestone lenses. Of those sufficiently preserved

to measure attitudes, they strike predominantly to the northwest and dip gently (less than 30 degrees) to the northeast. Several poorly developed, steeply southwest dipping faults, or kink bands, are also present in the outcrop. Axial trends of the kink bands range from south 20 to 27 degrees east, and plunge 20 degrees to the southeast; their axial planes dip to the southwest at 65 to 75 degrees. Two small folds in the Chattanooga Shale were observed; both of these folds trend south 31 west, and plunge at 51 and 44 degrees to the southwest.

Data gathered for this outcrop were limited due to a lack of adequate marker beds in the shales. Attitudes were measured on the thicker limestone interbeds. Typically, these interbeds were not associated with small scale structures, thus, they serve only as indicators of gross geometry of the outcrop. A system of closely spaced fractures striking subparallel to bedding makes attitudes in the shales difficult to ascertain.

Study Area 4. Caryville Mountain

The Caryville Mountain transect begins at the bridge across Cove Creek on the northbound side of Interstate 75. This location lies in the footwall of the Pine Mountain thrust system, approximately 100 yards southwest of the Jacksboro tear fault segment. Exposed at the bridge are rocks of the Slatestone Group. Lithologies include dark gray to black shales, with thin coal interbeds, and thin to medium

bedded light to medium gray sandstones. The shales occur nearest the bridge. Bedding strikes north 27 degrees west and is vertical to slightly overturned to the southwest (Fig. E-4). Other relationships in the shales are difficult to distinguish due to weathering and extensive fracturing. A single carbonate bed occurring in the shales has been stretched by boudinage.

Approximately 20 yards to the northwest of the shale outcrop several small westward facing folds occur in sandstone beds. These folds are characterized by a chevron geometry and plunge 27 degrees toward south 26 degrees east. Considering other small scale folds in the outcrop, axial trends range from due north to north 30 degrees west. Both northwest and southeast plunges are observed, with plunge amounts being generally less than 20 degrees. Map data (Fig. 18, p. 43) indicate that this exposure lies on the northeast limb of a northwest-southeast trending anticline. Such structures commonly occur along the Jacksboro fault adjacent to the Powell Valley anticline, and may indicate blind imbrication, but exposure does not permit further documentation of the style of footwall deformation.

Location 2 lies approximately 1 mile north of the Cove Creek outcrop. Regionally, it lies in the axis of a major north trending syncline, and is approximately one quarter of a mile northeast of the Jacksboro fault. Rocks of the Newman Limestone are exposed along the southbound lane of the highway. Here the lower parts of the Newman consist of thin to thick bedded limestones, with thin shale beds (up to 8 inches) as minor constituents. In the lower parts of the Newman, shale interbeds increase in both frequency and thickness.



Figure E-4. Vertical beds in shales of the Slatestone Group at Cove Creek bridge on Interstate 75. Carbonate bed exhibits boudinage. The dominate strike direction is north 17 degrees west.

The dominant structural element of the outcrop is a northwest plunging syncline, which is bound on the northeast by a small back-thrust. Southwest of the syncline, rocks are undeformed and dip to the north at approximately 35 degrees. Northeast of the syncline, numerous small folds and faults occur. The outcrop sketch in Fig. E-5 give a summary of the structures present. Although the major folds and faults are most apparent in the carbonate rocks, the density of deformation features is much higher in the shales. The trends of fold axes vary between north 20 degrees east and north 60 degrees west, and axial planes dip to the northeast or northwest (respectively). All folds have a northward plunge component.

The positioning of this outcrop with respect to larger scale structures suggests that the outcrop scale features are related to contraction in the core of the syncline in which they reside. The more northwesterly trend of the minor structures may reflect a rotational component caused by drag and lateral folding along the Jacksboro fault and its attending lateral ramp.

This outcrop is an excellent illustration of lithologic controls of deformational style. Folds in the shales have wavelengths on the order of inches (Fig. E-6), whereas folds in the carbonates have wavelengths on the order of feet to tens of feet. Additionally, the density of thrust faults is much higher in the shales; many of these faults merge into a detachment zone at the base of the overlying carbonates. Only three faults truncate the limestones. In effect, the shales acted as weak rocks, and the carbonates acted as stronger rocks.

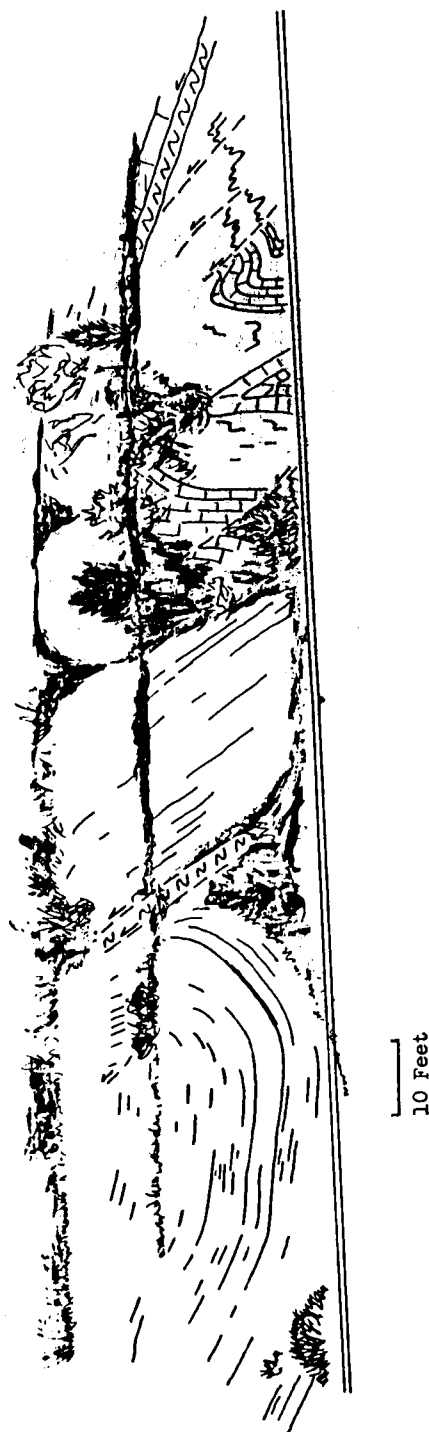


Figure E-5. Outcrop sketch of structures in the Newman Limestone near Caryville.



Figure E-6. Photograph of numerous small, tight folds in shales of the Newman.

VITA

Everett Rutherford, Jr., was born in Knoxville, Tennessee, on October 29, 1957. He attended Gibbs Elementary School in Knoxville and was graduated from Gibbs High School in June 1975. In June 1975 he entered The University of Tennessee, Knoxville, and received a Bachelor of Arts degree in geology in December 1980.

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