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I am submitting herewith a thesis written by Milan A. Heath II entitled “Structural and Stratigraphic Investigations at the Southwest End of the Tellico-Sevier Syncline, Southeast Tennessee.” I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geology.

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Structural and Stratigraphic Investigations at the Southwest

End of the Tellico-Sevier Syncline, Southeast Tennessee

A Thesis
Presented for the
Master of Science Degree
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Milan A. Heath II
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ABSTRACT

The southern Appalachian Valley and Ridge is composed of a wedge of Cambrian through Pennsylvanian siliciclastic and carbonate rocks, deformed during latest Paleozoic by the collision of Laurentia and Gondwana. This collision caused the southern Appalachian foreland fold-thrust belt to deform as a critically tapered wedge. This study utilized structural and stratigraphic data to examine the mechanical behavior and timing of emplacement of the southwest end of the Tellico-Sevier syncline within this wedge.

The study area is located in southeast Tennessee at the southwest end of the Tellico-Sevier syncline, which is in the first Valley and Ridge thrust sheet west of the Blue Ridge. The Tellico-Sevier syncline is a northeast-plunging syncline that extends from Etowah, Tennessee, northeast to southwestern Virginia. The northwest limb is bounded by the Chestuee fault, which is thought to be the decollement upon which the syncline was transported. The southeast limb of the syncline is truncated by the Conasauga Creek fault, which emplaced an overturned anticline of Knox and Conasauga Group rocks. Four balanced and retrodeformed cross sections were constructed through the study area, three perpendicular to the trend of the syncline and one parallel. In addition, there was one other section (D-D') that was not retrodeformed and balanced. Cross sections B-B' and D-D' have apparent normal dip-slip fault displacement; however, all map-scale faults in the cross sections and study area are thrust faults. Examination of the cross sections and map-view fault relationships indicates that the northwest limb of

the syncline formed first and the southeast limb formed later when the Chestuee thrust sheet underthrust itself. After the southeast limb was formed, the decollement that was transporting the Chestuee thrust sheet was pinned and an overturned anticline formed as a displacement gradient fold. This order of thrusting and folding is interpreted to mean that the syncline and overturned anticline formed by out-of-sequence thrusting, thus indicating that emplacement of the Valley and Ridge foreland fold-thrust belt as a critically tapered wedge was partially accommodated by out-of-sequence thrusting.

TABLE OF CONTENTS

CHAPTER 1	1
INTRODUCTION	1
<i>Location</i>	<i>3</i>
<i>Valley and Ridge Stratigraphic and Structural Framework</i>	<i>3</i>
<i>Approach</i>	<i>5</i>
<i>Previous Work</i>	<i>7</i>
<i>Research Objectives</i>	<i>9</i>
CHAPTER 2	10
STRATIGRAPHY AND LITHOLOGIC DESCRIPTIONS	10
<i>Conasauga Group</i>	<i>10</i>
<i>Knox Group</i>	<i>12</i>
<i>Chickamauga Group</i>	<i>14</i>
<i>Interpretation</i>	<i>29</i>
CHAPTER 3	31
STRUCTURAL GEOLOGY	31
<i>Mechanical Attributes of Foreland Fold-Thrust Belts</i>	<i>36</i>
Mesoscale Structure	40
<i>Macroscopic Structure</i>	<i>49</i>
<i>Geologic Map</i>	<i>50</i>
<i>Cross Sections</i>	<i>52</i>
<i>Cross Section Discussion</i>	<i>57</i>
<i>Discussion</i>	<i>60</i>
<i>Conclusions</i>	<i>62</i>
CHAPTER 4	64
CONCLUSIONS	64
REFERENCES CITED	66
Appendices	76
<i>Appendix A1</i>	<i>77</i>
<i>Appendix A2</i>	<i>84</i>
<i>Vita</i>	<i>97</i>

LIST OF FIGURES

FIGURE

1-1.	Simplified tectonic map of part of the southern Appalachian Valley and Ridge and Blue Ridge.	2
1-2.	Location of the study area in eastern Tennessee.	4
1-3.	Geologic map of the study area showing major structures and stratigraphic divisions.	6
1-4.	Middle Ordovician stratigraphic columns used by previous workers in and around the study area.	8
2-1.	Generalized stratigraphic column and stratigraphic relationships between stratigraphic units in the study area (column not to scale).	11
2-2.	Mascot Dolomite-Lenoir Limestone contact and Middle Ordovician unconformity across the road from the Nonaberg Church on State Route 39 (pencil indicates scale).	15
2-3.	Gastropod <i>Maclurites magnus</i> (Neuman, 1955) at the same location as in Fig. 2-2.	17
2-4.	Athens Shale on the southeast limb of the syncline containing parallel-concentric flexural-slip folds.	19
2-5.	Chapman Ridge Sandstone with large tabular cross beds.	22
2-6.	Trace fossils on bedding surface in Chapman Ridge Sandstone.	22
2-7.	Crossing symmetrical ripples in Chapman Ridge Sandstone.	23
2-8.	The Athens Shale-Chapman Ridge Sandstone gradational contact.	24
2-9.	Packstone composed of bryozoans, crinoids, and brachiopods.	26
2-10.	Calcareous mudstone with rare bryozoan from the limestone in the Chapman Ridge Sandstone.	26
2-11.	Boundstone with compaction and tectonic stylolites from a facies of the limestone in the Chapman Ridge Sandstone.	27
2-12.	Wackestone composed of whole and disarticulated bryozoan from the limestone in Chapman Ridge Sandstone.	27
3-1.	Geologic map of the study area showing stratigraphic divisions and major structures.	32
3-2a.	Parallel-concentric cross sections of the Tellico-Sevier syncline.	33
3-2b.	Parallel-concentric cross sections of the Tellico-Sevier syncline.	34
3-2c.	Parallel-concentric cross sections of the Tellico-Sevier syncline.	35
3-3.	Equal area, lower hemisphere, projection of 544 poles to bedding.	41
3-4.	Equal area, lower hemisphere, projection of trend and plunge of fold hinges and poles to axial surfaces.	42
3-5.	Different mesoscale fold geometries in the study area.	43
3-6.	Mesosopic open fold in Chapman Ridge Sandstone.	44
3-7.	Mesosopic tightly folded overturned folds in Chapman Ridge Sandstone.	44

3-8.	Fault-related fold in the Athens Shale-Chapman Ridge gradational contact zone.	45
3-9.	Oblique-slip fault in Chapman Ridge Sandstone.	47
3-10.	Strong cleavage in tightly folded Athens Shale directly below the Chapman Ridge Sandstone contact.	48
3-11.	Steeply dipping weak cleavage in flat-lying Athens Shale directly below the Chapman Ridge Sandstone contact on the southeast limb of the main syncline.	48
3-12.	Tectonic stylolite in the Chapman Ridge limestone on northwest limb of the main syncline 1.5 km northwest of the hinge.	49
3-13.	Fence diagram of the cross sections in a 3-D array.	51
3-14.	Stratigraphic thicknesses for each individual Chickamauga Group unit calculated from each cross section.	54
3-15.	Structural development of the study area illustrating growth of major faults and folds.	59
A-1.	Profile view showing Import Image command.	78
A-2.	Profile view showing Column menu, New Column command, and currently selected column.	79
A-3.	Profile view showing Set Top Type menu, Top Types, available Profiles, and currently opened project.	81
A-4.	Restoration module view showing Restoration menu and Restoration steps.	82

LIST OF PLATES

PLATE

Plate I. Geologic Map of a Portion of the Athens, Englewood, Etowah, and Mecca Quadrangles, Tennessee.

Plate IIA. Parallel-concentric cross sections at the southwest end of the Tellico-Sevier syncline.

Plate IIB. Angular-parallel cross sections at the southwest end of the Tellico-Sevier syncline.

Plate IIC. Plunge-parallel E-E' cross section at the southwest end of the Tellico-Sevier syncline.

Plate III. Station locations in the Athens, Etowah, Englewood, and Mecca 7.5 Minute Quadrangles, Tennessee.

CHAPTER 1

INTRODUCTION

The Tennessee Valley and Ridge is part of the southern Appalachian Alleghanian foreland fold-thrust belt (Fig. 1-1), and is composed of a wedge of Cambrian through Pennsylvanian siliciclastic and carbonate rocks. Formation of the southern Appalachians during latest Paleozoic time was caused by the collision of Laurentia and Gondwana (Hatcher, 1989; Hatcher et al., 1990). Deformation produced a critically tapered wedge: the foreland thickened and shortened by internal imbrication and propagation of the basal detachment (Chapple, 1978; Davis et al., 1983; Woodward, 1987). The purpose of this study was to examine mechanical behavior and timing of formation of a map-scale syncline using structural and stratigraphic data, collected over two field seasons, in a two-dimensional balanced cross-section analysis.

The study area is located in the Middle Ordovician Tellico-Sevier belt (Neuman, 1955) that occupies most of the syncline of Cambrian and Ordovician rocks in the first thrust sheet west of the Blue Ridge (at this latitude). Geologic mapping by Robey (2000) in part of the southwest hinge of the syncline in the study area confirmed that sufficient exposure exists to permit detailed 1:24,000-scale geologic mapping. Stratigraphic relationships previously mapped regionally at 1:62,500 (Rodgers, 1953) and at 1:24,000 to the northeast using physical and biostratigraphic principles (Neuman, 1955) have been examined more closely at the southwest end of the syncline. A complete section of

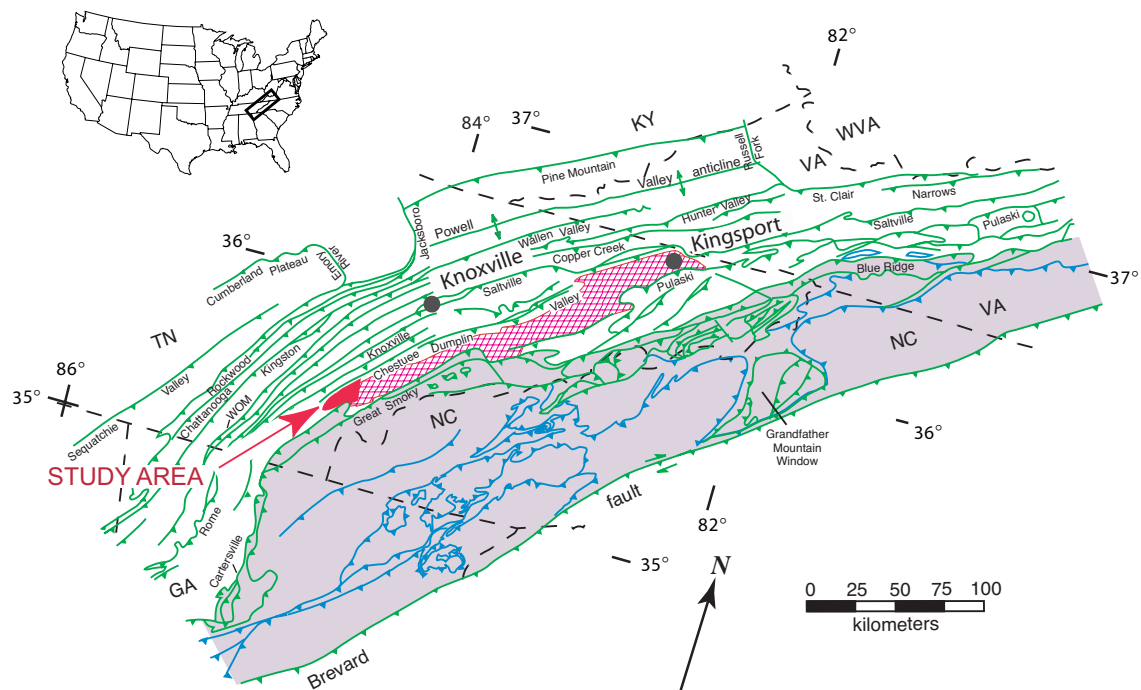


Figure 1-1. Simplified tectonic map of part of the southern Appalachian Valley and Ridge and Blue Ridge. The study area is in red, red cross-hatched pattern shows extent of Middle Ordovician rocks in the same syncline. Blue Ridge is shaded lavender, the Valley and Ridge and Plateau are unshaded. Green lines are major Alleghanian faults, blue are major pre-Alleghanian faults. Modified from Hatcher et al. (1990). WOM - White Oak Mountain.

Middle Ordovician Chickamauga Group sequence below the upper Sevier Shale is present in the area studied.

Location

The area studied is located in southeastern Tennessee, approximately 95 km (50 mi) southwest of Knoxville and 16 km (10 mi) southeast of Athens (Fig. 1-2, Plate 1). Portions of four 7.5-minute quadrangles (Athens, Englewood, Etowah, and Mecca) comprise the study area, which lies mostly in McMinn County with a smaller part in Monroe County. The area studied is approximately 172 km² (66 mi²). It is composed of ridges up to 400 m (~1200 ft) elevation with valleys as low as 250 m (~800 ft). Bedrock exposure is typically best along ridges, steep slopes, eroded logging roads, in man-made road cuts, and in quarries.

Valley and Ridge Stratigraphic and Structural Framework

This research was conducted at the southwest end of the Tellico-Sevier syncline, which is cored by Middle and Upper Ordovician rocks and flanked to the northwest and southeast by Knox Group, Conasauga Group, and Rome Formation (Hardeman, 1966). The syncline trends 057°, 3°. The northwest limb dips between 30-45° SE. The southeast limb ranges from upright, dipping 30° NW at the southwest end of the syncline, to nearly vertical, dipping 80° NW at the east end of the study area, to overturned just to the east of the study area.

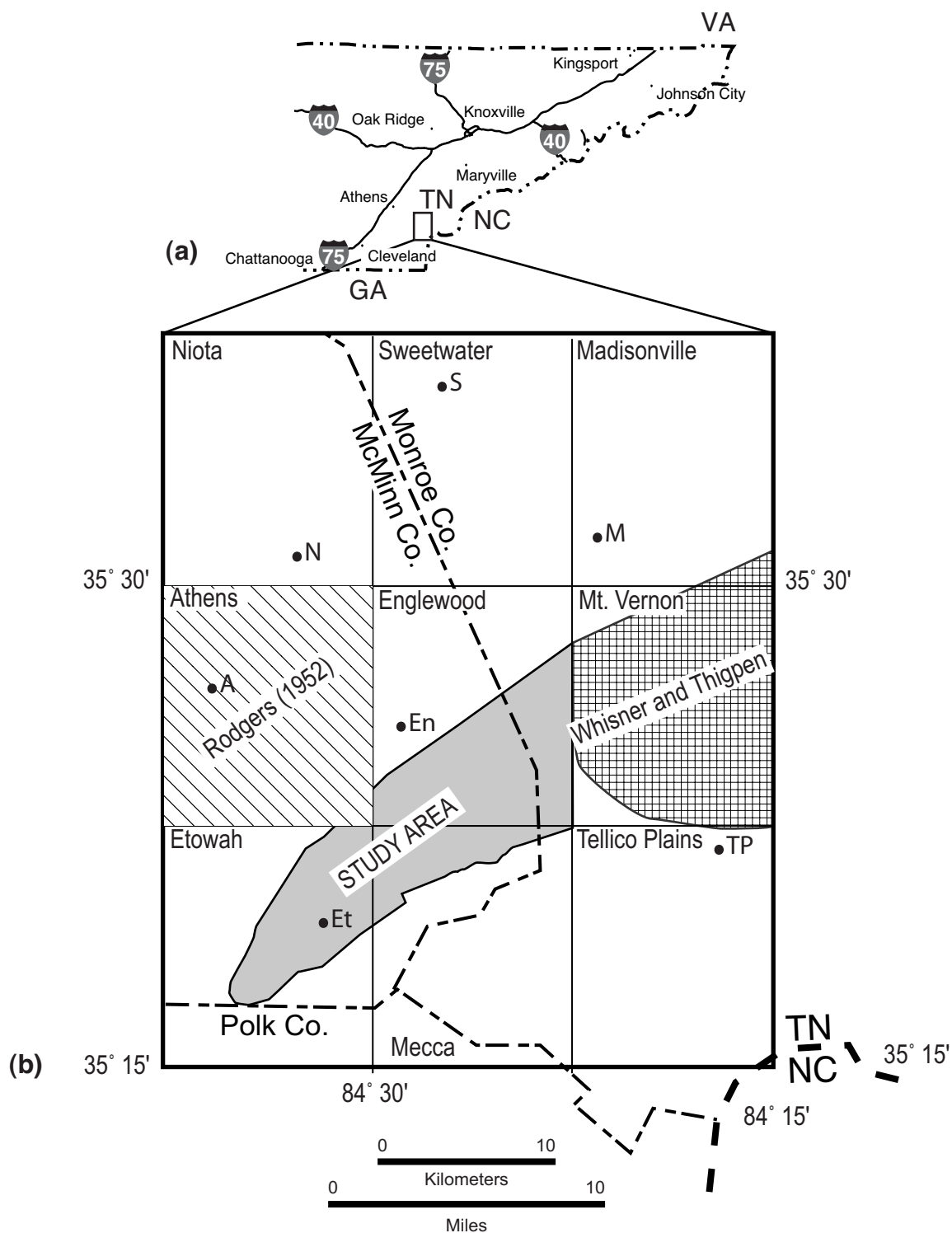


Figure 1-2. Location of the study area in eastern Tennessee. (a) Index map of east Tennessee. (b) Index map of quadrangle maps and geologic mapping in and adjacent to the study on 7.5-minute quadrangle grid. A - Athens. En - Englewood. Et - Etowah. M - Madisonville. N - Niota. S - Sweetwater. TP - Tellico Plains.

The Upper Cambrian to Lower Ordovician Knox Group is approximately 900 m thick and is composed primarily of cherty dolostone with some interbedded limestone and thin beds of dolomite- or chert-cemented sandstone. The dolostone weathers to reddish clay that contains chert and sandstone fragments (Hatcher et al., 1992). Subdivision of the Knox Group is accomplished by mapping characteristic cherts and sandstone markers.

Some 1360 m of Middle Ordovician Chickamauga Supergroup rocks are preserved in the area studied. They consist of interbedded calcareous shale, limestone, sandstone, sandy limestone, and calcareous sandstone. This is less than the 2500+ m estimated for the entire thickness of Chickamauga Supergroup rocks by Shanmugam and Walker (1978) preserved farther northeast in the same syncline. Thigpen (2002) estimated 1870 m of pre-Bays Sandstone Middle Ordovician rocks are present, along with 305 m of Bays Sandstone (incomplete section).

Approach

This thesis utilized data collected in the field and in the laboratory. Twelve months of field work was conducted during two field seasons. Geologic mapping was conducted on 1:24,000 scale 7.5-minute quadrangle base maps to record structural and lithologic data, stratigraphic contacts, and station locations (Fig. 1-3; Plate I). Bedding data, mesoscopic fault orientations, and kinematic data such as slickenlines and tectonic stylolite orientations were measured using a Brunton compass. Some 542 structural data

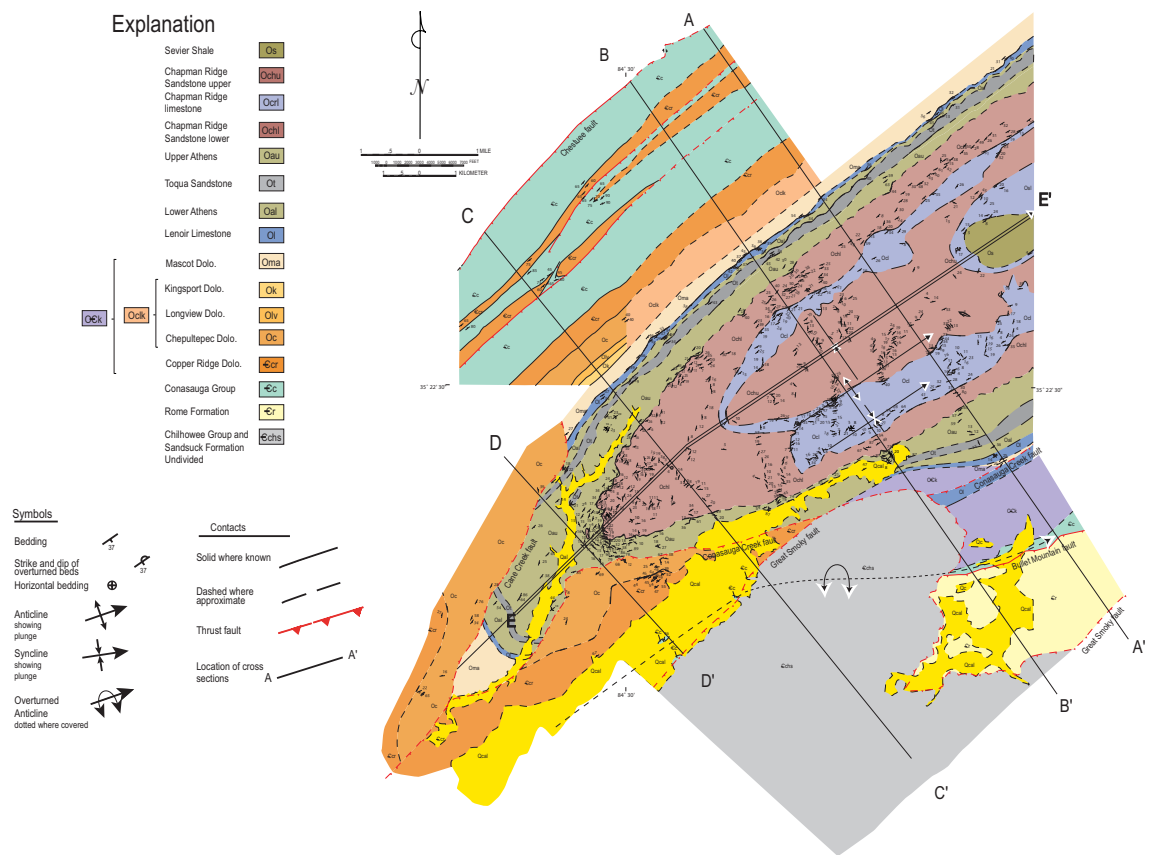


Figure 1-3. Geologic map of the study area showing major structures and stratigraphic divisions.

stations and many more outcrop occurrences were recorded. Structural data and stratigraphic contacts were compiled on topographic digital raster graphs (DRGs) of the field area, modified in Adobe Photoshop,™ and imported into Adobe Illustrator.™ Four serial cross sections were constructed perpendicular to the trend of the syncline and one parallel to trend using a combination of outcrop width and measurements of bedding dip (Plates IIA, IIB, IIC). The cross sections were then exported from Adobe Illustrator™ as *jpeg*s, and imported and registered in LithoTect 2D,™ a two-dimensional cross-section construction and analysis program. Cross sections were retrodeformed and balanced using the angular-parallel and concentric-parallel fold algorithms in LithoTect 2D.

Previous Work

Previous stratigraphic and structural studies in and adjacent to the study area have been conducted by Rodgers (1953), Neuman (1955), Kashfi (1971), Shanmugam and Walker (1978), Robey (2000), Thigpen (2002), and Whisner (in progress) (Fig. 1-4). Rodgers (1953) mapped both the structure and stratigraphy of the study area at 1:62,500 and the Athens quadrangle at 1:24,000 (Rodgers, 1952). Neuman (1955) mapped the stratigraphy of the syncline northeast of the study area at 1:24,000. Shanmugam and Walker (1978) studied the Sevier Shale in the same syncline approximately 85 km (55 mi) to the northeast. Whisner (in progress) mapped the structure and stratigraphy of portions of the Tellico Plains, Mt. Vernon, Tallassee, Rafter, Vonore, and Madisonville quadrangles. Thigpen (2002) mapped the structure and stratigraphy of a portion of the

NW		Knoxville Syncline		SE SW		Etowah-Kingsport Syncline				NE	
Rodgers (1952)		Cattermole (1955)		Present Study		Kashfi (1971)		Neuman (1955)		Shanmugam (1978)	
Ottosee Shale		Ottosee Shale		Sevier Shale		Ottosee Shale		Sevier Formation Bacon Bend Member		Sevier Formation	
Holston Formation		Chapman Ridge Sandstone		Limestone at base of Sevier Shale		Tellico Formation (Notchy Creek Facies)		Interbedded limestone member			
				Ocr				Chota Formation			
				Limestone							
				Chapman Ridge Sandstone							
Athens Shale		Holston Formation		Athens Shale (upper)		Athens Shale (Upper, Middle, Lower Members)		Tellico Formation			
				Blockhouse Shale Dark shale member				Blockhouse Formation			
				Toqua Sandstone				Toqua sandstone Member			
Athens Shale				Athens Shale (lower)						Whitesburg limestone Member	
Lenoir Limestone Mosheim Member		Lenoir Limestone Mosheim Member		Lenoir Limestone (Mosheim Member)				Lenoir Limestone Argillaceous limestone member Mosheim Member Douglas Lake Member		Lenoir Formation Main Body Mosheim Member	

Figure 1-4. Middle Ordovician stratigraphic columns used by previous workers in and around the study area.

Mt. Vernon quadrangle between Whisner's and my map area. Kashfi (1971) mapped the structure and stratigraphy of portions of the Tellico Plains, Mt. Vernon, Tallassee, and Madisonville quadrangles.

Research Objectives

- Collect sufficient field data to construct publishable 1:24,000-scale geologic maps and cross sections.
- Resolve previously unknown stratigraphic relationships in the field area.
- Characterize the structure of the southwest end of the Tellico-Sevier syncline in southeastern Tennessee.
- Employ geometric relationships to resolve the kinematic and possibly the mechanical evolution of the syncline.
- Utilize LithoTect 2D to refine cross sections.

CHAPTER 2

STRATIGRAPHY AND LITHOLOGIC DESCRIPTIONS

The rocks in the study area range in age from Late Cambrian to Middle Ordovician and record an upward change from a passive margin carbonate shelf to a foredeep basin, which collected sediments shed from highlands to the southeast during the Taconic orogeny (Shanmugam and Walker, 1980; Hatcher et al., 1989; Rankin et al., 1989). The Upper Cambrian and Lower Ordovician Knox Group was mapped using chert float and sandstone marker beds diagnostic of specific units. Conversely, the Middle Ordovician Chickamauga Supergroup had excellent bedrock exposure, which permitted ready identification and mapping of rock units. Geologic mapping was carried out to accomplish several stratigraphic goals: (1) to subdivide the Chickamauga and Knox using previously identified divisions from outside the study area; (2) to identify stratigraphic relationships not previously recognized (Fig. 2-1); and (3) to better understand the depositional framework of the rocks in the study area.

Conasauga Group

The Middle and Upper Cambrian Conasauga Group is approximately 600 m thick in East Tennessee (Rodgers, 1952; Swingle, 1959; Hatcher et al., 1992), and can be divided into the Nolichucky Shale and Maynardville Limestone in the southeast portion of the Valley and Ridge. Rodgers (1952) divided the Conasauga Shale in the Athens

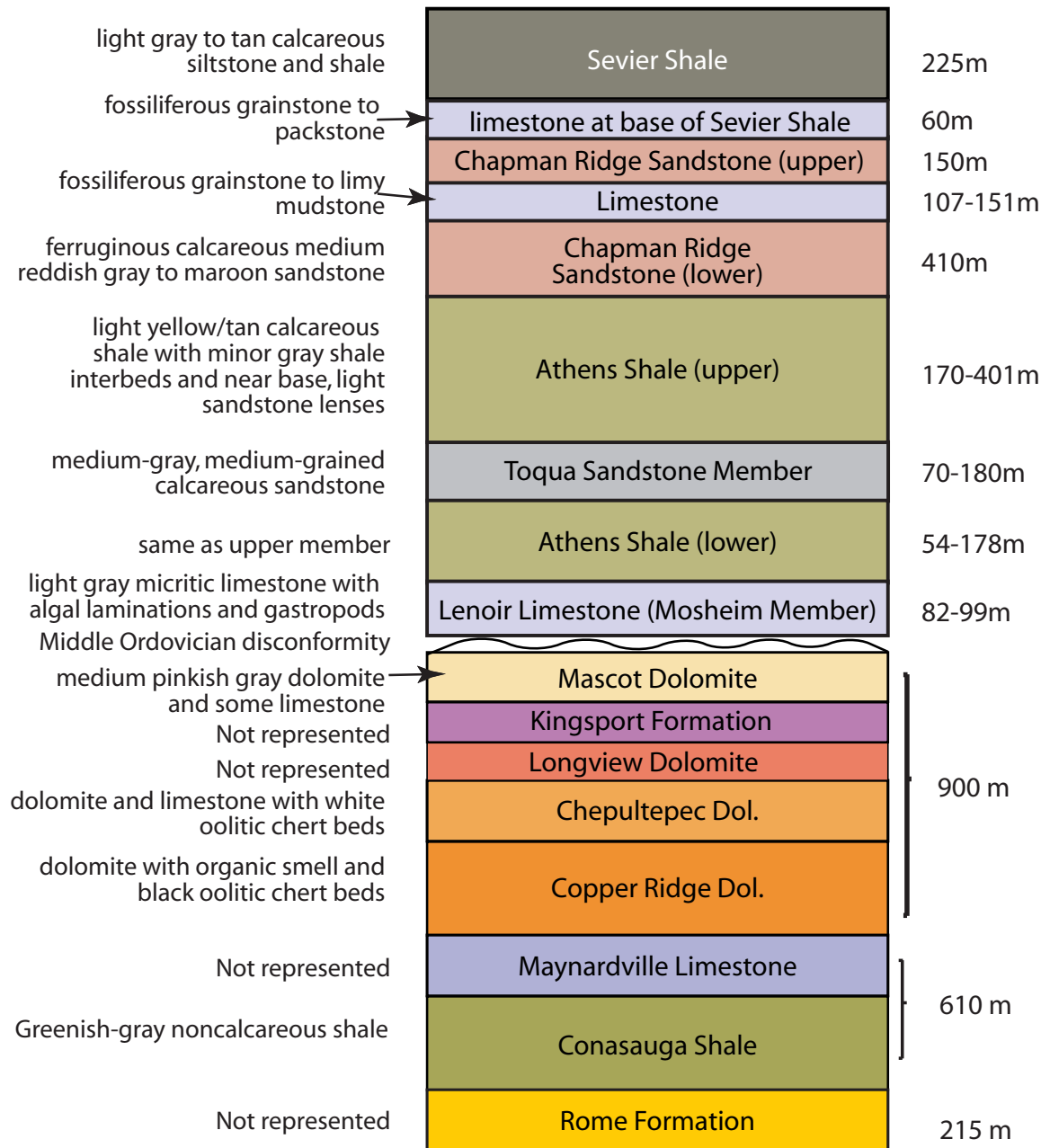


Figure 2-1. Generalized stratigraphic column and stratigraphic relationships between stratigraphic units in the study area (column not to scale). Thickness variations for each unit of the Athens Shale are calculated from the cross sections (Figs. IIA, IIB) based on consistent bedding dips and outcrop width measured in the field.

quadrangle into a main shale body of greenish-gray noncalcareous shale, and the Maynardville Limestone, a blue limestone and gray dolomite. The Nolichucky Shale, which was identified in one location in the study area, is an olive green to brown noncalcareous fissile shale. All of the Maynardville Limestone is covered throughout the area studied, so the Conasauga Group is not subdivided in Plate I.

Knox Group

The Upper Cambrian and Lower Ordovician Knox Group is 700-1000 m thick in Tennessee (Hardeman, 1966; Hatcher et al., 1992) and can be subdivided into five units: the Copper Ridge Dolomite, Chepultepec Dolomite, Longview Dolomite, Kingsport Formation, and Mascot Dolomite (Fig. 2-1). Only the Copper Ridge, Chepultepec, and Mascot Dolomites were mapped in the field area. The Knox Group was subdivided using chert and sandstone markers and occasional outcrop exposures.

Copper Ridge Dolomite. Bedrock exposures of Copper Ridge Dolomite are rare, but dark gray to grayish-brown, saccharoidal, mottled, fine- to medium-grained dolostone with small calcite veins and dolomite/calcite-lined vugs were observed in fresh exposures. When freshly broken the dark gray saccharoidal dolomite gives off the fetid odor of hydrocarbons (“dead oil”). The combination of ooids with alternating black and white bands associated with algal (“cryptozoan”) chert and fetid-smelling dolostone are the primary diagnostic characteristics of the Copper Ridge Dolomite (Hatcher et al., 1992).

Soils in the Copper Ridge Dolomite are typically clay-rich and tan to light red with occasional zones of yellow saprolitic chalky residuum and accompanying brown soil. White chert residuum is common and ranges from centimeter to hand sized. A complete section is not present, but is approximately 300 m thick in the Cleveland area (Swingle, 1959).

Chepultepec Dolomite. Only one bedrock exposure of Chepultepec Dolomite was found in the field area. It consists of light gray, medium to thickly bedded dolostone with bedding-parallel stylolites. Weathered surfaces have a cracked elephant-skin appearance, typical of slightly weathered dolostone surfaces. The contact between the Copper Ridge and Chepultepec Dolomite is marked by dolomite-cemented sandstone as much as 5 m thick at the base of the Chepultepec. In weathered outcrop the sandstone is medium to dark brown, with cross bedding and well-rounded quartz grains. Where fresh the sand grains are frosted and translucent. In areas with no outcrop the contact is traced using the abundant sandstone float. The Chepultepec contains a characteristic white-matrix chert with white to light tan concentrically banded ooids. Oolitic chert float blocks are rarely larger than 3 by 3 cm. Soils are clay rich and generally tan to light orange.

Mascot Dolomite. The Mascot Dolomite is primarily a light gray and pinkish gray to yellowish-gray, fine-grained to aphanitic dolostone with lesser amounts of light to medium gray aphanitic limestone. In contrast to most other Knox units, the upper Mascot

is relatively well exposed. Exposure is typically in open fields and wooded areas and crops out as low ridge-like exposures. Interformational contacts between the dolomite and limestone are rarely exposed. A complete section of the Mascot is not present in the study area, but Swingle (1959) reported it to be approximately 150 m thick in the Cleveland area.

Knox (Middle Ordovician) Unconformity. Separating the Knox and Chickamauga Groups is the Middle Ordovician disconformity. The unconformity consists of an erosion surface upon which extensive karst topography was developed removing large intervals of the upper Knox, producing local relief of 100 m or more (Neuman, 1955; Mussman and Read, 1986). Mesoscale exposures of the unconformity are commonly more irregular than ordinary bedding surfaces in either the Knox or overlying Middle Ordovician units (Fig. 2-2). The mapped unconformity (Fig. 1-3, Plate I) is very linear suggesting the unconformity in the study area has little erosional relief. Oolitic hematite was observed at several localities on the unconformity surface.

Chickamauga Group

The Chickamauga Group consists of an assemblage of dominantly clastic (to the east) and carbonate (in the west) rocks that define an early Middle Ordovician foredeep basin (Shanmugam and Walker, 1980; Rankin et al., 1989). The southwest end of the Tellico-Sevier syncline is composed of calcareous shales, sandstones, and limestones,



Figure 2-2. Mascot Dolomite-Lenoir Limestone contact and Middle Ordovician unconformity across the road from the Nonaberg Church on State Route 39 (pencil indicates scale). About 5 cm of basal Douglas Lake Member is present.

which are easily subdivided. Thickness of the incomplete Chickamauga Group section in the study area is 1360 m, which is much less than the 2500 m estimated by Shanmugam and Walker (1978).

Lenoir Limestone. The Lenoir Limestone has been described in several ways in the Sevier basin. Rodgers (1952) described the Lenoir Limestone as a massive aphanitic limestone similar to the Mosheim Member near Knoxville. Neuman (1955) subdivided the Lenoir Limestone into three members: the basal Douglas Lake Member (reddish

impure clastic limestone) (Bridge, 1955), the Mosheim Member (massive, fossiliferous pure limestone), and an argillaceous limestone member (typical Lenoir). Kashfi (1971) mapped the Lenoir Limestone as part of the lower member of the Athens Shale and described it as a calcareous facies within the lower Athens Shale. Shanmugam (1978) divided the Lenoir into a main body of skeletal packstone and wackestone, and the Mosheim member, similar to Neuman's (1955) subdivisions.

The Lenoir Limestone in the study area can be subdivided into three units. The basal Douglas Lake Member directly above the contact is approximately 5 cm thick, although rip-up clasts of dolostone and chert from the Mascot are found in the basal 0.3 m of the Lenoir Limestone. The middle unit is 2 to 3 m thick and is a light gray fine-grained algally laminated limestone. Algal laminations are black, 0.3 to 1 cm thick and planar to broken. The gastropod *Maclurites magnus* is occasionally found within the algal lamination zone (Fig. 2-3) (Neuman, 1955). Fifteen or more specimens were identified in one exposure. The Mosheim Member, which is the main body of the Lenoir Limestone in the field area, is composed of massive-bedded, light to medium gray, aphanitic limestone.

Athens Shale. Rodgers (1952), described a light-colored calcareous, nodular, argillaceous shale in the Athens quadrangle, in contrast with the Athens Shale that Hayes (1894, 1895) defined near Athens, Tennessee, which was a black shale. Neuman (1955) separated the Athens Shale into three units: the Blockhouse Shale (dark gray calcareous



Figure 2-3. Gastropod *Maclurites magnus* (Neuman, 1955) at the same location as in Fig. 2-2.

shale), the Toqua Sandstone (gray calcareous sandstone), and the Lower Tellico Formation (mixed calcareous sand and shale unit). Shanmugam (1978) identified the lower portion of the Athens as the Blockhouse Formation (calcareous clay-rich shale) and the upper portion he grouped into the Sevier Formation (mixed calcareous sand and shale unit). Kashfi (1971) divided the Athens Shale into an upper and lower calcareous olive-gray shale separated by a calcareous yellow-gray middle sandstone unit.

The contact between the Lenoir Limestone and Athens Shale does not crop out in the field area, but is marked by the first valley outboard of (down sequence from) the

Toqua Sandstone Member of the Athens Shale. The Athens Shale can be subdivided into three units: a lower shale unit (54 to 178 m), the middle Toqua Sandstone Member (70 to 180 m), and an upper shale unit (170 to 401 m). Thickness variations for each unit of the Athens Shale are calculated from the cross sections (Plates. IIA, IIB) based on consistent bedding dips and outcrop width measured in the field. Both the upper and lower shales are lithologically indistinguishable and are identified by their position relative to the Toqua Sandstone Member. The Athens Shale is a light to medium gray, calcareous silty shale (Fig. 2-4) that weathers light yellowish tan to dark tan. Fresh exposures of Athens Shale are rare and the weathered shale is more commonly observed. In outcrop the Athens Shale is finely laminated with 1 to 10 mm beds. In fresh outcrop bedding is identified by lighter-colored layering and in weathered outcrop by fissile parting along bedding surfaces. In weathered outcrop shale chips frequently collect at the base of exposures and in the soil. At one location (behind Haren Construction Co. on US 411 in Etowah) limestone nodules are interbedded with the lower shale member. This zone is approximately 15 m thick with irregularly distributed pancake- to egg-shaped nodules 8-30 cm in diameter. Some nodules contain graptolites of the type *Normalograptus euglyphus* and *Didymograptus sp.* that occur elsewhere in the southern Appalachians in the upper Middle to lower Upper Ordovician Athens Shale and equivalent facies (S. C. Finney, written comm., 2003).



Figure 2-4. Athens Shale on the southeast limb of the syncline containing parallel-concentric flexural-slip folds. Located on east side of State Route 39, 900 m north of State Route 39 and Mecca Pike intersection.

Toqua Sandstone Member. The Toqua Sandstone Member of the Athens Shale is located approximately 150 m above the base of the Athens Shale-Lenoir Limestone contact and forms a low ridge along the outer parts of the syncline. The Toqua Sandstone consists of light gray, thin- to medium-bedded calcareous sandstone composed of well-rounded, fine- to medium- grained quartz grains cemented with calcite. The sandstone contains well-defined beds 2 to 12 cm thick with regular interbeds of clay-rich siltstone similar to the shale in the upper and lower members of the Athens Shale. Cross bedding was identified in a single outcrop (located approximately 600 m south of Nonaburg Church on State Route 39 on the east side of the road in the woods). In weathered outcrop it is medium-brown with a pockmarked appearance, frequently with a porous rind. The interbedded shale weathers yellowish tan.

Chapman Ridge Sandstone. The Chapman Ridge Sandstone was defined by Cattermole (1955) as gray to red, hematitic calcareous sandstone interbedded with calcareous shale, in order to distinguish it from the “Tellico Sandstone” originally defined by Keith (1895). Keith (1895) originally thought that it correlated with the Tellico Sandstone, but it was later shown by Cattermole (1955) not to correlate in Knoxville, Tennessee. Neuman (1955) continued to use the Tellico Sandstone name to identify the first mixed sandstone and shale unit above the Middle Ordovician unconformity. Walker et al. (1983), however, recognized that the Chapman Ridge Sandstone *is* correlative with the Tellico Sandstone in the Middle Ordovician basin. The Chapman Ridge Sandstone in the study area is equivalent to the Upper Tellico Sandstone of Neuman (1955). Here it consists of a

lower sandstone overlain by bryozoan-rich, carbonate bank-edge limestone, overlain by an upper sandstone unit.

The Chapman Ridge Sandstone in fresh outcrop is a medium-gray to maroon calcareous, ferruginous (hematitic) medium-grained sandstone with rare interbeds of tan shale. It weathers to rusty-red-brown to reddish-purple-brown porous sandstone from a dissolution of the sparry calcite cement. Coarser-grained sandstone is less common and is identified by larger high-relief sand grains on weathered surfaces. Quartz sand grains are angular. Beds are 1 to 24 cm thick and in fresh outcrop tops of beds are marked by a darker brown or red siltstone or claystone layer less than 1 mm thick with detrital mica flakes on bedding surfaces. Both tabular and trough cross bedding are present (Fig. 2-5). It is unusual, however, for cross bedding to occur below the lower member of the Chapman Ridge limestone. Trace fossils (Fig. 2-6) and symmetrical ripples (Fig. 2-7) have been observed directly above the Athens Shale-Chapman Ridge contact.

The contact between the Chapman Ridge Sandstone and Athens Shale is gradational and changes character from the northwest to the southeast limb of the syncline. On the northwest limb the contact zone is 75 to 100 m thick and consists of 2 to 12 cm thick beds of interfingering shale and ferruginous sandstone. The contact zone on the southeast limb of the syncline is 75 to 100 m thick and consists of individual shale and sandstone interbeds 0.5 to 1 m thick with a greater proportion of shale than sandstone. Within both contact zones the proportion of sandstone increases up section until no shale remains (Fig. 2-8).



Figure 2-5. Chapman Ridge Sandstone with large tabular cross beds. The larger tree trunk is approximately 18 cm in diameter. Located approximately 1.2 km north of Old Mecca Pike on east side of Gordon Hollow, across stream.



Figure 2-6. Trace fossils on bedding surface in Chapman Ridge Sandstone. Knife is 12 cm long. Located in quarry across from Burger, 1.8 km south of Nonaberg Church on State Route 39.



Figure 2-7. Crossing symmetrical ripples in Chapman Ridge Sandstone. Knife is 12 cm long. Same location as Fig. 2-6.

(a)



(b)



Figure 2-8. The Athens Shale-Chapman Ridge Sandstone gradational contact. (a) Lower part of the contact zone showing thinner sandstone beds and more shale along with a mesoscopic fault with 24 cm displacement. (b) Upper part of the contact zone containing a larger proportion of sandstone beds. Twelve-cm knife for scale. Both located on east side of State Route 39, 1.6 km south of Nonaberg Church.

Limestone in the Chapman Ridge Sandstone. An interbedded limestone and shale unit occurs in the Chapman Ridge Sandstone and consists dominantly of interbedded limestone, with lesser amounts of medium-gray calcareous shale. Neuman (1955) mapped a stratigraphically similar unit, which he named the Chota Formation and described as a medium-gray to red sandy limestone that occasionally contains lithic fragments. Kashfi (1971) mapped a similar limestone unit 200 m thick, which he called the Notchy Creek facies or Hawkins Member of the Tellico Formation and correlated it with the Holston Limestone.

The contacts between the limestone and sandstone were not observed in the map area and were mapped based on last outcrop appearance. Several different lithologies occur in the limestone: light to medium-gray packstone composed of bryozoans, crinoids, and brachiopods in a matrix of lime mud (Fig. 2-9); light gray to brown calcareous mudstone with rare bryozoans (Fig. 2-10); light gray to pink dirty-white weathering boundstone with purple ooids, and frequent tectonic and compaction stylolites (Fig. 2-11); medium-gray to brown wackestone composed of whole and disarticulated large bryozoans (Fig. 2-12); and light purple to brown grainstone composed of partially recrystallized disarticulated bryozoans. The interbedded shale consists of light to medium gray laminated silty shale; it is yellow to tan when weathered.

Limestone at the base of the Sevier Shale. The contact between the Chapman Ridge Sandstone and Sevier Shale is marked by a 60-m thick stylolitic pinkish-gray to maroon



Figure 2-9. Packstone composed of bryozoans, crinoids, and brachiopods. Limestone in Chapman Ridge Sandstone. Knife is 12 cm long. Located on east side of State Route 39 next to Adams Cemetery.



Figure 2-10. Calcareous mudstone with rare bryozoan from the limestone in the Chapman Ridge Sandstone. Bryozoan is 5 cm long. Located on west side of State Route 39 1.2 km south of Adams Cemetery.



Figure 2-11. Boundstone with compaction and tectonic stylolites from a facies of the limestone in the Chapman Ridge Sandstone. Located on east side of State Route 39 200 m south of Adams Cemetery.



Figure 2-12. Wackestone composed of whole and disarticulated bryozoan from the limestone in Chapman Ridge Sandstone. Round object in center is cross section of bryozoan. Located on west side of State Route 39 1.3 km south of Adams Cemetery.

packstone to grainstone with abundant fossils. The limestone lies at the base of the Sevier Shale and forms karst topography. With the exception of a quarry, the best outcrop is found in caves and sinkholes. In contrast to the Chapman Ridge limestone, this limestone contains few, if any, clastic impurities and resembles the Holston Marble.

Sevier Shale. The Sevier Shale was originally defined by Keith (1895) as interbedded shale, shaly limestone, and sandstone similar to the Athens Shale. Rodgers (1952) and Kashfi (1971) mapped the shale above the Holston Limestone as the Ottossee Shale, a mixed lithology similar to the Sevier Shale of Keith (1895). Neuman (1955) redefined the Sevier Formation as the shale and sandstone between the Chota and Bays Formations.

The contact between the Sevier Shale and Chapman Ridge Sandstone in the northeast portion of the study area is a limestone unit approximately 60 m thick, which is a pinkish-gray fossiliferous limestone. On the southeast limb the contact cannot be observed and is identified by the appearance of weathered yellow-tan Sevier Shale. Sevier Shale weathers to a yellow tan to medium-brown, thinly bedded (0.5 to 2 mm), calcareous shale. It is very similar to the Athens Shale and can only be differentiated by its position above the Chapman Ridge Sandstone. Only a partial section of approximately 225 m of the Sevier Shale exists in the field area. In the northeast portion of the study area the Sevier Shale forms low-relief hills and valleys (and in places sinkholes, because of the limestone at the base of the Sevier Shale) and thus is poorly exposed.

Interpretation

Algal laminations, burrows, and conglomerates in the lower unit of the Lenoir Limestone (*sensu lato*) suggest a peritidal shelf environment (Benedict and Walker, 1978). Analysis of bryozoans, sponges, and algae by Shanmugam and Walker (1978) indicates water depths of less than 10 m. The transition from the Douglas Lake Member to the main Mosheim Member (nodular limestone facies) may represent a transition to a deeper water environment where precipitation of calcareous mud was the primary depositional mechanism (Shanmugam and Walker, 1978).

With the exception of cross bedding observed in the Toqua Sandstone, no sedimentary structures were observed in the Athens Shale. Shanmugam and Walker (1978), however, identified sedimentary structures such as graded bedding, convolute laminations, and Bouma sequences related to both slope and basin depositional systems. Benedict and Walker (1978) identified a decrease in algae occurrences up-section, further suggesting a deepening environment. The Whitesburg Limestone (basal member of the Blockhouse Shale) contains ostracods and echinoderms indicative of water depths of 150 to 200 m, and has been interpreted as a slope deposit by Walker (1977) and Shanmugam and Walker (1978). It was not identified in the area mapped. Paleobathymetric reconstruction of the Blockhouse Shale by Shanmugam and Walker (1978, 1980) was based on the presence of open-water graptolites, deep water tintinnines, and a lack of sedimentary structures found above wave base (e.g. current bedding, wave-ripple marks,

etc.). These indicate water depths greater than 200 m and potentially as deep as 600 to 800 m.

The location of the Chapman Ridge Sandstone above the Athens Shale creates a problem with regards to Shanmugam and Walker's (1978) basin model of the Blockhouse and Sevier Shale. First, transportation of sand-sized grains to the water depth suggested by Shanmugam and Walker (1978) does not seem reasonable. Second, the hematitic character of the Chapman Ridge Sandstone may require at least intermittent subaerial exposure during diagenesis (Boggs, 1987); however, transportation and deposition of previously oxidized hematitic sand as the Chapman Ridge Sandstone may account for its hematitic nature. Last, massive cross bedding, ripple marks, and trace fossils suggest a high-energy shallow water environment.

Interbedded limestone and shale in the Chapman Ridge limestone and limestone at the base of the Sevier, suggest a return to a shallow-water reef environment that was periodically inundated by clastic material or an environment with fluctuating water depth that could only intermittently support a reef when it was in the photic zone. Furthermore, disarticulated bryozoans and brachiopods suggest a high energy depositional environment or a far traveled source for the fossils.

CHAPTER 3

STRUCTURAL GEOLOGY

The southern Appalachian foreland fold-thrust belt was formed during the latter stages of continent-continent collision between Laurentia and Gondwana as part of the late Paleozoic Alleghanian orogeny (Fig. 1-1). Specifically, deformation of the Pennsylvanian-Permian foreland basin into a foreland fold-thrust belt was a byproduct of emplacement of the late Alleghanian Blue Ridge-Piedmont composite crystalline thrust sheet (Hatcher, 1989; Hatcher et al., 1990).

The sedimentary sequence in the Valley and Ridge records the change from a Cambro-Ordovician passive margin to a westward prograding foreland basin during the Middle Ordovician to Silurian Taconic orogeny to a Pennsylvanian to Permian foreland basin during the Alleghanian orogeny (Rankin et al., 1989). This assemblage had an overall wedge shape, and as it was deformed, became a critically tapered wedge that thickened and lengthened by internal deformation, and addition of material to the toe of the wedge (Chapple, 1978; Elliott, 1980; Dahlen et al., 1984). Macroscale deformation produced map-scale folds and thrust faults including the syncline, anticline, and faults examined in this thesis (Figs. 3-1, 3-2a, 3-2b, 3-2c). Brittle deformation was typically controlled by the mechanical properties of individual sedimentary units and the depositional geometry of the foreland wedge (Willis, 1893; Wood and Bergin, 1970; Harris and Milici, 1977; Woodward, 1987; Hatcher et al., 1989). Thick, strong units,

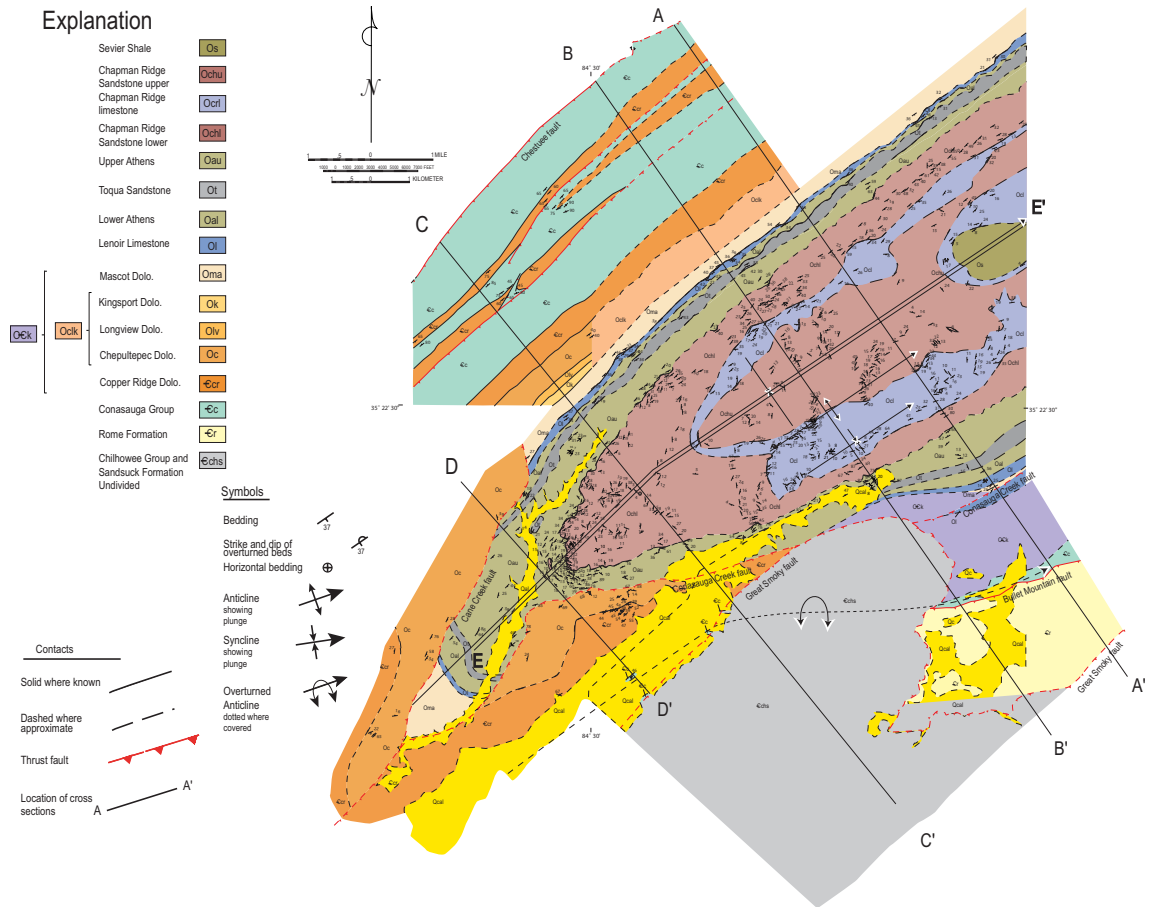


Figure 3-1. Geologic map of the study area showing stratigraphic divisions and major structures. See Plate I for credits for mapping to the northeast and southeast.

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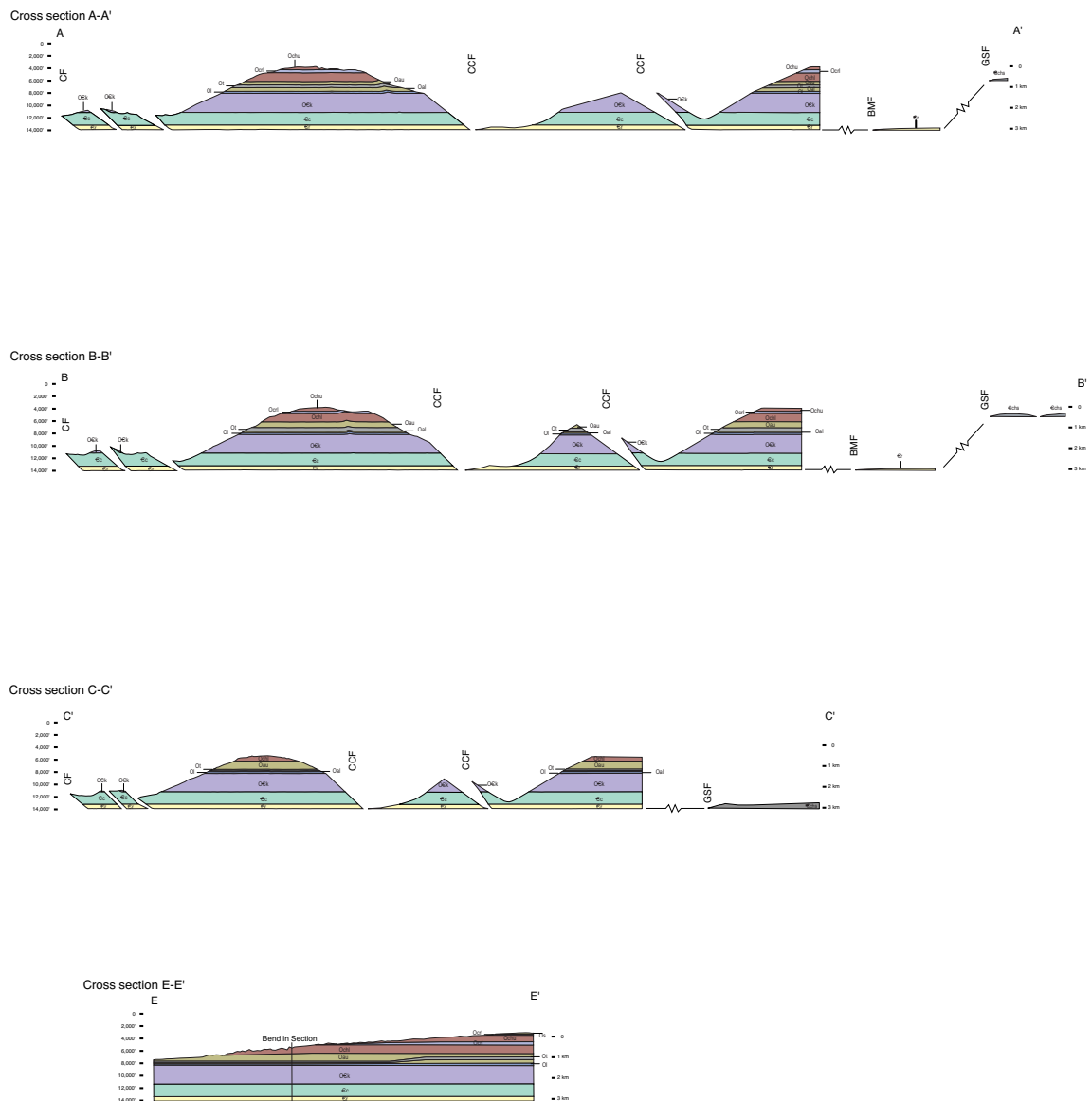


Figure 3-2. Continued. (b) Retrodeformed parallel-concentric cross sections of the Tellico-Sevier syncline. No vertical exaggeration. See Figure 3-10 for explanation and location of cross sections. CF - Chestuee fault. CCF - Conasauga Creek fault. BMF - Bullet Mountain fault. GSF - Great Smoky fault.

such as carbonates and sandstones, tend to fault or form large open folds, whereas thinner, weak mixed units of shale and sandstone form smaller tight folds or deform internally by pressure solution, although carbonates do deform by pressure solutions as well (Reks and Gray, 1983). This chapter examines meso- and macro-scale deformation at the southwest end of the Tellico-Sevier syncline.

Mechanical Attributes of Foreland Fold-Thrust Belts

Attempts to understand the mechanics of thin-skinned fold-thrust belts without employing horizontal compressive forces as the driving force utilized a gravitational spreading mechanism to explain the thrusting and transport of large fault blocks (Gwinn, 1964, 1970; Milici, 1975; Elliott, 1976). Elliott (1976) identified the following parameters as necessary for the formation of a thrust belt by gravitational spreading: (1) material strength of the basal detachment and wedge are homogeneous and weak; (2) thrusts move in the direction of topographic slope even when the basal detachment dips in a hinterlandward direction; (3) the main force exerted on a thrust sheet is gravitational (body force), except in the toe where compressive horizontal stress is applied by the main body of the thrust sheet; (4) continent-continent collision is not required for formation of a foreland thrust belt; and (5) low levels of shear stress, caused by gravity, can be magnified along the tips of thrusts, which require an order of magnitude greater stress than gravity produces.

Although models of gravitational spreading (Price, 1973; Elliott, 1976) answered some questions about thrust belt formation in a few thrust belts, it had numerous inconsistencies when applied to all thrust belts: (1) homogeneous incompetent wedges do not exist in nature [except possibly in accretionary wedges (Davis et al., 1983)]; (2) internal shortening by thrusting occurs throughout thrust belts and not just in the toe; (3) surface slope is not required for the formation of thrust belts; (4) surface slope exists in areas where thrusting is not presently occurring (Chapple, 1978).

Chapple (1978) formulated a mechanical model for thin-skinned thrust belts utilizing horizontal compressive stress rather than gravity to overcome resistance to basal sliding. He identified the following common parameters for all thin-skinned thrust belts: (1) deformation in the thrust belt is thin skinned (i.e., occurs above the crystalline basement); (2) the basal layer on which the thrust belt rides and detachs (Rome shale in the southern Valley and Ridge) is weaker than the rocks in the wedge; (3) the thrust belt is wedge shaped before and after deformation, with transport and thrusting from the thick to thin end; (4) during deformation the wedge may change size, but it always maintains a wedge shape; and (5) the wedge and basal detachment behave as a perfectly plastic material on the scale of the thrust belt (Chapple, 1978).

Davis et al. (1983) further refined Chapple's (1978) requirement for the maintenance of the wedge shape during deformation. They demonstrated that for the thrust belt to slide stably the wedge must maintain a critical taper on the edge of failure. Specifically, fold-thrust belts require a surface slope, whereas accretionary wedges,

which are typically submarine do not require a surface slope. If the wedge taper is too low it will thicken by internal deformation and continue sliding once critical taper is reached. If the taper is too great, the wedge will decrease its slope by addition of material in the toe. Furthermore, the internal material behavior of the wedge was identified as Coulomb behavior, which could be represented using the Coulomb failure criterion ($|\tau| = \mu\sigma_n$ where τ is shear stress, μ is the coefficient of friction, and σ_n is normal stress) and could also include effects of pore pressure (Davis et al., 1983).

The thin-skinned nature of the southern Appalachian foreland fold-thrust belt required for both Chapple's (1978) and Davis et al. (1983) models of thrust behavior has been shown to exist by Harris (1970), Harris and Milici (1977), and Mitra (1988). Harris (1970) and Harris and Milici (1977) concluded that the southern Valley and Ridge was formed by thin-skinned deformation using thrust geometries, well, seismic reflection, and surface data. Mitra (1988) also concluded that basement rocks were not involved in the formation of the Valley and Ridge from surface, well, and seismic reflection data. The conclusion that basement rocks are not involved in the Valley and Ridge ignores the Holston-Iron Mountain thrust sheet, which contains both Precambrian Cranberry Gneiss (basement) and Knox rocks in the same thrust sheet. The occurrence of basement rocks in a thin-skinned system requires compression to be the driving force for thrust-belt formation because a gravitational spreading model cannot account for basement involvement in a shallowly dipping thrust system (Geiser, 1978).

Buckle folding is produced by the application of force parallel to the layering of rocks (Biot, 1961, 1965a, 1965b). Because thrust belts are originally composed of a horizontally layered wedge and the maximum compression acting on the wedge is near horizontal, most folding that occurs must be the result of buckling. Biot (1961, 1965a, 1965b) demonstrated that it is possible for rocks to behave viscously over geologically long periods of time and form folds whose amplitudes and wavelengths are controlled by their competency. Currie et al. (1962) found through theoretical, experimental, and field-based research that buckling occurs in a strong layer when a layer-parallel force exceeds its critical strength and the ratio of the strength of strong to weak layers is greater than 100:1. If the force does not exceed the critical strength then the layer only shortens until the force exceeds the critical strength, then it buckles. This suggests that layer-parallel shortening normally precedes buckle folding. Furthermore, fold wavelength is linearly related to the thickness of the competent layer (Currie et al., 1962). Ramberg (1960, 1961) performed experiments forming buckle folds and identified a property, which he named concentric-longitudinal strain. He demonstrated that the inner and outer arcs of buckle folds are separated by a neutral surface, which experienced no longitudinal strain and no length change. During fold formation the outer arc was extended and the inner arc compressed.

The following sections discuss the different mesoscale and macroscale structure data sets. This discussion will be followed by interpretations of the various data sets that will relate to the discussions in this section.

Mesoscale Structure

Outcrop-scale deformation is manifested as faults, folds, stylolites, and in rare cases, slickenlines and pencil cleavage. Approximately 542 structural data stations and many more outcrop and float occurrences were recorded (Fig. 3-3). In addition, approximately 120 dip-strike measurements collected by Robey (2000) were compiled into the geologic map, along with a few measurements made by Rodgers (1952). The majority of strain indicators, including pencil cleavage, mesoscale folds, and bedding-perpendicular stylolites, occur on the southeast limb of the syncline closest to the Great Smoky fault.

Folds. Mesoscale folds were observed in the Athens Shale, Chapman Ridge Sandstone, and limestone in the Chapman Ridge Sandstone. Mesofolds occur alone and in association with mesoscale thrust faults. Mesofolds are more common on the limbs of the macroscale syncline with a much higher frequency on the southeast limb, and are rare in the hinge.

Folds typically are symmetric to asymmetric, have horizontal to shallow plunge ($<30^\circ$), are tight to gentle ($30\text{-}170^\circ$ interlimb angle), and are upright to steeply inclined (axial surfaces dipping $30\text{-}90^\circ$) (Figs. 3-4; 3-5). Fold shape ranges from concentric to kinks and folds are mostly parallel (Figs. 3-5; 3-6; 3-7).

Fold geometries are similar or parallel based on the competency contrast between layers (Donath and Parker, 1964). Folds in interbedded units (e.g., layered shales and

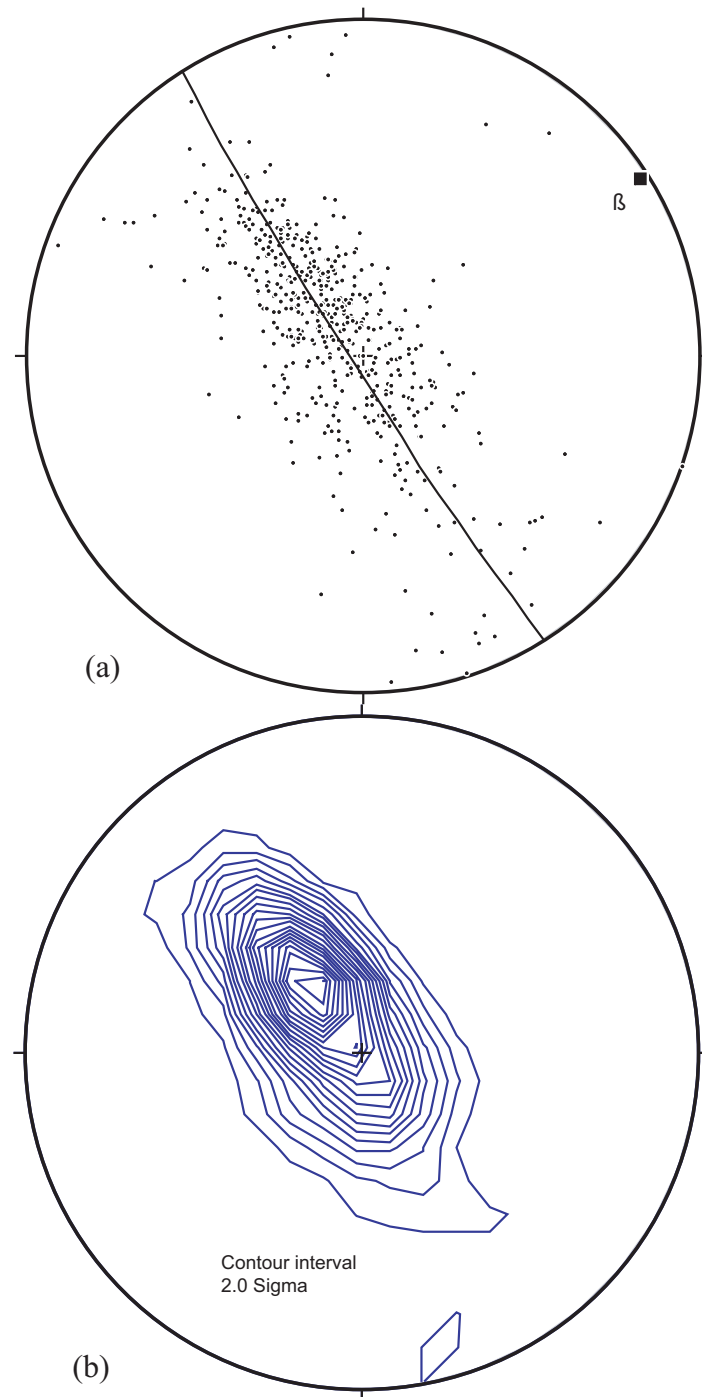


Figure 3-3. Equal area, lower hemisphere, projection of 544 poles to bedding. (a) Scatter plot with best-fit great circle for the data. Filled box is the beta axis for the data and is 057, 3. (b) Kamb 2s contours (after Kamb, 1959). Plots made using the Stereonet 6.2.1, program by R. W. Allmendinger, 2002, Cornell University.

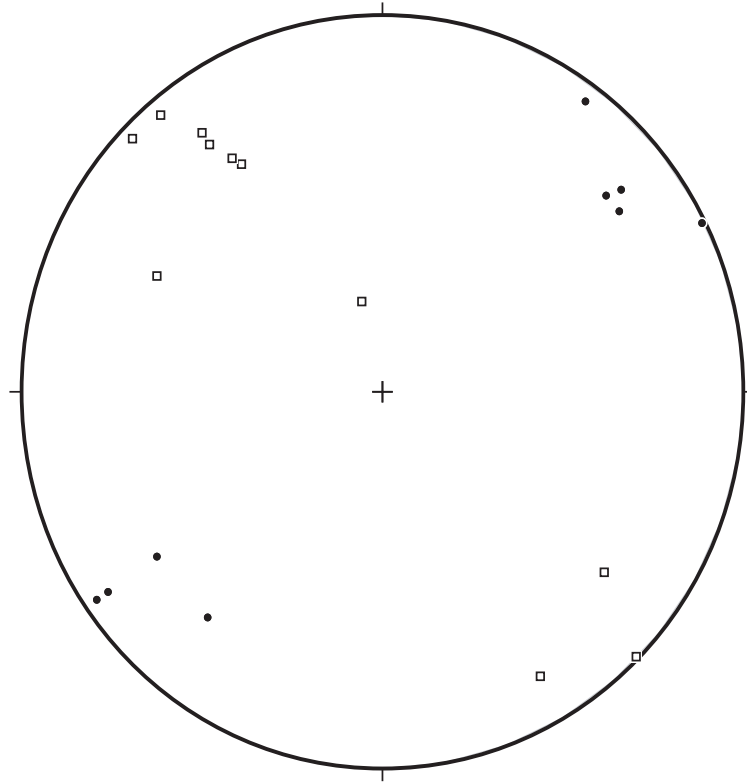


Figure 3-4. Equal area, lower hemisphere, projection of trend and plunge of fold hinges and poles to axial surfaces. Fold hinges are filled circles, $N = 9$. Poles to axial surfaces of folds are open boxes, $N = 11$.

limestones in the Chapman Ridge limestone) are similar and have thickened hinges; when one limb is pinned, similar chevron folds form (Fig. 3-5b). Folds in homogeneously bedded lithologies are parallel or concentric-parallel (Fig. 3-5a). The consistency of layer thickness in the parallel folds indicates that they formed by flexural slip, in which layers slipped past one another (Donath and Parker, 1964). Donath and Parker (1964) stated that similar folds form by flexural flow as less competent lithologies flow from limb to hinge during folding; however, the similar folds in the field area have thickened hinges due to compression of material in the hinge and without of material from the limbs.

Figure 3-5. Different mesoscale fold geometries in the study area. (a) Parallel-concentric fold with rounded hinges in Athens Shale. Perspective is looking northeast down the plunge of the syncline. Rock hammer for scale. Located on east side of State Route 39 900 m north of State Route 39 and Mecca Pike intersection. (b) Chevron fold in interbedded shale and calcareous sandstone in Chapman Ridge limestone, note small fault in fold hinge. Perspective is looking southwest up the plunge of the syncline. Field notebook for scale. Located on west side of State Route 39 1 km north of State Route 39 and Mecca Pike intersection.

(a)



(b)





Figure 3-6. Mesoscopic open fold in Chapman Ridge Sandstone. Width of view is approximately 40 m viewed to the northeast. Fold is on northwest limb of main syncline near hinge. Location is on State Route 39 approximately 4 km south of Nonaburg Church on east side of road.



Figure 3-7. Mesoscopic tightly folded overturned folds in Chapman Ridge Sandstone. View is to northeast on southeast limb of main syncline. Knife for scale is approximately 12 cm. Location is ~1 km from Old Mecca Pike on Gordon Hollow Road.

Faults. Mesoscale oblique-slip and thrust faults occur in the study area. The thrust faults occur in interbedded lithologies where folding alone could not accommodate stress (Currie et al., 1962). Fold-related faults are typically subparallel to axial surfaces (Fig. 3-5b). Faults that are the primary (dominant) structure tend to cut across bedding at a high angle (i.e., 30-60°) and verge to the southeast (Fig. 3-8). These probably are antithetic faults to those normally expected with a northwest transport direction or related to southeast-vergent folds (Fig. 3-5). Displacement on mesoscale thrust faults is between 1 and 12 cm.



Figure 3-8. Fault-related fold in the Athens Shale-Chapman Ridge gradational contact zone. The fault displaces both sandstone and shale, but folding only occurs in the less competent shale. Perspective is to the northeast. Pencil indicates scale. Located on east side of State Route 39 approximately 1.5 km south of Nonaburg Church.

Two high angle oblique-slip faults were observed approximately 20 m apart in an abandoned quarry. Both strike roughly N83E; one dips 40° NW and the other 68° NW (Fig. 3-9). Dip-slip displacement is roughly 0.3 m for both of them. A strike-slip movement component was identified by slickenlines on one of the fault surfaces, indicating last movement on the fault was dextral (Fig. 3-9b). Neither fault was traceable beyond the quarry because of small displacements and thick soil cover.

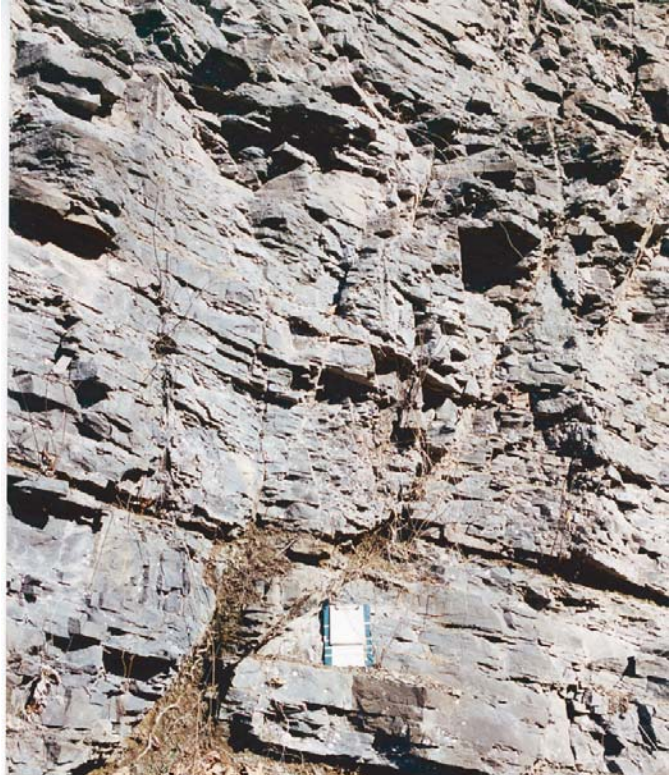
Pencil Cleavage. Pencil cleavage was identified once on the northwest limb and several times on the southeast limb of the main syncline in the Athens Shale. In tightly folded shale axial planar cleavage forms in the hinges of folds and its intersection with bedding forms pencils (Fig. 3-10). In more open folds the pencils are blockier or not well developed (Fig. 3-11). Cleavage is strike-parallel and dips between 50° and 80° northwest and southeast.

Pressure Solution. Bedding-normal stylolites occur irregularly in Chapman Ridge limestone and strike roughly northeast to southwest (Fig. 3-12). Teeth on the stylolites are up to 1 cm long. The stylolites dip, with respect to bedding, between 70° and 90° and strike roughly northeast-southwest.

Layer-Parallel Slip. Bedding-parallel slickenlines were observed in several freshly exposed folds. Within the Chapman Ridge Sandstone a set of N11W-trending

Figure 3-9. Oblique-slip fault in Chapman Ridge Sandstone. (a) Perspective is looking to the northeast. (b) Closeup of striations on the fault surface showing dextral movement. Clipboard for scale in both pictures. Same location as Figure 2-7.

(a)



(b)

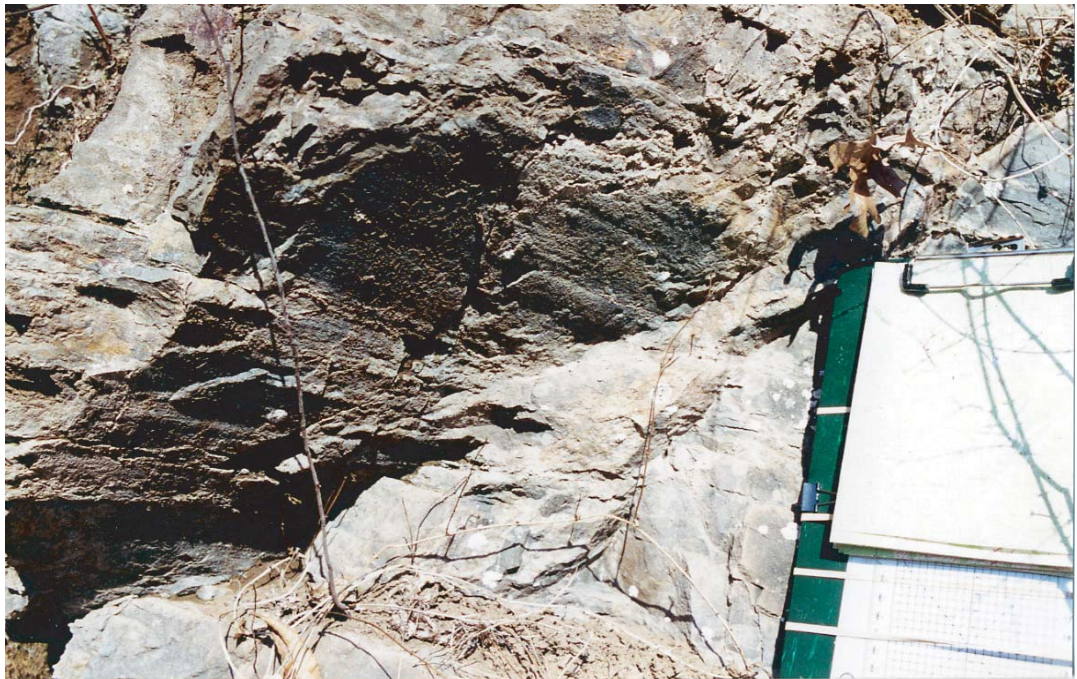




Figure 3-10. Strong cleavage in tightly folded Athens Shale directly below the Chapman Ridge Sandstone contact. Small pencils occur on the outcrop and as float below it. Brunton compass indicates scale. Black lines represent bedding; red lines represent cleavage. Both sets are slightly offset. Located on west side of Prospect Gap Road, approximately 300 m east of intersection with State Route 39.



Figure 3-11. Steeply dipping weak cleavage in flat-lying Athens Shale directly below the Chapman Ridge Sandstone contact on the southeast limb of the main syncline. Brunton compass for scale. Located on west side of Prospect Gap Road approximately 300 m east of intersection with State Route 39.

Figure 3-12. Tectonic stylolite in the Chapman Ridge limestone on northwest limb of the main syncline 1.5 km northwest of the hinge. Location is on State Route 39 approximately 3 km south of Nonaburg Church on east side of road.



slickenlines was identified in the hinge of a one-meter-scale fold. Slickenlines and slickenfibers also occur in open and tightly folded Athens Shale and are spaced 5 to 15 mm apart on parallel bedding planes.

Macroscopic Structure

The Tellico-Sevier syncline extends from southwest of Etowah northeast some 230 km to Kingsport and into Virginia at a 057° trend. In the study area, it plunges 3° northeast and is approximately 16 km, including two small imbricate thrusts in the hanging wall of the Chestucee fault to the northwest (Fig. 3-1; Plate I).

Geologic Map

The Tellico-Sevier syncline is asymmetrical and is cored by Middle Ordovician rocks (Plate I, Fig. 3-1). The nose of the main syncline has a rounded open geometry. The increasing lower Athens Shale outcrop width from each limb into the hinge indicates that the syncline plunges very shallowly to the northeast. The northwest limb is bounded by the Chestuee fault, which is composed of folded and faulted Conasauga and Knox Group rocks. Looking down plunge (to the northeast), the northwest limb of the syncline is asymmetric and is underlain by a subsurface hanging-wall ramp and imbricated flat (Fig. 3-2a, 3-2b, 3-2c, 3-13). The southeast limb of the syncline contains a parasitic anticline-syncline pair, which forms a small subsurface flat and a larger ramp (Fig. 3-2; Plates IIA and IIB) truncated by the Conasauga Creek fault. Southeast of the Conasauga Creek fault is an overturned anticline, cored by Conasauga Shale at the surface, that was overridden by the Great Smoky fault, whose hanging wall contains Sandsuck Formation and Chilhowee Group rocks. The overturned anticline plunges gently northeast, but the trace of the hinge and axial surface of the anticline diverge northwestward from the axial trace of the syncline (Fig. 3-1, Plate I; Hardeman, 1966) and from the Conasauga Creek fault.

Two thrust faults were mapped, one along the southeast limb of the syncline (Conasauga Creek fault) that separates the anticline to the southeast from the main syncline and is traceable throughout the map area, while the other (Cane Creek fault) was traced southwestward along the northwest limb into the axial zone of the syncline and

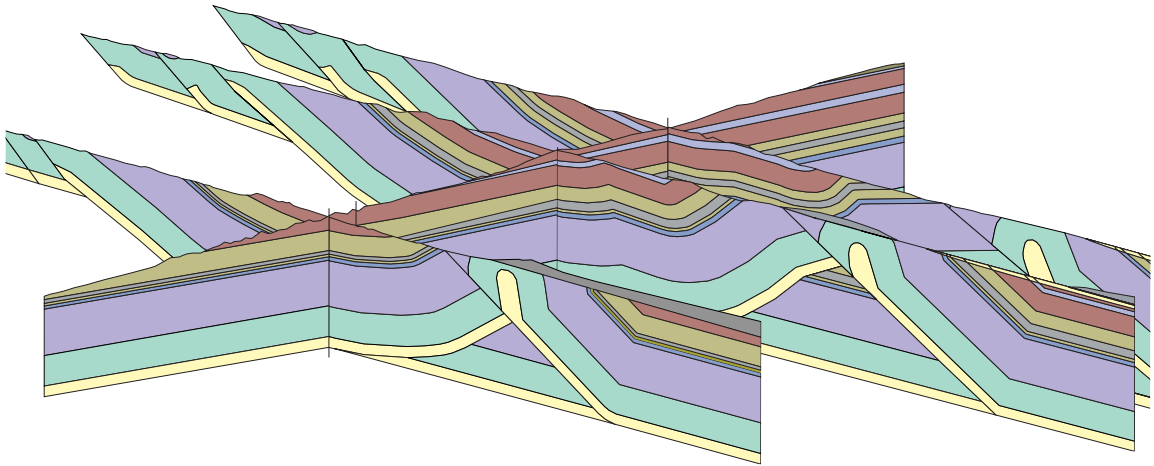


Figure 3-13. Fence diagram of the cross sections in a 3-D array. Refer to figure 3-10 for explanation of units.

places Athens Shale and Mascot Dolomite in fault contact (Fig. 3-1). Based on the crosscutting relationship of the Conasauga Creek and Cane Creek faults, the map reveals (Fig. 3-1, Plate I) that the rocks in the hanging wall of the Conasauga Creek fault are continuous along the fault; and the rocks on either side of the Cane Creek fault terminate where they meet the Conasauga Creek fault. This relationship indicates that the Conasauga Creek fault is younger. Both faults probably formed by an overtightened fold that required faulting through a limb or hinge to accommodate continued deformation (Fig. 3-2c). The Conasauga Creek fault may terminate north of Tellico Plains where the southeast limb of the main syncline is no longer faulted (Hardeman, 1966).

Cross Sections

Five cross sections were constructed to the base of the thrust sheet beneath the Tellico-Sevier syncline (Plate II, Figs. 3-2a, 3-2b, 3-2c, 3-13). Four were constructed perpendicular (A-A', B-B', C-C', D-D') and one parallel (E-E') to the trend of the syncline. The across-strike cross sections were constructed from the Chestuee fault on the northwest to beneath the Great Smoky fault to the southeast. The Chestuee fault was chosen as the northwestern boundary for the sections because it is assumed to be the fault on which the syncline was transported. Sections were constructed into the Great Smoky thrust sheet to the southeast because it overthrust the southeast flank of the syncline. Depth to basement was determined from seismic reflection data that reveal two stacked thrust sheets above the basement (Hatcher et al., 1998). The hinge-parallel cross section

was constructed from the southwest terminus of the Middle Ordovician outcrop in the syncline to the northeast edge of the study area (Plate 1; Fig. 3-1).

The cross sections were first constructed in Adobe Illustrator by transferring surface geologic and structural data from the 1:24,000-scale map (Plate 1) to topographic profiles made from U. S. Geological Survey 7.5 minute quadrangle topographic maps. Stratigraphic unit thicknesses in each cross section were calculated from a combination of outcrop width on the geologic map and average dip of each unit (Fig. 3-14), except for the Rome Formation, Conasauga Group, and Knox Group for which average Valley and Ridge thicknesses were used (Swingle, 1959; Hatcher et al., 1992). The one discrepancy in thickness is with the Conasauga Group, which Swingle (1959) estimated to be thinner than 600 m; this is based, however, on poor outcrop exposure across faults.

Cross-section construction was based on the following assumptions: (1) deformation occurred by plane strain with dominant transport parallel to cross sections A-A', B-B', C-C', D-D' (Plate IIA and IIB, Fig. 3-2a); (2) a cross section in a foreland fold-thrust belt that will not balance cannot be correct; a similarly located section that will balance may be correct (Elliott, 1983); (3) all deformation at the scale of the cross sections was brittle and any penetrative deformation and strain were small enough to be inconsequential; and (4) shortening and deformation of the stratigraphic units here was by buckling accompanied by flexural-slip. If the overturned anticline in the hanging wall of the Conasauga Creek fault had formed by fault-bend or fault-propagation folding, the footwall cutoff angle of the overturned anticline would have been between 13° and 36°

	A-A'	B-B'	C-C'	D-D'
Sevier Shale	NP	NP	NP	NP
Limestone	NP	NP	NP	NP
Upper Chapman Ridge Sandstone	PS	PS	NP	NP
Limestone	151m	107m	NP	NP
Lower Chapman Ridge Sandstone	408m	410m	PS	NP
Upper Athens Shale	170m	287m	401m	PS
Toqua Sandstone	133m	180m	70m	70m
Lower Athens Shale	178m	65m	54m	54m
Lenoir Limestone Mosheim Member	96m	99m	82m	82m
Knox Group	914m	914m	914m	914m
Conasauga Goup	610m	610m	610m	610m
Rome Formation	215m	215m	215m	215m

Figure 3-14. Stratigraphic thicknesses for each individual Chickamauga Group unit calculated from each cross section. Thicknesses for Rome Formation, Conasauga Group, and Knox Group are based on mapping by other authors (see text). Thickness variations for each unit of the Athens Shale are calculated from the cross sections (Plates. IIA, IIB) based on consistant bedding dips and outcrop width measured in the field. Relative thicknesses shown, not exactly to scale. NP - Not present in cross section. PS - Partial section in cross section.

(Suppe, 1983; Mitra, 1990). A displacement-gradient fold model in LithoTect™ has produced cutoff angles of 29°, 36°, and 36° for sections A-A', B-B', and C-C', respectively. Cross sections B-B' and D-D' have apparent normal dip-slip fault displacement; however, all faults in the cross sections are thrust faults.

Cross sections in Adobe Illustrator were converted to *jpeg* format and were brought into LithoTect™ 1.8, a section balancing and modeling program still in development by Geologic Systems, LLC (2003) of Boulder, Colorado. LithoTect™ is a cross section retrodeformation and balancing program that removes deformation by folding and faulting using geometry field algorithms based on kinematic and geometric rules for parallel and similar fold geometries that mimic known rock deformation mechanisms (Geiser, 2002). Cross sections can be constructed in LithoTect™ using imported structural and stratigraphic data or data traced from imported raster files. Forward modeling of retrodeformed sections was not possible because LithoTect does not yet implement competency contrasts. Balancing and retrodeforming were accomplished using both angular- and parallel-concentric flexural-slip geometries in the program. Parallel-concentric or angular-parallel geometries were employed in sections because the majority of mesoscale folds in the study area exhibited a geometric style that was between angular-parallel or parallel-concentric; in map view the syncline displays a parallel-concentric geometry.

The northwest limb of the anticline on the southeast side of Conasauga Creek fault is overturned and dips from 25-60° southeast into the hinge of a larger syncline;

interpreted to exist to the southeast beneath the Great Smoky thrust sheet. The common limb between the anticline and syncline dips approximately 60° southeast (Fig. 3-2a).

Minimum displacement on the Chestuee fault was estimated from sections A-A', B-B', and C-C' to be 17.9-20.8 km based on the difference between the hanging wall and footwall cutoffs of the top of the Rome Formation. Displacement on the Conasauga Creek fault is 2.3-3.5 km. Displacement on the Cane Creek fault is 0.4 km. Estimated displacement differences between the parallel-concentric and angular-parallel cross sections (Plates IIA and IIB) are within five percent of one another, with the angular-parallel models yielding approximately five percent greater displacement.

A wedge-shaped block of Cambrian and Ordovician rocks underlying the southeast limb of the syncline and the overturned anticline is required to balance the cross sections. If this is correct, the Conasauga Creek fault has a much greater displacement than is apparent from surface relationships, because it would retrodeform to the southeast side of the wedge (Fig. 3-2b, Plates IIA and IIB). If the geology portrayed in the state geologic map of Tennessee (Hardeman, 1966) to the northeast of the field area is correct, displacement on the Conasauga Creek fault must increase from zero to the northeast of the field area to 8 km at the southwest end of the syncline. In addition, the wedge-shaped block may continue in the subsurface to the southwest where a similar syncline of Middle Ordovician rocks reappears in the Parksville quadrangle (Sutton, 1971). The southeast limb of that syncline is also faulted at the surface.

Cross Section Discussion

In the nose of the syncline (sections C-C' and D-D'), both limbs of the Tellico-Sevier syncline are symmetrical with respect to one another. Further down plunge in sections A-A' and B-B' the syncline is asymmetrical due to a parasitic anticline-syncline pair on the southeast limb, which create a volume problem beneath the Rome Formation on the base of the thrust sheet (Figs. 3-2a, 3-2b, 3-13). The southeast limb of the main syncline is cut by the Conasauga Creek fault, which in the hanging wall is composed of an overturned anticline of Cambrian and Ordovician rocks. In map view the trend of the Tellico-Sevier syncline and the overturned anticline are not parallel to the northeast and southwest, thereby suggesting that they did not form contemporaneously, and instead, formed during two separate events (Fig. 3-1). The Tellico-Sevier syncline and the wedge of material beneath its southeast limb (and the Conasauga Creek fault) becomes wider as the syncline plunges to the northeast.

Two types of balancing discrepancies occur in the retrodeformed sections; volume and cutoff angle inconsistencies. The volume problems are manifested as small bumps on the top of the Knox Group in the core of the retrodeformed syncline, which propagate upward (Fig. 3-2b). These bumps exist because LithoTect™ is unable to correctly retrodeform the core of open to tight folds using both parallel deformation models. The footwall and hanging wall cutoff angle discrepancies occur because LithoTect™ can only retrodeform a single deformation event. Based on the discrepancies in the cutoff angles,

it appears that many of the folds in association with faults did not form contemporaneously, but at different times.

Martin (1997) constructed similar cross sections to the northeast of the study area. He accounted for the southeast limb of the Tellico-Sevier syncline with a blind fault that ramped through the Rome Formation, Conasauga and Knox Groups, and flattened in the top of the Knox Group beneath the southeast limb of the syncline. The hanging wall of the fault carried an upright anticline with a fault-propagation fold geometry. Martin's (1997) interpretation is not valid for the study area, though, because the Conasauga Creek fault here transported an overturned anticline to the present-day erosion surface. Martin's interpretation also implies that the syncline and anticline formed contemporaneously during the development of the blind fault. In the study area this interpretation is impossible because the anticline would have to be structurally above and to the northwest of the southeast limb of the syncline for them to be related. This relationship between the syncline and overturned anticline suggests that the southeast limb of the syncline formed first by underthrusting, which was then followed by the formation of the anticline when the detachment was pinned, causing a detachment fold to form (Fig. 3-15) (Wickham, 1995). Once the anticline was formed and overturned the proto-Conasauga Creek fault propagated through the fold and the anticline was transported up the Conasauga Creek fault truncating the southeast limb of the Tellico-Sevier syncline. Because the fold formed first and the fault later, LithoTect was unable to correctly balance and retrodeform the hanging wall of the Conasauga Creek fault (Plate IIA and IIB).

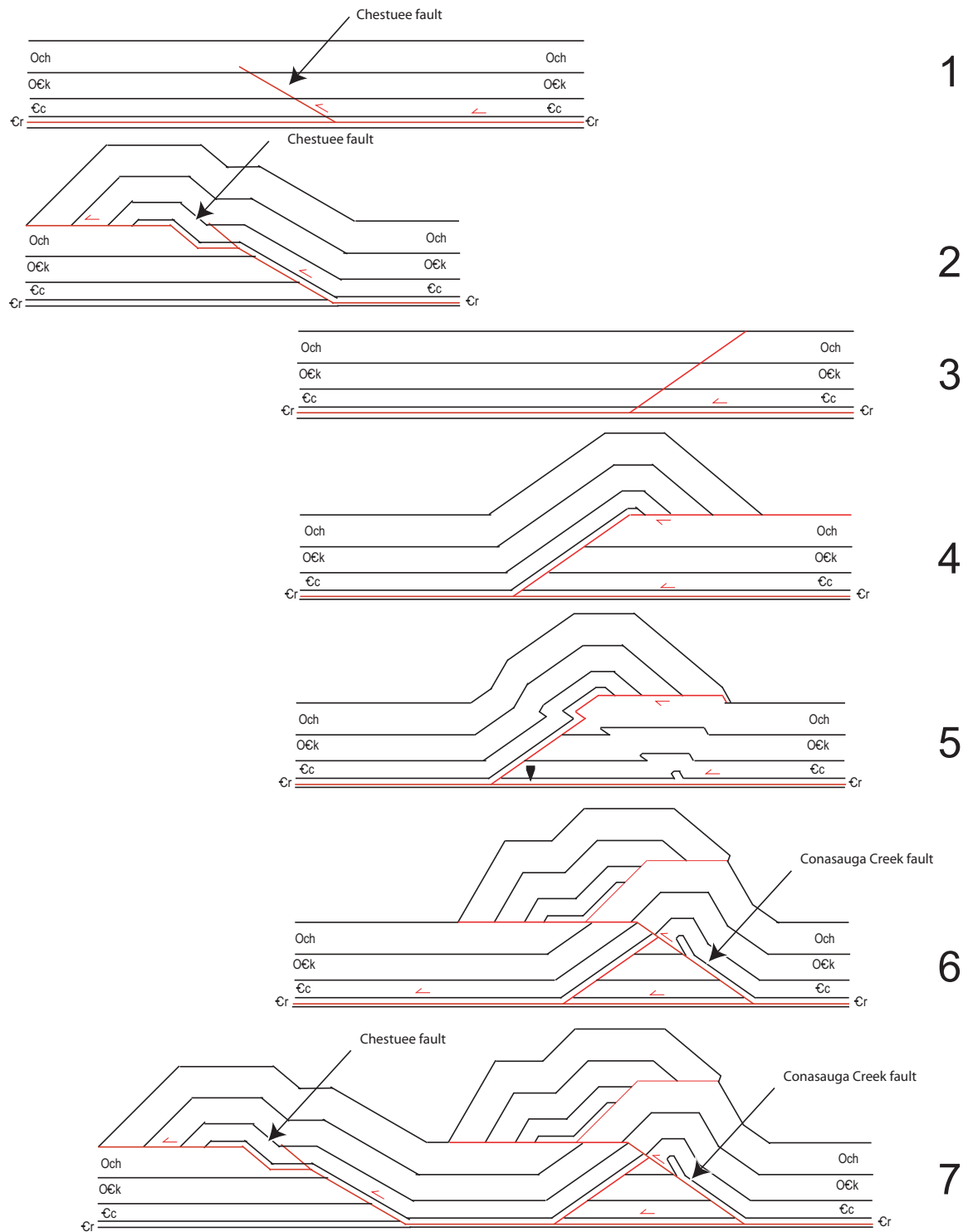


Figure 3-15. Structural development of the study area illustrating growth of major faults and folds. No vertical exaggeration. Red lines are faults. Cr - Rome formation. Cc - Conasauga Group. OEK - Knox Group. Och - Chickamauga Group.

Discussion

Traditionally, the order of thrusting during the formation of a foreland fold-thrust belt had two end-member possibilities: a foreland to hinterland thrusting progression (Milici, 1975) and a hinterland to foreland sequence (Elliott, 1980; Woodward and Beets, 1988). A third possibility is that emplacement occurred from hinterland to foreland accompanied by out-of-sequence thrusting permitting the thrust sheet to maintain critical taper (Woodward, 1987).

The relative age of the northwest and southeast limbs of the Tellico-Sevier syncline is constrained by the crosscutting relationship of the Cane Creek and Conasauga Creek fault. Because the Cane Creek fault is truncated by the Conasauga Creek fault, it must be older indicating that the northwest limb formed first and then the southeast limb formed later. The northwest limb of the Tellico-Sevier syncline formed as the Chestuee thrust sheet was transported up a lower footwall ramp and onto an upper footwall flat. Once the thrust sheet was emplaced onto the upper footwall ramp several imbricates of the Chestuee fault formed at the leading edge. At the same time the Cane Creek fault on the present-day northwest side of the Tellico-Sevier syncline formed in response to tightening and folding of the thrust sheet as it was transported up the footwall ramp due to the inability of the Knox Group carbonates to fold (Fig. 3-2c).

Relative timing and order of thrusting for emplacement of the Conasauga Creek fault and overturned anticline are constrained by the relationships of rocks on either side

of the Conasauga Creek fault separating the Tellico-Sevier syncline and the overturned anticline on the opposite side. The southeast limb of the syncline formed after the northwest limb of the main syncline when a forelandward-dipping fault cut down-section in the direction of transport (Figs. 3-2, and 3-16), producing a backthrust geometry. As the fault formed the hinterland side (footwall) of the fault underthrust the Chestuee sheet, which passively produced the southeast limb of the Tellico-Sevier syncline with its parasitic anticline and syncline (Fig. 3-16). Geometrically this produces apparent backthrust motion to the southeast on the fault and in the thrust sheet. Movement at all times was to the northwest and consistent with the general transport direction of other Valley and Ridge thrusts.

After formation of the southeast limb of the Tellico-Sevier syncline, the decollement became pinned and an anticline formed as a fault displacement-gradient fold. Tightening of the anticline caused it to become overturned, at which point the Conasauga Creek fault propagated up and transported the anticline to its present location, cutting the southeast limb of the syncline.

Two main problems exist with the model presented thus far: (1) space problems occur beneath the two parasitic folds in the syncline and (2) the order of thrusting and emplacement of the Chestuee thrust sheet. The space beneath the parasitic anticline and syncline on the southeast limb of the syncline can be accounted for in two ways: as shale imbricates or horses left behind and accreted to the top of the basal thrust sheet as ramps while the Chestuee thrust sheet traveled over it, or by imbrication and duplexing the basal

thrust sheet beneath the Chestuee thrust sheet. Based on the crosscutting relationship of the Conasauga Creek and Cane Creek faults two episodes of out-of-sequence thrusting are required; first, the underthrusting of the Chestuee thrust sheet to form the southeast limb of the Tellico-Sevier syncline after the northwest limb of syncline formed, and second, the pinning of the detachment to form the overturned anticline and Conasauga Creek fault. Use of out-of-sequence thrusting and the geometry of the present cross sections produce the simplest explanation for the surface structure and geometry and is geologically valid; as such, it is the best solution, given the present data available.

Conclusions

- 1) The order of thrusting and formation of the Tellico-Sevier syncline and overturned anticline requires at least two phases of out-of-sequence thrusting to explain the present day geometry.
- 2) The Tellico-Sevier syncline and overturned anticline formed during two separate events and are not genetically related to one another. Evidence for this relationship is their divergence along trend and their geometric relationship in cross section.
- 3) Based on the balanced parallel-concentric cross sections, minimum displacement on the Chestuee fault is 17.9-20.8 km. Displacement on the Conasauga Creek fault is 2.3-3.5 km. Displacement on the Cane Creek fault is 0.4 km. Use of the angular-parallel cross sections yields approximately 5 percent greater displacement.

4) Construction of cross sections using both angular-parallel and parallel-concentric geometries produced no substantial differences in the folding or thrusting history or the geometry of the deformed cross sections except for the aforementioned line length differences.

CHAPTER 4

CONCLUSIONS

1. Algal laminations, burrows, and conglomerates in the lower unit of the Lenoir Limestone (*sensu lato*) suggest a peritidal shelf environment (Benedict and Walker, 1978).
2. The transition from the Douglas Lake Member to the main Mosheim Member may represent a transition to a deeper water environment where precipitation of calcareous mud was the primary depositional mechanism (Shanmugam and Walker, 1978).
3. Sedimentary structures and fossils identified in the Athens Shale indicate a deepening environment up section with depths of at least 150 to 200 m and potentially 600 to 800 m (Walker, 1977; Benedict and Walker, 1978; Shanmugam and Walker, 1978, 1980).
4. Position of the Chapman Ridge Sandstone above the Athens Shale indicates that the Sevier basin shallowed after the deposition of the Athens Shale. The ferruginous nature of the Chapman Ridge Sandstone requires at least intermittent subaerial exposure during diagenesis (Boggs, 1987)); however, transportation and deposition of previously oxidized hematitic sand as the Chapman Ridge Sandstone may account for its hematitic nature.
5. The Chapman Ridge limestone, and limestone at the base of the Sevier Shale, suggest a return to a shallow-water reef environment that was periodically inundated by clastic

material or an environment with fluctuating water depth that could only intermittently support a reef when it was in the photic zone.

6. The order of thrusting and formation of the Tellico-Sevier syncline and overturned anticline requires at least two events of out-of-sequence thrusting to explain the present-day geometry.

7. The Tellico-Sevier syncline and overturned anticline formed during two separate events and are not genetically related to one another. Evidence for this relationship is their divergence along trend and their geometric relationships in cross section.

8. Based on the balanced parallel-concentric cross sections, minimum displacement on the Chestuee fault is 17.9-20.8 km. Displacement on the Conasauga Creek fault is 2.3-3.5 km. Displacement on the Cane Creek fault is 0.4 km. Use of the angular-parallel cross sections yields approximately 5 percent greater displacement.

9. Construction of cross sections using both angular-parallel and parallel-concentric geometries produced no substantial differences in the folding or thrusting history or the geometry of the deformed cross sections, except for the aforementioned line-length differences.

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Appendices

Appendix A1

Cross-Section Construction and Restoration in LithoTect

end points farthest apart on the cross sections and was scaled by LithoTect™ to the correct map coordinates.

Within LithoTect™ different types of lines can be drawn to represent stratigraphic tops, faults, intraformational markers, boundaries, etc. These lines can then be identified as specific units or faults. A geologic column must be created in order to identify a specific line type; in this case three columns were created: Cambro-Ordovician stratigraphy, faults, and markers. New columns were created and modified using the *New Column* menu in the column window (Fig. A-2).

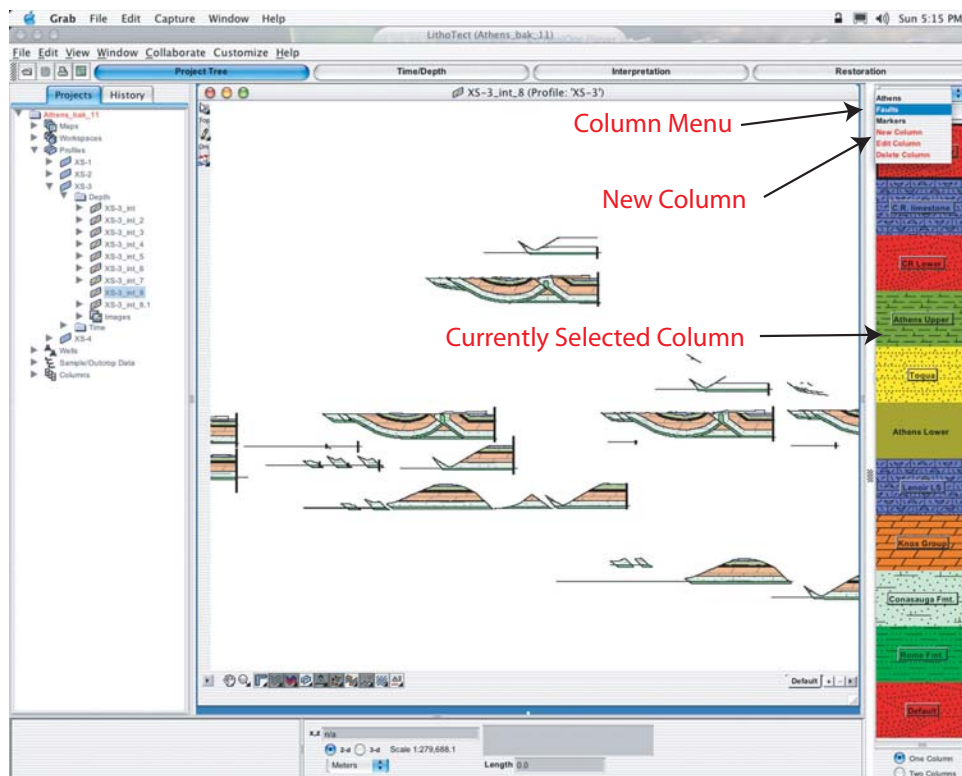


Figure A-2. Profile view showing Column menu, New Column command, and currently selected column.

Once the map view *jpeg* of the cross-section lines was calibrated, the four cross-section lines were traced as new profile lines and named. A new depth interpretation was created for each cross-section line in each profile folder. After the new depth interpretation was created, a new window was opened in the depth interpretation using the *Import Image* (Fig. A-1) option to import and calibrate a *jpeg* of the cross section in the same manner as the base map. This procedure was repeated for each of the three remaining cross sections.

After the cross-section image was calibrated, the topography was traced using the *Topography/Outcrop* line type (Fig. A-3). Next, the uppermost rock unit top was traced using the *top* line. Before the line was completed, another top was projected above and below the currently active line using the stratigraphic thicknesses calculated for each lithologic unit. Either the parallel-concentric or angular-parallel projection geometry was employed depending on which geometry was to be used to construct a particular cross section. The entire cross section was sequentially constructed from the top down using the method of tracing the previous projection and then projecting the next calculated stratigraphic top.

After the cross section was constructed, the *Restoration* module was opened and the following restoration options were chosen: interactive operation mode; flexural-slip model; region transformation; and parallel-concentric or angular flexural-slip systems geometry (depending on the construction geometry of the section being restored) (Fig. A-4). Because the cross sections were restored to the top of the Rome Formation and

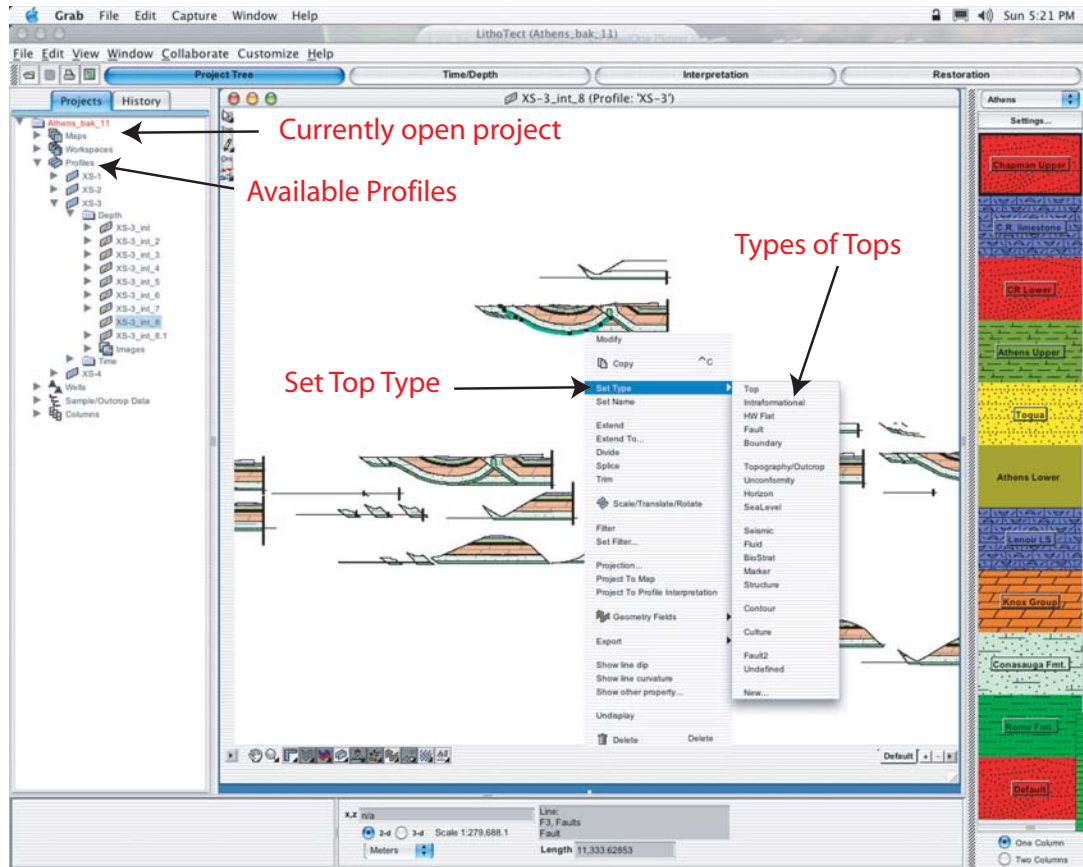


Figure A-3. Profile view showing Set Top Type menu, Top Types, available Profiles, and currently opened project.

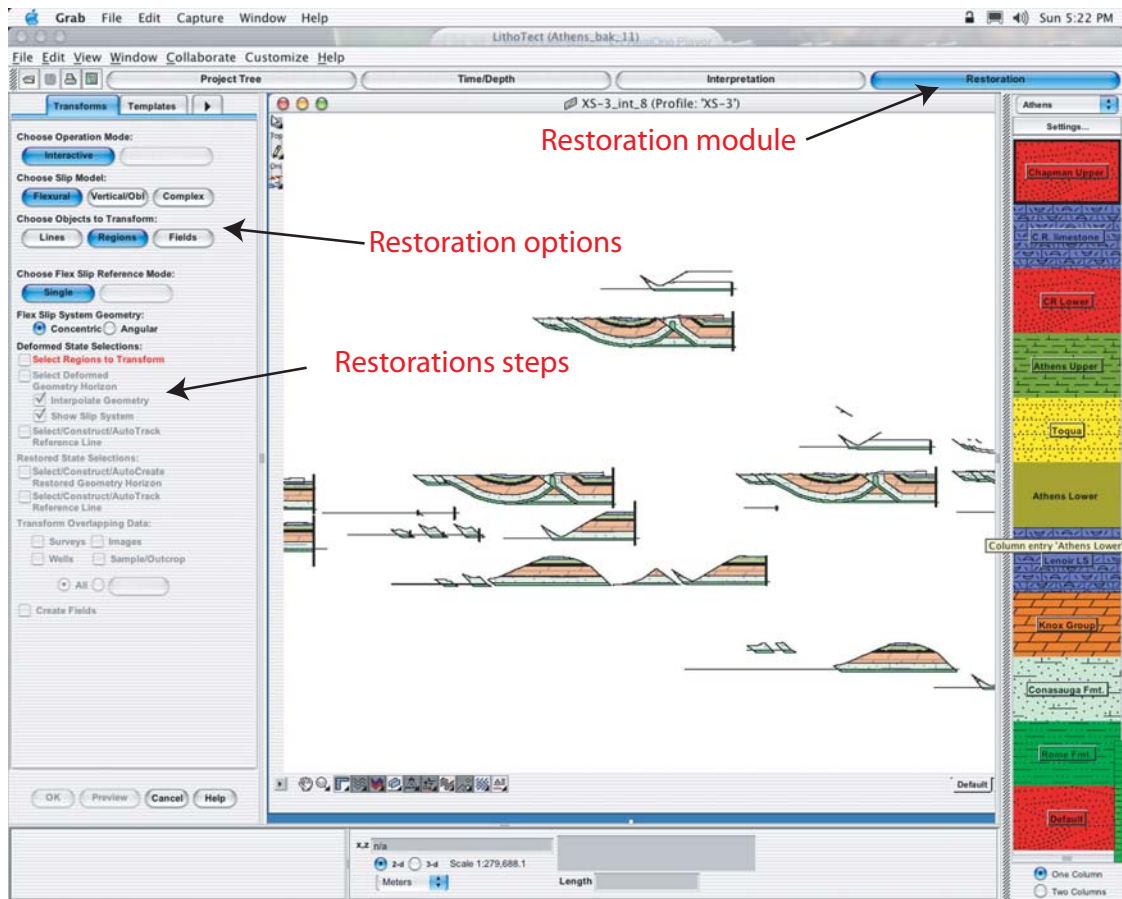


Figure A-4. Restoration module view showing Restoration menu and Restoration steps.

restored from hinterland to foreland (southeast to northwest), a horizontal Rome top with a vertical pin line on the right (hinterland) side (all cross sections were drawn looking to the northeast) was constructed beneath the deformed cross section and a vertical pin line was drawn on the hinterland end of the deformed Rome top where it was truncated by a fault (e.g. Conasauga Creek fault). The horizontal Rome top serves as the restored horizon to which the deformed section would be flattened. Next the deformed regions, Rome top, and pin lines were selected. The Rome top and pin lines were then selected in the restored state and the restore command executed, thus creating a restored cross section flattened on the top of Rome.

Errors in the deformed section would appear in the restored section as irregular stratigraphic thicknesses (bulges and depressions), inconsistent hanging wall and footwall cutoff angles, bulges on fault surfaces, and irregular line lengths. Errors were corrected in the deformed section by adjusting stratigraphic thicknesses, line lengths, and fault cutoff angles, and then repeating the restore command. If misfits persist or new errors appear, corrections are made and the process repeated until the best and most consistent retrodeformed section is attained. Unfortunately, the algorithms in LithoTect™ are capable only of retrodeforming one event; the overturned anticline on the southeast side of the Conasauga Creek fault probably formed in two stages.

Appendix A2

Structural and Rock Type Data for the Study Area

Explanation of abbreviations used in the table headings of the field data.

Station	Station number recorded in field notes.
Lithology	Lithology observed: 1: Copper Ridge Dolomite 2: Chepultepec Dolomite 3: Longview Dolomite 4: Kingsport Formation 5: Mascot Dolomite 6: Lenoir Limestone 7: Yellow tan shale (Athens Shale) 8: Light gray sandstone 9: Ferruginous sandstone 10: Medium gray sandstone with ferruginous cross bedding 11: Medium gray sandstone 12: Fossiliferous limestone 13: Yellow tan shale (Sevier Shale) 14: Red siltstone or mudstone 15: Conasauga Shale
Geom. Element	Type of structural measurement taken.
Strike/Trend	Strike or trend of the bedding surface or fold.
Dip/Plunge	Dip or plunge of bedding surface or fold.
Dip D.	Dip direction (quadrant).

Station	Lithology	Geom Element	Strike/Trend	Dip/Plunge	Dip D
1	7	location			
2	6	bedding	N60E	36	SE
3	6	bedding	N63E	36	SE
4	7	bedding	N46E	34	SE
5	7	bedding	N37E	36	SE
6	7	bedding	N55E	34	SE
7	8	bedding	N61E	38	SE
8	8	bedding	N58	42	SE
9	7	bedding	N31E	30	SE
10	7	bedding	N53E	28	SE
11	11	bedding	N51E	26	SE
12	9	bedding	N56E	38	SE
13	9	bedding	N63E	43	SE
14	9	bedding	N72E	24	SE
15	9	bedding	N72E	22	SE
16	9	bedding	N55E	21	SE
16		lineations	N81W	40	NW
16		fault	N86E	68	NW
17	8	bedding	N40E	22	SE
18	12	bedding	N86W	13	SW
19	11	bedding	N67W	20	NE
20	11	bedding	N35E	20	NW
21	11	bedding	N33E	14	NW
22	10	bedding	N70E	23	NW
23	9	bedding	N26W	6	SW
24	9	bedding	N55W	5	NE
25	9	bedding	N26W	10	SW
26	9	bedding	N76E	9	NW
27	9	bedding	N38W	11	SW
28	9	bedding	N15E	9	SE
29	9	bedding	N27E	10	SE
30	9	bedding	N50E	10	SE
31	9	bedding	N78E	8	SE
32	9	bedding	N31E	13	SE
33	9	bedding	N74E	10	SE
34	9	bedding	N29E	16	NW
35	11	bedding	N24E	19	NW
36	13	bedding	N40E	20	NW
37	13	bedding	N56E	33	NW
37		fault	N55E	54	SE
37		lineations	N49E	76	SE
38	10	bedding	N74E	15	NW
39	9	bedding	N79E	12	NW
40	9	bedding	N52E	4	SE
41	9	bedding	N45E	19	SE
42	9	bedding	N75E	9	SE
43	9	bedding	N47E	26	SE
44	13	bedding	N78E	22	SE
45	12	bedding	N80E	15	SE
46	13	bedding	N71E	13	SE
47	13	bedding	N42E	21	SE
48	13	location			
49	12	bedding	N77W	18	SW
50	13	bedding	N76E	25	SE

51	12	bedding	N6E	7	NW
52	12	bedding	N6E	21	NW
53	13	bedding	N35E	3	NW
54	11	fold limb	N4E	8	SE
54		fold limb	N29E	70	SE
55	11	fold axis	S55W	25	
55		fold axis	S39W	24	
55		fold axis	S35W	21	
55		fold limb	N46E	31	SE
55		fold limb	N31E	58	NW
55		fold axis	S33W	7	
56	8	bedding	N86W	10	SW
57	9	bedding	N85E	87	NW
58	9	bedding	N62W	67	SW
59	11	bedding	N58E	10	NW
60	9	bedding	N74E	34	NW
61	11	bedding	N55E	39	NW
62	9	bedding	N56E	49	NW
63	8	bedding	N75E	80	NW
64	7	bedding	N68E	81	NW
65	7	bedding	N83E	73	SE
66	7	fold axis	N36E	5	
66		fold limb	N55E	24	NW
66		fold limb	N30E	68	SE
67	7	fold axis	S55W	8	
67		fold limb	N22E	25	NW
67		fold limb	N71E	21	SE
68	9	bedding	N56E	80	SE
69	8	bedding	N75E	30	NW
70	9	bedding	N5E	8	NW
71	10	bedding	N42W	4	NW
72	9	bedding	N74W	21	NE
73	9	bedding	N89W	9	SW
74	10	bedding	N31E	7	SE
75	9	bedding	N50E	13	SE
76	9	bedding	N2W	11	SW
77	9	bedding	N80E	45	NW
78	11	bedding	N72E	29	NW
79	9	bedding	N75E	15	NW
80	9	bedding	N78W	35	NE
81	11	bedding	N40W	9	NE
82	11	bedding	N61W	14	NE
83	11	bedding	N25W	4	NE
84	11	bedding	N21E	6	SE
85	9	bedding	N30E	9	SE
86	13	bedding	N46E	11	SE
87	9	bedding	N65E	11	SE
88	9	location			
89	13	bedding	N75W	25	NE
90	13	bedding	N70E	17	NW
91	9	bedding	N25E	27	SE
92	9	location			
93	9	bedding	N34E	12	SE
94	9	bedding	N30E	12	SE
95	9	bedding	N68W	4	SW

96	9	bedding	N3E	8	SE
97	9	bedding	N14E	12	SE
98	9	bedding	N2W	8	NE
99	9	bedding	N35E	18	SE
100	9	bedding	N5W	8	NE
101	9	bedding	N2E	8	SE
102	9	bedding	N54E	15	SE
103	13	bedding	N67E	12	SE
104	9	bedding	N65E	18	SE
105	9	bedding	N48E	30	SE
106	5	bedding	N61E	34	SE
107	6	bedding	N54E	34	SE
108	7	bedding	N50E	44	SE
109	8	bedding	N57E	34	SE
110	11	bedding	N37E	20	SE
111	7	bedding	N63E	23	SE
112	7	bedding	N52E	26	SE
113	9	bedding	N43E	35	SE
114	9	bedding	N60E	20	SE
115	9	bedding	N55E	24	SE
116	9	bedding	N46E	21	SE
117	9	bedding	N21E	16	SE
118	7	bedding	N56E	43	SE
119	7	bedding	N14W	20	NE
120	7	bedding	N79W	29	NE
121	7	bedding	N78E	20	NW
122	9	bedding	N50W	27	NE
123	10	bedding	N88E	15	NW
124	11	bedding	N52E	11	NW
125	9	bedding	N55E	5	NW
126	9	bedding	N9E	3	NW
127	9	bedding	N17E	6	NW
128	7	bedding	N67W	27	NE
129	7	bedding	N70E	18	NW
130	7	bedding	N65E	16	NW
131	9	bedding	N76E	4	NW
132	9	bedding	N28E	10	NW
133	9	bedding	N72E	11	NW
134	9	bedding	N46E	19	NW
135	9	bedding	N71E	21	SE
136	9	bedding	N42E	11	SE
137	9	bedding	N69W	11	SW
138	9	bedding	N56E	34	NW
139	9	bedding	N69W	17	NE
140	9	bedding	N80W	61	NE
141	7	bedding	N19E	13	NW
142	7	bedding	N71E	36	NW
143	6	bedding	N37E	36	NE
144	6	bedding	N71E	22	SE
145	5	bedding	N55E	40	SE
146	6	bedding	N62E	42	SE
147	6	bedding	N58E	35	SE
148	5	bedding	N50E	54	SE
149	6	bedding	N70E	34	SE
150	6	bedding	N55E	34	SE

151	6	bedding	N52E	37	SE
152	5	bedding	N58E	45	SE
153	5	bedding	N60E	37	SE
154	5	bedding	N51E	38	SE
155	5	bedding	N58E	37	SE
156	5	bedding	N60E	33	SE
157	5	bedding	N49E	29	SE
158	5	bedding	N46E	38	SE
159	7	bedding	N39E	46	SE
160	5	bedding	N47E	36	SE
161	5	bedding	N48E	39	SE
162	5	bedding	N19E	16	SE
163	7	bedding	N44E	19	SE
164	7	bedding	N51E	40	SE
165	6	bedding	N56E	36	SE
166	5	bedding	N54E	45	SE
167	6	bedding	N65E	32	SE
168	8	bedding	N64E	31	SE
169	5	bedding	N61E	21	SE
170	8	bedding	N76E	13	SE
171	5	bedding	N49E	46	SE
172	5	bedding	N49E	30	SE
173	5	bedding	N46E	31	SE
174	7	fold limb	N54E	77	NW
174		fold limb	N45E	69	SE
174		fold limb	N35E	75	NW
174		fold limb	N29E	45	SE
174		fold axis	N51E	16	
174		fold limb	N55E	77	NW
174		fold limb	N63E	19	NE
174		fold axis	N52E	7	
175	7	bedding	N41E	31	SE
176	7	bedding	N56E	23	SE
177	7	fold axis	N54E	20	
177		fold limb	N86E	43	NW
177		fold limb	N8E	22	SE
178	7	bedding	N28E	23	SE
179	5	bedding	N53E	27	SE
180	6	bedding	N53E	34	SE
181	6	bedding	N57E	37	SE
182	8	bedding	N75E	68	NW
183	8	bedding	N80E	78	NW
184	7	bedding	N72E	89	NW
185	7	bedding	N84E	79	SE
186	7	bedding	N50E	69	SE
187	7	bedding	N74E	85	SE
188	1	bedding	N51E	47	SE
189	1	bedding	N57E	54	SE
190	1	bedding	N51E	36	SE
191	1	bedding	N44E	59	SE
192	1	bedding	N49E	55	SE
193	1	bedding	N28W	24	NE
194	7	bedding	N68E	78	NW
195	2	bedding	N80E	39	SE
196	2	bedding	N62E	25	SE

197	2	bedding	N10W	14	SE
198	1	bedding	N62E	52	SE
199	1	bedding	N19E	90	
200	2	bedding	N87W	49	NE
201	2	bedding	N82W	38	NE
202	1	bedding	N54E	44	SE
203	1	bedding	N53E	45	SE
204	1	bedding	N39E	44	SE
205	1	bedding	N47E	45	SE
206	1	bedding	N56E	67	NW
207	7	bedding	N48E	44	SE
208	7	fold limb	N34E	28	SE
208		fold axis	N62E	10	
208		fold limb	N36E	32	SE
208		fold limb	N65E	66	NW
209	2	bedding	N86E	26	SE
210	2	bedding	N15E	18	SE
210		cleavage	N55W	86	SW
211	2	bedding	N31E	22	SE
212	2	bedding	N35E	34	SE
213	2	bedding	N23E	58	SE
214	1	bedding	N9E	27	NW
215	1	bedding	N85W	22	SW
216	2	bedding	N48E	9	NW
217	15	bedding	N42E	46	SE
218	2	bedding	N82E	16	NW
219	2	bedding	N43E	15	SE
220	7	bedding	N59E	57	NW
221	7	bedding	N45E	59	NW
222	7	bedding	N80W	13	NE
223	7	bedding	N85E	12	NW
224	7	bedding	N28W	15	SW
225	7	bedding	N54E	56	SE
226	6	bedding	N45E	14	SE
227	6	bedding	N30E	25	NW
228	7	bedding	N33E	24	SE
229	7	bedding	N38E	14	SE
230	9	bedding	N44W	14	NE
231	7	bedding	N46W	10	NE
232	7	bedding	N53W	15	NE
233	7	bedding	N8W	19	NE
234	9	bedding	N36W	20	SW
235	9	bedding	N45E	5	SE
236	9	bedding	N14E	17	SE
237	7	bedding	N78E	14	SE
238	7	bedding	N80E	60	NW
239	7	bedding	N57W	31	NE
240	7	bedding	N15E	20	SE
241	7	bedding	N14E	9	SE
242	9	bedding	N38E	29	SE
243	9	bedding	N5W	1	NE
244	7	bedding	N81E	16	NW
245	7	bedding	N60W	10	NE
246	12	bedding	N35E	8	NW
247	7	bedding	N85W	5	NE

248	9	bedding	N70W	4	SW
249	9	bedding	N61E	26	SE
250	7&8	bedding	N56E	21	SE
251	7	bedding	N34E	21	SE
252	7	bedding	N36E	20	SE
253	7	bedding	N44E	60	NW
254	7	bedding	N61E	47	NW
255	7&8	bedding	N53E	21	NW
256	7	bedding	N65E	81	NW
257	7	bedding	N65E	74	NW
258	8	bedding	N66E	54	NW
259	8	bedding	N77E	87	SE
260	7	bedding	N50E	63	SE
261	7	bedding	N29E	44	SE
262	9	bedding	N32E	30	SE
263	9	bedding	N55E	24	SE
264	12	bedding	N36E	29	SE
265	9	bedding	N87E	85	SE
266	9	bedding	N23E	9	NW
267	9	bedding	N34E	34	NW
268	9	bedding	N74E	9	NW
269	9	bedding	N72E	17	NW
270	9	bedding	N59E	11	NW
271	9	bedding	N63E	16	NW
272	9	bedding	N47E	10	NE
273	12	bedding	N75W	4	NW
274	10	bedding	N78E	14	SE
275	10	bedding	N64E	53	SE
276	7	bedding	N51E	50	SE
277	7	bedding	N57E	53	SE
278	7	bedding	N50E	48	SE
279	7	bedding	N52E	28	SE
280	8	bedding	N48E	25	SE
281	7	bedding	N78E	35	SW
282	9	bedding	N64W	21	NW
283	7	bedding	N63E	24	SE
284	9	bedding	N50E	12	SE
285	7	bedding	N38E	20	SE
286	9	bedding	N72W	16	SW
287	9	bedding	N38E	22	SE
288	9	bedding	N51E	54	NW
289	9	bedding	N20E	18	NW
290	9	bedding	N18W	23	NE
291	9	bedding	N35E	32	SE
292	7&8	bedding	N65E	20	SE
293	8	bedding	N71E	23	SE
294	9	bedding	N68E	13	SE
295	7	bedding	N53E	25	SE
296	9	bedding	N68E	31	SE
297	10	bedding	N63E	15	SE
298	13	bedding	N45E	15	SE
299	13	bedding	N47E	5	SE
300	13	bedding	N18E	22	SE
301	12	bedding	N82E	39	NW
302	12	bedding	N62E	4	NW

303	12	bedding	N64W	19	NE
304	12	bedding	N16E	15	SE
305	12	bedding	N14E	19	SE
306	13	bedding	N12E	16	SE
307	9	bedding	N51W	6	NE
308	7	bedding	N50W	75	SW
309	7	bedding	N63E	22	SE
310	9	bedding	N70E	14	SE
311	12	bedding	N66E	21	SE
312	12	bedding	N55E	16	SE
313	12	bedding	N63E	26	SE
314	12	bedding	N48E	19	SE
315	7	bedding	N73E	9	SE
316	9	bedding	N8E	17	SE
317	10	bedding	N16E	18	SE
318	11	bedding	N13E	4	SE
319	9	bedding	N65E	31	NW
320	7	bedding	N68E	41	NW
321	7	bedding	N50E	64	NW
322	7	bedding	N45E	14	NW
323	13	bedding	N64E	8	NW
324	12&13	bedding	N79W	21	NE
325	9	bedding	N52W	10	SW
326	9	bedding	N75E	5	NW
327	7	bedding	N48E	14	SE
328	2	bedding	N14W	39	NE
329	7&8	bedding	N45E	26	SE
330	13	bedding	N70E	19	SE
331	9	bedding	N60E	28	SE
332	9	bedding	N58E	32	SE
333	9	bedding	N46E	31	SE
334	9	bedding	N40E	26	SE
335	9	bedding	N44E	49	SE
336	9	bedding	N44E	28	SE
337	9	bedding	N39E	50	SE
338	9	bedding	N45E	55	SE
339	9	bedding	N48E	38	SE
340	9	bedding	N55E	35	SE
341	7	bedding	N68E	15	SE
342	9	bedding	N50E	42	SE
343	9	bedding	N69E	25	SE
344	9	bedding	N62E	61	SE
345	9	bedding	N76E	40	SE
346	9	bedding	N48E	43	SE
347	9	bedding	N48E	32	SE
348	9	bedding	N50E	48	SE
349	9	bedding	N53E	30	SE
350	9	bedding	N58E	19	SE
351	12	bedding	N49E	34	SE
352	12	bedding	N45E	20	SE
353	9	bedding	N16E	36	SE
354	9	bedding	N46E	8	SE
355	9	bedding	N56E	18	SE
356	7	bedding	N56E	15	SE
357	7	bedding	N41E	59	SE

358	9	bedding	N66E	22	SE
359	9	bedding	N48E	42	SE
360	9	bedding	N61E	25	SE
361	12	bedding	N37E	45	SE
362	13	bedding	N19E	10	SE
363	12	bedding	N45E	25	SE
364	12	bedding	N38E	24	SE
365	12	bedding	N73E	14	SE
366	13	bedding	N53E	8	SE
367	13	bedding	N34E	26	SE
368	9	bedding	N39W	24	NE
369	9	bedding	N72E	28	NW
370	9	bedding	N34E	6	SE
371	9	bedding	N26E	11	SE
372	13	bedding	N52E	16	SE
373	13	bedding	N64E	28	SE
374	12	bedding	N86E	16	NW
375	12	bedding	N78W	4	NE
376	13	bedding	flat		
377	12	bedding	N72E	6	SE
378	12&13	bedding	N59W	8	SW
379	12	bedding	N50E	16	SE
380	12	bedding	N52E	23	SE
381	12	bedding	N34W	11	SW
382	12	bedding	N38W	10	SW
383	9	bedding	N35W	13	NE
384	9	bedding	N45W	22	NE
385	7&8	bedding	N69W	12	SW
386	7&8	bedding	N42W	33	SW
387	7	bedding	N42E	22	SE
388	7	bedding	N61E	44	SE
389	7	bedding	N38E	34	SE
390	12	bedding	N34E	13	SE
391	12	bedding	N85E	19	SE
392	9	bedding	N74E	19	SE
393	9	bedding	N74E	13	SE
394	12&9	bedding	N68E	28	NW
395	12&9	bedding	N72E	25	NW
396	13	bedding	N71E	32	NW
397	13	bedding	N54E	24	NW
398	9	bedding	N43E	15	NW
399	9	bedding	N49E	19	NW
400	9	bedding	N60E	14	SE
401	9	bedding	N64E	17	NW
402	9	bedding	N45W	16	NE
403	9	bedding	N72W	19	NE
404	9	bedding	N70E	18	NW
405	9	bedding	N42E	16	NW
406	9	bedding	N6W	5	NE
407	9	bedding	N39W	16	NE
408	9	bedding	N64W	3	NE
409	9	bedding	N60E	13	SE
410	9	bedding	N88W	14	SW
411	9	bedding	N25W	21	NE
412	12&9	bedding	N60E	30	SE

413	12&9	bedding	N58E	25	SE
414	12&9	bedding	N88E	8	SE
415	13	bedding	N25W	4	SW
416	12&9	bedding	N78W	7	SW
417	12&9	bedding	N74W	22	SW
418	12&9	bedding	N47W	15	SW
419	12&9	bedding	N83E	17	SE
420	12&9	bedding	N59E	20	SE
421	12&9	bedding	N68W	7	SW
422	12&9	bedding	N66E	15	SE
423	12&9	bedding	N83W	15	SW
424	9	bedding	N89E	21	SE
425	13	bedding	N49E	17	NW
426	8	bedding	N7E	35	SE
427	13	bedding	flat		SE
428	9&12	bedding	flat		SE
429	9&12	bedding	N19E	4	SE
430	9&12	bedding	N46E	14	SE
431	13&11	bedding	N56E	12	SE
432	13&11	bedding	N57E	16	SE
433	9	bedding	N87E	7	SE
434	12	bedding	N26W	34	NE
435	9	bedding	N64W	16	NE
436	9	bedding	N64E	29	SE
437	9	bedding	N82W	23	NE
438	13	bedding	N39W	16	NE
439	13	bedding	N46W	4	NE
440	9	bedding	N27W	8	NE
441	13	bedding	N86E	10	NW
442	9&7	bedding	N72E	24	SE
443	9&7	bedding	N64E	28	SE
444	9	bedding	N60E	21	SE
445	9	bedding	N54E	50	SE
446	9	bedding	N76E	27	SE
447	9	bedding	N74E	24	SE
448	9	bedding	N62E	32	SE
449	9	bedding	N35E	40	SE
450	9	bedding	N80E	25	SE
451	9	bedding	N35E	26	SE
452	9	bedding	N46E	25	SE
453	9	bedding	N82E	34	SE
454	9	bedding	N40E	27	SE
455	13	bedding	N52E	25	SE
456	13	bedding	N31E	16	SE
457	13	bedding	N47E	17	SE
458	13	bedding	N58E	24	SE
459	13	bedding	N34E	19	SE
460	13	bedding	N64E	22	SE
461	13	bedding	N67E	22	SE
462	13	bedding	N41E	16	SE
463	11	bedding	N54E	40	SE
464	9&7	bedding	N88E	30	SE
465	9	bedding	N47E	34	SE
466	9	bedding	N66E	33	SE
467	9	bedding	N70E	25	SE

468	9	bedding	N24W	7	SW
469	9	bedding	N5W	13	NE
470	9	bedding	N2E	9	NW
471	9	bedding	N11W	14	NE
472	9	bedding	N86E	15	SE
473	12	bedding	N47W	25	SW
474	12	bedding	N67E	10	SE
475	9	bedding	N21E	23	SE
476	12	bedding	N18E	6	SE
477	9	bedding	N54E	25	SE
478	12	bedding	N20E	17	NW
479	9	bedding	N16W	20	NE
480	9	bedding	N51E	32	SE
481	12	bedding	N78E	10	NW
482	12	bedding	N8W	11	SW
483	9	bedding	N18E	13	SE
484	10	bedding	N8W	13	SW
485	13	bedding	N56E	78	NW
486	13	bedding	N42E	61	NW
487	9	bedding	N26E	56	NW
488	9	bedding	N72E	15	NW
489	9	bedding	N23W	20	NE
490	13	bedding	N42W	21	NE
491	9	bedding	N10W	10	NE
492	9	bedding	N15E	16	SE
493	9	bedding	N6W	24	NE
494	9	bedding	N80E	19	NW
495	9	bedding	N4W	8	NE
496	13	bedding	N62E	19	NW
497	9	bedding	N41E	26	NW
498	9	bedding	N63E	14	NW
499	9	bedding	N8E	12	NW
500	9	bedding	N47W	20	NE
501	9	bedding	N84E	7	SE
502	9	bedding	N69E	14	NW
503	12	bedding	N15E	18	SE
504	12	bedding	N3W	19	SW
505	9	bedding	N46E	25	SE
506	13	bedding	N58E	9	SE
507	9	bedding	N84E	19	SE
508	9	bedding	N49E	35	SE
509	7	bedding	N36E	39	SE
510	7	bedding	N42E	23	SE
511	7	bedding	N55E	40	SE
512	7	bedding	N33E	21	SE
513	7	bedding	N38E	44	SE
514	7	bedding	N22E	38	SE
515	7	bedding	N14E	25	SE
516	7	bedding	N20E	86	SE
517	7	bedding	N34E	64	SE
518	2	bedding	N42E	54	SE
519	2	bedding	N28E	76	SE
520	9&7	bedding	N26E	28	SE
521	9	bedding	N30E	26	NW
522	9	bedding	N24E	18	NW

523	9	bedding	N26E	26	SE
524	9	bedding	N64E	9	SE
525	9	bedding	N68E	28	SE
526	7	bedding	N48E	25	SE
527	9	bedding	N55E	40	SE
528	12&9	bedding	N61W	13	NE
529	13	bedding	N6W	17	NE
530	12	bedding	N2W	11	NE
531	12	bedding	N55E	35	SE
532	9	bedding	N81E	26	NW
533	9	bedding	N61E	4	NW
534	12&9	bedding	N26E	24	SE
535	12&9	bedding	N27E	8	SE
536	9	bedding	N85E	25	SE
537	7	bedding	N20E	19	SE
537		fold axis	N63E	0.0	
538	7	cleavage	N22E	73	NW
538		bedding	N22E	17	SE
539	7	fold limb	N23E	48	SE
539		fold limb	N66E	46	NW
539		fold axis	N50E	20	
540	7	fold limb	N58E	64	SE
540		fold limb	N64E	34	NW
540		fold axis	S55W	4	
541	5	bedding	N20E	26	NW
542	13	bedding	N62E	19	SE

VITA

Milan Austin Heath II was born in Towson, MD on June 24, 1977 to Melville F. Heath II and Brigitte Michel Heath. He was raised in Baltimore, MD where he attended McDonogh School from 1983 until 1996 when he graduated. Milan attended Franklin and Marshall College in Lancaster, PA where he received his Bachelor of Arts degree in Geology in May 2000. The following fall he began work toward his Master of Science degree at the University of Tennessee, Knoxville. Milan graduated with his Master of Science degree in the summer of 2003.