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SURFACE AND SUBSURFACE STRUCTURES OF THE WESTERN VALLEY AND
RIDGE IN TENNESSEE AND GEOMETRY AND KINEMATICS THAT PERMIT
RECONSTRUCTION OF THE TENNESSEE SALIENT, SOUTHERN APPALACHIANS

A Dissertation
Presented for the
Doctor of Philosophy Degree
The University of Tennessee, Knoxville

Jennifer Kathleen Whisner
August 2010

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DEDICATION

This dissertation is dedicated to my family.

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I must first thank my advisor, Dr. Robert D. Hatcher, Jr., for his patience, support and unwavering confidence in my ability, and for teaching me when to hyphenate cross section. I would also like to thank other members of my committee, past and present: Dr. Bill Dunne, for getting me moving when I needed it most; Dr. Rick Williams for helpful discussions at opportune times; Dr. Ken Orvis for thought-provoking questions; and Dr. Greg Baker, Dr. Micah Jessup, and Dr. John Wilkerson for coming to the rescue and generously agreeing to give their time to serve on my committee. I must also thank Dr. Kay Reed, Assistant Graduate Dean at the University of Tennessee, for agreeing to allow me to finish after an extended absence.

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Last, but definitely not least, I would like to thank my family. My parents and parents-in-law waited, patiently, for us to get done, and waited, patiently, for us to get jobs, and are still waiting, patiently, for us to come back to Michigan as often as possible. Your love and support are tremendous! My sons Aaron and Zachary give me uncountable reasons

to be happy every day. I would also like to thank my husband Chris, without whom I **truly** would have been reduced to a pile of sniveling goo. Your support made this possible, and I could go on and on about how you've saved me on a daily basis, but I won't – you always know what I'm going to say anyway.

ABSTRACT

The southern and central Appalachian foreland fold-thrust belt comprises a series of orogen-scale curves that extend from Alabama to New York. One of these is the Tennessee salient, a foreland-convex curve that extends from Cartersville, Georgia, to Roanoke, Virginia. Development of a kinematic model for deformation in the salient has been hindered by a paucity of penetrative deformation in this generally low temperature, low volume-loss portion of the orogen.

Industry seismic reflection lines provide greater resolution of subsurface geometry of both the basement surface and the overlying fold-thrust belt, confirming some previous interpretations and changing others. A series of cross sections based on the seismic reflection data incorporates the improved understanding of basement geometry, as well as new interpretations of fold-thrust belt structures such as a sub-thrust detachment fold along the western margin of the Valley and Ridge, a smaller detachment fold along the Cumberland Escarpment, and a duplex below the Knoxville sheet in southeastern Tennessee.

The cross sections, combined with recently published analyses of calcite twin strain and paleomagnetic data around the salient, provide sufficient data to develop a new palinspastic reconstruction method and to propose a kinematic model for development of the salient. The basis of the reconstruction method is, in areas where the front of the indenter is oriented oblique to transport, the maximum shortening direction and particle displacement paths are also oblique to the bulk transport direction. Cross sections, kinematic indicators, and palinspastic reconstructions suggest that the Tennessee salient is a primary arc formed by a combination of uniform displacement in a single direction and transport-parallel simple shear (plane strain), that most major faults formed initially curved in front of the irregularly shaped Blue Ridge-Inner Piedmont indenter, and that transport in the fold-thrust belt may have occurred by plan view movement on networks of minor faults, which permitted forelandward propagation of the curved faults without significant rotation. Although

the technique does not provide a unique solution, the resulting palinspastic restoration is kinematically admissible and geometrically reasonable. So, it may improve palinspastic restorations of facies in basins with no vertical axis rotations and minimal penetrative strain. Attachments are in PDF format and may be opened with Adobe Reader™.

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PART 1

Introduction

The southern and central Appalachians comprises a series of orogen-scale curves that extend from Alabama to New York (Figure 1-1). This dissertation investigates the geometry and kinematic development of one of these curves, the Tennessee salient, and specifically addresses the problem of restoring deformation in a curved orogen. Results from this investigation yield insights into the development of the salient on a variety of scales, from outcrop to orogen.

Curved orogens present a problem to construction of balanced 2D cross-sections, a commonly used method of structural analysis. Rocks in curved orogens often move not only perpendicular to the trends of major structures (generally assumed for balanced cross-section construction), but also oblique to this assumed direction of transport. This calls into question the validity of structural conclusions drawn from traditional cross-section construction and restoration methods used in curved orogens, and makes palinspastic reconstruction of the pre-deformation orogen difficult. While the original purpose of the dissertation was to develop a true 3D model for deformation in a curved fold-thrust belt, a new 2D method for reconstructing the salient addresses many of the problems the 3D model was intended to address.

The Tennessee salient is foreland-convex curve that extends from Cartersville, Georgia, to Roanoke, Virginia. Major factors contributing to the shape of the salient and location include its position in an embayment along the rifted Laurentian margin, the presence of a thick accumulation of passive margin and clastic wedge sediments, and the geometry of the indenting Blue Ridge-Inner Piedmont composite crystalline thrust sheet (Thomas, 1977, 2006; Hatcher, 1989; Macedo and Marshak, 1999; Hnat, 2009). Although structure at the ground surface is geometrically well delimited by high quality geologic mapping, the salient is not as well kinematically delimited, because of a paucity of penetrative deformation in this generally low temperature, low volume-loss portion of the orogen. This study combines new and published geometric, lithostratigraphic, kinematic and seismic reflection data to provide a new perspective on the evolution of the Tennessee salient

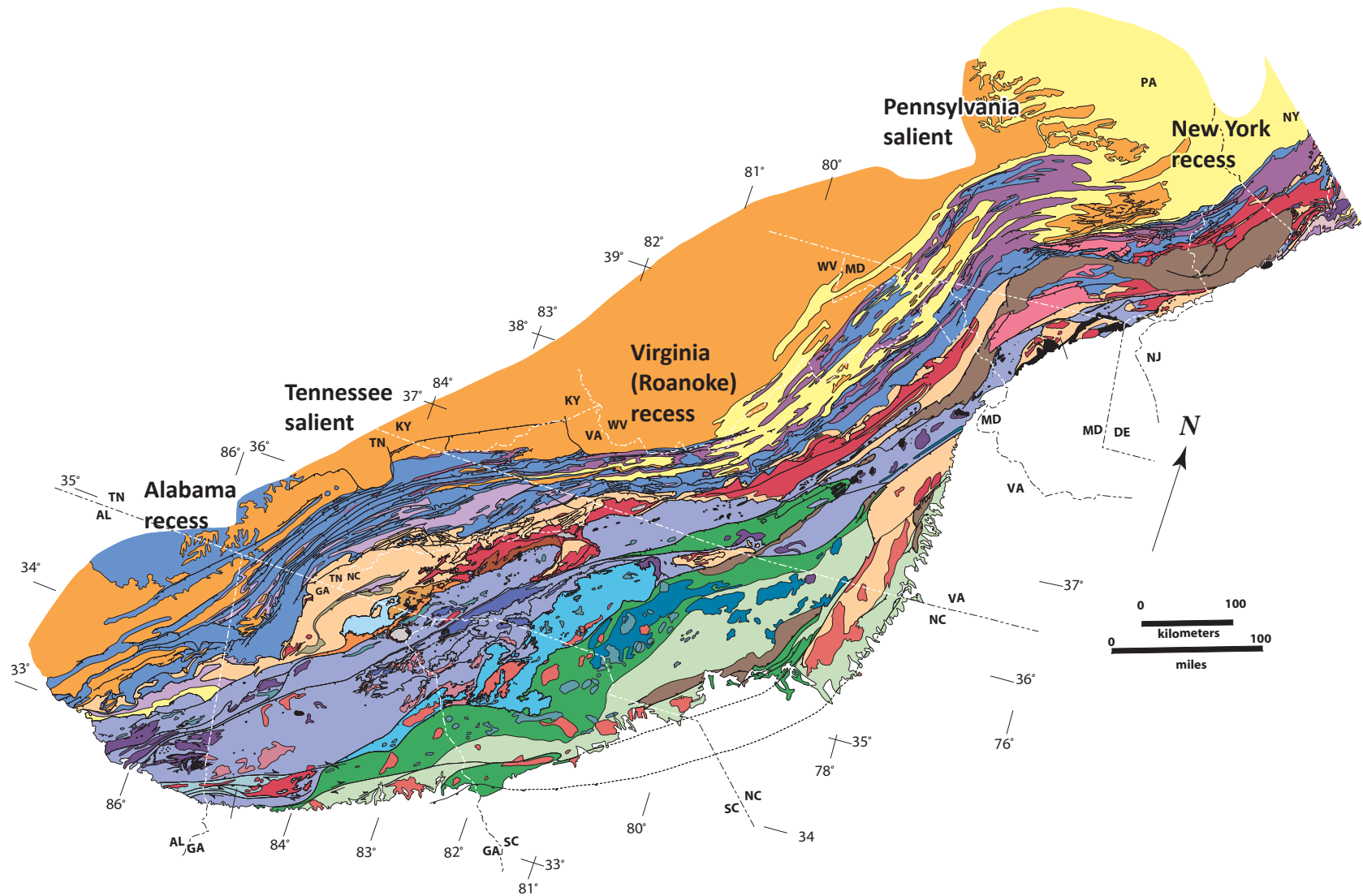


Figure 1-1. Tectonic map showing the structural grain of the southern and central Appalachians and locations of salients and recesses (after Hatcher et al., 2007).

OUTLINE OF DISSERTATION

Part 1 provides an overview of the contents of the dissertation.

Part 2, published as Whisner and Hatcher (2003) in the *Oil and Gas Journal* describes a previously unrecognized sub-thrust detachment fold and potential hydrocarbon play along the western edge of the Valley and Ridge in East Tennessee. This section provides an introduction to the stratigraphy and structural style of the salient, as well as to structures derived from interpretation of industry seismic reflection data.

Part 3 provides a synopsis of a Geological Society of America poster describing deformation in the core of a Type II triangle zone (Couzens and Wiltchko, 1996) observed in an outcrop along the western side of the Valley and Ridge in the Tennessee salient. The Pennsylvanian rocks in a railroad cut near Rockwood, Tennessee, may be a small-scale analogue for deformation in the Eureka structure described in Part II (unresolvable on available seismic reflection lines) and are a microcosm of the intense deformation that can occur in triangle zones along the outer margins of fold-thrust belts. This poster will be transformed into a paper after the defense and will likely be submitted to the *Journal of Structural Geology*.

Part 4, published as Hatcher, Lemiszki, and Whisner (2007) in Geological Society of America Special Paper 433, provides an overview of the intrinsic (ex: lithology, fluids, geometry of basin and indenter) and extrinsic (ex: burial depth, temperature, strain rate) variables that provided the sometimes temporally changing boundary conditions for deformation in the salient. It discusses in detail the geometry and influence of the basement surface on sediment deposition and subsequent deformation, as well as the difficulties inherent in restoring rocks subjected to heterogeneous strain in a curved orogen.

Part 6 is to be submitted to *Geosphere*. Industry regional seismic reflection line data donated to Prof. Robert D. Hatcher, Jr. at the University of Tennessee, Knoxville; collected and compiled data on shortening directions; and regional calcite twin strain and

paleomagnetism data published by Hnat et al., (2008), Hnat (2009), and Hnat et al. (2009) are the basis for a new synthesis of the development of the southern Appalachian fold-thrust belt.

Geologists have been wrestling with restoring deformed rocks in the Appalachians for more than 100 years (cf. Hayes, 1891) (Figure 1-2). Geologists' recent understanding of fold-thrust belt development in the salient is represented by two sets of serial cross sections (Roeder et al., 1978; Woodward, 1985) and the palinspastic restoration of Roeder and Witherspoon (1978). The cross sections were based primarily on surface data collected during multiple generations of geologic mapping, with little to no seismic reflection data to delimit subsurface thrust or basement geometries. The cross sections of Roeder et al. (1978) incorrectly depict polyphase deformation along the eastern side of the fold-thrust belt, with later pulses accommodated in part by development of additional late thrusts, which broke through from the basal detachment to the surface (Fig. 1-3). The cross sections presented in Woodward (1985) (Fig. 1-4) assumed in-sequence deformation (Woodward and Beets, 1988). These cross sections are admissible (in agreement with all geologic data available at that time) and viable (restorable to a geologically reasonable undeformed state) (Elliott, 1983), but are not everywhere serially compatible. Neither compilation explained the kinematic details of the deformation illustrated in cross sections, although Roeder and Witherspoon (1978) explicitly restored at least the most northwesterly thrust sheets "along radially converging lines to the southeast," acknowledging use of a radial thrusting kinematic model for at least part of the salient. This model cannot be used for highly curved or high-displacement orogens, e.g., the southern Appalachians, because restored cross sections intersect in the hinterland.

Hnat (2009) suggested that the Tennessee salient developed without rotation in a fanned stress field via displacement gradients accommodated by cataclastic flow (Ismat and Mitra, 2004), based on calcite twin strain data and the lack of rotation recorded by remagnetized rock units. This model is most similar to transport-parallel simple shear.

This section integrates new structural interpretations that arise from seismic images of the subsurface into a new set of serially compatible cross sections, and develops a

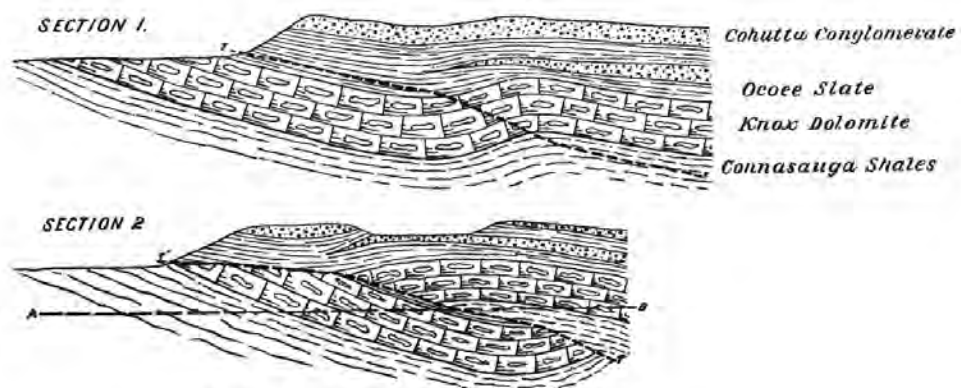
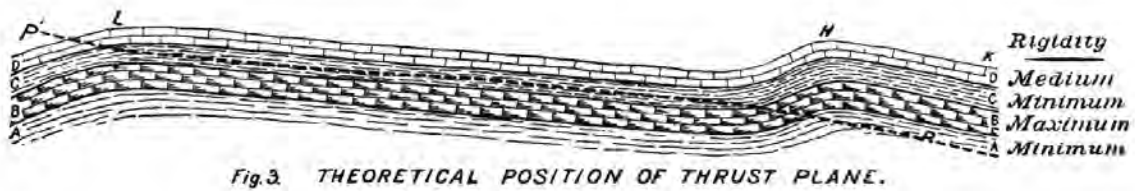
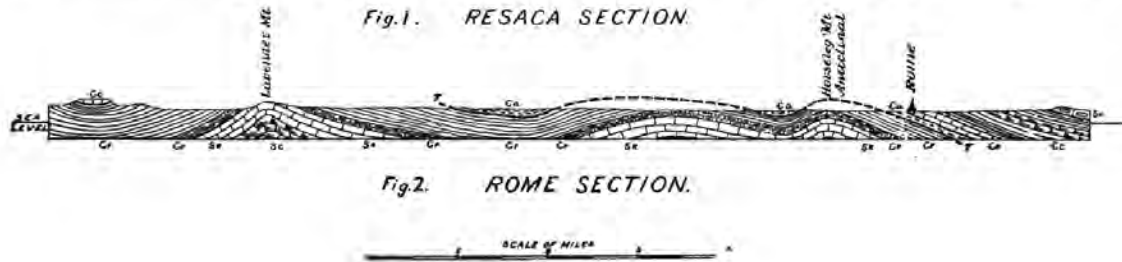
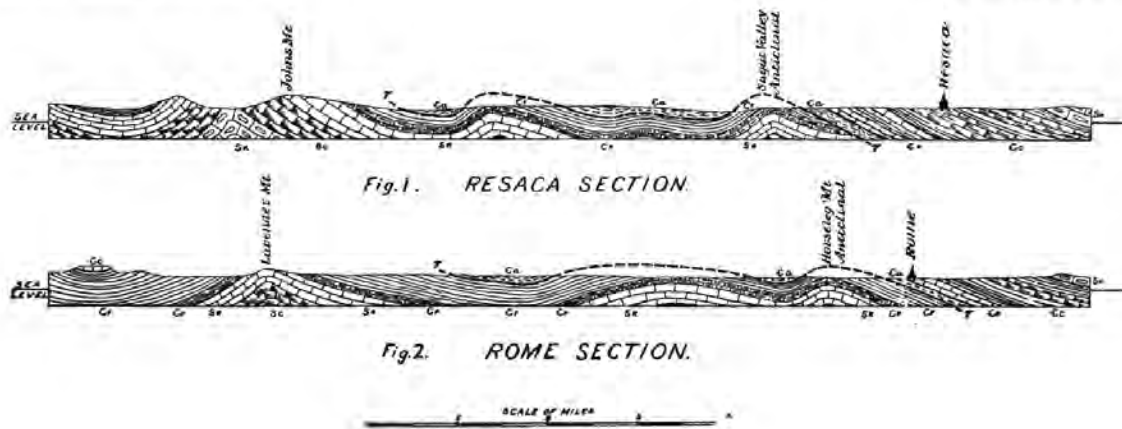


Fig. 4. HOLLY CREEK SECTION—1 DEAL= (1) before (2) after horizontal thrust.

Figure 1-2. Earliest known attempt to restore deformed Appalachian rocks (from Hayes, 1891).

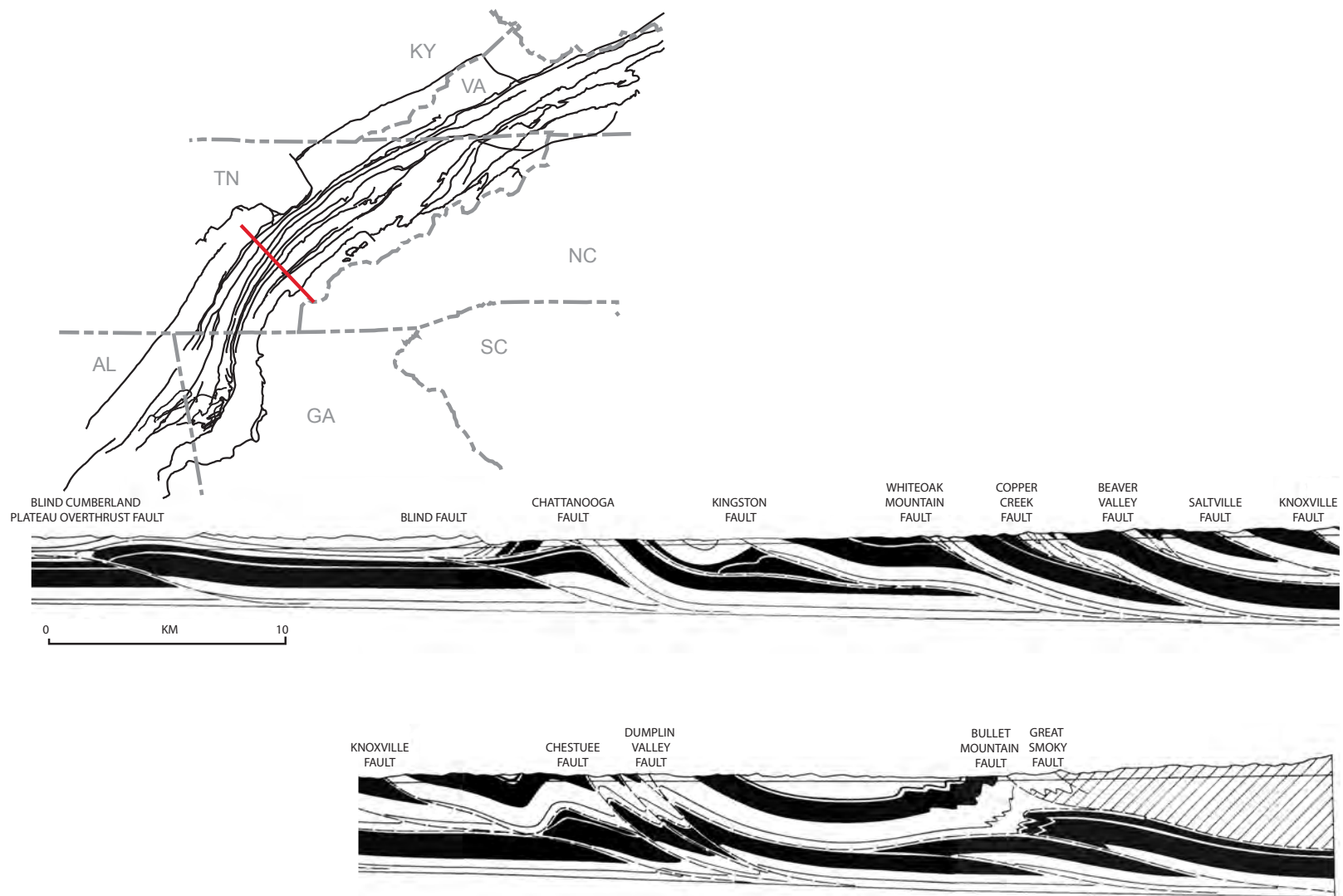


Figure 1-3. Sample cross section from Roeder et al. (1978) showing polyphase deformation. Approximate location shown with red line.

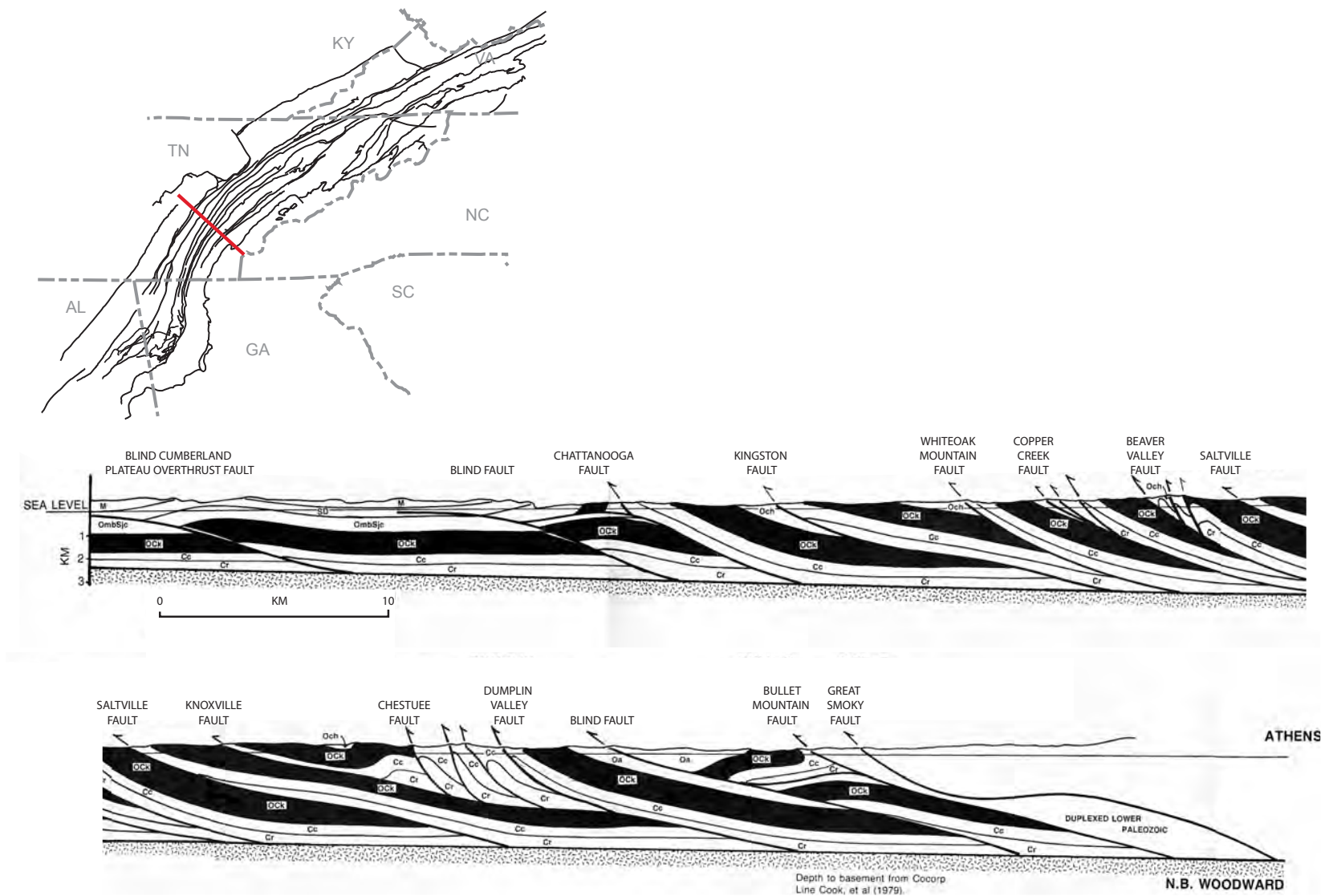


Figure 1-4. Sample cross section from Woodward (1985). Approximate location shown with red line.

kinematically admissible model for deformation of the Tennessee salient. In addition, it applies a new method for palinspastic reconstruction to the serial cross sections, resulting in a model of the pre-Alleghanian configuration of the fold-thrust belt units and an estimate of displacement on the Blue Ridge-Inner Piedmont indenter.

Part 6 summarizes the conclusions of the dissertation research.

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PART 2

Detachment folds and triangle zones along the Eastern Cumberland Escarpment, Tennessee

This chapter was published in the *Oil and Gas Journal*. The full citation of the paper is:

Whisner, J. B., and Hatcher, R. D., Jr., 2003, Detachment folds and triangle zones; unexplored hydrocarbon potential along eastern Cumberland Escarpment, Tenn: *Oil and Gas Journal*, v. 101, p. 38-44.

As primary author, my contributions included data collection and compilation, most of the writing, and figure construction.

ABSTRACT

An 80 km-long unexplored subsurface detachment fold exists in the southern Appalachian thrust belt just east of the Cumberland Escarpment in eastern Tennessee. The Eureka structure involves Ordovician and older rocks that are productive elsewhere in eastern Tennessee, Kentucky, Ohio, and Virginia, and here lie within the oil-gas window. The eastern Cumberland Plateau Escarpment rises 400 to 600 m at the western boundary of the Valley and Ridge in eastern Tennessee. Isolated oil and gas wells and industry seismic reflection lines provide subsurface geologic data and resolution of structural geometry beneath the Escarpment. Seismic lines reveal a deep 80 km-long detachment fold just east of the Escarpment in the Chattanooga fault footwall. This major untested structure is located well inside the oil-gas window and contains known (Knox and Middle Ordovician) oil and gas-producing units.

Deformation in thickened units in the Eureka structure varies along strike from development of a triangle zone and splaying off the basal detachment to sub-seismic scale complex folding and faulting. Above the detachment fold, the Chattanooga, Harriman, Rockwood, and Cranmore Cove faults dismembered a single thrust sheet in a foreland-to-hinterland deformation sequence. The thrust sheet evolved with three major detachment

levels: (1) Rome formation; (2) Silurian siltstones and shales; and (3) Upper Mississippian and Pennsylvanian rocks, the latter extending westward under the Plateau as a blind thrust.

Between the blind thrust and overlying Rockwood and Cranmore Cove faults, Mississippian and Pennsylvanian rocks are substantially deformed in an exposed shallow detachment fold near Rockwood, Tennessee, and Pennsylvanian rocks develop faults dipping toward both the foreland and hinterland. The shallow detachment fold is an exhumed analog for the deep detachment fold, which is possibly the largest unexplored structure in the Appalachian region.

INTRODUCTION

The collision of Africa with Laurentia stacked sheets of Early Cambrian to Pennsylvanian rocks along the eastern margin of North America during the Mississippian-Permian Alleghanian orogeny, (Rodgers, 1970; Roeder et al, 1978; Hatcher, et al., 1989) forming the Appalachian foreland fold- thrust belt.

The eroded remains of the fold-thrust belt today comprise the Appalachian Valley and Ridge and Cumberland/Alleghany Plateau (Fig. 2-1). As much as 50% shortening across the fold-thrust belt in East Tennessee is concentrated along a few major thrust faults (Hatcher et al, 1989) (Fig. 2-1).

Numerous structural studies (Rich, 1934; Rodgers, 1953; Rodgers, 1970; Harris and Milici, 1977; Woodward, 1985) and decades of detailed geologic mapping (Hardeman, 1966) have characterized the surface and subsurface geometry in the fold-thrust belt in East Tennessee. Much of the geology and structure along the eastern Cumberland Plateau Escarpment in Tennessee was resolved in the 1960s and 1970s (Swingle, 1960; Milici and Leamon, 1975; Milici, 1996) (Fig. 2-2).

Previous subsurface analysis along the Escarpment relied on isolated oil and gas wells and occasional coal tests (Milici, 1996). Additional wells, along with industry seismic

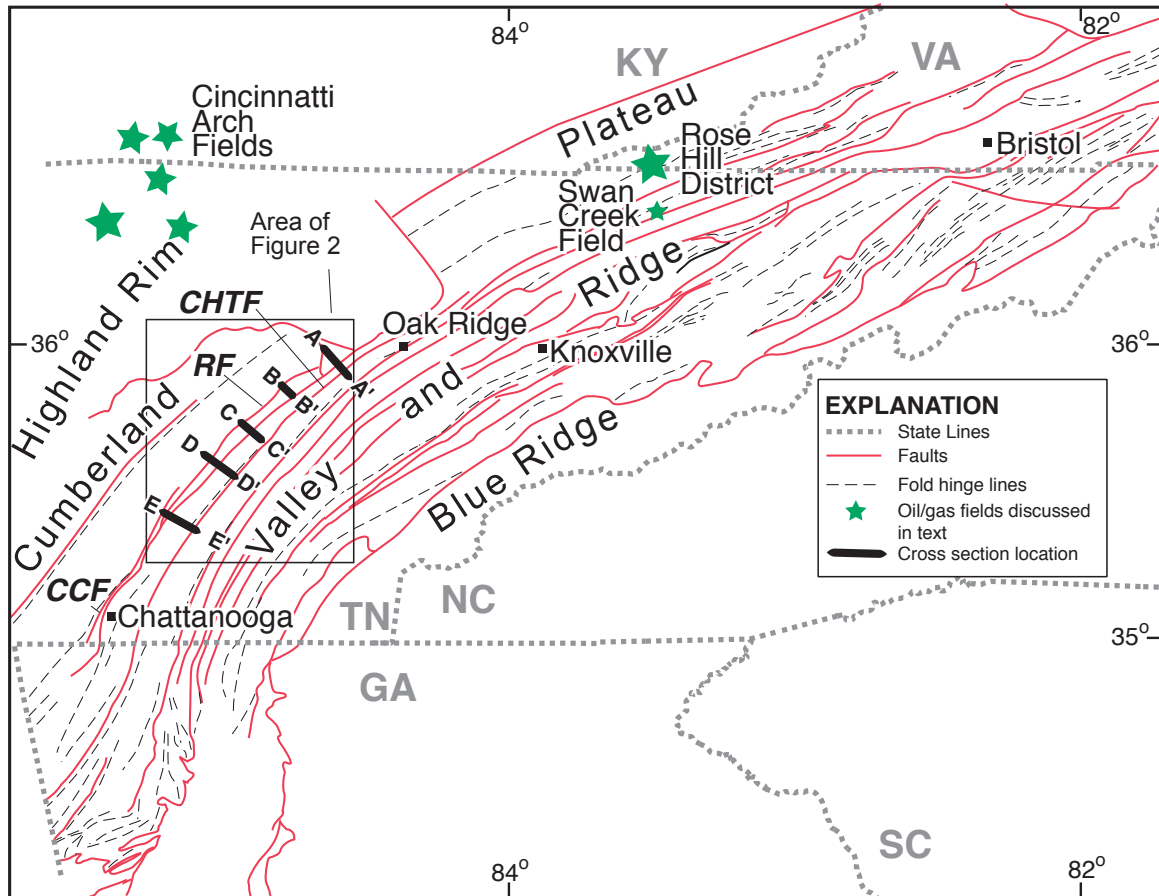


Figure 2-1. Cross section lines and traces of major faults and folds, after Hardeman, (1966).

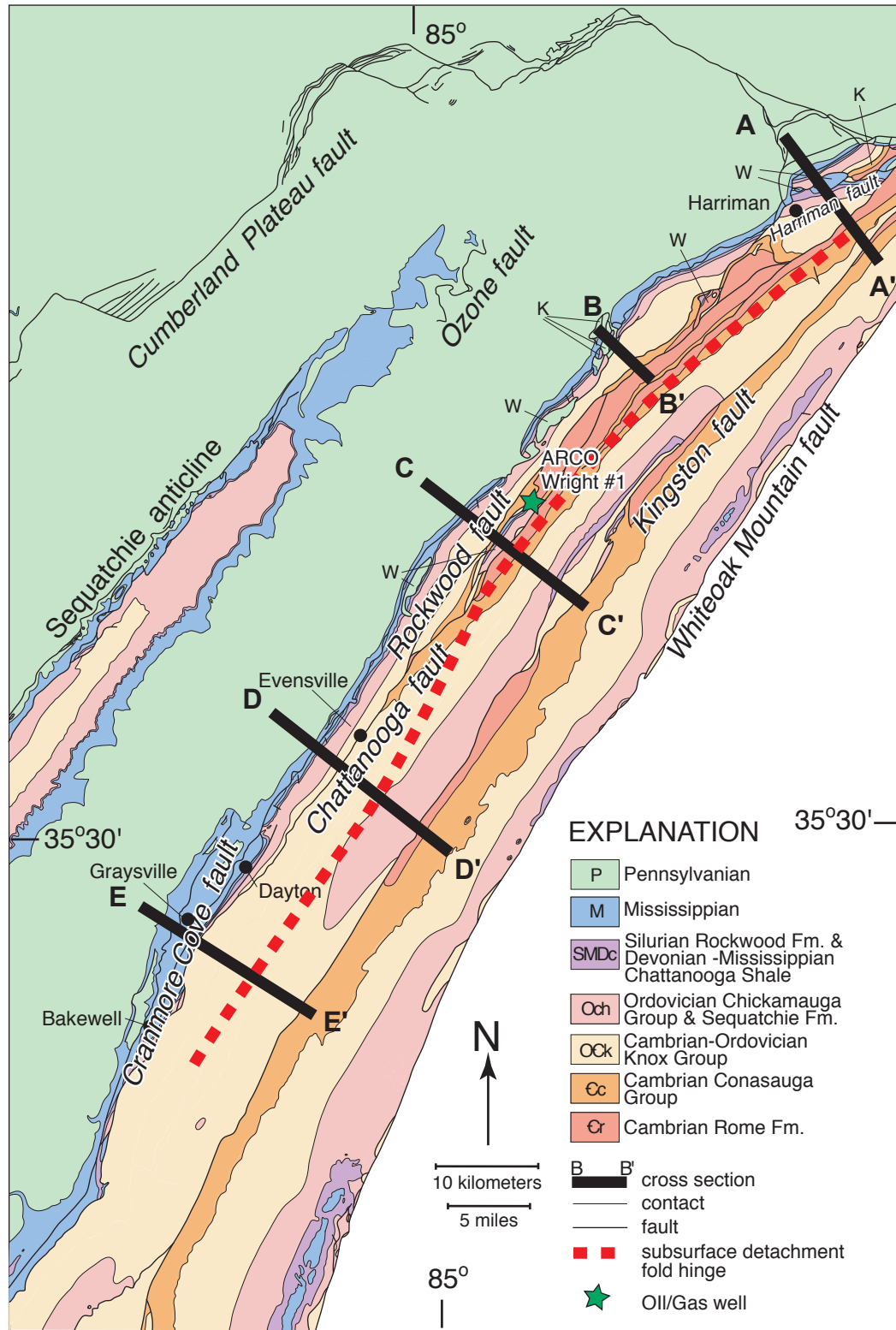


Figure 2-2. Geologic map of the eastern Cumberland escarpment with cross section locations, after Hardeman (1966).

reflection data, permit more robust interpretation of subsurface structure and identification of the Eureka structure.

STRATIGRAPHY

The stratigraphy of the Valley and Ridge in East Tennessee consists of alternating weak and strong units above the Rome formation master décollement, which rests on largely undeformed basement (Fig. 2-3). Above the weak Rome formation lies the Conasauga Group (mostly shale to the west). Where the Rome locally becomes either too thin or too strong, the Conasauga is the basal weak detachment layer and the oldest unit exposed along thrust faults (Rodgers, 1953; Swingle, 1960). At the top of the Conasauga is the Maynardville limestone that, together with the massive (up to 900 m) Knox Group carbonates and the western facies of Middle-Upper Ordovician limestones, make up the 1,600-m-thick strong unit in the section.

The Middle Ordovician regional unconformity separates the Knox Group from the overlying Chickamauga Group, in which weak units sometimes act as a middle detachment horizon between the lower Rome/Conasauga and potential upper Devonian-Mississippian Chattanooga shale, Mississippian Pennington, and Pennsylvanian detachment zones.

The Chattanooga shale unconformably overlies Ordovician to Silurian rocks throughout much of East Tennessee. The Chattanooga shale is a source of oil and gas here, and its correlatives to the northeast (the “Devonian shale”) source major plays in the Appalachian basin (Milici, 1996). Mississippian rocks along the Escarpment grade upward from carbonates and shales to dominantly clastics, and the Fort Payne formation and Newman limestone (“Big Lime”) are common oil and gas reservoirs in the Cumberland Plateau. The overlying Pennsylvanian deltaic sandstones, shale, and coal are deformed only in the western portions of the fold-thrust belt in East Tennessee.

FOLD-THRUST BELT STRUCTURE

The Alleghanian fold-thrust belt in East Tennessee consists of up to 12 imbricate thrust sheets with displacements ranging from a few to over 100 km. Both the number of faults and fault displacement decrease to the northeast into Virginia and southwest into Georgia and Alabama (Fig. 2-1). Deformation style varies both along and across the fold belt, with folding dominating at the surface in the eastern belts, in contrast with closely spaced imbricate faulting to the west (Rodgers, 1953; Hardeman, 1966; Harris and Milici, 1977) and increased folding again in northwest Georgia and southwest Virginia (Fig. 2-1).

Along the eastern Cumberland Escarpment, the Chattanooga fault lies above relatively shallow locally folded faults (Rockwood, Harriman, Cranmore Cove) (Fig. 2-2). Previous work suggested that the Rockwood-Chattanooga fault system was originally similar to the Pine Mountain block: a single thrust sheet with two major detachment levels and fault-related folding (Swingle, 1960). This idea was refined by adding the Cranmore Cove sheet to the Rockwood-Chattanooga system, and suggesting that the original thrust sheet had three detachment zones: the Rome formation, Silurian to Lower Mississippian shaly units, and upper Mississippian/lower Pennsylvanian weak units (Milici and Leamon, 1975; Milici, 1979) (Figs. 2-3 and 2-4).

Fig. 2-4a shows an earlier interpretation of structural development along the Escarpment (Milici, 1979). First, the middle décollement was deflected into a higher zone by a blind thrust cutting from the basal Cambrian detachment into the Chickamauga Group. Then translation up the upper ramp created a short wavelength ramp anticline in Pennsylvanian and Mississippian rocks along the Escarpment. Fault lockup at this anticline forced additional movement to be accommodated by splays that developed in a foreland-to-hinterland sequence (Fig. 2-4a).

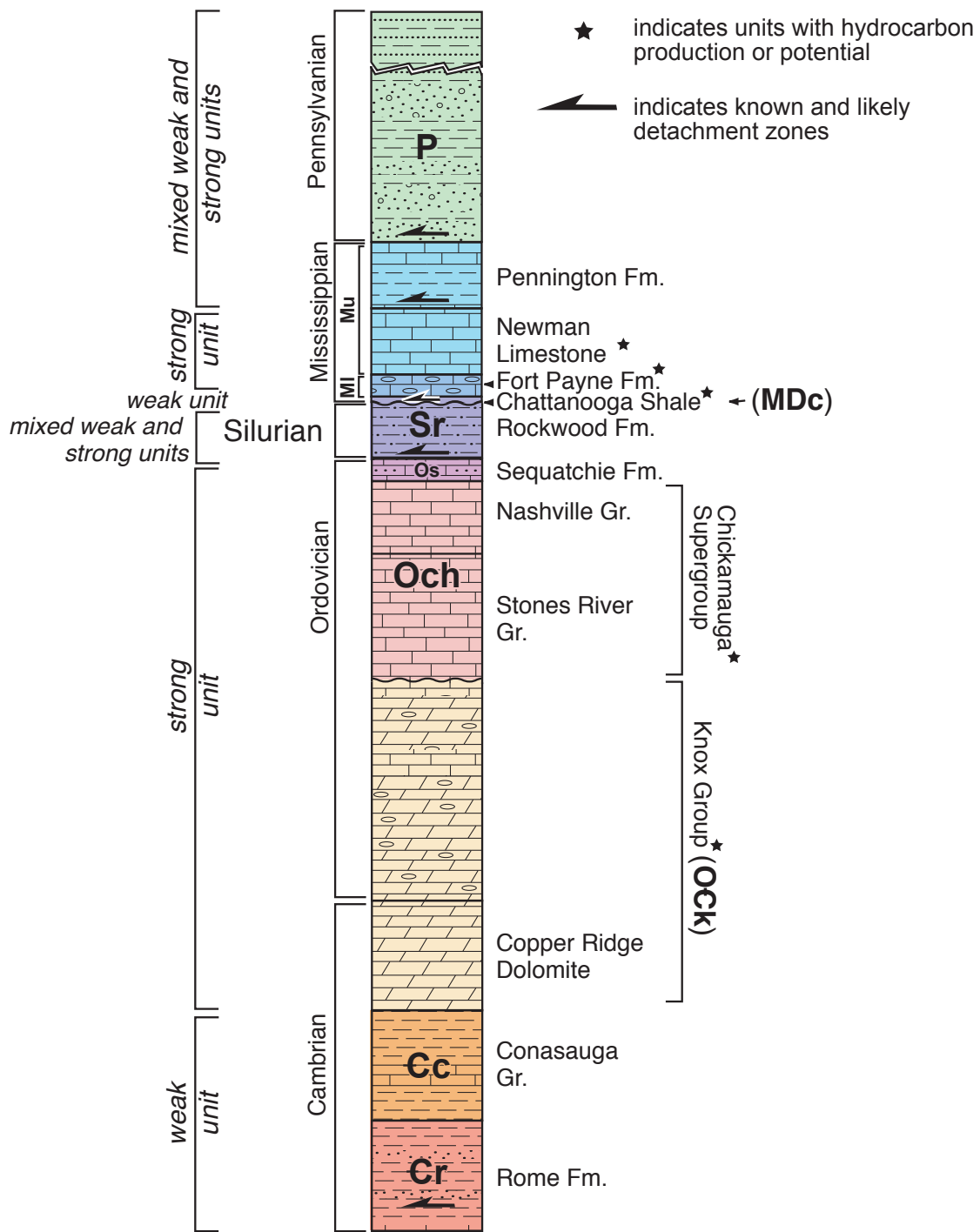
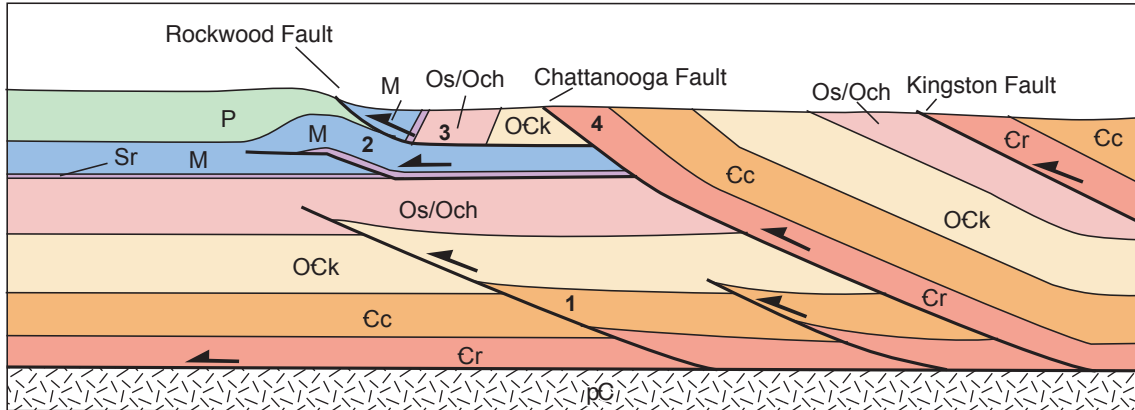


Figure 2-3. Generalized stratigraphy for the eastern Cumberland Escarpment area.

a) Modified from Milici, 1979



b) New interpretation

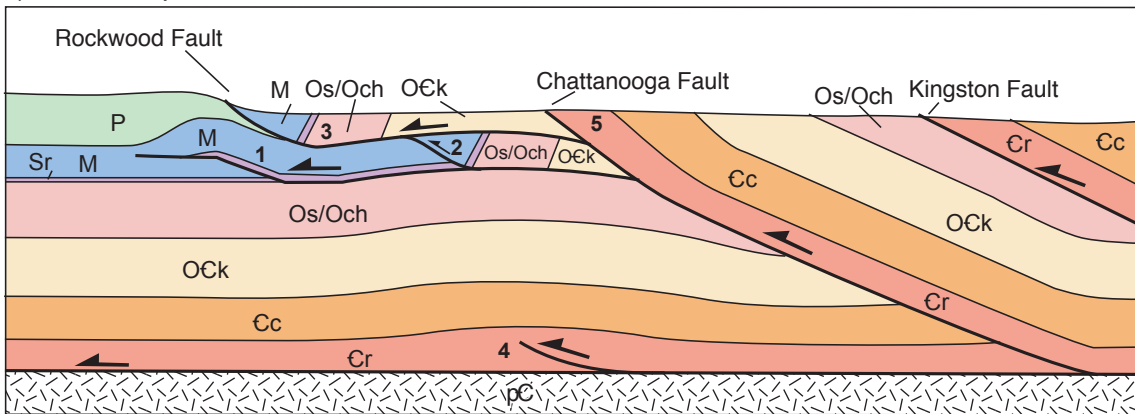


Figure 2-4. Diagram showing generalized structure and order of fault development along the eastern Cumberland Escarpment, Tennessee. a) Modified from Milici (1979). b) Proposed by the authors.

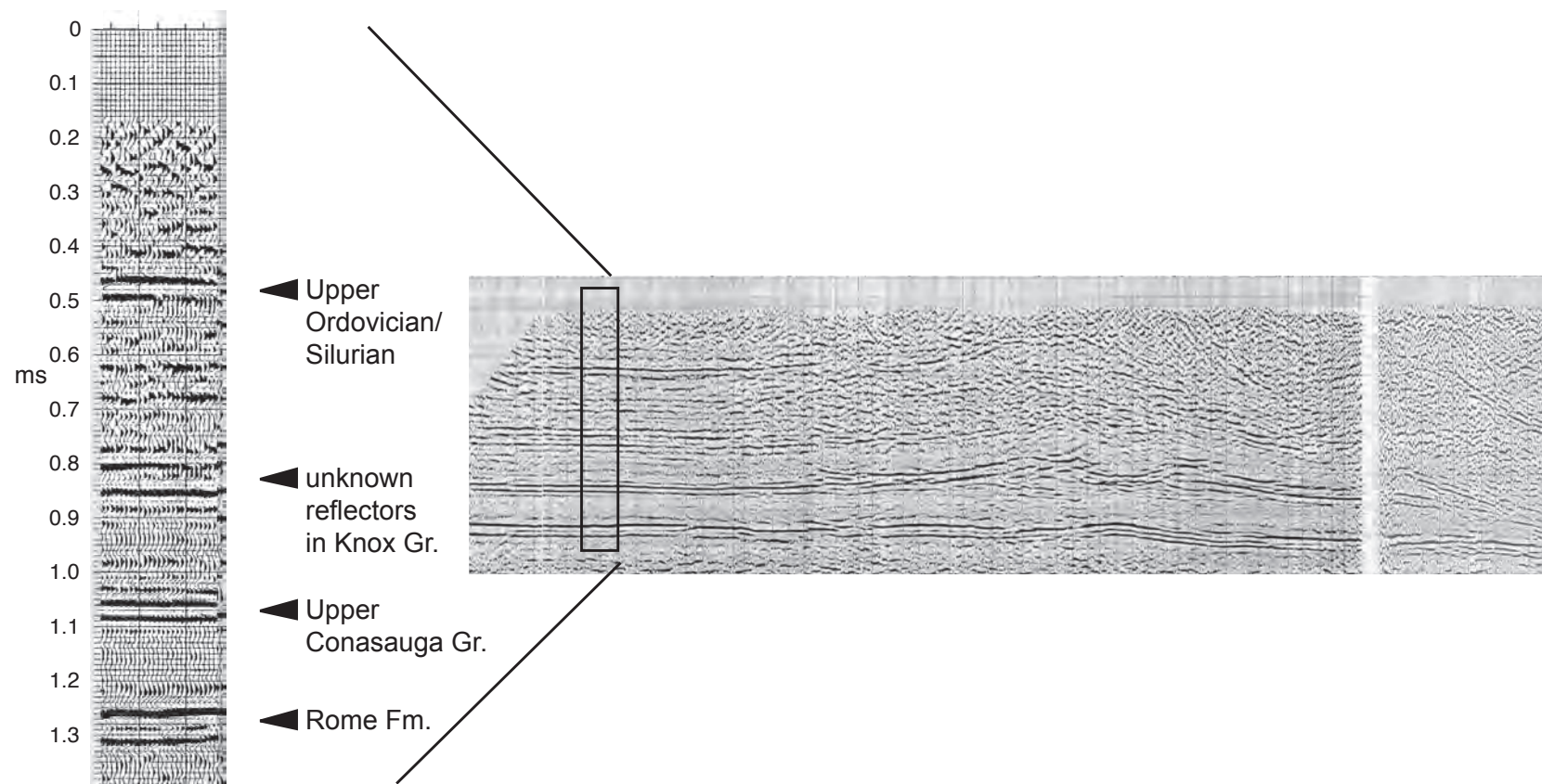


Figure 2-5. Sample seismic reflection data with major reflector packages.

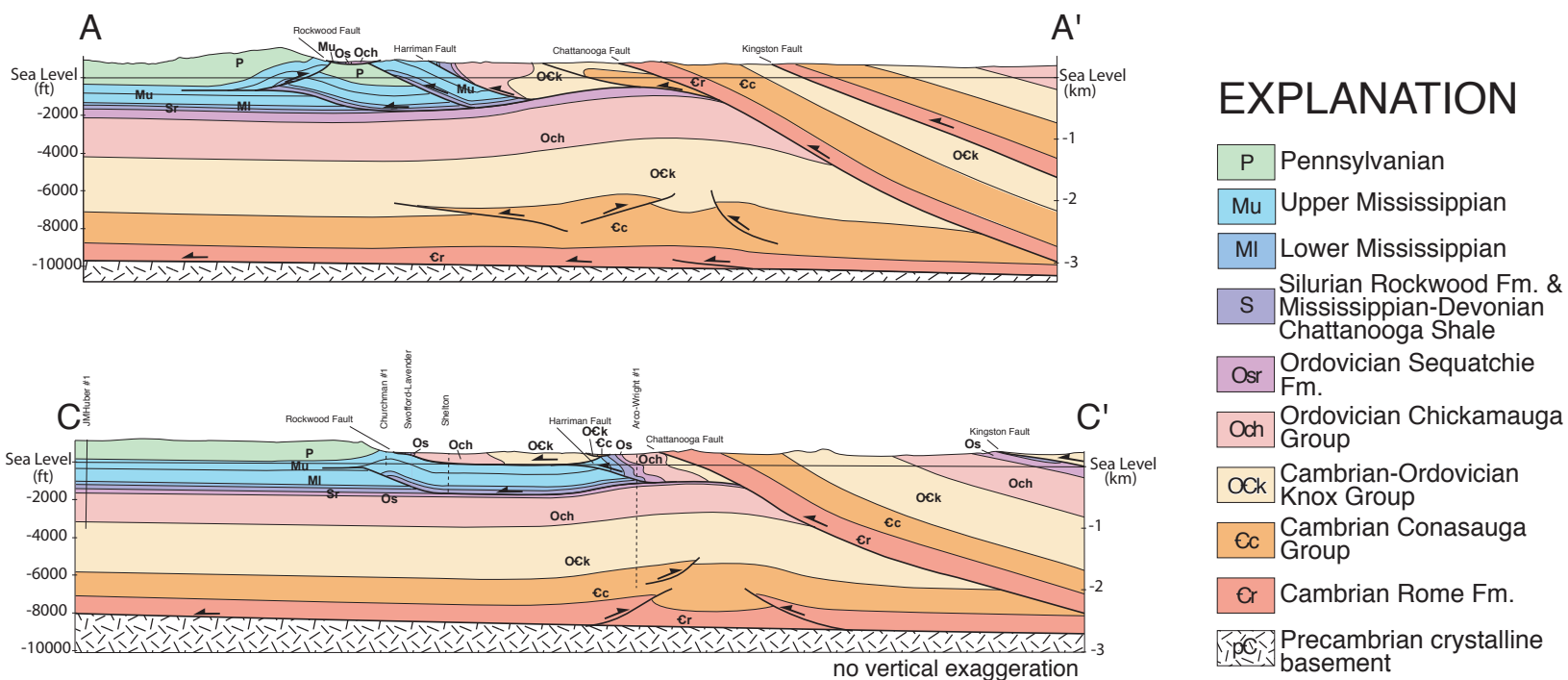


Figure 2-6. Cross sections A-A' and C-C' across the eastern Cumberland Escarpment.

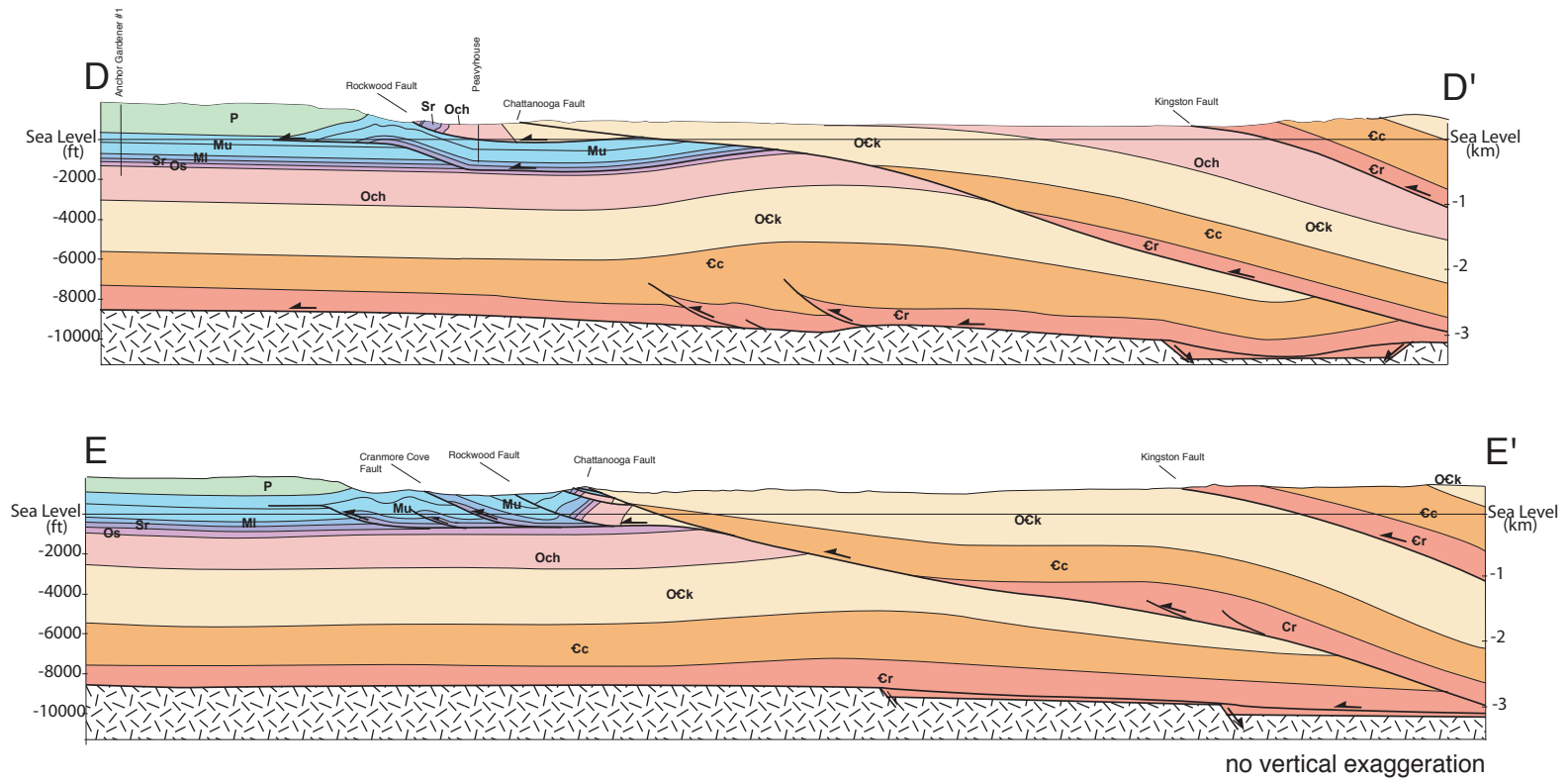


Figure 2-7. Cross sections D-D' and E-E' across the eastern Cumberland Escarpment. Explanation is the same as Figure 2-6.

INTERPRETATION

Cross sections A-A', D-D', and E-E' are based on processed industry seismic lines (Fig. 2-5) in addition to surface and well data (Figs. 2-2, 2-6, and 2-7). Lines B-B' and C-C' were constructed using surface geologic map data and well data from the Tennessee Division of Geology oil and gas well database (Faust, 1998).

In our cross sections, faults propagated as single thrust sheet with detachment levels in the Rome formation, Rockwood formation/Chattanooga shale, and Pennington formation, though the upper detachment steps down to the SW through a lateral ramp from Mississippian to Silurian rocks near Dayton, Tennessee.

Movement on the detachment folded the Pennsylvanian rocks of the Escarpment into a ramp anticline above a blind thrust that tipped out in Mississippian/lower Pennsylvanian units. With additional shortening, several faults broke through the original thrust sheet in a foreland-to-hinterland sequence, creating imbricates and horses comprised of various parts of the lower ramp anticline (Fig. 2-4b), consistent with the conclusions of earlier work (Milici and Leamon, 1975; Milici, 1979). Our new cross sections, however, also differ significantly from previous sections. The Chattanooga fault near Harriman, Tennessee, follows a continuous ramp from the surface to the basal detachment, rather than being cut off at shallow depth by the Kingston fault (Fig. 2-6, Sec. A-A'), so Plateau rocks with hydrocarbon potential do not extend as far under the Valley and Ridge as previously suggested (Swingle, 1960; Milici, 1979; Woodward, 1985). There is no blind thrust from the Rome to the Chickamauga that deflects the sole thrust into an upper Mississippian detachment beneath the Cumberland Escarpment anticline (contrast Fig. 2-4a and Fig. 2-4b). A third shallow thrust sheet (Harriman sheet), exposed in windows through splays in the Chattanooga fault footwall, extends from Harriman to Spring City, Tennessee (Figs. 2-2, 2-6, and 2-7). And finally, a detachment fold in the footwall of the Chattanooga fault, discussed below, postdates

formation of the original thrust sheet and bows up both footwall and hanging wall units/structures.

EUREKA DETACHMENT FOLD

Many published cross sections (Roeder et al., 1978, Woodward, 1985) limit footwall deformation in East Tennessee to shallow map-scale synclines above the Knox strong unit. Lack of seismic and well data to constrain subsurface geometry, the small amount (<10%) of internal strain in thrust sheets (Lutz, 1987), and widespread application of structural development models not requiring footwall deformation suggested that brittle failure, bulk transport, and hanging-wall deformation dominate fold-thrust belt deformation.

Seismic reflection data, however, suggest footwall deformation may be more extensive than previously thought. A fractured subthrust anticline, cored by a “mushwad”(Thomas, 2001; Tavernier 2001) or by duplexes of Cambrian shales and carbonates, (Hatcher et al., 2001) comprises the structural framework for Swan Creek field in northeastern Tennessee (Fig. 2-1), and exploration below the easternmost Middle Ordovician synclinerium in East Tennessee also suggests structural complexity near the basal detachment (Hatcher et al, 2001).

Interpretation of industry seismic lines and well data suggests that Rome-Conasauga thickness increases in the Chattanooga fault footwall, folding the rocks above it in a long wavelength-low amplitude detachment fold that is traceable some 80 km from Harriman to Graysville, Tennessee (Fig. 2-2).

Deformation style changes along the length of the fold from disharmonic folding at the south end, to splaying, to development of a triangle zone to the north. In section A-A' (Fig. 2-6), the structure facilitating thickening of the sub-Knox Cambrian units is a triangle zone.

Classic Type I triangle zones (Couzens and Wiltchko, 1996) formed in the cores of folds in the central Appalachian Plateau, where blind faults dipping toward both the

hinterland and foreland rise from Upper Silurian evaporite and shale into the cores of detachment anticlines (Gwinn, 1964; Schumaker et al., 1985) (Fig. 2-8).

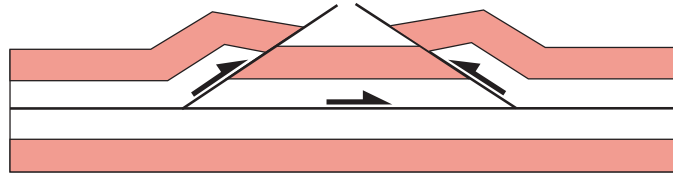
The Eureka structure beneath the Chattanooga thrust along Conasauga Group, and in Section A-A' consists of hinterland and foreland-dipping faults in the core of the detachment fold above a single, basal detachment layer, a Type I triangle zone. Both Type I and Type II (Canadian Rockies Foothills) triangle zones have been identified in the southern and central Appalachians (Wilson and Schumaker, 1992; Couzens and Wiltschko, 1996; Hatcher and Whisner, 1998).

Approximately 40 km north-northeast of section A-A', the ARCO/Oxy No. 1 well was drilled to basement in the Chattanooga fault footwall (Fig. 2-1). Shallow faults (less than 1 km depth) identified in the well log and in several industry seismic lines occur in units and at depths very close to those interpreted in section A-A'. No faults were identified in the Rome or Conasauga, however, and lower unit thicknesses in the ARCO/Oxy No. 1 well were similar to the undeformed thicknesses of these units in seismic reflection lines farther south-east. Between sections A-A' and D-D', faulting in the triangle zone diminishes as displacement on the northwest-dipping splay goes to zero and southeast-dipping thrusts become dominant (Fig. 2-6 and Fig. 2-7). Farther southwest at line E-E', obvious splays off the basal detachment have disappeared, leaving only the increasing thickness of Cambrian units.

Unfortunately, small-scale internal deformation is not resolved in the seismic reflection data. Therefore, in lines D-D' and E-E', the internal deformation of the Eureka detachment fold is inferred from: (1) deformation of exposed Cambrian units, and (2) deformation of units with similar mechanical properties in an analogous structure in Pennsylvanian rocks in the Rockwood fault footwall (discussed below).

The Rome formation and Conasauga Group are commonly depicted in regional cross sections as gently dipping uniform thickness panels at the base of thrust sheets. In many

a) Schematic diagram (after McClay, 1992)



b) Example Type I triangle zone (after Gwinn, 1964)

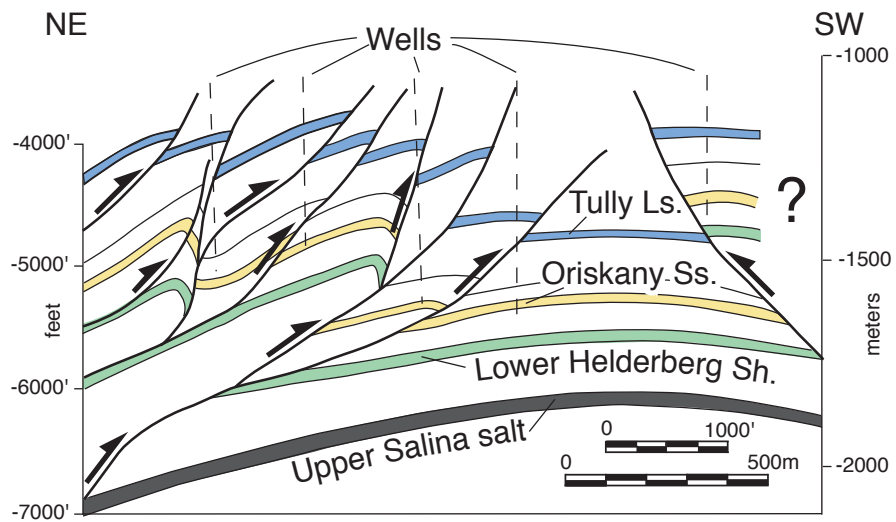


Figure 2-8. Type I Triangle zones. a) Schematic diagram of a Type I triangle zone (after McClay, 1992). b) Example Type I triangle zone in the Central Appalachian Plateau (after Gwinn, 1964).

locations, however, these units display complex outcrop- to map-scale folding and faulting (Hardeman, 1966; Woodward, 1985).

This scale of faulting must be present in section D-D', where splays off the basal detachment cut up into the Conasauga Group, and in section E-E', where no splays are revealed in the seismic reflection data (Fig. 2-6) because fault displacements are too small to account for all the thickening in the core of the detachment fold. The seismic lines, however, do not reveal substantial thickening or faulting in the Knox; instead the Knox is gently buckled above the thickened units below.

SHALLOW DETACHMENT FOLD STRUCTURE

A possible outcrop- to map-scale analogue for the Eureka sub-Chattanooga detachment fold exists in Pennsylvanian Plateau rocks in the Rockwood fault footwall (a shallow footwall splay of the Chattanooga fault) (Fig. 2-9). Highly deformed sandstone, coal and shale occur in the core of a tight anticline beneath the Rockwood fault and are well exposed in a railroad cut near Rockwood, Tennessee (Swingle, 1960; Milici, 1996) (Fig. 2-10).

Lithology in the Rockwood exposure mimics that of the subsurface detachment fold, in which a competent unit was thrust over interbedded incompetent and competent units and tightened into a detachment fold (Figs. 2-6, 2-7, and 2-10), though on a scale of meters to tens of meters. Intense deformation in the interior of the shallow detachment fold is manifested in both west-northwest- and east-southeast-dipping thrusts, folds that are asymmetric in both directions, noncylindrical folds, crenulated shale, fanning of and movement on preexisting fractures in sandstone, and high vitrinite reflectance in impure coal.

Fold style varies with both lithology and bed thickness. Thin- to medium- bedded sandstones form short wave- length tight and noncylindrical folds, while massive (>1 m) beds form open, long-wavelength folds. Both west-northwest- and east-southeast-directed thrust faults broke over-tightened folds (Fig. 2-10a). At the east end of the outcrop,

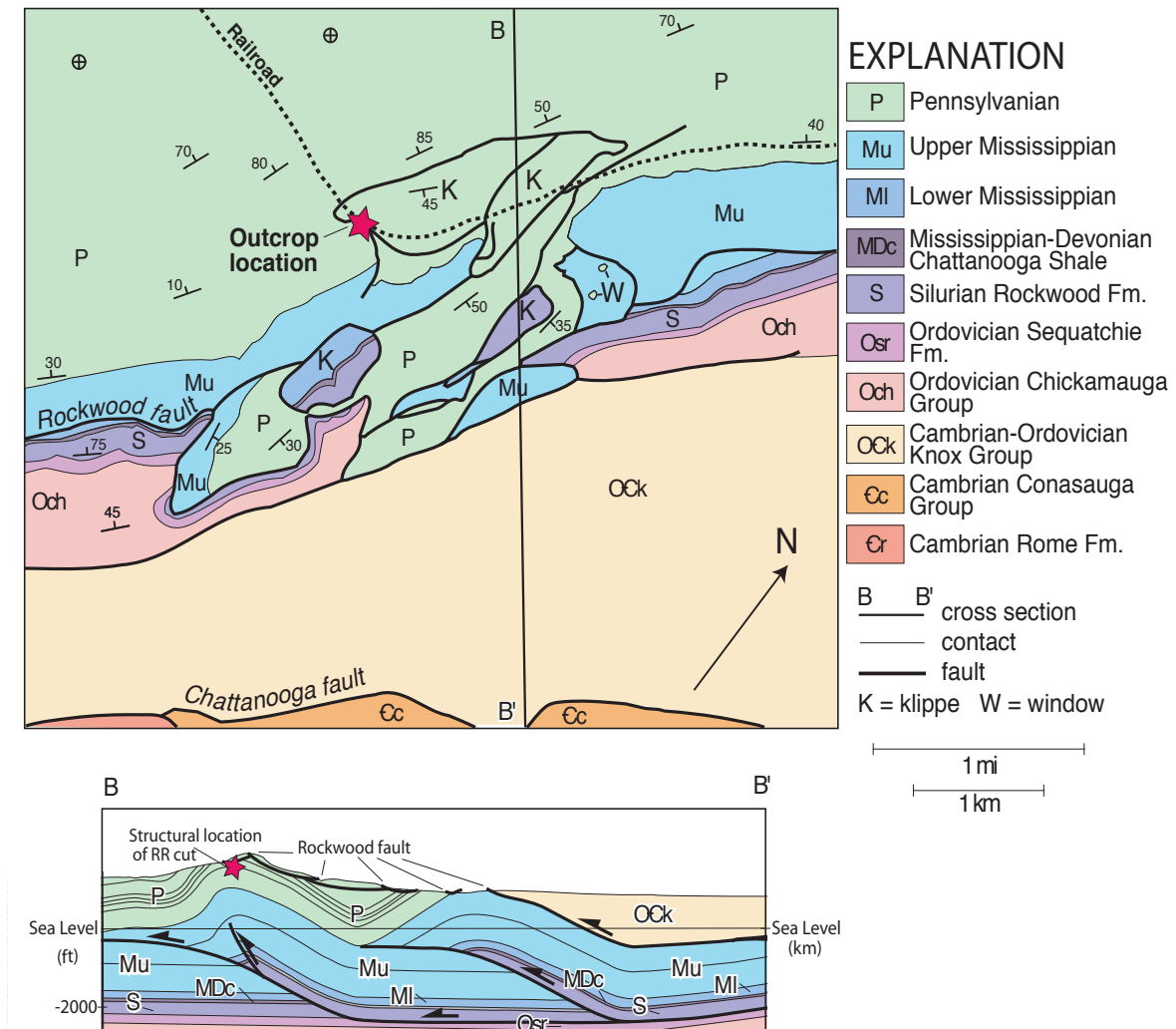
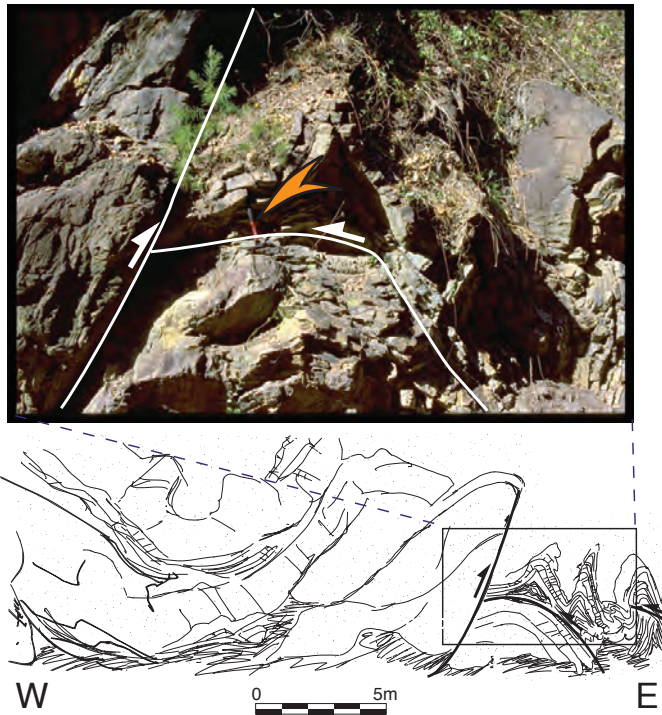


Figure 2-9. Expanded view of geology and structure near Rockwood, Tennessee (map after Swingle, 1960).

a) Non-cylindrical folds



b) Faults dip to both east and west



c) Fold axis orientations

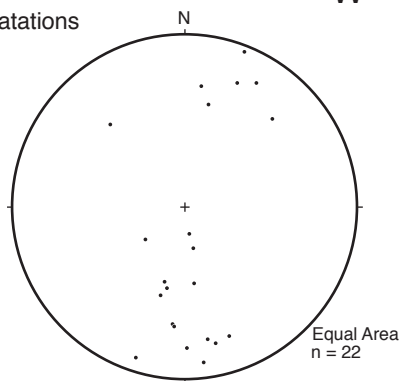


Figure 2-10. Details of the Rockwood, Tennessee, railroad cut.

noncylindrical folds are identified by curved fold hinges (Fig. 2-10b), and fold plunges that reverse from south to north across the tracks (Fig. 2-10c). Shales deformed by folding or fracturing to accommodate the surrounding more competent sandstones are thickened in many fold hinges.

We conclude that the variety and complexity of mesoscopic deformation in the railroad cut probably mimics the subseismic-scale deformation in weak and strong units in the major subsurface detachment fold and other Valley and Ridge structures.

HYDROCARBON POTENTIAL

The open, linear, 80 km-long, Eureka detachment fold below the Chattanooga thrust could be a major hydrocarbon trap in the western Valley and Ridge, given the potential source and reservoir rocks in the structure (Fig. 2-2).

Conodont alteration index values (CAIs) for exposed Ordovician rocks near the Escarpment indicate that thermal maturity is favorable as well. CAIs are between 1.5 and 2.5, similar to those in the Swan Creek field (Epstein et al., 1977; Orndorff et al., 1998), well inside the oil-gas window.

Although most of the approximately two dozen wells drilled near this structure have been dry, few wells on the Plateau were drilled into units deeper than Mississippian, even fewer wells tested Ordovician or older units on either side of the Cumberland Escarpment, and none were optimally located and drilled near the crest of the detachment fold (Tavernier, 2001). The ARCO Wright No. 1 well drilled in Rhea County just off the crest contains both oil and gas (Faust, 1998)(Fig. 2-2).

Obvious drilling targets would be the upper Knox and Stones River (Black River) and Nashville (Trenton) Groups, which are productive reservoirs in Swan Creek field in northeastern Tennessee and on the Cumberland Plateau and Highland Rim (Fig. 2-1 and 2-3). These reservoirs may be self sourced: The Cambrian Copper Ridge Dolomite at the base of the Knox is organic-rich (Whisner and Hatcher, 1998), and USGS gas chromatography

data (Burrus, 1998) indicated that oil from the Swan Creek field has an algal (probably Ordovician) source (Hatcher et al. 2001), potentially from Stones River and Nashville Group rocks.

The Knox unconformity play has also been productive near the Tennessee- Kentucky border on the Cincinnati arch, where tectonically controlled fractures enhanced the reservoir (Baranoski et al. 1996) (Fig. 2-1). Although primary porosity is most important in the Swan Creek field, secondary fracture porosity is locally enhanced by folding and faulting (Lutz, 1987; Clendening and McCown, 1999) (Fig. 2-10). Folding of the Knox in the detachment fold may have increased fracture density, increasing the potential reservoir volume. Fracture studies in higher thrust sheets around Oak Ridge, Tennessee (Fig. 2-1), however, indicate most Knox Group fractures predate thrusting and that younger deformation was accommodated on existing fractures (Hatcher et al. 1992).

A deeper, higher risk play could also be pursued in the basal Knox Group Copper Ridge Dolomite. It emits a fetid odor on fresh surfaces (Rodgers, 1953; Hatcher et al. 1992) and is productive in north-central Ohio fields (Baranoski et al. 1996).

Intervals in the Stones River Group produce oil in Swan Creek field, (Clendening and McCown, 1999) whereas the Trenton Group has produced oil since 1943 in Rose Hill field on the Powell Valley anticline in south- western Virginia (Miller and Fuller, 1954) (Fig. 2-1). Both Groups are productive farther north in Kentucky and Tennessee in many wells along the Cincinnati arch and in three gas fields developed in the late 1970s and early 1980s on the Cumberland Plateau and Highland Rim 40-75 km west of the Chattanooga fault (Faust, 1998).

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PART 3

Deformation in the core of the Southern Appalachian triangle zone

This chapter was presented as a poster at a 1998 meeting of the Geological Society of America. The full citation for the poster is:

Hatcher, R. D., Jr., and Whisner, J. B., 1998, Deformation in the core of the Southern Appalachian triangle zone, Geological Society of America Abstracts with Programs, v. 30, p. 234.

As second author, my contributions included data collection and compilation, most of the writing, and figure construction.

ABSTRACT

Triangle zones occur in the outer parts of the southern and central Appalachian foreland where dominant foreland-vergent thrusts truncate hinterland-vergent passive roof duplexes. The most prominent southern Appalachian triangle zone is traceable from the Jacksboro fault (southwest end of the Pine Mountain block) in Tennessee, to Alabama, where Lower Cambrian to Lower Ordovician rocks weak and strong rocks are thrust over Carboniferous siliciclastic rocks. The highly deformed core of this triangle zone is best exposed in a railroad cut near Rockwood, Tennessee.

The Rockwood exposure consists of medium-bedded to massive sandstone molasse of the Pennsylvanian Sewanee Formation, underlain by interbedded shale, coal, and sandstone of the Pennsylvanian Gizzard Group. Pennsylvanian rocks were thrust NW over the portion exposed in the cut. Room problems in this upper (exposed) part of the triangle zone resulted in intense strain, which decreases to near zero only 150 m to the west. Strain was partitioned between different lithologies, and between beds of the same lithology that vary in primary thickness. Folds in sandstone beds range from open in massive beds to closed in thinner beds, contain numerous fracture sets, and are faulted. Non-cylindrical folds here have wavelengths that vary from cm-size in shale, to 10 m in sandstones, and were deformed by

a combination of flexural slip and brittle flexural flow. Folds verge both in the direction of primary transport (northwest) and also southeast due to the convergence of the northwest-directed thrusts with the northwest-dipping Carboniferous rocks. Crenulation cleavage is present in some shale in the cores of tight anticlines; crenulation surfaces parallel fold axial surfaces.

While the geometry of this triangle zone is typical, the intense deformation present may represent an end-member for deformation style for triangle zones worldwide.

INTRODUCTION

A triangle zone has recently been recognized in the outer part of the southern Appalachian foreland fold-thrust belt. Triangle zones in general comprise a structural front that marks the transition from more complex deformation in the more internal parts of a fold-thrust belt to the less complex outer parts where shortening gradually diminishes to zero. The southern Appalachian triangle zone is traceable from the Jacksboro fault (at the southwest end of the Pine Mountain block) in Tennessee to Alabama, along the boundary between two physiographic provinces: the Valley and Ridge, and the Cumberland Plateau, which locally comprise two deformed components [lesser (Plateau), and greater (Valley and Ridge)] of the foreland fold-thrust belt. Convergence of the two provinces is marked by a prominent topographic feature called Walden Ridge (cross sections in Plate I), caused by movement of a thick package of Lower Cambrian to Pennsylvanian rocks of the Valley and Ridge up a ramp, and over Carboniferous siliciclastic rocks of the Plateau. In the footwall of this easternmost thrust of the Valley and Ridge (either the Rockwood or Chattanooga fault) (Plate I), Plateau rocks are folded into a tight syncline at the boundary, forming a triangle-shaped zone of intense deformation. The highly deformed core of the southern Appalachian triangle zone is best exposed in a railroad cut near Rockwood, Tennessee, in the footwall of the Rockwood fault. Despite the fact that this is a well known and frequently visited field trip stop, no previous structural analysis is known to have been completed.

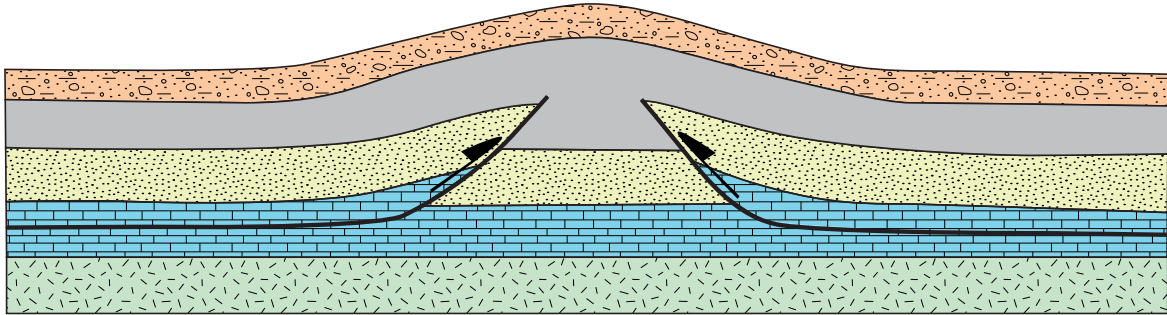
The Rockwood exposure consists of medium-bedded to massive sandstone molasse of the Pennsylvanian Sewanee Conglomerate, underlain by interbedded shale, coal, and sandstone of the Pennsylvanian Whitwell Shale. The Sewanee rocks were thrust to the northwest over Pennsylvanian rocks exposed along the railroad. Room problems in the upper portion of the triangle zone (exposed in the cut) resulted in intense deformation, which decreases to near zero only 150 m to the west (Plate II).

All rock units in the outcrop are highly deformed (folded and fractured), especially the shales and coals of the Pennsylvanian Gizzard Group. The intense brittle deformation in the core of the triangle zone likely extends as far down as the detachment in the Chattanooga Shale, and may have produced fractured reservoirs sealed by shales in different parts of the section. We here report the results of efforts to characterize the deformation in this well-exposed portion of the triangle zone.

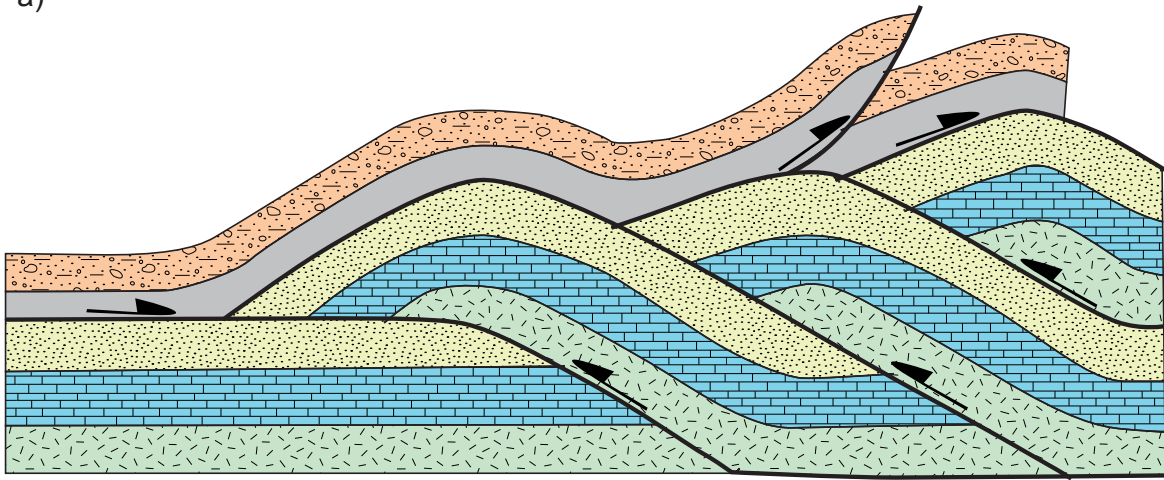
TRIANGLE ZONES

Triangle zones were divided by Couzens and Wiltchko (1996) into two classes (Fig. 3-1). Type I triangle zones occur above very weak horizons, where more competent units respond to compression by forming symmetric, oppositely verging faults (Price, 1986), potentially in combination with detachment folds (Gwinn, 1964), creating a triangle-shaped zone of deformation (Plate I)

Type II triangle zones (Fig. 3-1b) require two detachment horizons: one as a floor thrust accommodating forelandward migration of competent rocks, and one as a roof thrust, as in the figure depicting a structure in the foothills of the Canadian Rockies, (Plate I). Backthrusting (retrocharriage, e.g. Roeder, 1973) on this passive roof thrust allows the duplex to continue displacement into the foreland without appreciable deformation of the overlying rocks. The passive roof duplex (Banks and Warburton, 1986) that delaminates rocks above the roof thrust is essentially a triangle-shaped wedge, and was named a triangle zone for its characteristic shape in seismic reflection lines.



a)



b)

Figure 3-1. Triangle zones (after Couzens and Wiltchko, 1996). a) Type I triangle zone.
b) Type II triangle zone.

The southern Appalachian triangle zone at Rockwood displays many of the characteristics of a Type II triangle zone, although there is no massive delamination with oppositely vergent structures.

FOLDING

Fold style in the Rockwood cut varies widely. Shale is tightly folded, especially in the cores of anticlines. At one location (photo 4, Plate II) folding was sufficiently intense to have initiated formation of a crenulation cleavage. In most of the exposure, however, fracturing is more common than folding in shales (photo 2, Plate II). The geometry of sandstone folds generally depends on their thickness. Massive ($>1\text{m}$) beds form open, long wavelength folds, and folds in medium- to thinly bedded sandstone are frequently tight, with proportionally shorter wavelengths. Thrust faults verging both east and west break fold limbs (photos 5 and 6, Plate II) where the rocks could no longer accommodate shortening via buckling. Many folds are asymmetric to overturned, and may verge to either the foreland or the hinterland (rétrocharriage). At the east end of the outcrop, curved fold hinges (photo 7, Plate II) reveal the non-cylindrical nature of the folds in the thin to medium-bedded sandstone and shale, as does the variation in the plunge of fold axes (photos 5, 6, and 7, Plate II) but most folds plunge to the south. On the south side of the tracks, however, most folds plunge to the north (photos 1, 3, and 4, Plate II). Abundant slickenlines on fracture surfaces and disharmonic folding in the cores of large folds suggest that deformation occurred primarily by flexural slip, although hinge thickening in shales in some folds indicates flexural flow may also have occurred.

FRACTURES

Fracture characteristics in the Rockwood railroad cut vary in different lithologies. The organic-rich shales are penetratively fractured and have high vitrinite reflectance values (not quantitatively determined). Sandstone units contain spaced fractures, with fracture

spacing frequency inversely proportional to bed thickness (photos 5, 6, and 7 in Plate II). The aperture on most fractures is small (<0.5 mm). Minor displacement on fractures is common and ranges from 1-3 cm, as measured on exposed bedding surfaces. Fracture planes, especially in thicker sandstone beds may exhibit slickenlines, but the slickensides are generally not stepped, so motion sense on the surfaces could not easily be determined. The fractures appear by visual inspection to occur as four separate steeply dipping sets (photo 8 in Plate II). One set strikes generally east-west parallel to the trend of the exposure. A second set strikes near north-south almost perpendicular to the exposure (subparallel to axial surfaces). This set appears to fan around the folds, which implies that it formed before folding occurred. The third and fourth sets are most easily observed on bedding surfaces. They are sub-orthogonal, and obliquely cross fold axial planes at an oblique angle. Most fracture measurements were obtained from the first and second sets, because these are most frequently exposed. A plot of all fold axes (both directly measured and calculated from β and π plots) is depicted in Plate I, along with a 1% area plot and a Rose diagram of the same data.

SUMMARY

The study area is located in folded units in the footwall of the westernmost thrust of the Valley and Ridge. Deformation in the Rockwood railroad cut is intense. Strong units (sandstones) define the geometry of non-cylindrical, hinterland- and foreland-verging folds. Fold axes plunge to both the north-northeast and south-southwest. Folds deformed by a combination of flexural slip (slickenlines, disharmonic folding) and flexural flow (weak beds thicken brittly in hinges). Sandstone units are frequently thrust both up-to-the-west and up-to-the-east where folds could no longer accommodate shortening. Shales are pervasively folded and are fractured, and generally deformed to accommodate the surrounding more competent rocks. Sandstones have a more predictable pattern of joint sets, some of which formed prior to folding.

This zone of intense deformation best fits the Type II triangle zone category, although it does not have a well-defined passive roof. But it clearly is a triangle zone geometrically and kinematically, because it occurs in the forelandmost edge of a fold-thrust belt, has low displacement, a generally triangular shape, intense deformation with both foreland, and hinterland senses of vergence.

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PART 4

Character of rigid boundaries and internal deformation of the Southern Appalachian foreland fold-thrust belt

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As third author, my contributions included compiling data, georeferencing, calculating correct elevations for basement surface and creating the basement surface contour diagram; constructing or revising and palinspastically restoring cross sections; contributions to other diagrams; and some writing connected to interpretation of basement geometry and cross sections. The majority of the writing was done by my coauthors, Robert D. Hatcher, Jr., and Peter Lemiszki.

ABSTRACT

The deformed wedge of Paleozoic sedimentary rocks in the southern Appalachian foreland fold-thrust belt is defined by the configurations of the undeformed basement surface below and the base of the Blue Ridge–Piedmont megathrust sheet above, together with the topographic free surface above the thrust belt. The base of the Blue Ridge–Piedmont sheet and undeformed basement surface have been contoured using industry, academic, and U.S. and state geological survey seismic-reflection and surface geologic data. These data reveal that the basement surface dips gently SE in the Tennessee embayment from Virginia to Georgia, and it contains several previously unrecognized normal faults and an increase in dip on the basement surface, which produces a topographic gradient. The basement surface is broken by many normal faults beneath the exposed southern Appalachian foreland fold-thrust belt in western Georgia and Alabama closer to the margin and beneath the Blue

Ridge–Piedmont sheet in Georgia and the Carolinas. Our reconstructions indicate that small-displacement normal faults form beheaded basins over which thrust sheets were not deflected, whereas large-displacement normal faults (e.g., Tusquittee fault) localized regional facies changes in the early Paleozoic section and major Alleghanian (Permian) structures. These basement structures correlate with major changes in southern Appalachian foreland fold-thrust belt structural style from Virginia to Alabama.

Several previously unrecognized structures along the base of the Blue Ridge–Piedmont sheet have been interpreted from our reconstructions. Large frontal duplexes composed of rifted-margin clastic and platform rocks obliquely overridden along the leading edge of the Blue Ridge–Piedmont sheet are traceable for many kilometers beneath the sheet. Several domes within the Blue Ridge–Piedmont sheet also likely formed by footwall duplexing of platform sedimentary rocks beneath, which then arched the overlying thrust sheet. The thickness and westward limit of the Blue Ridge–Piedmont sheet were estimated from the distribution of low-grade footwall metamorphic rocks, which were observed in reentrants in Georgia and south-western Virginia, but are not present in simple windows in Tennessee. These indicate that the original extent of the sheet is near its present-day trace, whereas in Georgia, it may have extended some 30 km farther west.

The southern Appalachian foreland fold-thrust belt consists mostly of a stack of westward-vergent, mostly thin-skinned thrusts that propagated westward into progressively younger units as the Blue Ridge–Piedmont sheet advanced westward as a rigid indenter, while a few in northeastern Tennessee and southwestern Virginia involved basement. Additional boundary conditions include temperatures <300 °C and pressures <300 MPa over most of the belt. The southern Appalachian foreland fold-thrust belt thrusts, including the Blue Ridge–Piedmont megathrust sheet, reach >350 km displacement in Tennessee and decrease both in displacement and numbers to the SW and NE.

Much of the Neoproterozoic to Early Cambrian rifted-margin succession was deformed and metamorphosed during the Taconic orogeny, and it is considered part of the

rigid indenter. Only the westernmost rocks of the rifted-margin succession exhibit ideal thin-skinned behavior and thus are part of the southern Appalachian foreland fold-thrust belt. Palinspastic reconstructions, unequal thrust displacements, and curved particle trajectories suggest that deformation of the belt did not occur by plane strain in an orogen that curves through a 30° arc from northern Georgia to SW Virginia. Despite the balance of many two-dimensional cross sections, the absence of plane strain diminishes their usefulness in quantifying particle trajectories. Coulomb behavior characterizes most individual faults, but Chapple's perfectly plastic rheology for the entire thrust belt better addresses the particle trajectory problem. Neither, however, addresses problems such as the mechanics of fault localization, out-of-sequence thrusts, duplex formation, three-dimensional transport, and other southern Appalachian foreland fold-thrust belt attributes.

INTRODUCTION

Foreland fold-thrust belts are components of collisional orogens worldwide. Besides being thin-skinned, these belts are characterized by: listric thrusts that rise from a basal weak zone near the basement-cover contact; faults that ramp more steeply across strong units to higher detachments, or to the surface; and an initial undeformed, continentward-thinning sedimentary wedge. Furthermore, mechanical models for thrust-belt growth require that the wedge shape be maintained as it is shortened and thickened into the deformed state (Chapple, 1978; Dahlen, 1990). Because intrinsic and extrinsic space-time variables exist, important individual differences and along-strike variations occur in foreland fold-thrust belts. Structural style is determined by intrinsic variables including stratigraphic parameters, anisotropy, bonding between lithologies, fluids, original shapes of the continental margin and platform, shape of the indenter, and basement irregularities. Thrust spacing initially appears to be related to stratigraphic thickness, but this may be an oversimplification. Extrinsic variables relate to the deformational history of a region and include changes in burial depth, temperature, fluid pressure, and strain rate during thrusting, along with the

lithospheric thermal regime at the time of collision. These and other variables give rise to parts of foreland fold-thrust belts that are fold dominated and contain relatively few faults (e.g., Jura and MacKenzie Mountains, Alabama and central Appalachians), while other segments are thrust dominated and contain several master faults and numerous subsidiary faults (e.g., southern Canadian Rockies, Bergamesc Alps, Tennessee southern Appalachians). Our purpose here is to discuss the regional shapes of the bounding surfaces (fixed boundary conditions) that existed during the development of the southern Appalachian foreland fold-thrust belt and their influence on the final shape of this part of the thrust belt. We also intend to explore these influences and to examine the deformed volume from an orogen-scale perspective to better understand the kinematics and mechanics that produced the southern Appalachian foreland fold-thrust belt that we see today.

Thrust-sheet deformation can occur by folding and faulting, with local internal pressure-solution strain (layer-parallel shortening) (e.g., Geiser and Engelder, 1983). The concept of structural-lithic units (SLU) has been applied to the southern part of the southern Appalachian foreland fold-thrust belt at different scales to emphasize the interplay between structural style and deforming unit properties (Willis, 1893; Currie et al., 1962; Woodward, 1988). Specifically, Currie et al. (1962) defined a structural-lithic unit as part of a stratigraphic section that has a characteristic response to deformation. The strain mechanism, however, may also change for a particular structural-lithic unit, because deformational conditions change through time. As a result of interactions between these and other variables (see previous paragraphs), numerous exceptions exist to the predicted deformational style exhibited by a particular rock unit or segment of a foreland fold-thrust belt, and make it difficult to apply the structural-lithic unit concept at the thrust-system scale. Geometric models based on relatively few variables are appealing, but they are ultimately not useful for detailed analysis because they oversimplify the system and yield unrealistic structures (see, for example, Ramsay, 1991).

The boundaries considered to be most fixed in many foreland fold-thrust belts (e.g., southern and central Appalachians, Alps, Scandinavian Caledonides) are the shapes of the bounding surfaces—the base of the rigid indenter and the top of the rigid basement (Fig. 4-1). The shapes of these surfaces can potentially influence not only structures that form near the indenter front and near the basement surface, but, because they are so fundamental, they also can influence structures that form below the free (topographic) surface within the deforming wedge far from the boundaries. Therefore, many tectonic structures in a thrust belt are the products of superimposed local and orogen-scale stresses within the deforming wedge that are generated by the rigid bounding Blue Ridge–Piedmont megathrust sheet indenter surfaces. When reconstructing the structural evolution of a thrust system, the conditions at the boundaries and within the deforming wedge should be identified. Subsurface data were examined to determine the shape of the basement surface beneath the southern Appalachian foreland fold-thrust belt and the present shape of the Blue Ridge–Piedmont megathrust indenter. Pressure and temperature data were used to evaluate the forelandward extent of Blue Ridge–Piedmont sheet loading, to better outline the original indenter shape, and the evolving eastward extent of the free surface of the wedge. These results will influence present and future three dimensional (3-D) reconstructions of the southern Appalachian foreland fold-thrust belt.

The southern Appalachian foreland fold-thrust belt (Fig. 4-2) consists of a wedge-shaped stack of mostly west-vergent, mostly thin-skinned thrusts located above the undeformed Mesoproterozoic basement (lower bounding surface) that occur in the exposed foreland and beneath the Blue Ridge–Piedmont composite crystalline megathrust sheet (upper bounding surface) from Alabama to Maryland. The Blue Ridge–Piedmont sheet was the rigid indenter that deformed the foreland during the Carboniferous–Permian Alleghanian orogeny, and it consists of rifted-margin and platform sedimentary rocks and some Mesoproterozoic basement. The third boundary is the unconfined topographic free surface (Fig. 4-1). The classic Appalachian foreland fold-thrust belt at first appears amenable to two-

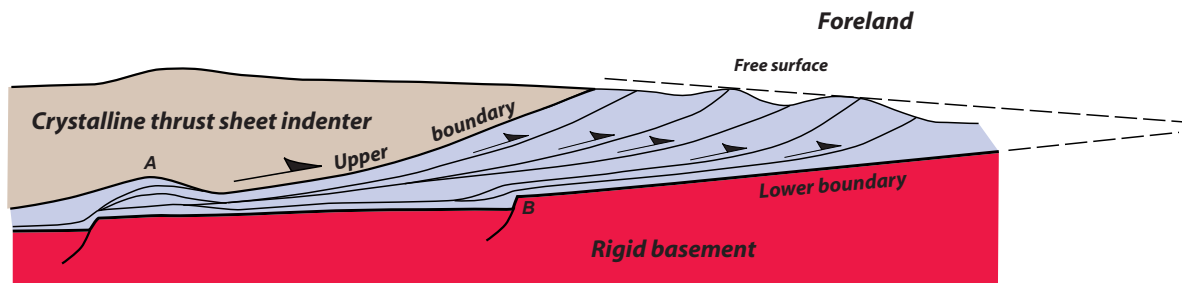


Figure 4-1. Primary boundaries of foreland fold-thrust belts. Additional boundary conditions include temperatures $<300^{\circ}\text{C}$ and pressures $<400\text{ Mpa}$. A—Ancient rift fault beneath the crystalline indenter nucleates an antiformal stack duplex that arches the crystalline sheet. B—Rift fault beneath the platform nucleates a foreland fold-thrust belt thrust.

Figure 4-2. (a) Alleghanian faults (red) in the SAFT; names of faults discussed in the text are indicated, along with several others. Older faults shown in black. HM–IM–Holston Mountain–Iron Mountain fault. MCW–Mountain City window. WOM–Whiteoak Mountain fault. NYA–New York–Alabama magnetic lineament of King and Zietz (1978). CL–Clingman magnetic lineament of Nelson and Zietz (1983). Abbreviations and unlabeled colors in index map: PMW–Pine Mountain window. SRA–Smith River allochthon. SMW–Sauratown Mountains window. GMW–Grandfather Mountain window. Red–Middle Proterozoic Grenville basement. Yellow–Cowrock terrane. Pink–Cartoogechaye terrane. Note that all of the Laurentian margin rocks, except the most frontal thrust sheet, were deformed and metamorphosed during earlier events, so they consist of Paleozoic basement and, together with the pre-Paleozoic components, make up the indenter in the Alleghanian thrust system. Compiled from Hatcher et al. (1990). (b) Simplified tectonic map of the southern Appalachians with Alleghanian faults in red. Shortening (in percent) is shown along four restored cross sections that extend from the Plateau to the Coastal Plain (see Hatcher et al., 1990 for all sections). Large arrows indicate transport directions, particularly within the Blue Ridge–Piedmont composite crystalline thrust sheet; those along the westernmost Cumberland Plateau and Pine Mountain blocks were determined by Kilsdonk and Wiltschko (1988). Small arrows represent normals to the hinges of narrow macroscopic folds (compiled from published state geologic maps of Alabama [Osborne and others, 1989], Georgia [Pickering, 1976], Tennessee [Hardeman, 1966], and Virginia [Johnson, 1993]). Shortening (in percent) is also indicated along four restored sections (from Hatcher et al., 1989, 1990). The 15° divergence between the traces of the Jacksboro and Emory River faults may indicate both divergence in transport direction and the orientation of lateral ramps. Red lines represent Alleghanian (Pennsylvanian–Permian) faults. Black toothed lines are earlier thrusts. Brown areas in the Blue Ridge and Piedmont represent Grenville (1.1 Ga) basement; note that the BRP indenter consists of Grenville basement plus Paleozoic basement generated during Taconian, Neoacadian, and early Alleghanian deformation and metamorphism (Hatcher, 1999). *T*–Location of Tusquitee, North Carolina. SCW–Shooting Creek window. TFD–Tallulah Falls dome. (c) Cross section with shortening >350 km illustrating thin-skinned structural style for Alleghanian deformation across the southern Appalachians (simplified from section B–B' in Hatcher et al., 1990). Cross section in (c) is the one indicated in (b) with 54% shortening.

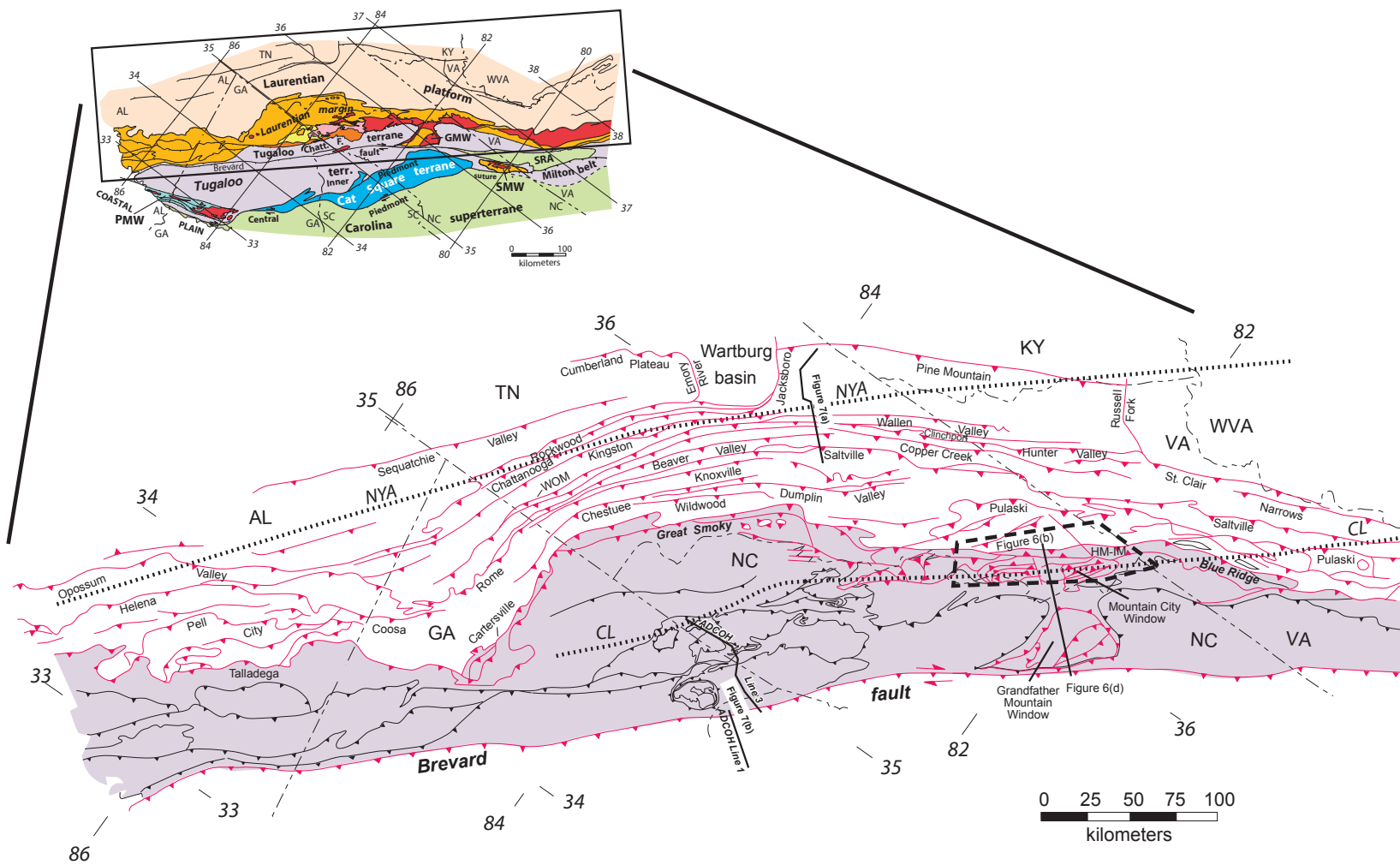
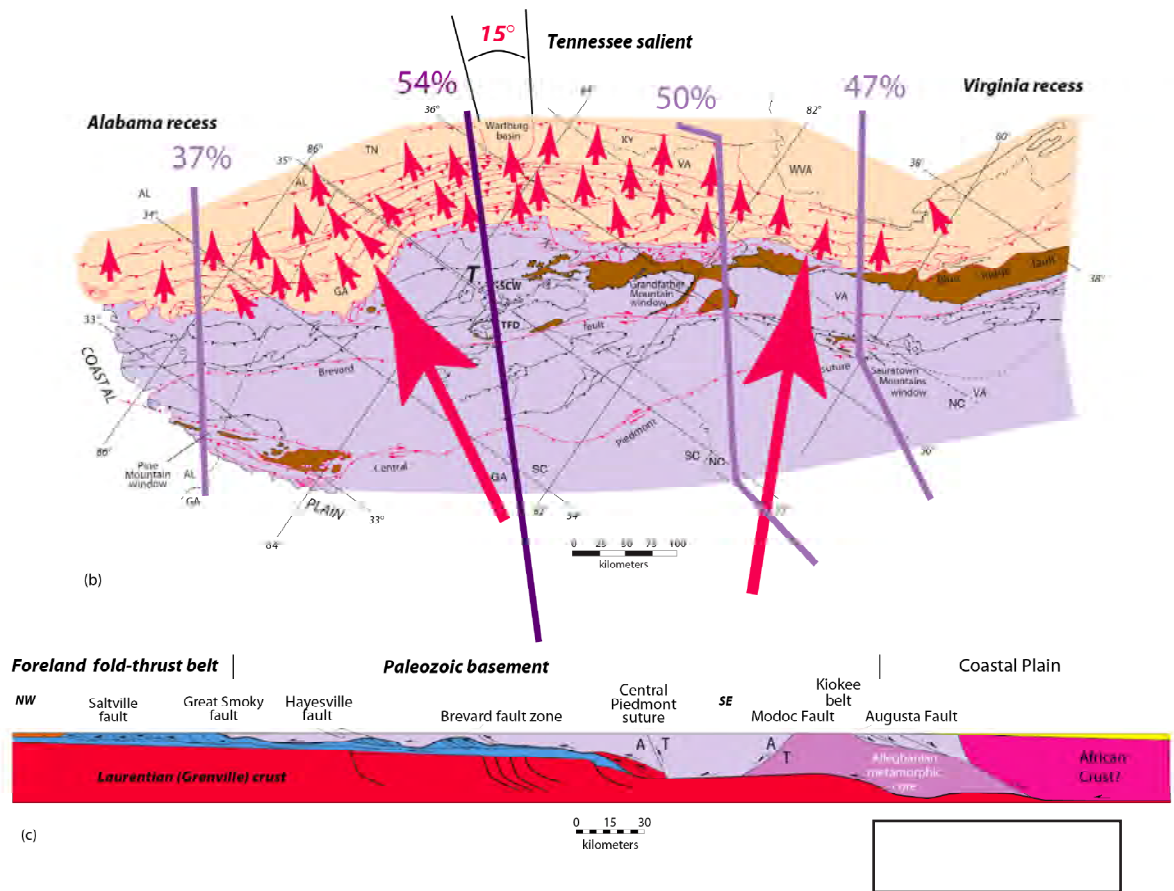


Figure 4-2 continued.



dimensional (2-D) balanced cross-section analysis and fits current models for foreland fold-thrust belt development (e.g., Davis et al., 1983; Dahlen, 1990). The southern Appalachians are a strongly curved, thrust-dominated orogen that describes a convex-west arc of 30° from northern Georgia through Tennessee into southwestern Virginia (Fig. 4-3); a similar arc exists in Pennsylvania (Geiser, 1988; Geiser in Hatcher et al., 1989a; Hatcher et al., 1990; Faill, 1998). Across-strike thrust populations vary from three to five across the belt in NE Alabama and SW Virginia to 12 across the Tennessee segment (Fig. 4-2a). The segment with the greatest number of thrusts is also the one that contains the thrusts with the largest displacements: >50 km on at least three (Fig. 4-4), with a restorable displacement of >350 km on the Blue Ridge–Piedmont sheet. The problem of reconstruction of curved segments of orogens has been addressed in a number of studies, but without a satisfactory solution (e.g., Geiser, 1988; Laubscher, 1988; Marshak, 1988, 2004). A kinematic solution may be achieved by adherence to principles of conservation of volume, but a mechanical solution is not possible without assuming a rheology for body deformation of the rock mass (Chapple, 1978). Some success with kinematics has been achieved by estimating body strain (e.g., with the calcite strain gauge), which has yielded the conclusion that transport-parallel simple shear (line length not constant), rather than curved particle paths, is the dominant mechanism in part of the northern Subalpine Chain in France (Ferrill and Groshong, 1993). The Jura Mountains and Helvetic Alps, however, display a radiating pattern of transport vectors (Platt et al., 1989; Hindle and Burkhard, 1999). Several variables influence thrust-belt curvature: (1) shape of the indenter; (2) basement obstacles; and (3) the number of deformation events. Indenter shape exerts a strong control on the amount of local shortening in the foreland and influences development of the regional stress field, both of which are manifested in the curvature of the thrust belt. For example, the shape of the southern Appalachian foreland fold-thrust belt generally mimics the geometry of the Blue Ridge–Piedmont sheet front (Figs. 4-2b and 4-3). The map view shape of the Blue Ridge–Piedmont sheet has been affected by erosion, so additional data, such as burial-depth estimates of foreland rock

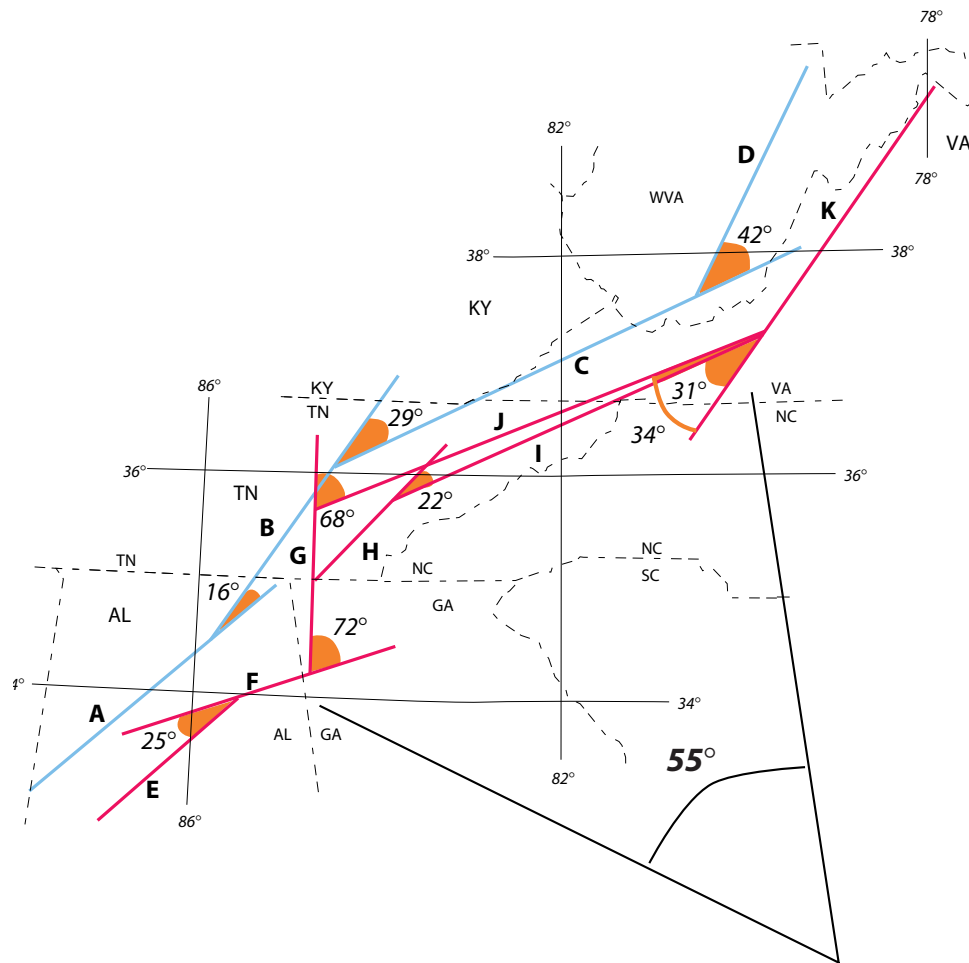


Figure 4-3. Angles between curved segments within the southern Appalachians. Red lines represent segments of the Blue Ridge front (Talladega, Cartersville, Great Smoky, Miller Cove, Holston-Iron Mountain, and Blue Ridge faults); blue lines represent segments measured along the eastern edge of the Cumberland (Allegheny) Plateau, also a structural front. Note that, if the up-dip projection of the BRP sheet is implemented, as suggested in Figure 8 below, the angle on the front from Georgia to Virginia is 75-80° and not ~105° as it is at the present erosion level. The arc of the entire Tennessee salient is ~55°. A–Alabama Plateau. B–Alabama-Georgia-Tennessee Plateau. C–Tennessee-Virginia Plateau. D–Virginia Plateau. E–Alabama Blue Ridge. F–Alabama-Georgia Blue Ridge. G–Georgia-Tennessee Blue Ridge. H–Tennessee-Georgia Blue Ridge. I–Tennessee Blue Ridge. J–Tennessee-Virginia Blue Ridge. K–Virginia Blue Ridge.



Figure 4-4. Southeast-dipping Saltville thrust exposed in road cut on Broadway Avenue 100 m N of I-640 in Knoxville, Tennessee. Light-colored carbonate in footwall is upper Knox Group dolomite; multicolored unit in the hanging wall is the Lower Cambrian Rome Formation. Steep dip here is related to later arching of the hanging wall as other thrust sheets propagated northwest of the Saltville. (Photo taken in 1978; Ray Price in yellow rain jacket in foreground.)

units, are needed to correct for this. Foreland basement obstacles that existed prior to or developed during thrusting are considered to be primary controls that can influence thrust-belt curvature (Macedo and Marshak, 1999). Evaluation of primary basement controls of southern Appalachian foreland fold-thrust belt curvature was not possible before now for lack of subsurface data. Local stratigraphic anomalies that correlate with basement features may become piercing points for thrust-system reconstructions. Even if individual thrust-sheet displacements are poorly known, the magnitude and direction of shortening for a portion of the thrust system may then be identified and provide an important limit for reconstructions.

Multiple deformation events manifested as changes in the regional shortening direction through time have been documented in the central and southern Appalachians (Roeder, 1975; Geiser and Engelder, 1983; Evans, 1994). Roeder (1975), using local structural analysis, argued for polyphase thrusting in the Tennessee portion of the southern Appalachian foreland fold-thrust belt, but his conclusions remain unsubstantiated. Bartholomew and Schultz (1980) observed coaxial superposed mesoscopic folds in the Pulaski thrust sheet in southwestern Virginia. These studies emphasize the difficulty of separating local overprinting from incremental variations in regional shortening direction.

Deformation of the Appalachian and other foreland fold-thrust belts at outcrop scale is clearly brittle and involves: fold mechanisms, such as buckling and flexural slip; brittle faulting, which produces cataclasis, rigid-body rotation and translation, and contractional and extensional faulting (Norris, 1958; Harris and Milici, 1977); and other fracturing mechanisms. The presence of semiductile deformation mechanisms, such as flexural flow, cleavage, and body strain, suggests that these mechanisms also contribute to overall foreland fold-thrust belt deformation. Chapple (1978) formulated a model for foreland fold-thrust belts based on plastic rheology. Today, based on the papers by Davis et al. (1983), Dahlen (1990), and others, most assume that the deformation in foreland fold-thrust belts occurs by brittle (Coulomb) processes. Elliott (1976) suggested that thrust faults propagate as a “ductile bead” along the tip line of a propagating thrust, and the displacement on a

thrust propagates incrementally as a smeared-out (Somigliana) dislocation (Price, 1988), reintroducing the possibility of ductile deformation at meso- and microscales. Wojtal (1992), using southern Appalachian foreland fold-thrust belt examples, constructed a model for continuous flow in mesoscale thrust zones involving both plane and nonplane strain that assumed a viscous rheology on the scale of loose lines in individual thrust sheets. Woodward (1987) also pointed out the difficulties of applying critical-wedge concepts developed in sandbox experiments and accretionary complexes to foreland fold-thrust belts—in this case, models developed for brittle deformation.

TECTONIC HISTORY AND PRESENT-DAY STRUCTURAL FRONTS

The southern Appalachian foreland fold-thrust belt has a sinuous trace that extends from the Virginia recess through the Tennessee salient to the Alabama recess, and these features had to have evolved from promontories and embayments in the pre-Appalachian continental margin (Thomas, 1977, 1991) (Fig. 4-2b). The western deformation limit of the belt occurs in the Cumberland-Allegheny Plateau (e.g., Hatcher et al., 1990), and the SE border of the exposed belt occurs at the present-day surface along the trace of the Blue Ridge–Piedmont sheet. The belt contains a stratigraphic succession that formed after the late Neoproterozoic to early Paleozoic breakup of Rodinia followed by sediment accumulation along the irregular Laurentian margin. This rifted margin evolved into a carbonate platform (shelf) that, by the late Early Cambrian, faced the open Iapetus ocean. By the end of Early Ordovician time, the carbonate platform in most of eastern North America was exposed by a eustatic sea-level drop, was subaerially eroded, producing as much as 150 m of topographic relief and extensive karst topography, and then was submerged again with renewed carbonate deposition. The Neoproterozoic to Ordovician margin was inverted, and the eastern carbonate platform was buried in the Middle Ordovician by formation of a foredeep basin. This basin was filled by a westward-advancing clastic wedge derived from uplifted parts of the eastern platform as Taconian arcs and deep-water sediments collided with, were

obducted onto, and loaded the outer margin. Clastic- wedge deposition persisted into the Silurian (molasse) until the southern Appalachian platform was uplifted. Erosion removed most Middle Silurian to Middle Devonian deposits, but clastic deposition resumed in the Late Devonian and continued into the early Mississippian (Ettensohn, 2004). These units probably represent the Neocadian clastic wedge in the southern Appalachians, which are capped by middle Mississippian carbonates. The Pennsylvanian-Permian Alleghanian clastic wedge advanced westward across the foreland and into the Appalachian foreland basin as final construction of the orogen began during the north- to-south zippered joining of Africa with Laurentia (Hatcher, 2002). More detailed summaries of the Paleozoic tectonic history of the U.S. Appalachians can be found in Hatcher et al. (1989b).

The Blue Ridge–Piedmont crystalline sheet master décollement formed within the ductile-brittle transition in previously deformed and metamorphosed Paleozoic crust, and propagated upward into bedding thrusts in the unmetamorphosed weak Lower Cambrian clastic rocks (Sandsuck Formation and Chilhowee Group). The master décollement then propagated into the clastic-evaporite succession (Rome Formation), which rests on Grenvillian basement. Middle- and upper-level detachments in the foreland that formed in Cambrian, Ordovician, Devonian-Mississippian, and Pennsylvanian shale and coal are linked by ramps that formed in thick strong units of massive Cambrian-Ordovician carbonate and younger sandstone. The assembled rifted margin, carbonate platform, and eastward-thickening clastic wedges were driven westward in snowplow fashion in front of the advancing Blue Ridge–Piedmont crystalline thrust-sheet indenter (Figs. 4-1, 4-2, and 4-5). Folded faults and map patterns support the contention that thrusts propagated outward from the interior of the orogen, but Milici (1975) used the truncating relationships among thrusts in the Tennessee Valley and Ridge to conclude that thrusts propagated from the foreland toward the hinterland. The presence of a continuous sequence from crystalline basement into the Ordovician (Knox) carbonate in the Shady Valley syncline in the northeastern Valley and

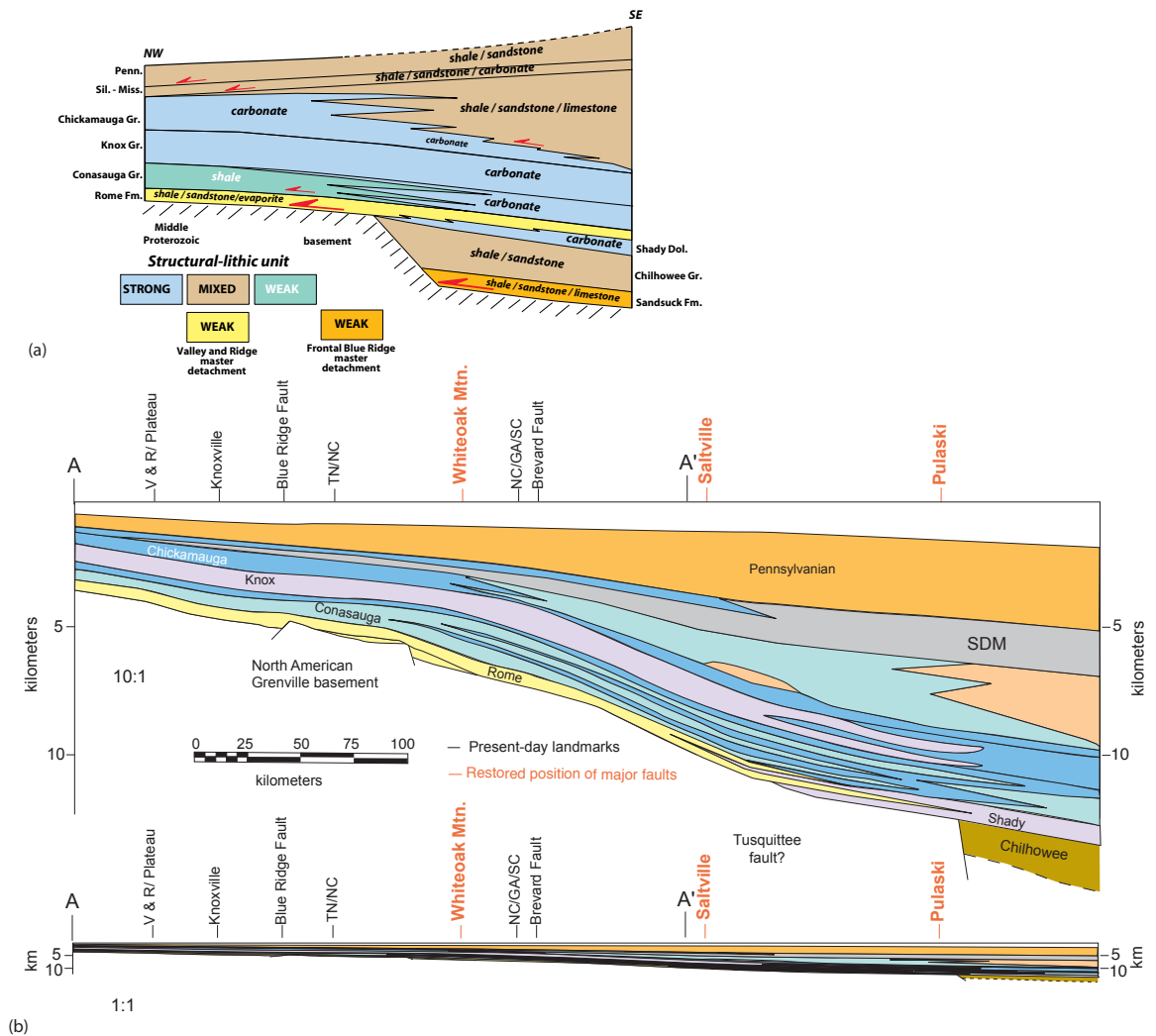


Figure 4-5. (a) Simplified restored stratigraphic section through the Tennessee SAFT. Dip section showing location of detachment zones, and definition of SLUs based on changes in lithology of the depositional sequence. Red arrows indicate regional detachment units. (b) Palinspastic facies diagram across the SAFT approximately at the latitude of Knoxville, Tennessee, quantitatively reconstructed by retrodeforming major faults and facies boundaries. The Pulaski fault is projected southward into the section. Blue—limestone facies. Lavender—dolomite facies. Green—shale facies. Light orange—coarse clastics and turbidites. Gray—siltstone facies. Light yellow—sandstone, shale and dolomite intertidal facies. SDM—Silurian, Devonian, and Mississippian rocks.

Ridge of Tennessee (Hardeman, 1966) suggests that other processes, such as out-of-sequence thrusting, may have created most of these truncations (Woodward, 1985).

The shape of the Blue Ridge structural front, defined by changes in strike of the (Blue Ridge–Piedmont) frontal thrust, is quite variable from Virginia to Alabama (Fig. 4-2a). Smaller variations occur along the Cumberland-Allegheny Plateau front, but the changes in trend are subparallel and bound an arcuate fold-thrust belt. From Tennessee northeastward into the Virginia recess, the strike of Valley and Ridge structures rotates through an arc of 30° (Fig. 4-3). Rodgers (1970) pointed out that the change in strike does not take place smoothly. Instead, central and southern Appalachian structures interfinger and appear to overprint each other in a broad displacement transfer zone in southwestern Virginia (Couzens et al., 1993; Spraggins and Dunne, 2002). These strike changes in the southern Appalachians are smoothly curving arcs with little to no surface expression of structures that developed to accommodate the change in shortening direction. Thomas (1991) suggested that cratonward thrust propagation was greater through a thicker sedimentary wedge deposited in the Tennessee and Pennsylvania embayments compared with the thinner succession deposited on the promontories. This affected the sinuous trace of the southern Appalachian foreland fold-thrust belt, so that salients of the fold-thrust belt coincide with embayments and recesses coincide with promontories in the ancient continental margin. While this concept may explain part of the structural relationships in salients and recesses, most of the rifted-margin succession was penetratively deformed and metamorphosed earlier, so by the Alleghanian, this assemblage was Paleozoic basement, and the master detachment propagated through it along the ductile-brittle transition.

A substantial across-strike change in structural style within the southern Appalachian foreland fold-thrust belt occurs at the boundary between the Cumberland-Allegheny Plateau and the Valley and Ridge. The front is defined either by a fault, foreland syncline, or a frontal monocline. This frontal structure locally has a triangle-zone geometry (Gwinn, 1964; Gordy et al., 1977; Jones, 1987, 1996; Hatcher and Whisner, 1998). The boundary between

the Valley and Ridge and the Blue Ridge coincides approximately with the northwestern limit of Mesoproterozoic basement rocks in Virginia and late Neoproterozoic rift-fill sedimentary and volcanic rocks farther south in the hanging wall of the Blue Ridge–Piedmont thrust sheet. The Blue Ridge front consists of a series of faults named (from SW to NE): Talladega, Cartersville, Great Smoky, Miller Cove, Holston–Iron Mountain, and Blue Ridge faults (Fig. 4-2a).

REGIONAL STRATIGRAPHIC FRAMEWORK

The entire sedimentary sequence in the southern Appalachian foreland fold-thrust belt has an eastward-thickening wedge-shaped geometry below which the autochthonous Mesoproterozoic basement dips SE toward and beneath the Blue Ridge–Piedmont crystalline thrust sheet (Figs. 4-2c and 4-5). Throughout most of the southern Appalachian foreland foldthrust belt, the basal décollement propagated through the Early to Middle Cambrian rifted-margin clastic rocks immediately above the basement (Rome Formation and Conasauga Group) (Rodgers, 1953; Milici, 1975; Thomas, 1988) (Fig. 4-5). The Rome Formation is composed of shale and siltstone, with lesser amounts of sandstone, dolostone, limestone, and evaporite. This sequence had a westward clastic source, and it becomes more carbonate-rich toward the east. Although the exact thickness of the Rome Formation is difficult to determine because its base is mostly faulted across the exposed southern Appalachian foreland fold-thrust belt, isopach maps indicate that the thickness reaches 600 m (Harris and Milici, 1977; Rankin et al., 1989). The basement was active during the time when the Rome Formation was deposited because sedimentation was affected by normal faults bounding the subsurface Rome trough in Kentucky (Gao et al., 2000) and by basement faulting in Alabama (Thomas, 1986, 1991; Thomas and Bayona, 2005).

Conasauga Group facies also change regionally from clastic-rich to the west to carbonate-rich to the east, with thickness and lithologic variations across the Appalachian basin (Rodgers, 1953) (Fig. 4-5). Palinspastic maps indicate a general thickness increase

toward the SE. A local depocenter has been identified in the middle of the Tennessee salient (Luttrell basin of Hasson and Haase, 1988). These major thickness and lithologic changes in the Early (Rome) to Middle Cambrian (Conasauga) clastic interval may reflect depositional responses to basement highs and lows.

The Late Cambrian to Early Ordovician Knox Group extends across the entire southern Appalachian foreland fold-thrust belt and is the mechanically strong stratigraphic unit in the carbonate sequence. The carbonate sequence thickens at the base (eastward) where older Conasauga Group facies become carbonate rich, and also thickens at the top where the younger Chickamauga Group is dominantly carbonate (Fig. 4-5). The Knox Group in Tennessee may also contain a local thickness increase related to the Luttrell basin (Rankin et al., 1989). Greater carbonate-sequence thickness, which produced greater mechanical strength, localized ramps between lower and upper detachments and formed the strut for southern Appalachian foreland fold-thrust belt thrust sheets.

A middle detachment exists in mudstone-shale-rich intervals in the Middle Ordovician Chickamauga Group. Near the Blue Ridge front, the detachment occurs in the shaly Lenoir Limestone or the overlying Sevier Shale, but farther NW, the detachment is in the Moccasin Formation (top of Stones River [Black River] Group). An important upper detachment horizon in northeastern Tennessee and Virginia is the interval including the Devonian-Mississippian Chattanooga Shale and Silurian clastic rocks. The Chattanooga Shale thins from ~700 m in southwestern Virginia and 300 m in northeastern Tennessee to 16 m farther west along the Tennessee-Kentucky border (Harris and Milici, 1977). As a result, the Pine Mountain fault, which ramps into the Chattanooga Shale (Rich, 1934), locally steps down stratigraphically toward the SW into Silurian clastic rocks (Harris, 1970; Milici, 1975). Farther SW in the Sequatchie Valley–Cumberland Plateau overthrust sheet, lower Mississippian Grainger Formation and early Pennsylvanian Gizzard Group shale and coal act as upper detachment surfaces, presumably because the Chattanooga to Silurian clastic interval is too thin (Wilson and Stearns, 1958; Harris, 1970). The unfaulted Wartburg basin

separates the Pine Mountain thrust sheet from the Cumberland Plateau overthrust sheet (Fig. 4-2a).

REGIONAL STRUCTURAL FRAMEWORK

The southern Appalachian foreland fold-thrust belt is a classic thin-skinned foreland fold-thrust belt (Fig. 4-1). The anisotropy produced by stratigraphic units with contrasting strength and/or thickness was recognized early as a major influence on both fold and fault style (Hayes, 1891; Willis, 1893; Butts, 1927; Rich, 1934; Suppe, 1983). Hayes (1891), working in the southern Appalachian foreland fold-thrust belt in Georgia, was one of the first to attempt palinspastic reconstruction of thrust sheets. Butts (1927), and later Rich (1934), however, used the deformation style of the Pine Mountain thrust sheet to explain bedding-parallel and bedding-oblique thrust faults (ramps) in sedimentary strata. Rich's ramp-flat thrust model has been applied with great success both to the Appalachians and other thrust belts (Bally et al., 1966; Dahlstrom, 1970; Harris, 1970; Price and Mountjoy, 1970; Royse et al., 1975; Boyer and Elliott, 1982). The Blue Ridge–Piedmont indenter thus consists of basement—crust consisting of rocks deformed and metamorphosed during a previous orogeny (Hatcher, 1999). This includes all rocks penetratively deformed and metamorphosed during the Grenvillian, Taconian, Neoacadian, and early Alleghanian orogenies.

The southern Appalachian foreland fold-thrust belt is composed of three to more than ten major thrust sheets (Fig. 4-2a), where several master faults (e.g., Rome-Saltville, Copper Creek, Whiteoak Mountain–Clinchport–Hunter Valley–Wallen Valley, Pulaski) are traceable along strike for hundreds of kilometers. Thrust faults generally strike NE, dip toward the SE, and are responsible for over 120 km of shortening (Roeder et al., 1978). Several major faults end in the Virginia recess and increase horizontal displacement and stratigraphic separation southwestward from zero to several kilometers. Within the Virginia recess, Carboniferous rocks are preserved in synclines in several major thrust sheets and in windows (Johnson, 1993). In the Tennessee salient, 12 subparallel thrust faults crop out in an across-strike

distance of only 50 km, recording more than 300 km of shortening. Southward from the Tennessee salient, the thrust belt changes character as: (1) the number of thrust faults and the displacement on them decrease; (2) Carboniferous rocks are again abundant in footwall synclines; and (3) folds are again an important part of the structural style.

Direct evidence for the influence of basement features on thrust-belt development is sparse (Wiltschko in Hatcher et al., 1989a), although the location of thrust ramps may be influenced by pre-existing normal faults that form steps in the basement surface (Wiltschko and Eastman, 1983; Thomas, 1986; Schedl and Wiltschko, 1987). Jacobeen and Kanes (1974) documented a relationship between basement geometry and thrust-ramp position in the central Appalachians. Previous data for the depth and geometry of the basement surface beneath the southern Appalachian foreland fold-thrust belt consisted of a few drill holes; short, isolated seismic-reflection profiles; and depth estimates from magnetic surveys (e.g., Watkins, 1964). In general, the top of the basement was considered to be a smooth, gently SE-dipping surface (Milici, 1970, his Figure 3-3; Harris, 1979; Roeder et al., 1978). Probably the most conclusive evidence of the influence of basement faults on thrust-belt structure is in Alabama, where Thomas (1982, 1986, 2001) identified a down-to-the-SE basement normal fault that subsequently localized the ramp beneath the Birmingham anticlinorium. Both stratigraphic variations and soft-sediment deformation in several units across the Birmingham anticlinorium indicate activity of the basement fault throughout the Paleozoic. Harris and Milici (1977) suggested that several thrust faults in Tennessee were deflected upward from the basal décollement by warps in the basement surface. Woodward (1988) concluded that the presence of basement in thrust sheets around the Mountain City window did not influence thrust-belt structural style.

The Shady Valley thrust sheet (Holston–Iron Mountain fault) west of the Mountain City window (Fig. 4-6), however, contains stratigraphy ranging from Mesoproterozoic basement (or the Neoproterozoic Mt. Rogers Formation in NE Tennessee and SW Virginia) to a continuous section from the Lower Cambrian Chilhowee Group into the Lower Ordovician

Figure 4-6. (a) Stratigraphic section in the Shady Valley (Holston-Iron Mountain)-Stone Mountain thrust sheet (from King and Ferguson, 1960). Vertical thicknesses are relative, with the Knox Group ~1 km. MO–Middle Ordovician rocks. OCK–Knox Group. CC–Conasauga Group. CR–Rome Formation. CS–Shady Dolomite. CE–Erwin Formation. CH–Hampton Formation. CU–Unicoi Formation. ZMR–Mt. Rogers Formation. ZB–Beech Granite. YC–Middle Proterozoic basement rocks. (b) Geologic map of northeastern Tennessee. Thrust faults are shown in red. ZGS–Great Smoky Group. ZA–Ashe Formation. JC–Johnson City. E–Elizabethton. RM–Roan Mountain. From Hardeman (1966), modified with data from King and Ferguson (1960). (c) Cross section across the Limestone Cove inner window and the Mountain City window, with retrodeformed section below. From Diegel (1985). (d) Cross section and retrodeformed stacked thrust sheets from the Valley and Ridge across the Brevard fault zone in northeastern Tennessee and western North Carolina. Modified from cross sections by King & Ferguson (1960), Bryant and Reed (1970), Boyer & Elliott (1982), and Diegel (1985). Section location is shown in Figure 2a.

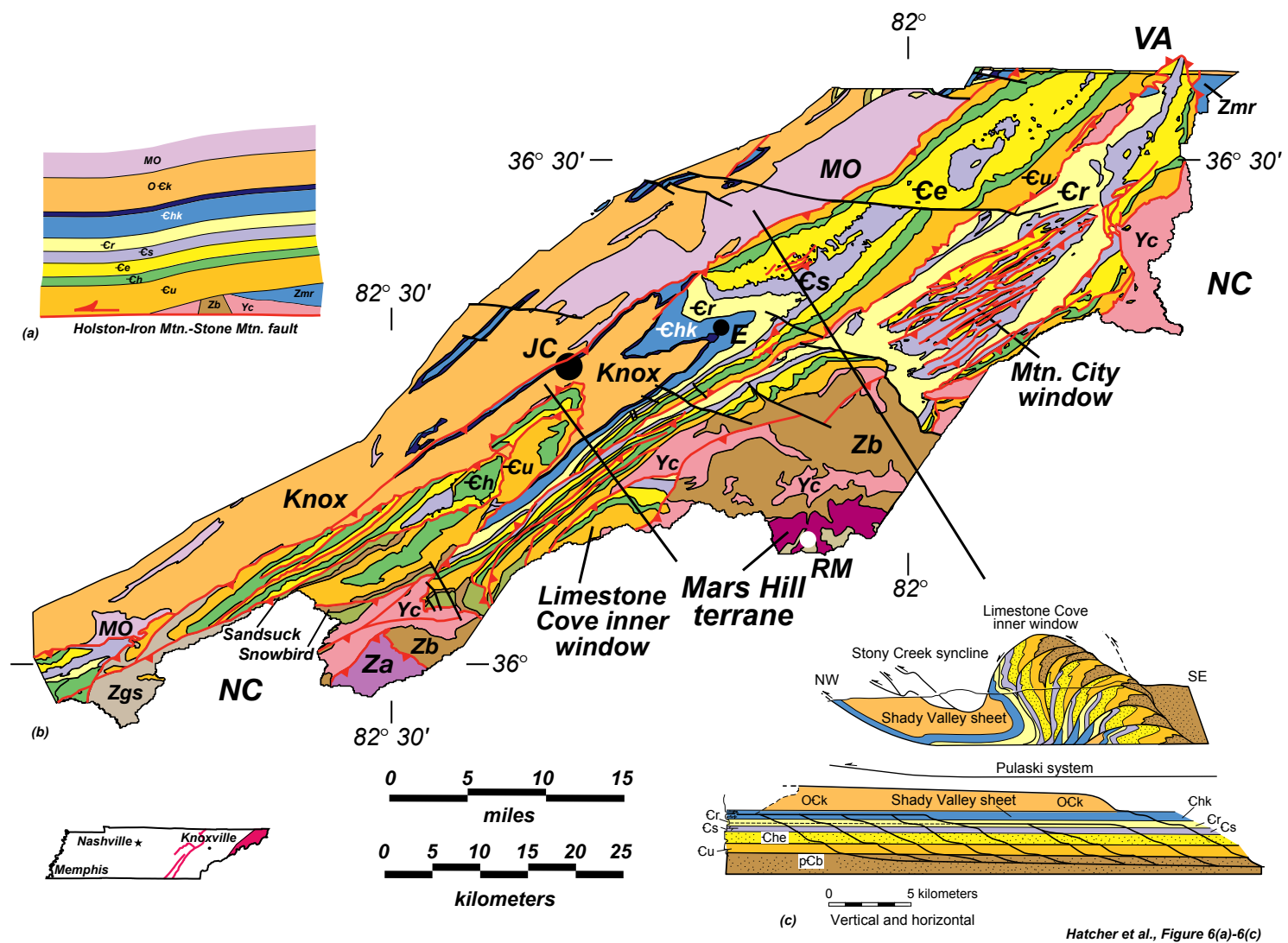
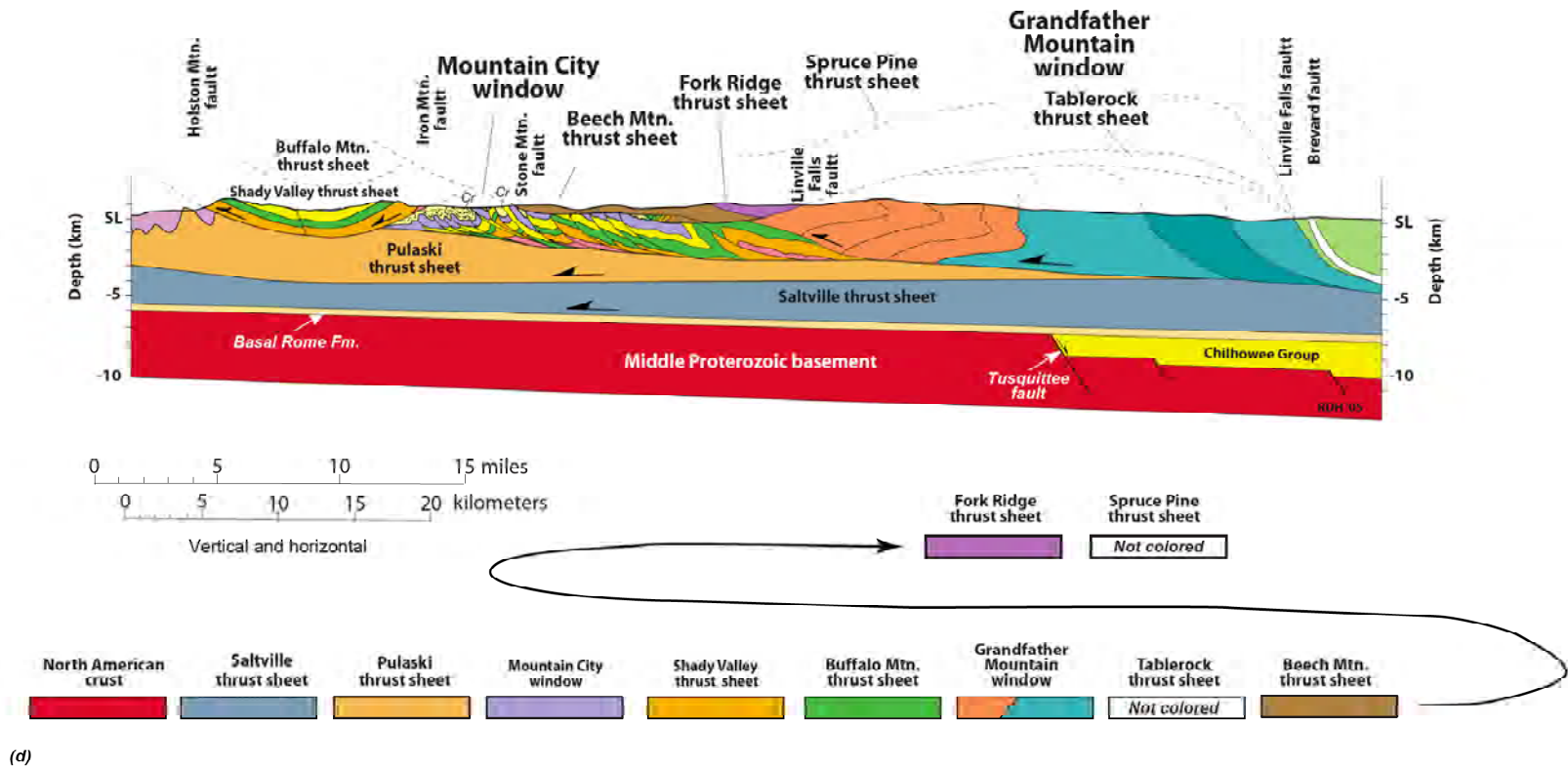


Figure 4-6 continued.



(Knox Group) (King and Ferguson, 1960; Hardeman, 1966). Stratigraphy in this thrust sheet thereby ties the thin-skinned Valley and Ridge structural style from the Valley and Ridge into the western Blue Ridge. We therefore attach much greater significance to this fault system and its relationships to thrust sheets to the NW and SE than did Woodward (1988). The Shady Valley thrust sheet arches above the Mountain City window and joins the Stone Mountain thrust sheet, which transports mostly basement, around the NE end of the Mountain City window (King and Ferguson, 1960, their Plate 1). The Shady Valley–Stone Mountain sheet represents a transition from the strictly thin-skinned sheets to the NW (Pulaski, Saltville) into the Stone Mountain basement sheet to the SE, bringing with them implications not only for the southern Appalachian foreland fold-thrust belt, but for foreland fold-thrust belts worldwide. This illustrates that the traditional thin-skinned thrusting concept should be modified to include thrusts that propagate from a subhorizontal detachment in the ductile-brittle transition into the sedimentary cover (e.g., Hatcher, 2004). The SE-dipping Holston–Iron Mountain thrust propagated from the basement through the upper Unicoi Formation (basal Chilhowee Group) into the Cambrian rift-to-drift sequence, suggesting that this fault system preserves a hanging-wall ramp from the ductile-brittle transition in the basement (Fig. 4-6; cross sections in King and Ferguson, 1960, their Plate 17). This thrust sheet thus preserves the lower detachment that formed in the basement and undeformed remnants of the overlying rifted-margin succession (Figs. 4-5 and 4-6). The Shady Valley–Stone Mountain thrust sheet thus provides an important structural tie from the Blue Ridge–Piedmont sheet into the southern Appalachian foreland fold-thrust belt. The Great Smoky thrust sheet farther southwest (Fig. 4-2a) less spectacularly preserves a lower detachment in the Cambrian (?) Sandsuck Formation (Walden Creek Group, Ocoee Supergroup), much of the Sandsuck Formation, all of the Chilhowee Group, Shady Dolomite, and part of the Rome Formation (Hardeman, 1966; King et al., 1968, their Plate 1; Carter, 1994, his Plate 1). Nevertheless, this bedding thrust provides another tie to southern Appalachian foreland fold-thrust belt geology, representing the easternmost thrust sheet in the Valley and Ridge.

The Great Smoky thrust sheet is cut off by the Miller Cove thrust sheet, which transports earlier deformed and metamorphosed Ocoee Supergroup rocks, and some Mesoproterozoic basement. The Miller Cove fault (and equivalents) is thus an abrupt western limit of the Blue Ridge–Piedmont sheet from the latitude of Knoxville, Tennessee, southward into Alabama (Fig. 4-2a), but the Shady Valley–Stone Mountain thrust sheet to the NE provides a less clear transition from the Blue Ridge–Piedmont sheet into the southern Appalachian foreland fold-thrust belt. Other frontal duplexes and remnants of Chilhowee Group rifted-margin sequence rocks occur from northern Georgia to Alabama (Costello, 1984; Sears, 1988), providing additional ties between Blue Ridge and southern Appalachian foreland fold-thrust belt structure.

BOUNDARIES OF SOUTHERN APPALACHIAN FORELAND FOLD-THRUST BELT DEFORMATION

Initial parameters prior to southern Appalachian foreland fold-thrust belt deformation consist of the basement surface, the basal geometry of the future Blue Ridge–Piedmont thrust sheet, and the mechanical properties of the rocks that comprise the deforming mass (Fig. 4-1). Temperature-pressure conditions, fluid pressure, and strain rate are additional influences on mechanical properties. The erosion surface maintained during deformation was a free surface of the deforming wedge (Davis et al., 1983), whereas the base of the Blue Ridge–Piedmont sheet geometry evolved during emplacement.

We have constructed contour maps of the top of the basement surface beneath the southern Appalachian foreland fold-thrust belt, and the base of the Blue Ridge–Piedmont sheet from industry, academic, and U.S. and state geological survey seismic reflection profiles (e.g., Fig. 4-7), surface geologic maps, and well data (Figs. 4-8 and 4-9). Crustal seismic lines in the more internal parts of the orogen (Cook et al., 1983; Costain et al., 1989) further delimit basement surface geometry even where thrust displacement on the Blue

Figure 4-7. (a) Industry across-strike seismic reflection profile from the Pine Mountain block southeastward to northeast of Knoxville. Note the steeper dip of faults southeast of the Pine Mountain fault. We assume that steepening occurred as the master décollement propagated westward rotating thrusts that had already formed to the southeast to steeper dips. Also note the gentle southeast dip of the basement surface (immediately beneath the series of strong reflectors—Rome Formation shale and sandstone—that rests on basement) from northwest to southeast. (b) ADCOH (Appalachian Ultradeep Core Hole Project site investigation) (1) seismic reflection line (west segment, Line 3, processing included automatic gain control and whitening; east segment, Line 1, included all of that in line 3 and time migration) and (2) automatic line drawing. (From Costain et al., 1989 and Hatcher et al., 1989, Plate 8). Despite the location of (b) deep in the crystalline Appalachians, the gently southeast-dipping set of reflectors resting on basement is still visible here, along with a strongly arched segment of the BRP sheet above an antiformal stack duplex. Locations of both seismic reflection lines are shown in Figure 2a.

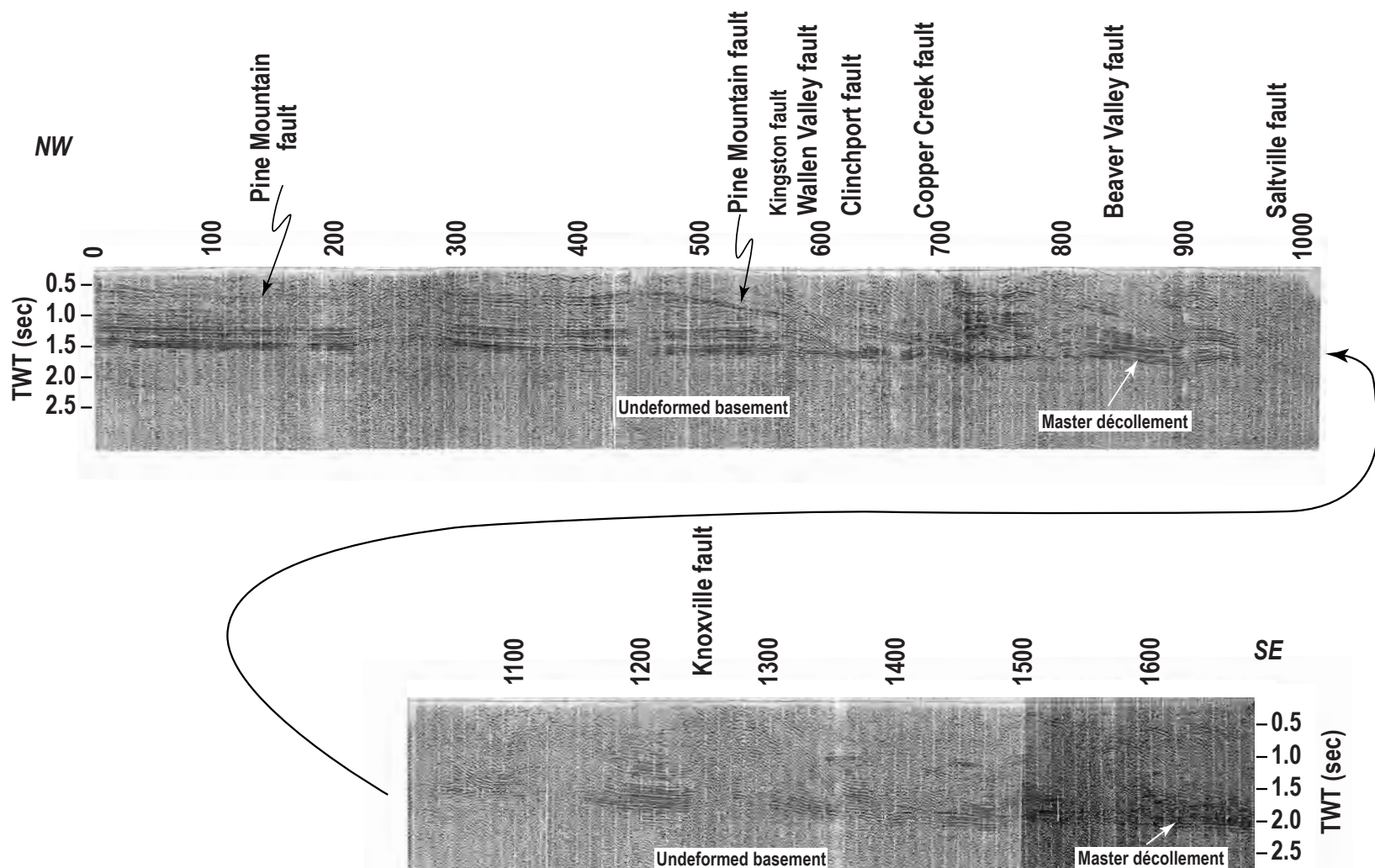


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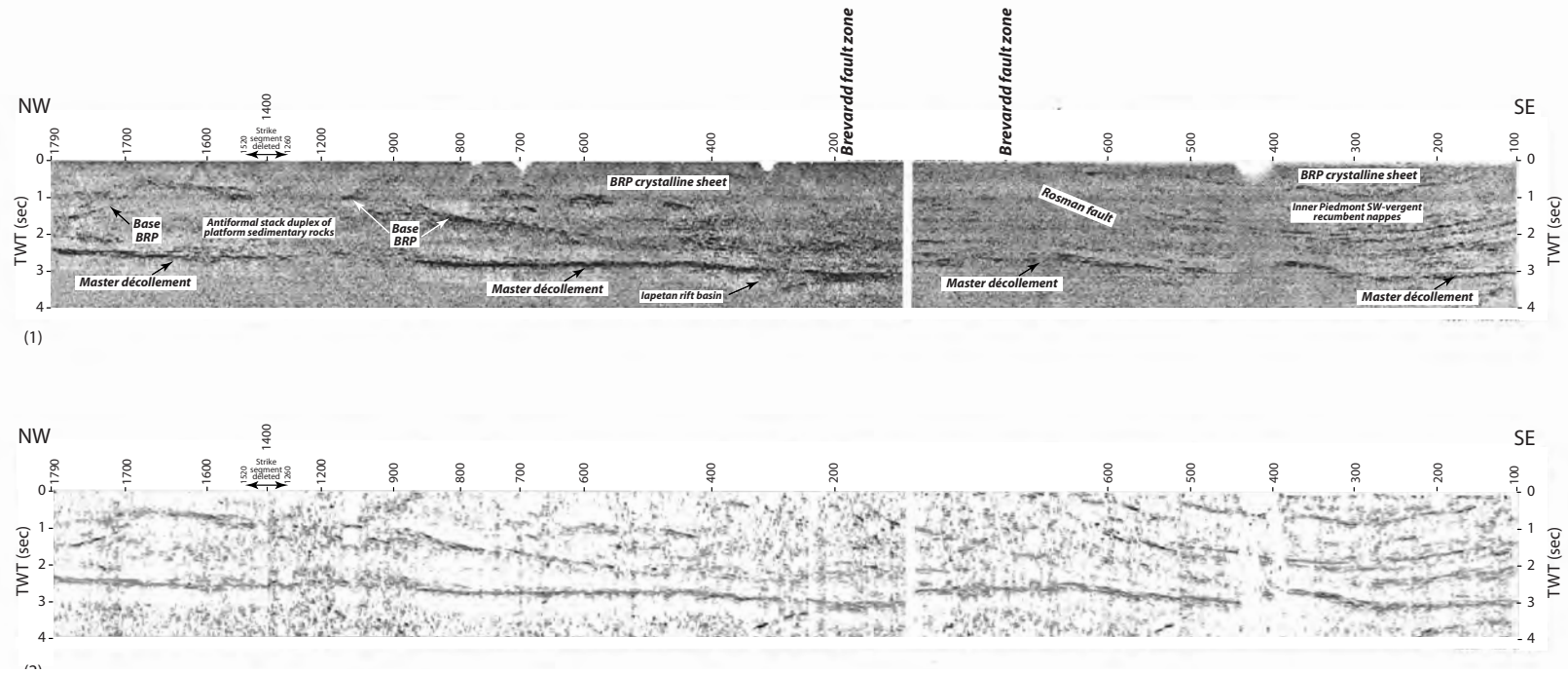


Figure 4-8. (a) Basement depths in the southern Appalachians estimated from seismic reflection data. (Compiled by R. D. Hatcher, Jr. and P. J. Lemiszki 1996-97; modified through 2005). (b) Picks and distribution of data used in construction of the basement surface.

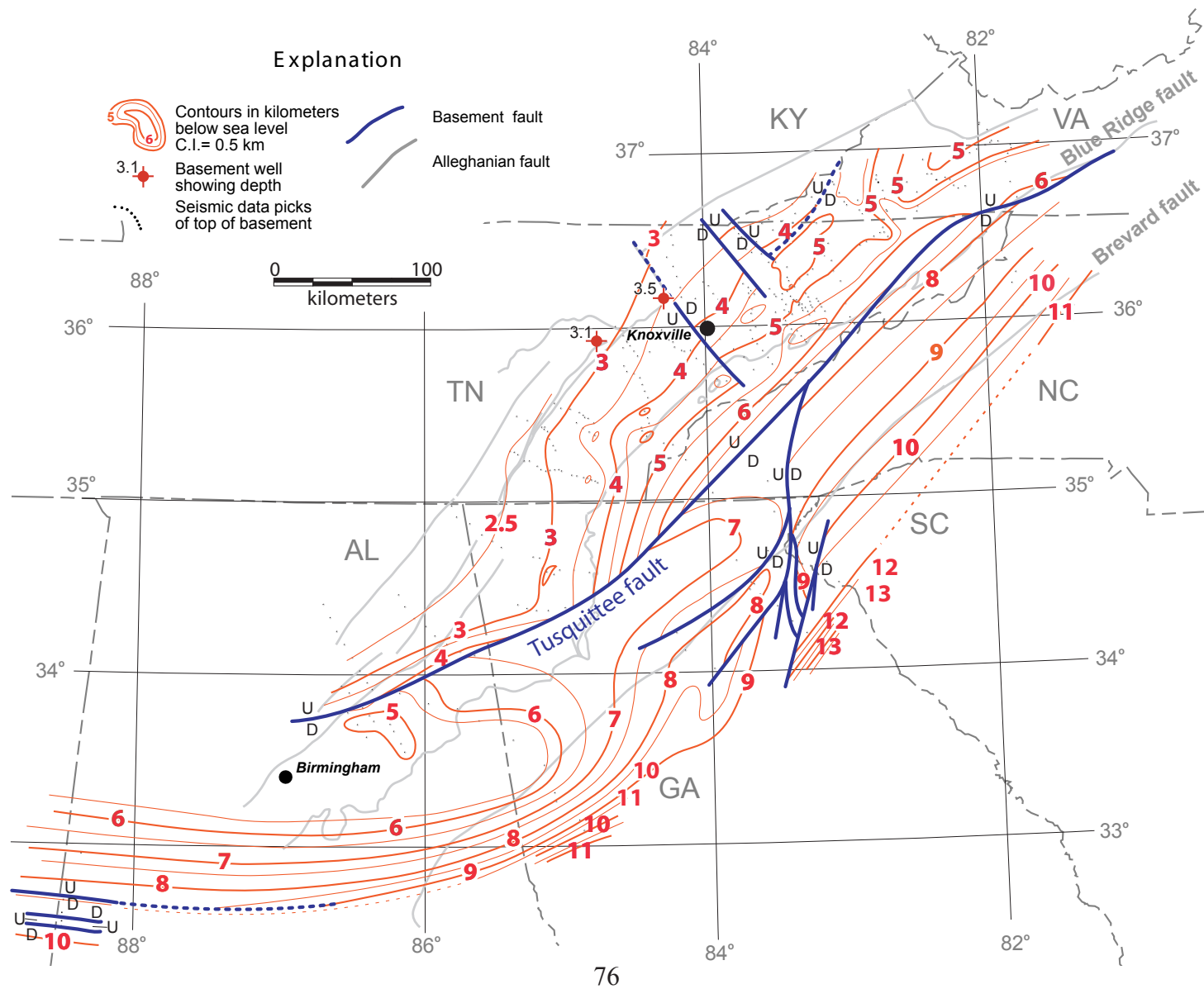
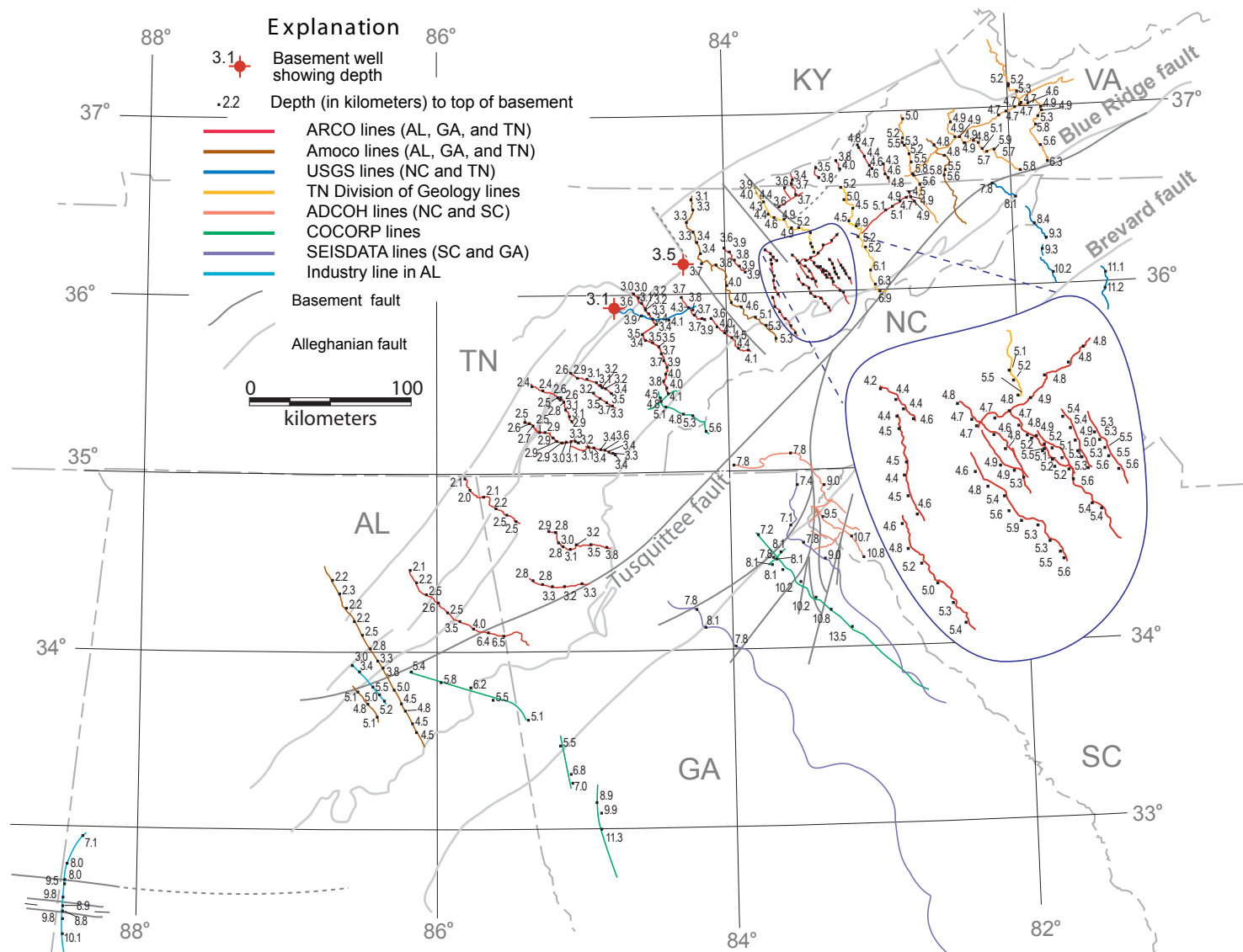


Figure 4-8 continued.



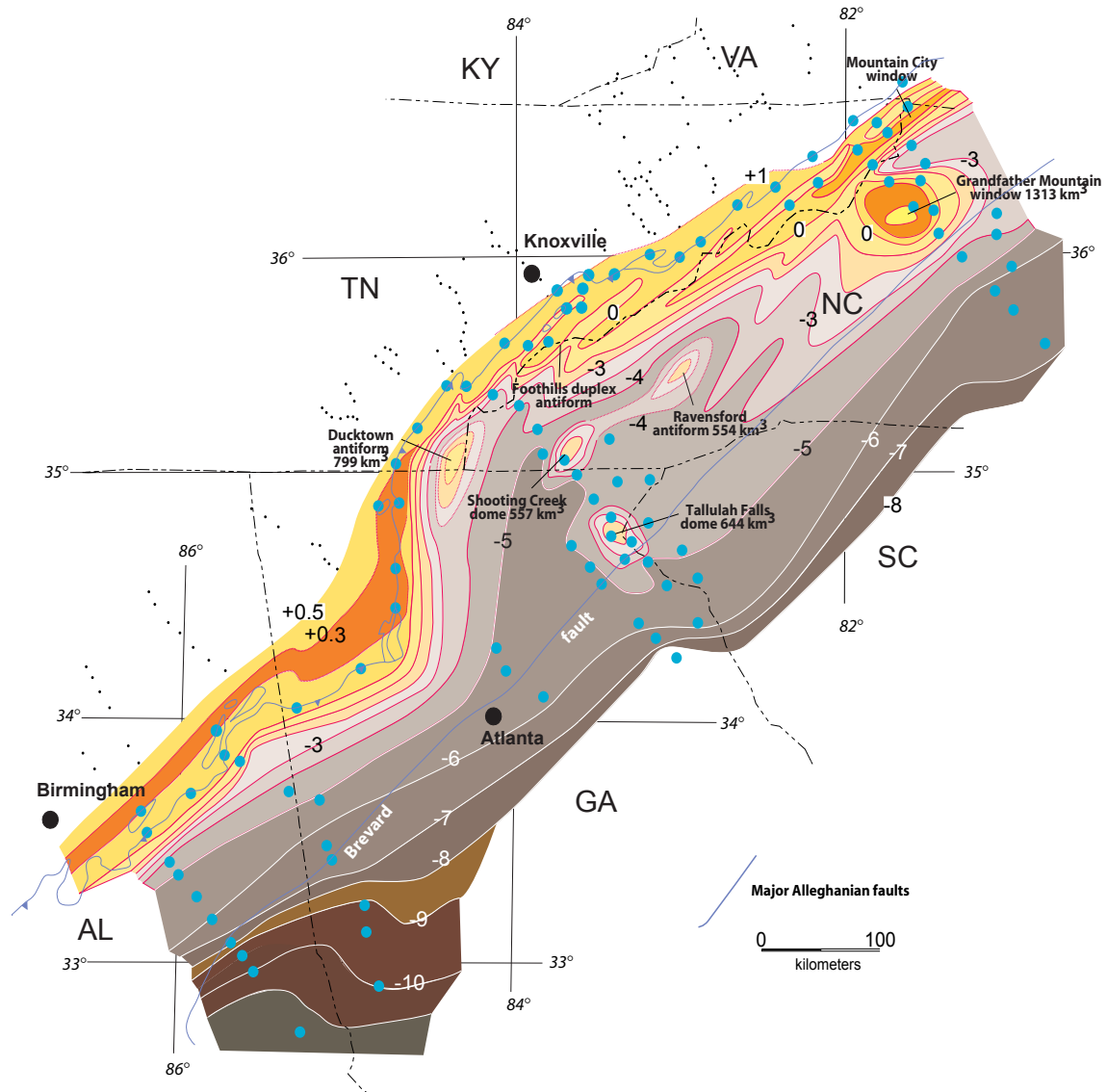
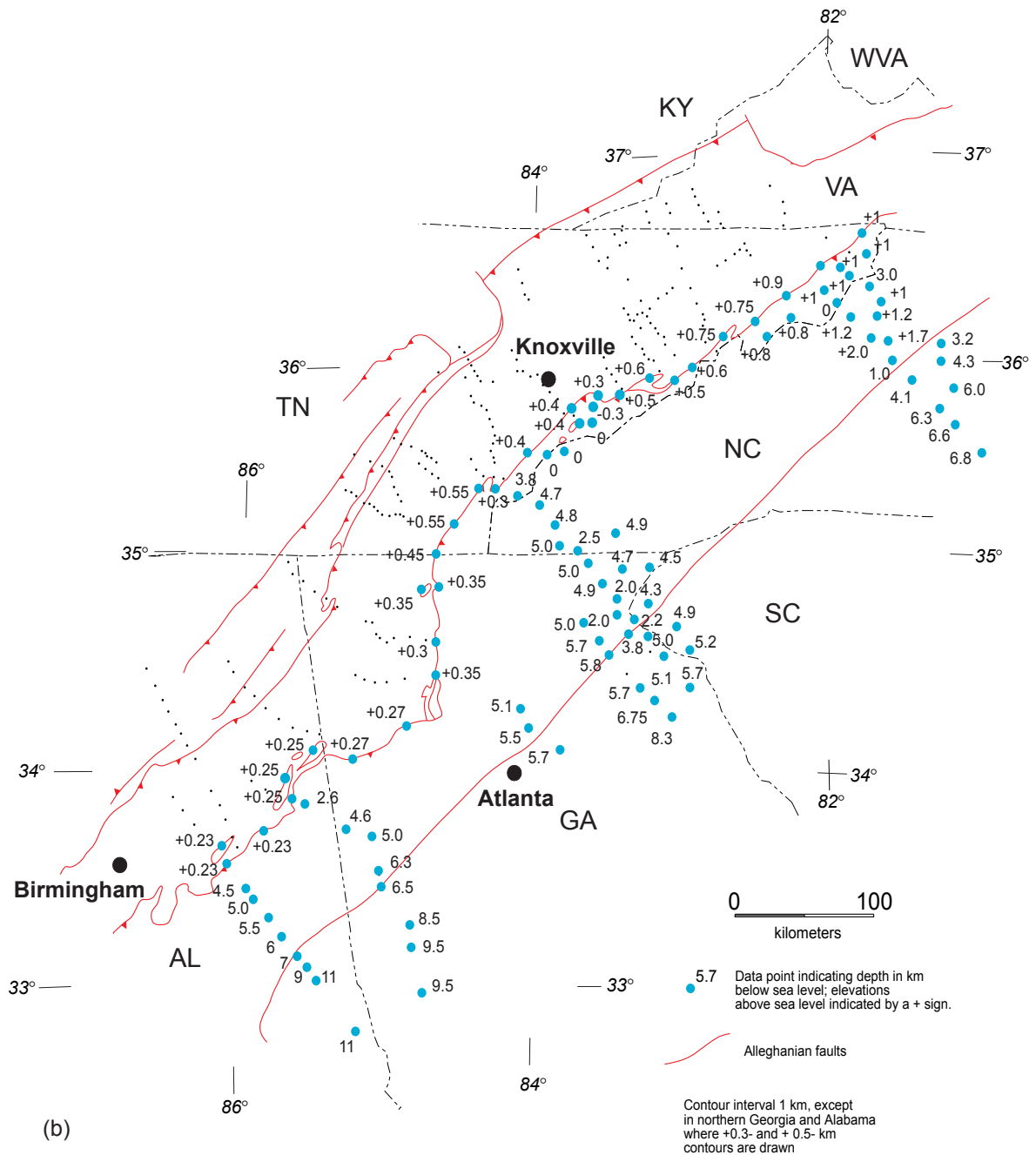


Figure 4-9. (a) Roof geometry of the SAFT (base of Blue Ridge–Piedmont thrust sheet): Preliminary estimate from seismic reflection and surface data in the southern Appalachians. Indicated volumes of closed structures (subthrust duplexes) were estimated using GeoSec™ 3–D. (b) Picks and distribution of data used in construction of the base of the BRP sheet. Blue dots indicate exact locations of points used for depth determination in seismic reflection profiles.

Figure 4-9 continued.



Ridge–Piedmont megathrust sheet exceeds 300 km. The basement and Blue Ridge–Piedmont maps were contoured by hand because of the nature and distribution of data.

The data employed are of variable quality and consist of unmigrated and migrated seismic-reflection profiles, collected using either vibroseis or dynamite sources (Fig. 4-7). The base of the sedimentary section (on top of basement) produces a strong reflector package that separates a lower, nearly transparent (reflection-free) basement from the highly reflective sedimentary section (Fig. 4-7). Although the base of the sedimentary section is relatively easy to see, few basement normal faults are apparent in the data (Figs. 4-7 and 4-8b). The depth to the top of the basement was determined by employing a constant velocity of 2.75 km/s (two-way travelttime, TWT) for Valley and Ridge seismic lines and 3.0 km/s TWT for seismic lines in the Blue Ridge and Piedmont. Two basement holes in Tennessee (Fig. 4-8) provided local calibration of estimated velocity.

Basement Surface Reconstruction

The basement surface beneath the southern Appalachian foreland fold-thrust belt (Fig. 4-8a) represents the surface formed during the Neoproterozoic as the Grenville mountains were eroded, and is also a post-Neoproterozoic to Early Cambrian rifting erosion surface. This surface has been imaged in 2-D seismic-reflection profiles, but no attempt has been made, before now, to construct a contoured map of this surface from these data. Watkins (1964) attempted a reconstruction using aeromagnetic data, but data limitations prevented him from recognizing many details. The basement surface consists of a gently SE-dipping surface cut by several (previously unrecognized) large- and small-displacement normal faults (Fig. 4-8a). Most faults dip toward the margin.

The most prominent basement feature beneath the southern Appalachian foreland fold-thrust belt and Blue Ridge–Piedmont sheet is a large normal fault traceable from Alabama to Virginia (Fig. 4-8a). This fault was first recognized by Thomas (1986) near Birmingham, Alabama, and was called the “Alabama basement fault” by Rankin et al.

(1989). We suggest renaming the entire fault the Tusquittee fault for a small town and mountains located in North Carolina about halfway along its mapped extent (Fig. 4-2b). Although several data gaps exist along the fault trace, the Tusquittee fault has a consistent 2.5 km down-to-the-SE displacement. Shumaker (1996) mapped a normal fault in southern West Virginia that connects northward with a major basement fault system in the central Appalachians; this fault may connect to the south with the northern end of the Tusquittee fault, where Shumaker estimated a displacement of ~300 m. The Tusquittee fault passes beneath the Blue Ridge–Piedmont thrust sheet between northern Georgia and Virginia, reappears in the Valley and Ridge in northeastern Tennessee, then trends back beneath the Blue Ridge–Piedmont sheet just north of the Tennessee-Virginia state line near the margin of the map. Thomas (1986) recognized the importance of the Tusquittee fault in localizing both sedimentation and subsequent deformation in the Alabama foreland fold-thrust belt.

The other dominant feature in the basement reconstruction is the prominent NE–SW–trending gradient located along the entire SE margin of the map (Fig. 4-8a). This gradient probably outlines part of the ancient Laurentian margin modified by Neoproterozoic–Cambrian rifting. The shallowing trend toward the SW may outline the transition from the Alabama promontory to the faulted “Tennessee” embayment (actually located in the Carolinas and NE Georgia). The gradient is truncated by the Tusquittee fault, particularly on its SE side. Moreover, the change in orientation of the gradient mimics the shape of the Alleghanian Blue Ridge structural front in Georgia, Tennessee, and Alabama. The palinspastic location of this feature may have influenced sedimentation patterns and subsequent deformation in the Appalachian basin in Georgia, Tennessee, and southwestern Virginia. The Tusquittee fault and accompanying increased slope of the basement surface do not correlate with the location of the “Appalachian gravity gradient” that Rankin (1975), and Hatcher and Zietz (1980), correlated with the location of the eastern subsurface limit of the platform at the latitude of the southern Appalachian foreland fold-thrust belt. Hatcher and Zietz (1980) recognized that the gravity gradient is a more complex feature because it

corresponds to the location of the central Piedmont suture in the hanging wall of the Blue Ridge–Piedmont sheet.

Smaller normal faults break the basement surface beneath the southern Appalachian foreland fold-thrust belt in Georgia, the Carolinas, and Tennessee (Fig. 4-8a). A concentration of NE-trending basement normal faults with displacements of 2 km or less was clearly imaged in Appalachian Ultradeep Core Hole Project (ADCOH) (Costain et al., 1989) and Consortium for Continental Reflection Profiling (COCORP) (Cook et al., 1983) deep seismic-reflection profiles, and in potential field data (Favret and Williams, 1988), beneath the Blue Ridge–Piedmont sheet in NE Georgia and adjacent South Carolina. One N-S fault in this system may join the Tusquittee fault.

Four small-displacement basement normal faults have been mapped in NE Tennessee and SW Virginia (Mitra, 1988) (Fig. 4-8a), and they extend from the Pine Mountain thrust sheet to the present Blue Ridge front. These faults strike NE and NW and have 0.25 to 1 km displacements. Available seismic-reflection data, however, poorly delimit their northeastward extent into Virginia, but the data indicate that they may end NE of Knoxville, Tennessee. We interpret one of these faults to lie directly beneath the Jacksboro fault. This fault may extend southeastward across the southern Appalachian foreland fold-thrust belt to immediately SW of the present surface location of the simple windows (Tuckaleechee Cove, Cades Cove, etc., see TCW in Fig. 4-2a) in the frontal Blue Ridge–Piedmont sheet. This fault steps down to the NE, and, together with two other NW-striking faults that step down to the SW, it defines a low in the basement surface that extends SE from beneath the Pine Mountain thrust sheet. These three faults have a similar orientation to cross-strike structural discontinuities and lineaments documented elsewhere in the Appalachian basin (Wheeler et al., 1979; Thomas, 1990). The fourth fault in this area steps down to the SE and strikes subparallel to the Tusquittee fault. This fault is interpreted to merge with one of the NW-striking faults and defines a triangular-shaped basement high beneath the Pine Mountain thrust sheet. How far this fault extends into Virginia is presently unknown.

Base of the Blue Ridge–Piedmont Sheet Reconstruction

The base of the Blue Ridge–Piedmont sheet was reconstructed from seismic-reflection and surface geologic data. It consists of an undulating surface that maintains a gentle homoclinal SE dip interrupted by numerous antiforms and synforms, some of which have several kilometers of structural relief (Fig. 4-9a). Several antiforms, including the Grandfather Mountain and Sauratown Mountains windows (in North Carolina), and the Pine Mountain window (in west-central Georgia and east-central Alabama), are now breached by erosion, and others, like the Tallulah Falls dome and Shooting Creek dome (and window) (Fig. 4-2b), have been crossed by seismic reflection lines (e.g., Costain et al., 1989). They reveal that early Paleozoic rifted-margin and platform rocks beneath the Blue Ridge–Piedmont sheet are deformed into antiformal stack duplexes (Boyer and Elliott, 1982; Hatcher et al., 1989a; Hatcher, 1991) (Figs. 4-7 and 4-9a).

These sub–Blue Ridge–Piedmont sheet antiforms are traceable far beyond their initially apparent limited extent (Fig. 4-9a). Frontal linear duplexes also developed obliquely and en echelon beneath the leading edge of the Blue Ridge–Piedmont sheet and are traceable for considerable distances beneath the sheet.

Additional Boundary Conditions

The deformation conditions for the eastern part of the southern Appalachian foreland fold-thrust belt deformed wedge beneath the Blue Ridge–Piedmont sheet in northern Georgia can be estimated from our reconstruction and existing data, including the threshold of greenschist-facies metamorphism (~300 °C, 400 MPa; Weaver and Broekstra, 1984). Because of its very large displacement, the Blue Ridge–Piedmont sheet doubtlessly was an erosion (emergent) thrust that accompanied surface exposure of much of the southern Appalachian foreland fold-thrust belt in the unconfined part of the deforming wedge. The updip limit of the belt is unknown, but conodont alteration index (CAI) data (Fig. 4-10a) and mineral assemblages provide important information about burial depth. Low-grade

metamorphic rocks with CAI values >4.0 are exposed in a large reentrant in Georgia (Epstein et al., 1977). Rocks in Tuckaleechee Cove and other simple windows farther north or along the frontal edge in Tennessee are not metamorphosed, where CAI values are 3.5 or less (Orndorf et al., 1988). These relationships suggest that the updip westward extent of the Blue Ridge–Piedmont sheet is near the present-day fault trace and that the sheet was never very thick here. In Georgia, however, it may have extended as much as 30 km farther west of the present-day trace, and was at least 3 km thicker than the frontal 30 km in Tennessee, as suggested by the metamorphic grade of footwall rocks. This close correlation of Blue Ridge–Piedmont sheet thickness with CAI data in the southern Appalachian foreland fold-thrust belt is important: much lower CAI values in the more western parts of the belt indicate much lower pressure and temperature conditions during deformation. Higher CAI and illite crystallinity index values in northeastern Georgia, southwestern Virginia, and northeasternmost Tennessee indicate not only higher pressure and temperature conditions during deformation, but also much greater westward extent of the Blue Ridge–Piedmont sheet in these two areas immediately following emplacement. Additional temperature data from burial curves (e.g., Steinhauß and Walker, 1997) indicate that Cambrian and Ordovician rocks in the western part of the belt in Tennessee were subjected to temperatures of 120–175 °C, whereas the same rocks in the eastern exposed belt were subjected to temperatures of 145–200 °C, again consistent with CAI data. Illite crystallinity index studies by Weaver and Broekstra (1984) from the southern Appalachian foreland fold-thrust belt immediately west of the Blue Ridge–Piedmont sheet in northwestern Georgia yield results that parallel the CAI data: illite crystallinity index values decrease systematically toward the SE and identify an anchizone to epizone metamorphism plateau SE of a steeper west- to-east gradient from lower to higher grade across the Georgia southern Appalachian foreland fold-thrust belt (Fig. 4-10b).

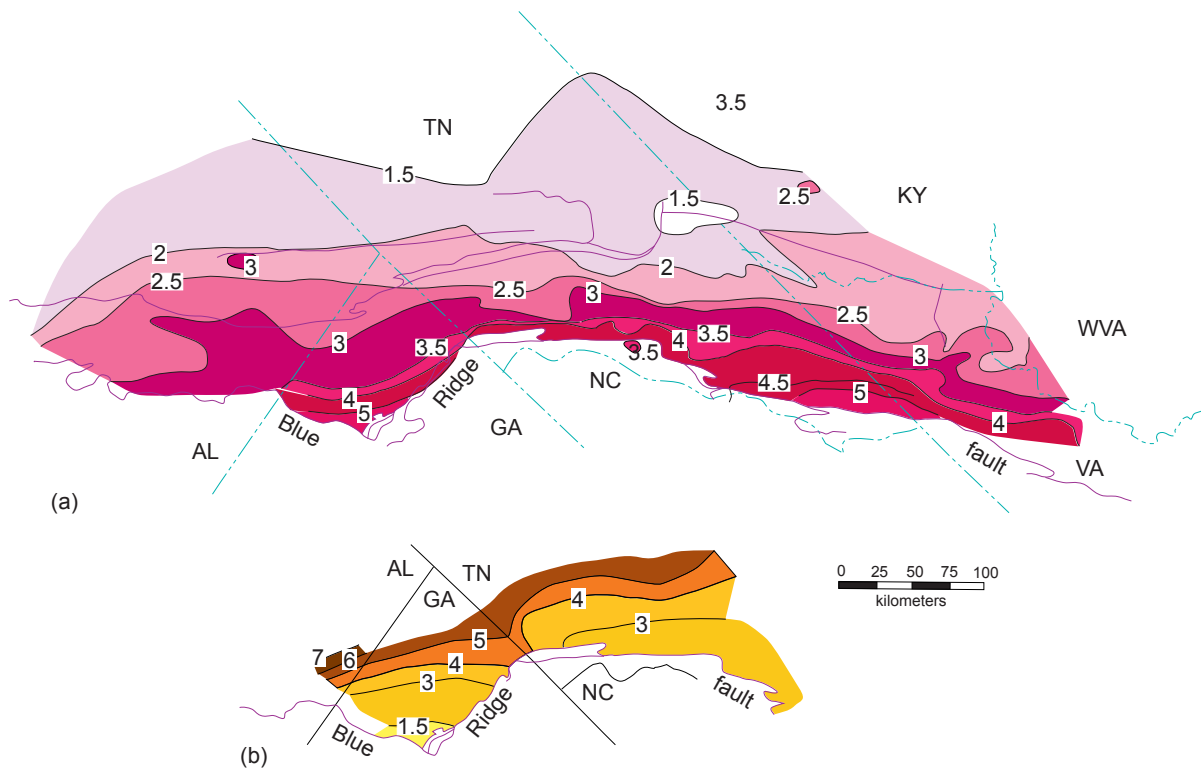


Figure 4-10. Thermal maturation indicators for the SAFT. (a) Conodont alteration index (CAI) map for the SAFT (after Epstein et al., 1977; Harris and Milici, 1977; Orndorf et al., 1988). Note that higher CAI values indicate higher grade. (b) Illite crystallinity index values for part of the SAFT (after Weaver and Broekstra, 1984). Note that lower illite crystallinity index values indicate higher grade and that values of less than 1.5 are in the chlorite zone of metamorphism.

DISCUSSION

We have described the upper and lower bounding surfaces of the southern Appalachian foreland fold-thrust belt, along with many properties of the deformed belt. These surfaces are not only bounding surfaces, but they are also structures that strongly influenced the internal geometry of the deformed volume of platform sedimentary rocks that lie between. The wedge geometry that existed before deformation was likely deformed in an inside-out fashion, but with some smaller displacement, out-of-sequence thrusts forming in Tennessee where maximum shortening occurs (Dumplin Valley, Chestuee, Wildwood). This suggests subcritical Coulomb wedge behavior (e.g., Woodward, 1987) in the southern Appalachian foreland fold-thrust belt until shortening approached maximum values, then deformation of the SE part of the wedge may have switched to supercritical behavior. The Blue Ridge–Piedmont sheet free surface would have developed with $\alpha = 0$ as the Blue Ridge–Piedmont sheet propagated along the ductile-brittle transition; the surface slope (β) would likewise have developed with an angle of 0° . As the Blue Ridge–Piedmont sheet ramped from the ductile-brittle transition first into unmetamorphosed weak shales of the rifted-margin succession, and then into the Rome Formation resting on Mesoproterozoic basement, dip on the detachment would have increased on the ramp, then decreased once the Blue Ridge–Piedmont thrust propagated into the Rome Formation and arrived on the platform. The topographic free surface of the Blue Ridge–Piedmont thrust probably maintained a near-uniform elevation throughout once it passed the crustal ramp. The brittle Rosman fault component of the Brevard fault zone that lies within the Blue Ridge–Piedmont sheet also is an out-of-sequence thrust (e.g., Hatcher, 2001), but this fault does not extend past the projected region of maximum displacement of the Blue Ridge–Piedmont sheet—between Atlanta and the Grandfather Mountain window (Fig. 4-2a). It likely propagated into a suitably oriented part of the existing Brevard fault zone as the Blue Ridge–Piedmont sheet approached the crustal ramp (Hatcher, 1971, 2001; Thomas, 1986).

Correlations of stratigraphic patterns and basement structures are needed for accurate reconstruction of a deeply eroded curved orogen. If unique stratigraphic patterns or anomalies are identified, such as a thickness increase related to a local depocenter, thrust-system restoration could be guided by basement features that may have caused thickness changes, such as basement faults (Thomas, 1986).

Timing

All available data suggest that the basement faults in our basement surface reconstruction are old (post–565 Ma; Aleinikoff et al., 1995), rift-related features that formed during development of the Neoproterozoic-Cambrian Laurentian continental margin. There is no evidence of Neoproterozoic or younger reactivation of the New York–Alabama aeromagnetic gravity lineament (King and Zietz, 1978), or the Clingman aeromagnetic lineament (Nelson and Zietz, 1983) (Fig. 4-2a). Correlations between palinspastically restored Cambrian and Ordovician isopach thicknesses in the southern Appalachian foreland fold-thrust belt (e.g., Rodgers, 1953; Hasson and Haase, 1988) and the Tusquittee fault suggest that thickness trends may be tied to early Paleozoic movement on the fault. None of the basement faults were reactivated during Alleghanian folding and thrusting, but they may have served as important passive features that influenced sedimentation and structural development (e.g., Thomas, 1986). Inversion of basement structures and the development of foreland basement uplifts, like those in the Rockies and Andes, did not occur here during deformation, although crustal loading has been linked to the evolution of cratonic arches and basins, such as the Cincinnati arch and Appalachian basin (Quinlan and Beaumont, 1984). Subduction polarity with respect to the North American craton probably was not the same in the southern and central Appalachians as in these Tertiary orogens, and we suggest that A-type subduction was dominant in the Alleghanian orogen.

Primary and Secondary Basement Controls

Our basement surface reconstruction permits evaluation of the primary and secondary controls of basement structure on the structural development of the southern Appalachian foreland fold-thrust belt, but the data currently define the basement surface transition from the Tennessee salient to the Alabama recess better than the transition into the Virginia recess. For example, the change in orientation of the subsurface basement gradient from Tennessee into Alabama is partly reflected in the curvature of the overlying thrust belt (Figs. 4-2 and 4-3). The concave map geometry toward the craton and thinned stratigraphies of recesses (e.g., Thomas, 1977) may be viewed as primary basement obstacles that influenced regional stress/strain fields, particle trajectories, and shortening directions within the deforming southern Appalachian foreland fold-thrust belt. Particular attributes of the basement surface that may have affected the structural development of the thrust belt are: (1) changes in gradient, both parallel and oblique to thrust-belt structural strike; (2) basement obstacles; and (3) basement steps caused by Neoproterozoic to Cambrian rift-related normal faulting.

Boyer (1995) and Mitra (1997) proposed that a direct relationship exists between the dip of the basal detachment and the width of a thrust belt. We define the width of the southern Appalachian foreland fold-thrust belt as the distance between the Blue Ridge–Piedmont sheet and the Pine Mountain or Cumberland Plateau faults, but we recognize that the trailing edge of the foreland has been overridden by the Blue Ridge–Piedmont sheet and that the thrust belt does not extend past the Wartburg basin (Fig. 4-2a). Furthermore, we assume that the increased slope in the basement surface represents the original dip of the basal detachment, because the Rome Formation is in the exposed hanging walls of all major thrust sheets in the southern and central Appalachians, except the Pine Mountain and Cumberland Plateau thrust sheets (and Plateau sheets farther north), which formed along an upper-level detachment (Gwinn, 1964; Harris and Milici, 1977). There also had to have been negative isostatic effects of overthrusting of the Blue Ridge–Piedmont sheet onto the platform and the load imposed, but these may have been mitigated by rebound as the

Appalachians were eroded. The basement surface gradient NW of the Tusquittee fault is a fairly consistent 1.5° except for the area beneath and to the SE of the Pine Mountain thrust sheet, where it is interrupted by several normal faults that strike parallel and perpendicular to the strike of the southern Appalachian foreland fold-thrust belt. Ignoring the narrowing of the belt near the Wartburg basin, the consistent basement surface gradient correlates well with the consistent width of the thrust belt. The gradient flattens slightly in northern Georgia, which corresponds to a slight narrowing of the width of the fold-thrust belt, especially when the forelandward extent of the Blue Ridge–Piedmont sheet is restored. Therefore, there may be a direct but subtle relationship between the width of the fold-thrust belt and the basement surface gradient NW of the Tusquittee fault.

Although data are sparse, the basement surface gradient SE of the Tusquittee fault is quite variable, and it is disrupted by the N-S–striking normal-fault complex imaged in the ADCOH seismic-reflection lines (Fig. 4-6). In NE Tennessee and northwestern North Carolina, the U.S. Geological Survey seismic-reflection data (Harris et al., 1981) indicate that the basement surface slope dip doubles to $\sim 3^\circ$ SE. In the area between the Tusquittee fault and the normal-fault complex, there may be a subtle basement high, and the gradient may even slope gently back to the NW toward the Tusquittee fault. The relatively flat basement surface defining the basement high begins to steepen onto the Alabama promontory where the gradient slopes gently to the NE toward the normal-fault complex. The basement gradient on the SE side of the Alabama promontory is similar to that in NE Tennessee. If we again assume that the basement surface gradient parallels the dip of the basal detachment, the taper angle of the advancing thrust wedge will decrease as it advances over the Tusquittee fault (or elsewhere) onto the less steep basement gradient to the NW. This would cause the thrust wedge to thicken internally for it to be able to continue advancing onto the foreland. Such a scenario may be responsible for the late (Permian?) reactivation of the Brevard fault, which occurs within the “rigid” indenter at this point in the development of the southern

Appalachian foreland fold-thrust belt. It may also be responsible for the development of the antiformal-stack duplexes in platform rocks beneath the Blue Ridge–Piedmont thrust sheet.

Steps in the basement surface may also influence the development and location of thrust-belt structures. A down-to-the-SE step on a normal fault, such as the Tusquittee fault, will form a notch in the basement surface. A notch can form a perturbation in the regional stress field that initiates development of a thrust fault at the front of an advancing thrust-belt wedge. The Pulaski fault is considered to be one of the major southern Appalachian foreland fold-thrust belt thrust faults that extends from Virginia into Tennessee, where it is overridden by the Blue Ridge–Piedmont thrust sheet. Palinspastic restorations of the thrust belt restore the Pulaski fault to approximately overlie the step in the basement surface produced by the Tusquittee fault. Although speculative, it is possible that nucleation of the Pulaski fault occurred by a perturbation in the regional stress field as the thrust wedge advanced over the Tusquittee fault.

Thomas (1986) similarly concluded that the Tusquittee fault is responsible for the out-of-sequence, brittle, dip-slip Alleghanian reactivation of the Brevard fault zone (Rosman fault) as the Blue Ridge–Piedmont thrust sheet passed up the ramp and temporarily locked at the inflection point at the crest of the ramp. This also accompanied transportation of numerous Knox Group horses (see Hatcher et al., 1989a, their Figure 31; Hatcher, 2001) into the Brevard fault zone.

Secondary basement structural controls on sedimentation patterns also exist in the southern Appalachian platform margin. These effects produced lithologic and thickness variations that changed the mechanical characteristics of the stratigraphy. Isopach maps based on existing palinspastic reconstructions of part of the southern Appalachian foreland fold-thrust belt contain thickness trends from the Rome Formation through the Knox Group that correlate with mapped basement features (Read in Rankin et al., 1989). Regional thickness gradients and depocenters, however, do not directly overlie mapped basement features, with the exception of the southwestern extent of the Tusquittee fault

near Birmingham, Alabama (Thomas, 1986). Potentially correlative basement features that may be responsible for these anomalies lie just SE of these thickness trends. This would be expected, because the isopach maps employ palinspastic base maps that used poorly constrained data on the amounts and directions of thrust displacement. Although the estimated displacement of each thrust fault may be questioned, correlation of a stratigraphic anomaly with a basement feature may improve estimates of total shortening in the southern Appalachian foreland fold-thrust belt.

Major facies changes and the westward limit of thick rifted- margin sedimentation, along with the locus of the Cambrian rift- to-drift transition, were probably controlled by the shape of the basement surface. Rodgers (1953) pointed out that major facies changes occur in the Conasauga (Middle-Upper Cambrian) and Knox (Upper Cambrian–Lower Ordovician) Groups at the Pulaski fault in Tennessee and SW Virginia. The abrupt westward disappearance of pre–Rome Formation clastics in thrust sheets west of the Blue Ridge frontal faults has long been known, with the exception of those beneath the Pulaski sheet in southwestern Virginia (Johnson, 1993). Palinspastic restoration of the thrust sheets in the Tennessee southern Appalachian foreland fold-thrust belt by Roeder and Witherspoon (1978) and Finney et al. (1996) provided rough estimates of the original locations of major faults that record these changes. The Tusquittee fault appears to be located west of the major facies change in the retrodeformed Cambrian-Ordovician carbonate bank. This basement fault not only influenced facies development but may also have served as a fault that nucleated several smaller-displacement faults in the Birmingham anticlinorium in Alabama (Thomas, 1986).

Internal Deformation of the Southern Appalachian Foreland Fold-Thrust Belt

The broad arcuate trace of the Blue Ridge–Piedmont sheet is probably partly related to the original shape of the continental margin, as suggested by basement surface geometry (Thomas, 1991) (Fig. 4-8a), because the Blue Ridge–Piedmont sheet is largely composed of the already deformed and metamorphosed rifted-margin succession and older basement, with

only the frontal Great Smoky fault system behaving as a thinned-skinned thrust. Additional factors that probably contributed to the curvature of this system are heterogeneous strain that produced nonparallel particle trajectories within the Blue Ridge–Piedmont sheet and southern Appalachian foreland fold-thrust belt.

The shape of the Blue Ridge–Piedmont indenter was partly determined by the shape of the Neoproterozoic–Cambrian continental margin, but its earlier Paleozoic history prior to being transported onto the Laurentian platform also influenced its shape. The rocks comprising proximal parts of the thrust sheet were polydeformed and metamorphosed and were likely accreted to the most distal part of the Laurentian margin during the Taconic orogeny. A group of suspect and exotic terranes was later accreted to the Taconian collage during the Late Devonian– Mississippian Neoacadian orogeny (e.g., Merschat et al., 2005). Both the Taconian and Neoacadian events formed new continental crust—basement—that was cold and rigid by the time the late Alleghanian collision occurred to complete formation of the indenter and transport it onto the Laurentian margin as the Blue Ridge–Piedmont sheet (Hatcher, 1999, 2004).

A curved foreland fold-thrust belt, like the southern Appalachian (Fig. 4-2), is not likely to have deformed by straight-line particle trajectories and plane strain within thrust sheets, because particle trajectories should curve in an orogen that curves through an arc of 30° from northern Georgia to southwestern Virginia (Figs. 4-2a and 4-3). In addition to an originally irregular continental margin, basement faults, stratigraphic thickness and facies changes, and the original shape of the Blue Ridge–Piedmont sheet indenter also influenced emplacement trajectories of both individual thrust sheets and total volume strain of the southern Appalachian foreland fold-thrust belt (Fig. 4-2b). Intuitively, 3-D heterogeneous deformation should be favored, but Ferrill and Groshong (1993) determined that displacement vectors are parallel in a curved portion of the French Subalpine chain. Displacement vectors in the Jura Mountains, Helvetic Alps, and Penninic Alps, however, display a radiating pattern (Platt et al., 1989; Hindle and Burkhard, 1999). Displacement

vectors in the southern Appalachian foreland fold-thrust belt can be approximated using normals to hinge lines of map-scale folds (Fig. 4-2b), and available mesoscopic data (folds, slickenlines, tectonic stylolites). These data indicate curved thrust-emplacement pathways (Fig. 4-2b). Despite apparent the balance of many 2-D cross sections, the absence of plane strain diminishes their utility for quantifying particle-displacement trajectories.

Displacement vectors and magnitudes for the Pine Mountain and Cumberland Plateau faults (Fig. 4-2b) were determined from the orientations of the Russell Fork, Jacksboro, and Emory River tear faults (Fig. 4-2a). Although these faults may not all be kinematically linked, they probably are representative of the kinematics in the part of the southern Appalachian foreland fold-thrust belt where they occur and when they formed. Displacement vectors are assumed to parallel motion on tear faults, which are generally orthogonal to the strike of the thrust faults. The Emory River and Jacksboro faults distend a 15° arc across the Wartburg basin (Figs. 4-2a and 4-2b). Both the Cumberland Plateau and Pine Mountain faults reach maximum displacement on the tear faults at the SW (Jacksboro) and NE (Emory River) ends of each fault block, respectively. Displacement along the Russell Fork fault at the NE end of the Pine Mountain block (Fig. 4-2a) is ~ 7 km but increases southwestward to 17 km along the Jacksboro fault (Rich, 1934). The Cumberland Plateau fault system reaches its maximum displacement of 5 km at its NE end along the Emory River tear fault. Linear displacement particle-path trajectories with unequal displacement are probably responsible for creating the 15° arc between the two fault systems, and these faults may represent the last displacement path trajectory of the southern Appalachian foreland fold-thrust belt.

Alternatively, both the curvature in the southern Appalachian foreland fold-thrust belt and the 15° angular discordance may be attributed to rotations about vertical Euler poles, analogous to the analysis of Price and Sears (2000) and Sears and Hendrix (2004) for the northern Rockies. This alternative model would also require formation of the Tennessee segment of the southern Appalachian foreland fold-thrust belt on a promontory, not a reentrant in the continental margin.

Determination of regional slip-line orientations may be possible in a foreland fold-thrust belt using Hansen's (1971) method, which employs fold hinge-line orientations and shear sense of asymmetric mesoscopic folds. We have attempted to apply the method using particle trajectories derived from both mesoscopic (slickenlines, tectonic stylolites, asymmetric folds) and macroscopic structures (hinges of narrow mapped folds) (Fig. 4-2b). If this is a correct indicator of trajectories within the thrust sheets in which the synclines and other indicators occur, the southern Appalachian foreland fold-thrust belt sheets restore to an area to the SE in the Carolinas and Georgia beneath the present Blue Ridge–Piedmont sheet (Figs. 4-11 and 4-12b). A mechanism involving homogeneous strain and outward propagation from the Blue Ridge–Piedmont indenter would predict that the thrusts in this region have smaller displacements toward the outer convex arcs of the southern Appalachian foreland fold-thrust belt and greater displacement in the inner convex arcs of the thrust belt. This is not the case, however, because the southern Appalachian foreland fold-thrust belt in the Tennessee salient is dominated by two or three large thrusts separated by a number of smaller-displacement thrusts. The outermost thrusts, Pine Mountain and Sequatchie Valley–Cumberland Plateau, do have small displacements.

An array of cross sections has been constructed around the Tennessee salient and subsequently retrodeformed (Figs. 4-11 and 4-12). Different fault systems can be traced though the cross-section array from Virginia to SE Tennessee, with smaller-displacement thrusts terminating within the array. It is clear from the sections that the master detachment propagated along the Rome Formation and ramped across the stronger carbonate section. Most southern Appalachian foreland fold-thrust belt thrusts were oversteepened at present outcrop following NW propagation of the next more western thrust, and their listric character is evident in both seismic-reflection profiles (e.g., Fig. 4-7a) and these cross sections. The overlapping retrodeformed sections and map (Figs. 4-12a and 4-12b) again point out the difficulty of understanding 3-D deformation in the southern Appalachian foreland fold-thrust belt or any strongly curved segment of a foreland fold-thrust belt. Dominance of

Figure 4-11. Cross sections around the Tennessee salient constructed using surface and seismic reflection data. Ocoee Supergroup and Chilhowee Group rocks of the BRP sheet are shades of greenish brown. The light blue color in Section 1 consists of basement and Grandfather Mountain Formation of the Grandfather Mountain window and frontal thrust sheets (see Fig. 6d for detailed section), Ashe-Tallulah Falls Formation rocks along the southeast flank of the Grandfather Mountain window and in the Inner Piedmont southeast of the Brevard fault zone, and the imbricated platform and rifted-margin sedimentary rocks in the subsurface beneath the BRP. The Rome Formation and overlying Conasauga Group are shades of brown. The Knox Group is tan. Middle and Upper Ordovician rocks are pink. Silurian, Devonian, and Mississippian rocks are purple. Mississippian where separated is blue. Pennsylvanian rocks are green. WV–Wallen Valley fault. WOM–Whiteoak Mountain fault. CC–Copper Creek fault. BV–Beaver Valley fault. S–Saltville fault. DV–Dumplin Valley fault. DVC–Dumplin Valley-Chestuee fault system. HM–Holston Mountain fault. GS–Great Smoky fault.

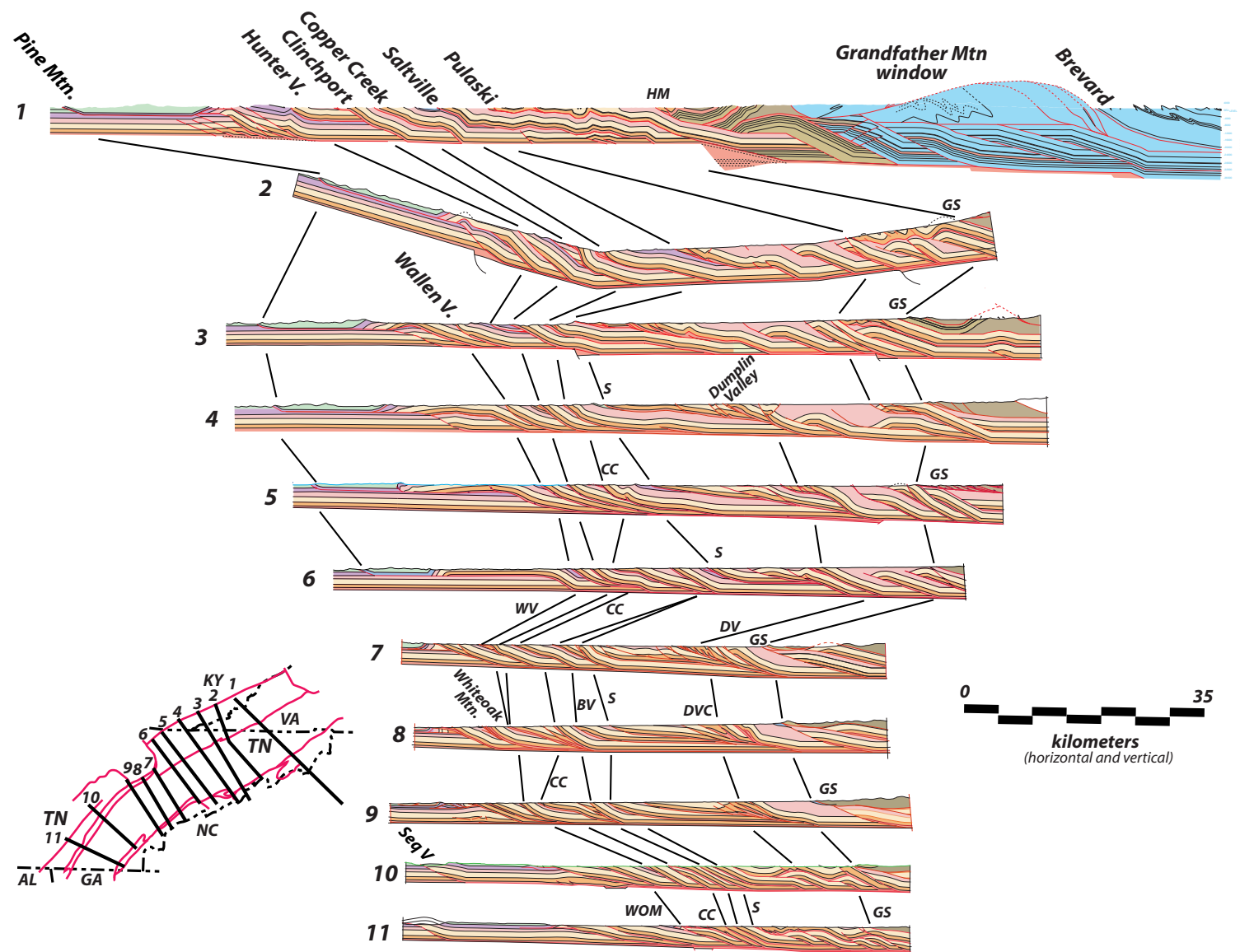
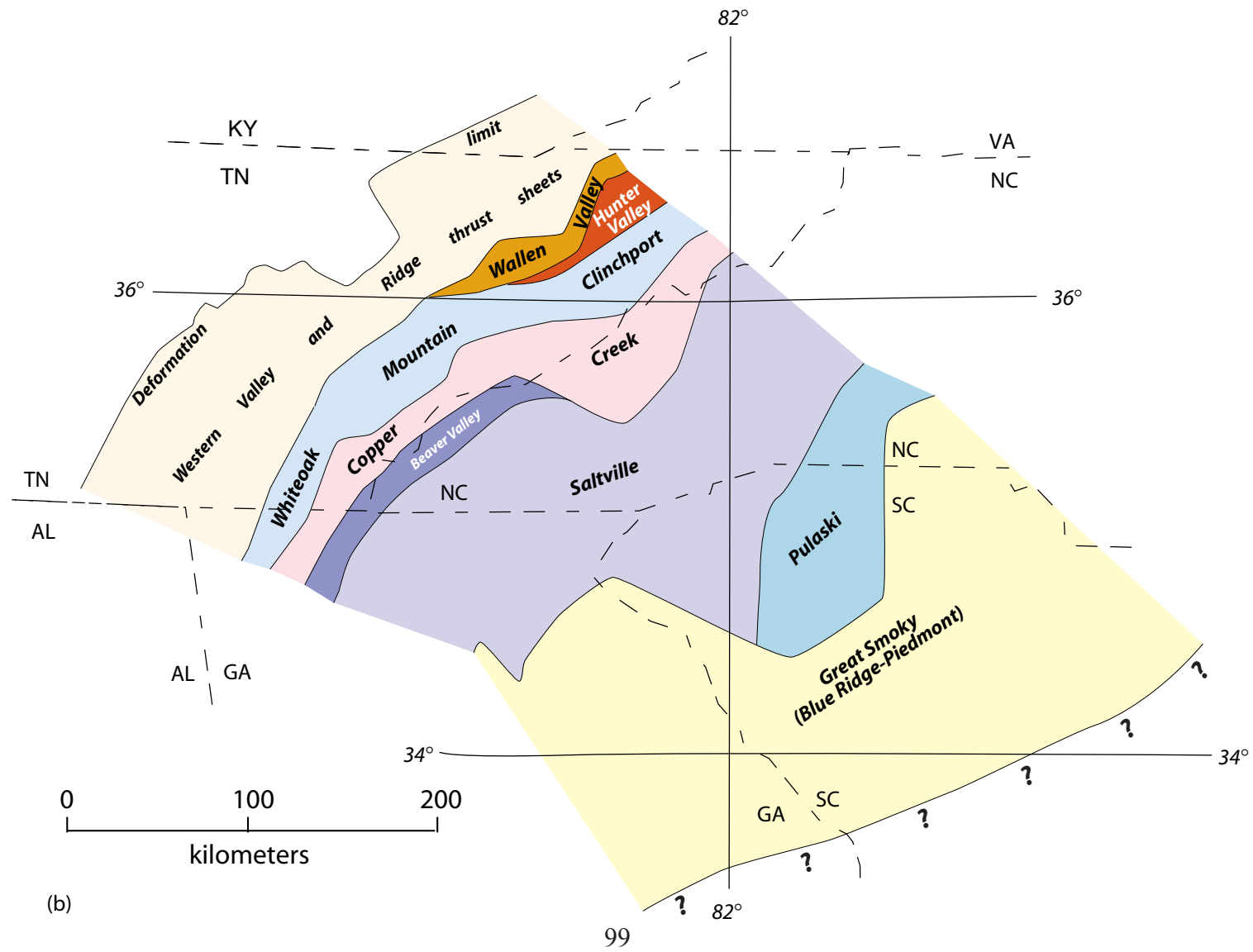


Figure 4-12. (a) Restored sections shown in Figure 11 arrayed in map view around the Tennessee salient. Note the overlap of some sections. (b) Palinspastic map constructed from sections in Figure 12(a). Note the sinuous geometry of the Great Smoky thrust near the southwestern edge of the map, in the area where the retrodeformed sections overlap.

Figure 4-12 continued.



(b)

certain faults, like the Saltville, occurs from southwestern Virginia to Georgia, but there also is a change in character of the Saltville at the latitude of Knoxville, where much of its displacement from Knoxville southward is transferred to the Beaver Valley fault. The Whiteoak Mountain fault dominates the western Valley and Ridge from Georgia to NW of Knoxville, where it branches and displacement is transferred to the Wallen Valley, Hunter Valley, and Clinchport faults. These faults are then traceable northeastward into Virginia, where they terminate. The relatively small-displacement, moderate along-strike length thrusts (Dumplin Valley, Chestuee, Wildwood; Fig. 4-2a) probably formed as out-of-sequence thrusts in a domain otherwise dominated by folding (Rodgers, 1953; and see Hardeman [1966] for map relationships) (Fig. 4-11). Retrodeformation of Valley and Ridge thrusts and the Blue Ridge–Piedmont sheet (upper bound) above the basement (lower bound) has permitted us to gain a better understanding of the shortening in the southern Appalachian foreland fold-thrust belt region of maximum total displacement (Figs. 4-2c and 4-13). The retrodeformed across-strike displacement of each thrust sheet through which a 2-D section is constructed across the southern Appalachian foreland fold-thrust belt (or any foreland fold-thrust belt) should have a relationship to the indenter, here the Blue Ridge–Piedmont sheet, such that

$$X = \sum_{i=1} x_i < Y_{gs}, \quad (1)$$

where X is total displacement estimated from retrodeformed foreland thrust sheets in a 2-D cross section, x_i is the displacement of individual faults in the section, and Y_{gs} is total displacement on the Blue Ridge–Piedmont sheet (or any indenter in any foreland fold-thrust belt). Equation 1 can be expanded to express the displacements of individual thrust sheets across the southern Appalachian foreland fold-thrust belt as

$$X_f = x_1 + x_2 + x_3 + \dots + x_n < Y_{gs}. \quad (2)$$

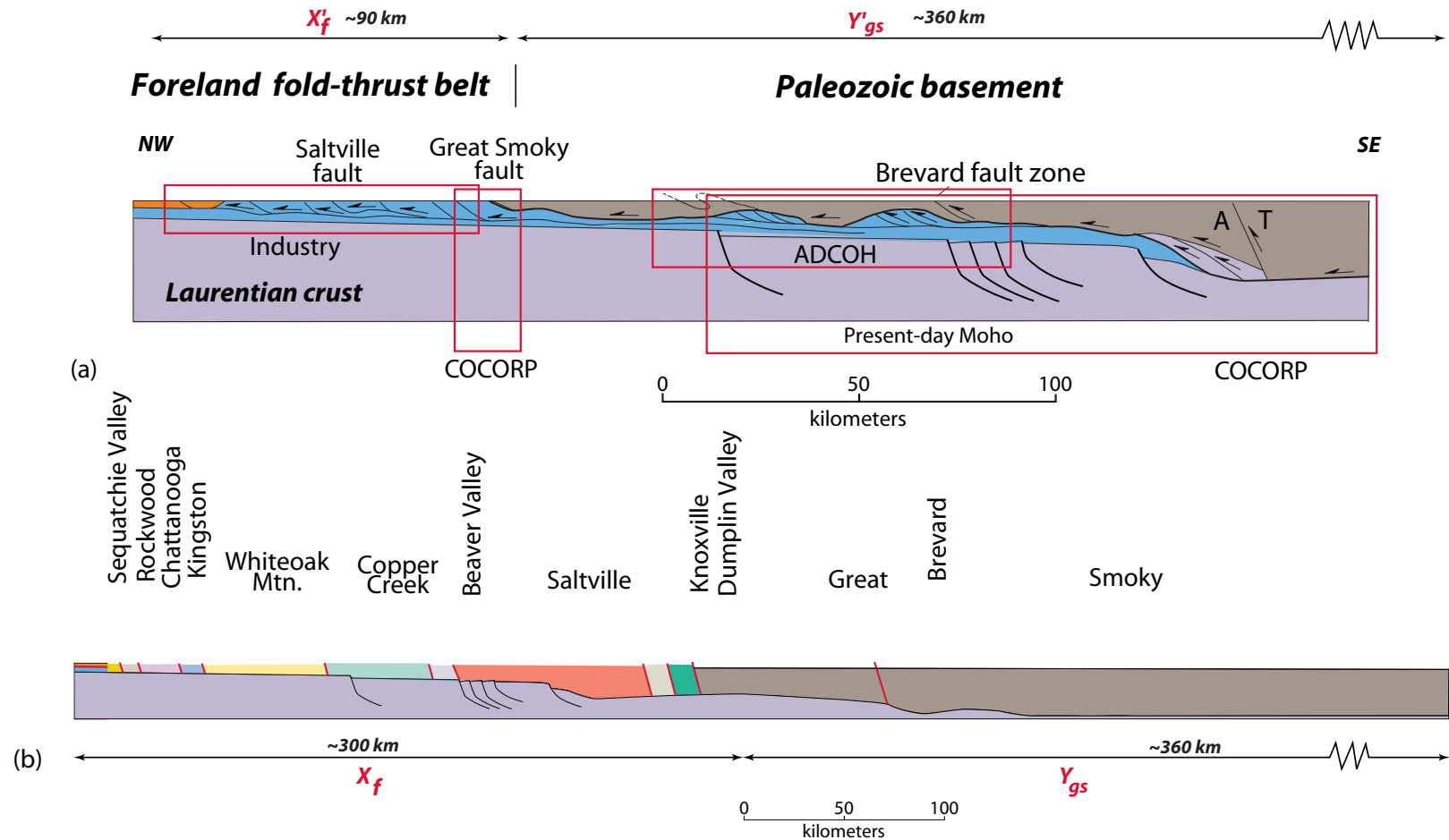


Figure 4-13. Restoration of the BRP section in Figure 2b. (a) Unrestored section showing locations of seismic reflection data (red boxes indicate sources of data) employed for construction of the section. X'_f is deformed width of the foreland fold-thrust belt; Y'_{gs} is the deformed width of the Great Smoky (BRP) thrust sheet. (b) Restored sections cartoon constructed by pulling apart the foreland thrusts and placing tectonic units end to end according to estimated displacements, but without respect to geometry, with the BRP thrust sheet shown intact. X_f is undeformed width of the foreland fold-thrust belt; Y_{gs} is the undeformed width of the BRP thrust sheet.

For individual thrust sheets in the Figure 4-13 cross section (from west to east), x_1 is the Sequatchie Valley thrust sheet, x_2 is the Rockwood thrust, x_3 is the Chattanooga thrust sheet, etc. (Table 4-1). If X_r is the width of retrodeformed foreland thrust sheets placed end to end, the width of the deformed thrust sheets in the southern Appalachian foreland fold-thrust belt would sum to less than the retrodeformed width. The cold Blue Ridge–Piedmont sheet, however, is shortened internally only by out-of-sequence thrusts (e.g., the Rosman fault, with ~20 km displacement; Hatcher, 2001), so the Blue Ridge–Piedmont indenter did not shorten proportionally, and

$$X_f' \ll Y_{gs}' + Y_{ros}', \quad (3)$$

where X_f' is the deformed width of the foreland fold-thrust belt, Y_{gs}' is the displaced emergent Blue Ridge–Piedmont sheet indenter, and Y_{ros}' is the displacement on the Rosman fault. The internal isolated domes in the Blue Ridge–Piedmont sheet probably also formed by interactive footwall-duplex arching of the advancing Blue Ridge–Piedmont thrust sheet (Hatcher, 1991) as it drove the southern Appalachian foreland fold-thrust belt deformation in front of and beneath it. These antiforms and synforms may ultimately have partially locked the Blue Ridge–Piedmont thrust sheet, transferring motion to the deforming southern Appalachian foreland fold-thrust belt footwall rocks. They also probably contain additional tens to >100 km of shortening not initially accounted for in Equations 1, 2, and 3. Taking this component into account, Equation (3) can be modified to

$$X_f' + X_d' = Y_{gs}' + Y_{ros}', \quad (4)$$

where X_d' is the amount of shortening in the sedimentary section beneath the Blue Ridge–Piedmont sheet.

Table 4-1. Estimated displacements for southern Appalachian thrust system named faults along regional cross section in Figure 4-12

<i>Fault</i>	<i>Minimum Total Displacement (km) (heave + throw)</i>	<i>Basis</i>
Sequatchie Valley-Cumberland Plateau overthrust	5	Last ramp toward foreland in system, and throw at ramp takes up most displacement; v. small displacement W of ramp
Rockwood	7	Width; short strike length
Chattanooga	20	Width; short strike length
Kingston	10	Width; short strike length
Whiteoak Mountain	80	Mid Ord. facies boundary; throw; long strike length
Copper Creek	50	Width; moderate strike length
Beaver Valley	10	Motion transferred from Saltville W of Knoxville; short strike length
Saltville	100	Width; v. long strike length (VA to AL); facies changes in Mid Ord.
Knoxville-Rocky Valley	10	Width; short strike length
Dumplin Valley-Chestuee	10	Width; short strike length; fold-related; may be out of sequence.
<i>Foreland Total</i>	<i>302</i>	
<i>Great Smoky</i>	<i>360</i>	Great strike length; measurable subsurface width based on seismic reflection data.

Expansion of this discussion to a detailed 3-D reconstruction of the internal parts of the southern Appalachian foreland fold-thrust belt wedge will permit better understanding of the kinematics and mechanics for development of the thrust stack in this and other curved foreland fold-thrust belts. Our recognition of the role played by a major crystalline thrust sheet and the other boundaries of the thrust system as controlling elements in the formation of the southern Appalachian foreland fold-thrust belt may represent some progress toward understanding the 3-D development of this and other foreland fold-thrust belts. Even so, present-day 3-D balancing techniques are at best “semiquantitative considerations of material balance” (Laubscher, 1988, p. 1313).

CONCLUSIONS

1. Boundaries of the southern Appalachian foreland fold-thrust belt consist of the basement surface below the belt, the base of the Blue Ridge–Piedmont sheet above, and the eroded topographic free surface of both the southern Appalachian foreland fold-thrust belt and Blue Ridge–Piedmont sheet. Additional boundary conditions consist of temperature and pressure maxima.

2. The basement surface observed beneath the southern Appalachian foreland fold-thrust belt is likely the same as it was throughout the Paleozoic, except for the effects of Alleghanian thrust loading. It is interrupted by several down-to-the-SE normal faults with displacements up to 3 km. The extensive Tusquittee fault is traceable from Alabama to Virginia. In addition, a major steepening of slope of the basement surface has been identified farther east on the Laurentian margin and similarly has been traced from Alabama to Virginia.

3. Palinspastic locations of southern Appalachian foreland fold-thrust belt thrusts suggest that these basement surface features may have profoundly affected original facies distributions and subsequent localization of faults and other structures as the southern Appalachian foreland fold-thrust belt was deformed.

4. The base of the Blue Ridge–Piedmont sheet is a SE- dipping surface interrupted by numerous antiforms that represent duplexes composed of southern Appalachian foreland fold-thrust belt footwall rocks. As these duplexes were constructed, they deformed the Blue Ridge–Piedmont thrust sheet as it moved forward. Many of these antiforms along the front of the sheet are quite linear, have relatively low structural relief (<2 km), and are traceable for many tens of kilometers; others farther into the sheet have more of an elliptical shape and several kilometers of structural relief.

5. The original shape of the basement surface exerted major influence on the deformed shape of the southern Appalachian foreland fold-thrust belt, as well as on the displacement vectors that tracked thrust-sheet emplacement.

6. Particle trajectories must curve in an orogen that traces a 30° arc from the inflection point of maximum curvature in N Georgia to the corresponding inflection point in SW Virginia, where thrusts have unequal displacements, so plane strain may have occurred locally but not regionally.

7. Plastic rheology for the entire thrust belt better addresses the particle trajectory problem than Coulomb behavior, but neither addresses problems of mechanics of localization of fault families, out-of-sequence thrusts, thrust spacing, and other attributes.

8. Displacement vectors within the southern Appalachian foreland fold-thrust belt may represent slip lines that track body deformation in the deforming wedge. Heterogeneous strain is responsible for the 3-D deformation plan of the southern Appalachian foreland fold-thrust belt, and probably other curved foreland fold-thrust belts.

9. Displacements of southern Appalachian foreland fold-thrust belt thrusts sum approximately to the minimum restorable displacement on the Blue Ridge–Piedmont megathrust sheet. Sub–Blue Ridge–Piedmont deformation of southern Appalachian foreland fold-thrust belt rocks (not quantifiable), along with out-of-sequence thrusting within the Blue Ridge–Piedmont sheet, increases the total displacement on the thrust system.

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PART 5

Between a rock and a hard place: Basement and indenter-influenced deformation in the Tennessee salient

ABSTRACT

The Tennessee salient is one of a series of curves in the southern and central Appalachian orogen from Alabama to New York. Multiple generations of geologic mapping and recently available industry seismic lines delimit the subsurface geometry. Although explanations for the location of the salient (original shape of the rifted margin, location of a thick wedge of sedimentary rocks) and general geometry (indenter-controlled) have been suggested, a kinematic model for its deformation has been stymied by a scarcity of penetrative deformation (contrasted with the Pennsylvania salient or the Jura). Map- and meso-scale structures and previous serial cross-section compilations suggest that the salient likely developed by radial thrusting. This kinematic model is problematic, as traditional techniques of cross-section construction and restoration create a room problem in the hinterland where, in a region with significant shortening, large thrust sheets must be restored to much smaller volumes or even points, and restored cross sections intersect. Recent work in the Tennessee salient with calcite twin strain and paleomagnetism indicates that structures did not rotate during development of the salient, and that faults originated as curved in a radial stress field. These data alone are insufficient to develop a kinematic model for the salient. A closer look at palinspastically restored cross sections, combined with these indicators of strain history, can add more detail to the kinematic development of the salient. Reconstruction of the foreland basin is problematic, however, as the indenter (the Blue Ridge-Piedmont composite crystalline thrust sheet) has an irregularly shaped front that is unlikely to be normal to the primary transport direction along its entire length. Where the front of the indenter is oriented oblique to transport, the maximum shortening direction is oblique to the transport direction, and is also likely oblique to the particle displacement paths. A new geometric technique is proposed for estimating particle displacement paths and reconstructing the foreland basin around a map-scale curve in a fashion consistent with the kinematic indicators. Based on this reconstruction, I propose that: 1) the Tennessee salient is

a primary arc that formed by a combination of uniform displacement in one direction (plane strain) and transport-parallel simple shear; 2) most major faults initiated with a curved shape in front of the irregularly shaped Blue Ridge-Piedmont indenter; 3) particle displacement trajectories and bulk-shortening directions are not parallel in all parts of the salient; 4) displacement trajectories differ among and, in some cases within, individual thrust sheets; 5) transport in the southern Appalachian fold-thrust belt may have occurred by movement on networks of minor faults, which permitted forelandward propagation of the curved faults without causing rotation; and 6) palinspastic restoration around curved orogens must be treated differently in primary arcs and secondary arcs (oroclines). Although the technique does not provide a unique solution, the resulting palinspastic restoration is kinematically admissible, geometrically reasonable, and more realistic than restoring thrust sheets to smaller and smaller areas along radially fanning cross sections. This result may be useful for accurate palinspastic restorations of facies in basins with no vertical axis rotations and low penetrative strain.

INTRODUCTION

The Tennessee salient is one of a series of alternating foreland-convex (Tennessee, Pennsylvania) and foreland-concave (Alabama, Virginia, and New York) curves in the southern and central Appalachian orogen. Although other Appalachian map-scale curves are recognized in physiographic/structural provinces from the Plateau to the Blue Ridge, the Tennessee salient is most apparent in the foreland fold-thrust belt that developed due to diachronous collision with Africa (Hatcher, 2002) during the Alleghanian orogeny. Rocks ranging from Neoproterozoic post-Grenville rift fill to the Pennsylvanian synorogenic clastic wedge are deformed in a classic thin-skinned fold-thrust belt (Rich, 1934; Thomas, 1977, 2006) along the eastern Laurentian margin. The structure and kinematic history of the curved Appalachian orogen have been discussed in some detail (Rodgers, 1970; Rankin, 1976; Thomas, 1976, 1977; Roeder et al., 1978; Schwartz and van der Voo, 1983; Eldredge et al.,

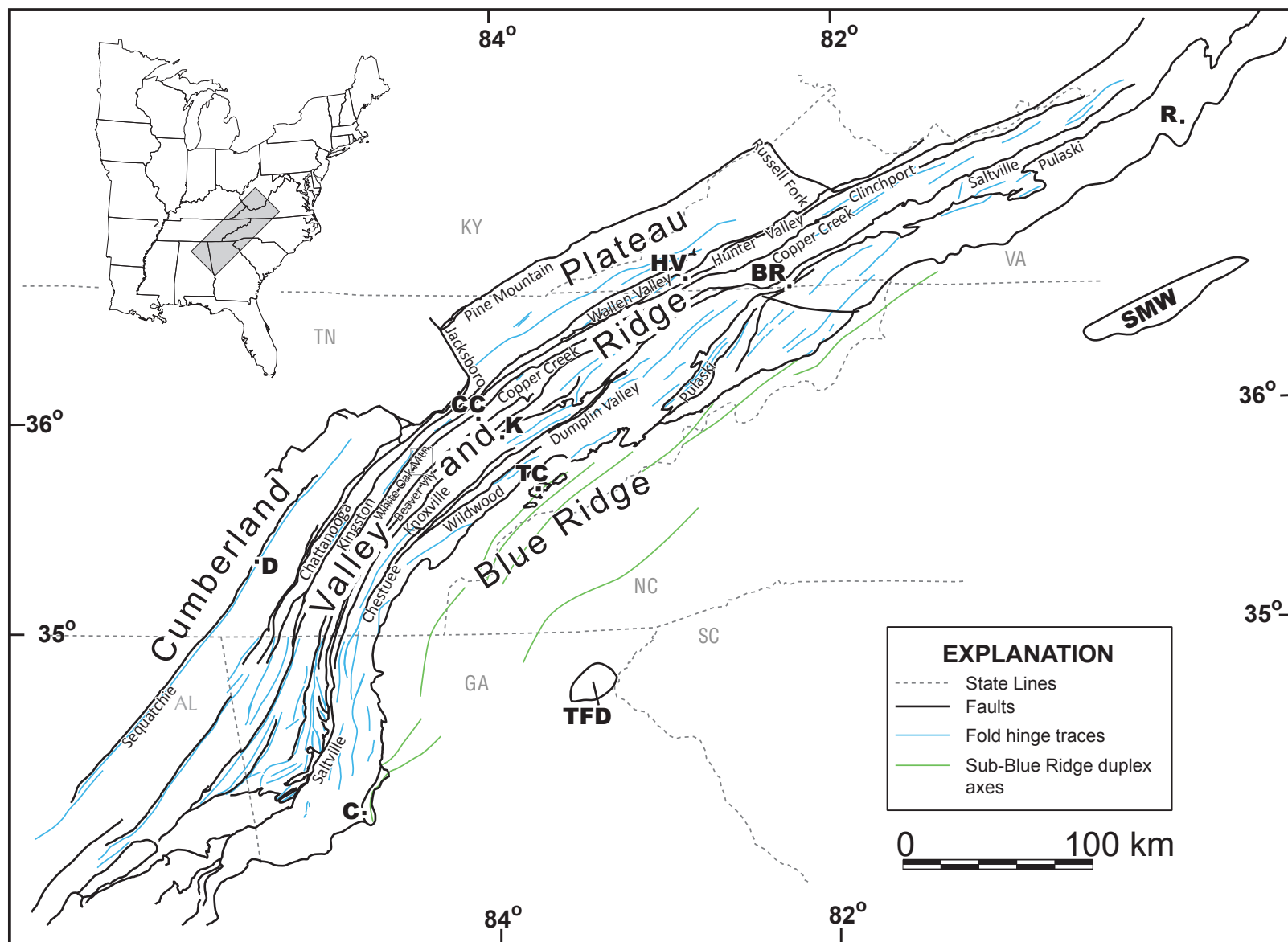
1985; Woodward, 1985; Dean et al., 1988; Kent, 1988; Hatcher et al., 1989; Marshak and Tabor, 1989; Gray and Stamatakis, 1997; Whitaker and Bartholomew, 1999; Spraggins and Dunne, 2002; Wise, 2004; Thomas and Bayona, 2005; and others), but a specific kinematic model for development of the Tennessee salient has not been proposed. This paper describes the 3D structure of primarily the Tennessee portion of the southern Appalachian foreland fold-thrust belt, and suggests that evaluating macroscale deformation in individual thrust sheets may shed light on the kinematic evolution of a map-scale curve in an area with abundant geometric data, but with limited indicators of incremental strain.

REGIONAL SETTING

The collision of Africa and Laurentia deformed the eastern margin of North America during the Mississippian-Permian Alleghanian orogeny (Rodgers, 1970; Hatcher et al., 1989; Hatcher, 2002). Layers of Early Cambrian to Pennsylvanian platform and clastic wedge rocks were stacked along the western margin of the Alleghanian mountain chain in a fold-thrust belt, the eroded remains of which today comprise the Appalachian Valley and Ridge and Cumberland/Alleghany Plateau (Fig. 5-1).

Numerous structural studies (e.g., Rich, 1934; Rodgers, 1953; Harris and Milici, 1977; Roeder et al., 1978; Woodward, 1985; Thomas and Bayona, 2005) and decades of geologic mapping at a variety of scales and levels of detail (Safford, 1869; Keith, 1895; Hayes, 1895; Wilbur, 1928; Rodgers, 1953; Milici et al., 1963; Hardeman, 1966; Smith and Green, 1968; Lawton et al., 1976; Szabo et al., 1988) have characterized the surface and subsurface geometry in the southern Appalachian fold-thrust belt. Basement faults are common beneath the thrust belt from northwest Georgia to Alabama, where post-Grenville rifts and transform faults may have remained active and influenced sedimentation and erosion through the early Pennsylvanian (Thomas and Bayona, 2005). These faults also later influenced the location of both strike-parallel and lateral ramps in the overlying, deforming fold-thrust belt (Bayona et al., 2003; Thomas and Bayona, 2005; Thomas, 2007). Basement

Figure 5-1. Simplified major faults and folds of the southern Appalachian Valley and Ridge and Cumberland Plateau physiographic provinces. D, CC, and HV mark locations of road cuts studied in detail by Wojtal (1986). Locations of Tennessee, North Carolina, and north-west Georgia sub-Blue Ridge structures inferred from contours on base of Blue Ridge (Hatcher et al., 2007). Locations of sub-Blue Ridge structures near Cartersville, Georgia, from Tull and Holm (2005). C = Cartersville, Georgia, K = Knoxville, Tennessee, TC = Tuckaleechee Cove, Tennessee, BR = Bristol, Tennessee, R = Roanoke, Virginia.



directly below the foreland fold-thrust belt in East Tennessee and Southwest Virginia, however, is generally gently southeast-dipping, is broken by fewer faults (Hatcher et al., 2007). Larger-displacement normal faults that lie generally east of the southern Appalachian fold-thrust belt outcrop belt are discussed below.

In the southern Appalachian fold-thrust belt, southeast-dipping thrust faults juxtapose older Paleozoic sedimentary units on younger ones, with deformation style and upper detachment levels varying both along and across the southern Appalachian fold-thrust belt. Folding dominates at the surface in the eastern belts in Tennessee and northwestern Georgia, in contrast with closely spaced imbricate faulting to the west, while folding increases into northwest Georgia and southwest Virginia (Fig. 5-1) (Rodgers, 1953; Hardeman, 1966; Harris and Milici, 1977; Hatcher in Hatcher et al., 1989). Recent detailed geologic mapping (Lemiszki, 2003; Bultman, 2005; Whitmer, 2005) recognized emergent imbricate faults in Rodgers' (1953) "belt of dominant folding," although with smaller displacements than most faults in his "belt of dominant faulting."

At the latitude of Knoxville, Tennessee, the southern Appalachian fold-thrust belt consists of up to 10 imbricate thrust sheets (Fig. 5-1) with displacements ranging from a few kilometers to over 100 km. Much of the fold-thrust belt is shortened as much as 50%, with shortening concentrated along a few major thrust faults (Hatcher in Hatcher et al., 1989, Whisner et al., 2004; Hatcher et al., 2007). Both the number of faults and fault displacements decrease to the northeast into Virginia, and southwest into Georgia and Alabama.

The amount of curvature in the Tennessee salient varies from internal to external portions of the southern Appalachian fold-thrust belt. Structures across the southern Valley and Ridge between Roanoke, Virginia, and Bristol, Tennessee, trend between northeast-southwest and east-northeast-west-southwest. Between Bristol and Knoxville, Tennessee, the structures follow a generally northeast-southwest trend. Between Knoxville and Cartersville, Georgia, the dominant structural trend changes approximately 20° counterclockwise (from

060-065 to 040) along the western margin of the southern Appalachian fold-thrust belt and 60° counterclockwise (from 060-065 to north-south) along its eastern margin (Fig. 5-1).

CURVED MOUNTAIN CHAINS

Most mountain chains contain curved segments recognized by changing structural trends frequently expressed in topography. These curved segments may be classified either as primary, indicating an original arcuate shape, or as secondary, if their curvature changed through time (Carey, 1955; Ries and Shackleton, 1976; Marshak, 1988, 2004). Curves in which structures changed strike during development of the curve, such as secondary arcs, are termed oroclines or rotational arcs; curves in which strike did not change are referred to as non-rotational arcs (Marshak, 1988). Possible reasons for formation of curved orogens include: (1) irregular original shape of a continental margin or indenter; (2) lateral variations in original taper of the orogenic wedge; (3) areal variations in lithology, stratigraphic thickness, or detachment extent and rheology; (4) lateral variation in the strain field, rotation of crustal blocks about a vertical axis; (5) changes in stress direction; (6) multiple deformations; (7) interactions with strike-slip faults; (8) oblique collision of crustal blocks; (9) interactions of the orogen with foreland obstacles; and (10) interactions with preexisting basement topography or zones of weakness (Carey, 1955; Ries and Shackleton, 1976; Thomas, 1976, 1977; Eldredge et al., 1985; Marshak, 1988; Schmidt et al., 1988; Ferrill and Groshong, 1993; Marshak et al., 1992; Marshak and Wilkerson, 1992; Marshak and Flöttman, 1996; Mitra, 1997; Macedo and Marshak, 1999; Fox and Vendeville, 2000; Gomes et al., 2003; Wise, 2004; Marshak, 2004). As many as ten different qualitative geometric-kinematic models, or variations on models for salient formation have been suggested by Ries and Shakleton (1976), Marshak (1988), Ferrill and Groshong (1993), and Hindle and Burkhard (1999). As Marshak (1988) and Craddock et al. (1988) noted, particles in a map-scale curve could travel many possible paths between their initial and final positions, so as much information as possible is needed on particle displacement trajectories to differentiate

among the various models. The small amount of kinematic data available in the southern Appalachian fold-thrust belt makes it difficult to distinguish among some of the models. I have chosen to evaluate 6 models: pure bending, curve-parallel simple shear, transport-parallel simple shear, uniform displacement-uniform shortening (plane strain), Piedmont glacier style (bulk non-plane strain), and radial thrusting (Fig. 5-2).

Four primary controls on the curvature of the Tennessee salient have been proposed. Rankin (1976) and Thomas (1977, 1991) connected the curvature to the irregular shape of the original rifted Laurentian margin along which sediments were deposited. Hatcher et al. (1989) pointed out that the Tennessee salient is centered on the area of maximum thickness of the Taconic clastic wedge. Based on the geometry of major structures and the fact that the apex of the salient does not occur where total sediment thickness is greatest, however, Macedo and Marshak (1999) concluded that the most important influence was the shape of the Alleghanian indenter (the Blue Ridge-Inner Piedmont composite crystalline thrust sheet [BRP]). Work by Hnat (2009) and Hnat et al., (2009) indicated that the curvature is primary, and Hnat (2009) proposed differential displacement as the mechanism for salient formation. None of these studies, however, classify the Tennessee salient in terms of the kinematic models described above, although the interpretation of Hnat (2009) could possibly be explained as model 6 (radial thrusting), or a combination of models 3 (transport parallel simple shear) and 4 (uniform displacement-uniform shortening (Fig. 5-2)). Roeder et al. (1978) and Woodward (1985) compiled serial cross sections around the Tennessee salient, although without benefit of much of the seismic reflection data used in this study. In both cases, cross sections were restored and balanced along lines perpendicular to the major structures. This suggests that most contributors had in mind a kinematic model akin to radial thrusting (model 6 in Fig. 5-2), although this model creates a room problem in the hinterland as strike-parallel line lengths are restored to shorter and shorter paths [to visualize, reverse the arrows on model 5 (Fig. 5-2)].

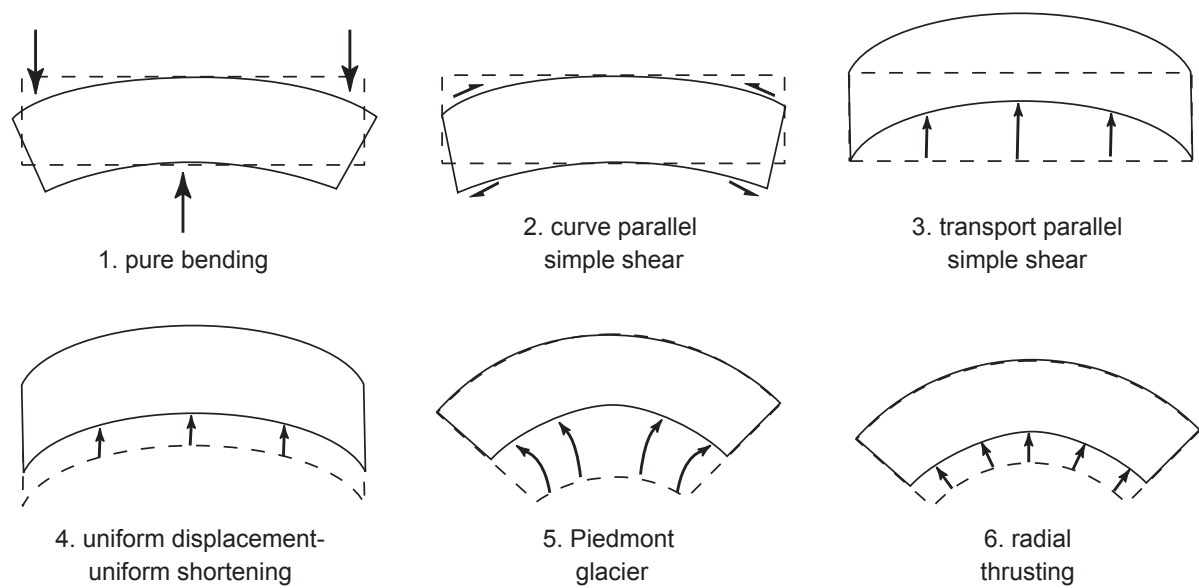


Figure 5-2. Selected kinematic models after Ferrill and Groshong (1993) and Hindle and Burkhard (1999). Dashed lines indicate undeformed shape; solid lines indicate deformed shape. Arrows show the direction(s) of bulk displacement.

CROSS SECTIONS

Analysis of the development of the Tennessee salient begins on a macroscale, with fifteen cross sections extending from the Tennessee-Virginia border to the Tennessee-Georgia border (Fig. 5-3). The two southernmost cross sections are by Germán Bayona, and have been modified from Thomas and Bayona (2005). Readers are referred to Thomas and Bayona (2005) for detailed discussion of palinspastically restored cross sections in the Alabama recess (including the southern end of the Tennessee salient).

The Tennessee salient has excellent surface geologic control in the form of several generations of mapping (e.g., Rodgers, 1953; Hardeman, 1966; Pickering, 1976; over 100 7.5-minute quadrangle geologic maps in Tennessee, and numerous theses and dissertations). Several COCORP and ADCOH crustal seismic lines provide good control on the geometry of both the basement surface and the base of the composite crystalline Blue Ridge-Piedmont thrust sheet that pushed and in many places overrode the deforming Alleghanian foreland (Cook et al., 1979; Hatcher, 1991; Hatcher et al., 1994, 2007; Hatcher and Hooper, 2004) (Fig. 5-4). ADCOH lines traversing south-central east Tennessee and continuing east to the central Blue Ridge revealed previously unresolved details of the structure beneath the Blue Ridge-Piedmont (BRP) (Hatcher et al., 1987). In addition, over 1200 line-kilometers of donated industry seismic data extending from Alabama to southwestern Virginia provide vital subsurface geometric control that was not available to previous researchers (Fig. 5-5). These data, along with other survey, government, and academic institution seismic lines and scattered well data, allowed construction of closely spaced (approximately 20 km separation) cross sections that are geometrically well constrained in the subsurface.

Constraints and Assumptions

Important boundary conditions that delimit cross-section construction and kinematic analyses include temperature and pressure conditions, indenter shape, depth to and geometry of the basement surface, and shortening directions. Cross-section construction must also

Figure 5-3. View of 15 balanced cross sections around the Tennessee salient. Red lines mark locations of Alleghanian faults from Hardeman (1966), Rader and Evans (1993), Pickering (1976), and Szabo et al. (1988). Shaded panels show the deformed shape of selected fault surfaces from exposed trace of the fault to branch line along the basal detachment. The shapes of the fault surfaces are delimited by cross section lines and interpolated between them. Dashed lines are form lines showing the inferred changing shape of the fault surface between cross-section lines: the color of the form line is a darker version of the color of the fault surface. Theoretically, one could develop an additional cross section along each set of form lines. Cross sections 1-9, 11, and 13 are revised from Hatcher et al. (2007). Cross sections TB1 and TB2 are after Thomas and Bayona (2005).

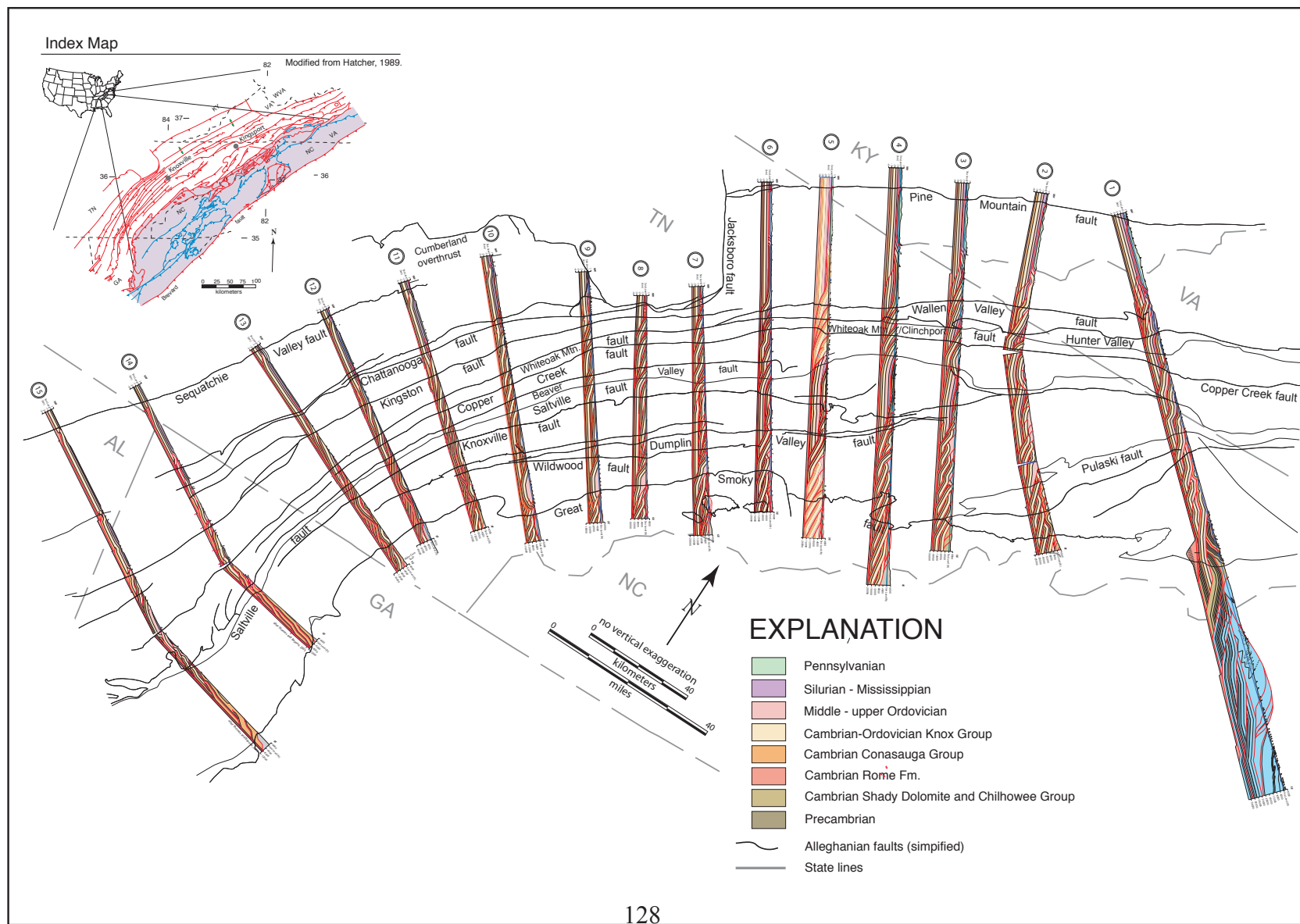


Figure 5-4. Contours in kilometers below sea level on the surface of rifted Middle Proterozoic crystalline basement, and the locations of major basement faults. The Tusquittee fault is a major down-to-the southeast fault that may have localized thickened deposits of Neoproterozoic rift sediments later deformed in the southern Appalachian fold-thrust belt (Hatcher et al., 2007). Smaller displacement faults exist between Knoxville, Tennessee, and the Tennessee/Kentucky/Virginia border. The basement fault traced through Knoxville may also be partly responsible for the location of the Jacksboro tear fault at the southwest end of the Pine Mountain block (Hatcher et al., 2007), as well as along-strike displacement transfer from the Wallen Valley fault to the Kingston fault (this study). The well labeled with a depth of 3.5 km is the Arco/Oxy Sandford Heirs #1, and the well labeled with a depth of 3.1 km is the Ladd Petroleum T. J. Kemmer #1. (From Hatcher et al., 2007.)

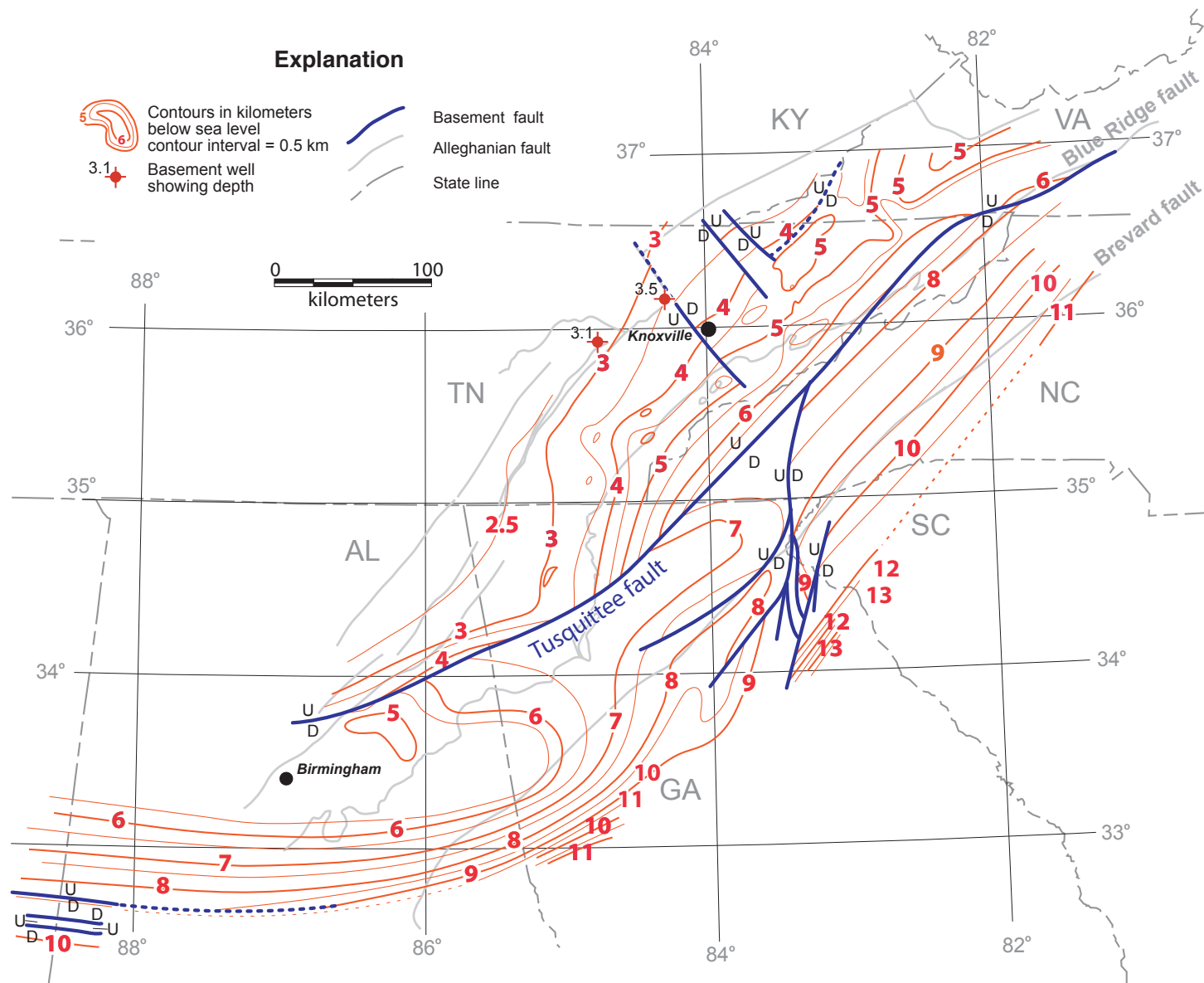
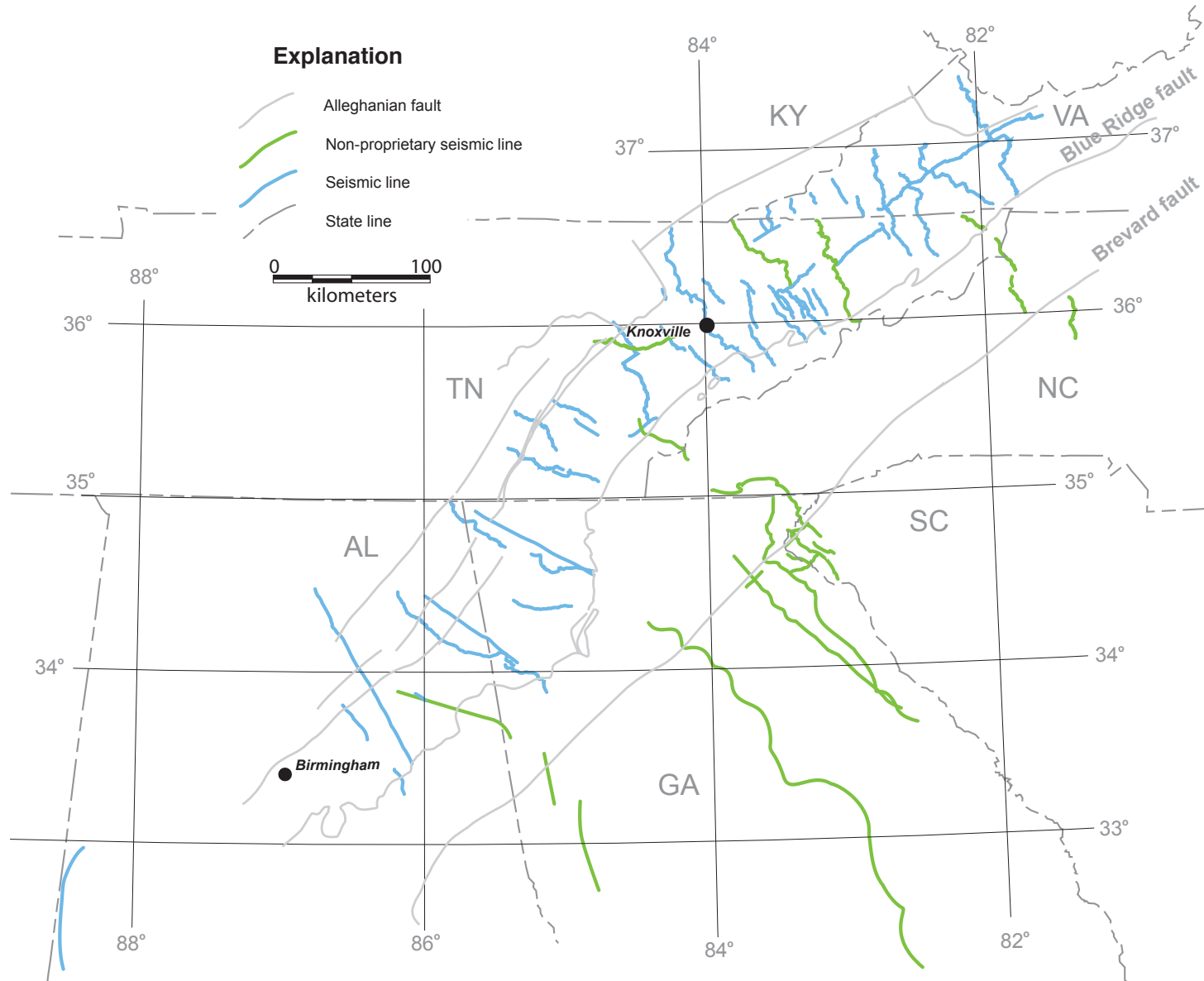


Figure 5-5. Locations of seismic lines used to develop the basement contour map of Hatcher et al. (2007). Proprietary and non-proprietary seismic reflection lines in East Tennessee, northwestern Georgia, and southwestern Virginia were also used for this study.



incorporate known variations in the stratigraphic column and associated mechanical effects, and kinematic analyses must be consistent with potential rotations about vertical axes recorded by paleomagnetism.

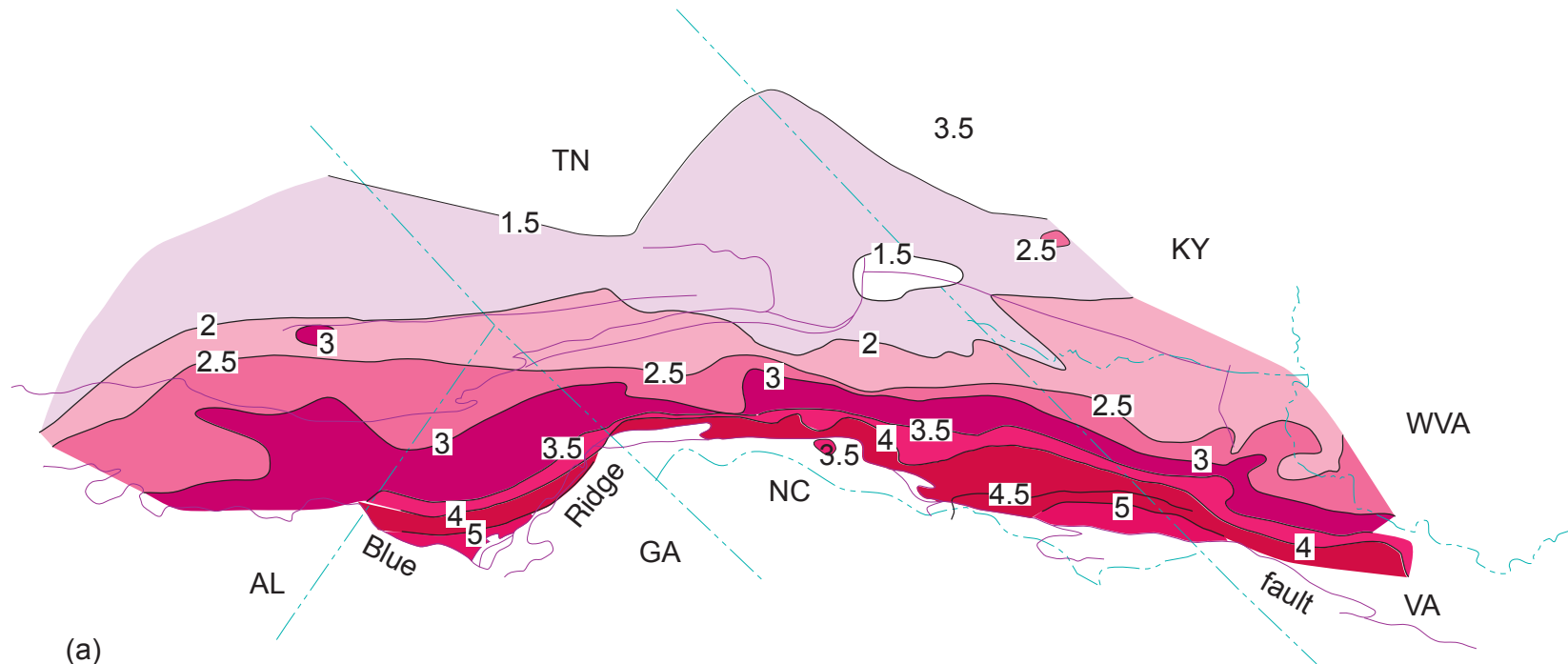
Temperature and Pressure Conditions

Estimates of temperature and pressure conditions in a fold thrust belt may be used to estimate burial depth, which is useful for inferring how much thrust sheet mass is missing, and by extension, to what degree displacement may be underestimated. Unlike younger fold-thrust belts such as the Sevier (DeCelles, 1994; DeCelles and Mitra, 1995), many hanging-wall ramps in the Tennessee salient are eroded, so only a minimum estimate of total shortening can be achieved with 2D balancing (Hatcher et al., 1989). In addition, synorogenic sediment in the southern Appalachian fold-thrust belt here has been largely eroded away. This makes it difficult to estimate the taper of the deforming sedimentary wedge, although the original taper is reasonably well delimited by geometry of the basement surface.

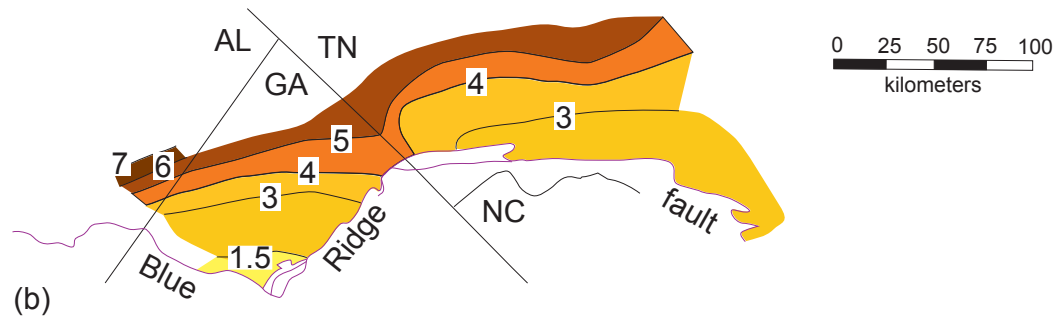
Conodont alteration indices (Epstein et al., 1977; Orndorff et al., 1988) and illite crystallinity indices (Weaver and Broekstra, 1984) (Fig. 5-6) can be used in combination with other analyses (mineral assemblages, fluid inclusion thermometry, burial curves) as proxies for temperature and pressure conditions, from which burial depth and pressures can be calculated. In general, the thermal maturity of southern Appalachian fold-thrust belt rocks increases from foreland to hinterland, subparallel to the trends of major structures.

Conodont alteration index values in the southern Appalachian fold-thrust belt along the frontal BRP are much higher (4 and above) in the reentrant in Georgia and in northeastern Tennessee and southwestern Virginia than they are along the promontory in central East Tennessee, and in several windows through the BRP sheet (Epstein et al., 1977; Orndorff et al., 1988) (Fig. 5-6). A conodont alteration index of 5 indicates a possible temperature range of 300-480° C (greenschist facies conditions; Epstein et al., 1977). The increased conodont

Figure 5-6. Thermal maturation indicators for the southern Appalachian foreland fold-thrust belt. a) Conodont alteration indices in Ordovician rocks (after Epstein et al., 1977; Harris and Milici, 1977; Orndorff et al., 1988). b) Illite crystallinity index from Weaver and Broekstra (1984). Higher thermal maturity is indicated by higher numbers for conodont alteration index and lower numbers for illite crystallinity; an illite crystallinity index less than 1.5 indicates chlorite grade metamorphism. (From Hatcher et al., 2007.)



(a)



(b)

alteration and illite crystallinity indices could be the result of hydrothermal alteration by fluids mobilized during the Alleghanian orogeny. Fluid migration out of the Alleghanian foreland basin is thought by some to be the source for Mississippi Valley-type lead-zinc ore deposits in the eastern U. S.. The increased indices could also be the result of additional burial by some combination of now eroded southern Appalachian fold-thrust belt thrust sheets, synorogenic sediments, and BRP rocks. Further south, adjacent to the reentrant in the BRP sheet in Alabama, southern Appalachian fold-thrust belt rocks reveal evidence of chlorite-grade ductile deformation, including sheath folds (Hatcher, 2008). Whatever the reason (fluids, greater burial depth by BRP or southern Appalachian fold-thrust belt thrust sheets), the deformation mechanism here contrasts sharply with the generally low-temperature, brittle deformation observed in most of the southern Appalachian fold-thrust belt.

Analyses of fluid inclusions in sphalerite from Mississippi Valley type mineral deposits in Lower Ordovician rocks mid-way across the southern Appalachian fold-thrust belt suggest that pre-Late Carboniferous mineralization (Bachtadse, et. al, 1987) occurred between 70 and 170° C (Zimmerman and Kesler, 1981; Taylor et al., 1983), and that the maximum temperature was not later exceeded. Burial curves (e.g., Steinhauff et al., 1999) also indicate temperatures in southern Appalachian fold-thrust belt rocks now exposed at the surface were higher to the east (145-200° C) than to the west (70-175° C). Under a lower than normal geothermal gradient of 20 °C [consistent with a location at the foreland side of an orogenic wedge (Barr and Dahlen, 1989)], temperatures calculated by Steinhauff et al. (1999) indicate burial by as much as 10 km of material on the hinterland side of the southern Appalachian fold-thrust belt, and as little as 6 km on the foreland side (Hatcher et al., 2007).

Basement

Seismic reflection data (Fig. 5-5) were used to determine depth to basement using a uniform 2.75 km/s two-way travel time for the Valley and Ridge, and a uniform 3.0 km/s two-way travel time for crystalline rocks (Hatcher et al., 2007). Federal government, state agency, academic and industry seismic reflection data, ranging from local, shallow lines to crustal scale lines provide a far more complete picture of the basement in the southern Appalachian fold-thrust belt than has been previously available (Fig. 5-4) (Hatcher et al., 2007). A discussion of the essential steps in seismic processing is useful to understanding the limitations of the donated industry data. Additional discussion can be found in numerous places. Sheriff and Geldart (1983) as well as more recent texts (cf. Telford et al., 1990) can provide more details.

Seismic reflection data are collected in the field using either an explosive source or a series of synchronized vibrating trucks. Processing begins with a static correction, or time shift of a seismic trace that compensates for such factors as the presence and thickness of surficial low velocity weathered material, or changing topography and elevation of sources and receivers. Signals from different receivers are most often gathered at a common midpoint (CMP) and the traces are stacked. This improves the signal to noise ratio when destructive interference of random signals (such as shot-induced noise) cancels out noise, and signals due to acoustic impedance changes in the subsurface are emphasized due to constructive interference accompanying stacking. Prior to stacking, normal moveout correction (NMO) (for horizontal layers) or combined dip moveout (DMO) and NMO corrections (for dipping layers) must be applied to the gathered traces to assure that stacking will result in enhanced signal/noise ratio. A velocity analysis determines the best stacking velocity for the NMO/DPO corrections. These steps are often iterated several times to optimize the velocity and statics models, and are best completed in consultation with a geologist familiar with the area, as it is easy to process out existing structures or process in

non-existent structures with incorrect velocities. Interpretation of seismic reflection lines can be complicated by complex structures, stratigraphic subtleties, and complex velocity profiles. Migration techniques aid in interpreting these complications by returning events assumed to occur directly below a CMP to their correct spatial locations. Migration may occur in both the time domain and depth domain, and present-day techniques allow both pre- and post-stacking migration. Pre-stack migrations are more data-intensive, and produce more accurate representations of the subsurface geometry, but were not common in the early 1980s when the donated seismic data were processed. It is assumed that all donated seismic reflection lines were migrated after CMP stacking.

Paper copies of migrated and unmigrated seismic lines arrived accompanied only by stickline and shotpoint maps. Although industry geologic interpretations likely existed, they were not shared with the author, thus cross sections were based solely on the author's interpretations of industry data. Velocity data existed only for Tennessee Division of Geology lines, so average velocities were calculated based on well data.

Oil and gas wells, especially those extending through the entire thickness of fold-thrust belt rocks are rare in the Valley and Ridge. Two wells that extend to basement and for which well logs and/or completion reports were available are located along the western side of the Valley and Ridge and in the Plateau: the Arco/Oxy Sandford Heirs #1, and the Ladd Petroleum T. J. Kemmer #1 (Fig. 5-5). No seismic velocity information was available from the wells, so they were instead used to calibrate an average time-depth conversion velocity. The lack of basement wells in the central and eastern Valley and Ridge means time-to-depth conversions are best delimited along the western extent of the Valley and Ridge.

The geometry and influence of basement on sedimentation and structural development is discussed at length in Hatcher et al. (2007). A brief summary is appropriate here. The gentle southeast dip of the majority of the crystalline basement directly below the current outcrop width of the southern Appalachian fold-thrust belt is broken only by a few small-displacement faults under its western edge in northeastern Tennessee. Further east

under the BRP thrust sheet, the large-displacement Tusquitee fault (nearly 2 km of down-to-the-southeast offset along part of its length), and other similar faults, likely influenced the thickness of structural-lithic units later deformed in the southern Appalachian fold-thrust belt (Fig. 5-4) (Hatcher, 1991; Hatcher et al., 2007). Unlike the southernmost southern Appalachian fold-thrust belt in Georgia and Alabama, basement faults in East Tennessee and southwestern Virginia were not active after the end of Neoproterozoic rifting, and little evidence exists of basement faults there influencing the location of thrust ramps or causing buttressing effects and mushroom development in the overlying deforming southern Appalachian fold-thrust belt (Tavernier, 2002; Hatcher et al., 2007). A possible exception to this is the Saltville fault, which restores to a position close to the Tusquitee fault. Perturbation of the stress field by this large buttress could potentially have nucleated the Saltville fault. The shape of the basement surface does appear to have affected the bulk trends of structures in the southern Appalachian fold-thrust belt, discussed below. Furthermore, it seems likely that the northwest-southeast striking, down-to-the-northeast, smaller displacement basement fault traced through Knoxville, Tennessee, may have influenced the development and geometry of faults whose restored along-strike positions lie adjacent to it. The vertical displacement across the Knoxville basement fault may have forced the transfer of displacement in the hanging wall of the Pine Mountain/Chattanooga thrust sheet from the Wallen Valley fault on the downthrown block on the northeast side of the fault to the Kingston fault, on the upthrown southwest side of the fault (Fig. 5-4). If the fault extends northwest (Hatcher et al., 2007), it may have been a secondary influence, after the southwestward thinning of the primary upper detachment for the Pine Mountain fault (Devonian-Mississippian Chattanooga Shale), on the development of the Jacksboro tear fault at the southwestern end of the Pine Mountain Block (Fig. 5-1).

Mechanical stratigraphy

Rocks deformed in the southern Appalachian fold-thrust belt for the most part have Cambrian to Pennsylvanian ages (older rocks are involved in one thrust sheet on the eastern edge of the southern Appalachian fold-thrust belt) and comprise passive margin and clastic wedge lithologies deposited after Iapetan rifting, through most of the Paleozoic. The basal detachment for most of the southern Appalachian fold-thrust belt is the Cambrian Rome Formation (Fig. 5-7), a clastic-dominated unit with sufficient shale and evaporite to act as a *décollement*. Older units are involved along the eastern side of the fold-thrust belt, where rocks as old as Early Cambrian (Chilhowee Group) appear in the Glade Mtn. and Lick Mountain anticlines in the Pulaski sheet in southwestern Virginia (Butts, 1933; Rodgers 1970), as well as in the transitional (BRP-Valley and Ridge) Holston-Iron Mountain sheet in northeastern Tennessee.

The overlying Middle-Upper Cambrian Conasauga Group in its shale-rich western facies is also a mechanically weak structural-lithic unit (Currie et al., 1962; Woodward and Rutherford, 1989), and has formed mushwads (Thomas, 2001) of shale in the cores of detachment folds in some parts of the fold-thrust belt in East Tennessee (Woodward in Woodward et al., 1985; Tavernier, 2002; Whisner and Hatcher, 2003), but predominantly in Georgia and Alabama (Thomas, 2001). Similar deformation is apparent at the surface in the Conasauga Group of southeasternmost Tennessee and northwestern Georgia, where the middle and lower carbonate units are thinner and less continuous (Swingle, 1959).

Carbonates of the Conasauga, Cambrian-Ordovician Knox Group, and Middle Ordovician Chickamauga Group make up the strongest structural-lithic unit in the southern Appalachian fold-thrust belt (Fig. 5-7). With a thickness in some places of more than 2 km, this strong unit acts a strut, controlling the spacing of faults and the wavelength of major folds, and limiting penetrative strain (Woodward et al., 1988; Wiltchko in Hatcher et al., 1989). Shale-rich western units in the Sevier basin facies of the Chickamauga Group

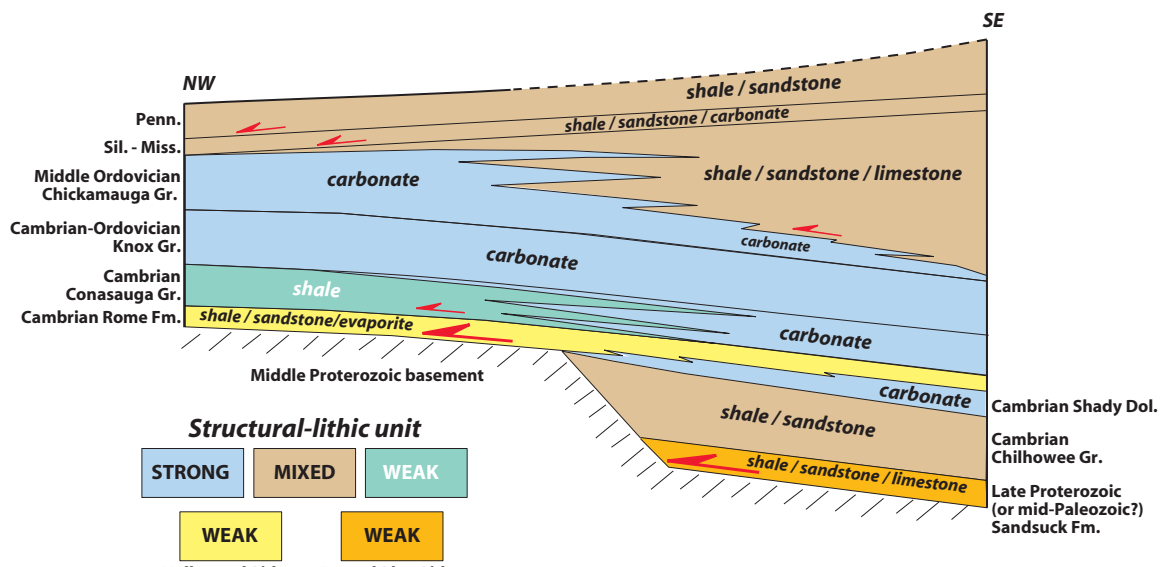


Figure 5-7. Major stratigraphic units, lithology, and mechanical behavior of units across strike in the southern Appalachian foreland fold-thrust belt (southern Appalachian fold-thrust belt). Red arrows indicate locations of major and minor detachment levels. Shale- and (to-ward the foreland) coal-rich units are the most common detachment units. (After Hatcher et al., 2007).

(Taconic clastic wedge) also act as weak detachment zones along the eastern edge of the southern Appalachian fold-thrust belt. The distal edge of the Acadian-Neocadian clastic wedge is present in the southern Appalachian fold-thrust belt in the form of the Devonian-Mississippian Chattanooga Shale (and overlying Grainger Formation), the upper detachment in the Pine Mountain block (Rich, 1934; Mitra, 1988), where thicknesses vary from nearly 300 m in northeastern Tennessee to only 30 m west of the Jacksboro fault. Coal layers and shale in the Pennsylvanian Alleghanian clastic wedge deposits also are utilized as the upper detachment in the Sequatchie-Cumberland Plateau fault system. Facies changes are expressed in map view as well. Woodward et al. (1988) pointed out that the east-west change in the Middle Ordovician Chickamauga Group from deep-water shale to carbonate shelf controls the location of a detachment horizon. Analysis of seismic reflection lines along the western margin of the southern Appalachian fold-thrust belt shows that the Conasauga Group is deformed and thickened in a type I triangle zone (Couzens and Wiltschko, 1996) below the Chattanooga fault (Figs. 5-1 and 5-3) where the Conasauga Group is primarily shale (Whisner and Hatcher, 2003).

Vertical-axis rotations

Paleomagnetic analyses are useful in determining the direction, amount, and timing of rotation about vertical axes in curved orogens. An orocline, for instance, in the sense of Carey (1955) is a secondary arc, created by bending of preexisting straight structures around a vertical axis (Model 1 of Fig. 5-3). A long history of paleomagnetic analysis exists in the Tennessee salient, although only one specifically evaluated oroclinal bending (Hnat et al., 2009). Paleomagnetic analyses by Schwartz and Van der Voo (1983) indicated that north of the Tennessee salient, the map-scale curves of the Pennsylvania salient and Roanoke recess cannot be explained purely by oroclinal bending. Stamatakis and Hirt (1994) analyzed additional paleomagnetic data on anomalous, outward (out-of the salient) vertical-axis rotations in the Pennsylvania salient, which Gray and Stamatakis (1997)

attributed to changing conditions as the wedge of deforming rock thickened through time, and gravitational effects caused diverging paleostress trajectories at the tapered ends of the wedge. Paleopole measurements for Cambrian units west of the straight 060 reach of the Tennessee salient are anomalous, and likely are the result of apparent polar wander during the Cambrian (Watts et al., 1980). Watts and Van der Voo (1979) concluded that Middle Ordovician units along the straight 060 segment of the salient contain no rotation and generally agree with contemporaneous paleopoles. Bachtadse et al. (1987) analyzed paleopoles in Knox Group carbonates (Fig. 5-3) associated with Mississippi Valley-type ore deposits in East Tennessee. Data collected in two locations along 060-oriented faults in the Saltville sheet revealed syn-Alleghanian, Early Permian paleopoles (not rotated about a vertical axis) for deposits in the Knox Group. Morrison and Ellwood (1986) presented data from Middle Ordovician- to Silurian-age rocks from a site in NW Georgia, and found that measured declinations and inclinations generally agree with age-appropriate paleopoles, and generally ruled out vertical axis rotations. Bayona et al. (2003) found paleomagnetic rotations across the Alabama recess are consistent with thrust motion over lateral ramps. Most recently Hnat et al. (2009) found no correlation between declination variation and structural trend in samples collected from Middle Ordovician, Silurian, or Cambrian units in the Tennessee salient and Alabama recess, and concluded that paleomagnetic results suggest curvature in the Tennessee salient has a primary origin. In sum, paleomagnetic data collected around the southern Appalachian fold-thrust belt do not identify significant vertical axis rotations that could be attributed to large-scale motion such as oroclinal bending. Rather, most paleopoles, after adjusting for deformation, align with age-appropriate polar wander curves or reflect local, rather than regional, effects.

2D cross sections

Cross-section construction generally assumes that deformation occurred under conditions of volume-constant plane strain and no net angular shear (Bucher, 1933), and

that rocks moved perpendicular to the trends of major structures. Transport-parallel cross sections may also be drawn oblique to major structural trends (Groshong, 1999, p. 299; Bayona et al., 2003), but are far less common. A balanced cross section must agree with all available structural and kinematic data (admissibility) and be restorable to an undeformed state (viability) (Elliott, 1983; Geiser, 1988). These limitations eliminate many possible inconsistencies and inaccuracies, and ensure that the sections are consistent not only with local geology but also with fundamental geologic principles. In many places, however, it is possible to draw adjacent cross sections that adhere to all accepted rules of cross-section construction and balancing, yet are incompatible with each other (Geiser, 1988). It is also possible to have more than one viable and admissible interpretation for a single section. 2D balanced cross sections constructed using the most rigorous criteria and all available data may still be incorrect at least partly because deformation is 3D and non-planar.

Structural geologists can further refine potential interpretations and evaluate the 3D evolution of an orogen by drawing compatible, palinspastically restorable serial cross sections (e.g., Roeder et al., 1978; Woodward, 1985; Kulander and Dean, 1988; Mitra, 1988; Evans, 1989), or by approximating a volume balance by projecting thrust sheets onto horizontal surfaces using a block mosaic technique (Laubscher, 1965, 1981, 1987; Bitterli, 1990; Phillippe et al., 1996). These methods work along fairly straight segments of orogens, but are less useful in curved sections where substantial particle movement often occurs out of the plane of cross sections (Marshak, 1988; Ferrill and Groshong, 1993; Hindle and Burkhard, 1999) rendering any 2D section unrestorable.

Fifteen 2D cross sections across the Alleghanian fold-thrust belt (fold-thrust belt) in eastern Tennessee, southwestern Virginia, and northwestern Georgia were constructed at an approximately 20 km spacing. Although one premise of this work is that deformation in the fold-thrust belt cannot involve plane strain through the entire southern Appalachian fold-thrust belt, cross sections were constructed approximately perpendicular to the average strike of the structures crossed by the section (Dahlstrom, 1970; Boyer and Elliott, 1982;

Woodward et al., 1985) as an approximation of regional deformation. Seismic reflection coverage is not dense enough to permit cross-section construction based solely on seismic geometries, so additional constraints, such as the plane strain assumption (where appropriate), were required.

The plane strain assumption is likely correct for the entire width of the fold belt along the relatively straight northern (approximately 060-striking) arm of the salient, as well parts of the interior of the fold-thrust belt that maintain the same bearing almost as far south as cross section 11 (Fig. 5-3, Plate III). A finite-element model of deformation in the strongly curved Provo salient (Kwon and Mitra, 2004a) indicated the center of the salient deformed by plane strain, with non-plane strain near the lateral and oblique ramps that underlie the northern and southern boundaries of the salient. The Tennessee salient is not so strongly curved, and its relatively straight northern arm is unlikely to experience edge effects until very close to the Roanoke recess, whereas the southern arm has a larger radius of curvature, increasing the area potentially affected by non-plane strain. Analyses of movement on networks of small-displacement faults adjacent to major faults by Wojtal (1986) (study locations in Fig. 5-1) suggested that, although strongly non-coaxial, deformation along the straight arm (study locations HV and CC on Fig. 5-1) occurred by plane strain. At a location on the curved southern arm of the salient (D on Fig. 5-1), however, out-of-plane motion was noted on a limited number of strike-oblique faults.

Plane strain is assumed only if the cross sections are restored by retrodeforming line lengths along the line of the cross section. Even if plane strain is inappropriate, a geometrically well-constrained cross section can accurately represent the deformed state of rocks for a given cross section; the original shape of the deformed area, however, cannot be recreated by retrodeforming the cross sections as described above.

Basement geometry interpreted from seismic reflection data reveals a southeast-dipping Laurentian basement, above which the basal décollement for almost all the presently exposed fold-thrust belt lies in the Cambrian Rome Formation. The Rome Formation directly

overlies basement beneath the southern Appalachian fold-thrust belt. Other detachments occur in higher incompetent layers discussed above, whereas the Cambrian-Ordovician carbonate sequence is assumed to act as a strut, and primarily localize ramps, not flats.

Milici (1975), Harris (1976), Milici et al. (1979), and others have argued on the basis of seismic reflection data, outcrop patterns of the basal detachment unit (Cambrian Rome Formation), and fault cutoff patterns, that the Valley and Ridge developed from west (foreland) to east (hinterland) within a single original master thrust sheet. Woodward and Beets (1988), however, reasoned that cutoff-line maps and observations of folded faults at several key locations indicate that the southern Appalachian fold-thrust belt formed from hinterland to foreland, and Roeder et al. (1978), and authors in Woodward (1985) modeled deformation as dominantly hinterland to foreland. In addition, the presence of basement in thrust sheets to the east precludes the west-to-east mechanism (Geiser, 1978; Hatcher et al., 2007).

Thrust belt models described by Mandl and Shippam (1981) indicated that widely spaced, large-displacement faults may form early in a fold-thrust belt, followed later by out-of-sequence hanging-wall imbrication that causes the wedge to thicken and steepen, returning it to critical taper. The great lateral extent of the Whiteoak Mountain and Saltville faults (Figs. 5-1 and 5-3), compared with other faults in the salient, suggests that these could be early faults, with other imbricate faults, such as the Copper Creek and Beaver Valley in the Whiteoak Mountain hanging wall, and the Knoxville, Rocky Valley, Dumplin Valley, Chestuee, and Wildwood in the Saltville sheet, developing later in the deforming wedge (Hatcher, 2004).

Paleomagnetic data discussed in Hnat et al. (2009) suggest that sample sites closer to the BRP were more tilted than sites closer to the foreland when remagnetization occurred in the Late Carboniferous, which is consistent with a hinterland to foreland deformation pattern; however, illite age analysis results from Hnat (2009) suggest contemporaneous movement on faults across the entire width of the fold-thrust belt in the Early Permian. Synorogenic

sediments that could provide clues to the timing of fault activation and reactivation (DeCelles and Mitra, 1995) have been eroded from the majority of the southern Appalachian fold-thrust belt, remaining only in its western- and southernmost extent. Because the current level of erosion does not provide sufficient data to support out-of-sequence movement, deformation is assumed to have proceeded dominantly from hinterland to foreland.

Local exceptions to in-sequence deformation that may reflect simultaneous movement in different parts of the deforming wedge occur in the Copper Creek thrust sheet (cross sections 2 and 3, Fig. 5-3, Plates III and IV), the Pulaski fault, (cross sections 2 and 3, Fig. 5-3, Plates III and IV), and the footwall of the Great Smoky fault (cross sections 10 and 11, Fig. 5-3, Plates III and IV), discussed below.

Fault families

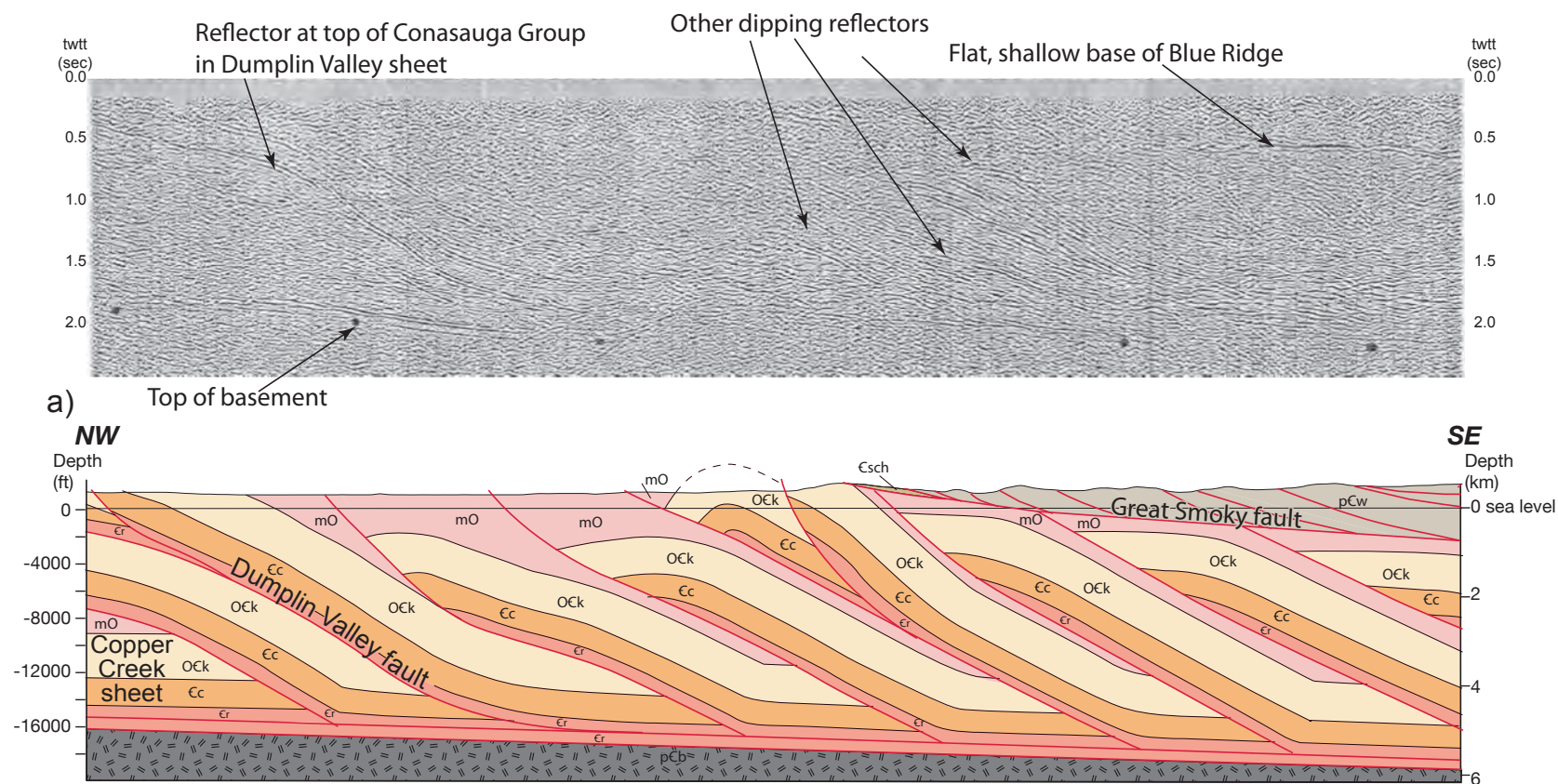
The Valley and Ridge consists of both high- and low-displacement faults. Faults can be divided into groups by their association with (lying in the hanging wall of) a single high-displacement fault. For convenience of discussion, the southern Appalachian fold-thrust belt is broken into several fault families, each of which encompasses a number of faults, and across and along which deformation style varies. The first two families: Easternmost Valley and Ridge family and the Holston-Iron Mountain sheet, which lie along the eastern margin of the southern Appalachian fold-thrust belt, play only a small role in the final cross sections, but are discussed here for completeness.

Easternmost Valley and Ridge Family. The Easternmost Valley and Ridge family of faults encompasses several faults (Great Smoky-English Mountain, Buffalo Mountain, and Holston-Iron Mountain) that bring up Lower Cambrian and older rocks along the western edge of the southern Appalachian fold-thrust belt. They mark the transition from the platform and clastic wedge rocks of the southern Appalachian fold-thrust belt to the overlying composite crystalline thrust sheet. The shallow dip of the frontal Blue Ridge thrusts has been

discussed by Keith (1923), Jonas (1932), King and Ferguson (1960), Neuman and Nelson (1965), and Harris (1979), among others. The Hatcher et al. (2007) analysis of seismic reflection lines that cross the Valley and Ridge-Blue Ridge transition and geologic mapping (cf. Hardeman, 1966) indicate that the frontal fault of the BRP is shallow and undulating, and dips gently to the southeast. The flat, shallow base of the frontal Blue Ridge can be seen on the right (east) side of Figure 5-8. The undulations at the base of the BRP thrust sheet are due to deformation by overridden duplexed rocks observed in windows through and reentrants in the Blue Ridge sheet, and in industry and government seismic reflection lines (Hatcher 1991; Tull and Holm, 2005; Hatcher et al., 2007). Duplexes deforming the BRP may consist of Neoproterozoic Ocoee to Lower Cambrian Chilhowee units, or of Paleozoic southern Appalachian fold-thrust belt platform and clastic wedge rock, and may be located between the base of the BRP and the top of basement, or between the BRP and an underlying southern Appalachian fold-thrust belt thrust (Boyer and Elliott, 1982; Hatcher et al., Woodward, 1989; Hatcher et al, 2007). In most of East Tennessee, the Blue Ridge front did not extend much further west than its present outcrop location, although klippen of Lower Cambrian rocks (Great Smoky sheet?) above the fold-thrust belt in Georgia and Alabama, and higher conodont alteration indices in reentrants in the BRP to the south (NW Georgia) and north (NE Tennessee and SW Virginia) suggest that a thin veneer of Blue Ridge may have covered the fold-thrust belt in the reentrants as well.

Holston-Iron Mountain sheet. The Holston-Iron Mountain thrust sheet in northeasternmost Tennessee provides the stratigraphic connection between Valley and Ridge and Blue Ridge, as it comprises a continuous section from the underlying Middle Proterozoic crystalline basement to Early Cambrian Chilhowee Group to Cambrian-Ordovician Knox Group. The décollement at its base bridges the brittle/ductile transition, exhibiting ductilely deformed mylonites on the east side of the Limestone Cove window where it brings up Precambrian Cranberry Gneiss, and brittle behavior along its western extent, where it places

Figure 5-8. Seismic reflection line and nearby cross section across the Valley and Ridge-Blue Ridge transition west-southwest of Knoxville, Tennessee. a) Industry seismic reflection line. Two-way travel-time shown in seconds. b) Portion of cross section 5 (Fig. 3, Plate I), which lies several miles north of the industry seismic line.



b)

mO	Middle - Upper Ordovician
OEk	Cambrian-Ordovician Knox Group
Ec	Cambrian Conasauga Group
Cr	Cambrian Rome Fm.
Esch	Cambrian Shady Dolomite and Chilhowee Group
pCw	Precambrian Walden Creek Group
pCb	Precambrian Laurentian Grenville basement

Chilhowee Group to Knox Group rocks atop Knox Group and Chickamauga Group rocks of the Pulaski thrust sheet in the southern Appalachian fold-thrust belt. Below the Holston-Iron Mountain sheet a Blue Ridge-warping duplex of Rome through Chilhowee rocks is exposed in the Mountain City window, connecting the platform and clastic wedge rocks exposed in the majority of the southern Appalachian fold-thrust belt with the underlying rift-drift facies that here lie directly above basement (Hardeman, 1966; Boyer and Elliott, 1982; Hatcher et al., 2007).

Pulaski Family. The Pulaski sheet lies below the Holston-Iron Mountain and Blue Ridge faults, and brings up rocks from Cambrian to Ordovician age in a sheet containing several lower-displacement, possible out-of-sequence faults: the Dunham Ridge, Spurgeon, and Bristol faults. The northern tip of the Pulaski-Staunton fault lies in a fold in northern Virginia (Fig. 5-1). The fault extends southwest around the Roanoke recess into Tennessee where, due to interaction of its shallow dip with topography, its trace curves back to the southeast near Newport, Tennessee (Rodgers, 1970). In East Tennessee, the Pulaski soles in Conasauga Group-equivalent (Honaker Dolomite), although further north in Virginia, the Pulaski brings up Rome Formation, and upper Chilhowee Group rocks are exposed in the Glade Mountain and Lick Mountain windows (Rodgers, 1970).

In cross section 1 (Plates III and IV), which extends across the Mountain City window, displacement on the Pulaski fault as depicted here is on the order of 100 km (55 miles), in accordance with Boyer and Elliott (1982) (60+ km), and Harris et al., (1981) in which the Pulaski restores far to the east of the down-to-the-southeast Tusquittee fault (Fig. 5-4) (compare to Kulander and Dean's (1988) minimum 3 km of displacement near the Pulaski fault's northern terminus north of Roanoke, VA). This amount of displacement seems very high; however, it is in relatively close agreement with the front edge of the Pulaski sheet in the succeeding cross section 2 (Fig. 5-3, Plate III, Plate IV). Here the Pulaski is restored just east of several imbricates in the underlying Saltville sheet, although

there are no seismic reflection data available to indicate the location of the Pulaski's branch line off the basal detachment. Such high displacement requires either rotation (more than 30° counterclockwise at the southern end) or substantial differential translation of the southern end of the fault, either of which would require the presence of a major tear fault at the southern margin (not observed), or that the fault continues along strike for a great distance below the BRP.

Lithology of the Sevier Shale in a flap of the leading edge of the Pulaski sheet is similar to the Sevier in the underlying Saltville sheet, suggesting low stratigraphic throw (Bultman, 2005). The presence of several horses in the trailing edge of the Saltville sheet below the Pulaski fault, however, requires substantial displacement on the Pulaski fault. Most seismic reflection lines that cross the Pulaski sheet have very poor signal return, so the space between the Pulaski and basement has been filled with the minimum amount of duplexed Saltville sheet required to provide continuity between cross sections. Horses are depicted with units from Rome Formation to lower Chickamauga Group, as these units are observed in imbricates in the Pulaski footwall, as well as horses exposed in windows through the BRP.

The Pulaski sheet is folded into nearly upright, slightly northwest-verging, tight folds, and is frequently broken by steep southeast-dipping faults (Rodgers, 1953, his Plate 15; Byerly, 1996). Geiser (1989) suggested that the Pulaski could be a Taconic or Acadian fault. Mapping by Byerly (1996) indicates that the Pulaski sheet is folded along with the underlying Sevier Shale in the Saltville sheet, and that the steeply dipping faults separating folds in the Pulaski sheet are not folded by duplexing of the underlying Saltville sheet. This suggests that both folds and faults likely were a response of the Pulaski sheet to imbrication of the underlying Saltville sheet (Bartholomew, 1987; Roeder et al., 1978; Woodward and Gray, 1985). More recent detailed mapping (Derryberry, unpublished mapping; Bultman, 2005; Whitmer, 2005), however, documented that the Pulaski sheet is not influenced by deformation in underlying duplexed Saltville sheet. The Pulaski fault truncates folds in its

footwall, indicating that both folds and faults likely represent deformation of the Pulaski sheet prior to its emplacement and imbrication of its footwall. In fact, the Pulaski must have some component of out-of-sequence deformation to truncate imbricates that formed in its footwall. A more detailed discussion of footwall deformation follows in the Saltville fault family section.

Extension of the Pulaski fault to the SW based on penetrative deformation of major carbonates, as well as changes in Knox and Conasauga Group facies, has been suggested by Lemiszki (2008). Additional detailed mapping (Derryberry, unpublished mapping) confirms that the Pulaski fault extends further southwest than is shown on the Hardeman (1966) state geologic map. The extension gives sub-Pulaski imbricates a more consistent geometry (east ends of cross sections 2 and 3, Fig. 5-3, Plate III) than they would have if the anomalously broad (compared to adjacent folded Saltville sheet imbricates) expanse of Knox near Newport, Tennessee, were assigned to an imbricate in the Saltville sheet. These data are incorporated into cross section 3 (Fig. 5-3, Plate III).

Saltville Family. The Saltville fault in East Tennessee is the expression of a structural front that may extend through the Appalachians from Georgia to the Cacapon Mountain anticlinorium of Maryland and West Virginia (Rodgers, 1970) and, as the Jacks Mountain anticlinorium, possibly as far northeast as the anthracite region of Pennsylvania (Nickelsen, 1988). The Saltville fault originates in the Sinking Creek anticline northwest of Roanoke, Virginia, (House and Gray, 1982; Couzens and Dunne, 1994), propagates southwestward as a fault into northeast Tennessee (Wiltschko in Hatcher et al., 1989), and continues into northwest Georgia as the Eastern Coosa fault of Thomas and Bayona (2005), where it terminates south of the apex of the Alabama recess (Fig. 5-1). The trace of the Saltville fault makes a large Z curve at the Tennessee-Virginia border, changing from 060 in Virginia to 130 as it crosses the state line and back to 060 in northeast Tennessee. Just northeast of Knoxville, the Saltville fault transfers some of its displacement to the Beaver

Valley fault, and continues southwestward at approximately the 060 orientation for another 60 km before gradually changing strike to north-south in northwest Georgia and back to east-northeast around the Alabama recess, along the remaining 250 km of its trace. In Alabama it is truncated by the Pell City and Jacksonville faults, which are in turn truncated by the Talladega fault (Thomas and Bayona, 2005). East of 82°W the sheet falls in Rodgers' "belt of dominant folding." Folding in this part of the Saltville sheet is expressed as anticlines and footwall synclines exposed at the surface in units from upper Middle Ordovician Bays to Cambrian-Ordovician Knox Group. Industry seismic reflection data, as well as detailed mapping (Lemiszki, 2003; Bultman, 2005; Whitmer, 2005), suggest that structure of the underlying Saltville sheet in the Sevier-Blountian basin is more complex than indicated on the state 1:250,000-scale map (Hardeman, 1966) (Fig. 5-9). Numerous imbricates, previously unmapped thrust faults, and even backthrusts deform the Saltville sheet directly west of and (using a downplunge view at the southernmost trace of the Pulaski fault) below the Pulaski sheet. The outcrops of Knox are the most obvious evidence of a large number of folds associated with moderate-displacement imbricate faults deforming the Saltville sheet (~8 km) but not the overlying Pulaski sheet. Based on the work noted above, several of these faults are assumed to be emergent at the present ground surface even where detailed mapping has not yet been conducted. Imbricate faulting and folding continue along strike to the southwest where many of the structures are overridden by the BRP, which is warped into *en echelon* folds by duplexing of the underlying Saltville sheet (Hatcher in Hatcher et al., 1989; Hatcher et al., 2007). Imbrication is best exposed where the Middle Ordovician section is thick (2.5 km or 8000+ ft) and dominated by shale. The orientation of imbricates is ~045, subparallel to the orientation of folds in its hanging wall (Pulaski sheet).

The appearance of the Saltville sheet changes southwestward along strike at about the latitude of Knoxville, where farther-traveled hanging-wall imbricates bring Cambrian Rome and Conasauga units to the surface, and again southeast of Knoxville, where the eroded width of the Sevier basin is narrower. Imbrication of rocks containing Sevier-Blountian

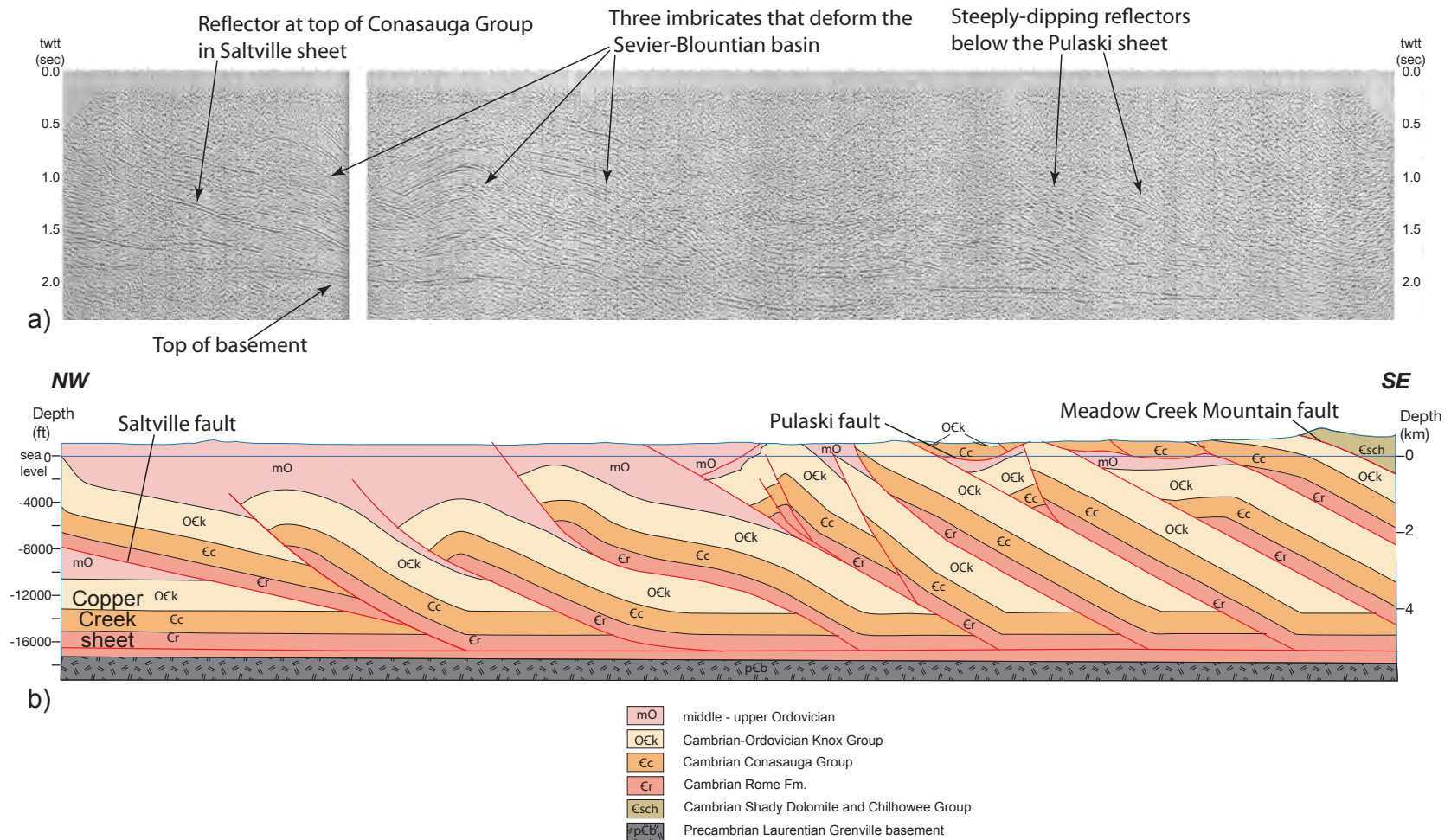


Figure 5-9. Seismic reflection line and nearby cross section across the Sevier basin northeast of Knoxville, Tennessee. a) Industry seismic reflection line. Two-way travel time shown in seconds. b) Portion of cross section 3 (Fig. 3, Plate I) near the industry seismic line showing imbrications in the Saltville sheet that extend to the east beneath the Pulaski thrust and also along strike to the southwest below the Blue Ridge.

basin facies does continue southwestward, albeit under the Blue Ridge, at least as far as Tuckaleechee Cove (Fig. 5-1), where Sevier Shale is exposed in a window through the BRP. Here, the Sevier lies above an eastern facies of the Cambrian-Ordovician Knox Group (Jonesboro Limestone) and is the footwall detachment for the Great Smoky fault.

Middle Ordovician rocks are also exposed at the surface along the west side of the Saltville sheet south of cross section 4 (Fig. 5-3, Plate III) where the Saltville fault moves down a lateral ramp atop the Copper Creek sheet from a flat in Mississippian and Chickamauga Group rocks (cross section 2, Fig. 5-3, Plate III) to a flat at the top of the Knox Group. The flat-on-flat geometry characteristic of the frontal portion of the Saltville sheet continues southward around the salient, into the Alabama recess (See cross sections 5 to 15, Fig. 5-3 and Plate III). Displacement of the Saltville thrust sheet on the Saltville fault is as much as 35 km, although the net displacement of the sheet (carried piggyback on faults in its footwall) is much greater (~90 km). Displacement remains consistent to the south around the salient: in northern Georgia and Alabama, displacement is nearly 25 km (Thomas and Bayona, 2005). Displacement is generally much less in the Saltville hanging wall on individual thrusts such as the Knoxville, Chestuee, Dumplin Valley, and Wildwood.

Knoxville/Rocky Valley/Chestuee/Dumplin Valley/Wildwood faults. The Knoxville fault is the longest (180 km or ~110 miles) of the major faults in the hanging wall of the Saltville sheet. It begins near Knoxville, Tennessee, emerging from a fold in the Saltville sheet along the 060-trending arm of the salient (Fig. 5-1). Displacement on the Knoxville fault increases moderately into southeast Tennessee and decreases again until it terminates in another fold in northwest Georgia, on the north limb of the Alabama recess. The Knoxville sheet has a relatively small stratigraphic throw (oldest Cambrian-Ordovician Knox Group unit overlies Middle Ordovician). Just northeast of the northern end of the Knoxville fault lies the Rocky Valley fault, a short (50 km) fault, unusual because it exploits an upper detachment in the basal Middle Ordovician (Woodward and Beets, 1988), placing uppermost Cambrian Rome Formation on Lenoir Limestone (Bridge and Hatcher, 1973). Two small

faults that displace the Rocky Valley sheet (cross section 5, Plates III and IV) were identified during exploratory drilling for Mississippi Valley-type mineral deposits (Bridge and Hatcher, 1973).

In the hanging wall of the Knoxville fault lies the moderate displacement Dumplin Valley fault (Cambrian Rome atop Middle Ordovician Chickamauga Group). Two other small imbricates are brought up by the Chestuee fault and the Wildwood fault. All three faults lose displacement southward, transferring shortening to the Knoxville and Saltville faults, and die in folds in Conasauga Shale in southeastern Tennessee north of the Tennessee/Georgia border (Swingle, 1959; Whisner, 2005).

The Dumplin Valley is the longest of the three faults. Its northern tip lies on the western side of the Sevier Basin in the area of moderate-displacement imbricates northeast of Knoxville. The Dumplin Valley also has the most displacement of the faults in the hanging wall of the Knoxville fault. The weak Cambrian structural-lithic unit in the hanging wall of the Dumplin Valley fault southeast of Knoxville is thickened by splays off the basal detachment and associated folds near Maryville, Tennessee (Cattermole, 1962; Hatcher, 1969). Here the basal detachment cuts down into the lower Rome Formation (Hardeman, 1966) or Shady Dolomite (Cattermole, 1955). This exposure, along with imbricated or possibly duplexed Rome and Conasauga in the hanging wall of the southern extent of the Whiteoak Mountain fault in Tennessee (Swingle, 1959, his Plate 2), and duplexed Cambrian units in the hanging wall of the Saltville fault northeast of Knoxville (Woodward and Gray, 1985), may be excellent analogues for thickening in the Rome and Conasauga that fills the core of the Type 2 triangle zone (cf. Gwinn, 1964) in the footwall of the Chattanooga fault, southwest of Knoxville (Whisner and Hatcher, 2003). Some displacement on the Dumplin Valley fault is transferred to these folds, but the fault continues southwestward, bringing up Conasauga Group in the hanging wall. Displacement is gradually transferred to the Chestuee fault in the footwall, and the Dumplin Valley grades into a fold in the Conasauga Group at its southern terminus north of Englewood, Tennessee.

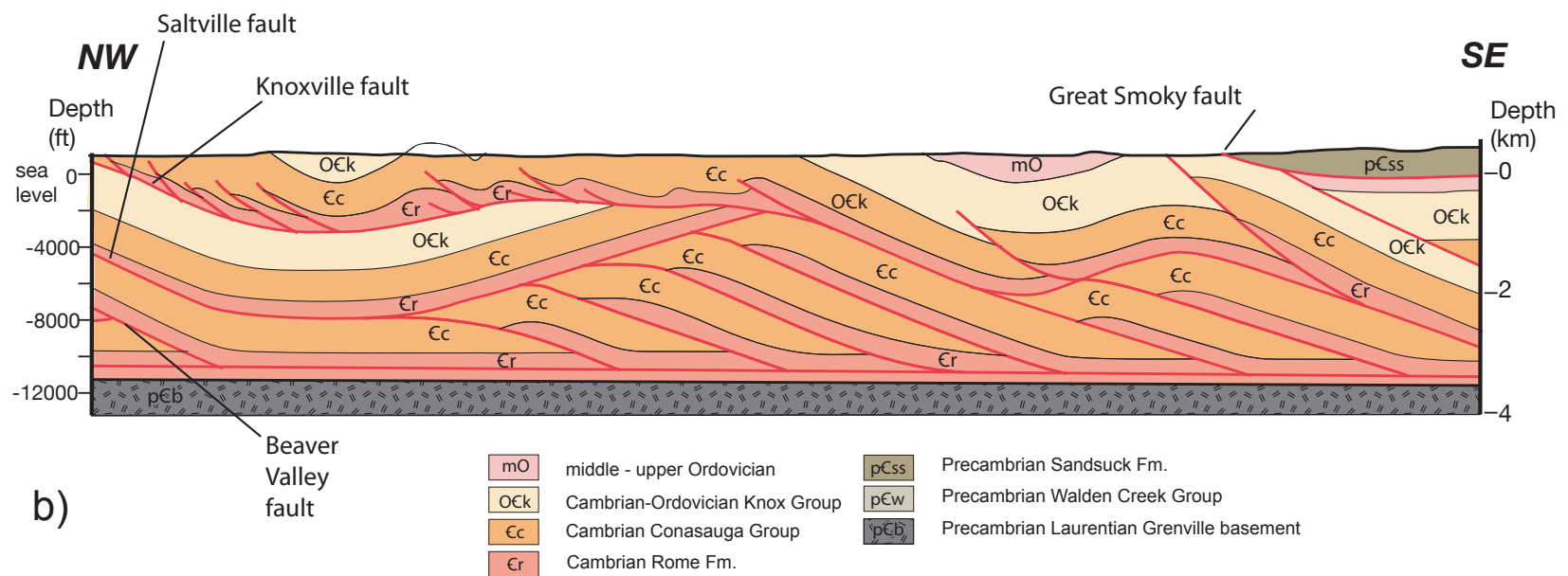
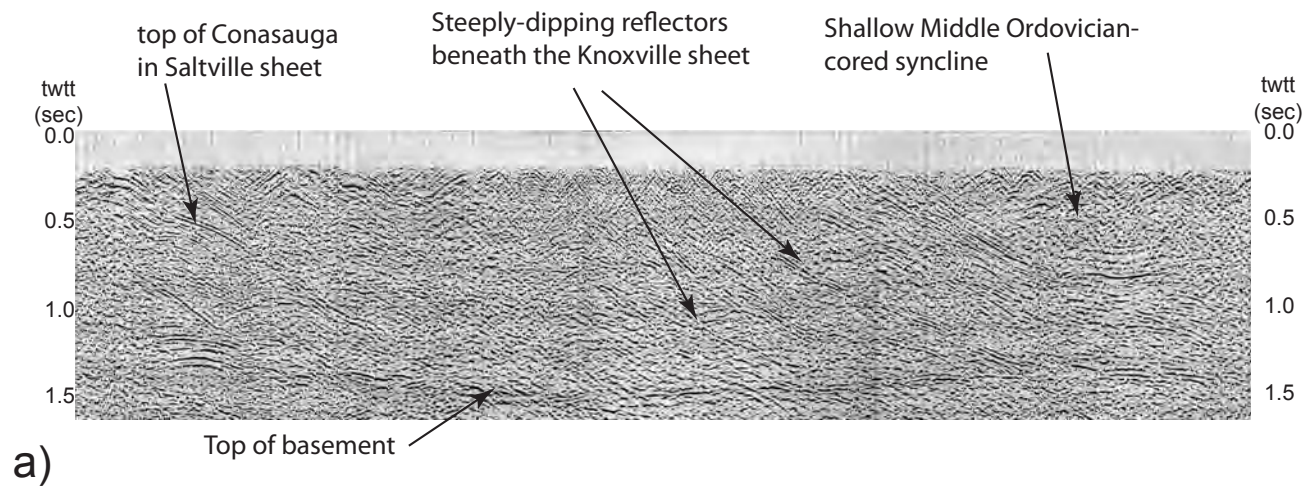
The Chestuee is a low-displacement fault in the footwall of the Dumplin Valley fault. The Chestuee outcrops northeast of Maryville, Tennessee, and extends southwestward to approximately 15 km north of the Tennessee-Georgia border, where it loses displacement in folded Conasauga Group rocks. In several locations it is displaced a kilometer or less on faults oblique to the main structural grain. The Wildwood fault is a similar low-displacement fault in the hanging wall of the Dumplin Valley fault.

Middle Ordovician-cored synclines lie in the hanging wall of the Knoxville fault. The depth to basement calculated from seismic reflection lines, combined with the thickness of stratigraphic units in the Knoxville sheet, suggest another thrust sheet must lie between the Knoxville fault and the basal detachment. The relatively small displacement on the Knoxville fault implies that the underlying thrust sheet cannot be the Saltville sheet. The Beaver Valley sheet is a more likely candidate. The volume between the Knoxville fault and basement poses an interesting room problem in the southeast corner of the fold-thrust belt in East Tennessee. The problem is not in the sense of too *little* room, as in the core of a tight fold, but rather a problem of too *much* room.

Basement depth shallows southward below the Tennessee salient (Fig. 5-4), decreasing the volume that must be filled with thrust sheets. However, there is a concomitant decrease in the thickness of the individual thrust sheets in this area. There remains, in some places, less than 1 km of Rome Formation and partial Conasauga Shale in the Knoxville sheet, up to a partial thickness of Knox Group in the Saltville sheet, and, at the latitude of Cleveland, Tennessee, (cross section 13, Fig. 5-3, Plate III) only Rome Formation and Conasauga Group in the Beaver Valley sheet. In addition, there is a decrease in the total number of thrusts at this latitude: the Chestuee, Dumplin Valley, and Wildwood pass into folds here (Swingle, 1959; Hardeman, 1966; Whisner, 2005), and the Knoxville fault itself dies out only 20 km south of the Tennessee-Georgia state line (Fig. 5-1, Plate III).

Additional constraints are provided by an industry seismic reflection line north of the Tennessee-Georgia border (Fig. 5-10) that contains several sets of moderate to steeply

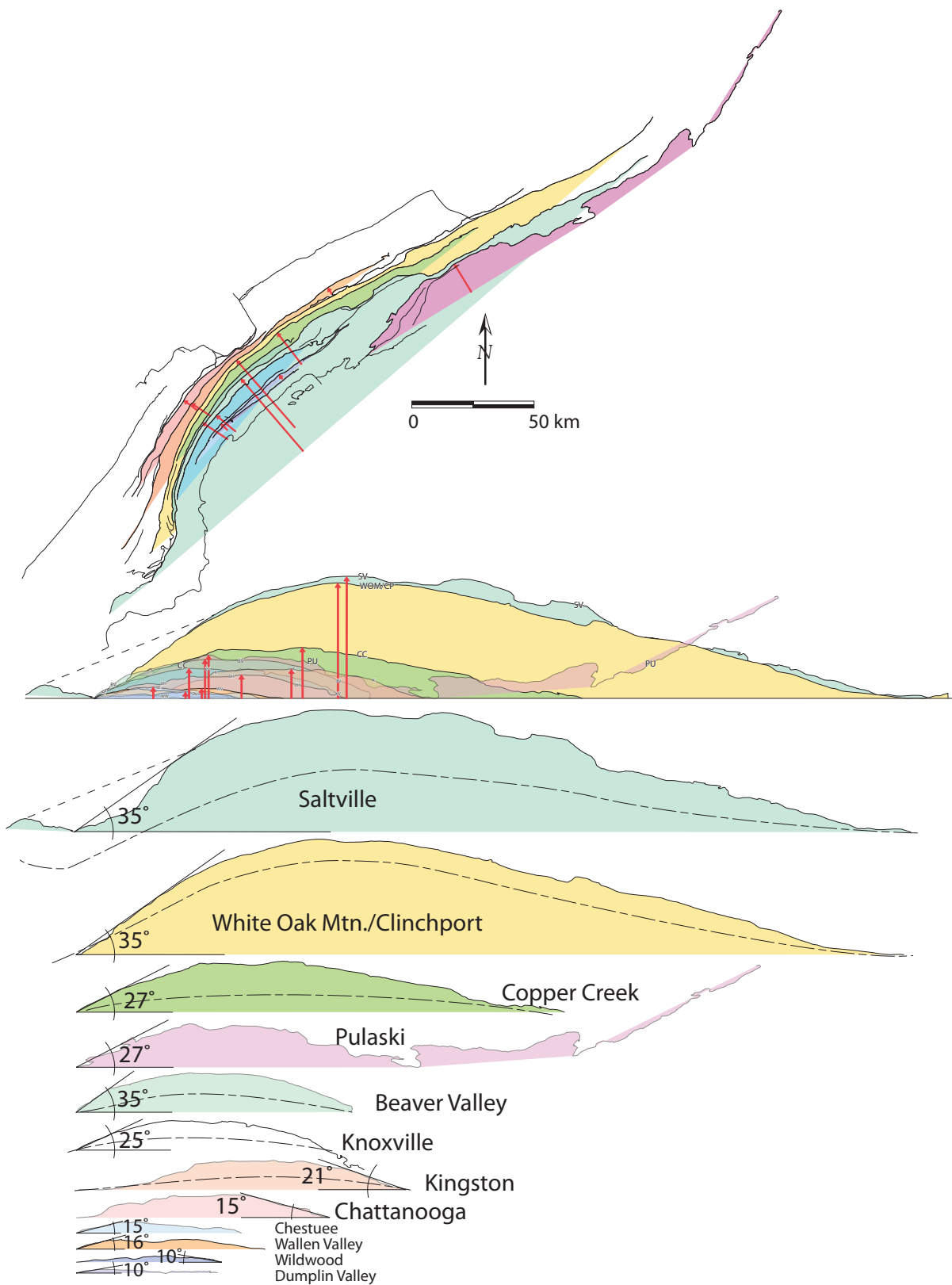
Figure 5-10. Seismic reflection line and nearby cross section across the Sevier basin just north of the Tennessee-Georgia border. a) Industry seismic reflection line with dipping reflectors beneath the thin Knoxville sheet. b) Portion of cross section 13 (Fig. 3, Plate I) near the industry seismic line, with dipping reflectors interpreted as duplexes of Beaver Valley sheet rocks in the footwall of the Saltville fault.



dipping homoclinal panels. The Whiteoak Mountain fault extends 640 km (400 miles) from northwestern Georgia into East Tennessee, where it continues northeast into Virginia, finally terminating in a fold north of the Roanoke recess. The Whiteoak Mountain fault is nearly as areally extensive as the Saltville fault (Figs. 5-3 and 5-11). Using Elliott's (1976) bow-and-arrow rule (Fig. 5-11), one can estimate the magnitude and the primary direction of shortening for a fault. For thrusts in the Canadian Rockies, Elliott (1976) found that maximum displacement on faults spanning a wide a range of lengths was approximately 7% of the linear distance between fault tips. The magnitude and direction of shortening for the Whiteoak Mountain and Saltville sheets look nearly identical by this method (Fig. 5-11), however, the estimated displacements are very high (80 km) and the magnitude of the maximum displacement vector would be closer to 12%. Seismic reflection data on which the cross sections were based clearly indicate that the maximum displacement on the Whiteoak Mountain fault is far less than the potential maximum allowed by transport-parallel simple shear of the bow-and-arrow method. Low displacement (10-15 km) relative to its length (360 km) and the lack of a strong displacement gradient in faults in its footwall suggest that this strongly curved fault must have originated as a curved fault. Northwest of Knoxville, the Whiteoak Mountain fault overrides footwall splays: the Wallen Valley fault and the Hunter Valley fault further north. From the branch point with the Wallen Valley fault northeastward to the terminus of the fault in Virginia, the Whiteoak Mountain is called the Clinchport fault. For simplicity, the entire fault is herein referred to as the Whiteoak Mountain fault.

Copper Creek fault. The Copper Creek sheet extends from southwestern Virginia to northwestern Georgia, and, at its widest point, contains nearly a complete Paleozoic section, with rock units below the Saltville sheet ranging in age from Cambrian to Mississippian. Near the Tennessee/Georgia border, however, much of the upper stratigraphic column has been cut out, and it consists of only Rome through Knox. The Copper Creek sheet also contains a structure explicitly drawn as out-of-sequence. In cross sections 2 and 3 (Fig. 5-3 and Plate III) a syncline cored by Mississippian units that brings up rocks as old as

Figure 5-11. Major faults in the southern Appalachian fold-thrust belt to which a modified “bow and arrow” (Elliott, 1976) method has been applied. Red arrows mark the inferred direction of maximum shortening for individual faults, and are drawn along the perpendicular to the chord connecting the two points on the fault nearest the hinterland across the widest part of the bow. Elliott estimated that displacement on faults in the Canadian Rockies as approximately equal to 7% of the chord length. This method allows one to estimate a minimum value for rotation (angles at ends of fault traces) or amount of differential transport required to produce the curved southern Appalachian fold-thrust belt faults from a straight line. The 7% estimate agrees with shortening from cross sections for some faults (Copper Creek, Chattanooga), and not at all for others, for which the bow and arrow method far overestimates transport (Whiteoak Mountain, Sequatchie Valley, etc). Dashed lines shows location of fault trace pre-deformation (relative only to that fault).



dipping reflectors under the Knoxville fault. Hatcher et al. (2007) depicted the Knoxville sheet as being displaced over several duplexes in the Saltville sheet. Putting displacement into the Knoxville sheet here is inconsistent with the lateral extent of the Knoxville sheet, which loses displacement into a fold south of the Georgia border. It is more likely that displacement on the Knoxville fault remains relatively low. Instead, displacement remains (relatively) high on the Saltville fault, which acts as the roof thrust for duplexes in the Beaver Valley sheet. This is consistent with the ~25 km of displacement on the Saltville fault above rocks of the Beaver Valley thrust sheet inferred by Thomas and Bayona (2005) (their Eastern Coosa fault over Dalton thrust sheet) in the northern Alabama recess. Duplexing the Beaver Valley sheet is also consistent with the mechanical properties of the rocks, as the duplexes occur primarily along an ~70 km along-strike stretch where the Beaver Valley sheet lacks a full thickness of the competent Knox Group and is comparatively weak. Starting just north of the latitude of Athens, Tennessee, the Saltville fault cuts from a flat near the top of the Knox Group down section to a flat in the Copper Ridge Dolomite (basal Knox Group) and into the Conasauga Group (Hardeman, 1966). It does not cut back up section into the Knox Group and Middle Ordovician units until 5-10 km south of the Tennessee-Georgia border (Hardeman, 1966). In cross section 14 in northern Georgia, the Beaver Valley sheet is thicker, and only one sub-Saltville horse is inferred (cross sections 12, 13, and 14, Fig. 5-3, Plates III and IV). The width of the fold-thrust belt between the Beaver Valley and Great Smoky faults is relatively narrow here as well (23 km), compared to the width at the latitude of Knoxville (35 km). This is also consistent with the interpretation of relatively constant displacement on the Saltville fault above a thinner, weaker Beaver Valley sheet that accommodates additional shortening by duplexing beneath the Saltville and Knoxville sheets.

Whiteoak Mountain Family. The Whiteoak Mountain family lies west of the Saltville family, and is part of Rodgers (1953) “zone of dominant faulting.” It consists of three primary thrust sheets (Whiteoak Mountain, Copper Creek, and Beaver Valley) that bring up Rome along at least part of their length, and are, for the most part, southeast-

Cambrian-Ordovician Knox Group has been drawn as forming along a backthrust that was later cut off by the advancing Saltville fault. Early backthrusts are consistent with analog and finite element models of fold-thrust belt development (cf. Dixon and Liu, 1992; Stockmal et al., 2007), and are a reasonable explanation for a footwall fold that is cut off by the Saltville fault. Other faults such as the Rocky Valley, Dumplin Valley, Chestuee, and Wildwood faults in the hanging wall of the Saltville fault *may* be out-of-sequence, but need not be interpreted as such, based on surface and seismic geometry.

Beaver Valley fault. Just northwest of Knoxville, a fold and splay off the basal detachment initiated the Beaver Valley thrust sheet in the hanging wall of the Copper Creek thrust. The fault trace extends to the northern part of the Alabama recess, just south of the Tennessee-Georgia border. Roeder and Witherspoon's (1978) palinspastic map of the Tennessee salient restores a large amount of displacement on the Beaver Valley fault. Here, the Beaver Valley sheet is restored much closer to the Copper Creek fault. Seismic reflection lines through Harriman and Felker, Tennessee, show that the Beaver Valley fault did not occur in the immediate footwall of the Saltville fault as depicted by Roeder et al. (1978) but rather tens of kilometers toward the foreland, and occupies a location similar to that of the Copper Creek fault, which lies in the Beaver Valley footwall. The Beaver Valley fault may have nucleated where it did because the total thickness (and likely the mechanical strength of the sheet) is lower in the Beaver Valley sheet than in the Copper Creek sheet (Fig. 5-12). As the Saltville thrust follows a flat in the Mississippian above the Copper Creek sheet for several tens of km northeast of Knoxville, so too, it follows a flat (although lower in the section, varying from the Middle Ordovician to as low as the Conasauga Group) above the Beaver Valley fault after its appearance 20 km north-northeast of Knoxville.

Western fault family. West of the Whiteoak Mountain fault lie several faults along the western edge of the southern Appalachian fold-thrust belt: the Hunter Valley, Wallen Valley, and Pine Mountain faults north of the Wartburg basin (Fig. 5-1), and the Kingston, Chattanooga, Rockwood, Sequatchie Valley, and Cumberland Plateau overthrust faults

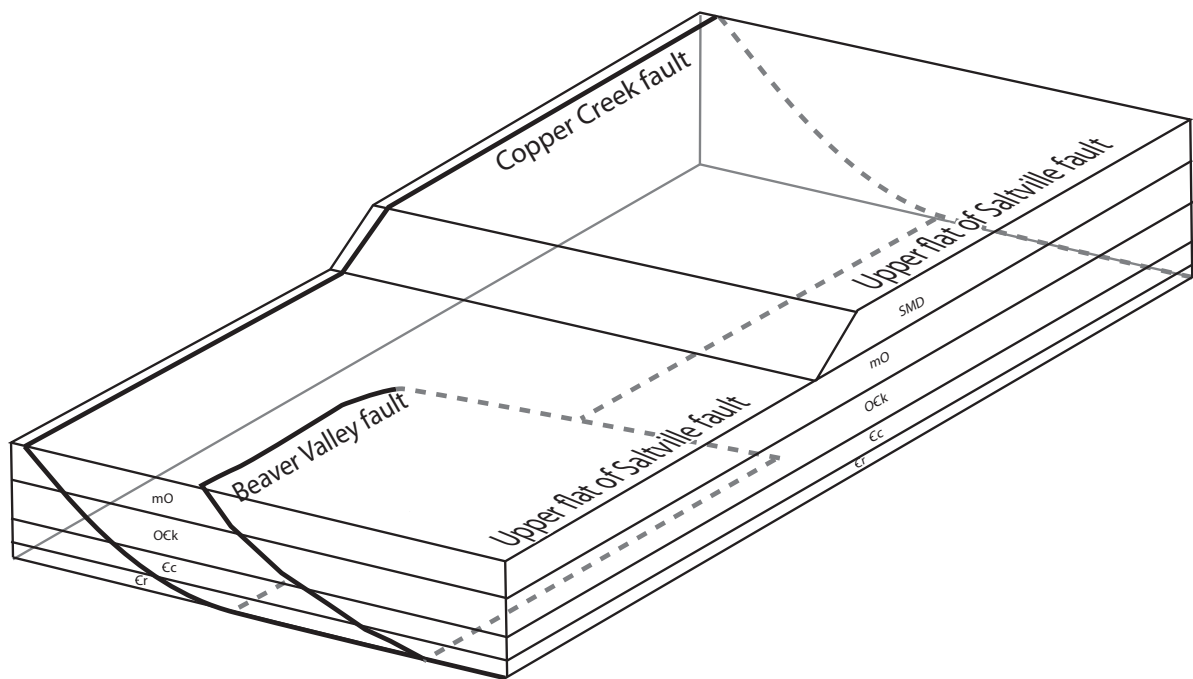


Figure 5-12. Beaver Valley fault nucleates where rocks are thinner and weaker south of lateral ramp in upper flat of Saltville fault.

primarily south of the basin, although the Chattanooga and Kingston faults originate due southeast of the basin (Fig. 5-1).

Wallen Valley fault. At its northeast end in southwest Virginia, the Wallen Valley fault, a footwall splay of the Whiteoak Mountain fault, is a small displacement (Mississippian-Devonian on Silurian) fault separating an anticline–syncline pair in the Middlesboro syncline northwest of Clinchport, Virginia. Stratigraphic throw increases southward along the fault, as increasingly older units (Knox, Conasauga, and Rome) in the hanging wall are placed over Middle Ordovician to Silurian age units in the footwall. The dip of the Wallen Valley fault changes along strike due to changes in deformation style in its footwall (duplexing in the footwall of Pine Mountain fault; Mitra, 1988). To the north, toward the Virginia/Tennessee border, the Wallen Valley fault carries a wide outcrop belt of folded and faulted young (Silurian through Mississippian) units. Both the Pine Mountain fault and the underlying duplexes in the vicinity of cross section 2 employ two lower detachments—one in the Rome, and one near the base of the Maynardville Limestone (Conasauga Group) (Fig. 5-3) (Mitra 1988). The duplexes disappear near the southwestern end of the Pine Mountain block (Mitra, 1988), and the Wallen Valley fault dips more steeply as it transfers displacement to the Kingston fault that developed in its footwall. The Wallen Valley fault does not significantly decrease displacement toward its southern terminus (cross sections 5 and 6, Fig. 5-3, Plate 2), suggesting that the southwest end of the fault, which extends below and is concealed by the overlying Whiteoak Mountain sheet, may end not in a fold, but rather in a tear fault related to the down-to-the-northeast basement fault that lies below the surface trace of the south end of the fault, similar to the movement on the underlying Pine Mountain thrust sheet, which has approximately 21 km of displacement.

Pine Mountain fault. The Pine Mountain thrust block is the westernmost moderate-displacement fault in Virginia, Kentucky, and NE Tennessee (Mitra, 1988). The Pine Mountain fault extends from Tennessee NE into Kentucky and Virginia, and generally places Devonian-Mississippian rocks in the hanging wall over Pennsylvanian rocks of the

Plateau in the footwall. It is bounded to the northeast by the Russell Fork tear fault, and to the south by the Jacksboro tear fault. The Pine Mountain area is the classic geologic model for thin-skinned thrusting. It is here that Rich (1934) explained the geometry of the Pine Mountain block as resulting from transport of planar units along a multi-level detachment fault, resulting in a fault-related syncline and anticline. These structures are further deformed by blind faulting and duplexing of the footwall block (Mitra, 1988). The Pine Mountain fault splays from the basal Rome detachment, and then ramps up to another detachment in the Chattanooga Shale. The southwestern extent of the Pine Mountain block appears to be controlled by the thickness of the upper detachment unit: the Chattanooga Shale thins from more than 300 m in southwestern Virginia and Kentucky to only 30 m just north of the Jacksboro fault. Displacement on the Pine Mountain fault decreases northward along strike, from 21 km near the Jacksboro fault to only 3 km near the Russell Fork fault (Rich, 1934; Mitra, 1988; this study). For a detailed discussion of the geometry and kinematics of the Pine Mountain block, see Mitra (1988) and references therein.

Kingston and Chattanooga faults. The northern end of the Kingston fault lies north-northwest of Knoxville, Tennessee, and the southern end terminates in folds in northwest Georgia. It may have initiated as displacement from the Wallen Valley fault was transferred south across the basement fault (Fig. 5-4). The Kingston fault dips steeply northeast of Knoxville near Clinton, Tennessee, because of buttressing against the essentially undeformed Wartburg basin block (Fig. 5-1). The Chattanooga fault lies in the footwall of the Kingston fault, and is the along-strike continuation of the Pine Mountain fault, that involves detachment along the basal Rome with a less extensive detachment in the Devonian-Mississippian Chattanooga Shale. The frontal Chattanooga fault is a blind fault that propagates along a higher detachment that delaminated Mississippian and Pennsylvanian rocks at the boundary between the Valley and Ridge and Cumberland Plateau (Part II; Milici, 1979; Whisner and Hatcher, 2003). Dip on both the Kingston and Chattanooga faults shallows substantially to the south. These shallow angles preserve something close to the

original dip on southern Appalachian fold-thrust belt faults, since minimal imbrication has occurred in their footwalls to steepen them, and they, or (for the Chattanooga fault) sub-seismic duplexing and thickening of the Conasauga Shale and Rome Formation, have bowed up and decreased the dip along much of the fault in the Eureka triangle zone discussed by Whisner and Hatcher (2003) (Part II). The shallow dip is additional evidence for hinterland-to-foreland deformation (forelandmost faults should be shallowest, because they have not been steepened by later faulting and transport in the footwall (Boyer and Elliott, 1982; McClay, 1992).

Sequatchie Valley fault-Cumberland Plateau overthrust. The Sequatchie Valley fault is a low-displacement fault along the foreland side of the southern Appalachian fold-thrust belt that outcrops for more than 220 km from just southwest of the Wartburg basin into Alabama, past the Alabama recess. The Sequatchie Valley fault is the westernmost fault to bring rocks as old as Cambrian-Ordovician Knox Group to the surface. The fault extends westward in Pennsylvanian units below the Plateau as the Cumberland Plateau overthrust (Milici, 1960) and terminates in anticlines at both its northern and southern ends. Pennsylvanian rocks are preserved in the physiographic Cumberland Plateau province, although the fault is still part of the southern Appalachian fold-thrust belt.

Discussion. The cross sections and restorations (Fig. 5-13, Plate IV) reveal interesting features of the southern Appalachian fold-thrust belt. The Eureka structure (thickened Conasauga Group and Rome Formation) (Whisner and Hatcher, 2003; Part III) is recognizable along the entire western side of the Valley and Ridge in Tennessee, and, in the southern end of the structure, appears to be roughly associated with a small northeast-southwest-trending basement graben. The thickened area was restored by area balancing. The Saltville is a far-traveled thrust sheet around the entire salient, and the underlying sheet (Copper Creek to the north and Beaver Valley from Knoxville southward) is extensive. Shortening by imbrication within the Saltville sheet in the Sevier basin northeast of Knoxville is overridden by the Blue Ridge, and the shortening location shifts westward

Figure 5-13. Cross sections and retrodeformed sections around the Tennessee salient. a) location diagram and explanation of units, b) Sections 1 through 6, c) Sections 7 through 11, and d) Sections 12 through 15. Retrodeformed sections are at half the scale of deformed sections.

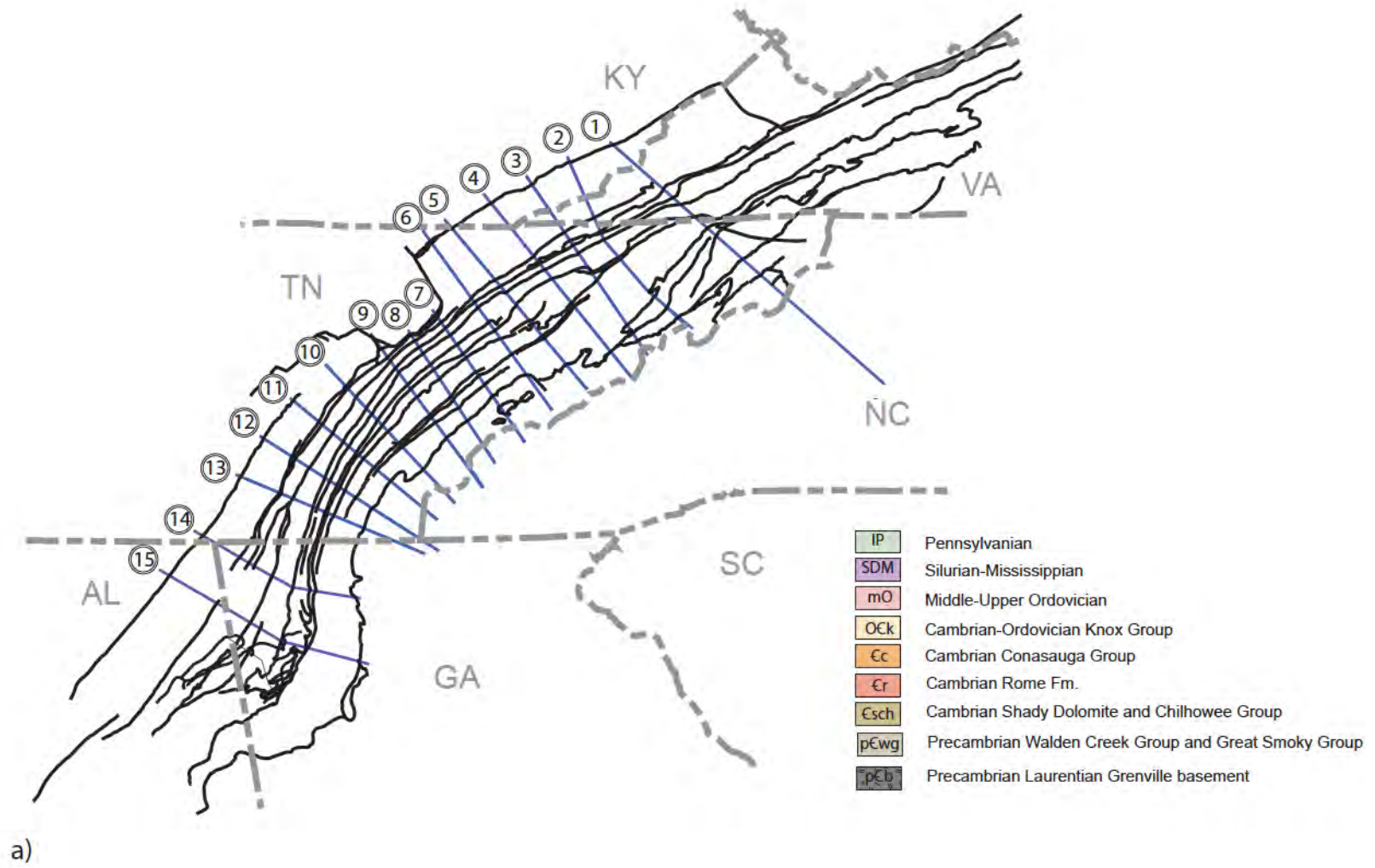


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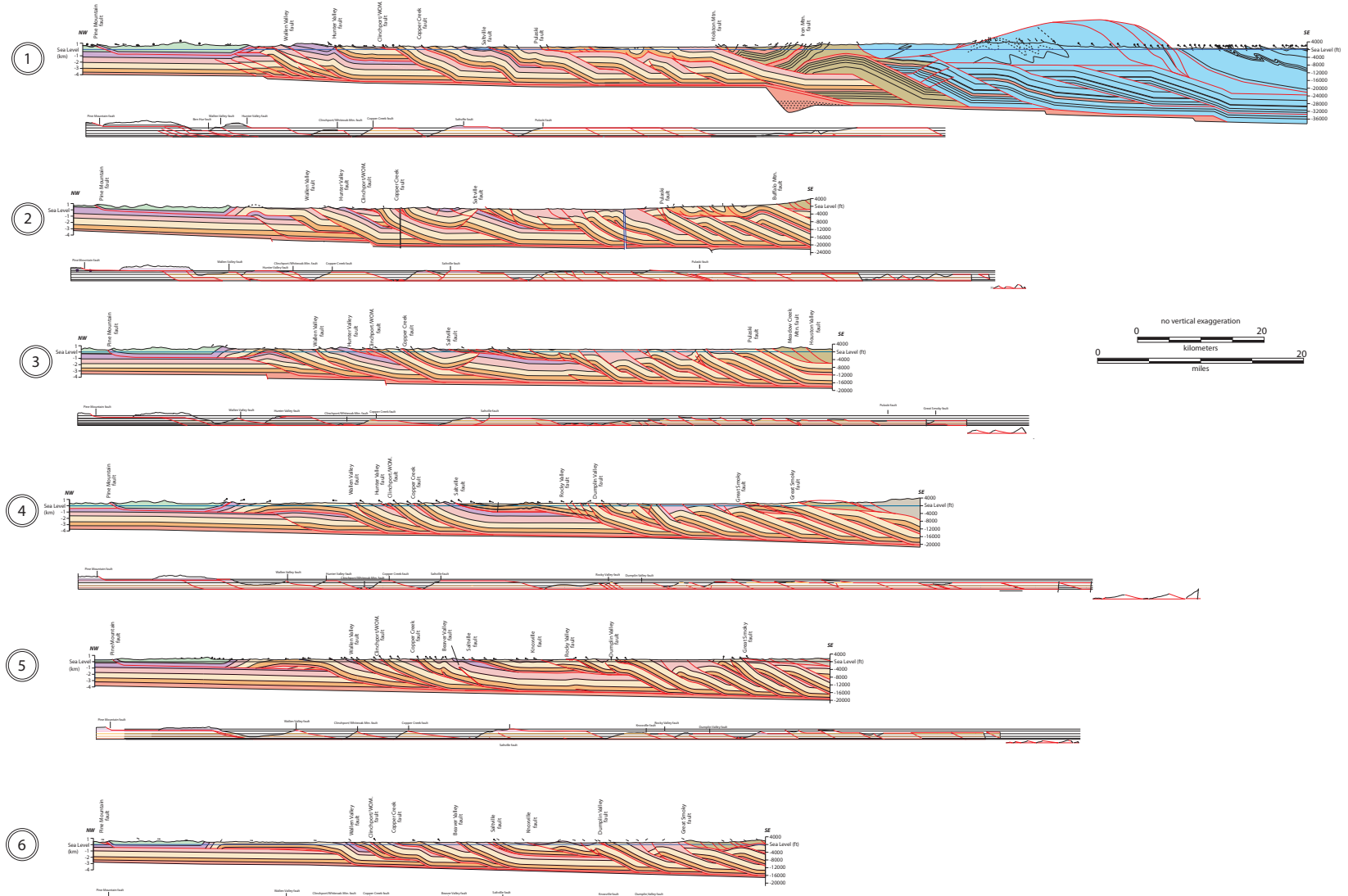


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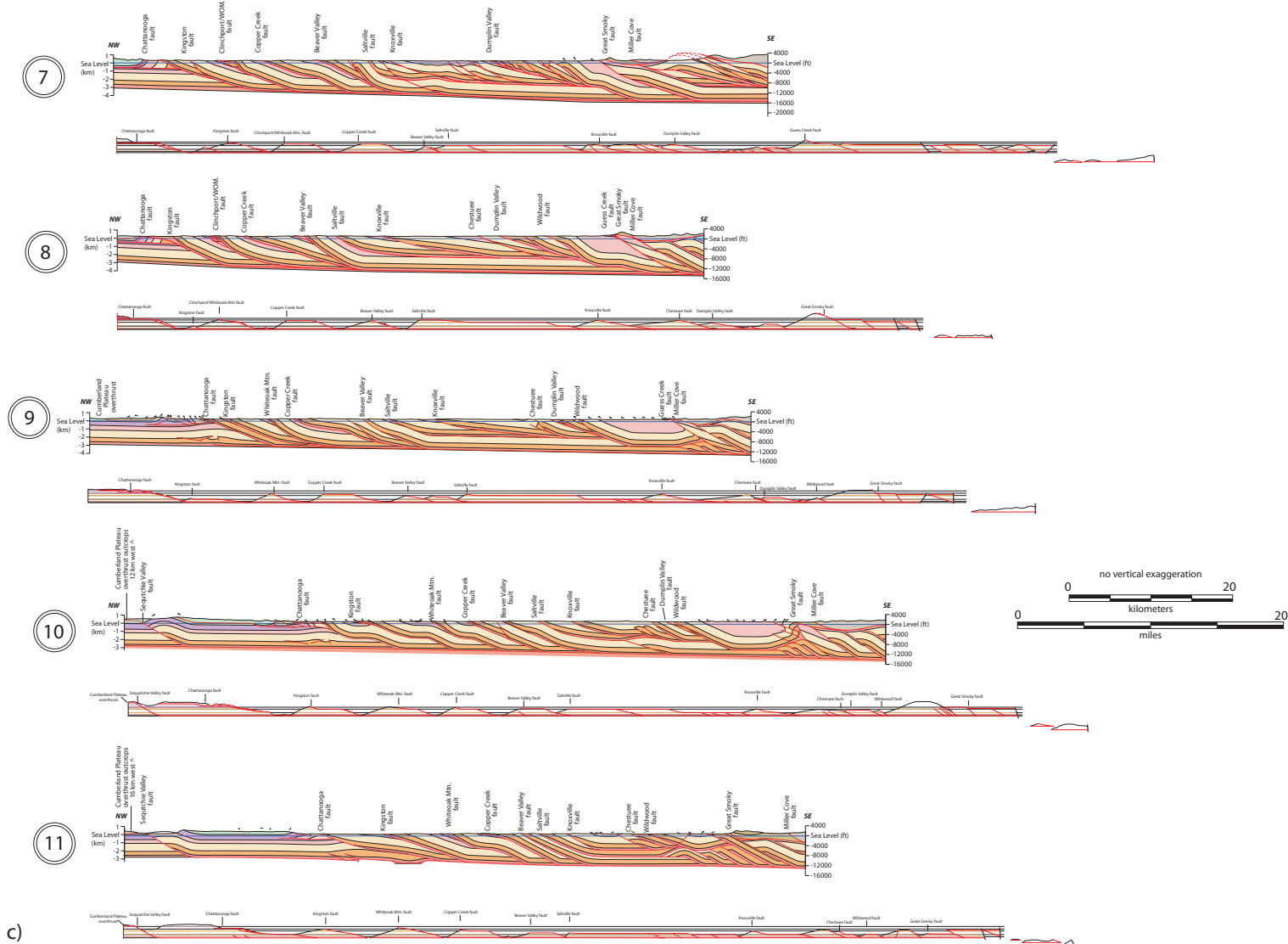
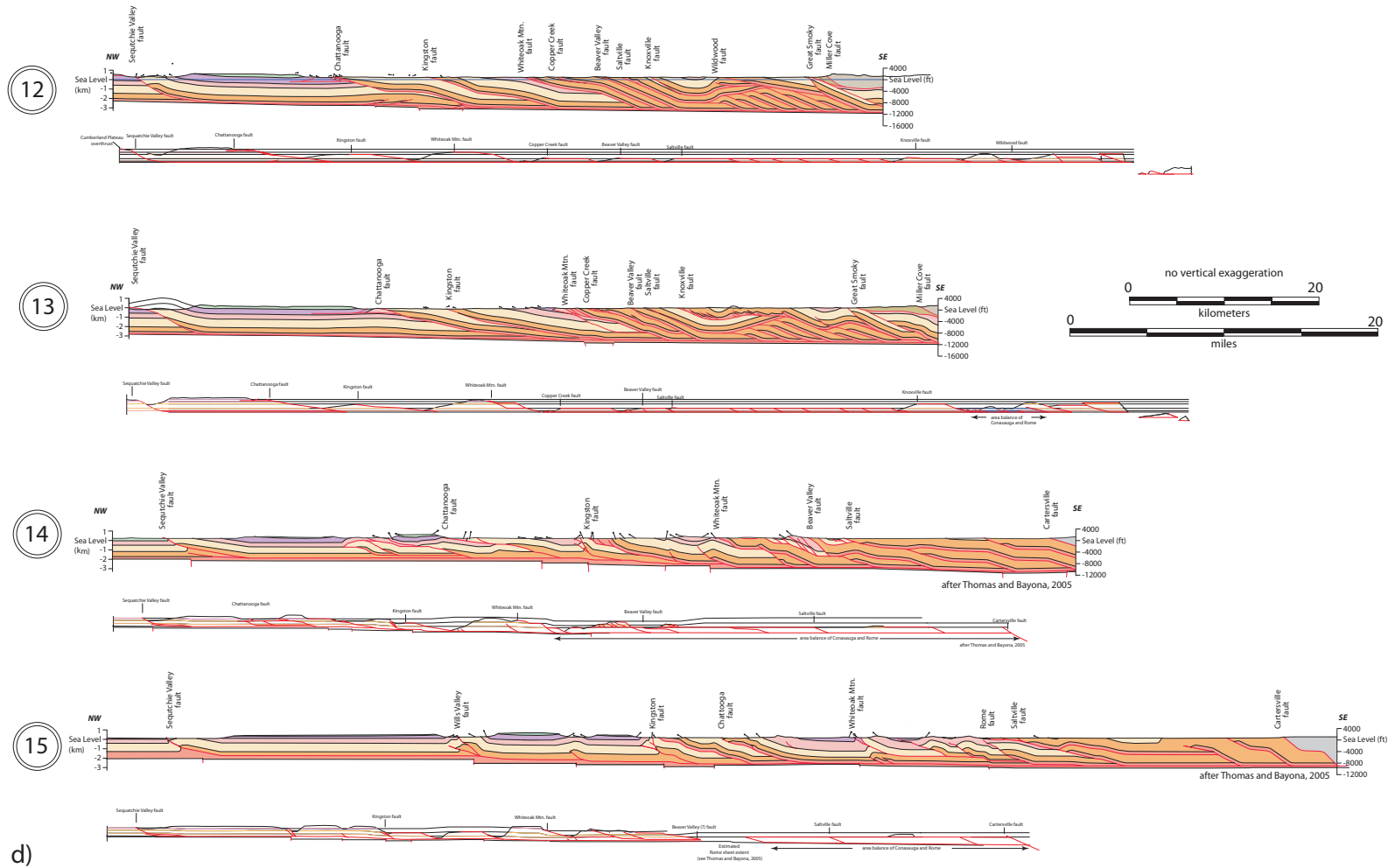


Figure 5-13 continued.



1977). Most rock units exposed in the southern Appalachian fold-thrust belt in East Tennessee are Middle Ordovician and older. Silurian (or Devonian-Mississippian, where Silurian rocks are not present in the stratigraphic section) to Pennsylvanian rocks are not as well exposed in the Tennessee portion of the salient, cropping out primarily in the external thrust sheets and from there, along strike into Virginia and Georgia-Alabama, presumably because the more internal thrust sheets have been subject to deeper levels of erosion.

Stratigraphic units older than Middle Ordovician may have been affected by strain transmitted from continental collision with a volcanic island arc and associated development of a never identified fold-and-thrust belt in the underlying Neoproterozoic rift to Ordovician passive-margin carbonate bank deposits (Finney et al., 1996; Whisner, 2005; Evenick et al., 2007). Although the collision must have occurred far outboard of the basin (no volcanic clasts or Ordovician zircons have been found in the Middle Ordovician clastic wedge in Tennessee (Hatcher et al., 2004)), similar stresses were transmitted and detected in the form of calcite twin strain as much as 800 km from the Alleghanian foreland (Craddock and van der Pluijm, 1989). Hnat (2008a) sampled carbonates both within and beyond the fold-thrust belt and successfully used them for calcite twin strain analysis. Rock units of suitable lithology for development of kinematic indicators, such as clean sandstones, or oolite beds for Fry and related methods also are not evenly distributed around the curve (House and Gray, 1982; Reks and Gray, 1983).

Perhaps the greatest obstacle to the analysis of incremental strain is the general lack of penetrative strain (Wiltschko et al., 1985; Lutz, 1987; Geiser, 1988), likely due to the strength of the large thickness (900+ m) of Cambrian-Ordovician dolostone and limestone, which act as strong structural lithic units (Woodward and Rutherford, 1989), as well as the shallow burial and depth of deformation. Penetrative strain is most often observed in areas with high thermal maturity or incompetent lithologies, such as such as Middle Ordovician mudrocks (Reks and Gray, 1983; Woodward et al., 1986; Ohlmacher and Aydin, 1995) that are of higher thermal maturity than the majority of the salient (Fig. 5-6) in Northeast

with increased displacement on the Saltville fault and duplexing in the underlying Beaver Valley sheet southwestward around the salient. The maximum displacement on the Saltville occurs south of Knoxville. Restoration of the imbrication and duplexing in (to the north) and below (to the south) the Saltville sheet, suggested by seismic reflection data, means that the retrodeformed thrust belt is as much as 310 km wide, even before it disappears under the Blue Ridge. Imbricates present in the Sevier basin and under the Pulaski fault northeast of Knoxville can be traced southwestward under the Blue Ridge, where they are no longer included in the cross sections. A large additional area of foreland rocks not included in the restoration is known to extend beneath the Blue Ridge (Hatcher et al., 1994, 2007), so although the restoration stops at the end of the cross sections, Alleghanian deformation of the Laurentian margin began outboard of the area discussed in this study.

KINEMATIC MODELS

The surface and subsurface geology in the southern Appalachian fold-thrust belt are delimited by high quality geologic map coverage, as well as abundant seismic reflection data (Figs. 5-4, 5-8, 5-9, and 5-10). The kinematic history of the fold-thrust belt is less well delimited, however, because of the paucity of penetrative fabric elements used to parse out incremental strain history and from which displacement trajectories used to distinguish among different kinematic models could be determined (cf. Hindle and Burkhard, 1999). The primary difficulties lie in the age and lithology of the units in the southern Appalachian fold-thrust belt, the distribution of facies around the salient, and the depth of erosion.

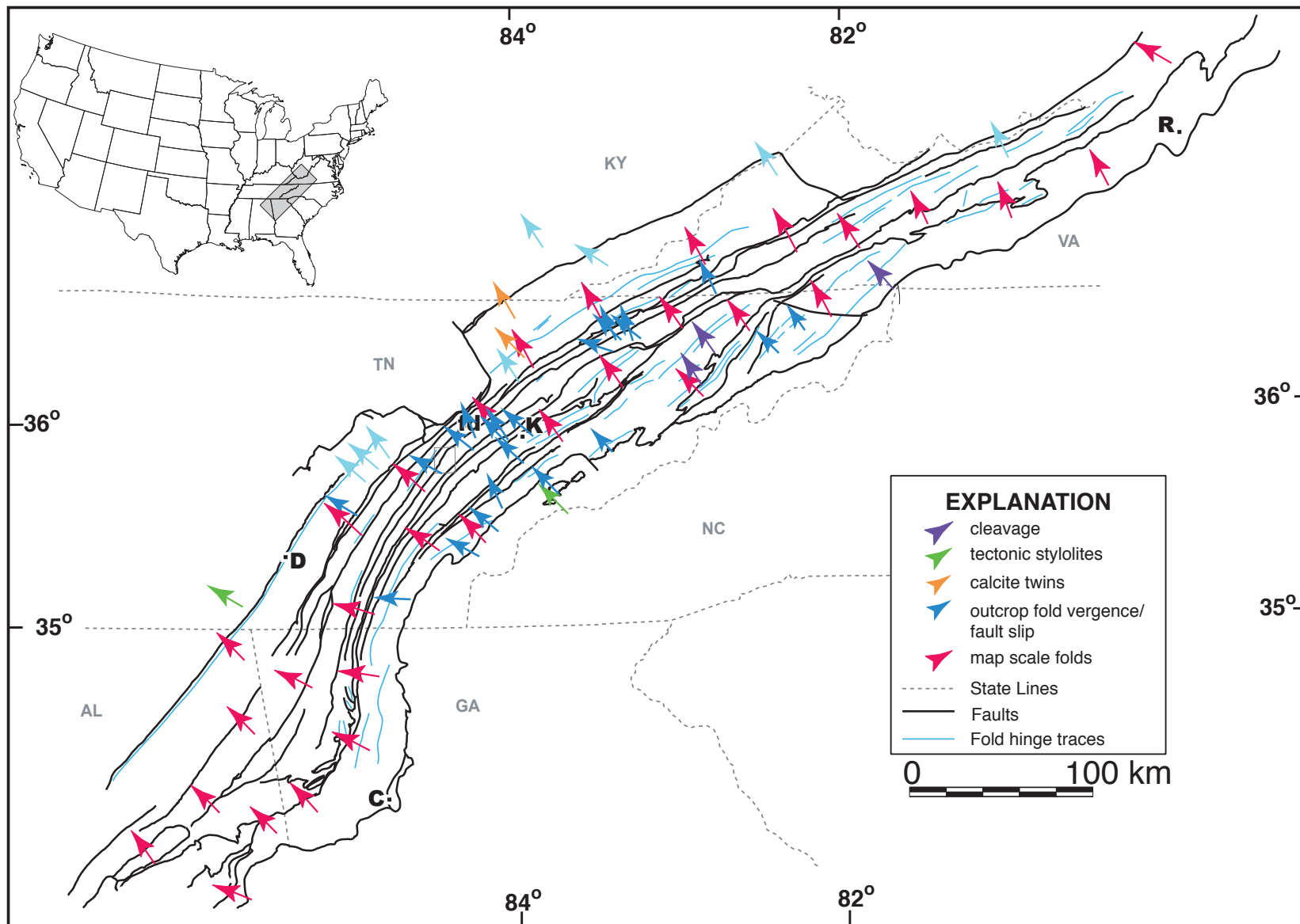
Rocks recording incremental strain data unambiguously attributable to Alleghanian deformation are not evenly distributed around the Tennessee salient. For example, preserved syn-orogenic Alleghanian units are scarce in the interior portions of the fold-thrust belt. The Tennessee salient is the depocenter for the Alleghanian (foreland part) and Taconic (hinterland part) clastic wedges (Thomas, 1977; Hatcher et al., 1989). The Alleghanian clastic wedge in the southern Appalachians began forming in the late Mississippian (Thomas,

Tennessee and southwestern Virginia. The magnitude of penetrative strain here varies from very small when compared to thrust displacement, to very large values of up to 35 percent horizontal shortening (Reks and Gray, 1983). Conasauga Group shale in northwest Georgia is similarly strained (Weaver and Broekstra, 1984). Penetrative strain in the middle of the fold-thrust belt was documented by House and Gray (1982) at the northern terminus of the Saltville fault in Virginia, predominantly in incompetent shale-rich units in the footwall and hanging wall of the Saltville fault.

Bulk strain, expressed by macro and meso-scale folds, demonstrates that the primary direction of shortening fans around the salient (Fig. 5-14). Incremental strain indicators, such as calcite twin strain, tectonic cleavage, tectonic stylolites, and fault slip data collected from a variety of sources, support this result, as do the results of Hnat et al. (2008a). Paleostress directions determined by Wojtal and Pershing (1991) at the three locations previously discussed (D, CC, and HV on Figure 5-1) are essentially perpendicular to the strike of the major faults. Paleostress directions determined from calcite twin strain analyses by Hnat et al. (2008a) fan more (85°) than the trends of the Tennessee salient structures around which they form (60°). The over rotation is unlikely to be the result of map view sinistral shear strain, because large-scale rotations have been ruled out by paleomagnetic data (Hnat et al., 2009). Depending on the location of over-rotated samples, this could be a reflection of local paleomagnetic direction rotations measured where thrust sheets in the Alabama recess lie atop lateral ramps (Bayona et al., 2003). Calcite twin sample locations and shortening directions, however, have not yet been published, so I note only that Hnat et al. (2008a) reported that the fanning stress directions preserved in calcite are observed both in and beyond the fold-thrust belt and match those predicted by an indenter with the shape of the frontal BRP.

It is unlikely that the entire range of stress and strain indicators developed concurrently, although they are presented together in Fig. 5-14. Rather, we infer that strain

Figure 5-14. Directions of both bulk and incremental strain around the Tennessee salient. Data are from field reconnaissance (this study), state geologic maps, 1:24,000-scale geologic quadrangle maps, unpublished master's theses and dissertations, and the following references: Reks and Gray (1983), Wiltschko et al., (1985), Wojtal (1986), Kilsdonk and Wiltschko (1988), and Railsback and Andrews, (1995).



indicators that formed throughout the evolution of the salient have similar orientations because the stress/strain field in which the salient developed remained relatively constant.

Sandbox analogue experiments by Macedo and Marshak (1999) showed that salient-recess pairs can develop from a uniform direction of push due either to irregular basin geometry, such as an adjacent promontory and embayment, or an irregularly shaped indenter. Sandbox experiments by Lickorish et al. (2002) and Hnat (2009) also indicated that salients can form with a uniform direction of shortening.

It is possible, however, that the shortening direction changed over time. Marshak and Tabor (1989) proposed that the limbs of the New York recess formed separately: north-south oriented structures formed early on the north limb and northwest-southeast oriented structures formed later to the south. Their interpretation was based on variations in structural style and shortening amounts between the two limbs, and overprinting of the two structural domains at the apex of the recess, and the analysis of Marshak (1986), which suggested that the Hudson Valley thrust belt (north-south limb of the Kingston orocline) is Acadian. Wise (2004) proposed a similar pattern for development of the Pennsylvania salient based on fold interference patterns and other secondary structures, and limited tangential extension, which is difficult to reconcile with the partial oroclinal bending model of Gray and Stamatakis (1997). Similar structures best explained by a two-stage model have not been observed in the Tennessee salient. Variations in structural style in the Tennessee salient are more closely connected to facies variations than location on a particular limb. Displacement is relatively consistent around the salient, significant structural overprinting has not been documented, and, although little tangential extension has been observed, little is required [(minimal radial thrusting and vertical axis rotations have been ruled out (Hnat et al., 2009)]. Thus the simpler explanation is that the entire salient formed at approximately the same time (not step-wise with different contraction directions) with a single shortening direction.

Could a change in direction of push have come not on an orogen-scale, but from a change in the shape of the BRP indenter? The frontal western Blue Ridge is unlikely to

have changed shape ductilely, because it was not subjected to high temperatures during Alleghanian deformation. The frontal BRP in East Tennessee recorded only anchizone metamorphism (Mersch et al., in prep), overridden foreland rocks exposed in East Tennessee have conodont alteration indices of only 3 to 3.5 (in the condensate to dry gas range) (Epstein et al., 1977) and even the early Alleghanian dextral deformation along the Brevard fault zone was achieved at greenschist facies conditions (Hatcher, 2001). The paucity of brittle across-strike or strike-oblique faults, in fact, the paucity of *any* Alleghanian faults in the Blue Ridge outboard of the Tennessee salient makes it unlikely that portions of the BRP indented independently and caused local changes in the timing or direction of shortening in the salient. The low temperature of the BRP, and paucity of internal Alleghanian deformation suggest that it would have moved as a cool, cohesive mass.

Information on rotation (or lack thereof) and timing of deformation in the salient also support a steady-state hypothesis for deformation in the salient. Paleomagnetic analyses by Hnat et al. (2009) indicated that deformation, including development of primary (non-oroclinal) curvature of the Tennessee salient, was in progress by the late Mississippian to early Pennsylvanian. Their data also indicate that rotation, which is a likely result of a changing stress field, did not occur later in development of the salient. Illite $^{40}\text{Ar}/^{39}\text{Ar}$ age analyses by Hnat (2009) further suggested that simultaneous deformation across the width of the fold-thrust belt continued into the late Early Permian (~278 Ma). The stress field that produced the salient may thus have existed for approximately 40 million years. These results conflict with the two-stage evolution of the Alleghanian stress field suggested by Engelder and Whitaker (2006): an initial dominant ENE-directed maximum horizontal stress across the central and southern Appalachians from approximately 305 to 290 Ma, followed by Early Permian detachment of the BRP and development of the curved Alleghanian map pattern. Hnat et al. (2009) and Hnat (2009) indicated the development of primary curvature in the Tennessee salient and adjacent Alabama recess initiated prior to and continued during the period of ENE maximum horizontal stress (Engelder and Whitaker, 2006). Late Paleozoic

dextral strike-slip motion on several major faults such as the Brevard (Hatcher, 2001) is consistent with early Alleghanian ENE-directed stress, but substantial strike-slip motion is not documented in the Tennessee salient. Rather, the direction of push is assumed to be uniform and northwest-directed, and similar to that causing the late, brittle, dip-slip, out-of-sequence reactivation of the Brevard fault zone (Hatcher, 2001).

Oroclinal bending and curve-parallel simple shear

The question of how to restore the Tennessee salient lies in understanding how it was deformed. The first question that must be answered is: what percentage of the total curvature is due to oroclinal bending? Vertical axis rotations are observed in other map-scale curves in the Alleghanian fold-thrust belt. As discussed above, numerous studies in the Pennsylvania salient reveal vertical axis rotations are responsible for at least part of the curvature of the salient (Geiser, 1988; Kent, 1988; Geiser in Hatcher et al, 1989; Stamatakos et al., 1996; Gray and Stamatakos, 1997; Hatcher and Geiser, 2010). Paleomagnetic rotations in rocks of the Alabama recess are consistent with rotation of thrust sheets moving over lateral and oblique ramps (Bayona et al., 2003). Most recently, analyses of paleopole directions in Cambrian through Ordovician rocks around the Tennessee salient (Hnat et al., 2009) reveal no correlation between declination and regional strike, although the authors noted that at least for their Cambrian and Silurian samples, the remagnetization was most likely Carboniferous-Permian, leaving open the possibility of earlier rotation. Wiltschko (in Hatcher et al., 1989) discussed the timing of Alleghanian deformation, noting that shortening may have occurred over as much as 80 million years, younging westward, and extending from the initial Mississippian, the age of the youngest rocks crosscut by the frontal Blue Ridge and equivalent faults, to the Pennsylvanian (in the southern Appalachian fold-thrust belt) and Permian (farther north) units that comprise the Alleghanian clastic wedge. Rotation of early southern Appalachian fold-thrust belt structures close to or beneath the indenter (the only structures that could potentially be young enough to have rotated pre-remagnetization) is not

unreasonable. Rotation cannot account for the bulk of curvature, however, because much of the deformation occurred within the Carboniferous-Permian remagnetization window. For example, Mississippian units are in the footwall along a portion of the Blue Ridge fault in Tennessee (Hardeman, 1966), Mississippian units are deformed in thrust sheets west of the Saltville fault, and Mississippian and Pennsylvanian units are involved in folding near the southern tip of the Whiteoak Mountain fault, one of the two longest and most strongly curved faults in the southern Appalachian fold-thrust belt (Fig. 5-1). Pennsylvanian rocks are also deformed in thrust sheets such as the Rockwood that lie west of the Whiteoak Mountain fault in the southern limb of the salient.

The main evidence of deformation by curve/parallel simple shear would be field data indicative of strike-parallel motion (such as asymmetrical mesoscopic folds verging northeast or southwest, or strike-parallel slickensides), which is not frequently observed in the salient. Another possible line of evidence would be the strike-parallel displacement of lithologic, stratigraphic, thermal maturity, or other map-scale boundaries. No such displacements have been identified. To answer the question posed above, the lack of rotation precludes shaping the salient by pure bending and the lack of field evidence for extensive strike-parallel motion precludes shaping the salient by curve-parallel simple shear (Fig. 5-2).

Radial thrusting/Piedmont glacier

The general trend of structures at all scales indicates shortening in the southern Appalachian fold-thrust belt occurred perpendicular to the major structures. Radial motion in a fold-thrust belt could be produced by gravitational forces in a 3D critical wedge with lateral taper, (Gray and Stamatakis, 1997), which could develop in strata deposited in an embayment along an irregular rifted margin (Thomas, 1977). Radial thrusting is also compatible with fanning paleostress directions indicated by calcite twin strain (Hnat, 2009) as well as the lack of rotation, making this model very tempting. As noted above, most sets of serial cross sections around the Tennessee salient have been drawn perpendicular to the

macroscopic fabric that fans around the southern Appalachian fold-thrust belt (Roeder et al., 1978; Woodward and Gray, 1985; Hatcher et al., 2007; Hatcher and Geiser, 2010), both implying the existence of substantial amounts of tangential extension (Ferrill and Groshong, 1993), and requiring restoration of areally extensive thrust sheets into smaller and smaller areas closer to the hinterland (Hindle and Burkhard, 1999; Whisner et al., 2004).

Strike-perpendicular joints could accommodate tangential extension, and have been noted by Wiltshko et al. (1985), Kilsdonk and Wiltshko (1988), and Lemiszki and Hatcher (1990), although not in sufficient numbers and of sufficient dilation to accommodate the required minimum of 40 percent tangential extension, based on a strict interpretation of radial thrusting.

Tangential extension has been documented, however, in some locations along the southern limb of the salient. For instance, analyses of populations of outcrop-scale faults in the hanging walls of a major fault on the western side of the southern Appalachian fold-thrust belt studied by Wojtal (1986) (Fig. 5-1, point D) indicated a substantial volume of material had moved out of the transport plane, assuming volume-constant deformation (a reasonable assumption given the lack of penetrative strain). Strike-parallel elongation here was observed primarily as motion on a small number of minor faults oblique to a vertical transport-normal plane. These displacements are insufficient to account for the calculated lost volume (Wojtal, 1986). It should be noted that Wojtal and Pershing (1991) stated that there is “shortening in [the] transport [direction] much greater than elongation normal to transport”. Short (1-5 km), steeply dipping map-scale faults oblique to the trends of major faults have been mapped in other locations along this limb of the salient (Swingle, 1959; Hardeman, 1966). Several of the transverse faults mapped by Swingle (1959) in four quadrangles north of the Tennessee-Georgia border contain horizontal slickensides that record movement oblique to the primary shortening direction. Although movement on these faults is unlikely to account for more than a few percent of strike-parallel elongation, their presence is indicative of non-plane-strain deformation along the southern limb of the salient.

Application of the radial thrusting model in both its pure and its modified forms (piedmont glacier style) is thus problematic in two respects: 1) a room problem is generated when thrust sheets are restored into ever smaller areas toward the hinterland; and 2) documented macroscopic and mesoscopic features in this study are insufficient to accommodate substantial strike-parallel extension. Strict radial thrusting and its variation, the piedmont glacier mechanism, can be considered only a minor component of the deformation plan.

Transport-Parallel Simple Shear and Uniform Direction-Uniform Shortening

The lack of vertical-axis rotation also presents problems with the third possible kinematic model, transport-parallel simple shear (Fig. 2). In simple shear, rotation of material lines increases with increasing shear (Fig. 5-15). A minimum of thirty-five degrees is the amount of rotation that would be necessary to generate the most strongly curved portions of the longest (and most strongly curved) faults in the southern Appalachian fold-thrust belt, the Saltville and Whiteoak Mountain faults, by transport-parallel simple shear from an initially straight line. Meso- and macroscale features, such as abundant cross-strike faults (Ferrill and Groshong 1999), that could accommodate simple shear in this direction are not observed in these thrust sheets. Microscale structures are less well studied, however; penetrative microscale deformation sufficient to produce plan view simple shear of 35° would also likely rotate paleomagnetic poles [indicated by arrows in Figure 5-15(a)]. Cogne and Perroud (1985), Hirt et al. (1986), Cogne and Perroud (1987), Borradaile (1997), Cioppa and Kodama (2003), Borradaile and Hamilton (2009) and others indicated that paleomagnetic poles behave as material lines that are rotated by finite grain-scale strain as well as bulk deformation. As remanent magnetization directions do not appear to have been rotated, and macro- to meso-scale features that could accommodate transport-parallel plan view simple shear are not found, model 3: transport-parallel simple shear accomplished by most common

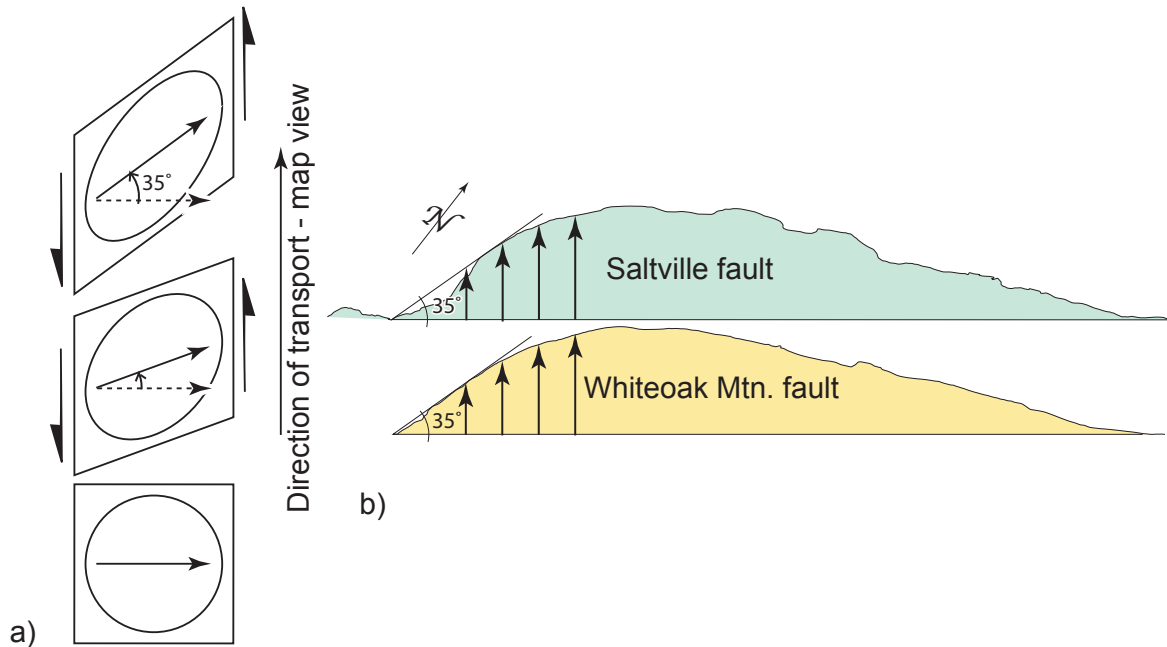


Figure 5-15. Material lines are rotated in map view during transport-parallel simple shear. a) Map view diagram showing simple shear sufficient to rotate an originally horizontal line 35° counterclockwise. The diagram demonstrates the transport-parallel simple shear that would be required to create the most strongly curved faults in the southern Appalachian fold-thrust belt (Saltville and Whiteoak Mountain faults, see also Fig. 1) from an originally straight line, as shown in b). The transport direction is assumed to be perpendicular to a line connecting the northern terminus of each fault with either the point on the southern end of the fault closest to the hinterland (Saltville) or the southern terminus of the fault (Whiteoak Mountain). This direction is not necessarily the assumed transport direction on other faults, or on the salient as a whole. These two faults are of particular interest because, based on the current erosional exposure of the southern Appalachian fold-thrust belt, the Whiteoak Mountain and Saltville faults would require the most transport-parallel simple shear. Faults in b) are shown at the same scale and the same orientation.

deformation mechanisms can also be eliminated for the major faults, although we may still find it useful for minor faults.

For instance, Hnat et al. (2008b) actively sought evidence for vertical axis rotations along the Jones Valley fault at the southern margin of the Alabama recess. They found that no vertical axis rotations had occurred during movement on the fault, which had a minimum potential counterclockwise apparent rotation of 15° , with evidence of up to 23° apparent rotation, due to a displacement gradient along its 80 km fault length, as would be expected with transport-parallel simple shear. Thus, faults with smaller angles of apparent rotation and smaller amounts of differential displacement, strict transport-parallel simple shear *could* be compatible with kinematic data in the Tennessee salient. This model would work well for the Knoxville, Kingston, Chattanooga, and smaller faults (Fig. 5-11) for which the maximum “rotation” angle would be about 25° and the maximum displacement would be less than 25 km.

Palinspastically restored cross sections help tell the rest of the story. The bow-and-arrow method on which the transport-parallel simple shear model is based likely overestimates the amount of displacement that has occurred on faults in the southern Appalachian fold-thrust belt. Elliott’s (1976) bow and arrow method is based on his observation that for faults in the Canadian Rockies, displacement was approximately equal to 7% of the length of the line connecting fault tips. Although the Whiteoak Mountain thrust sheet as a whole is far-traveled (movement on the Whiteoak Mountain fault, and subsequent motion piggybacked on the underlying faults), the displacement required to restore hanging-wall cutoffs (or an erosional surface—hanging-wall cutoffs are mostly eroded in the southern Appalachian fold-thrust belt) back down the fault to the footwall cutoffs against which they originally rested is seldom more than 10 or 12 km (Fig. 5-13). This contrasts markedly with the maximum 42 km of displacement predicted by the bow and arrow method. Much less differential transport or map view shearing would be required, however, if the Whiteoak Mountain fault originated strongly curved, rather than straight (Fig. 5-16). This is true of

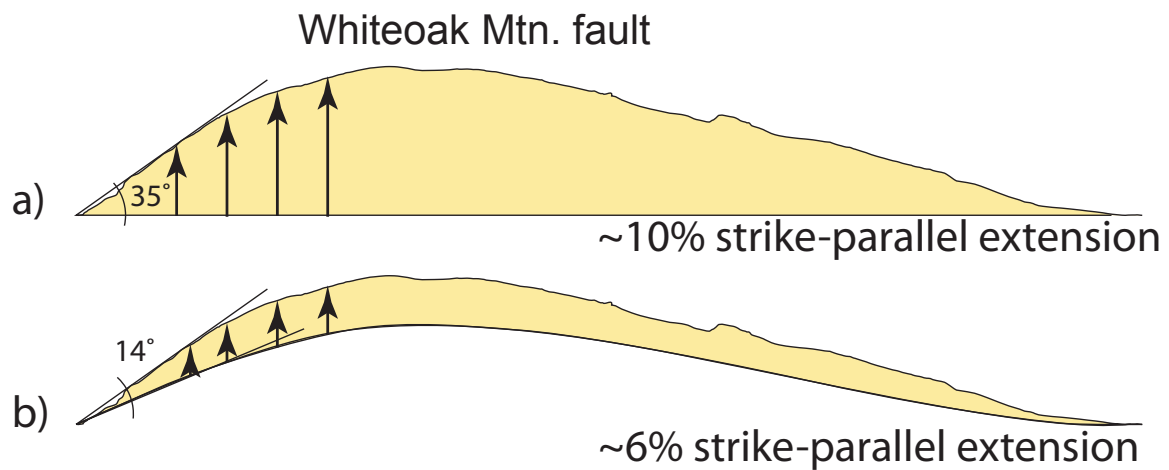


Figure 5-16. Comparing transport-parallel simple shear effects on an initially straight fault and an initially curved fault. a) Creating the Whiteoak Mountain fault shape from an initially curved fault by transport-parallel simple shear as envisioned by Ferrill and Groshong, 1993. b) Creating the Whiteoak Mountain fault shape from an initially curved fault. Both the amount of transport-parallel simple shear and the strike-parallel extension required to create a curved fault are decreased if the initial shape of the fault is curved.

most of the other major faults in the southern Appalachian fold-thrust belt, which generally have individual fault displacements in the range of 5-15 km (although total displacement of each thrust sheet increases toward the hinterland as thrust sheets that have locked up are carried farther toward the foreland on footwall thrusts). The Saltville sheet experienced more displacement (up to 38 km on the fault alone), but restored cross sections indicate that it, too, likely originated as a curved fault [this is to be expected in a salient that is at least partly indenter controlled (Macedo and Marshak, 1999)].

All of this differential transport, however, should produce some map view simple shear, and none has been observed. How can this be explained? Self-similar propagation of faults and folds via “cataclastic flow” was proposed by Hnat et al. (2008b) to explain the development of 15° to 23° of potential rotation without vertical axis rotations along the Jones Valley fault. Fischer and Woodward (1992) pointed out that true self-similar deformation is more likely the exception than the rule in geologic deformation as variation in intrinsic and extrinsic factors will induce variation in the geometry of structures related to a propagating fault. Gray and Mitra (1993) detailed some of the effects of 4D variation in the location of different deformation fronts in a single orogen, which would potentially preclude self-similar deformation.

“Cataclastic flow,” as the term is used by Ismat and Mitra (2001, 2005) and Kwon and Mitra (2004b) is related to Wojtal’s (1986) “deformation by populations of minor faults.” This concept of grain-boundary sliding on a macroscale has been used primarily to describe deformation in a transport-parallel plane (Fig. 5-17). Note that, although the overall shape of the original circle-in-the-square has changed, and that on the scale of the square, deformation is continuous and homogeneous, not one of the individual fault-bounded blocks has rotated. If this diagram were assumed to lie in the X-Y plane of the strain ellipsoid, however, it also presents a useful way of thinking about how curved faults and thrust sheets could develop and propagate without causing any rotation as each sub-block moves, but does not rotate, while the bulk strain is one of map-scale simple shear. Small movements could occur on a

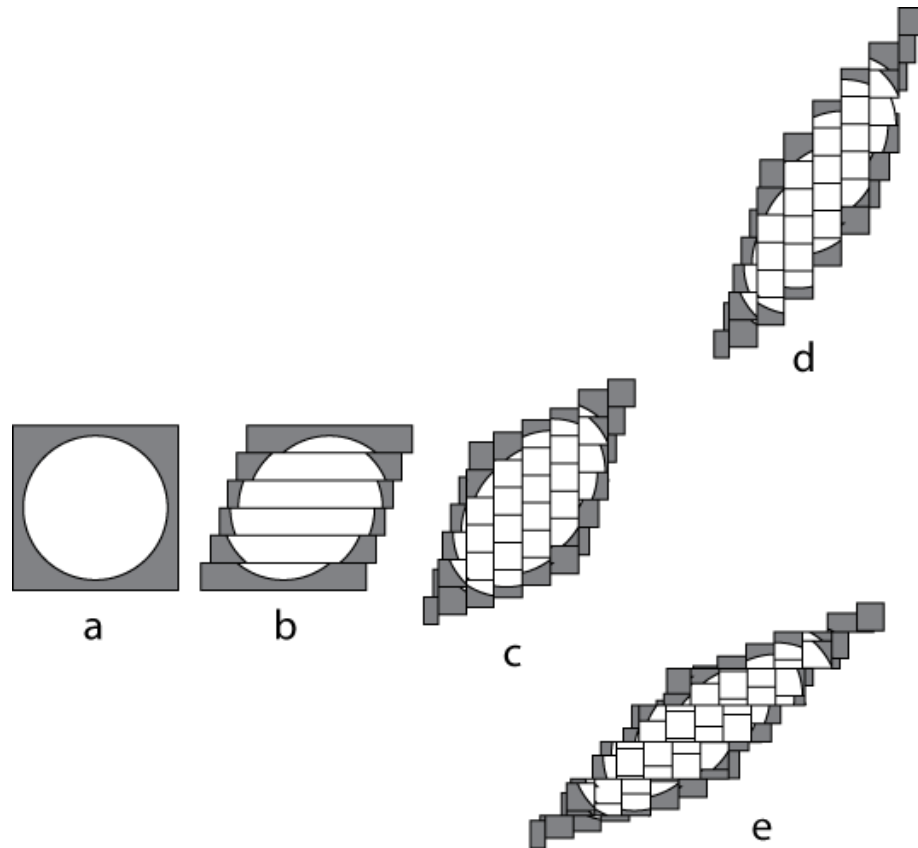


Figure 5-17. “Cataclastic flow” (Ismat and Mitra, 2001) and “deformation by populations of minor faults” (Wojtal, 1986) showing thickening and flattening strains developed by movement on discrete surfaces without rotation of individual mini-fault-bounded blocks. This mechanism has been used to describe movement in a vertical plane parallel to transport. It could also be invoked as a *map-view* explanation of how curved faults and thrust sheets could develop and propagate without rotation.

wide variety of joint and minor fault surfaces such as those on the southern limb of the salient described by Swingle (1959) and Wojtal (1986), and that include Alleghanian strike-parallel, strike-perpendicular, and even cross-strike joints, as well as joints that evolved in older stress fields. This movement could accommodate a plan view bulk shear strain without rotations of the initial stress field as recorded by calcite twin strain (Hnat et al., 2008a), or paleomagnetic directions (Hnat et al., 2009). Macedo and Marshak (1999) noted that the plan view shear strain observed in their sandbox models could be attained by different types of deformation, including displacements on fault-bounded blocks without rotation. Movement by transport-parallel simple shear with a non-rotational mechanism for accommodating shear would be compatible with the geology of the salient. Although this mechanism may be possible, there are not enough data available to confirm this hypothesis in the area that deformed by nonplane strain.

POSSIBLE BASEMENT INFLUENCE ON THE FOLD-THRUST BELT

Macedo and Marshak (1999) identified several essential controls on salient development. Of the causes they discussed, two that have been proposed for the Tennessee salient, and that also can be distinguished on the basis of the geometry of major structures are: 1) the depth and extent of the sedimentary basin; and 2) the shape of the advancing indenter. Basin-controlled salients are identified based on the convergence of structures away from the apex (point along the leading edge of the salient with the greatest curvature) (Fig. 5-18). Indenter-controlled salients are identified based on divergence of structures away from the apex. Macedo and Marshak (1999) identified the Tennessee salient among those controlled by the shape of an indenter. Close inspection of the southern limb of the salient, however, shows that, while faults on the foreland side of the southern Appalachian fold-thrust belt do diverge, several major faults with tens of kilometers of displacement, including the Whiteoak Mountain and Saltville faults (closer to the indenter) are closest together on the southern limb, rather than near the apex at the latitude of Knoxville (Fig.

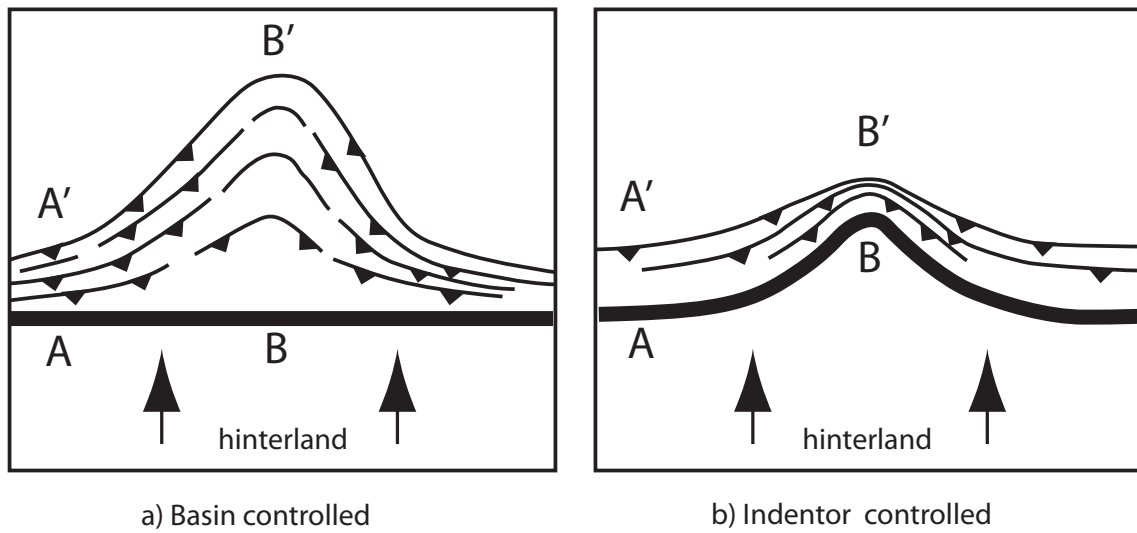


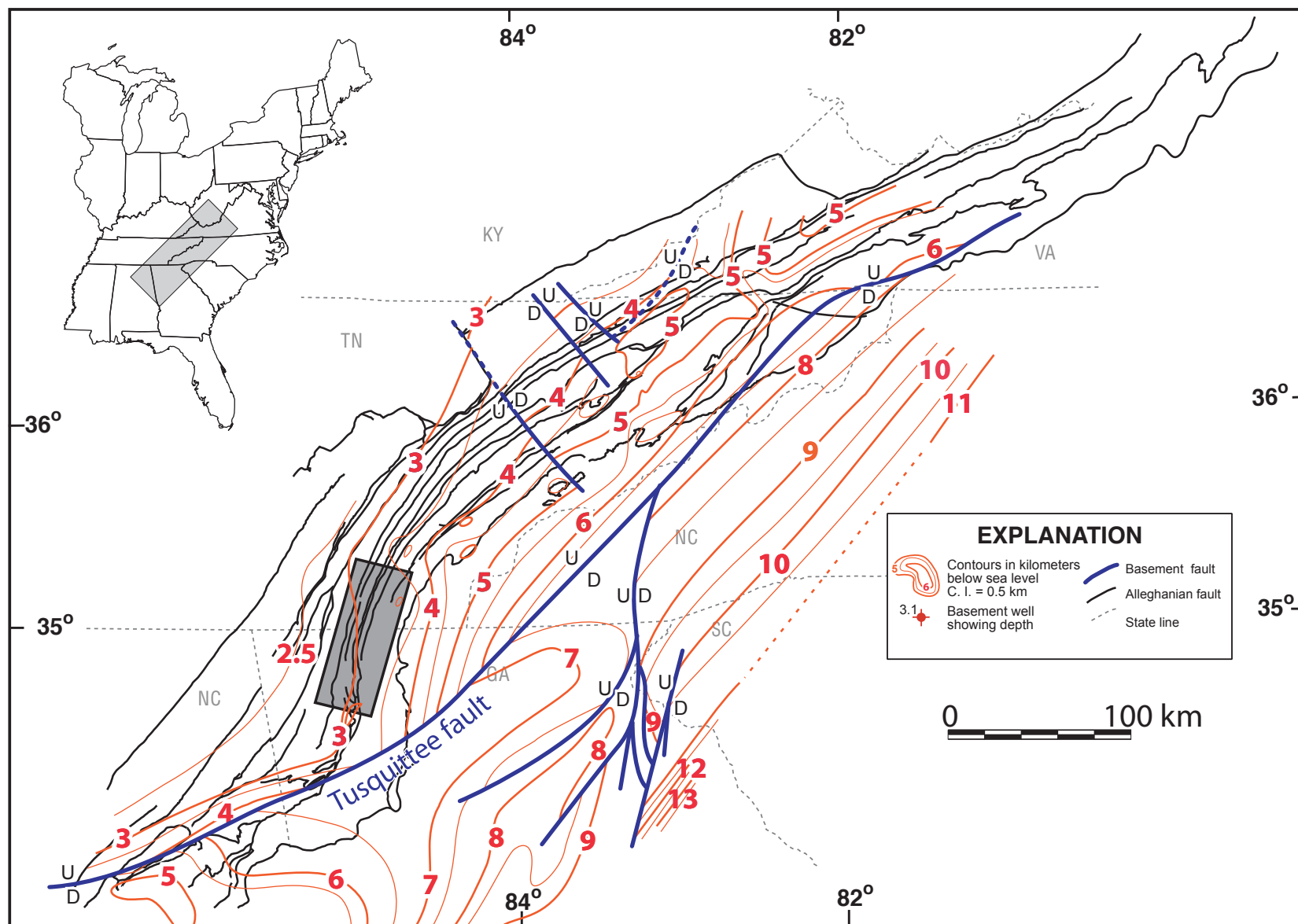
Figure 5-18. Comparison of general geometry of basin- and indenter-controlled salients. After Macedo and Marshak (1999).

5-19). This suggests that basement topography also influenced the shape of the southern limb of the salient. Figure 5-19 shows basement shallowing gently southward around the Tennessee salient, with the exception of the large-scale down-to-the-southeast Tusquittee fault. It also identifies the area in which faults converge on the southern limb. Beneath the fold-thrust belt in this area, the dip on the basement surface is noticeably lower than the dip just to the east (east of the current edge of the Blue Ridge). Faults that restore to positions west of this change in dip diverge at the southern end of the southern Appalachian fold-thrust belt (Fig. 5-19), suggesting that their geometry has less to do with the shape of basement than with the shape of the approaching indenter. Faults that restore to the east of the change in dip do not diverge, but rather converge. Deforming southern Appalachian fold-thrust belt rocks pushed in front of (and below) the advancing BRP thrust sheet would have been affected by perturbations in the stress field due to the change in basement gradient in northwestern Georgia and southeastern Tennessee. Interactions between the basement high and the impinging indenter must not have caused significant rotation on the southern limb, however, because no significant paleomagnetic rotations were measured (Hnat et al., 2009). The change in slope of the basement surface may also have influenced the location of flats in the Saltville, Beaver Valley, and Whiteoak Mountain sheets, with decreases in thrust sheet thickness and mechanical strength causing duplexing and a narrower width for that portion of the fold-thrust belt.

PALINSPASTIC RESTORATION

Hatcher and Geiser (2010) discussed three requirements for a standard retrodeformation of 2D cross sections: 1) plane strain occurs normal to strike; 2) displacement vectors are normal to strike; and 3) the units being restored have undergone volume-constant deformation. A non-standard restoration technique must be applied to the salient, because all of these requirements cannot be met across the entire curve.

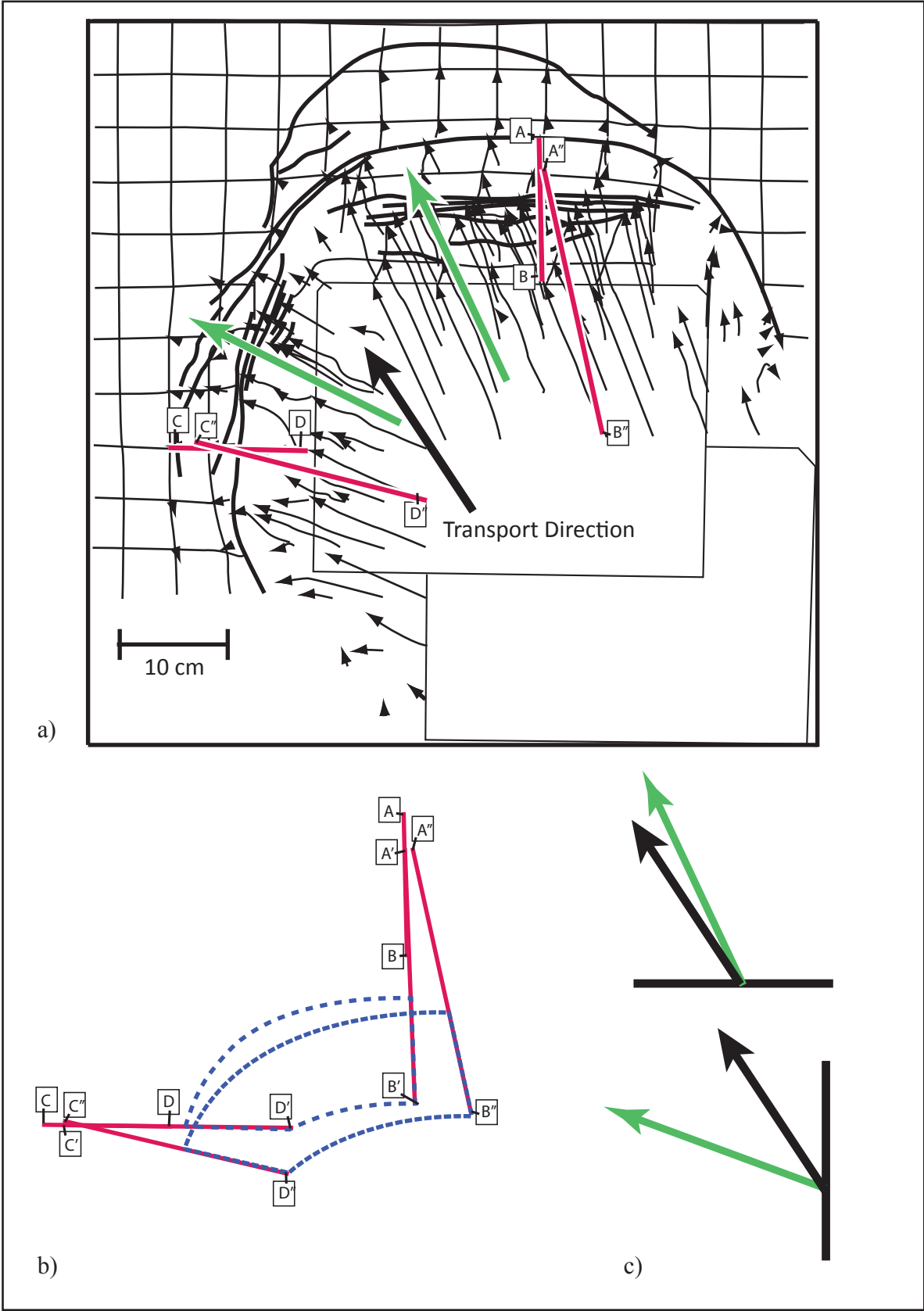
Figure 5-19. Alleghanian faults and basement surface contours. Area of convergence highlighted in gray. Contour diagram after Hatcher et al. (2007).



The requirement for volume-constant deformation is met by most of the Tennessee salient, which was deformed at generally low temperatures, and further shielded from volume loss by the thick Cambrian-Ordovician carbonate struts. Minimal pressure solution strain is present. It is likely that the first requirement, that plane strain be normal to strike, also applies for at least one limb of the salient [the long, 060-trending limb that extends from the Knoxville area to the Roanoke recess (Fig. 5-1)]. Plane strain here is consistent with the paleostress directions from calcite twin strain (Hnat, 2009), detailed fault analyses by Wojtal (1986), and other indicators of macro- and meso-scale shortening directions collected by the author and compiled for this study (Fig. 5-14).

It appears that the plane strain requirement cannot be met for the entire salient. In addition, the requirement that displacement vectors be normal to strike is almost certainly *not* consistent with deformation in the salient. The foreland seems to record multiple, divergent directions of shortening, and the indenter has an irregular shape. This is significant because Hindle et al. (2000) noted that if the frontal surface of an indenter is oriented oblique to the direction of transport, the maximum shortening direction in the foreland (and the macroscopic structural grain) will be oblique to the transport direction, and thus displacement vectors would *not* be parallel to strike normals. Radial thrusting would be consistent with this requirement, but we have ruled it out as a major component of our kinematic model, because of room problems when restoring to the hinterland. If there is a dominant transport direction consistent with the transport-parallel simple shear model that, as discussed above, could potentially be applied to all but the highest displacement faults in the salient, then *somewhere* along the irregular boundary of the BRP indenter, the displacement vectors must occur oblique to strike normals. Lickorish et al. (2002) used a sandbox model to track the displacement paths of particles on the surface of a volume being deformed by (among other paths) a diagonally approaching indenter (Fig. 5-20). In this example, the area drawn between the particle-displacement-derived sections is about 20 percent larger than that drawn between the sections retrodeformed parallel to the maximum shortening directions. Note that

Figure 5-20. Results of a sandbox experiment involving diagonal emplacement of a rectangular indenter, after Lickorish et al., 2002. a) Wide black arrow shows direction of indentation. Thinner arrows show actual displacement paths for points on the model surface. Cross sections lines A-B and C-D are oriented perpendicular to major structures and parallel to the transport direction that would be inferred from fault geometry. A-B and C-D show length and orientation of deformed lines. A''-B'' and C''-D'' show length and orientation of restored lines based on actual particle displacement. b) Dashed lines show the potential difference in area between points restored along the maximum shortening direction (A'-B' and C'-D') vs. along the particle displacement directions documented during the experiment (A''-B'' and C''-D''). c) Comparison of the indenter surface orientation, the transport direction (black arrow) and the actual displacement path trajectories (green). Surfaces are similarly oriented for convenience.



the space problems associated with retrodeformation along fanned cross sections in a curved orogen would be ameliorated somewhat using particle displacement trajectories, because the true displacement paths are slightly more parallel than those that would be inferred based solely on fault geometry. Zwiengel et al. (1998) also conducted sandbox experiments in which a rectangular indenter was diagonally emplaced. They, too, noted that 1) all experiments produced primary arcs (initial faults were curved) and 2) the finite displacement vectors lay at an angle between the direction of transport and the normal to structural trends.

So we use the Zwiengel et al. (1998) and Lickorish et al. (2002) models as a basis for considering how the Tennessee salient may have formed. The indenter—the BRP—has an irregular surface that echoes the curvature of the salient. If we assume a single movement direction, only a limited portion of the Blue Ridge front could be normal to the transport direction. The long, more-or-less straight northern limb of the salient, as well as some of the internal parts of the fold-thrust belt farther south, may represent that portion of the salient that developed where transport and shortening coincide (plane strain). Additional evidence of a single direction of push may be found beneath the BRP, where the long axes of stacked duplexes are oriented subparallel to the straight limb of the salient (Hatcher et al., 2007), even as far south as Cartersville, Georgia (Tull and Holm, 2005) (Fig. 5-1). In addition, folds in the footwall of the Saltville fault just south of the apex of the Alabama recess have a similar orientation (Fig. 5-1).

Figure 5-21 illustrates the area of plane-strain that occurs where the regional direction of transport is normal to the front of the indenter, and thus is parallel to both the maximum shortening direction and the likely direction of particle movement. The directions of regional push, maximum shortening direction, and likely particle transport for each cross section are listed in Table 5-1. Where the regional direction of transport is oblique to the front of the indenter, as along the southern limb of the salient, non-plane strain develops. For convenience, based on the Lickorish et al. (2002) models, the direction of particle motion is assumed to be near its likely maximum divergence from the maximum shortening direction,

Figure 5-21. Comparison of the inferred regional transport direction for the Tennessee salient with the directions of maximum shortening and particle displacement directions. Solid thick black line is the front of the Blue Ridge indenter. Dashed thick black line indicates areas of higher than usual thermal maturity that may have been covered by a greater westward extent of the Blue Ridge thrust sheet. Narrow, parallel black lines indicate the transport direction for the salient as a whole. Blue arrows indicate the maximum shortening direction, normal to the structural grain (often assumed to be the transport direction). Red arrows show the inferred particle displacement directions, which are assumed (for convenience) to bisect the angle between the transport and maximum shortening directions. The area of plane strain, where the three vectors are essentially coincident, is indicated by gray shading.

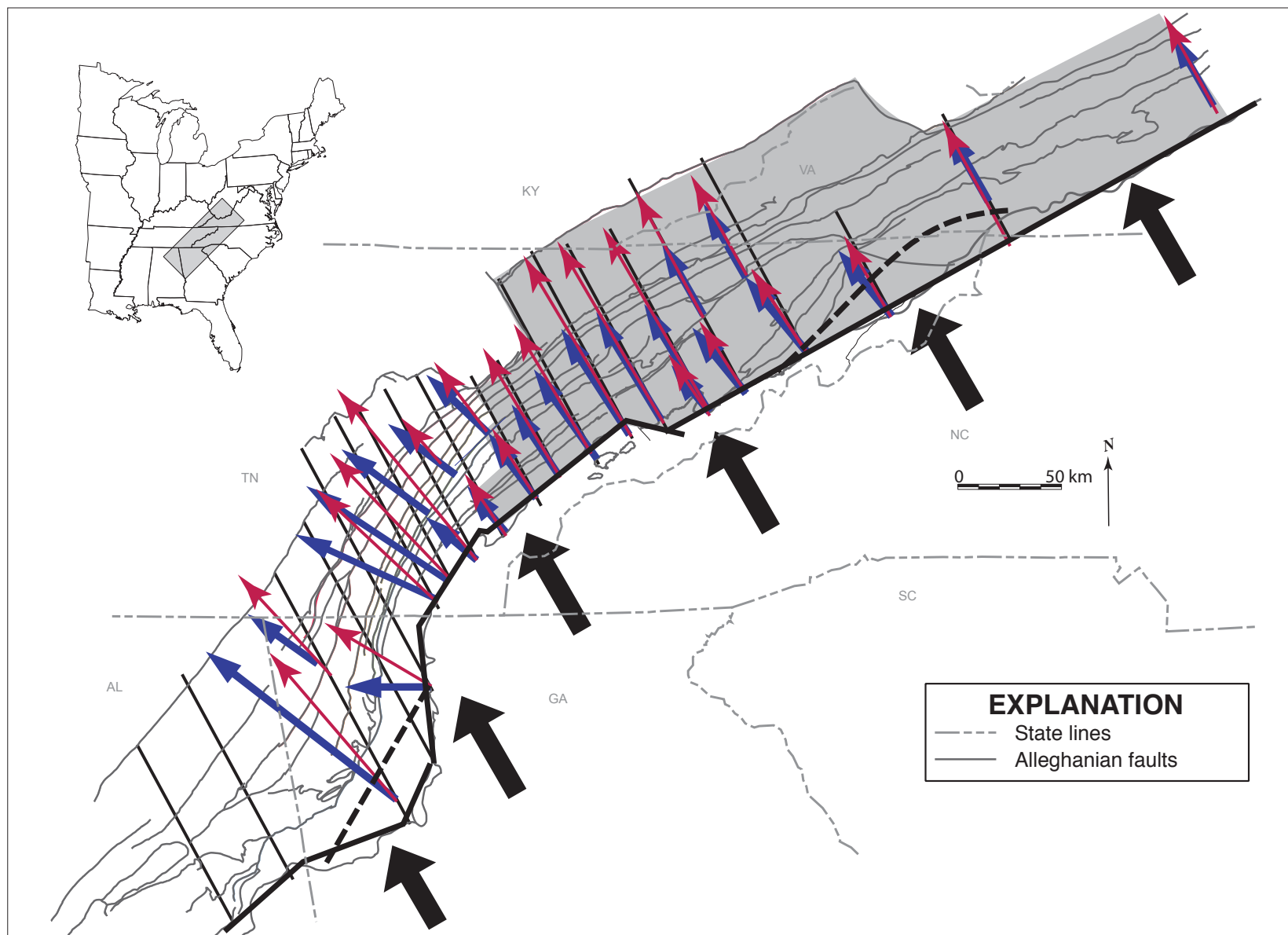


Table 5-1. Comparison of transport direction, maximum shortening direction and calculated particle displacement direction for cross sections 1-15 shown on Figure 5-21.

Cross section	Direction (Azimuth)		
	Transport	Maximum Shortening	Particle Displacement
CS1 ¹	332	321	326
CS2h ²	332	320	326
CS2f ³	332	332	332
CS3h	332	321	327
CS3f	332	332	332
CS4h	332	319	326
CS4f	332	329	331
CS5	332	329	331
CS6	332	324	328
CS7	332	324	328
CS8	332	326	329
CS9h	332	320	326
CS9f	332	314	323
CS10h	332	320	326
CS10f	332	307	320
CS11h	332	310	321
CS11f	332	310	321
CS12	332	304	318
CS13	332	295	314
CS14h	332	270	301
CS14f	332	305	319
CS15h	332	308	320

¹ CS = cross section

² where structural trends change orientation, h indicates the directions closer to the hinterland

³ where structural trends change orientation, f indicates the directions closer to the foreland

or halfway between the regional transport direction and the maximum shortening direction. Figure 5-21 shows that a large portion of the salient may be treated as if it were deformed by plane strain. Figure 5-22 demonstrates how a well-constrained cross section that did *not* deform by plane strain may be used to estimate the original location of material moving into the plane of the cross section.

Cross-section creation, restoration, and palinspastic restoration was an iterative process. Some cross-section restorations were revised on the basis of the palinspastic restoration (Fig. 5-23). Where hanging-wall cutoffs are eroded, it was generally assumed that one sheet started where another sheet ended, with no erosion at the leading edge of the thrust sheet. There are several places where this assumption appears to be invalid. These locations were identified based on the disagreement of several restored fault locations per cross section with equivalent restored positions on either side. For example, in cross sections 7 and 8 (Fig. 5-3, Plates III and IV), the Whiteoak Mountain, Copper Creek, Beaver Valley, and Saltville faults restored to locations more than 10 km closer to the foreland than in the adjacent cross sections 6 and 9. It was assumed that the frontal portions of the Chattanooga thrust sheet and the Whiteoak Mountain thrust sheet were lost to erosion. Adding in this lost length brought the two cross sections into better agreement with adjacent cross sections and the general trends. An inconsistency with only one fault was assumed to be a cross-section construction error, and cross-sections were revised as necessary. Table 5-2 presents displacement values for major faults measured along each cross section.

Most of the restored faults are slightly curved. Because of the original curved fault shapes, most faults in the southern Appalachian fold-thrust belt could have been formed by transport-parallel simple shear through a small enough angle that vertical axis rotations would not be necessary (Fig. 5-16). The presence of macro- and mesoscale faults along the southern limb that could accommodate some strike-parallel elongation is also consistent with this model, as are Hnat et al.'s (2009) paleomagnetic results indicating no rotation, Hnat's

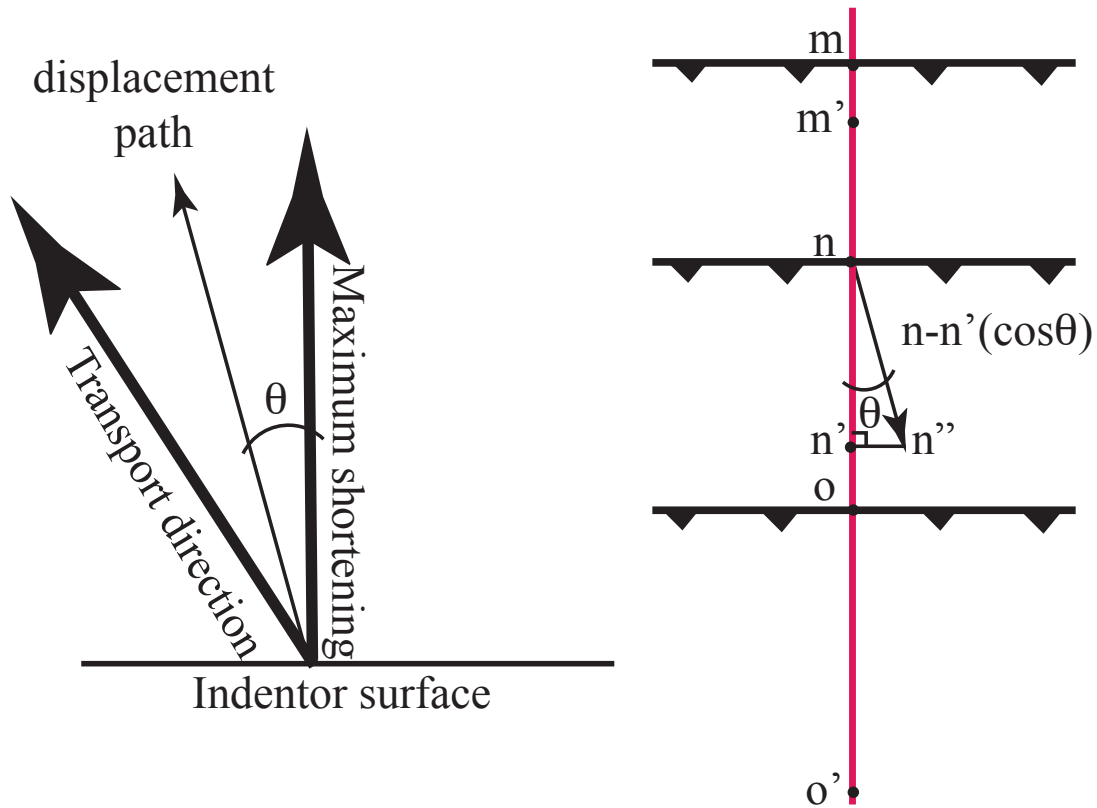


Figure 5-22. Approximating the pre-deformation geometry of a deformed thrust belt in an indenter-driven salient for which the transport direction is not perpendicular to the orientation of the indenter surface, using cross sections perpendicular to strike. Points at m, n, and o are in deformed position along cross section (red line) oriented perpendicular to the maximum shortening direction. Points m', n', and o' are in retrodeformed position. If the angle θ can be estimated, then any point (n) can be restored to a better location (n''), which is at a distance $n-n'(\cos \theta)$ along a line segment at the angle θ to the direction of maximum shortening

Figure 5-23. Palinspastic restoration of the Tennessee salient. a) Narrow black lines show the length of cross section lines restored parallel to the maximum shortening direction (inferred to be perpendicular to the macroscopic structural grain). Note that some lines intersect, creating a room problem. Solid colored lines indicate post-deformation fault locations. Colored dots show the restored locations of faults present in each cross section, based on inferred particle displacement paths. Note that in this method, the lines to which faults restore do not intersect. Dashed lines show the palinspastically restored locations of each fault. Stars show the restored location of the Blue Ridge for each cross section. A larger version of this figure is presented in Plate V. b) Simplified view of the reconstruction showing deformed and restored locations of major faults.

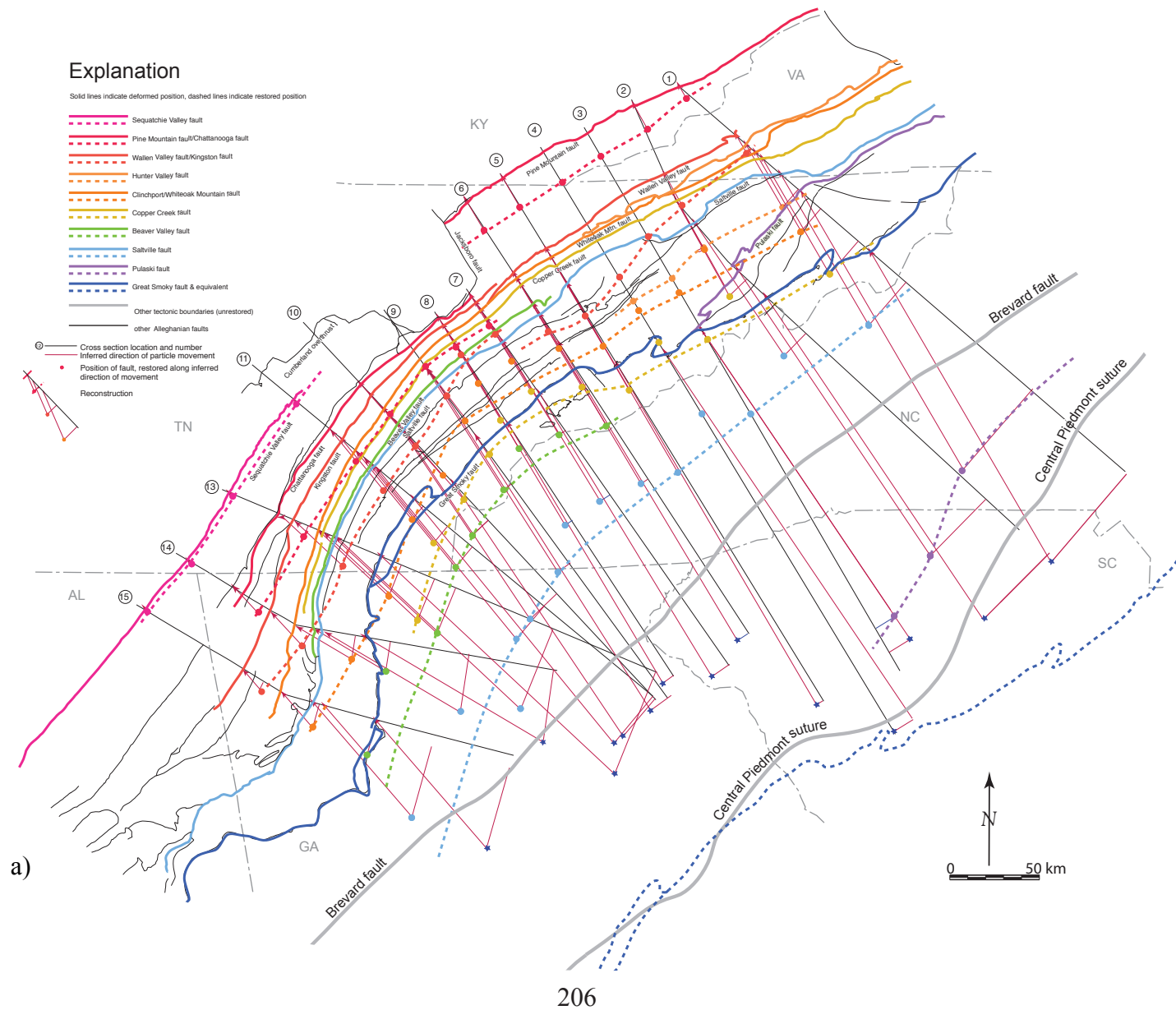


Figure 5-23 continued.

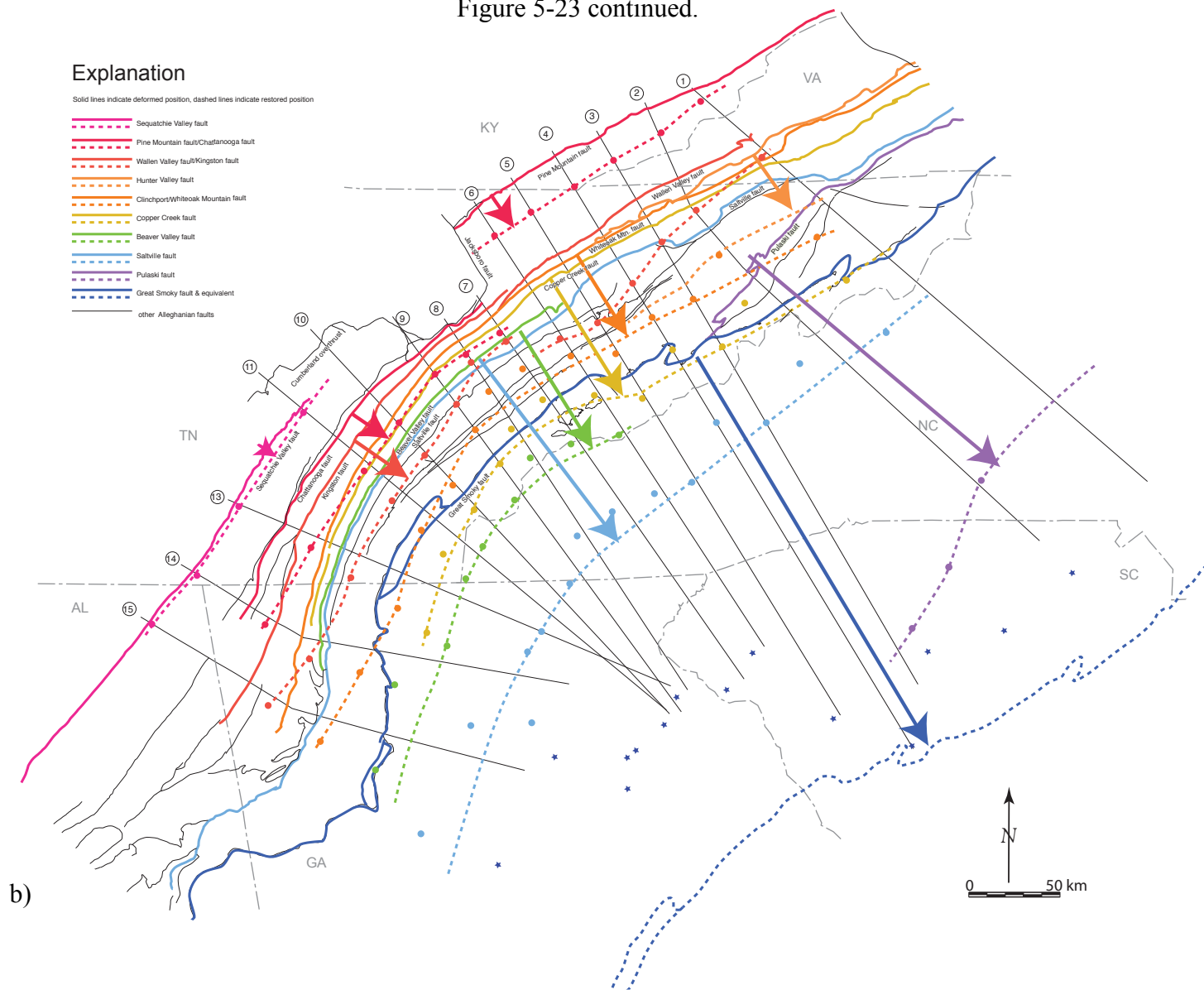


Table 5-2. Displacements on major faults in the Tennessee salient, calculated from cross sections 1-15 (Figure 5-3, Plate II).

Fault	CS1 ¹	CS2	CS3	CS4	CS5	CS6	CS7	CS8	CS9	CS10	CS11	CS12	CS13	CS14	CS15
Sequatchie										2	2	3	2	1	
Chattanooga							4	10	8	12	9	10	12	3	
Kingston							2	1	11	12	10	11	14	11	10
Pine Mtn.	2 ²	9	12	18	20	21									
Wallen Valley	2	1	8	7	13	13									
Hunter Valley	19	7	15	10											
Whiteoak Mtn.	5	5	2	2	10	5	9	11	6	8	9	12	11	10	2
Copper Creek	16	19	20	10	15	16	11	14	13	9	9	11	10		
Beaver Valley						9	10	6	4	7	7	8	8	13	4
Saltville	17	19	21	27	31	23	27	36	38	35	29	25	26	23	22
Knoxville							1	7	9	7	11	11	11		
Chestuee								1	2	3	4	1			
Dumplin Valley				13	12	10	8	5	5	2					
Wildwood									1	1	3	1			
Pulaski	110	31	21												

¹ CS = Cross section

² All displacements in kilometers

(2009) calcite twin results suggesting an initial radial, indenter-related stress regime, and the indicators of bulk shortening directions collected and presented in Figure 5-14.

The regional trend, however, seems to be of uniform displacement in a uniform direction. It is difficult to establish whether displacement was in fact uniform around the salient. Imbrication and duplexing in the Saltville sheet that is exposed in northeast Tennessee is covered by Blue Ridge rocks further to the south, and was not included in the cross sections. This results in an apparent change from higher displacement on the Blue Ridge thrust sheet to lower displacement as one moves from north to south, whereas this is actually an artifact of cross section construction. It is quite possible that there is an equally large amount of displacement in the southern limb of the salient, given the great lateral extent of foreland basin units present between the base of the Blue Ridge and the top of basement as imaged in seismic reflection data (Hatcher et al., 1994). Assuming the greatest displacement for which we have evidence is the correct (minimum) displacement, the Blue Ridge would have originated somewhere in the Carolinas and Georgia near the current location of the Central Piedmont suture (Fig. 5-23).

CONCLUSIONS

A new set of serial cross sections constructed around the Tennessee salient combined with indicators of strain history has clarified the kinematic development of the Tennessee salient. Non-conventional methods are required to palinspastically restore a curved orogen that has experienced non-plane strain. A general understanding of particle displacement directions for areas with non-plane strain in the Tennessee salient and similar non-rotated, constant-volume fold-thrust belts can be gained by assessing the difference between the maximum shortening direction and the primary transport direction. Well-constrained conventionally constructed cross sections may be geometrically restored along approximate particle displacement directions to estimate the original location of material that has moved into the section from out-of-plane. While this method does not provide a unique solution

in this kinematic-indicator scarce environment, it results in a structurally viable restoration. Fault geometries across both the Alabama recess and Tennessee salient contain evidence of both basin (basement surface contour) and indenter control. The palinspastically restored cross sections suggest that the Tennessee salient is a primary arc that formed by transport-parallel simple shear by propagation of faults, many of which originated as curved due to the impinging, curved BRP indenter. The overall deformation, however, is likely one of uniform displacement (taken up on different faults in different parts of the salient) in a uniform, regional, northwesterly direction. Particle displacement trajectories are not parallel to the maximum shortening directions around the entire salient, and in fact differ both among and, in some cases, within individual thrust sheets. Transport in the southern Appalachian fold-thrust belt may have occurred by *plan view* movement on populations of small faults (cataclastic flow), which permitted foreland-ward propagation of the curved faults and differential transport without causing rotation. Movement on populations of small faults also accommodated some of the modest tangential extension accompanying non-plane strain deformation in the southern limb of the salient. These results may assist those working in similar non-rotational arcs in developing more accurate restorations of paleoenvironments and facies trends in foreland basins.

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PART 6

Summary of Conclusions

PART 2 CONCLUSIONS

This dissertation yields insights into the development of the salient on a variety of scales, from outcrop to orogen. One of the first results was the recognition of a previously unidentified detachment fold along the western edge of the Valley and Ridge in East Tennessee. An open, linear, 80 km-long detachment fold (Eureka structure) identified in seismic reflection lines exists below the Chattanooga thrust in the western Valley and Ridge of East Tennessee.

This structure could be a major hydrocarbon play given the potential source and reservoir rocks involved. It contains the upper Knox (Knox unconformity play) and Stones River (Black River) and Nashville (Trenton) Groups, which are productive reservoirs in Swan Creek field in northeastern Tennessee and on the Cumberland Plateau and Highland Rim. These units may be self sourced by algal sources in the Stones River and Nashville Groups in Middle Ordovician units, and by the Cambrian Copper Ridge Dolomite in the Knox Group. Conodont alteration index values for potential Ordovician source rocks indicate that thermal maturity is also favorable (between 1.5 and 2.5), well inside the oil-gas window.

Although many wells drilled near this structure have been dry, most were located off the crest of the structure and/or in rocks much younger (Mississippian) than those expected to produce hydrocarbons. The ARCO Wright No. 1 well drilled in Rhea County just off the crest contains both oil and gas.

The crest of the structure is expected to have increased fracture density due to folding and faulting, increasing the potential reservoir volume. Fracture studies in higher thrust sheets around Oak Ridge, Tennessee show that fractures predate thrusting and that younger deformation was accommodated on existing fractures (Hatcher et al. 1992). These units, however, have not been bowed upward over the crest of a detachment fold, as have the rocks in the Eureka structure.

PART 3 CONCLUSIONS

Details of deformation in the core of the triangle zone are not resolvable on seismic reflection lines. A possible analogue for this type of doubly-verging deformation lies in the footwall of the westernmost thrust of the Valley and Ridge. Rocks in a railroad cut near Rockwood, Tennessee are intensely folded and faulted, with competent units defining the geometry of non-cylindrical, hinterland- and foreland-verging folds. Folds formed by a combination of flexural slip and flexural flow, and fold axes plunge to both the north-northeast and south-southwest. Sandstones contain four joint sets, two of which formed prior to folding and are fanned around folds.

This zone of intense deformation best fits the Type II triangle zone category because it occurs in the foreland-most edge of a fold-thrust belt, has low displacement, a generally triangular shape, and intense deformation with both foreland, and hinterland senses of vergence.

PART 4 CONCLUSIONS

This dissertation also considers the boundary conditions under which deformation in the Tennessee salient occurred. Boundaries of the southern Appalachian foreland fold-thrust belt consist of the basement surface below the belt, the base of the Blue Ridge–Piedmont sheet above, and the eroded topographic free surface of both the southern Appalachian foreland fold-thrust belt and Blue Ridge–Piedmont sheet. Temperature and pressure maxima are additional boundary conditions.

The basement surface observed beneath the southern Appalachian foreland fold-thrust belt is likely the same as it was throughout the Paleozoic, except for the effects of Alleghanian thrust loading. It is interrupted by several down-to-the-southeast normal faults with displacements up to 3 km such as the extensive Tusquittee fault, which is traceable from Alabama to Virginia. In addition, a major steepening of slope of the basement surface

has been identified farther east on the Laurentian margin and similarly has been traced from Alabama to Virginia.

The original shape of the basement surface exerted major influence on the shape of the southern Appalachian foreland fold-thrust belt, as well as on the displacement vectors that tracked thrust-sheet emplacement. Palinspastic locations of southern Appalachian foreland fold-thrust belt thrusts suggest that these basement surface features may have profoundly affected original facies distributions and subsequent localization of faults and other structures as the southern Appalachian foreland fold-thrust belt was deformed.

The base of the Blue Ridge–Piedmont sheet is a southeast-dipping surface interrupted by numerous antiforms that represent duplexes composed of southern Appalachian foreland fold-thrust belt footwall rocks. As these duplexes were constructed, they deformed the Blue Ridge–Piedmont thrust sheet as it moved forward. Many of these antiforms along the front of the sheet are quite linear, have relatively low structural relief (<2 km), and are traceable for many tens of kilometers; others farther into the sheet have more of an elliptical shape and several kilometers of structural relief.

Plastic rheology for the entire thrust belt better addresses the particle trajectory problem than Coulomb behavior, but neither addresses problems of mechanics of localization of fault families, out-of-sequence thrusts, thrust spacing, and other attributes.

Particle trajectories must curve in an orogen that traces a 30° arc from the inflection point of maximum curvature in northern Georgia to the corresponding inflection point in southwestern Virginia, where thrusts have unequal displacements, so plane strain may have occurred locally but not regionally. Displacement vectors within the southern Appalachian foreland fold-thrust belt may represent slip lines that track body deformation in the deforming wedge. Heterogeneous strain is responsible for the 3-D deformation plan of the southern Appalachian foreland fold-thrust belt, and probably other curved foreland fold-thrust belts.

Displacements of southern Appalachian foreland fold-thrust belt thrusts sum approximately to the minimum restorable displacement on the Blue Ridge–Piedmont megathrust sheet. Sub–Blue Ridge–Piedmont deformation of southern Appalachian foreland fold-thrust belt rocks (not quantifiable), along with out-of-sequence thrusting within the Blue Ridge–Piedmont sheet, increases the total displacement on the thrust system.

PART 5 CONCLUSIONS

A new set of serial cross sections constructed around the Tennessee salient combined with indicators of strain history has clarified the kinematic development of the Tennessee salient. Non-conventional methods are required to palinspastically restore a curved orogen that has experienced non-plane strain. A general understanding of particle displacement directions for areas with non-plane strain in the Tennessee salient and similar non-rotated, constant-volume fold-thrust belts can be gained by assessing the likely particle displacement directions where the maximum shortening direction and the primary transport direction do not coincide, due to emplacement of an irregularly-shaped indenter. Well-constrained conventionally constructed cross sections may be geometrically restored along approximate particle displacement directions to estimate the original location of material that has moved into the section from out-of-plane. While this method does not provide a unique solution in this kinematic-indicator scarce environment, it results in a structurally viable restoration.

Fault geometries across both the Alabama recess and Tennessee salient record evidence of both basin (basement surface geometry) and indenter control. The palinspastically restored cross sections suggest that the Tennessee salient is a primary arc that formed by transport-parallel simple shear on faults, some of which originated as curved due to the impinging, curved Blue Ridge–Piedmont indenter. Particle displacement trajectories are not parallel to the maximum shortening directions around the entire salient, and in fact differ both among and, in some cases, within individual thrust sheets. The overall deformation, however, is likely one of uniform displacement (taken up on different faults in

different parts of the salient) in a uniform, regional, northwesterly direction. Although the relatively straight northern arm of the salient deformed by plane strain, much of the curve central area and southern arm did not. Transport in the southern Appalachian fold-thrust belt may have occurred by *plan view* movement on populations of small faults (cataclastic flow), which permitted foreland-ward propagation of the curved faults and differential transport without causing rotation. Movement on populations of small faults also accommodated some of the modest tangential extension accompanying non-plane strain deformation in the southern limb of the salient. These results may assist those working in similar non-rotational arcs in developing more accurate restorations of paleoenvironments and facies trends in foreland basins.

APPENDIX

Date	Station	I.D. #	Feature	Bedding		Fold Axis		Axial Plane		Inter-limb	Fold	Joint		Lineation		Sense of Slip	Other plane		Rock Unit	Comments	Lat	Long
Strike	Dip	Plunge	Trend	Strike	Dip	Plunge	Trend	Strike	Dip	<	Verg.	Strike	Dip	Plunge	Trend		Strike	Dip				
07/07/98	RW											N 76 W	78 N							tunnel folds	35 51 0.60 N	84 43 41.58 W
07/07/98	RW											N 66 W	61 N							tunnel folds	35 51 0.60 N	84 43 41.58 W
07/07/98	RW											N 7 E	59 W							tunnel folds - calculated FA = 46, 329	35 51 0.60 N	84 43 41.58 W
07/07/98	RW		fold 2	N 34 W	60 W															tunnel folds	35 51 0.60 N	84 43 41.58 W
07/07/98	RW		fold 2	N 64 E	60 E	46 S	S 15 W													tunnel folds - calculated FA = 53, 195	35 51 0.60 N	84 43 41.58 W
07/07/98	RW		fold 3									N 70 W	90							tunnel folds - perpendicular to F.A.	35 51 0.60 N	84 43 41.58 W
07/07/98	RW		fold 3	N 4 W	74 W															tunnel folds	35 51 0.60 N	84 43 41.58 W
07/07/98	RW		fold 3	N 31 W	54 W															tunnel folds	35 51 0.60 N	84 43 41.58 W
07/07/98	RW		fold 3	N 80 W	43 E															tunnel folds	35 51 0.60 N	84 43 41.58 W
07/07/98	RW			N 45 E	42 S															too much poison ivy	W of Lat/long above	
07/07/98	RW					23 S	S 10 E													isoclinal fold - massive bedding	W of Lat/long above	
07/07/98	RW	a	fold f	N 60 W	78 N															small λ folds W of tunnel	W of Lat/long above	
07/07/98	RW	b	fold f	N 34 W	81 E															small λ folds W of tunnel	W of Lat/long above	
07/07/98	RW	c/d	fold f	N 7 E	78 W	42 N	N 40 W													small λ folds W of tunnel	W of Lat/long above	
07/07/98	RW		fold a	N 15 W	83 W															small λ folds W of tunnel	W of Lat/long above	
07/07/98	RW		fold a	N 10 W	55 W	7 N	N 34 W													small λ folds W of tunnel	W of Lat/long above	
07/07/98	RW		fold a/b	N 25 E	21 se															small λ folds W of tunnel	W of Lat/long above	
07/07/98	RW		fold a/b	N 0 E	49 E															small λ folds W of tunnel	W of Lat/long above	
07/07/98	RW		fold b	N 85 W	21 S	20 S	S 26 E													small λ folds W of tunnel	W of Lat/long above	
07/07/98	RW		fold b	N 38 W	49 W															small λ folds W of tunnel	W of Lat/long above	
07/07/98	RW		fold b	N 15 W	81 W															small λ folds W of tunnel	W of Lat/long above	
07/07/98	RW		fold c	N 7 W	75 E															small λ folds W of tunnel	W of Lat/long above	
07/07/98	RW		fold c			33 S	N 10 E													small λ folds W of tunnel	W of Lat/long above	
07/07/98	RW		fold c	N 25 W	60 W															small λ folds W of tunnel	W of Lat/long above	
07/07/98	RW		big fold			29	N 45 E													big fold in massive ss just W of tunnel folds	W of Lat/long above	
07/07/98	RW		fold g			6 N	N 35 E													far west of exposure	35 50 59.37 N	84 43 47.14 W
07/07/98	RW		fold g	N 23 E	61 E															far west of exposure	35 50 59.37 N	84 43 47.14 W
07/07/98	RW		fold g	N 19 E	53 E															far west of exposure	35 50 59.37 N	84 43 47.14 W
07/07/98	RW		fold g									N 75 W	12 S	6 S	S 35 E					lineation= slickenline on fracture surface	35 50 59.37 N	84 43 47.14 W
07/07/98	RW		fold g	N 75 W	21 N															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/15/98	RW	1	fold b	N 2 W	54 E															small λ folds W of tunnel	W of Tunnel Lat/Long	
10/15/98	RW	2	fold b	N 5 E	55 E															small λ folds W of tunnel	W of Tunnel Lat/Long	
10/15/98	RW	3	fold b	N 6 E	61 E															small λ folds W of tunnel	W of Tunnel Lat/Long	

Date	Station	I.D. #	Feature	Bedding		Fold Axis		Axial Plane		Inter-limb	Fold	Joint		Lineation		Sense of Slip	Other plane		Rock Unit	Comments	Lat	Long
				Strike	Dip	Plunge	Trend	Strike	Dip	<	Verg.	Strike	Dip	Plunge	Trend		Strike	Dip				
10/15/98	RW	4	fold b	N 2 E	46 E															small λ folds W of tunnel	W of Tunnel Lat/Long	
10/15/98	RW	5	fold b	N 21 E	27 E															small λ folds W of tunnel	W of Tunnel Lat/Long	
10/15/98	RW	6	fold b			24 E	S 22 E													measured on different beds	W of Tunnel Lat/Long	
10/15/98	RW	7	fold b			30 S	S 27 E													measured on different beds	W of Tunnel Lat/Long	
10/15/98	RW	8	fold b	N 65 W	45 S															small λ folds W of tunnel	W of Tunnel Lat/Long	
10/15/98	RW	9	fold b	N 39 W	50 S															small λ folds W of tunnel	W of Tunnel Lat/Long	
10/15/98	RW	10	fold b	N 50 W	74 S															small λ folds W of tunnel	W of Tunnel Lat/Long	
10/15/98	RW	11	fold b	N 30 W	39 S															small λ folds W of tunnel	W of Tunnel Lat/Long	
10/15/98	RW	12	fold b	N 25 W	76 S															small λ folds W of tunnel	W of Tunnel Lat/Long	
10/15/98	RW	13	fold b	N 19 W	86 S															small λ folds W of tunnel	W of Tunnel Lat/Long	
10/15/98	RW	14	fold b					N 25 W	62 W											small λ folds W of tunnel	W of Tunnel Lat/Long	
10/15/98	RW	15	fold b					N 27 W	87 W											small λ folds W of tunnel	W of Tunnel Lat/Long	
10/15/98	RW	1	fold b			11 S	S 2 E													small λ folds W of tunnel	W of Tunnel Lat/Long	
10/15/98	RW	2	fold a	N 15 W	76 W															small λ folds W of tunnel	W of Tunnel Lat/Long	
10/15/98	RW	3	fold a	N 2 E	71 W															small λ folds W of tunnel	W of Tunnel Lat/Long	
10/15/98	RW	4	fold a	N 12 W	62 W															small λ folds W of tunnel	W of Tunnel Lat/Long	
10/15/98	RW	5	fold a	N 27 W	83 W															small λ folds W of tunnel	W of Tunnel Lat/Long	
10/15/98	RW	6	fold a	N 3 W	25 W															small λ folds W of tunnel	W of Tunnel Lat/Long	
10/15/98	RW	7	fold a	N 16 E	36 E															small λ folds W of tunnel/best fit great circle 263/80 N - fa = 173,10	W of Tunnel Lat/Long	
10/15/98	RW	1	fold g	N 25 E	84 E															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/15/98	RW	2	fold g	N 11 E	78 E															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/15/98	RW	3	fold g	N 35 E	66 E															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/15/98	RW	4	fold g	N 24 E	65 E															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/15/98	RW	5	fold g	N 20 E	72 E															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/15/98	RW	6	fold g	N 20 E	70 E															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/15/98	RW	7	fold g	N 24 E	60 E															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	1	fold k	N 12 E	29 W															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	2	fold k	N 15 W	18 W															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	3	fold k	N 13 W	17 W															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	26	fold k	N 9 W	29 W															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	5	fold k	N 20 E	8 W															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	6	fold k/j	N 13 E	10 E															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	7	fold k/j	N 67 E	12 E															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	8	fold k/j	N 57 E	28 E															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	9	fold k/j	N 59 E	24 E															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	10	fold k/j	N 44 E	14 E															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	11	fold j/i	N 34 W	24 W															far west of exposure	35 50 59.37 N	84 43 47.14 W

Date	Station	I.D. #	Feature	Bedding		Fold Axis		Axial Plane		Inter- limb <	Fold Verg.	Joint		Lineation		Sense of Slip	Other plane		Rock Unit	Comments	Lat	Long
				Strike	Dip	Plunge	Trend	Strike	Dip			Strike	Dip	Plunge	Trend		Strike	Dip				
10/16/98	RW	12	fold j/i	N 66 W	15 S															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	13	fold j/i	N 43 E	43 N															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	14	fold j/i	N 75 E	24 N															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	15	fold j/i	N 82 E	13 S															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	16	fold j/i	N 73 E	14 S															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	17	fold j/i	N 71 E	11 N															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	18	fold i/h	N 31 E	5 N															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	19	fold h/g	N 36 E	25 N															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	20	fold h/g	N 20 E	19 N															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	21	fold h/g	N 1 W	22 N															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	22	fold h/g	N 8 E	32 W									31	N 79 E					slickenline	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	23	fold h/g	N 12 E	12 N															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	24	fold h/g	N 11 E	30 N															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	?	fold h/g	N 89 E	14 S									5	S 34 E					slick - up to N	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	25	fold h/g	N 80 E	4 N															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	26	fold g	N 75 E	22 N															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	27	fold g	N 85 W	19 N															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	28	fold g	N 22 E	20 E															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	29	fold g	N 4 E	36 E															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	30	fold g	N 2 W	49 E															far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F1	W limb k									N 30 W	86 W							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F2	W limb k									N 20 W	82 W							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F3	W limb k									N 74 W	85 E							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F4	W limb k									N 88 E	90 N							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F5	hinge j									N 4 W	84 W							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F6	hinge j									N 14 W	79 W							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F7	fold i									N 11 E	60 E							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F8	fold i									N 21 W	71 W							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F9	fold i									N 4 W	85 W							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F10	fold i									N 31 W	89 W							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F11	fold h/g									N 62 W	51 W							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F12	fold h/g									N 2 E	89 W							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F13	fold h/g									N 72 E	74 S							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F14	fold h/g									N 18 W	87 W							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F15	fold h/g									N 62 W	79 W							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F16	fold h/g									N 65 W	78 E							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F17	fold h/g									N 70 W	74 N							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F18	fold h/g									N 84 W	78 W							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F19	fold h/g									N 81 E	84 N							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F20	fold h/g									N 82 W	86 W							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F21	fold h/g									N 90 W	68 N							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F22	fold h/g									N 76 E	72 W							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F23	hinge/E limb g									N 30 W	86 W							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F24	hinge/E limb g									N 76 E	36 N							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW	F25	hinge/E limb g									N 64 E	38 N							far west of exposure	35 50 59.37 N	84 43 47.14 W
10/16/98	RW		fold b1			23	N 23 E													small folds below b & c	W of Tunnel Lat/Long	
10/16/98	RW		fold b2			39	N 13 E													small λ folds W of tunnel	W of Tunnel Lat/Long	
10/16/98	RW		fold b3			30	N 8 E													small λ folds W of tunnel	W of Tunnel Lat/Long	
10/16/98	RW	F1	fold b									N 62 W	12 N							small λ folds W of tunnel	W of Tunnel Lat/Long	

Date	Station	I.D. #	Feature	Bedding		Fold Axis		Axial Plane		Inter-limb	Fold	Joint		Lineation		Sense of Slip	Other plane		Rock	Comments	Lat	Long
				Strike	Dip	Plunge	Trend	Strike	Dip	<	Verg.	Strike	Dip	Plunge	Trend		Strike	Dip	Unit			
10/16/98	RW	F2	fold b									N 42 W	49 N							small λ folds W of tunnel	W of Tunnel Lat/Long	
10/16/98	RW	F3	fold b									N 15 W	38 E							small λ folds W of tunnel	W of Tunnel Lat/Long	
10/16/98	RW	F4	fold b									N 20 W	80 W							small λ folds W of tunnel	W of Tunnel Lat/Long	
10/16/98	RW	F5	fold b									N 50 W	41 W							small λ folds W of tunnel	W of Tunnel Lat/Long	
10/21/98	RW	tunnel	tunnel									N 84 W	76 N							tunnel folds	35 51 0.60 N	84 43 41.58 W
10/21/98	RW	tunnel	tunnel									N 36 W	83 N							tunnel folds	35 51 0.60 N	84 43 41.58 W
10/21/98	RW	tunnel	tunnel									N 65 E	80 N							tunnel folds	35 51 0.60 N	84 43 41.58 W
10/21/98	RW	tunnel	tunnel									N 25 E	87 N							tunnel folds	35 51 0.60 N	84 43 41.58 W
10/21/98	RW	tunnel	tunnel			53	S 7 E													tunnel folds	35 51 0.60 N	84 43 41.58 W
10/21/98	RW	tunnel	tunnel			32	S 6 W													tunnel folds	35 51 0.60 N	84 43 41.58 W
10/21/98	RW	tunnel	tunnel			31	S 5 W													tunnel folds	35 51 0.60 N	84 43 41.58 W
10/21/98	RW	tunnel	tunnel			19	S 1 E													tunnel folds	35 51 0.60 N	84 43 41.58 W
10/21/98	RW	tunnel	tunnel			18	N 30 E													tunnel folds	35 51 0.60 N	84 43 41.58 W
10/21/98	RW	tunnel	tunnel			70	S 12 E													tunnel folds	35 51 0.60 N	84 43 41.58 W
10/21/98	RW	tunnel	tunnel			77	S 10 W													tunnel folds	35 51 0.60 N	84 43 41.58 W
10/21/98	RW	tunnel	tunnel			66	S 50 W													tunnel folds	35 51 0.60 N	84 43 41.58 W
10/21/98	RW	tunnel	tunnel			50	S 12 W													tunnel folds	35 51 0.60 N	84 43 41.58 W
03/06/00	² WB1	1	1a	N 79 E	70 se														Cr	sliver of Rome along Tellico Reservoir 60 ft above water	35 37 1.11 N	84 13 15.32 W
03/06/00	WB1	2	1b	N 55 E	62 NW														Cr	"	35 37 1.11 N	84 13 15.32 W
03/06/00	WB1	3	1c	N 69 E	72 NW														Cr	"	35 37 1.11 N	84 13 15.32 W
03/06/00	WB1	4	1d	N 79 E	60 se														Cr	"	35 37 1.11 N	84 13 15.32 W
03/06/00	WB1	5				6	S 74 W												Cr	"	35 37 1.11 N	84 13 15.32 W
03/06/00	WB1	6				36	S 61 W												Cr	"	35 37 1.11 N	84 13 15.32 W
03/06/00			calc ab			20	251													"		
03/06/00	WB2	1				26	S 65 W												Cr	sliver of Rome along Tellico Reservoir at water level	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	2				11	S 52 W												Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	3	2a	N 52 E	89 S														Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	4	2b	N 28 W	19 W														Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	5	2c	N 47 E	76 N														Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	6	2d	N 41 E	48 N														Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	7				17	S 66 W												Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	8	3a	N 61 E	80 S														Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	9	3b	N 46 E	23 N														Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	10	3c	N 67 E	60 S														Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	11	3			9	S 52 W												Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	12	4a	N 51 E	81 S														Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	13	4b	N 61 E	23 N														Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	14	4c	N 46 E	71 S														Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	15	4			0	S 56 W												Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	16	4			23	S 54 W												Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	17		N 66 E	43 N														Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	18				14	S 56 W												Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	19	5a	N 59 E	86 N														Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	20	5b	N 51 E	24 N														Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	21	5c	N 44 E	77 S														Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	22	5			4	S 59 W												Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	23	5			1	S 60 W												Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	24	5			24	S 62 W												Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	25	6a	N 64 E	80 S														Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	26	6b	N 71 E	52 S														Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	27	6c	N 48 E	33 N														Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	28	6d	N 50 E	50 N														Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	29	6e	N 50 E	79 N														Cr	"	35 36 59.45 N	84 13 16.76 W

Date	Station	I.D. #	Feature	Bedding Strike Dip	Fold Axis Plunge Trend	Axial Plane Strike Dip	Inter- limb	Fold Verg.	Joint Strike Dip	Lineation Plunge Trend	Sense of Slip	Other plane Strike Dip	Rock Unit	Comments	Lat	Long
03/06/00	WB2	30	6		20 S 61 W								Cr		35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	31	7a	N 46 E 62 N									Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	32	7b	N 69 E 57 S									Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	33	7		17 S 53 W								Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	34	8a	N 56 E 71 N									Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	35	8b	N 60 W 12 W									Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	36	8c	N 59 E 81 S									Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	37	8		10 S 55 W								Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	WB2	38	8		3 S 66 W								Cr	"	35 36 59.45 N	84 13 16.76 W
03/06/00	CL1	1	9	N 31 W 65 E									Cr	Rome just NW of Mocking Crow Mtn off of HWY 315/Reliance Rd	35 18 13.86 N	84 23 22.54 W
03/06/00	CL1	2	9	N 55 E 39 E									Cr	"	35 18 13.86 N	84 23 22.54 W
03/14/00	WB4	1		N 41 W 20 N					N 10 E 88 se				Ol	Pellissippi Pkwy just E of reservoir N side of hwy	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	2							N 81 W 85 S				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	3							N 70 W 81 S				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	4							N 3 W 89 W				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	5							N 20 E 71 W				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	6		N 15 W 26 N					N 22 W 88 E				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	7							N 30 W 81 W				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	8							N 77 E 84 S				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	9							N 44 W 80 S				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	10							N 7 E 80 W				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	11							N 48 E 82 E				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	12		N 33 W 20 E					N 23 E 84 E				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	13							N 3 W 72 W				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	14							N 85 E 84 S				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	15							N 80 E 81 S				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	16							N 11 E 88 W				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	17							N 83 W 79 S				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	18							N 62 E 84 N				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	19							N 42 E 82 E				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	20							N 57 W 69 S				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	21							N 52 W 63 W				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	22							N 30 E 80 W				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	23							N 80 E 75 N				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	24							N 21 E 81 W				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	25							N 32 E 84 W				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	26							N 64 W 78 S				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	27							N 20 W 80 E				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	28							N 53 W 89 N				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	29							N 39 W 84 W				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	30							N 23 E 87 W				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	31							N 90 E 87 S				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	32							N 40 E 70 W				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	33							N 65 W 78 S				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	34							N 75 W 85 N				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	35							N 65 E 83 S				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	36							N 23 W 82 N				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	37							N 64 W 74 N				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	38							N 50 W 70 S				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	39							N 54 W 83 S				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	40							N 60 W 89 S				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	41							N 58 W 64 S				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	42							N 60 E 90 S				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	43							N 39 E 79 S				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	44							N 64 E 89 S	11	N 64 E	W	Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	45							N 21 W 68 W				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	46							N 31 W 72 W				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	47							N 22 W 87 N				Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	48							N 69 W 87 N	9	S 70 E	N	Ol	"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	49							N 62 W 79 S	7	S 62 E	N	Ol	"	35 50 59.25 N	84 0 17.32 W

Date	Station	I.D. #	Feature	Bedding		Fold Axis		Axial Plane		Inter-limb	Fold	Joint		Lineation		Sense of Slip	Other plane		Rock	Unit	Comments	Lat	Long
				Strike	Dip	Plunge	Trend	Strike	Dip	<	Verg.	Strike	Dip	Plunge	Trend		Strike	Dip					
03/14/00	WB4	50										N 65 W	89 N						Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	51										N 10 E	89 W						Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	52										N 5 E	86 E						Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	53										N 2 E	88 E						Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	54										N 66 W	81 S	40	S 67 E	N			Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	55										N 69 W	86 N	13	S 69 E	N			Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	56										N 57 W	88 se	6	S 57 E	N			Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	57		N 24 W	12 N							N 13 W	88e						Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	58										N 4 E	86e						Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	59										N 53 W	86 S	11	S 57 E	N			Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	60										N 22 W	60 S	13	S 10 E	S			Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	61										N 40 W	76 S	12	S 46 E	S			Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	62										N 33 W	72 S	12	S 26 E	S			Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	63										N 46 W	76 S	15	S 47 E	S			Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	64										N 35 W	72 S	8	S 37 E	S			Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	65										N 16 E	77e						Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	66										N 75 E	90 S						Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	67										N 14 E	84 W						Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	68										N 30 W	84 W	7	N 30 W	S			Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	69										N 47 W	80 W	0	N 41 W	S			Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	70										N 56 W	78 N	0	N 58 W	S			Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	71										N 80 E	89 S	8	S 80 W	W			Ol		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	72										N 61 W	74 S	13	S 60 E	t			Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	73										N 52 W	70 S	15	S 42 E	t			Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	74										N 55 W	76 S	17	S 55 E	t			Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	75										N 55 E	73 S						Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	76										N 51 E	89 S						Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	77										N 5 E	68 W						Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	78										N 4 E	58 W						Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	79										N 53 W	60 W	16	S 39 E	t			Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	80										N 49 W	86 S	15	S 55 E	t			Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	81										N 15 E	83 W						Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	82										N 52 W	70 W	25	S 43 E	t			Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	83										N 31 W	68 W						Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	84										N 4 W	73 W	5	S 1 E	N			Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	85										N 5 W	66 W						Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	86										N 52 W	58 N	12	S 57 E	N			Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	87										N 39 W	86 W	14	S 39 E	N			Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	88										N 13 W	78 W						Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	89										N 1 E	63 W	8	N 4 W	t			Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	90										N 23 W	62 W						Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	91										N 69 E	89 S						Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	92										N 78 E	70 N						Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	93										N 64 E	86 N						Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	94										N 25 W	76 W	9	N 27 W	t			Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	95		N 17 W	13 E							N 30 W	60 W	38	S 8 E	N			Oh		"	35 50 59.25 N	84 0 17.32 W
03/14/00	WB4	96										N 72 W	87 S	20	S 72 E	t			Oh		"	35 50 59.25 N	84 0 17.32 W
03/20/00	WB5	1		N 27 W	15 E							N 12 W	54 W						Ol		Pellissippi Pkwy just E of reservoir S side of hwy - long wavelength fold (more W)	35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	2										N 6 W	S 3 W						Ol		"	35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	3										N 13 W	53 W						Ol		"	35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	4		N 25 W	36 E							N 9 W	53 W						Ol		"	35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	5										N 12 W	89 W						Ol		"	35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	6		N 18 W	21 E							N 30 W	85 W						Ol		"	35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	7										N 23 E	88 N						Ol		"	35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	8		N 4 W	25 E							N 6 W	77 W						Ol		"	35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	9										N 14 W	71 W						Ol		"	35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	10										N 23 W	77 W						Ol		"	35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	11										N 4 E	55 W	0	S 7 W	t			Ol		"	35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	12		N 8 W	15 E							N 4 W	79 W						Ol		"	35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	13										N 6 W	72 W						Ol		"	35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	14		N 27 E	13 E							N 4 W	89 E						Ol		"	35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	15										N 6 W	69 W						Ol		"	35 50 57.92 N	84 0 19.58 W

Date	Station	I.D. #	Feature	Bedding		Fold Axis		Axial Plane		Inter-limb	Fold	Joint		Lineation		Sense of Slip	Other plane		Rock	Comments	Lat	Long
				Strike	Dip	Plunge	Trend	Strike	Dip	<	Verg.	Strike	Dip	Plunge	Trend		Strike	Dip	Unit			
03/20/00	WB5	16		N 16 E	24 E							N 7 W	84 W						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	17	fold a			10	N 42 E	N 50 E	50 S	100									Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	18		N 30 E	71 W														Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	19		N 52 E	4 S									26	N 62 W	t			Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	20		N 32 E	31 N									22	N 68 W	t			Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	21																	Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	22	fold b			23	N 32 E	N 36 E	65 E	120									Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	23		N 47 E	44 N									39	N 65 W	t			Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	24		N 62 E	32 N									26	N 46 W	t			Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	25		N 55 E	32 N							N 25 W	60 W	25	N 63 W	t			Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	26		N 46 E	43 N									40	N 60 W	t			Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	27		N 5 E	49 N									41	N 57 W	t			Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	28		N 89 E	22 N							N 23 W	89 E						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	29										N 84 W	31 S						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	30		N 56 E	40 N							N 6 W	90						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	31										N 56 W	88 N						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	32		N 44 E	53 N														Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	33	minor a			11	N 32 E	N 6 E	19 E	120									Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	34	minor b			23	N 20 E	N 11 E	43 E	120									Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	35	minor c			14	N 42 E	N 35 E	55 S	120									Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	36		N 71 E	23 N							N 55 E	88 N						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	37										N 41 W	86 W						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	38										N 50 W	88 S						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	39										N 38 E	85 N						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	40										N 35 E	76 E						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	41										N 44 E	89 N						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	42		N 38 E	24 E							N 51 W	72 S	14	S 49 E	N			Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	43										N 42 W	67 S						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	44										N 41 E	87 N						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	45										N 79 E	71 N						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	46										N 42 E	79 N						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	47		N 30 E	24 E							N 12 E	64 W						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	48										N 53 W	57 S						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	49										N 20 E	73 W						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	50										N 49 W	89 S						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	51										N 40 W	60 S						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	52										N 14 W	65 W						Oi		35 50 57.92 N	84 0 19.58 W
03/20/00	WB5	53										N 20 E	87 E						Oi		35 50 57.92 N	84 0 19.58 W
																				Pellissippi Pkwy just E of reservoir S side of hwy - shorter wavelength folds (more E)		
03/27/00	WB6	1		N 38 E	59 S	6	S 45 W	N 32 E	48 N	60									Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	2		N 46 E	80 S														Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	3		N 2 W	53 N														Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	4		N 61 E	24 N							N 35 E	71 E						Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	5										N 30 E	81 E						Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	6										N 71 W	89 S						Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	7										N 79 W	76 S						Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	8										N 48 E	65 E						Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	9										N 40 E	44 E						Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	10		N 40 E	31 W							N 22 W	78 E						Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	11										N 50 W	89 S						Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	12										N 28 W	84 N						Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	13	minor d	N 27 E	36 N	10	N 45 E	N 36 E	70 N	45									Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	14	minor e			9	N 41 E	N 37 E	73 N	45									Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	15	minor f			7	N 38 E	N 30 E	54 S	150									Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	16	minor g			8	N 32 E	N 22 E	61 S	130									Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	17	minor h	N 56 E	22 N	10	N 50 E	N 45 E	44 S	90									Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	18	minor h/l	N 60 E	70 N														Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	19	minor i	N 50 E	21 N	7	N 46 E	N 38 E	41 S	90									Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	20	minor j	N 44 E	23 N	8	N 38 E	N 52 E	47 S	120									Oi		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	21	minor/k	N 48 E	55 N														Oi		35 50 57.87 N	84 00 12.85 W

Date	Station	I.D. #	Feature	Bedding		Fold Axis		Axial Plane		Inter- limb	Fold	Joint		Lineation		Sense of Slip	Other plane		Rock	Comments	Lat	Long
Plunge	Trend	Strike	Dip	Plunge	Trend	Strike	Dip	Plunge	Trend	Strike	Dip	Plunge	Trend	Strike	Dip	Plunge	Trend	Strike	Dip	Unit		
03/27/00	WB6	22	minor k	N 51 E	25 N	8	N 39 E	N 35 E	64 S	120				28	N 42 W	t			OI		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	23		N 51 E	26 N									43	N 60 W	t			OI		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	24		N 48 E	42 N									31	N 61 W	t			OI		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	25		N 50 E	26 N									23	N 55 W	t			OI		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	26		N 31 E	18 N									16	N 80 W	r			OI		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	27										N 79 W	86 N	29	S 46 E	t			OI		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	28		N 42 E	39 S									41	S 40 E	t			OI		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	29		N 40 E	42 S														OI		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	30	minor l	N 35 E	17 S	3	S 35 W	N 22 E	45 N	90									OI		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6	31	minor l	N 20 E	15 E														OI		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6		minor l	N 40 E	70 E														OI		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6		minor l	N 40 E	73 E														OI		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6		minor l/m	N 35 E	49 W														OI		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6		minor m	N 38 E	77 E	2	S 26 W	N 40 E	66 W	50									OI		35 50 57.87 N	84 00 12.85 W
03/27/00	WB6		minor l/m	N 24 E	60 W	5	N 45 E	N 30 E	77 N	50									OI		35 50 57.87 N	84 00 12.85 W
05/03/00	TC7											N 8 W	88 NE						Ock	filled veins	35 40 40.82 N	83 43 1.79 W
05/03/00	TC7											N 17 W	89 NE						Ock		35 40 40.82 N	83 43 1.79 W
05/03/00	TC7											N 22 W	89 NE						Ock		35 40 40.82 N	83 43 1.79 W
05/03/00	TC7											N 24 W	82 NE						Ock		35 40 40.82 N	83 43 1.79 W
05/03/00	TC7											N 18 E	89 NE						Ock		35 40 40.82 N	83 43 1.79 W
05/03/00	TC7											N 83 E	66 SE						Ock		35 40 40.82 N	83 43 1.79 W
05/03/00	TC7											N 62 E	67 SE						Ock	cut off by N 80 E set	35 40 40.82 N	83 43 1.79 W
05/03/00	TC7											N 57 E	60 NE						Ock		35 40 40.82 N	83 43 1.79 W
05/03/00	TC7													31 SE	N 41 W				Ock	stylolite teeth - open fractures slightly younger than stylolites	near Lat/long above	
05/03/00	TC7					32s	208	N 36 E	84 SE										Ock	10 m 1/2 wavelength	near Lat/long above	
05/03/00	TC7											N 84 E	87 S						Ock	filled joint	near Lat/long above	
05/03/00	TC7											N 16 W	82 NE						Ock	filled joint	near Lat/long above	
05/03/00	TC7											N 28 E	75 NE						Ock	filled joint	near Lat/long above	
05/03/00	TC7											N 61 E	76 NW						Ock	conjugate/filled joint	near Lat/long above	
05/03/00	TC7											N 83 W	82 SW						Ock	conjugate/filled joint	near Lat/long above	
05/03/00	TC7																		Ock	terminate at beds like cross beds	near Lat/long above	
05/03/00	TC7											N 79 E	13 SE						Ock	terminate at beds like cross beds	near Lat/long above	
05/03/00	TC7											N 83 E	17 SE						Ock	cross beds	near Lat/long above	
05/03/00	TC7											N 27 W	87 NE						Ock	lg-scale joints	near Lat/long above	
05/03/00	TC7											N 87 W	78 NE						Ock	lg-scale joints	near Lat/long above	
05/03/00	TC7											N 61 E	86 NW						Ock	lg-scale joints	near Lat/long above	
05/03/00	TC7											N 24 W	89 NE						Ock	lg-scale joints	near Lat/long above	
05/03/00	TC7											N 64 E	71 SE						Ock	lg-scale joints	near Lat/long above	
05/03/00	TC7					25 W	N 36 W	N 73 W	61 NE										Ock	clump of tight folds backlimb of bottom exposed imbricate	near Lat/long above	
05/03/00	TC8											N 82 W	34 NE						Ock		35 40 46.46 N	83 43 10.51 W
05/03/00	TC8											N 2 E	84 W						Ock	"	near Lat/long above	
05/03/00	TC8											N 81 E	49 NW						Ock	"	near Lat/long above	
05/03/00	TC8																		Ock	possible cleavage/bedding intersection	near Lat/long above	
05/03/00	TC8											N 44 E	32 SE						Ock	backlimb of bottom exposed imbricate	near Lat/long above	
05/03/00	TC8											N 73 E	88 SE						Ock	"	near Lat/long above	
05/03/00	TC8											N 73 W	54 NE						Ock	"	near Lat/long above	
05/03/00	TC8											N 43 E	87 SE						Ock	"	near Lat/long above	
05/03/00	TC8																N 57 E	33 SE	Ock	stylolitic cleavage	near Lat/long above	
05/03/00	TC8			N 9 W	29 NE														Ock		near Lat/long above	
05/03/00	TC8											N 37 E	81 SE						Ock		near Lat/long above	
05/03/00	TC8											N 18 W	79 SW						Ock	conjugates ?	near Lat/long above	
05/03/00	TC8											N 23 W	73 NE						Ock	conjugates ?	near Lat/long above	
05/03/00	TC8											N 25 W	84 SW						Ock		near Lat/long above	
05/03/00	TC8											N 45 W	72 S						Ock		near Lat/long above	

Date	Station	I.D. #	Feature	Bedding	Fold Axis	Axial Plane	Inter-limb	Fold	Joint	Lineation	Sense	Other plane	Rock	Unit	Comments	Lat	Long
05/03/00	TC8								N 42 E 46 E				Ock			near Lat/long above	
05/03/00	TC8								N 46 W 79 NE				Ock			near Lat/long above	
05/03/00	TC8								N 13 W 84 NE				Ock			near Lat/long above	
05/03/00	TC8								N 82 W 56 NE				Ock			near Lat/long above	
05/03/00	TC8								N 32 W 72 NE				Ock			near Lat/long above	
05/03/00	TC8											N 8 W 87 NE	Ock		fault	near Lat/long above	
05/03/00	TC8				22	82		N 87 E 71 NW					Ock		"drag" fold	near Lat/long above	
05/03/00	TC8											N 41 E 81 W	Ock		stylolitic cleavage in drag fold	near Lat/long above	
05/03/00	TC8			N 19 E 18 SE									Ock			near Lat/long above	
05/03/00	TC8												Ock		joints in massive carb/ NOT stylolitic	near Lat/long above	
05/03/00	TC8								N 41 E 81 W				Ock		"	near Lat/long above	
05/03/00	TC8								N 72 E 84 SE				Ock		"	near Lat/long above	
05/03/00	TC8								N 17 W 84 NE				Ock		"	near Lat/long above	
05/03/00	TC8								N 74 E 72 NW				Ock		"	near Lat/long above	
05/03/00	TC8								N 57 W 77 SW				Ock		"	near Lat/long above	
05/03/00	TC8								N 67 W 47 NE				Ock		"	near Lat/long above	
05/03/00	TC8								N 14 E 89 N				Ock		"	near Lat/long above	
05/03/00	TC8			N 37 E 28 SE									Ock		"	near Lat/long above	
05/03/00	TC8								N 49 E 77 SE				Ock		"	near Lat/long above	
05/03/00	TC8								N 83 E 82 NW				Ock		"	near Lat/long above	
05/03/00	TC8								N 81 W 77 E				Ock		stepover in joint	near Lat/long above	
05/03/00	TC8												Ock		discontinuous filled joints	near Lat/long above	
05/03/00	TC8								N 81 W 81 SW				Ock		"	near Lat/long above	
05/03/00	TC8								N 37 E 82 NW				Ock		"	near Lat/long above	
05/03/00	TC8								N 82 E 70 S				Ock		"	near Lat/long above	
05/03/00	TC8								N 15 E 79 W				Ock		"	near Lat/long above	
05/03/00	TC8								N 81 E 82 W				Ock		"	near Lat/long above	
05/03/00	TC8								N 27 E 73 S				Ock		"	near Lat/long above	
05/03/00	TC8								N 21 W 79 SW				Ock		"	near Lat/long above	
05/03/00	TC8								N 13 W 77 SW				Ock		"	near Lat/long above	
05/03/00	TC8								N 43 W 54 SW				Ock		"	near Lat/long above	
05/03/00	TC8								N 23 E 56 SE				Ock		"	near Lat/long above	
05/03/00	TC8			N 57 W 12 NE									Ock		"	near Lat/long above	
05/03/00	TC8								N 37 E 57 SE				Ock		"	near Lat/long above	
05/03/00	TC8								N 33 E 84 NW				Ock		"	near Lat/long above	
05/03/00	TC8								N 36 E 84 NW				Ock		"	near Lat/long above	
05/03/00	TC8								N 52 E 82 SE				Ock		thin-bedded zone	near Lat/long above	
05/03/00	TC8									16 SE	N 58 E		Ock		displacement vector	near Lat/long above	
05/03/00	TC8												Ock		fault - orientation	near Lat/long above	
05/03/00	TC8											N 64 E 22 N	Ock		varies	near Lat/long above	
05/03/00	TC8												Ock		fault - orientation	near Lat/long above	
05/03/00	TC8											N 88 W 54 NE	Ock		varies	near Lat/long above	
05/03/00	TC8								N 53 E 27 SE				Ock		shear joint	near Lat/long above	
05/03/00	TC8								N 47 E 31 NW	14	133		Ock		slick on shear joint	near Lat/long above	
05/03/00	TC8								N 43 E 31 SE				Ock		shear joint	near Lat/long above	
05/03/00	TC8								N 66 E 62 SE				Ock		shear joint	near Lat/long above	
05/03/00	TC8								N 73 E 31 NW				Ock		shear joint	near Lat/long above	
05/03/00	TC8								N 77 E 47 NW				Ock		shear joint	near Lat/long above	
05/03/00	TC8								N 43 E 88 NW				Ock		younger through-going	near Lat/long above	
05/03/00	TC8								N 13 W 61 W				Ock			near Lat/long above	
05/03/00	TC8												Ock		fault, movement	near Lat/long above	
05/03/00	TC8				8 NE	N 73 E				14 S	S 14 E		Ock		direction, and drag fold axis	near Lat/long above	
05/03/00	TC8											N 53 E 26 SE	Ock		fault before ramp	near Lat/long above	
05/03/00	TC8											N 6 E 13 E	Ock		massive carb	near Lat/long above	
05/03/00	TC8								N 13 E 68 NW				Ock		massive carb	near Lat/long above	
05/03/00	TC8								N 83 W 78 SW				Ock		massive carb	near Lat/long above	
05/03/00	TC8								N 11 W 76 SW				Ock		massive carb	near Lat/long above	
05/03/00	TC8								N 52 E 54 NW				Ock		massive carb	near Lat/long above	

Date	Station	I.D. #	Feature	Bedding Strike Dip	Fold Axis Plunge Trend	Axial Plane Strike Dip	Inter- limb < Verg.	Fold	Joint Strike Dip	Lineation Plunge Trend	Sense of Slip	Other plane Strike Dip	Rock Unit	Comments	Lat	Long
05/03/00	TC8								N 7 E 82 W				Ock	massive carb	near Lat/long above	
05/03/00	TC8								N 37 W 83 W				Ock	massive carb	near Lat/long above	
05/03/00	TC9											N 37 E 31 SE	Ock	calcite filled veins Middle O turbidites over Ock in new roadcut	35 40 46.19 N 83 47 08.76 W	
05/03/00	TC9			N 22 E 34 NW									mO		"	"
05/03/00	TC9								N 9 W 63 SW				mO		"	"
05/03/00	TC9								N 68 W 38 SW				mO		"	"
05/03/00	TC9								N 12 E 43 SE				mO	en echelon	"	"
05/03/00	TC9								N 16 E 61 NW				mO		"	"
05/03/00	TC9								S 8 W 16				mO		"	"
05/03/00	TC9								N 42 E 44 E				mO	filled shear fracture	"	"
05/03/00	TC9				19 SW S 68 W	N 59 E 24 NW							mO	folded vein	"	"
05/03/00	TC9								N 63 W 76 NE	42 SE S 83 E			mO	slick - down to SE unfilled set perp to above	"	"
05/03/00	TC9								N 12 E 84 NW	69 NE N 43 E			mO	slick	"	"
05/03/00	TC9								N 43 E 32 NW				mO	filled veins	"	"
05/03/00	TC9								N 47 E 18 SE				mO	filled veins	"	"
05/03/00	TC9								N 22 E 24 SE				mO	filled veins	"	"
05/03/00	TC9								N 88 W 74 NE	2 W S 88 W			mO	slick	"	"
05/03/00	TC9								N 29 E 69 NW	62 NW N 68 W			mO	slick	"	"
05/03/00	TC9								N 27 E 83 NW				mO	slick overprint!	"	"
05/03/00	TC9								N 11 W 77 W	77 W N 78 W			mO	lineation = slick on joint	"	"
05/03/00	TC9				19 S S 52 W	N 38 E 34 SE			N 56 E 74 NW				mO	z fold	"	"
05/03/00	TC9								N 82 W 66 SW	17 W N 82 W			mO	slick	"	"
05/03/00	TC9								N 87 W 78 NE	6 W N 87 W			mO	slick	"	"
05/03/00	TC9								N 76 W 64 SW	16 W N 76 W			mO	slick	"	"
05/04/00	TC10								N 53 W 74 SW				Ock	location approximate!! Crest of lowest exposed Cedar Bluff duplex	35 40 40.82 N 83 43 1.79 W	
05/04/00	TC10								N 33 E 88 SE				Ock	"	near Lat/long above	
05/04/00	TC10								N 22 E 84 N				Ock	"	near Lat/long above	
05/04/00	TC10			N 61 W 12 N					N 17 E 83 NW				Ock	"	near Lat/long above	
05/04/00	TC10								N 39 W 69 SW				Ock	"	near Lat/long above	
05/04/00	TC10								N 55 W 84 SW				Ock	"	near Lat/long above	
05/04/00	TC10								N 21 E 86 NW				Ock	"	near Lat/long above	
05/04/00	TC10								N 24 E 82 NW				Ock	"	near Lat/long above	
05/04/00	TC10								N 64 W 83 S				Ock	"	near Lat/long above	
05/04/00	TC10								N 70 E 25 N				Ock	"	near Lat/long above	
05/04/00	TC10			N 44 W 15 NE									Ock	crest	near Lat/long above	
05/04/00	TC10			N 49 E 38 NW									Ock	forelimb	near Lat/long above	
05/04/00	TC10								N 47 E 77 SE				Ock	forelimb	near Lat/long above	
05/04/00	TC10								N 19 E 86 NW				Ock	forelimb	near Lat/long above	
05/04/00	TC10								N 75 W 89 N				Ock	forelimb	near Lat/long above	
05/04/00	TC10								N 62 E 79 E				Ock	forelimb	near Lat/long above	
05/04/00	TC10								N 4 W 67 NE				Ock	forelimb	near Lat/long above	
05/04/00	TC10								N 33 E 63 NW				Ock	forelimb	near Lat/long above	
05/04/00	TC10								N 41 W 73 NE				Ock	forelimb	near Lat/long above	
05/04/00	TC10								N 48 W 62 SW				Ock	forelimb	near Lat/long above	

Date	Station	I.D. #	Feature	Bedding		Fold Axis		Axial Plane		Inter-limb	Fold	Joint		Lineation		Sense of Slip	Other plane		Rock Unit	Comments	Lat	Long
Strike	Dip	Plunge	Trend	Strike	Dip	Strike	Dip	Strike	Dip	<	Verg.	Strike	Dip	Plunge	Trend		Strike	Dip				
05/04/00	TC10			N 51 E	49 NW														Ock		near Lat/long above	
05/04/00	TC10			N 42 E	49 NW														Ock		near Lat/long above	
05/04/00	TC10			N 30 E	17 E														Ock	backlimb of next duplex down	near Lat/long above	
05/04/00	TC10											N 18 W	87 W						Ock	"	near Lat/long above	
05/04/00	TC10											N 85 E	74 N						Ock	"	near Lat/long above	
05/04/00	TC10											N 47 E	85 NW						Ock	"	near Lat/long above	
05/04/00	TC10											N 54 W	89 S						Ock	"	near Lat/long above	
05/04/00	TC10											N 17 W	66 W						Ock	"	near Lat/long above	
05/04/00	TC10											N 13 W	73 W						Ock	"	near Lat/long above	
05/04/00	TC10											N 50 E	72 W						Ock	"	near Lat/long above	
07/12/00	MO1					9 S	S 87 E	N 87 E	57 N	120	S								Om	folds in Middle O' Moccasin below CC fault	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					14 S	S 81 E	N 81 W	48 N	120	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					1 S	S 73 W	N 83 W	43 N	120	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					8 N	N 79 E	N 69 E	73 N	90	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					1 S	S 88 E	N 79 E	20 N	90	N								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					2 S	S 78 W	N 85 W	21 S	90	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					1 S	S 65 W	N 74 E	42 N	90	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					1 N	N 79 W	N 80 W	67 S	90	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					6 S	S 66 W	N 78 E	40 S	90	N								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					32 S	S 56 W	N 83 W	47 S	8	N								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					10	N 80 E	N 86 E	33 S	80	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					11 S	S 89 E	N 84 E	81 S	70	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO2					15S	S 40 W	N 34 E	71N	110	N								Cr	Oodles of small folds in Rome shales and ss in War Ridge cut on HWY 31	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					13S	S 34 W	N 37 E	74N	80	N								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					2S	S 43 W	N 30 E	62N	80	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					18S	S 42 W	N 36 E	75N	90	vertical								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					26S	S 41 W	N 40 E	68S	80	N								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					21S	S 66 W	N 65 E	67N	80	NS								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					11S	S 62 W	N 67 E	69N	90	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					22S	S 47 W	N 23 E	85N	70	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					4S	S 25 W	N 28 E	73N	50	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					25S	S 48 W	N 50 E	84N	50	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					2S	S 33 W	N 38 E	75S	40	N								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					16N	N 37 E	N 48 E	71N	80	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					17N	N 41 E	N 30 E	64S	90	N								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					4N	N 37 E	N 38 E	78S	70	N								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					14S	S 31 W	N 41 E	73N	90	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					7S	S 48 W	N 48 E	71S	90	N								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO3					29 N	N 65 E	N 58 E	81 S	90	N								Cr	More Rome along HWY 31 just N of Big War Creek, across from War Creek Baptist Church. Asymmetrical folds under minor fault	36 27 35.32 N	83 14 18.73 W
07/12/00	MO3					25 N	N 68 E	N 64 E	68 E	90	N								Cr	"	36 27 35.32 N	83 14 18.73 W
07/12/00	MO3					26 N	N 64 E	N 68 E	72 E	90	N								Cr	"	36 27 35.32 N	83 14 18.73 W
07/12/00	MO3					6N	N 78 E	N 74 E	40 W		S								Cr	"	36 27 35.32 N	83 14 18.73 W
07/12/00	MO4					11 S	S 32 W	N 39 E	43 E	110	W								Mg(?)	Mg (more likely) or Sc around corner wavelength 10-20 m		
07/12/00	MO4					8 S	S 49 W	N 44 E	71 W	120	E								Mg(?)	"		
07/12/00	MO4					24 S	S 45 W	N 34 E	79 E	160	W								Mg(?)	"		

				Bedding		Fold Axis		Axial Plane		Inter-	Fold	Joint		Lineation		Sense	Other plane		Rock			
Date	Station	I.D. #	Feature	Strike	Dip	Plunge	Trend	Strike	Dip	<	Verg.	Strike	Dip	Plunge	Trend	of Slip	Strike	Dip	Unit	Comments	Lat	Long
05/04/00	TC10			N 51 E	49 NW														Ock		near Lat/long above	
05/04/00	TC10			N 42 E	49 NW														Ock		near Lat/long above	
																				backlimb of next duplex down	near Lat/long above	
05/04/00	TC10			N 30 E	17 E														Ock	"	near Lat/long above	
05/04/00	TC10											N 18 W	87 W						Ock	"	near Lat/long above	
05/04/00	TC10											N 85 E	74 N						Ock	"	near Lat/long above	
05/04/00	TC10											N 47 E	85 NW						Ock	"	near Lat/long above	
05/04/00	TC10											N 54 W	89 S						Ock	"	near Lat/long above	
05/04/00	TC10											N 17 W	66 W						Ock	"	near Lat/long above	
05/04/00	TC10											N 13 W	73 W						Ock	"	near Lat/long above	
05/04/00	TC10											N 50 E	72 W						Ock	"	near Lat/long above	
																				fold in Middle O' Moccasin below CC fault		
07/12/00	MO1					9 S	S 87 E	N 87 E	57 N	120	S								Om		36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					14 S	S 81 E	N 81 W	48 N	120	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					1 S	S 73 W	N 83 W	43 N	120	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					8 N	N 79 E	N 69 E	73 N	90	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					1 S	S 88 E	N 79 E	20 N	90	N								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					2 S	S 78 W	N 85 W	21 S	90	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					1 S	S 65 W	N 74 E	42 N	90	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					1 N	N 79 W	N 80 W	67 S	90	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					6 S	S 66 W	N 78 E	40 S	90	N								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					32 S	S 56 W	N 83 W	47 S	8	N								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					10	N 80 E	N 86 E	33 S	80	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					11 S	S 89 E	N 84 E	81 S	70	S								Om	"	36 27 49.62 N	83 14 28.84 W
																				Uddies of small folds in Rome shales and ss in War Ridge cut on HWY 31		
07/12/00	MO2					15S	S 40 W	N 34 E	71N	110	N								Cr		36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					13S	S 34 W	N 37 E	74N	80	N								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					2S	S 43 W	N 30 E	62N	80	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					18S	S 42 W	N 36 E	75N	90	vertical								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					26S	S 41 W	N 40 E	68S	80	N								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					21S	S 66 W	N 65 E	67N	80	NS								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					11S	S 62 W	N 67 E	69N	90	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					22S	S 47 W	N 23 E	85N	70	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					4S	S 25 W	N 28 E	73N	50	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					25S	S 48 W	N 50 E	84N	50	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					2S	S 33 W	N 38 E	75S	40	N								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					16N	N 37 E	N 48 E	71N	80	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					17N	N 41 E	N 30 E	64S	90	N								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					4N	N 37 E	N 38 E	78S	70	N								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					14S	S 31 W	N 41 E	73N	90	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					7S	S 48 W	N 48 E	71S	90	N								Cr	"	36 27 47.05 N	83 14 30.29 W
																				more Rome along HWY 31 just N of Big War Creek, across from War Creek Baptist Church. Asymmetrical folds under minor fault		
07/12/00	MO3					29 N	N 65 E	N 58 E	81 S	90	N								Cr		36 27 35.32 N	83 14 18.73 W
07/12/00	MO3					25 N	N 68 E	N 64 E	68 E	90	N								Cr	"	36 27 35.32 N	83 14 18.73 W
07/12/00	MO3					26 N	N 64 E	N 68 E	72 E	90	N								Cr	"	36 27 35.32 N	83 14 18.73 W
07/12/00	MO3					6N	N 78 E	N 74 E	40 W		S								Cr	"	36 27 35.32 N	83 14 18.73 W
																				Mg (more likely) or Sc around corner wavelength 10-20 m		
07/12/00	MO4					11 S	S 32 W	N 39 E	43 E	110	W								Mg(?)	"		
07/12/00	MO4					8 S	S 49 W	N 44 E	71 W	120	E								Mg(?)	"		
07/12/00	MO4					24 S	S 45 W	N 34 E	79 E	160	W								Mg(?)	"		

Date	Station	I.D. #	Feature	Bedding		Fold Axis		Axial Plane		Inter-limb	Fold	Joint		Lineation		Sense of Slip	Other plane		Rock Unit	Comments	Lat	Long
				Strike	Dip	Plunge	Trend	Strike	Dip	<	Verg.	Strike	Dip	Plunge	Trend		Strike	Dip				
05/04/00	TC10			N 51 E	49 NW														Ock	near Lat/long above		
05/04/00	TC10			N 42 E	49 NW														Ock	near Lat/long above		
05/04/00	TC10			N 30 E	17 E														Ock	backlimb of next duplex down	near Lat/long above	
05/04/00	TC10											N 18 W	87 W						Ock	"	near Lat/long above	
05/04/00	TC10											N 85 E	74 N						Ock	"	near Lat/long above	
05/04/00	TC10											N 47 E	85 NW						Ock	"	near Lat/long above	
05/04/00	TC10											N 54 W	89 S						Ock	"	near Lat/long above	
05/04/00	TC10											N 17 W	66 W						Ock	"	near Lat/long above	
05/04/00	TC10											N 13 W	73 W						Ock	"	near Lat/long above	
05/04/00	TC10											N 50 E	72 W						Ock	"	near Lat/long above	
07/12/00	MO1					9 S	S 87 E	N 87 E	57 N	120	S								Om	folds in Middle O Moccasin below CC fault	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					14 S	S 81 E	N 81 W	48 N	120	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					1 S	S 73 W	N 83 W	43 N	120	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					8 N	N 79 E	N 69 E	73 N	90	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					1 S	S 88 E	N 79 E	20 N	90	N								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					2 S	S 78 W	N 85 W	21 S	90	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					1 S	S 65 W	N 74 E	42 N	90	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					1 N	N 79 W	N 80 W	67 S	90	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					6 S	S 66 W	N 78 E	40 S	90	N								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					32 S	S 56 W	N 83 W	47 S	8	N								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					10	N 80 E	N 86 E	33 S	80	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO1					11 S	S 89 E	N 84 E	81 S	70	S								Om	"	36 27 49.62 N	83 14 28.84 W
07/12/00	MO2					15S	S 40 W	N 34 E	71N	110	N								Cr	Oodles or small folds in Rome shales and ss in War Ridge cut on HWY 31	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					13S	S 34 W	N 37 E	74N	80	N								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					2S	S 43 W	N 30 E	62N	80	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					18S	S 42 W	N 36 E	75N	90	vertical								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					26S	S 41 W	N 40 E	68S	80	N								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					21S	S 66 W	N 65 E	67N	80	NS								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					11S	S 62 W	N 67 E	69N	90	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					22S	S 47 W	N 23 E	85N	70	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					4S	S 25 W	N 28 E	73N	50	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					25S	S 48 W	N 50 E	84N	50	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					2S	S 33 W	N 38 E	75S	40	N								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					16N	N 37 E	N 48 E	71N	80	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					17N	N 41 E	N 30 E	64S	90	N								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					4N	N 37 E	N 38 E	78S	70	N								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					14S	S 31 W	N 41 E	73N	90	S								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO2					7S	S 48 W	N 48 E	71S	90	N								Cr	"	36 27 47.05 N	83 14 30.29 W
07/12/00	MO3					29 N	N 65 E	N 58 E	81 S	90	N								Cr	More Rome along HWY 31 just N of Big War Creek, across from War Creek Baptist Church. Asymmetrical folds under minor fault	36 27 35.32 N	83 14 18.73 W
07/12/00	MO3					25 N	N 68 E	N 64 E	68 E	90	N								Cr	"	36 27 35.32 N	83 14 18.73 W
07/12/00	MO3					26 N	N 64 E	N 68 E	72 E	90	N								Cr	"	36 27 35.32 N	83 14 18.73 W
07/12/00	MO3					6N	N 78 E	N 74 E	40 W		S								Cr	"	36 27 35.32 N	83 14 18.73 W
07/12/00	MO4					11 S	S 32 W	N 39 E	43 E	110	W								Mg(?)	Mg (more likely) or Sc around corner		
07/12/00	MO4					8 S	S 49 W	N 44 E	71 W	120	E								Mg(?)	wavelength 10-20 m		
07/12/00	MO4					24 S	S 45 W	N 34 E	79 E	160	W								Mg(?)	"		

VITA

Jennifer Bergin Whisner was born in East Grand Rapids, Michigan, to John and Susan Bergin. She spent her formative years at the Marywood Montessori school before transitioning to the excellent schools of East Grand Rapids, Michigan. She received a Bachelors of Science degree in chemistry from the University of Michigan followed by a Masters of Science degree in hydrogeology from Western Michigan University. Jennifer graduated with a Doctor of Philosophy degree from the Department of Earth and Planetary Sciences at the University of Tennessee, Knoxville, in August, 2010.