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Tectonic inversion and basement buttressing: an example from the central Appalachian Blue Ridge province

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Abstract

The structural geometry of the central Appalachian Blue Ridge province is primarily the result of Paleozoic contractional deformation. However, the Tye River fault zone in the western Blue Ridge of central Virginia preserves an extensional map pattern. These ENE–WSW striking faults place Neoproterozoic to early Cambrian volcanic and sedimentary rocks over Grenvillian granitic basement. Detailed mapping, cross-section restoration, and balancing reveals partially inverted faults, original half grabens, and significantly thicker cover units on hanging walls. The orientation and geometry of the Tye River fault zone, as well as the thickness changes in the cover rocks are inconsistent with extensional reactivation of Paleozoic reverse faults during Mesozoic rifting. The extrusion and deposition of cover rocks was contemporaneous with normal displacement on the Tye River fault zone and the formation of rift basins recording ~5% crustal extension. Faults were reactivated as Paleozoic contractional structures, but an extensional map pattern is generally still preserved. Regional shortening of 10–20% was accomplished primarily by folding of the cover rocks rather than by reactivation of older faults. The basement formed a rigid buttress that controlled the geometry of folding in the cover sequence. © 2002 Published by Elsevier Science Ltd.

Keywords: Tectonic inversion; Basement buttressing; Appalachians; Blue Ridge

1. Introduction

Tectonic inversion structures may develop where pre-existing extensional faults are reactivated as reverse faults during later contractional deformation. Contractional displacement on reactivated faults brings the hanging wall up relative to the footwall and may bring the hanging wall back to its pre-extensional position (Fig. 1). If contractional faulting does not proceed past the original pre-extensional geometry an extensional map pattern will be preserved, whereas a contractional map pattern will result if reactivation exceeds the pre-extensional position of the units.

Tectonic inversion is most easily recognized in syn-rift and passive margin sequences that have been extruded from their basin during contraction (Cooper et al., 1989). Many inverted basins have been identified with seismic data, but a number of field studies have also recognized inversion structures (i.e. Butler, 1989; McClay et al., 1989; Lamarche et al., 1999). The geometry of the earlier extensional basin plays a significant role in the geometry of the reactivated structures and reverse faults in regions of tectonic inversion have more complex geometries than simple low-angle thrusts that deform flat-lying strata (McClay and Buchanan, 1992). Regions of tectonic inversion have been documented in a number of contractional mountain belts including the Alps, Andes, and Canadian Cordillera (Butler, 1989; McClay et al., 1989; Coward et al., 1991; Ramos et al., 1996).

Rigid basement blocks may act as a buttress against thrust translation and play a significant role in the geometry of reactivated structures (Welbon, 1988; Butler, 1989; Hayward and Graham, 1989). The rheologic contrast between rigid basement and layered cover rocks may lead to buckling in the cover sequence rather than reactivation of pre-existing faults and the generation of backthrusts in the cover sequence. However, with the exception of a few studies (Butler, 1989; Henning and Muehlberger, 1990; Butler, 1997; Chen, 1998) basement buttressing has rarely been documented.

In this study we report on the Tye River fault zone, a suite of six faults, that places Neoproterozoic to early Paleozoic rift-related cover rocks over Grenvillian basement in the Blue Ridge province of the central Virginia Appalachians. These faults are interpreted as original rift-related

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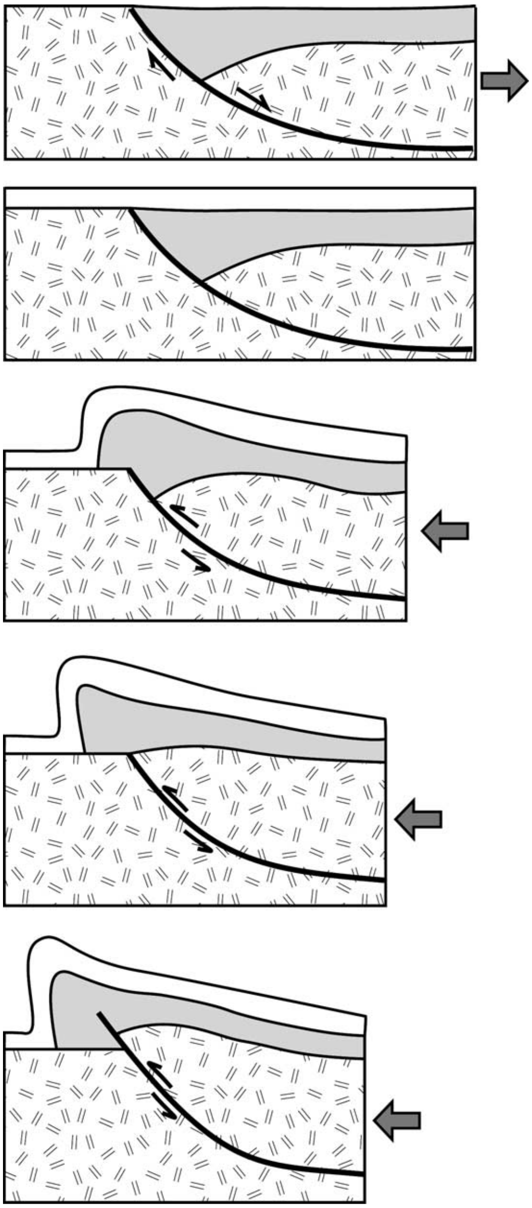

Fig. 1. Generalized cross-sections of an original extensional basin with synsedimentary deposits that is later inverted during contraction.

extensional faults that were reactivated as contractional faults during regional shortening in the Paleozoic. Contractional deformation involved both inversion of extensional faults and folding in the cover sequence. Basement buttresses played a significant role in the partitioning between shortening due to fault inversion and folding.

2. Geologic setting

In central and northern Virginia the Blue Ridge province is a broad anticlinorium that formed during Paleozoic contractional deformation (Mitra and Elliott, 1980; Evans, 1989) (Fig. 2). The region is characterized by northeast–southwest striking reverse faults, folds, and in many locations a southeast-dipping penetrative foliation. Seismic reflection profiles indicate that the Blue Ridge is allochthonous and has been thrust to the northwest over Paleozoic carbonates of the Valley and Ridge province (Harris et al., 1982; Pratt et al., 1988; Evans, 1989). Rocks exposed in the Blue Ridge include Grenvillian (~1 Ga) granitic gneisses, Neoproterozoic metabasalts of the Catoctin Formation, and siliciclastic rocks of the Neoproterozoic to early Cambrian Chilhowee Group (Fig. 3). Neoproterozoic units in the Blue Ridge formed during continental rifting associated with the opening of the Iapetus Ocean and are overlain by Cambrian passive margin sedimentary rocks of the Valley and Ridge (Rankin et al., 1989; Simpson and Eriksson, 1989) (Fig. 3).

Individual faults in the Tye River fault zone (TRFZ) place Neoproterozoic to early Cambrian cover rocks over Grenvillian basement in the central Virginia Blue Ridge (Figs. 2 and 4). Bloomer and Werner (1955) and Werner (1966) interpreted the TRFZ as a series of thrusts that truncate closely spaced folds. Bartholomew et al. (1991) suggested that the extensional map pattern preserved along the TRFZ might be the result of Mesozoic extension associated with the opening of the Atlantic Ocean. Evans et al. (1998) showed the westernmost faults in the TRFZ cutting the low-angle Blue Ridge thrust, implying post-Paleozoic extensional movement for the TRFZ.

Faults with a younger-over-older relationship have been documented in a few locations in the central Appalachians. Root (1970) reports an extensional map pattern associated with the Antietam Cove fault in southern Pennsylvania. In Maryland and northern Virginia, the Short Hill fault places Neoproterozoic to early Paleozoic cover rocks on Grenvillian basement and is interpreted to be a reactivated extensional fault (Wotjal, 1989; Brezinski, 1992; Southworth and Brezinski, 1996). Approximately 35 km southwest of the TRFZ the Snowden fault places Chilhowee Group cover rocks on basement and is interpreted to be a folded synsedimentary normal fault (Simpson and Eriksson, 1989; Spencer et al., 1989). In the eastern Blue Ridge, Bailey and Simpson (1993) report a number of mylonite zones that record extensional deformation and are interpreted to be Neoproterozoic rift-related structures.

3. Tye River fault zone

3.1. Overview

The Tye River fault zone includes six separate faults that are exposed in a $10 \times 18\ \text{km}^2$ area approximately 30 km northeast of Lexington, Virginia (Figs. 2 and 4). Werner (1966) originally mapped the TRFZ at 1:62,500; we have remapped the TRFZ at 1:24,000. To the north of the TRFZ we used structural data from Knetchel (1943). Faults in the Tye River fault zone are 1.5–14 km in length, strike 035° to 075°, and dip 60–70° to the southeast (Fig. 4). Bedding in

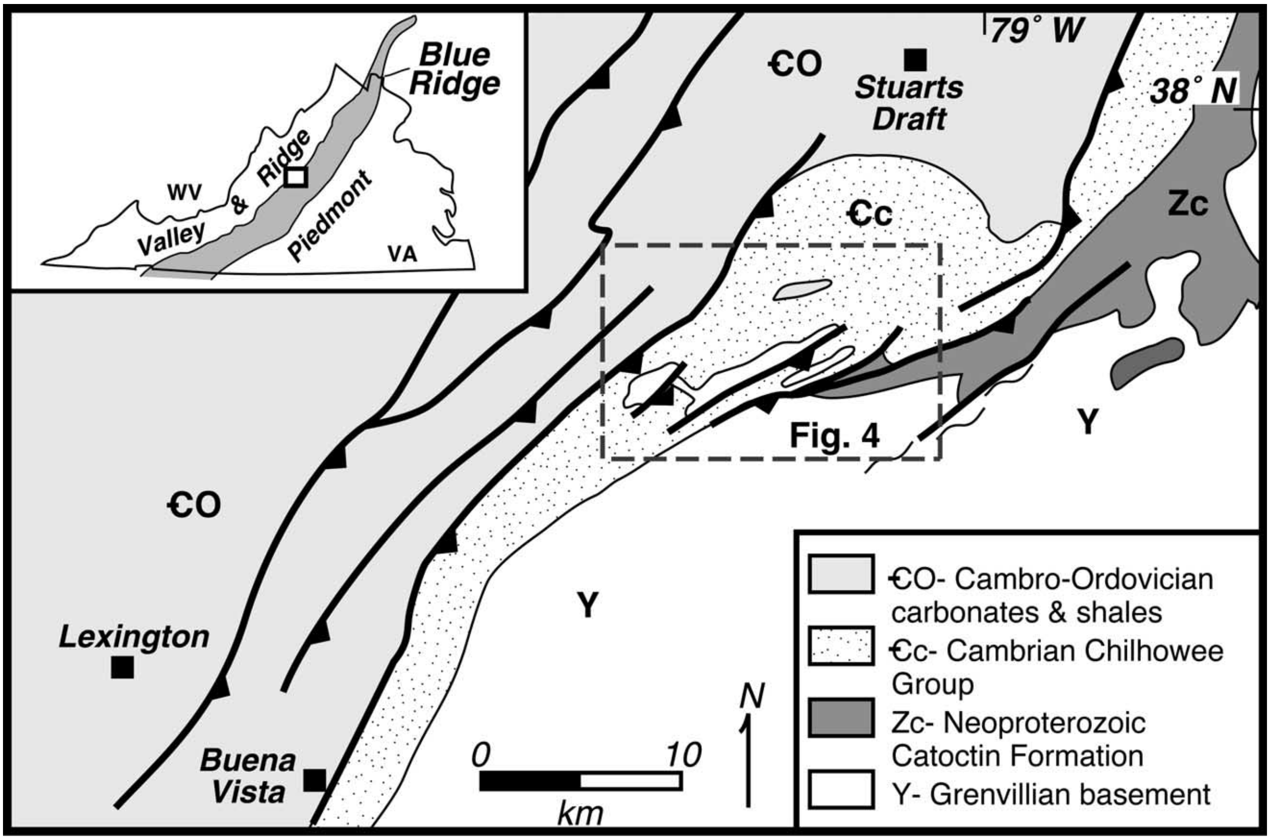

Fig. 2. Generalized geologic map of the central Virginia Blue Ridge province and Tye River fault zone area (in the dashed box). Modified from Virginia Division of Mineral Resources (1993).

the hanging wall of the TRFZ dips towards the faults, away from the faults, and at high angles to the faults (Fig. 4).

All of the rocks have experienced lower greenschist facies metamorphism and a penetrative foliation defined by aligned phyllosilicates is present in many of the fine-grained rocks. For the sake of brevity the prefix 'meta' is omitted from the remainder of the text, but should be assumed for these rocks. Foliation strikes to the east-northeast, dips moderately to the southeast (Fig. 5a), and is interpreted to have formed during regional Paleozoic shortening (Bartholomew et al., 1991). Bedding typically strikes northeast, dips gently to steeply to the southeast and northwest, and defines gently plunging folds (Fig. 5b).

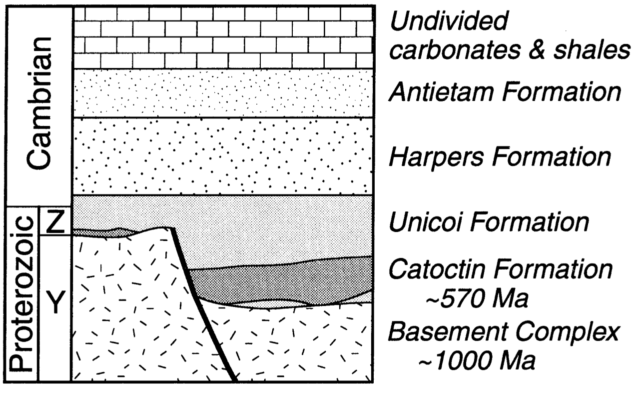

Fig. 3. Generalized stratigraphy of the Blue Ridge province, central Virginia.

3.2. Stratigraphy

Grenvillian (∼1000 Ma) granitic basement rocks exposed along the TRFZ include megacrystic charnockite, leucocratic granulite gneiss, and K-feldspar rich granitic gneiss (Werner, 1966; Sinha and Bartholomew, 1984; Virginia Division of Mineral Resources, 1993). Basement rocks are unconformably overlain by arkosic to phyllitic rocks and basalts of the Catoctin Formation. In the TRFZ area, Werner (1966) mapped thin, discontinuous arkoses and phyllites beneath the Catoctin Formation as the Swift Run Formation. Clastic rocks that crop out below and between basalt flows are identical to rocks in the overlying Unicoi Formation (Fig. 3). These rocks are not laterally continuous and commonly interfinger with basalt and fine-grained sedimentary rocks. Based on these field relations we map all sedimentary rocks between and below the basalts as part of the Catoctin Formation. The 570 ± 36 Ma Catoctin Formation forms a sequence of basalts with minor interlayers of arkosic sandstone and tuff (Werner, 1966; Badger and Sinha, 1988). To the northeast of the TRFZ, the Catoctin Formation thickens to 400–900 m (Gathright,

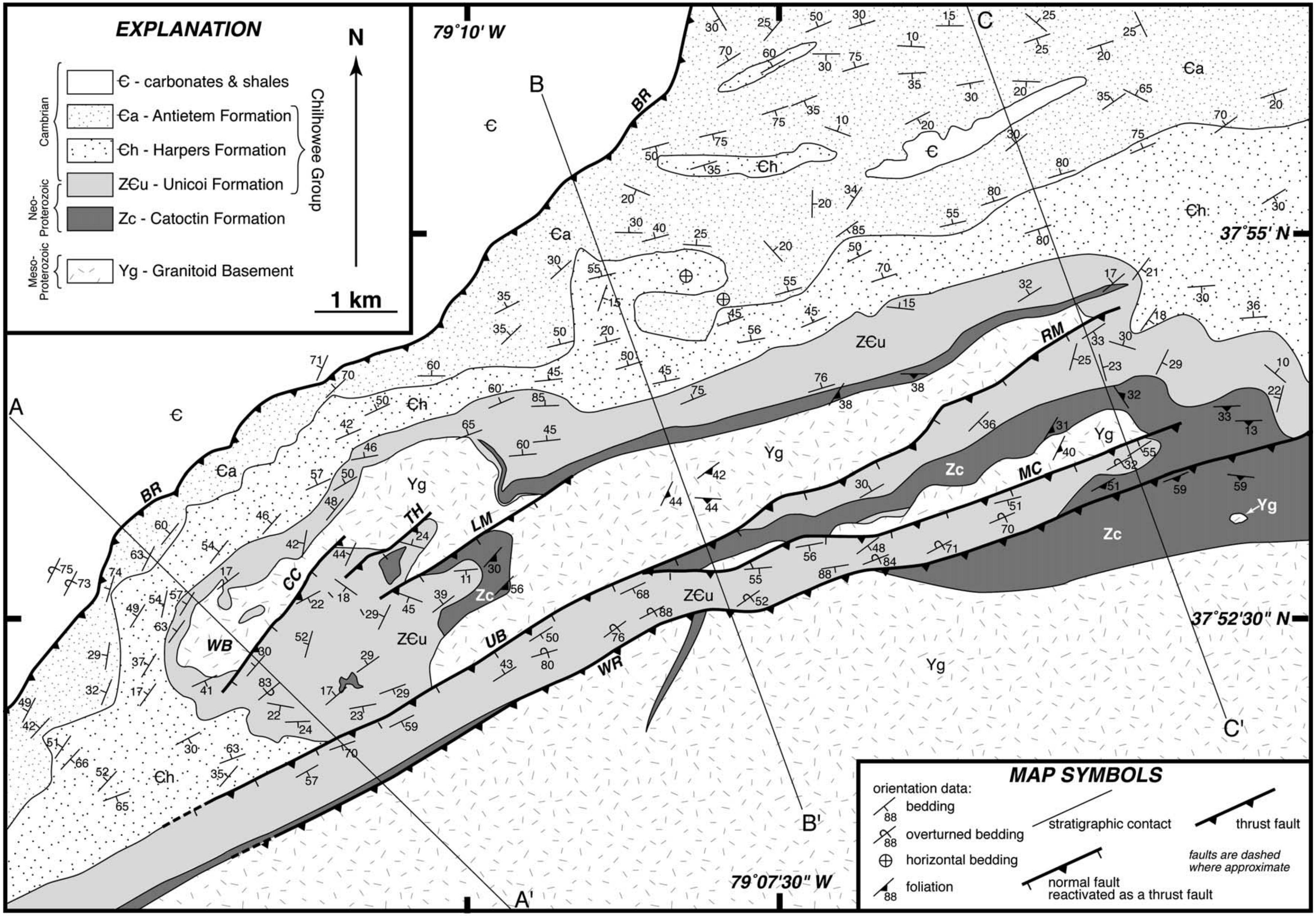

Fig. 4. Geologic map of the Tye River fault zone based on 1:24,000 scale mapping. BR = Blue Ridge fault. The Tye River fault zone includes: CC = Contact Creek fault, LM = Little Mary's fault, MC = Mill Creek fault, RM = Round Mountain fault, TH = Turkey Hollow fault, UB = Upper Big Mary's fault, WB = western basement anticline, WR = Whetstone Ridge fault.

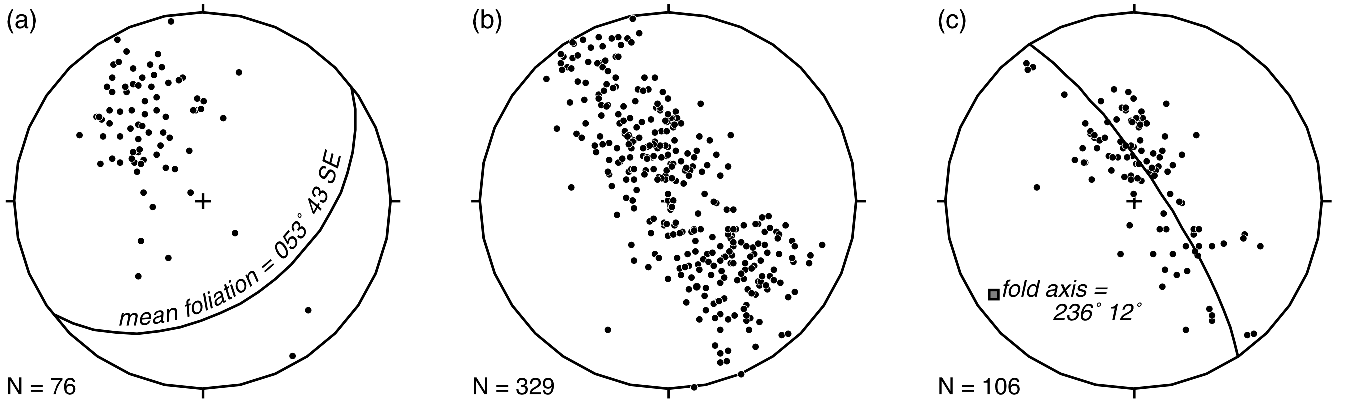

Fig. 5. (a) Equal area stereogram of poles to foliation for the TRFZ area with mean foliation great circle. (b) Equal area stereogram of poles to bedding for the TRFZ area. (c) Equal area stereogram of poles to bedding in the Unicoi Formation in the hanging wall of the Contact Creek fault. Best fit π-girdle defines a gently southwest plunging fold axis.

1976; Bartholomew, 1977). In the TRFZ area, basalts are up to 150 m thick, but are not always present. South and west of the TRFZ, the Catoctin Formation is absent.

The Unicoi Formation is a heterogeneous unit at the base of the Chilhowee Group. In the TRFZ area, the Unicoi is composed of arkosic sandstone, quartz pebble conglomerate, quartz arenite, feldspathic wacke, micaceous quartz wacke, and laminated siltstone. On the western flank of the Blue Ridge, immediately above the Blue Ridge thrust, the Unicoi Formation is ~100 m thick and unconformably overlies the basement (Fig. 6). To the east, in the hanging wall of the Contact Creek fault the Unicoi Formation is 350 m thick (Fig. 6). Dramatic thickness changes across the hanging wall and footwall blocks of the TRFZ are consistent with a syn-rift origin for the lower Unicoi Formation. Arkosic conglomerates are most

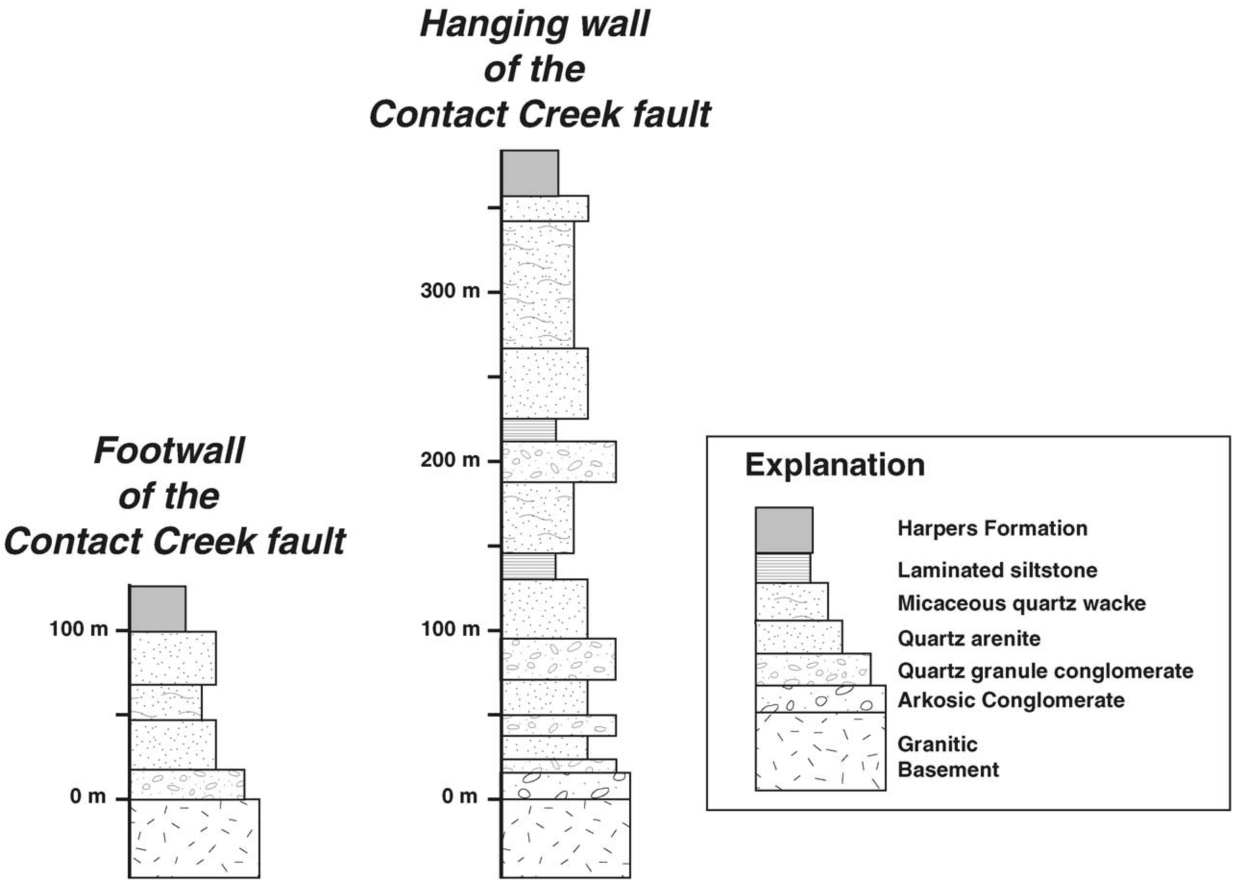

Fig. 6. Composite stratigraphic sections of the Unicoi Formation in the footwall and hanging wall of the Contact Creek fault.

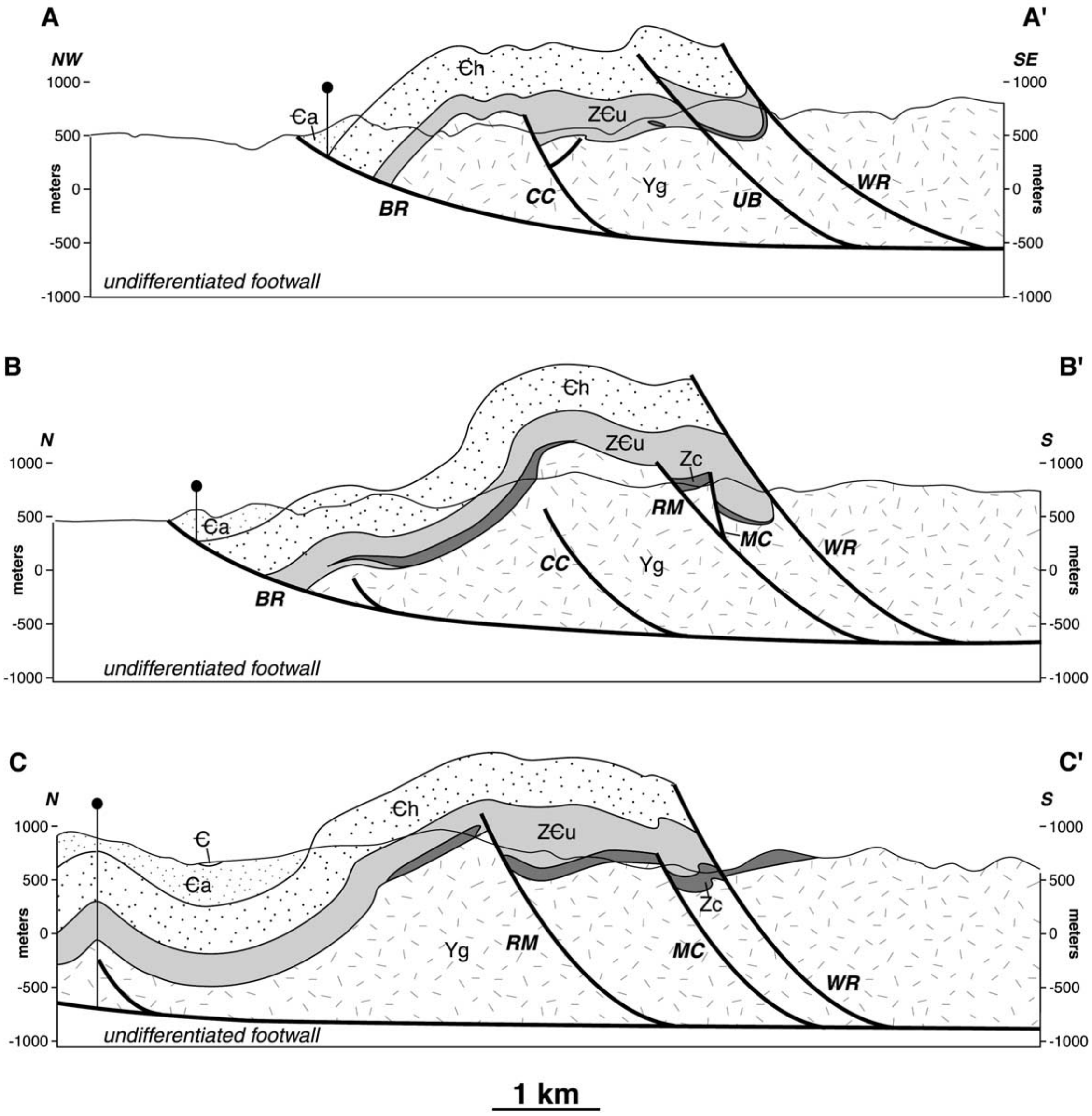

Fig. 7. Deformed cross sections A–A′, B–B′, and C–C′. Vertical line marks pinline for restoration. See Fig. 4 for fault abbrevations.

common at the base of the Unicoi and near faults. In southwestern Virginia, trace fossils from the middle part of the Unicoi Formation indicate deposition during the Neoproterozoic/Cambrian transition (Simpson and Sundberg, 1987). The lower Unicoi Formation is interpreted to have been deposited on alluvial fans and braid plains during active rifting, whereas the upper Unicoi Formation is interpreted as a nearshore marine deposit that formed during the incipient phase of passive margin formation (Simpson and Eriksson, 1989).

The Harpers and Antietam Formations conformably overlie the Unicoi Formation. On the western flank of the Blue Ridge the Harpers Formation forms a 300–400 m thick package of thinly bedded sandstones, siltstones and interlayered quartz arenites. The Antietam Formation is a ~250 m thick unit of well-cemented quartz arenites. Both units are interpreted as shallow marine passive margin deposits (Simpson and Eriksson, 1989; Walker and Simpson, 1991).

3.3. Structure

Geologic cross-sections were originally constructed across the TRFZ at 1:24,000 (Fig. 7). Structural data were projected onto section lines via downplunge projection in regions where a local fold axis was well defined (Fig. 5c). Sections were constructed, balanced, and restored following the standard methods outlined by Woodward et al. (1985) and De Paor (1988). The Catoctin, Unicoi, and Harpers Formations are line and area balanced, while the basement complex is only area balanced (Fig. 8). Several assumptions were made in the construction of these sections and their restorations. The Antietam and Harpers Formations are shallow marine units (Simpson and Eriksson, 1989) and assumed to have a constant thickness. West of the TRFZ and above the Blue Ridge thrust the basement is not offset by normal faults and the Unicoi Formation is assumed to maintain a constant thickness within each section. The Unicoi Formation does thicken to the northeast along strike.

Sections also assume plane strain and do not take into account internal strain (meso- to micro-scale) in the cover rocks. Basement rocks are commonly massive, although a weak fabric defined by greenschist facies minerals is present at a few locations. The weakly to moderately developed foliation in the cover sequence indicates that these rocks have been internally strained. In most Unicoi sandstones, detrital grains exhibit only a weak grain shape fabric suggesting that the total strain recorded in these rocks is small ($R_s \leq 1.2$). The southeast-dipping foliation (Fig. 5a) is axial planar to folds at both the outcrop- and map-scale. Based on these relations we interpret shortening estimates from cross sections as minimum values. The pinline for sections A–A′ and B–B′ is the hanging wall cutoff of the Harpers–Antietam contact on the Blue Ridge fault. Section C–C′ is pinned in the core of an anticline in the hanging wall of the Blue Ridge fault. Cross-sections were restored so that the Harpers–Unicoi contact is horizontal.

The Midvale fault is exposed along the western edge of the Blue Ridge (Werner, 1966). Leeper et al. (1997) and Evans et al. (1998) considered the Midvale fault to be the frontal Blue Ridge thrust. Northwest of the TRFZ, the Blue Ridge fault system brings upright rocks of the Antietam Formation onto shales and carbonates of the Waynesboro and Elbrook Formations (Figs. 4 and 7). Based on the map trace and outcrop scale thrusts, the Blue Ridge fault is interpreted to dip 10–20° to the southeast and flatten at depth. Regionally, the Blue Ridge fault system is gently dipping, locally folded, and experienced northwestward displacement of at least 10 km (Bailey, 1994). The Blue Ridge fault has been interpreted to be a late Paleozoic (Alleghanian) thrust (Evans, 1989; Bartholomew et al., 1991; Bailey and Simpson, 1993). The TRFZ soles onto the Blue Ridge fault (Fig. 7) and probably also experienced Alleghanian contraction; however, earlier Paleozoic movement cannot be precluded. As the structural geometry of the Blue Ridge fault's footwall is not the focus of this study it is undifferentiated on the deformed and restored cross-sections.

Faults are rarely exposed, but at a few locations down-dip slickenlines occur although the kinematics (normal or reverse) were not resolvable. Discrete fractures and veins of cataclasite are uncommon, but occur within 20 m of faults in the TRFZ. Cataclasite veins associated with the TRFZ are composed of quartz, epidote, and muscovite and are consistent with lower greenschist facies conditions. In thin section, inter- and intra-granular fractures are the dominant microstructures. Original feldspar grains are partially or completely replaced by fine-grained muscovite, quartz, and epidote.

A basement anticline is exposed in the hanging wall of the Blue Ridge fault in A–A′ (Fig. 7). Cover rocks on the west limb of this basement anticline dip to the northwest and are cut off by the Blue Ridge fault (Figs. 4 and 7). Units above the basement anticline are uprightly folded. The eastern side of this basement structure is truncated by the extensional Contact Creek fault (Figs. 4 and 7). The Contact Creek fault restores to a listric normal fault bounding a half graben filled with a thick sequence of Unicoi Formation in the hanging wall (Fig. 8). The Upper Big Mary's fault places Unicoi Formation on Unicoi Formation in A–A′ (Fig. 7), but the unit exposed in the footwall changes along strike (Figs. 4 and 9a). Between the Contact Creek and Upper Big Mary's fault, the Unicoi Formation is gently folded with the exception of a minor southeast verging (hinterland-verging) overturned anticline (Fig. 7). This overturned anticline may be the expression of a northwest-dipping backthrust that tips out in the basement. Hinterland verging backthrusts in the basement are common structures in tectonically inverted regions (McClay and Buchanan, 1992). The Whetstone Ridge fault places basement on the Catoctin Formation as a reverse fault in A–A′, but tips out to the southwest (Figs. 4 and 7).

A major basement anticline dominates section B–B′ (Fig. 7). The northern limb of this structure dips moderately to the northwest and is folded by an open, parasitic anticline–syncline pair. Two southeast-dipping extensional faults are exposed on the southern limb of this anticline. The Round Mountain fault places the Catoctin and Unicoi Formations on basement and the Mill Creek fault places Unicoi Formation on basement and the Catoctin Formation (Fig. 9b). The Mill Creek fault is interpreted to be a northeastern extension of the Upper Big Mary's fault and the Round Mountain fault a splay. The Unicoi Formation is exposed in a northwest verging overturned syncline between the Mill Creek and Whetstone Ridge faults (Fig. 7). In the restored section the Round Mountain and Mill Creek faults are listric normal faults that bound half grabens (Fig. 8). The total extensional displacement on these structures is 300–450 m.

In C–C′ two major folds are present: a carbonate-cored syncline and a basement-cored anticline (Fig. 7). The Round Mountain and Mill Creek faults crop out on the southern limb of the anticline. These faults display extensional map patterns and tip out to the northeast as the Catoctin Formation wraps around the end of these structures (Fig. 4). On the restored section two half grabens filled with Catoctin and Unicoi rocks are evident (Fig. 8). The Whetstone Ridge fault places Catoctin on Catoctin in C–C′. To the northeast the Whetstone Ridge fault places Catoctin on the Unicoi and Harpers Formations (Bartholomew, 1977).

Collectively, the TRFZ restores to a fault bounded set of linked basins filled with a relatively thick sequence of Catoctin volcanics and lower Unicoi sedimentary rocks. The strike length of the restored structure is ~15 km and

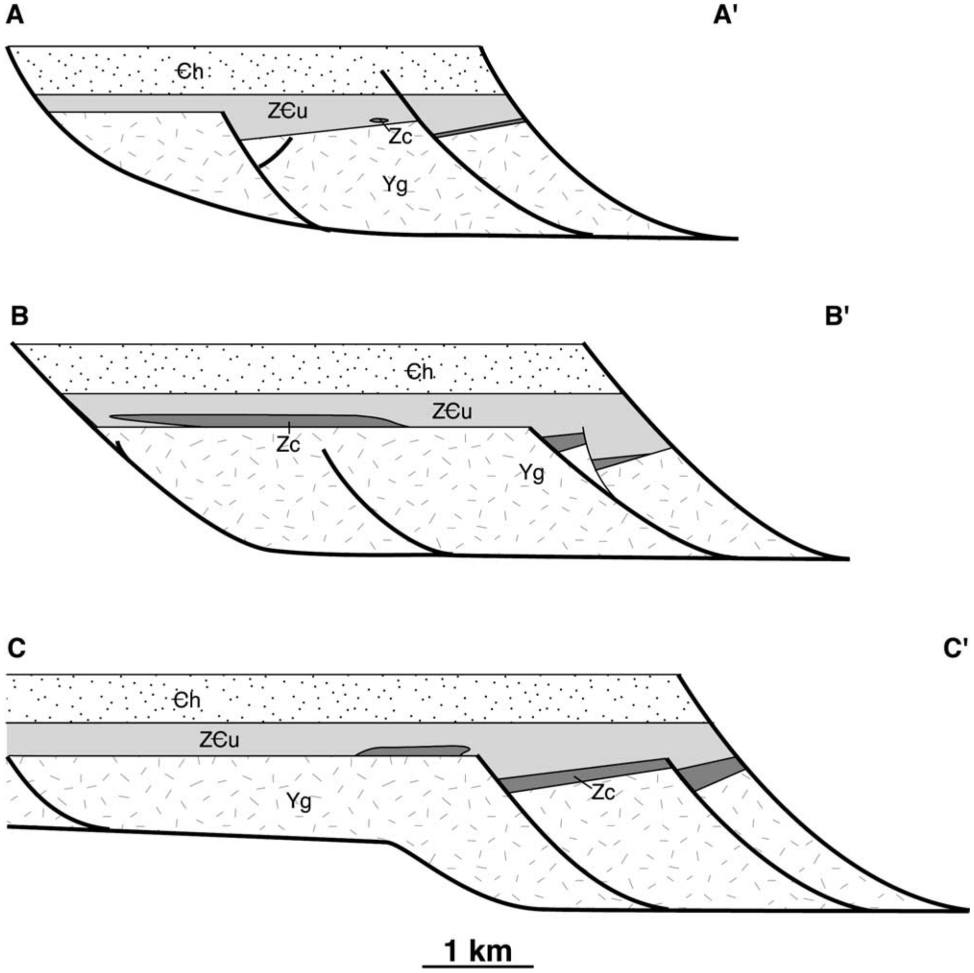

Fig. 8. Restored cross-sections A–A′, B–B′, and C–C′.

at least 4–5 km in width. The total southeastern extent of these basins is unknown because they are cut off along the Whetstone Ridge fault. The northwest to southeast changes in the thickness of basalts and Unicoi Formation are consistent with normal displacement on the TRFZ during the extrusion and deposition of these units. The Harpers Formation is not offset (in an extensional fashion) by any of these structures and suggests that extensional motion on the TRFZ had ceased by the early Cambrian.

Neoproterozoic to early Cambrian extension of the upper basement contact by normal slip in the TRFZ records 4–6% extension (Table 1). Subsequent Paleozoic contraction resulted in 6–19% shortening (Table 1). The total shortening of the basement is a reflection of both the early extension and later contraction. Although the total finite deformation is contractional, an extensional map pattern is preserved in the study area. With the exception of part of the Upper Big Mary's fault, none of the original normal faults exhibit a contractional map pattern. Inversion of original normal faults as thrusts did not accommodate a significant portion of the contraction; folding of the cover sequence accommodated most of this contraction.

4. Discussion

4.1. Mesozoic extension and pre-existing basement topography

Bartholomew et al. (1991) and Evans et al. (1998) suggested the TRFZ experienced post-Paleozoic extensional movement. Eastern North America underwent an episode of continental rifting during the opening of the Atlantic Ocean in the early Mesozoic. In Virginia, evidence of rifting is recorded by 225–205 Ma fault bounded basins, a swarm of early Jurassic basaltic dikes, and brittle reactivation of ductile high-strain zones in the Piedmont (Manspeizer et al., 1989). Based on a number of lines of evidence we argue that the TRFZ is not a Mesozoic structure. The Catoctin and Unicoi Formations are significantly thicker in hanging wall blocks than on footwalls (Figs. 6–8), consistent with contemporaneous volcanism, deposition and faulting. The TRFZ is not parallel to known Mesozoic structures. Mesozoic normal faults in the Virginia Piedmont strike 010° to 030° and basaltic dikes strike 340° to 360° implying a ENE to ESE Mesozoic extension direction

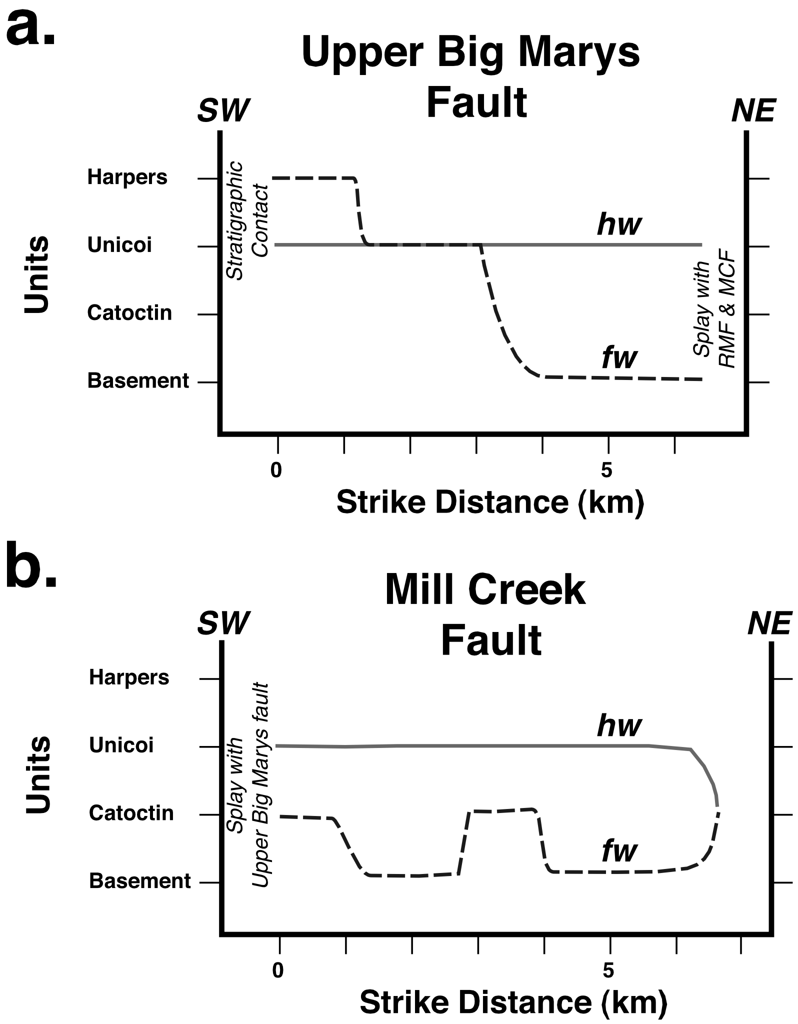

Fig. 9. (a) Stratigraphic separation diagram for the Upper Big Mary's fault. (b) Stratigraphic separation diagram for the Mill Creek fault.

(Fig. 10). Faults of the TRFZ strike 035° to 075° implying an extension direction of SE to SSE (Fig. 10). The TRFZ is also significantly further west (~50 km) than known Mesozoic structures. Cataclasite veins associated with the TRFZ contain minerals and microstructures consistent with lower greenschist facies conditions. Known Mesozoic faults experienced conditions at or below the zeolite facies (Glover et al., 1989). These data do not support a Mesozoic age for extensional movement on the TRFZ.

In northern Virginia, Gathright (1976) noted that significant relief was present on the basement surface during Catoctin volcanism. In the TRFZ area, basement contacts are planar features with relatively straight map traces, a pattern more consistent with faults than an irregular erosional contact (Fig. 4). Cover rocks are asymmetrically distributed with respect to the basement (e.g. the Catoctin Formation is not present on both sides of the basement high; Fig. 4). Asymmetric structures would, however, form in units that have been rotated above listric normal faults. Based on these observations it is unlikely that basement exposures associated with the TRFZ are simply topographic highs on an ancient landscape.

Table 1
Shortening and extension estimates across the Tye River fault zone

	A–A′	B–B′	C–C′
% Contraction			
Upper Harpers contact	15%	14%	10%
Upper Unicoi contact	19%	16%	12%
Upper Basement contact	14%	12%	6%
% Extension			
Upper Basement contact	6%	4%	6%

4.2. Reactivation and basement buttressing

The TRFZ still preserves an extensional map pattern, yet cross-section restoration indicates the region experienced >10–20% bulk contraction. At the map scale the contractional strain is recorded primarily by folding of the cover rocks not extensive reactivation of the TRFZ. The maximum amount of contractional displacement on any of the

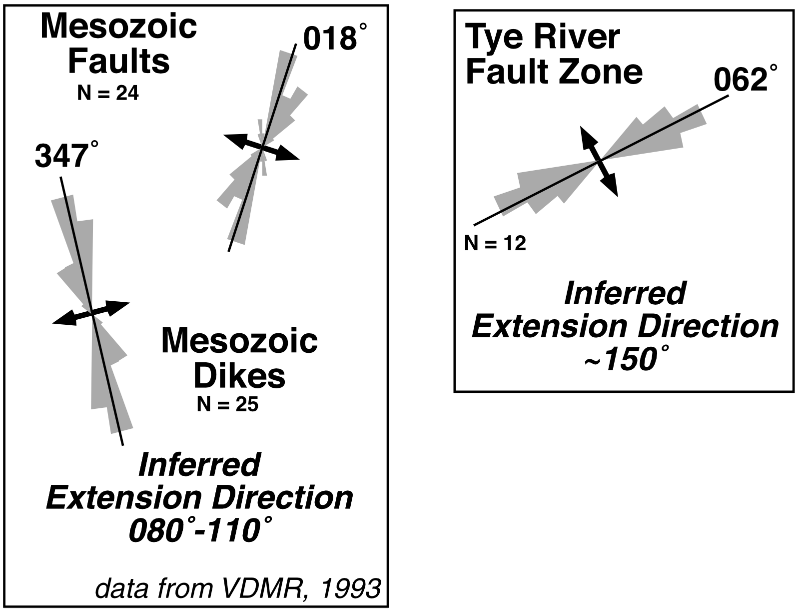

Fig. 10. Rose diagrams of the strike trace of Mesozoic faults in the central and northern Virginia Piedmont, the strike trace of Mesozoic dikes in the western Piedmont, Blue Ridge, and Valley and Ridge, and the strike trace of the Tye River fault zone. Largest petals represent 30% of the data.

reactivated faults is 100–300 m. Although pre-existing weaknesses (i.e. faults) commonly reactivate during later deformation a number of factors may have prevented the TRFZ from significant contractional reactivation. The original dip of the TRFZ is ~60°; during subhorizontal compression, normal stresses acting across these moderately dipping faults may have been greater than the shear stresses, thus inhibiting slip across these faults. Geologists have long recognized the rheologic contrast between basement and cover rocks (Willis, 1893; Ramsay, 1982). The mechanical difference between the coarse-grained granitic basement and the layered cover rocks may have played a significant role as the cover rocks should buckle and form a penetrative foliation more readily than the basement.

A systematic change in the fold geometry of the cover sequence is related to the position of basement highs. In sections B–B′ and C–C′ above and to the northwest of the major basement high, folds are broad and open with large wavelengths (~2–3 km; Fig. 7). Folds in the cover sequence above the half-grabens in sections A–A′, B–B′, and C–C′ are much shorter in wavelength (≤1 km; Fig. 7). In sections B–B′ and C–C′ cover rocks in the hanging wall of the Mill Creek fault have been folded into tight overturned folds bounded by a significant basement buttress to the northwest. In section A–A′ the Unicoi is folded into an upright syncline above the Upper Big Mary's fault. In contrast to sections B–B′ and C–C′ there is no basement high to the northwest of the Upper Big Mary's fault in section A–A′, locally shortening in the Unicoi is less, and significant inversion along the Upper Big Mary's fault has occurred. To the northeast, the Upper Big Mary's fault places Unicoi against basement and the syncline in the hanging wall is overturned at this location (Fig. 4).

The basement-cored footwalls of original extensional faults appear to have served as a rigid buttress against which the cover rocks shortened. The total shortening across the TRFZ was accommodated by two mechanisms: (1) inversion of original normal faults, and (2) folding of the cover sequence. The location of basement buttresses controls the partitioning of shortening between these mechanisms. Where buttresses are present, shortening was primarily accomplished by folding of the cover sequence (B–B′ and C–C′). In the absence of a basement buttress more shortening was accomplished by inversion.

5. Conclusions

The three dimensional structural geometry of the Tye River fault zone is the result of Neoproterozoic extension and subsequent Paleozoic contraction. Later contraction did not reactivate all of the normal faults beyond their pre-extensional geometry, resulting in an extensional map pattern. Shortening was accomplished by folding of the cover rocks with minor tectonic inversion. The location and geometry of folds in the cover sequence was controlled by basement buttresses in the footwall blocks of extensional faults, suggesting that basement buttressing plays a significant role in the geometry of tectonically inverted structures and the partitioning of deformation in these regions.

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References

Badger, R.L., Sinha, A.K., 1988. Age and Sr isotopic signature of the Catoctin volcanic province: implications for subcrustal mantle evolution. Geology 16, 692–695.

Bailey, C.M., 1994. Temporal, kinematic, and strain analysis of granite tectonites from the central Appalachians. Ph.D. thesis, Johns Hopkins University.

Bailey, C.M., Simpson, C., 1993. Extensional and contractional deformation in the Blue Ridge Province, Virginia. Geological Society of America Bulletin 105, 411–422.

Bartholomew, M.J., 1977. Geology of the Greenfield and Sherando quadrangles, Virginia. Virginia Division of Mineral Resources Publication 4, 43.

Bartholomew, M.J., Lewis, S.E., Hughes, S.S., Badger, R.L., Sinha, A.K., 1991. Tectonic history of the Blue Ridge basement and its cover, central Virginia. In: Schultz, A., Compton-Gooding, E. (Eds.). Geologic Evolution of the Eastern United States Field Trip Guidebook. pp. 57–90 Virginia Museum of Natural History Guidebook 2.

Bloomer, R.O., Werner, H.J., 1955. Geology of the Blue Ridge in central Virginia. Geological Society of America Bulletin 66, 579–606.

Brezinski, D.K., 1992. Lithostratigraphy of the western Blue Ridge cover rocks in Maryland. Maryland Geological Survey Report of Investigations 55, 39.

Butler, R.W.H., 1989. The influence of pre-existing basin structure on thrust system evolution in the western Alps. In: Cooper, M.A., Williams, G.D. (Eds.). Inversion Tectonics. pp. 105–122 Geological Society Special Publications 44.

Butler, R.W.H., 1997. Late Proterozoic rift faults and basement-cover relationships within the Ben More thrust sheet, NW Scotland. Journal of the Geological Society 154, 761–764.

Chen, A., 1998. Geometric and kinematic evolution of basement-cored structures; intraplate orogenesis within the Yanshan Orogen, northern China. Tectonophysics 292, 17–42.

Cooper, M.A., Williams, G.D., de Graciansky, C., Murphy, R.W., Needham, T., de Paor, D., Stoneley, R., Todd, S., Turner, J., Ziegler, A., 1989. Inversion tectonics — a discussion. In: Cooper, M.A., Williams, G.D. (Eds.). Inversion Tectonics, pp. 335–347 Geological Society Special Publication 44.

Coward, M., Gillcrist, R., Trudgill, B., 1991. Extension structures and their tectonic inversion in the western Alps. Geological Society Special Publication 56, 93–112.

De Paor, D.G., 1988. Balanced sections in thrust belts. Part 1: construction. American Association of Petroleum Geologists Bulletin 72, 73–90.

Evans, M.A., 1989. The structural geometry and evolution of foreland thrust systems, northern Virginia. Geological Society of America Bulletin 101, 339–354.

Evans, N.H., Harbor, D., Spencer, E.W., 1998. Geology of eastern Rockbridge County. 28th Annual Virginia Geologic Field Conference Guidebook, p. 41.

Gathright II, T.M., 1976. Geology of the Shenandoah National Park, Virginia. Virginia Division of Mineral Resources Bulletin 86, 93.

Glover, L., III, Evans, N.H., Patterson, J.G., Brown, W.R., 1989. Tectonics of the Virginia Blue Ridge and Piedmont. 28th International Geological Congress Field Trip Guidebook T363, pp. 59.

Harris, L.D., de Witt, W., Jr., Bayer, K.C., 1982. Interpretative seismic profile along Interstate I-64 from the Valley and Ridge to the Coastal Plain in central Virginia. U.S. Geological Survey Oil and Gas Investigations Chart OC-123.

Hayward, A.B., Graham, R.H., 1989. Some geometrical characteristics of inversion. In: Cooper, M.A., Williams, G.D. (Eds.). Inversion Tectonics, pp. 17–39 Geological Society Special Publications 44.

Henning, P.H., Muehlberger, W.R., 1990. Laramide fault inversion, basement buttressing, and evaporite tectonics in the Cordilleran thrust front along the Texas/Chihuahua border. Geological Society of America Abstracts with Programs 22 (7), 184.

Knetchel, M.M., 1943. Manganese deposits of the Lyndhurst–Vesuvius district, Augusta and Rockbridge counties, Virginia. U.S. Geological Survey Bulletin 940, 163–198.

Lamarche, J., Mansy, J.L., Bergerat, F., Averbuch, O., Hakenberg, M., Lewandowski, M., Stupnicka, E., Swidroska, J., Wajsprych, B., Wieczorek, J., 1999. Variscan tectonics in the Holy Cross mountains (Poland) and the role of structural inheritance during Alpine tectonics. Tectonophysics 313, 171–186.

Leeper, M., Giorgis, S., Bailey, C.M., 1997. Structural relations in the western Blue Ridge, Nelson and Rockbridge Counties, Virginia. Geological Society of America Abstracts with Programs 29 (3), 31.

Manspeizer, W., DeBoer, J., Costain, J.K., Froelich, A.J., Coruh, C., Olsen, P.E., McHone, G.J., Puffer, J.H., Prowell, D.C., 1989. Post-Paleozoic activity. In: Hatcher Jr, R.D., Thomas, W.A., Viele, G.W. (Eds.). The Appalachian–Ouachita Orogen in the United States, pp. 319–374 The Geology of North America F-2.

McClay, K.R., Buchanan, G., 1992. Thrust faults in inverted extensional basins. In: McClay, K.R. (Ed.). Thrust Tectonics. Chapman & Hall, pp. 93–104.

McClay, K.R., Insley, M.W., Anderton, R., 1989. Inversion of the Kechika Trough, northeastern British Columbia, Canada. In: Cooper, M.A., Williams, G.D. (Eds.). Inversion Tectonics, pp. 235–257 Geological Society Special Publications 44.

Mitra, G., Elliott, D., 1980. Deformation of the basement in the Blue Ridge and the development of the South Mountain cleavage. In: Wones, D.R. (Ed.). The Caledonides in the USA, pp. 307–312 Virginia Polytechnic Institute and State University Department of Geological Sciences Memoir 2.

Pratt, T.L., Coruh, C., Costain, J.K., Glover, L., III, A., 1988. geophysical study of the Earth's crust in central Virginia: Implications for crustal structure. Journal of Geophysical Research 93, 6649–6667.

Ramos, A., Cegarra, M., Cristallini, E., 1996. Cenozoic tectonics of the high Andes of west central Argentina (30–36° S latitude). Tectonophysics 259, 185–200.

Ramsay, J.G., 1982. Rock ductility and its influence on the development of tectonic structures in mountain belts. In: Hsu, K.J. (Ed.). Mountain Building Processes, Academic Press, New York, pp. 111–127.

Rankin, D.W., Drake Jr, A.A., Glover III, L., Goldsmith, R., Hall, L.M., Murray, D., Ratcliffe, N.M., Read, J.F., Secor Jr, D.T., Stanley, R.S., 1989. Pre-orogenic terranes. In: Hatcher Jr, R.D., Thomas, W.A., Viele, G.W. (Eds.). The Appalachian–Ouachita Orogen in the United States, pp. 7–101 The Geology of North America F-2.

Root, S.I., 1970. Structure of the northern terminus of the Blue Ridge in Pennsylvania. Geological Society of America Bulletin 81, 815–830.

Simpson, E.L., Sundberg, F.A., 1987. Early Cambrian age for synrift deposits of the Chilhowee Group of southwestern Virginia. Geology 15, 123–126.

Simpson, E.L., Eriksson, K.A., 1989. Sedimentology of the Unicoi Formation in southern and central Virgina: evidence for late Proterozoic to early Cambrian rift to passive margin transition. Geological Society of America Bulletin 101, 42–54.

Sinha, A.K., Bartholomew, M.J., 1984. Evolution of the Grenville terrain in central Virginia Appalachians. In: Bartholomew, M.J. (Ed.). The Grenville Event in the Appalachians and Related Topics, pp. 175–186 Geological Society of America Special Paper 194.

Southworth, C.S., Brezinski, D.K., 1996. How the Blue Ridge anticlinorium in Virginia becomes the South Mountain anticlinorium in Maryland. In: Brezinski, D.K., Reger, J. (Eds.). Studies in Maryland Geology, pp. 253–275 Maryland Geological Survey Special Publication 3.

Spencer, E.W., Bell, J.D., Kozak, S.J., 1989. Valley and Ridge and Blue Ridge Traverse, Central Virginia. 28th International Geological Congress Field Trip Guidebook T157, 67 pp.

Virginia Division of Mineral Resources, 1993. Geologic Map of Virginia. Virginia Division of Mineral Resources, scale 1:500,000.

Walker, D., Simpson, E.L., 1991. Stratigraphy of upper Proterozoic and lower Cambrian siliclastic rocks, southwestern Virginia and northeastern Tennessee. In: Schultz, A., Compton-Gooding, E. (Eds.). Geologic Evolution of the Eastern United States Field Trip Guidebook, pp. 121–159 Virginia Museum of Natural History Guidebook 2.

Welbon, A., 1988. The influence of intrabasinal faults on the development of a linked thrust system. Geologische Rundschau 77, 1–11.

Werner, H.J., 1966. Geology of the Vesuvius Quadrangle, Virginia. Virginia Division of Mineral Resources Report of Investigations 7, 53.

Willis, B., 1893. The mechanics of Appalachian structure. U.S. Geological Survey 13th Annual Report, pp. 212–281.

Woodward, N.B., Boyer, S.E., Suppe, J., 1985. An outline of balanced cross sections. University of Tennessee Department of Geological Sciences Studies in Geology 11, 86.

Wotjal, S., 1989. Blue Ridge anticlinorium and Massanutten synclinorium in western Maryland. In: Woodward, N.B. (Ed.). Geometry and Deformation Fabrics in the Central and Southern Appalachians Valley and Ridge and Blue Ridge, pp. 3–14 28th International Geological Congress Field Trip Guidebook T357.