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TRANSPRESSIONAL DOME FORMATION IN THE SOUTHWEST VIRGINIA PIEDMONT

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ABSTRACT. The Bowens Creek fault is the northeast extension of the Brevard zone and bounds the west side of the Smith River Allochthon terrane in the southwestern Virginia Piedmont. It is delineated by a series of domes and saddled anticlines. Several well developed domes at Altavista are associated with multiple crenulation cleavages, reverse faults, and dextral transcurrent shear indicators. Detailed structural analysis indicates that the domes were formed in a three stage deformational event that resulted from dextral transpression in a 15 km wide ductile deformation zone.

The foliation, structures, and stratigraphy were approximately horizontal prior to the transpressional event. In the first stage of the event, north-south trending en-echelon folds and crenulation cleavage were formed. The structures were variably rotated by northeast-trending dextral transcurrent shearing. The final stage of deformation is characterized by northeast-trending folds and crenulation cleavage. The interference pattern of the northeast-trending folds on the early north-south folds formed the domes and saddled antiforms. The domal structures are bounded by reverse faults active late in the transcurrent event. The domes are therefore proposed to be "positive flower" or "keystone" structures generated through compression across the transcurrent fault zone. The Altavista area forms an external zone to the Carboniferous dextral transcurrent Brookneal zone, 10 km to the east.

INTRODUCTION

The Bowens Creek fault forms the western boundary of the Smith River allochthon terrane in the southwest Virginia Piedmont (fig. 1). The Bowens Creek and Ridgeway-Chatham fault on the eastern side of the Smith River allochthon terrane (fig. 1) were proposed to be the surface expressions of the decollement upon which the allochthon was transported (Conley and Henika, 1970, 1973; Conley, 1978). The primary basis for the proposal of an allochthonous Smith River terrane was an erroneous Grenville age on the 462 Ma Leatherwood Granite (Odom and Russell, 1975) which intruded the amphibolite-grade rocks subsequent to the peak of metamorphism (Conley and Henika, 1973). The Blue Ridge rocks upon which the allochthon was believed to have been thrusted are Late Precambrian to Early Paleozoic in age (Conley and Henika, 1970, 1973; Conley, 1978). The Bowens Creek fault also coincides with the amphibolite-facies isograd of the Taconic metamorphism, which decreases in grade progressively to the west (Gates and

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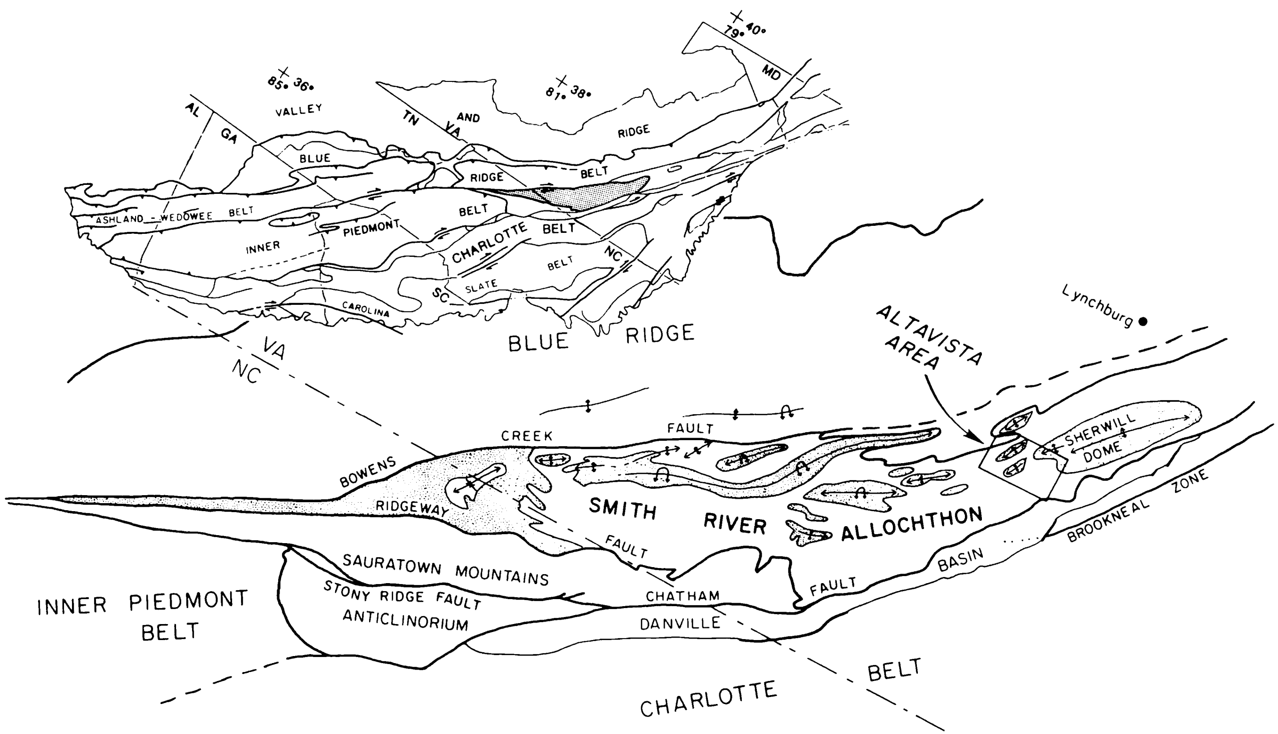

Fig. 1. Domes and faults of the Smith River Allochthon terrane of the southwest Virginia Piedmont with surrounding tectonic belts and major structural features (after Conley, 1978; Berquist, 1980; Marr, 1984; and Gates, Simpson, and Glover, 1986). In Smith River terrane: shaded area is Lynchburg-Basset Formation, unshaded area is Evington Group-Fork Mountain Formation. Inset: tectonic map of the southern Appalachians with major faults and provinces. Shaded area corresponds to Smith River Allochthon.

Speer, in review). The fault, therefore, appears to have thrust higher grade rocks over those of lower grade. Redden (1963) and Gates (ms, 1986), however, have mapped the rocks of the Blue Ridge directly into the Smith River terrane. The proposed >35 km of northwestward thrusting of the terrane (Conley, 1978, 1985) is therefore undocumented.

The Bowens Creek fault has been correlated by detailed mapping with the Brevard Zone (fig. 1) (Rankin, Espenshade, and Neuman, 1972; Espenshade and others, 1975; Rankin, 1975; Conley, 1978). Reed and Bryant (1964) and Bobyarchick (1984) have proposed a dextral transcurrent origin for late movement on the Brevard zone in North Carolina. Lemmon (1980) noted consistent northeast-trending, horizontal mineral stretching lineations near the transition of the Brevard into the Bowens Creek fault, supporting a strike-slip origin of the faults. Although a strike-slip origin for the Bowens Creek Fault was not previously proposed, Scheible (1980) questioned the thrust fault interpretation on the basis of steepness of dip and continuity in orientation of the fault zone.

A series of en-echelon domes and antiforms with saddled crests trend north to northeast and lie to the southeast of the Bowens Creek fault (Espenshade, 1954; Brown, 1958; Redden, 1963; Conley and Henika, 1970, 1973; Berquist, 1980; Price and others, 1980; Marr, 1984) (fig. 1). Transpressional dome and anticline formation is well documented in transcurrent fault zones (Wilcox, Harding, and Seely, 1973; Sylvester and Smith, 1976; Harding and Lowell, 1979; DeSmet, 1984). The structures are formed through compression across an otherwise transcurrent zone. The antiformal structures are produced by both reverse faulting and folding concurrent with the strike-slip movement or transpression (Harland, 1971). In this paper, the northeast trending domes in the Altavista area which include the Hundley dome, the Reed Creek dome, and the southern part of the large Sherwill dome (fig. 2) are analyzed in detail through evidence of stratigraphy, metamorphism, multiple crenulation cleavages, and meso-megascopic structures in order to evaluate the existence of transcurrent deformation in the Bowens Creek fault.

PRE-DOME GEOLOGY OF THE ALTAVISTA AREA

Stratigraphy.—The Late Precambrian Lynchburg Formation (Espenshade, 1954; Brown, 1958) is the oldest unit in the Altavista area and is exposed in the cores of the domes (fig. 2). The Lynchburg Formation is composed of metamorphosed arkosic to lithic conglomerate which grades upward into medium-grained, feldspathic sandstone to graywacke with thin micaceous laminations. Overlying the Lynchburg Formation is the Late Precambrian, metavolcanic Catoctin Formation (Brown, 1958). The medium- to coarse-grained Catoctin hornblende-andesine schists include discontinuous layers of quartzite of 5 to 60 m

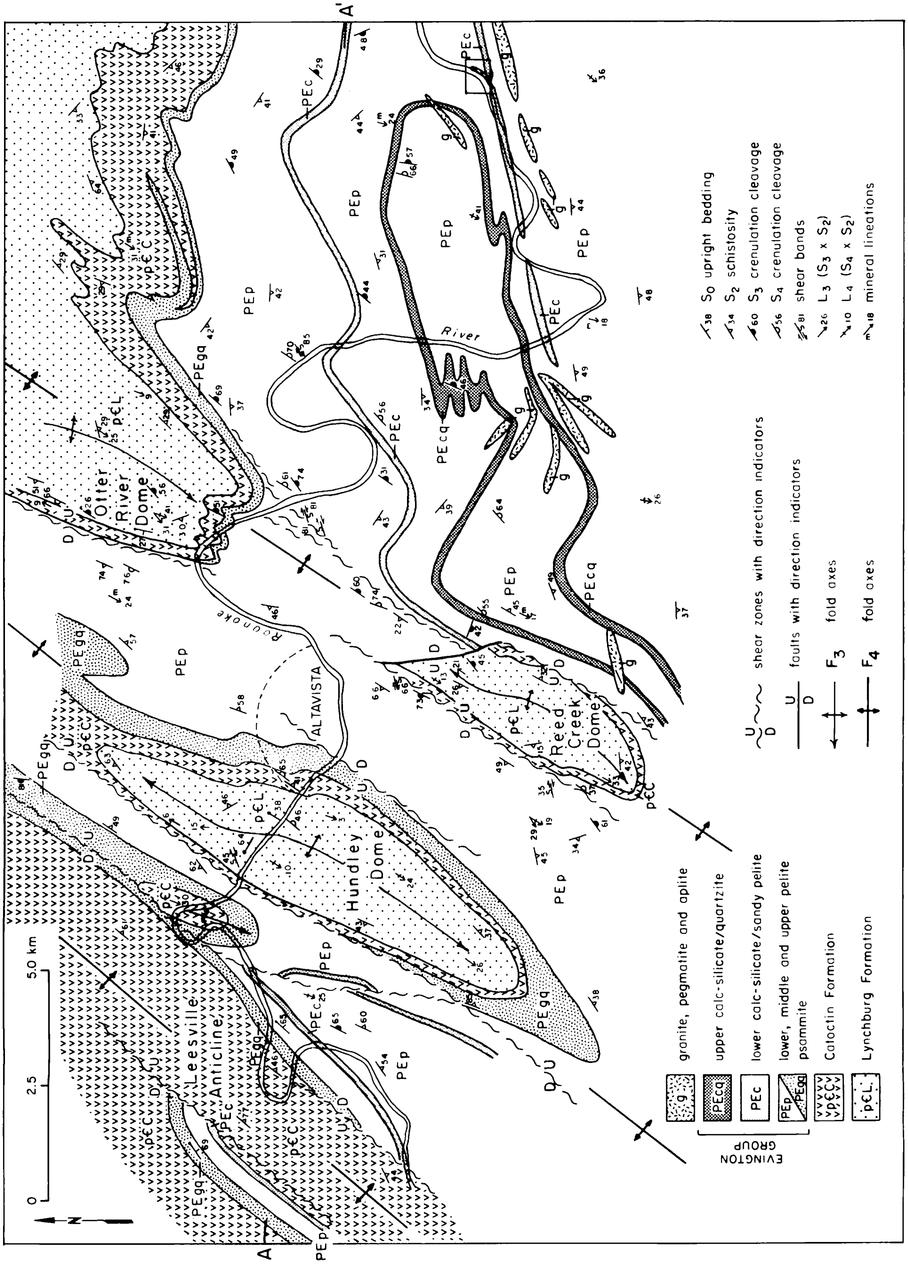

Fig. 2. Geologic map of the Altavista area.

thickness, local tonalitic pegmatites, or metamorphic segregations, and epidote-quartz layers and boudins.

The metasedimentary Evington Group of latest Precambrian to Cambro-Ordovician(?) age (Espenshade, 1954; Brown, 1958; Evans, ms, 1984) is in gradational contact with the Catoctin Formation. The Evington Group consists of a basal cross-bedded metagraywacke which coarsens upward into a massive quartzite. The upper Evington Group consists of a thick pelitic sequence with sporadic, thin calc-silicate/siltstone to sandstone layers. The pelitic rocks are sillimanite-staurolite-garnet schists to gneisses, which are retrograded to chloritoid-chlorite schists in discrete zones (Gates and Speer, in review). The pelites are locally migmatitic and intruded by garnet-tourmaline pegamatite, aplite, and granite dikes in the southern map area (fig. 2). The middle and upper portions of the pelitic unit contain two thinly layered calc-silicate units 5 to 50 m thick and composed of diopside–amphibole–garnet–epidote schist with pelitic laminations. Associated with the upper calc-silicate unit is a massive coarse-grained calc-silicate-bearing quartzite.

The Lynchburg through Catoctin units have been interpreted as a rift-basin sequence capped by rift-generated basalts (Brown, 1958, 1970; Rankin, 1975; Wehr and Glover, 1985). The overlying Evington Group has been interpreted as a rift-drift sequence (Wehr and Glover, 1985) and the deeper water equivalent of the Valley and Ridge shelf (Brown, 1970; Evans, ms, 1984; Patterson, 1987).

Taconic metamorphism.—The regional metamorphism of the Smith River terrane is proposed to have occurred during the Taconic Orogeny (Glover and others, 1983; Gates and Speer, in review). The peak of this M_1 metamorphism attained middle to upper amphibolite facies and is characterized by sillimanite and staurolite bearing assemblages (Conley and Henika, 1973; Gates, ms, 1981; Gates and Speer, in review). The Leatherwood Granite intrudes the Smith River area subsequent to the peak of metamorphism (Conley and Henika, 1973; Conley, 1978) and has been dated at 462 ± 20 Ma using Rb/Sr whole rock methods (Odom and Russell, 1975; 450 Ma by Rankin, 1975). Rb/Sr biotite-whole rock ages of 440 ± 22 Ma (Odom and Russell, 1975) were obtained from pelitic, sillimanite-staurolite gneisses in the center of the allochthon. These ages indicate that the amphibolite grade M_1 metamorphism is Ordovician (Taconic) in age.

Taconic structure.—The Taconic deformation, which is concurrent with M_1, exhibits D_1 and D_2 phases. The associated F_1 and F_2 fold generations are recumbent isoclinal and coaxial. S_1 and S_2 foliations were also developed during the D_1 and D_2 deformational events respectively. S_1 was transposed into the pervasive S_2 foliation and is preserved as intrafolial folds in pelitic gneisses and inclusions in porphyroblasts that are aligned oblique to the enclosing S_2 foliation. S_2 is defined by prismatic and platy minerals produced during the M_1 metamorphism (Gates and Speer, in review). A late M_1 retrogression produced slightly foliated to randomly oriented minerals apparently formed late in D_2. Because the M_1 metamorphism is Taconic in age and defines S_1 and S_2, both D_1 and D_2 are Taconic or older. Projections of poles to S_2 foliation in the eastern map area (fig. 3A) yield a tight cluster of points. These data were measured on the south flank of the Sherwill dome and appear

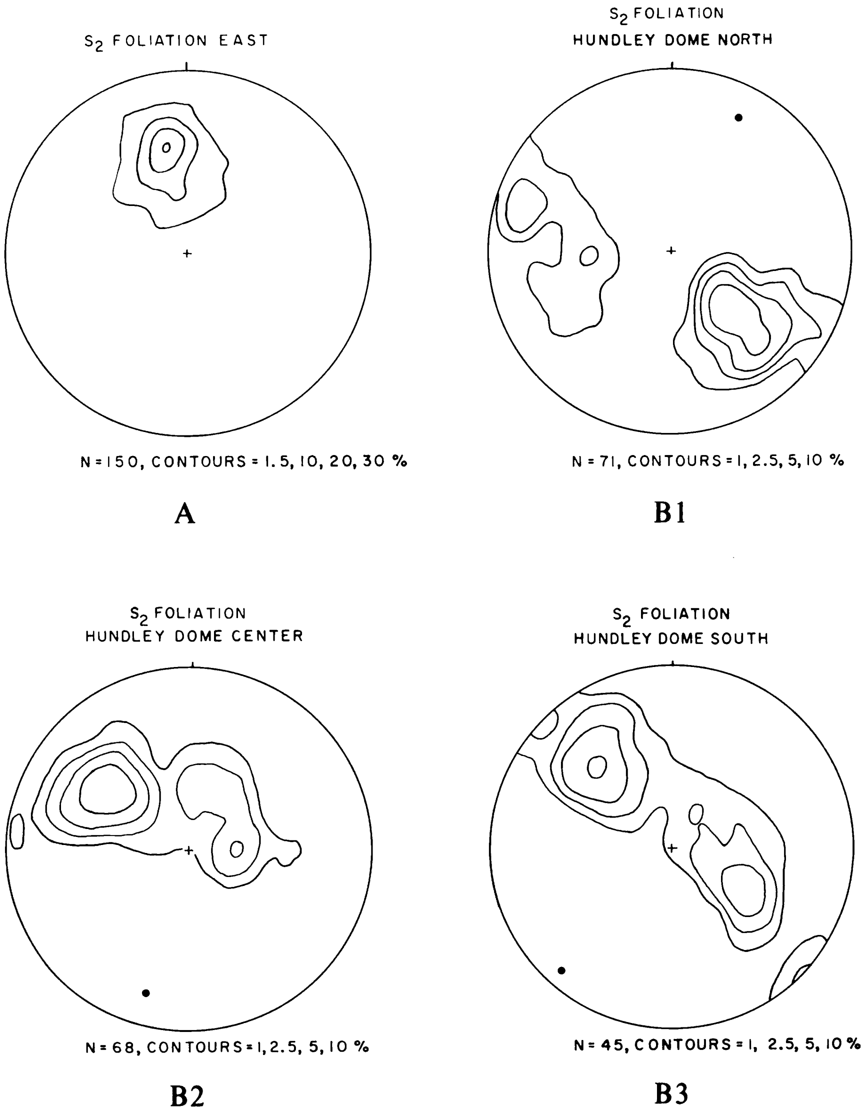

Fig. 3. Projections of poles to S_2 foliation: (A)—from the eastern Altavista map area; (B1)—northern; (B2)—central; and (B3)—southern Hundley dome as indicated.

to have undergone passive rotation from the nearly horizontal orientation following Taconic deformation. The nearly horizontal orientation is consistent with the interpretation of metamorphism, stratigraphy, and structure that the Altavista area is the footwall of a Taconic nappe (Gates and Speer, in review).

DOME GEOMETRY

The Hundley dome, the Reed Creek dome, and a flank dome on the composite Sherwill dome, herein named the Otter River dome (fig. 2), exhibit Lynchburg Formation in the cores and Catoctin Formation through lower Evington Group on the rims. The westernmost Hundley dome is lozenge-shaped with a slightly sigmoidal geometry. The northern half of the northwestern limb and southern half of the southeastern limb of the dome are straight, nearly parallel, and strike 045. The Catoctin Formation and lower Evington Group units are thinner along these sides than the others and locally reverse faulted. The other sides of the Hundley dome exhibit a more northernly strike, and the northeast half of the southeastern limb exhibits parasitic folds. The dome is generally divisible into three subareas on the basis of the orientation of the major fold axis and intersection lineations. Projections of these subareas (fig. 3B) show that the b-axes derived from poles to S_2 plunge 19/033 in the northern section, approx 21/195 in the central section, and 17/221 in the southern section. The axis therefore reverses plunge direction between the northern and central sections of the dome.

The geometry of the southern half of the Otter River dome (fig. 2) is similar to the Hundley dome, but the southern terminus contains many mesoscopic folds. The fold axis in the southern portion of the dome plunges 18/230 and 6/209 in the central. The Reed Creek dome (fig. 2) is the smallest and farthest south of those studied. The northwest side exhibits thinned units, is generally straight, and strikes 038, but the southeast side is concave to the west. The southwest and northeast sides are folded on both outcrop and map scale. The northwest and southeast sides are cut by east- and west-dipping reverse faults respectively which locally remove the Catoctin and lower Evington Group units. The plunge of the fold axis in the southern area is 22/234, the central 15/212, and the northern 8/226. The northern terminus of the dome is removed by a west-dipping reverse fault that strikes 356 (fig. 2).

STRUCTURAL ELEMENTS OF THE DOMES

Pre-dome structure.—The orientation of the stratigraphy and Taconic structures prior to dome formation appears to have been horizontal to slightly dipping. The assumption of original near horizontality is essential to the structural analysis and based on several lines of evidence. The stratigraphy and structures of the eastern map area display a consistent easterly strike and southerly dip. This area comprises the southern side of the Sherwill dome but exhibits only weak D_3 and D_4 structural elements characteristic of the northeast-trending, western map area (fig. 2). The cluster of poles to S_2 from the eastern area (fig. 3A) indicates a consistent orientation that deviates from horizontal only by the rotation required in Sherwill doming. To the south of Altavista and away from the influence of the dome, the S_2 foliation, stratigraphy, and structures are nearly horizontal (Marr, 1984). Unfolding the F_3 and F_4 folding from the projections of S_2 from the western area yields a nearly horizontal orientation. Original near horizontality is consistent with the present orientation of S_2 and the stratigraphy, because there is no dominant orientation or asymmetry reflecting a predeformational dip. Gates and Speer (in review) have shown that the Altavista area is the footwall of a Taconic nappe and was deformed and metamorphosed at depths of 18 km. Original near horizontality is consistent with this tectonic interpretation.

D_3 deformation.—The D_3 and D_4 deformational events formed the domes in the Altavista area (fig. 2). Structural features produced by these events appear intimately related in space and are best developed in discrete zones. Greenschist-grade platy mineral growth, which characterizes the M_2 metamorphism, defines the cleavages developed in these deformational events. Deformation is most intense around the domes in a belt approx 15 km wide. Weak crenulation cleavages formed in these events, however, occur far outside the belt.

Mesoscopic F_3 folds preserved in the Altavista area are upright, open to gentle, and symmetric to slightly asymmetric. Wavelength of the mesoscopic folds varies from 3 to 10 cm, and amplitude is 1 to 4 cm. In most cases however, F_3 folds have been rotated, tightened, and refolded during D_4. They occur in the Lynchburg Formation, Catoctin Formation, and calc-silicate rocks of the Evington Group. The S_3 crenulation cleavage (fig. 4) is tightly spaced (3–5 mm) and forms symmetric to slightly asymmetric, zonal microfolds (Gray, 1977) in the S_2 foliation. S_3 appears axial-planar to the F_3 mesoscopic structures, but both have been reoriented during the D_4 deformation. S_3 is well developed in micaceous units and overprints the slightly aligned to randomly oriented minerals of the M_1 retrogression. Aligned fine grained muscovite and chlorite replace the M_1 minerals along S_3 cleavage planes.

In the southeast corner of the study area (fig. 2), weakly developed intersection lineations ($S_3 \times S_2$ or L_3) in pelitic schists form a tight concentration (fig. 5A). The orientation is 24/197, and the tight clustering indicates that subsequent deformation was minor or involved only passive rotation. Plots of S_2 from the same area (fig. 3A) also yield a tight clustering. Around the domes, however, the L_3 lineations form a diffuse concentration, the trend of which ranges from that of the eastern area (197) to approx 255 and concentrates at 220 (fig. 5B). In the Hundley dome, L_3 lineations exhibit the same sigmoidal pattern as the major dome axis (fig. 2). Poles to S_3 form a girdle that defines a fold axis of 16/219 (fig. 5C). The early crenulation cleavage was therefore folded during a later event. The axis and distribution of poles to S_3

Fig. 4. Sample of mica schist from the upper Lynchburg Formation showing S_3 and S_4 crenulation cleavage intersections with the S_2 surface. Scale bar = 5 cm.

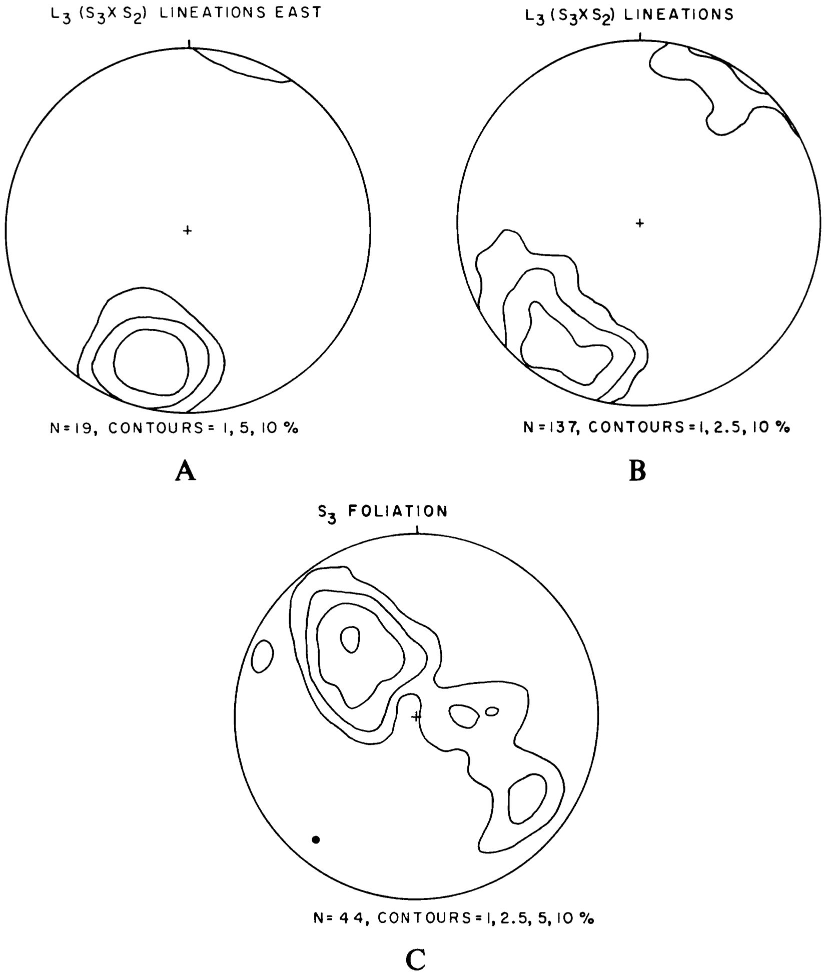

Fig. 5. Projections of: (A) L_3 lineations ($S_3 \times S_2$) from the eastern map area (minor D_4 deformation); (B) L_3 lineations from within the domed area; and (C) poles to S_3 from within the domed area.

throughout the area of the domes (fig. 5C) is nearly identical to the plot of poles to S_2 in the southern Hundley dome (fig. 3B).

Map-scale F_3 structures are identifiable in and between the domes (fig. 2). Interference of the F_3 folds with the northeast-trending F_4 anticlines produces the northeast and southwest closures of the domes. The original orientation of F_3 structures is difficult to determine because of subsequent rotation and refolding. The trend of the F_3 fold axes ranges from 188 to 240, and their plunge varies from 40 south to 15 north. Mesoscopic folds in the core of the Hundley dome and map scale structures there and between the Reed Creek and Otter River domes indicate that the initial orientations of F_3 axes were approximately horizontal and trended nearly north-south. Because the north-south oriented structures are only present along the northeast-trending Bowens Creek fault, they were probably originally en-echelon, as many still are (fig. 1).

D_4 deformation.—The F_4 folds trend northeast and are well developed on outcrop and map scale (fig. 2). Mesoscopic folds are tight, asymmetric, and axial planes dip to the southeast. Parasitic folds are well developed on the limbs and are best displayed in the Evington Group pelites. They are common on the northeast side of the Hundley, northeast and southwest side of the Reed Creek, and southern termination of the Otter River domes (fig. 2). Fold axes trend 225, and plunges range from 30 southwest to 10 northeast depending upon the position on the F_3 structure.

The S_4 crenulation cleavage overprints the S_2 and S_3 cleavages (fig. 4). S_4 is asymmetric to the northwest and narrowly (3–4 mm) to widely (1–2 cm) spaced with irregular to sinuous axes. The cleavage is a spaced, zonal type (Gray, 1977) forming microfolds in the S_2 pervasive foliation. Where S_4 crosses S_3, the interference pattern displays S_3 crenulation axes that wind sinuously across the S_4 axes (fig. 4) which resembles the megascopic fold pattern. Poles to S_4 yield a cluster of points that define an approximate plane of 036 64 SE (fig. 6A). The angle between the S_4 and S_3 crenulation cleavages is highly variable. S_3 usually trends more northerly than the northeast-trending S_4 (as in fig. 4), but locally S_3 is oriented more easterly than S_4. L_4 ($S_4 \times S_2$) intersection lineations trend

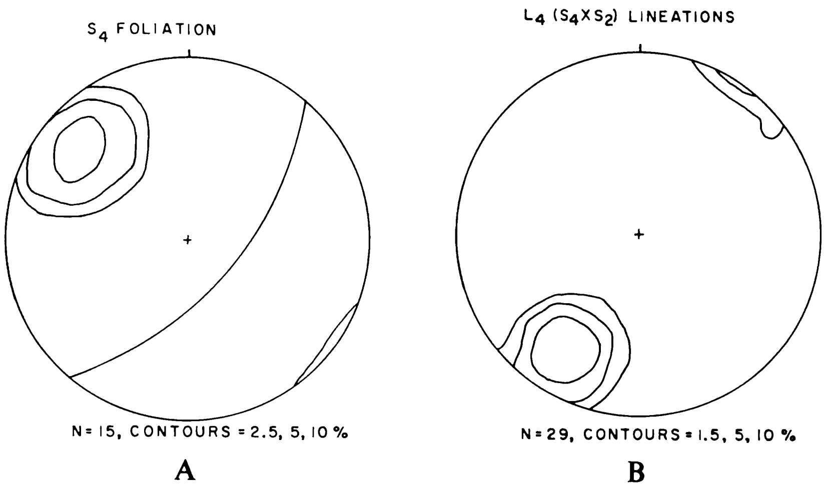

Fig. 6. Projections of (A) poles to S_4 crenulation cleavage and (B) F_4 fold axes and L_4 ($S_4 \times S_2$) intersection lineations.

approx 22/214 (fig. 6B), and their consistency indicates no subsequent deformation. The L_4 orientation is nearly identical to the b-axis defined by the poles to S_3 and those to S_2 in the southern Hundley dome. S_2 was folded during F_3, and both S_2 and S_3 were folded about an F_4 fold axis.

The map-scale F_4 folds produce the major northeast trend of the domes. The en-echelon, north-south F_3 structures form saddles on the F_4 northeast-trending anticlines. The domes therefore represent a type 1, 0° to 90° interference pattern (Ramsay, 1967). The F_4 folds are more asymmetric and inclined to overturned in the western portion of the map area than in the east (figs. 2 and 7).

Shear indicators.—Shear bands (extensional crenulation cleavage of Platt and Vissers, 1980) with consistent reverse-dextral offset also intersect the S_2 and S_3 crenulation cleavage. Poles to shear bands from the entire field area define a diffuse partial girdle. In areas where F_4 structures are poorly developed (between the Otter River and Reed Creek domes and in the central Hundley dome), the shear bands generally trend 071 65 southeast to vertical. The F_3 crenulation axes (L_3 lineations) are deformed and offset by the shear bands, which are in turn locally folded in F_4 folds, causing the variability in their orientation.

The shear bands are narrowly (3 mm) to widely (2 cm) spaced and best developed in the pelitic Evington Group schists. M_2 chlorite and muscovite grains are bent into "fish" (Eisbacher, 1970; Lister and Snoke, 1984), and fractured M_1 chloritoid is sigmoidal with tails trailing into the shear bands (fig. 8). Sigmoidal quartz ribbons (type 2B and 4B of Boullier and Bouchez, 1978) are layered with the mica, chlorite, and

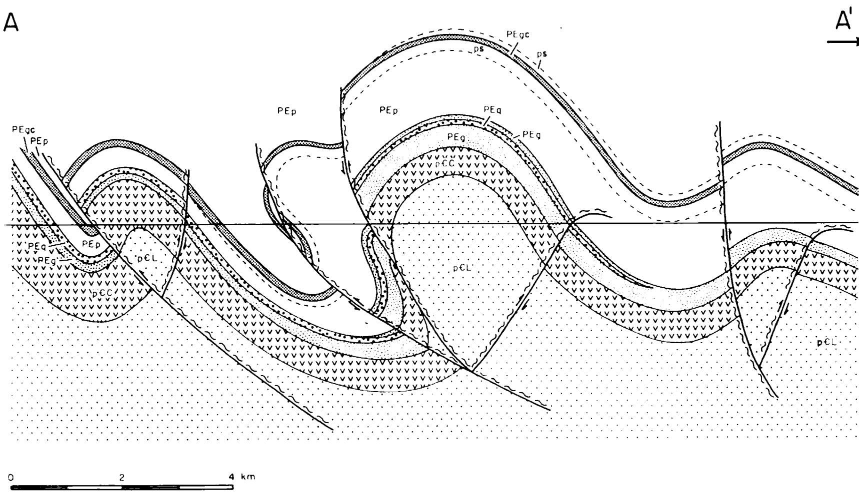

Fig. 7. Line-balanced, down-plunge projected (where possible) cross section of the western Altavista Area (west side of A-A′ to east-striking area). Section line and map units from figure 2.

Fig. 8. Photomicrograph of shear bands in chloritoid-chlorite, Evington Group pelitic schist: c = chloritoid, m = mica ± chlorite, q = quartz ribbon, and SB = shear bands with movement directions shown by arrows. Scale bar = 1 mm.

chloritoid. The shear bands are defined by fine recrystallized chlorite and muscovite and offset the earlier foliations. Kyanite is also kinked and bent into the shear bands. Thin granite and pegmatite veins in the Lynchburg Formation are offset in a dextral sense by spaced extensional step faults. The shear bands are rare, however, in the Lynchburg and Catoctin formations.

C and S bands (Berthe, Choukroune, and Jegouzo, 1979) are developed in mylonites in the small granite dikes of the southeastern map area (figs. 2 and 9). Early formed S planes (schistosity) defined by quartz ribbons (type 2B of Boullier and Bouchez, 1978) and aligned mica curve into C planes (*cisaillement* or shear planes) in a consistent dextral sense. Feldspar porphyroclasts show evidence of brittle fracturing followed by dynamic recrystallization along the grain margins. The resulting structure is a type I S-C mylonite (Lister and Snoke, 1984). The S-C mylonites support dextral shear, but because they are uncommon, they cannot be used for strain analysis.

Mineral lineations.—Mineral and mineral stretching lineations are common in the Altavista area. Biotite, muscovite, chlorite, and less commonly hornblende, tourmaline, staurolite, and rods of quartz are

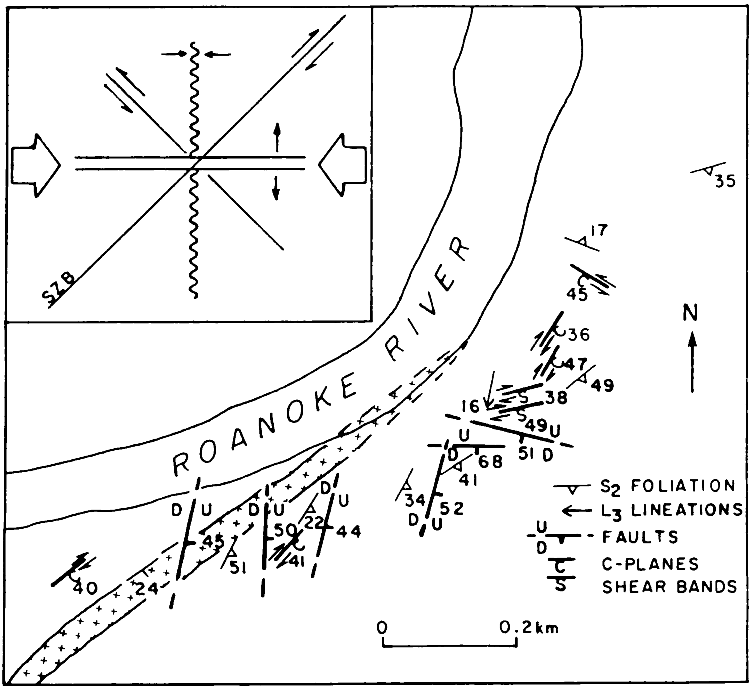

Fig. 9. Detailed geologic map of the eastern Altavista map area. Inset: simple shear model of principal stress with resulting dextral and sinistral shears and compression and extension directions.

aligned on the S_2 surface. The majority of the lineations are approximately parallel to the F_3 fold axes and L_3 intersection lineations, but there is variability in orientation. The mineral lineations in the granite mylonites of the southeastern map area are horizontal to slightly plunging and trend 045. Lineations in S-C mylonites are proposed to define the shear direction (Simpson and Schmid, 1983). Near vertical lineations in the reverse faults on the northwestern and southeastern sides of the domes and those associated with shear bands are similarly proposed to reflect movement direction. The majority of the lineations however are parallel to L_3 lineations, parallel to L_4 lineations, lie somewhere between the two, or show no apparent angular relationship. The variability of the orientations suggests that several sets of mineral lineations of varying age and degree of reorientation may exist. The main concentration of data, however, lies at 19/223 or approximately at the F_4 fold axis.

Faults.—There are many large and small ductile and locally brittle faults in the Altavista area. Offsets range from several centimeters to several meters for small faults and tens to hundreds of meters for large faults. Movement directions were determined by offset units, missing or tectonically "thinned" units, and "dragged" foliation against the fault plane, but in some cases, they were indeterminate. Three distinct groups of faults are apparent.

Minor reverse faults compose group one and exhibit strikes of 000 to 015 and steep dip angles to both east and west (fig. 9). The faults are present in the central and eastern map area. A large fault, apparently of group one, trends 356 and has faulted out the north end of the Reed Creek dome (fig. 2). Offset on this fault appears large (approx 250 m to 1 km) but cannot be estimated accurately.

Group two is represented by only four documented examples of normal faults oriented at approx 100 with variable dips to both north and south (fig. 9). Deformation in these faults is ductile to semi-brittle. The deformation episode with which these faults are associated is uncertain, but because they mainly occur in areas that experienced only mild D_4 deformation, and their movement sense and orientation is favorable to D_3 (fig. 9), they probably occurred during the D_3 event.

Group three reverse faults are the most common and strike 045 to 059 with dips of 45° to 60° both to northwest and southeast. Large faults of group three include reverse faults that bound both the northwestern and southeastern sides of the Hundley and Reed Creek domes and the Leesville anticline (fig. 2). The ductile faults locally exhibit intense cleavage development, thinned units, and steeply plunging, northwest or southeast oriented mineral lineations (pure dip-slip). These faults show shear in a reverse sense as indicated by the replication of stratigraphic units, which suggests that the domes emerged along faults as well as by folding (fig. 7). Because of their orientation and association with well developed S_4 crenulation cleavage, group three faults appear to have been active during the D_4 deformation.

Many other minor faults in the area have orientations that are appropriate for these groups, but for which movement directions could not be determined. Similarly, there are several minor faults in the area that cannot be classified into a group. Most of these faults are in another orientation or are strike-slip faults and represented by too few examples. Some of these may be a result of Triassic extension.

STRUCTURAL DEVELOPMENT

The structures in the Altavista area indicate a complex kinematic history. The domes, reverse faults, and multiple crenulation cleavages support a history of compressional tectonics, and other structural elements require deformation associated with transcurrent movement. The widespread shear bands, which form in initially anisotropic rocks (Platt and Vissers, 1980), indicate that dextral transcurrent movement occurred throughout the Altavista area. C and S bands (Berthe, Choukroune, and Jegouzo, 1979) in small granite bodies in the eastern map area also show consistent dextral movement. C planes, which are formed in initially isotropic rocks, are assumed to parallel the shear zone boundary (Berthe, Choukroune, and Jegouzo, 1979) which in this case is 045 to 050. The shallow plunge of the mineral lineations in the S-C mylonites and many of the shear bands also supports a dominantly transcurrent shear zone. The shear bands are oriented at $+21°$ to $+28°$ from the shear zone boundary as determined by the C planes and regional mapping of the Bowens Creek fault to the southwest (Conley, 1978). Gates, Simpson, and Glover (1986) found that shear bands in the nearby transcurrent Brookneal zone (fig. 1) similarly formed at $+24 \pm 3°$ to the shear zone boundary. The Brookneal zone is also dextral and oriented at 040.

The first post-Taconic structures formed in the Altavista area were the F_3 folds and S_3 crenulation cleavage. The initial orientation of the structures cannot be determined absolutely, but the weakly overprinted center of the Hundley dome and nearly undeformed S_3 crenulation cleavage of the eastern map area indicate a trend of approx 195 to 200. If the structures were produced in a dextral transcurrent simple shear system, they would have been formed with axial surfaces parallel to the X-Y plane of the finite strain ellipsoid (Ramsay and Graham, 1970; Ramsay, 1980). The D_3 structures (fig. 10A) would be analogous to the early S bands formed in isotropic rocks (Berthe, Choukroune, and Jegouzo, 1979; Simpson, 1984). In simple shear with a horizontal initial orientation (X-Y plane), the folds would have formed at $-45°$ to the shear-zone boundary (Ramsay and Graham, 1970). According to field and experimental observations, however, compressive structures in a transcurrent system actually form at approx $25°$ to $45°$ from the shear zone boundary (for actual estimates see Ghosh, 1966; Tchalenko, 1970; Wilcox, Harding, and Seely, 1973; Dubey, 1980; DeSmet, 1984; Ingles, 1985). This angle is dependent on the rheology of the rock (Tchalenko, 1970), the initial orientation of the anisotropies (Ramsay, Casey, and

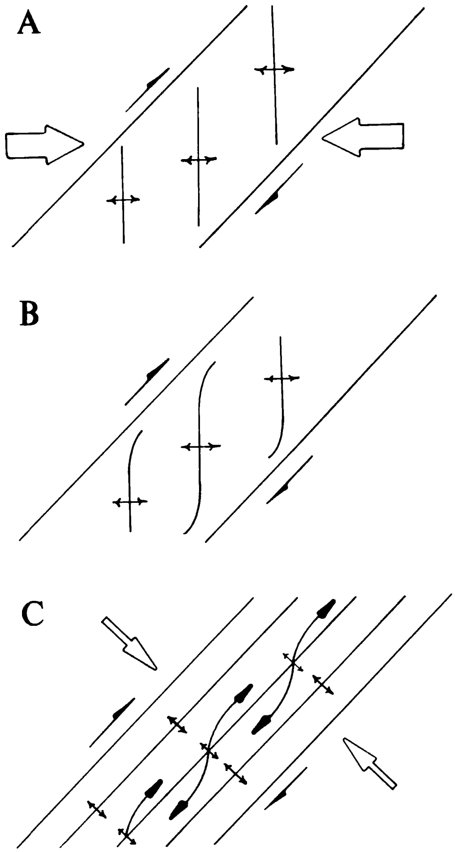

Fig. 10. Schematic diagrams of: (A) D_3 deformation with F_3 structures, shear zone boundary, and principal stress directions; (B) dextral shear and partial reorientation of structures; and (C) D_4 deformation with F_4 structures and reverse faults.

Kligfield, 1983), and the amount of pure shear or transpression in the system (Harland, 1971; Sanderson and Marchini, 1984).

The F_3 structures were formed en-echelon to the Bowens Creek Fault which has an approximate strike of 045 to 050. They had an initial orientation of 000 to 015 or the approximate orientation of the least deformed structures. These structures may have undergone minor clockwise rotation during the subsequent dextral shearing or F_4 folding event. In the eastern map area (fig. 9), where there is relatively little D_4 overprint, group one reverse faults are oriented at 35° to 45° from the strike of the C planes in the granite. In this area, normal faults are oriented approx 90° from the reverse faults, and a conjugate left lateral fault is oriented 75° from the C planes (fig. 9). This configuration of compressional, extensional, and conjugate faults is that predicted by the simple shear model.

After formation of the D_3 structures, those in the western map area were apparently rotated by dextral shearing (fig. 10B). Evidence for this phase is only well documented in the shearing of S_3 into the dextral shear bands. There is also a great variability (both positive and negative rotation) in the acute angle between S_3 and S_4 foliations. The variability in the angle cannot purely reflect the degree of reorientation of S_3 during D_4 deformation, or the angle would vary inversely with S_4 intensity. Such a relation was not observed and does not explain how S_3 could lie both to the east and north of S_4 in a single rock type if it had a consistent orientation prior to D_4.

The D_4 deformation (fig. 10C) produced the northeast-trending F_4 map scale and mesoscopic folds, S_4 asymmetric crenulation cleavage, group three reverse faults, and reverse shear zones on the northwest and southeast sides of the domes. Many of the early structures were refolded and transposed during the D_4 event. The D_4 structures reflect northwest directed compression and can be explained by two possible processes. The first is that of transpression as proposed by Harland (1971), Sylvester and Smith (1976), Harding and Lowell (1979), DeSmet (1984), and Sanderson and Marchini (1984) for many other fault systems. According to Sanderson and Marchini (1984), the angle of the compressional structures to that of the transcurrent zone is a function of the amount of pure shear or compression across the zone. Compressional features that parallel the transcurrent zone would require a system of pure compression with no simple shear.

Sylvester and Smith (1976), Wilcox, Harding, and Seely (1973) and Harding and Lowell (1979), however, found that reverse faults could be active concurrently with strike-slip faults. Low- to high-angle reverse faults that dip in opposite directions are synchronously active with nearby parallel strike-slip faults on portions of the San Andreas fault, Calif. and in the Ardmore Basin, Okla. The reverse faults emerged from basement, cut the cover rocks, and produced asymmetric structures that verge in opposite senses away from the central strike-slip zone. The fault movement caused emergence of antiformal, fault-bounded basement blocks in "keystone structures" (Sylvester and Smith, 1976) or "positive flower structures" (Harding and Lowell, 1979). The compression appears late in the development of the shear zone but synchronous with strike-slip movement (fig. 10). Sylvester and Smith (1976) attribute the two deformation types to tectonic transpression (Harland, 1971), where zones of pure compression and transcurrent shear are simultaneously operative in contrast to the model of Sanderson and Marchini (1984). Woodcock and Robertson (1982) found a similar combination of reverse and strike-slip faults in the Antalya complex of southwestern Turkey. They proposed that the oblique strain may have been resolved into concurrent compressional and transcurrent forces.

In Altavista, D_3 formed the en-echelon structures that were subsequently variably rotated. The D_4 event involved folding, cleavage development, and zones of intense deformation which parallel the shear zone boundary. The reverse faults occur on the northeast-trending limbs of the Reed Creek and Hundley domes and the Leesville anticline. Near-vertical mineral lineations, which overprint the northeast-trending lineations, have been found in the shear zones suggesting that they were pure dip-slip. The antiformal cores of the Altavista domes have therefore emerged through the cover rocks (fig. 7) as "keystone structures" described in the San Andreas system (Sylvester and Smith, 1976) or "positive flower structures" described in the Ardmore Basin (Harding and Lowell, 1979) and the Betic Cordilleras (DeSmet, 1984).

If the Rb/Sr and K/Ar mineral ages from the northern Brevard zone (356–300 Ma, in Conley, 1978) and Bowens Creek Fault (345–275 Ma; Fullagar and Dietrich, 1976; and D. Mose, personal commun., 1986) reflect the uplift associated with dextral transcurrent movement, then the fault was active during the Carboniferous to Permian. This period falls within the range imposed by the more solid age constraints which include Triassic-Jurassic brittle faulting and dike intrusion and Taconic deformation and metamorphism (440 Ma; Odom and Russell, 1975). The dextral Brookneal zone which lies 10 km to the east of Altavista was active from 324 to 300 Ma (Gates, Simpson, and Glover, 1986). The Carboniferous geometry may have been a transpressional Altavista area with structural vergence away from a central major transcurrent Brookneal zone (fig. 11).

DeSmet (1984) found that domal "positive flower" structures formed in the external zone of a major strike-slip fault in the Betic Cordilleras of southern Spain. The Crevillente strike-slip fault is flanked by inversely symmetrical zones of compressional structures that verge away from the central fault. De Smet (1984) proposed that a series of en-echelon structures were formed at 25° from the main shear zone boundary. The structures were then rotated in some cases and reverse faulted in others depending on local conditions. Finally, the zone was compressed producing thrust faults and asymmetric structures.

Graham (1978) has shown that transpressional deformation can occur in cover rocks above a transcurrent basement fault. The model requires that the cover rocks be capable of a significant amount of slip

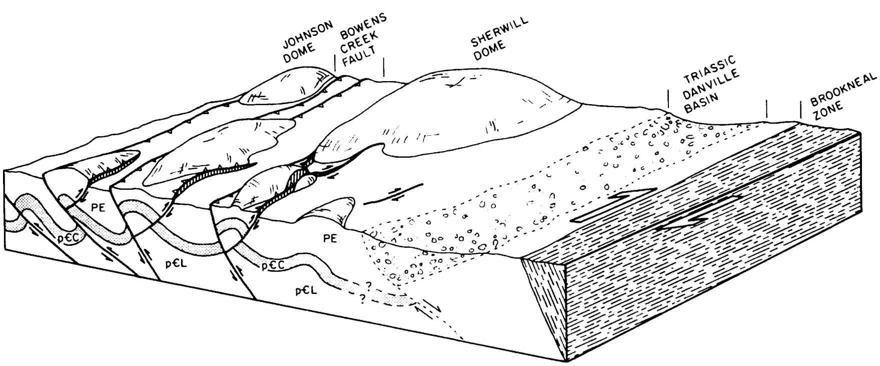

Fig. 11. Schematic structural topography block diagram of the Altavista to Brookneal area. Map units correspond to figure 2 (Catoctin Formation shaded). Block surface in the Evington Group.

on the basement. En-echelon folds are formed 45° from the strike of the underlying fault and rotated toward parallelism with progressive shear. The Altavista area (Bowens Creek fault) may similarly be the cover expression of dextral transcurrent or oblique shearing at depth.

A second possibility for Altavista is that the D_4 deformation may have occurred in a subsequent compressional event unrelated to D_3 and the dextral shearing. In this case, the D_3 north-trending en-echelon structures still formed in dextral transcurrent shearing. Because D_4 is purely compressional and post-dates D_3, this model is possible but requires a shift in compression direction. Both the D_3 and D_4 events were ductile, however, and took place under the same M_2 metamorphic conditions (middle to upper greenschist) suggesting a short time span between the two, as mineral ages indicate uplift during this deformation. The effects of the two events are also spatially similar.

TECTONIC IMPLICATIONS

The domes and Bowens Creek fault formed through the interaction of two deformational events (D_3 and D_4). If the D_3 and D_4 events were produced as two phases in a single transpressional event, then only one compression direction is required. According to the simple-shear model (Ramsay and Graham, 1970), the major compression direction lies 45° from the shear zone and perpendicular to the major structural trend. In both Altavista and Brookneal, compression would have been directed approximately east-west. If the D_3 and D_4 events are unrelated, then two compression directions are required. The D_3 compression was east-west, but the D_4 compression direction would have been oriented approximately southeast-northwest or perpendicular to the F_4 structural trend.

The main drawback in applying the formation of the Altavista domes to tectonic models is the lack of solid age constraints for each phase of deformation (D_3 and D_4). According to Fullagar and Dietrich (1984) and Mose (personal commun.) the Rb/Sr whole rock and mineral ages of 345 to 275 Ma from rocks along several portions of the Bowens Creek fault falls within that range and agrees with the activity range of the nearby, dextral Brookneal zone (fig. 1). The Brookneal zone exemplifies the Appalachian dextral shear system which extends from Maritime Canada to Georgia (Gates, Simpson, and Glover, 1986). Bradley (1980) summarized the transcurrent faults of the Northern Appalachians and found the peak activity to have occurred between 345 and 285 Ma. The age, metamorphic grade of deformation, and trend of the Bowens Creek deformation zone in Altavista is nearly the same as the Brookneal zone suggesting that both formed during the Carboniferous Appalachian dextral transcurrent event (Gates, Simpson, and Glover, 1986).

CONCLUSIONS

The Altavista area of the western Virginia Piedmont was domed subsequent to Taconic D_1 and D_2 deformation and M_1 metamorphism.

The terrane contained nearly horizontal foliation and structures prior to the development of the domes. The D_3 deformation produced en-echelon, north-south, symmetric map-scale and mesoscopic F_3 folds, S_3 crenulation cleavage, and group one small and large scale reverse faults. The D_3 structures were partially rotated by continued dextral shear across the area represented by dextral shear bands and dextral S-C mylonites in small granite bodies.

The subsequent D_4 deformation is concentrated in areas of well developed D_3 structures and is of similar metamorphic grade. D_4 structures include northeast-trending asymmetric F_4 map-scale and mesoscopic folds, S_4 crenulation cleavage and group three reverse faults, and shear zones on the limbs of the domes. The D_4 deformation produced "keystone" or "positive flower" structures represented by the northeast trending anticlines separated into domes by F_3 synclines.

The transpressional event is constrained to have occurred between Silurian and Triassic. It may be related to the Carboniferous Appalachian dextral transcurrent event as suggested by K/Ar and Rb/Sr age determinations. The nearby dextral transcurrent Brookneal zone exemplifies this event.

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