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LAYER PARALLEL SHORTENING: A MECHANISM FOR DETERMINING DEFORMATION TIMING AT THE JUNCTION OF THE CENTRAL AND SOUTHERN APPALACHIANS

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ABSTRACT. Near the transition from the southern Appalachians to the central Appalachians at the Roanoke recess, major southern Appalachian thrusts (~070°-striking) with steep initial ramps (~25° to 30°) are associated with footwall synclines with nearly vertical to overturned southeast-limbs. The 170-km long, overturned, Glen Lyn footwall syncline (to the St. Clair thrust) forms the structural front of the southern Appalachian fold and thrust belt southwestward from the recess. Deformed mudcracks, öolites, crinoid-stem plates, chert nodules, and bedding-normal burrows at 32 localities, mostly in the overturned limb, for 84 km from near Glen Lyn, Virginia (on the New River) to near Richlands, Virginia, primarily reflect presyncline layer parallel shortening (LPS) strain by intragranular mechanisms. The eastern part of the syncline averages 14 percent shortening attributable to LPS, assuming constant volume deformation, whereas in the western part, LPS averages 9 percent. Percent shortening for LPS strain is typically much lower (1-13 percent) in carbonates than it is in nearby clastic sedimentary rocks (3-21 percent), because strain is largely accommodated by outcrop-scale pressure solution along stylolites in the carbonates.

Restoration of overturned bedding to horizontal, taking into account the trend and plunge of the segments of the fold axis, yields LPS directions of 264° to 342° with an average of 316° and a standard deviation of 19°. Although 25 percent of the LPS directions are in the range of southern Appalachian trends (330°-345°), most are in the ranges of central Appalachian (44 percent) and transitional (31 percent) trends. All are oblique to the local trends (067°-081°) of the segments of the axis of the Glen Lyn syncline used for restoration of bedding to horizontal. Hence, 28 LPS strain-ellipses were rotated about a vertical axis, so that the local segments were aligned with the trend (067°) of the axis at Glen Lyn. LPS directions then range from 262° to 331°, with an average of 308° and a standard deviation of 17°. If anomalous shortening directions obtained for carbonates with very low percent (1 percent) LPS are excluded, then the average LPS direction is 311°. This principal LPS direction lies 26° from the perpendicular to the Glen Lyn syncline (067°) but is more consistent with shortening directions of ~300° in the central Appalachians reported by other workers. Earlier papers concluded that development of central Appalachian structures postdated development of southern Appalachian structures. However, preservation of central/transitional LPS strain in the overturned limb of this major southern Appalachian fold indicates that central/transitional Appalachian deformation initiated prior to formation of the Glen Lyn syncline, a southern Appalachian fold.

INTRODUCTION

Appalachian salients and recesses are inferred to be partially inherited from Precambrian features (Rankin, 1975, 1976; Thomas, 1977, 1991) and partially the result of Paleozoic deformation (Geiser and Engelder, 1983; Hatcher and others, 1989; Bartholomew, Henika, and Lewis, 1994). The transition from the central Appalachians to the southern Appalachians is marked by a change of ~35° in the regional trend of structures, forming the Roanoke recess (fig. 1). The Pulaski-Staunton thrust system is the easternmost system of the Appalachian foreland in Virginia, and it bends around the Roanoke recess, as do the Blue Ridge and Rockfish Valley-Fries thrust systems (fig. 1, large shaded area). Moreover, the internal Paleozoic fold-trends and Paleozoic foliation-trends of these thrust systems bend gradually around the Roanoke recess (Bartholomew,

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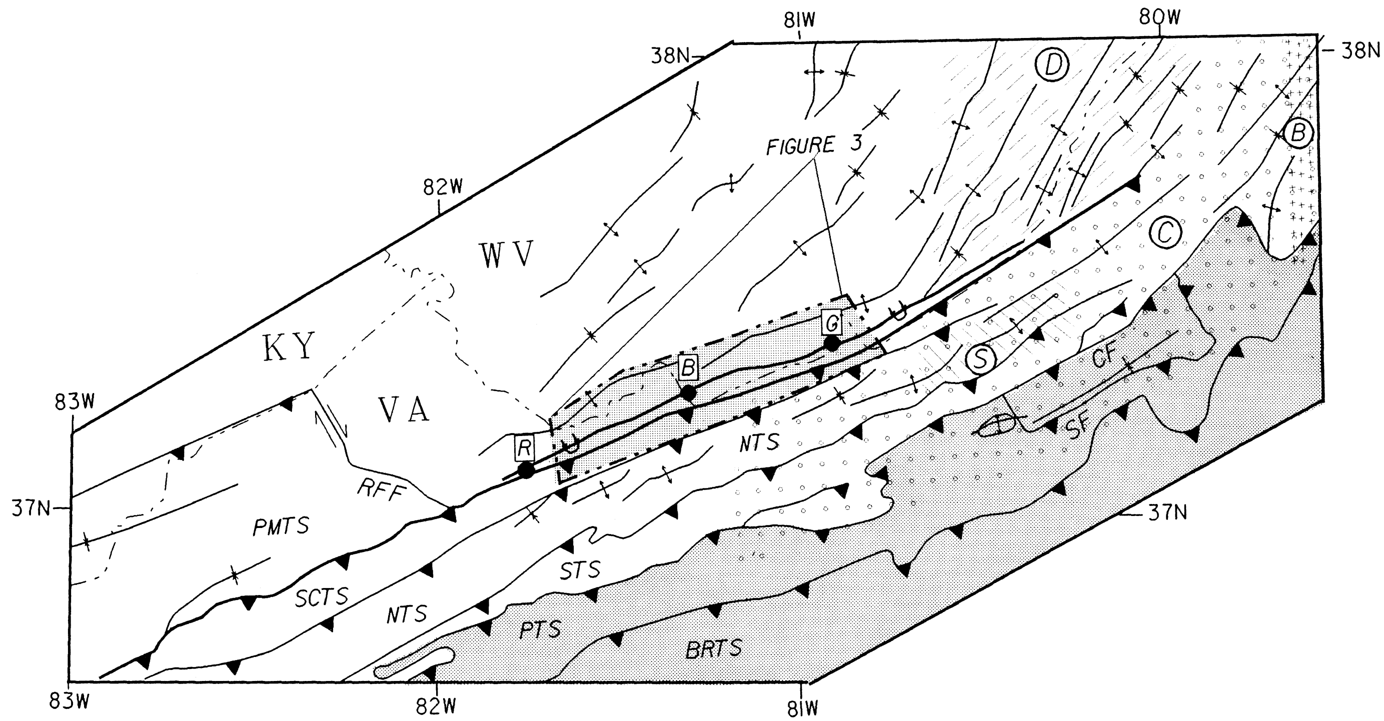


Fig. 1. Tectonic map of the Roanoke recess area (modified from Hatcher and others, 1990) with fold axes and major thrusts shown. Encircled B, D, S, C are areas studied by Bick (1986) (cross pattern), Dean, Kulander, and Skinner (1988) (back hashed), Simon and Gray (1982) (front hashed), and Couzens and others (1993) (dotted). Area outlined in heavy dashed lines and shaded (fig. 3); Circles with adjacent ensquared G, B, R- towns of Glen Lyn, Bluefield, Richlands; BRTS–Blue Ridge thrust system (shaded); CF–Catawba fault; PTS–Pulaski thrust system (shaded); SF- Salem Fault; STS- Saltville thrust system; NTS–Narrows thrust system; SCTS–St. Clair thrust system; PMTS–Pine Mountain thrust system; RFF– Russell Fork fault.

1981; Bartholomew and others, 1982), suggesting that the present-day expression of the recess folds these thrust systems.

In contrast, the folds and thrusts that are forelandward of the Pulaski-Staunton thrust system do not curve gradually around the recess but instead undergo several abrupt trend changes (fig. 1), which led Rodgers (1970) to suggest that two different structural systems represent the central and southern Appalachians. The field between the central and southern Appalachians, where structures have strikes intermediate between typical central (~035°) and southern (~070°) strikes, has become known as the transition zone in the literature. Structural features that strike at ~050°, coupled with an increased magnitude of LPS of intermediate trend (Couzens and others, 1993), suggest interference between central and southern Appalachian stresses within the recess.

Given the changes in structural trend that differentiate the central and southern Appalachians, the issue addressed here is whether the deformations effecting these two trends occurred simultaneously or sequentially at the Roanoke recess. If the latter is the case, we seek to elucidate the order in which the deformations occurred. Previous workers, whose studies are outlined below, have developed a common wisdom in which southern Appalachian deformation preceded deformation of the central Appalachians (Dean, Kulander, and Skinner, 1988; Couzens and others, 1993; Evans, 1994). We present new strain data in this paper from the Glen Lyn syncline, a key southern Appalachian structure in the recess, which demonstrate that central and transitional Appalachian strain predated the development of this fold. Given this evidence, suggesting the precedence of central and transitional Appalachian deformation over southern Appalachian deformation in this location, we believe that the tectonic synthesis for this portion of the Appalachians should be reviewed, and that more work is necessary to clarify timing relationships across the recess.

PREVIOUS WORK

Based primarily on the age of the youngest strata deformed in each region, Rodgers (1970) suggested that southern Appalachian structures formed prior to those in the central Appalachians. Bick (1986) used both map-scale fold-trends and inferred truncations of folds by thrusts in the transition zone (B on fig. 1) to conclude that southern Appalachian folds preceded central Appalachian folds. However, his cross sections are not balanced, faults are folded, and contacts are poorly exposed, so we believe this work cannot be reliably extended to a regional structural chronology. Dean, Kulander, and Skinner (1988) also supported Rodgers's premise with data from the Appalachian Plateau of southeastern West Virginia (D on fig. 1) and from the overturned limb of the Glen Lyn footwall syncline (a southern Appalachian fold). Their data indicate that central Appalachian folds, solution cleavage, and stylolitic joints are superimposed upon southern Appalachian structures.

In the transition area studied by Couzens and others (1993) (C on fig. 1), strain factorization in the Silurian Tuscarora quartz arenite showed that asymmetric compaction dominated finite strains, but strains of 5 and 10 percent LPS are recorded in the southern and central Appalachians, respectively. They indicated that both central and southern Appalachian strains are evident within the transition zone of the recess. Simon and Gray (1982) examined finite strain in a fault-bend fold in the Narrows thrust sheet of the southern Appalachians (S on fig. 1). Their analysis of mudcracks (19-28 percent LPS) and reduction spots (8-32 percent LPS) showed that LPS strain consistently reflected southern Appalachian deformation. Dominant shortening directions, as indicated by orientation of short axes of strain ellipsoids (the z-direction), in the central Appalachians are ~300° (Evans and Dunne, 1991; Couzens and others, 1993; Smart, Dunne, and Krieg, 1997), which is sub-perpendicular to the dominant, ~035°-trending, central Appalachian folds (Dean, Kulander, and Skinner, 1988; Evans, 1989; Wilson and

Shumaker, 1992). In contrast, shortening directions of 330° to 335° in the southern Appalachians (Simon and Gray, 1982; Wiltschko, Medwedeff, and Millson, 1985; Couzens and others, 1993), are sub-perpendicular to ~070°-trending southern Appalachian folds.

Footwall synclines with overturned southeast-limbs are found along the major southern Appalachian thrusts (Saltville, Narrows, and St. Clair thrusts) from the recess southwestward for distances of 75, 65, and 170 km, respectively (Bartholomew, Henika, and Lewis, 1994; Bartholomew and others, 1999). Fold-thrust geometry may change to lower angle ramps (~15°) without footwall synclines farther southwestward (Pine Mountain thrust; Mitra, 1988), but at the recess, footwall synclines are associated with these three major thrusts where they are characterized by steeper (~25° to 30°) ramps (Butts, 1933; Bartholomew and others, 1999; Woodward and Gray, 1985; Kulander and Dean, 1986). An important consequence of this association is the synchronicity of development between footwall synclines and superjacent thrusts (Suppe and Medwedeff, 1990). Thus, establishing an age of structural features relative to the footwall syncline effectively establishes the age relative to the thrust and vice versa.

An attribute of a major fold with a near vertical limb is that if deformational events producing small-scale structures and horizontal structures occur both before and after folding, then only the prefolding event would produce structures indicative of LPS in the vertical limb. In contrast, if the other limb were gently dipping, it would record both LPS events with their unique non-coaxial directions. Applying this approach to the Glen Lyn syncline (fig. 2) and using the conclusions of Dean, Kulander, and Skinner (1988), the subvertical limb of the Glen Lyn syncline should only contain LPS structures related to southern Appalachian shortening if central Appalachian deformation post-dated overturning of the fold limb. Our study examines the subvertical limb of the Glen Lyn syncline to determine whether central Appalachian LPS structures are absent. Their presence would force a reconsideration of the implications of the work by Dean, Kulander, and Skinner (1988).

GLEN LYN SYNCLINE AND ST. CLAIR FAULT

The Glen Lyn syncline (McDowell, 1982) is ~170 km long and trends 067° to 081° throughout the study area. The units exposed in the syncline (figs. 2 and 3) consist of Devonian shale overlain by a sequence of lower Mississippian strata: Price/Maccrady, Greenbrier, Bluefield, and Hinton formations. The axis of the syncline is primarily in the lower part of the Hinton Formation, and the adjacent Appalachian Plateau rocks include the upper Hinton (with the Princeton Sandstone) along with the Bluestone Formation and the lowermost Pennsylvanian rocks (fig. 3). Overturned bedding in the overturned limb of the syncline strikes locally from 060° to 077°. Dips vary from 35° to 90° southeast but are generally very steep. Shale, sandstone, and limestone of the Bluefield Formation provided 63 percent of our data, and 37 percent came from Devonian shale, the Greenbrier Group, and the Hinton Formation (table 1).

STRAIN DATA

LPS strain data are determined from objects on bedding surfaces along the overturned limb of the Glen Lyn syncline, such as mudcracks, burrows normal to bedding, öolites, small chert nodules, and segments of crinoid-stem plates normal to bedding (table 1). Due to outcrop size, steep dip, and inaccessibility, strain for mudcracks, burrows, chert nodules, and crinoid-stem plates were primarily determined from photographs of outcrops and photomicrographs of thin sections with öolites from which axes of each object were digitized (fig. 4).

Both fault-bend folds and small extensional faults are folded about the Glen Lyn syncline (fig. 2A) and are distinguished in the overturned limb by low and high,

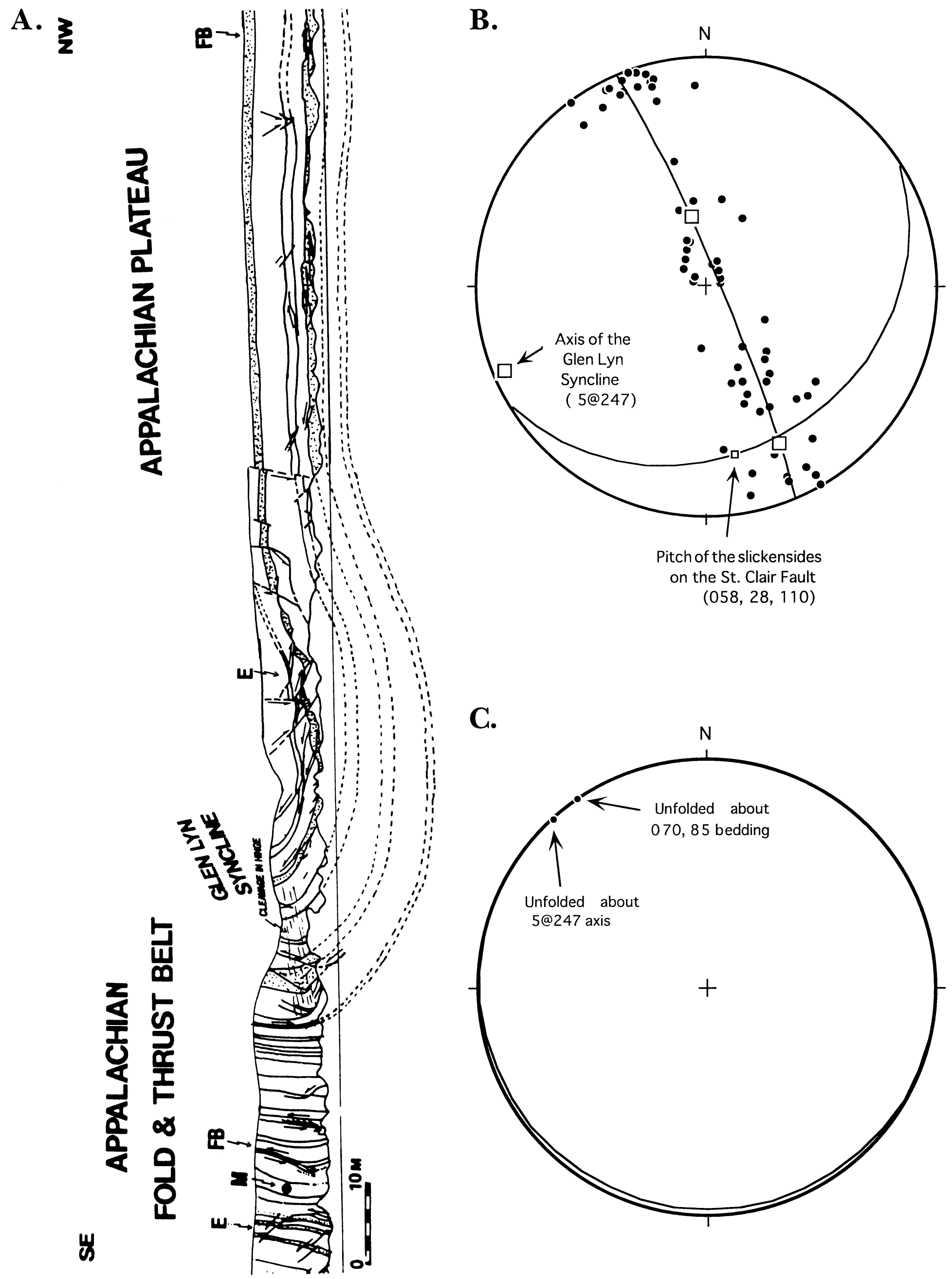


Fig. 2(A) Sketch of the exposure at Glen Lyn (locality 2–Table 1) (modified from Bartholomew, Henika, and Lewis, 1994); FB–fault bend folds; E–extensional faults; M–mudcracks at locality 2 (fig. 3) are along bed with layer parallel shear. (B) Plot of 65 poles to bedding measurements, defining the trend (247°) and plunge (5°) of the axis of the syncline; (C) The difference between unfolding the strain ellipse from site 2 simply around bedding versus around both bedding and the axis defined at Glen Lyn.

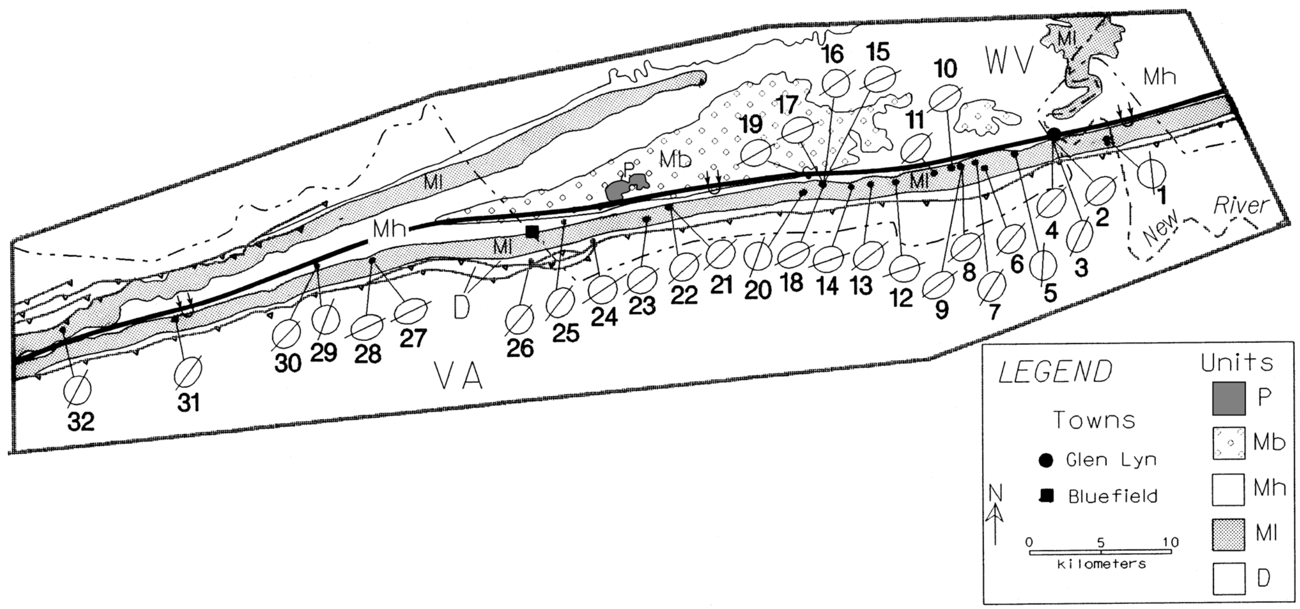


Fig. 3. Geologic map of the Glen Lyn syncline (modified from Virginia Division of Mineral Resources, 1993; Cardwell, Erwin, and Woodward, 1968; and McDowell, 1982). Locations and strain ellipses (with bedding restored to horizontal) shown are from this study (column SD on table 1); VA–Virginia; WV–West Virginia; Units: D–undivided Devonian strata; Ml–Lower Mississipian Price/Maccrady, Greenbrier and Bluefield Fms.; Mh–Hinton Fm.; Mb–Bluestone Fm.; P–undivided Pennsylvanian strata; St. Clair thrust system–black toothed lines.

Table 1

Structural data for sites 1 to 32 on figure 3

SI	S	U	LIT	ST	D	N	R_{NF}	ϕ	ER	P_{SD}	SD	NO	S_{TVL}	S_{CVD}	SH_{TVL}	SH_{CVD}
1	O	Mg	LS	067	45 OT	558	1.02	-79.3	8.7%	169	084@4	262	0.98	0.99	2%	1%
2	M	Mh	SS_F	070	85 OT	150	1.36	-14.1	13.3%	104	318@1	318	0.74	0.86	26%	14%
3	M	Mh	SS_F	070	85 OT	82	1.42	-36.6	13.5%	127	295@2	295	0.70	0.84	30%	16%
4	M	Mb	SS_F	068	53 OT	89	1.39	-17.8	12.8%	108	315@3	315	0.72	0.85	28%	15%
5	O	Mg	LS	067	35 OT	342	1.12	-59.8	7.0%	150	274@8	274	0.89	0.94	11%	6%
6	M	Mb	ST	068	54 OT	211	1.31	-34.7	12.9%	125	311@5	304	0.76	0.87	24%	13%
7	B	Mb	M	074	58 OT	319	1.24	-39.4	8.2%	129	303@3	296	0.81	0.90	19%	10%
8*	M	Mb	SS_F	070	58 OT	111	1.41	-22.5		113	321@3	314	0.71	0.84	29%	16%
9	M	Mb	SS_F	076	54 OT	48	1.58	-15.7	12.9%	106	324@1	317	0.63	0.79	37%	21%
10	M	Mb	M	071	58 OT	130	1.43	-16.6	15.4%	107	326@2	319	0.70	0.84	30%	16%
11	M	Mb	SS_F	069	55 OT	101	1.51	-15.0	7.6%	105	315@1	301	0.66	0.81	36%	19%
12	C	Mb	LS	076	61 OT	277	1.11	16.1	8.2%	106	162@0	328	0.90	0.95	10%	5%
13	O	Mb	LS	074	61 OT	467	1.34	-35.9	5.9%	126	143@0	309	0.75	0.87	25%	13%
14	M	Mb	ST	078	64 OT	194	1.24	-15.9	13.0%	106	161@1	327	0.81	0.90	19%	10%
15	B	Mb	M	076	68 OT	188	1.31	-20.9	9.2%	111	156@0	322	0.76	0.87	24%	13%
16	O	Mb	LS	083	46 OT	348	1.02	-26.4	9.1%	116	147@4	313	0.98	0.99	2%	1%
17	M	Mb	SS	085	60 OT	223	1.34	-16.8	10.6%	107	157@3	323	0.75	0.87	25%	13%
18	M	Mb	SS	085	60 OT	92	1.46	-19.6	13.1%	110	154@4	320	0.68	0.82	32%	18%
19	B	Mh	ST	073	70 OT	254	1.23	-27.2	8.9%	117	331@1	317	0.81	0.90	19%	10%
20	O	Mg	LS	103	72 OT	206	1.01	-83.1	10.2%	173	290@0	276	0.99	0.99	1%	1%
21	B	Mb	SS	078	71 OT	211	1.15	-29.8	10.1%	120	137@4	310	0.87	0.93	13%	7%
22	B	Mb	SS	085	78 OT	83	1.21	-29.9	8.6%	120	138@8	311	0.83	0.91	17%	9%
23	N	Mg	LS	081	68 OT	207	1.19	-21.0	14.4%	111	144@4	317	0.84	0.92	16%	8%
24	B	D	M	090	45 OT	153	1.09	-27.7	11.5%	118	147@2	320	0.92	0.96	8%	4%
25	B	Mh	ST	075	78 OT	339	1.24	-22.3	10.0%	112	29@10	302	0.81	0.90	19%	10%
26	B	D	M	083	55 OT	345	1.15	-32.0	12.0%	122	131@8	304	0.87	0.93	13%	7%
27	M	Mb	M_C	068	40 OT	83	1.45	-10.7	11.5%	101	154@0	330	0.69	0.83	31%	13%
28	M	Mb	M_C	060	45 OT	198	1.39	-15.0	12.4%	105	335@1	331	0.72	0.85	28%	15%
29	B	Mh	SS	076	44 OT	110	1.05	-46.6	7.8%	137	112@5	288	0.95	0.97	5%	3%
30	B	Mh	SS	070	46 OT	423	1.21	-29.5	13.2%	119	134@2	310	0.83	0.91	17%	9%
31	M	Mb	M_C	075	58 OT	138	1.41	-34.7	6.4%	125	126@4	302	0.71	0.84	29%	16%
32	B	Mb	SS	060	36	467	1.12	34.0	12.1%	56	117@4	293	0.89	0.94	11%	6%

SI: Site numbers correspond to those on figure 3.
S: strain indicator O = öolites; M = mudcracks; B = burrows; C = crinoids; N = chert nodules.
U: D = Devonian; Mg = Greenbrier Group; Mb = Bluefield Formation; Mh = Hinton Formation.
LIT: SS = sandstone; SS_F = fine grained sandstone; ST = siltstone; M = mudstone; MC = calcareous mudstone; LS = limestone.
ST = strike-right hand convention followed.
D = dip OT = overturned.
N = Number of objects measured.
*Measured directly on inclined outcrop.
R_{NF} = R from normalized Fry diagram.
Φ = the angle between the long axis of the strain ellipse and strike of bedding (negative is clockwise).
ER = Error.
P_{SD} = Pitch of shortening direction in outcrop.
SD = Trend and plunge of shortening direction unfolded about axis and bedding.
NO = Shortening direction normalized to a 067-trending (unkinked) fold axis.
s_{TVL} = s_3 calculated assuming total volume loss.
s_{CVD} = s_3 calculated assuming constant volume deformation.
SH_{TVL} = % shortening due to LPS calculated assuming total volume loss.
SH_{CVD} = % shortening due to LPS calculated assuming constant volume deformation.

respectively, cutoff-angles of bedding (Apperson and Bartholomew, 1993; Bartholomew, Henika, and Lewis, 1994). They indicate that macroscopic strain accommodation preceded rotation about the Glen Lyn synclinal axis. Their presence suggests that earlier LPS strain should be preserved in the overturned limb as well. Simon and Gray (1982) demonstrated that for low strains, the assumption of plane strain is valid. Thus, for this study, only LPS strain is being considered, plane strain is assumed, and bedding is designated as the XZ plane of the strain ellipsoid and produces the only strain ellipse under analysis.

Our original presentations (Bartholomew, 1995; Whitaker and Bartholomew, 1998a) relied on Fry (1979) diagrams (fig. 5). In this paper we have utilized INSTRAIN (Erslev, 1988; Erslev and Ge, 1990) to produce normalized Fry diagrams (fig. 5) for greater resolution and reproducibility for our analysis. This enabled us to include data on some öolite samples with very low strains and some small-burrow samples that were not resolvable using standard Fry diagrams. Axes of objects on photographs with a high density of nearest neighbors (mudcracks, öolites, and burrows) were digitized. These digitized data were then analyzed using the INSTRAIN computer program (Erslev, 1988; Erslev and Ge, 1990). The least squares best fit ellipse data (R_{NF} and associated ϕ, table 1) from normalized Fry diagrams (fig. 5) were used to calculate shortening magnitudes and directions for the different localities. Only at locality 8, where outcrop orientation and the bedding dip-angle affected photographs to produce oblique views, was the nearest neighbor technique (Ramsay and Huber, 1983) used directly upon the outcrop for strain determination. Locality 9 is from the same bed at a level where it could be photographed and digitized.

The orientations of S_3 in their present orientations within the overturned limb are scattered but generally plunge southwest (fig. 6A), indicating obliquely inclined northeast-southwest shortening. This direction does not correspond to a known Alleghanian compression direction for either the southern or central Appalachians, so we then retrodeformed bedding using R. W. Allmendinger's STEREONET v.4.9.6 program. The data for sites 1 to 32 (fig. 3) were restored to horizontal about strikes and dips of bedding planes (table 1) and corrected for the local trend and plunge of segments of the axis of the Glen Lyn syncline. The local trend and plunge of each segment was obtained from plots of poles to bedding using the STEREONET program (fig. 2B). The plunges and trends that we used for the respective sites were:

site 1: 3° @ 069°
sites 2-5: 5° @ 247° (fig. 2B, C);
sites 6-10: 3° @ 254°;
sites 11-20: 5° @ 081°;
sites 21-26: 4° @ 074°;
sites 27-32: 2° @ 071°.

When the overturned bedding is restored to horizontal, directions of S_3 (column SD on table 1) are consistently oriented northwest-southeast (fig. 6B). Restoration of overturned bedding to horizontal, taking into account the trend and plunge of the fold axis, yields LPS directions of 264° to 342° with an average of 316° and a standard deviation of 19°. Although 25 percent of the LPS directions are in the range of southern Appalachian trends (330°-345°), most are in the ranges of central (44 percent) and transitional (31 percent) trends. All are oblique to the local trends (67°-81°) of the Glen Lyn syncline used for restoration of bedding to horizontal.

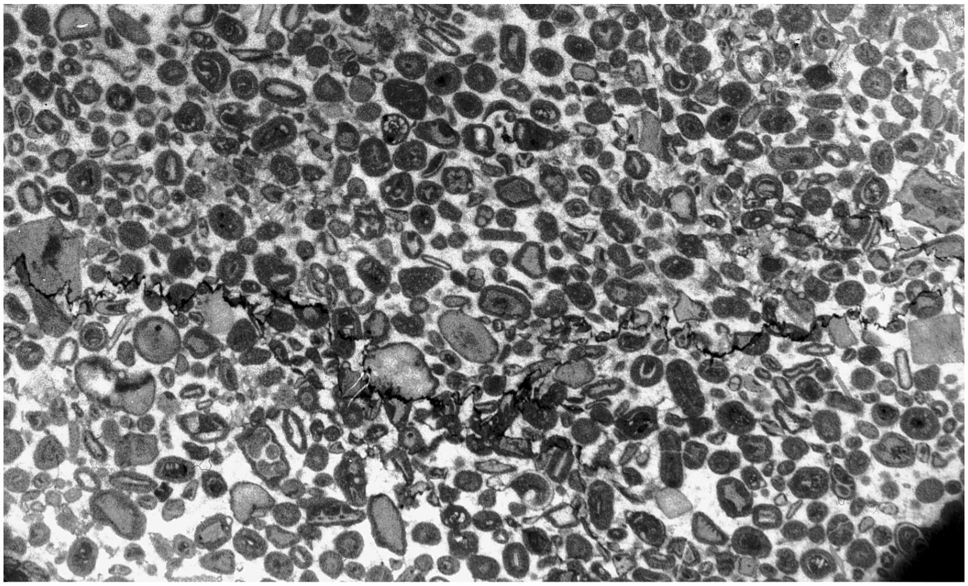
To provide a more meaningful comparison of LPS directions relative to the axis of the Glen Lyn syncline, we then rotated 28 LPS strain-ellipses about a vertical axis so that all local fold axes were aligned with the trend (067°) of the axis at Glen Lyn, and all

A.

Fig. 4. Typical objects digitized for strain analysis. (A) Photograph of mudcracks at locality 2 (fig. 2). The mudcracks are ~15 cm long.

shortening directions were plotted in the northwest quadrant (fig. 6C). LPS directions then range from 262° to 331°, with an average of 308°, and a standard deviation of 17°. After this rotation only two shortening directions are in the southern Appalachian range (330°-345°), 15 are in the central Appalachian range (295°-315°), 10 remain in the transitional range (315°-330°), and 5 anomalously indicate east-west shortening. If these anomalous directions associated with carbonates with very low percent shortening (1 percent) are excluded, because they obviously skew the data (fig. 6C), then the average shortening direction is 311°. This principal LPS direction (311°) thus lies 26° from the perpendicular to the Glen Lyn syncline (067°) but is only 6° from the perpendicular to the average trend (~35°) of central Appalachian folds. The 311° LPS direction is similar to shortening directions (~300°) in the central Appalachians determined by Evans and Dunne (1991), Couzens and others (1993), and Smart, Dunne, and Krieg (1997) and is virtually identical to the "rotated central Appalachian" shortening direction identified by Couzens and others (1993) within the transition zone.

The magnitude of the shortening (the numerical value of S_3) was determined by two different methods to constrain the range in magnitude if LPS developed solely by different mechanisms: first assuming total volume loss (that is, pressure solution) and



B.

C.

Fig. 4(B) photomicrograph of öolites at locality 13. Larger grains are 1-2 mm long. (C) Photograph of burrows at locality 32. Larger burrows are 1-1.5 cm in diameter.

then assuming constant volume deformation (that is, non-solution mechanisms). Given the low temperature (100°-150°C) of these sedimentary rocks at the time of deformation (Lewis and Hower, 1990), plastic flow is not as likely a deformation mechanism as intergranular mechanisms or pressure solution. Percent shortening calculated as total volume loss is consistently much higher than that calculated as constant volume deformation (table 1). We discuss below why the latter mechanism is more applicable to these data. The value of S_3, assuming constant volume deformation, varies from 0.79 to 0.99 with a mean value of 0.89 and a standard deviation of 0.05. Thus, the percent shortening ranges from 1 to 21 percent. This LPS strain would be attributable to intragranular mechanisms (grain boundary sliding, calcite twinning). Within the Tusca-

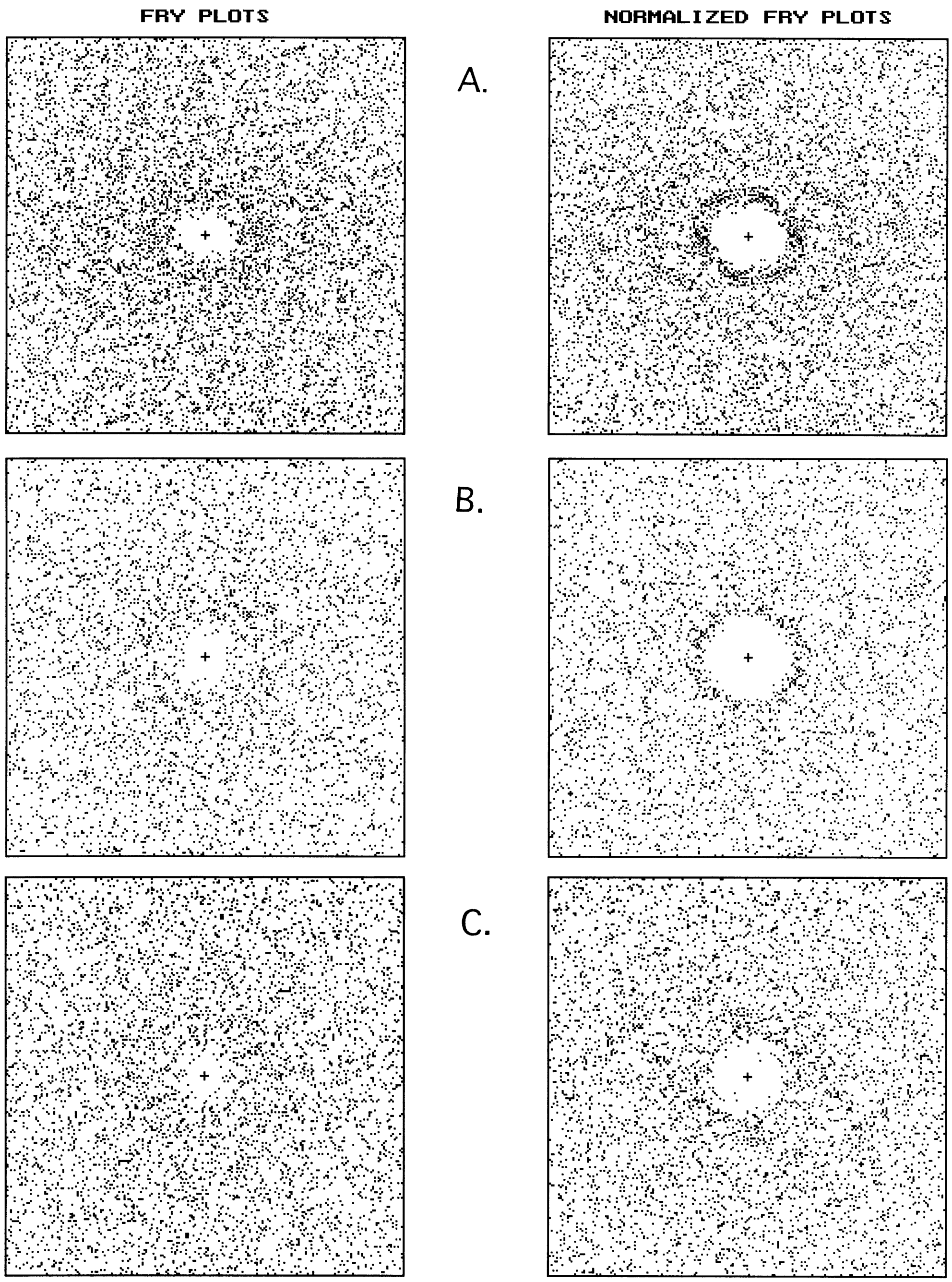


Fig. 5(A) Fry diagram and normalized Fry diagram derived from mudcracks at locality 2 (N = 150); (B) öolites at locality 16 (N = 348); (C) burrows at locality 32 (N = 467).

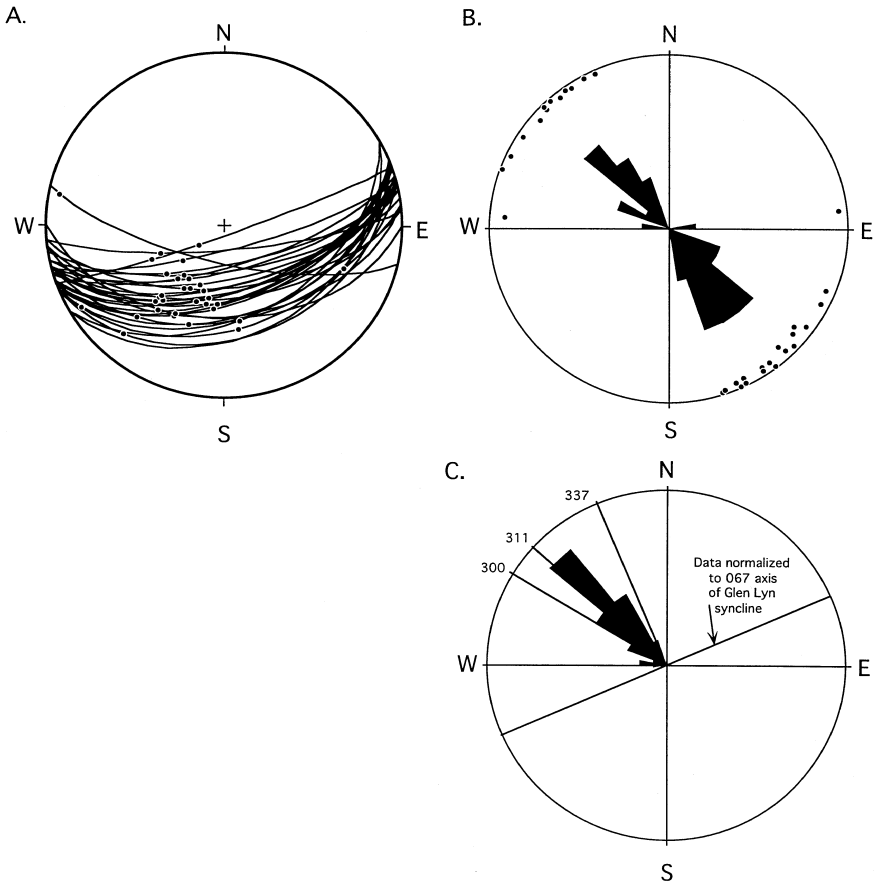


Fig. 6. Lower hemisphere, equal-area stereographic projections showing: (A) 32 short axes of strain ellipses plotted as pitches on bedding surfaces of the overturned limb of the Glen Lyn footwall syncline; (B) The same 32 axes plotted as lines after the bedding is restored to horizontal and corrected for local plunge of the Glen Lyn syncline and a rose diagram of these 32 axes. The circle equals 20 percent. These are the strain ellipses shown on figure 3 (column SD on table 1). (C) Rose diagram of the same 32 axes after the segments of the Glen Lyn syncline were rotated to 067°, the trend of the axis at Glen Lyn, (column NO on table 1). The circle equals 40 percent. The average trend of shortening directions in the central Appalachians (300°) from published sources, is shown for reference along with the perpendicular (337°) to the Glen Lyn syncline that trends near the 335° shortening directions for the southern Appalachians from published sources.

rora quartz arenite, Couzens and others (1993) estimated "central" and "southern" LPS of 10 and 5 percent, respectively, with both present within the transition zone of the recess. Simon and Gray's (1982) mudcrack data (19-28 percent LPS) for Moccasin mudstones are similar to the high end of LPS magnitudes determined during our study. Thus, our results are in reasonable agreement with previous work in the region.

Local variance in S_3 is lithologically controlled. Four of our samples are from carbonates of the Greenbrier Group, and three are from grainstone beds within the Bluefield Formation. Except for sites 13 and 23, which have shortening values similar to those for nearby mudcracks and/or burrows, the samples from carbonates yield strain ellipses that indicate notably lower (~3 percent) LPS strains than in adjacent clastic rocks (~15 percent) (fig. 7). We interpret these low strains as the contribution due to constant volume deformation by processes such as twinning because thin sections (fig. 4B) show

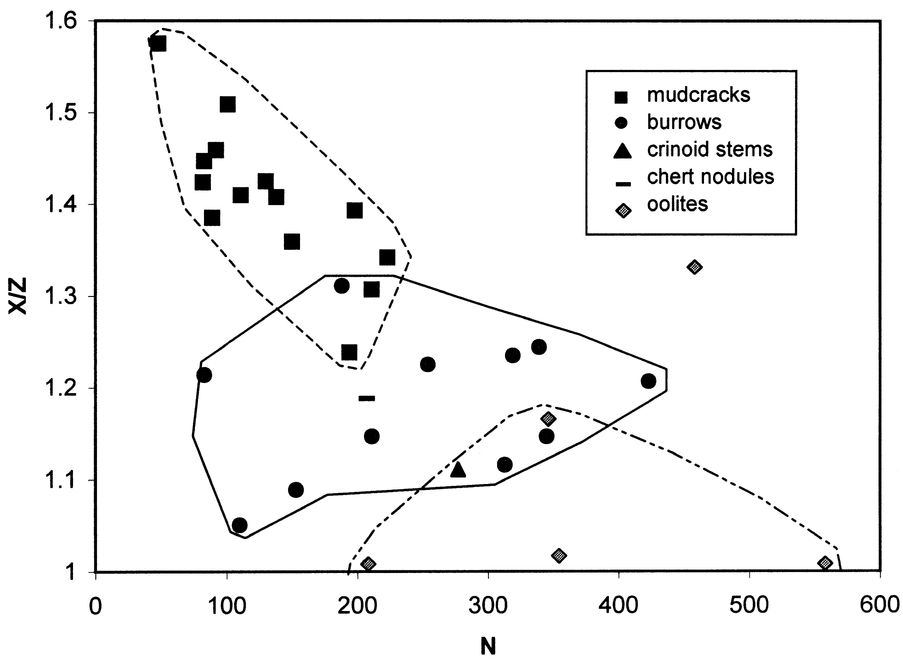


Fig. 7. Graph of N (number of objects) versus X/Z (ellipticity determined from normalized Fry diagrams).

extensive matrix among slightly elongated öolites and little evidence of solution at grain-to-grain contacts. Spraggins and Dunne (1998) also noted very low strains in carbonates of the Greenbrier Group in the adjacent Appalachian Plateau. We suggest that pressure solution along bedding-normal stylolites accommodated the difference in LPS in the coarser grained carbonates. Although we have not evaluated the effects of stylolites, they are generally present in exposures of grainstones. Moreover, Smart, Dunne, and Krieg (1997) showed that pressure solution was the dominant mechanism for LPS in the Greenbrier Group of the central Appalachians accounting for ~11 ± 5 percent shortening, assuming volume loss. At the scale of the photomicrographs used to determine the strain in the carbonates, the stylolites are obvious pressure-solution features (fig. 4B) with considerable shortening but were avoided in measurements of grains for this study.

A geographic distribution of the shortening magnitude is apparent as well. In the eastern portion of the study area, percent shortening is consistently higher than in the western portion. For sites 21 to 32 the LPS strain ranges from 3 to 16 percent and averages 9 percent, whereas for sites 1 to 20 (excluding both the low strains in carbonate sites and site 9 which had a minimal number of objects) it ranges from 10 to 19 percent and averages 14 percent. This suggests that a 5 percent change in strain magnitude occurs between sites 20 and 21.

DISCUSSION

From near Glen Lyn to ~10 km northeast of Bluefield, which overlaps the southwest-part of the area examined by Dean, Kulander, and Skinner (1988), the higher magnitude (~14 percent) LPS, herein interpreted as related to the central and transitional Appalachians, is folded in the Glen Lyn syncline, a structure related to southern Appalachian shortening. Hence, the central/transitional Appalachian LPS strain predated the syncline and the associated St. Clair fault. This contradicts the conclusions of Dean, Kulander, and Skinner (1988) and Couzens and others (1993) that central Appalachian deformation postdated that of the southern Appalachians. Farther southwest, the lower magnitude (9 percent), central/transitional Appalachian LPS occurs in both the overturned limb of the Glen Lyn syncline (sites 21-31 on fig. 3) and the upright limb (site 32) almost to Richlands, which is some 100 km beyond the transition from central to southern Appalachians shown by the trends of major folds in the fold and thrust belt on regional maps (Virginia Division of Mineral Resources, 1993; Dean, Kulander, and Skinner, 1988; Couzens and others, 1993). Thus, the lower magnitude LPS strain also predated the Glen Lyn syncline and St. Clair fault.

Still farther to the southwest, the Glen Lyn syncline ends just north of the Russell Fork fault at the northeast-end of the Pine Mountain thrust system (Wentworth, 1921; Rich, 1934; and Mitra, 1988) (fig. 1). The Pine Mountain thrust system occupies an equivalent structural position to the Glen Lyn syncline relative to the St Clair thrust system. Deformation mechanisms within the Tennessee portion of the Pine Mountain thrust system (Wiltschko, Medwedeff, and Millson, 1985; Kilsdonk and Wiltschko, 1988) produced an early shortening direction of ~300°, quite consistent with the shortening directions found in the central Appalachians (Evans and Dunne, 1991; Couzens and others, 1993; Smart, Dunne, and Krieg, 1997). This geographical distribution of 300° to 311° shortening directions suggests that central/transitional Appalachian LPS affected the forelandward margin of the southern Appalachian fold and thrust belt for at least 300 km southwest of the Roanoke recess. Thus, fold trends of the Appalachian Plateau (fig. 1), observable on regional maps (Hatcher and others, 1990) that extend beyond the Roanoke recess from West Virginia into Kentucky may well reflect this pre-southern Appalachian deformation because they are nearly perpendicular to the 311° LPS direction preserved in the Glen Lyn syncline. These Plateau folds are separated from sub-parallel "transitional" folds of the fold and thrust belt which occur in a wedge-shaped zone eastward of the terminus of the St. Clair thrust (Dean, Kulander, and Skinner, 1988). The intervening area is the 40 km-wide zone studied by Dean, Kulander, and Skinner (1988) where central Appalachian folds and the Glen Lyn syncline abut.

Various factors may explain why our results differ from conclusions of previous studies. Dean, Kulander, and Skinner (1988) documented evidence indicating that northeast-trending central Appalachian structures postdated east-northeast-trending southern Appalachian structures similar to the view, then held, of sequential development of the "Lackawanna phase" followed by the "Main phase" in the Appalachian Plateau of New York and Pennsylvania (Geiser and Engelder, 1983). On a very broad scale, our interpretation is not so incompatible with this tectonic synopsis of Dean, Kulander, and Skinner (1988) if a collisional model such as that of Sacks and Secor (1990) is envisioned. In their model, (1) early but ongoing oblique collision between north-moving Gondwana (Africa) and Laurentia is followed by (2) a north-south collision between Gondwana (South America) and Laurentia followed by (3) resumption of more east-west collisions of Gondwana (Africa) and Laurentia. These three stages could correspond to our (1) early LPS strain followed by (2) formation of southern Appalachian structures, followed by (3) resumption of central Appalachian deformation, which affected the area east of our study where Dean, Kulander, and Skinner (1988) worked.

Dean, Kulander, and Skinner (1988) examined solution cleavage and stylolitic joints, which developed during the principal phases of southern and central deformation, whereas we examined a pre-folding LPS strain. Thus, it is possible that the LPS strain we document does represent a significantly earlier Alleghanian event that was approximately coaxial with, but unrelated to, the main central Appalachian deformation. In this case, both the main central and southern Appalachian deformations would then overprint such an earlier, central/transitional event. One implication of this scenario might be that, prior to development of the St. Clair thrust and Glen Lyn syncline, central/transitional folds were widespread in the Plateau and included the "transitional" folds of the fold and thrust belt in the recess. With increasing displacement southwestward (Kulander and Dean, 1986; Bartholomew, 1987; Mitra, 1988) on the principal southern Appalachian thrust systems (Saltville, Narrows, St. Clair, and Pine Mountain), such central/transitional folds, as well as LPS-strain indicators, would be overprinted, deformed, and/or rotated clockwise toward more southern trends. Indeed, Couzens and others (1993) concluded that the central Appalachian shortening direction was rotated (clockwise) from the normal 300° to 310° within the transition zone whereas the 330° southern Appalachian shortening direction did not experience rotation (counterclockwise) to a more central orientation. Their conclusion supports our interpretation that central LPS predated southern Appalachian deformation.

The boundary between the central and southern Appalachian structural styles may have similarities to that documented in a re-evaluation of the Juniata culmination by Younes and Engelder (1999). They conclude that the Juniata culmination separates two independent, non-interfering, divergent, stress-field rotations and documented counterclockwise rotation in the central Appalachians just north of the Roanoke recess. If the recess stress fields were both independent and divergent, then the sequence that Dean, Kulander, and Skinner (1988) observed in the central Appalachians may have little to do with the sequence in the southern Appalachians. Strain studies in the recess (Couzens and others, 1993) and fracture relationships along the Glen Lyn syncline (Whitaker and Bartholomew, 1998b), however, seem to indicate that central and southern Appalachian stress fields overlapped and, hence, were not independent of one another, so sequential deformation and/or overprinting relationships are likely.

We believe the likely scenario is that initiation of central/transitional Appalachian deformation predated southern Appalachian deformation in the recess. The data from LPS strain, fracture sets, and fault-displacements, when coupled with Younes and Engelder's (1999) data, all suggest independent, but convergent and hence interfering, stress field rotations at the Roanoke recess in contrast with the divergent, non-interfering, rotations at the Juniata culmination. Although we can not address at this time, which was the final deformation (central or southern) in the Roanoke recess, we hope that our ongoing work in the recess may help decipher the complete deformational history of this classic area.

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