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Migration of deformation fronts during progressive deformation: evidence from detailed structural studies in the Pennsylvania Anthracite region, U.S.A.

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Abstract—Detailed study of selected outcrops in the Pennsylvania Anthracite region has resulted in identification of five, at least partly continuous, stages of Alleghanian progressive deformation. These structural stages are, in sequence: A—layer-parallel shortening and top-to-the-foreland, layer-parallel shear; B—a second episode of layer-parallel shortening; C—flexural-slip and flexural-flow folding; D—fold modification and late, thrust faulting; and E—late veining and fracturing. At each outcrop, an average shortening direction was determined for each observed structural stage. The mean regional shortening direction for each structural stage was calculated and maps showing the spatial distribution of the shortening directions for each stage were constructed. The mean regional shortening directions for the five structural stages successively rotated 25–30° clockwise during the evolution of the fold and thrust belt. Shortening directions for structural stages B and C over the region show a systematic clockwise change in orientation from hinterland to foreland, indicating that these structural stages of progressive deformation were time-transgressive on a regional scale.

INTRODUCTION

THIS study examines the regional patterns and sequences of development of small-scale structures in a classic fold and thrust belt, the Pennsylvania Anthracite region of the Appalachian Valley and Ridge Province. In this region, the Paleozoic sedimentary cover was detached from the Precambrian crystalline basement and thrust forward (Boyer & Elliot 1982) (to the north-northwest) during the Alleghanian orogeny at the end of the Paleozoic (Hatcher *et al.* 1989). The overall geometry is that of a blind fold and thrust belt (Dunne & Ferrill 1988) consisting of an unexposed bumpy-roof duplex in Cambro-Ordovician strata and an exposed roof sequence consisting of Silurian through Pennsylvanian rocks. The roof sequence is internally shortened by folding and the development of a complex array of small-scale structures (Gray 1991). In such a fold and thrust belt, the progression of structural evolution may be difficult to determine without exposures of more than one thrust sheet (e.g. Southern Appalachians, Rich 1934; Utah–Idaho–Wyoming thrust belt, Royse *et al.* 1975; Canadian Rockies, Bally *et al.* 1966, Dahlstrom 1969, Price & Mountjoy 1970) or preserved synorogenic deposits from which kinematic interpretations can be made (e.g. Sevier fold and thrust belt, Armstrong & Oriel 1965; Beartooth Laramide uplift, DeCelles *et al.* 1991). In addition, radiometric-age dating of structures in every selected outcrop across a region is not feasible and these techniques are not easily applied to the very low grade metamorphic assemblages typically found in blind fold and thrust belts (Frey 1987). This paper outlines an approach that relies exclusively on small-scale structural analysis at outcrops distributed throughout a blind fold and thrust belt to define the regional temporal and spatial evolution.

Small-scale structures have long been used to delineate the temporal progression of deformation at individual outcrops, but as Tobisch & Paterson (1988) elegantly pointed out, time correlation of structures between outcrops is extremely difficult. The same generation of any structure, such as a cleavage, found throughout a region may not have formed at the same time everywhere in the region (Means 1976). This is because even though a cleavage may represent a single physical event of deformation and metamorphism, the event may have migrated in time from place to place (Mitra & Elliott 1980). Thus, although a cleavage may be correlated over widely spaced areas by careful mapping, this does not necessarily mean that the cleavage formed at the same time everywhere. In emergent fold and thrust belts, pulses of cleavage development can be correlated with emplacement of individual thrust sheets, with some overprinting in earlier thrust sheets (Mitra & Elliott 1980), and an overall forward migration of cleavage fronts can be established (Mitra *et al.* 1984, Marshak & Engelder 1985). In a blind fold and thrust belt, however, the deformation pulses are not confined to individual thrust sheets and may migrate out over much larger areas. Overprinting of structures formed during successive deformation pulses is much more complex in this situation, making it difficult to establish a progression of structural evolution.

Many studies have documented an overall hinterland to foreland progression in faulting in fold and thrust belts (e.g. Rich 1934, Armstrong & Oriel 1965, Dahlstrom 1969, Boyer & Elliott 1982) and others have noted cleavage fronts advancing in front of thrust tips (Marshak & Engelder 1985, Nickelsen 1986); however, a forward progression in deformation should not be assumed (Perry 1978, Morley 1988, Boyer 1992). This

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study first establishes a temporal sequence of structural stages common to the region and then determines the spatial progression of deformation. The evolution of structures through time is established by examining cross-cutting relationships at individual, well-exposed outcrops, identifying a sequence of progressive structural stages that is characteristic of the region. Compilation of the regional orientation data for each stage yields estimates for each mean regional shortening direction. These results document a clockwise rotation in mean regional shortening direction during the structural evolution of the Anthracite region. In a region such as this where shortening directions have changed with time (i.e. paleostress trajectories have changed or the belt has undergone oroclinal bending), the progress of deformation may be mapped for different times during the formation of the fold and thrust belt. Compilation of the progressive deformation data from outcrops across the region allows analysis of spatial variations in shortening trends for each structural stage. In the case of the Pennsylvania Anthracite region, the observed clockwise change from hinterland to foreland in orientations of structures of the same stage indicates that certain structural stages were time transgressive. Structures of the same stage (e.g. a particular cleavage found everywhere in the belt) formed first in the hindward part of the belt and later in the forward part of the belt.

REGIONAL GEOLOGY

The Pennsylvania Anthracite region lies within the Central Appalachian Valley and Ridge Province, in the eastern half of the Pennsylvania salient where the Permo-Carboniferous, Alleghanian fold and thrust belt trends ENE–WSW (Fig. 1). The Valley and Ridge Province in this area is dominated by several doubly-plunging anticlinoria and synclinoria with wavelengths of 7–10 km. These folds are overturned toward the north-northwest in the internal part of the belt (south-southeast) and become more open and upright toward the foreland (north-northwest). The rocks exposed at the surface are Silurian through Pennsylvanian in age and are dominantly siliciclastic with a thin Siluro-Devonian carbonate succession. The Cambro-Ordovician carbonates that underlie the region are internally faulted and detached from the Silurian through Pennsylvanian by a regional, blind thrust fault near the Ordovician–Silurian contact (Epstein *et al.* 1974, Gray 1991). Some of the large Valley and Ridge folds are passive structures formed above internally-faulted Cambro-Ordovician rocks, whereas other folds formed in response to up-section propagation of thrust faults rooted in the Cambro-Ordovician strata (Gray 1991). Most of these faults are blind, although a few are exposed at the present erosion surface and may have been emergent (Fig. 1).

The Pennsylvania Anthracite region is bounded on the north-northwest by the Appalachian Plateau, composed of gentle and upright folds in less-deformed Middle and Upper Paleozoic rocks. To the south-southeast, the Anthracite region is bounded by the Great Valley Province, comprising thrust-faulted and tightly folded Cambro-Ordovician carbonates and slates. The Great Valley Province may have been subjected to more than one orogenic event including the Taconic (Ordovician), Acadian (Devonian) and Alleghanian (Pennsylvanian–Permian) orogenies. Exposed Valley and Ridge rocks of the Pennsylvania Anthracite region are post-Taconian and contain no convincing evidence of Acadian-age deformation (Faill 1985). The Alleghanian orogeny was therefore responsible for all of the deformation in the study area. During this same tectonic episode, the rocks were slightly metamorphosed and Carboniferous coals reached anthracite grade (Levine 1983).

The Pennsylvania Anthracite region is subdivided into the Southern, Middle and Northern coal fields and their surrounding regions (Wood *et al.* 1969). This study was restricted to the Middle and Southern Anthracite region with most of the data from the Southern Anthracite region. Prior to this study, the Pennsylvania Anthracite region had been mapped at a scale of 1:24,000 by the United States Geological Survey and the Pennsylvania Topographic and Geologic Survey (e.g. Wood *et al.* 1969, Epstein *et al.* 1974), but relatively little work had been done on the regional distribution, orientation and relative timing of small-scale structures.

Arndt & Wood (1960) divided the Anthracite region

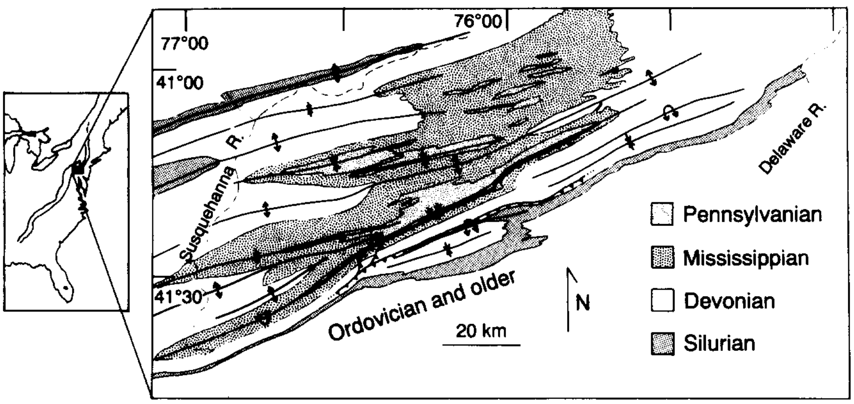

Fig. 1. Geologic map of the Pennsylvania Southern and Middle Anthracite region with index map in inset box. Standard symbols for fold traces and thrust faults.

into five domains, based on the degree of structural complexity and difference in structural styles. The least amount of deformation was found in the Appalachian Plateau in the foreland of the Anthracite region, and the domain with the highest degree of structural complexity was identified as the southernmost Anthracite region. Their study assumed that the styles and types of structures found in the Appalachian Plateau are representative of the earliest stage of regional progressive deformation, experienced instantaneously throughout the region. Subsequent stages of progressive deformation were restricted to increasingly smaller and hindward areas, thus producing a hindward increase in structural complexity. As Means (1976, p. 28) points out, spatial variations in the intensity or character of deformation alone should not be used to establish a temporal sequence. Differences in the rock (e.g. cement types, lithologic and stratigraphic variations) and environmental (e.g. pressure, temperature, fluid characteristics) parameters may cause important differences in the types of structures and structural sequence in different parts of a mountain belt. Therefore, rocks in complexly-deformed hinterland regions need not exhibit the same early stages of deformation as the less-deformed foreland. In this study, the establishment of a temporal sequence of structural stages was first done at individual outcrops throughout the region.

STRUCTURAL STAGES

The first detailed study of progressive deformation within the Pennsylvania Anthracite region was Nickelsen's (1979) classic study of the Bear Valley strip mine located in the Western Middle Anthracite region. His study of a single, superb outcrop carefully documented a six-stage sequence of structures formed during the Alleghanian orogeny. Following two stages of jointing, layer-parallel shortening caused the development of a bed-normal spaced cleavage and small folds. These structures were subsequently modified and transected by conjugate wrench faults and thrust faults. The final stages of deformation involved folding followed by fold flattening by conjugate wrench and extension faults. Our subsequent study of outcrops throughout the region has recognized that the 'Bear Valley sequence' is part of a progression of structural evolution common to the rest of the Middle and Southern Anthracite regions.

Five regionally-significant structural stages were identified across the Southern Anthracite region from the examination of cross-cutting relationships at many outcrops. Each structural stage is defined as a discrete phase of deformation, involving development of a characteristic set of structures such as faults, tectonic fabrics, folds and vein sets (Table 1, Fig. 2). It was beyond the scope of this study to measure populations and generations of joints. The orientation and development of joints record a relatively instantaneous stress state. The development of joints depends on a number of factors, such as differential stress and pore fluid pressures (Secor 1965), not necessarily directly related to orogenesis. Several joint studies have been done in this region and adjacent areas (Wood *et al.* 1969, Nickelsen & Hough 1967, Epstein *et al.* 1974, Nickelsen 1974, Engelder & Geiser 1980, Geiser & Engelder 1983, Orkan & Voight 1985). The relative timing, number of regional sets, and significance of these joints are the subject of continued dispute and a new contribution on this subject will require a large new pool of data.

Rather than use potentially-misleading similarities in current orientation, mineralogies, or morphologies (Williams 1988), correlation from structures of the same stage between outcrops was done on the basis of the type of deformation that the structures accomplished (e.g. contraction faulting to accomplish layer-parallel shortening prior to folding). Not all outcrops exhibit every regionally-significant structural stage. Similarly, some outcrops contain structures that were not easily related to those in other outcrops and therefore, those structures were regarded as local features. Deformation was, at least in part, continuous (see end of this section) with each new structural stage developing in continuity with, and in some cases, overlapping with, the preceding stage (as noted by Nickelsen 1979). Thus the term 'progressive deformation' is used to describe the succession of structures.

Table 1. Representative structures of stages A–E

Stage	Structures
A	Spaced or slaty cleavage and cleavage–bedding intersection lineations Conjugate wrench and wedge faults and associated slickensides Slickensides on bedding and associated gash veins
B	Spaced or crenulation cleavage Crenulation lineations and cleavage–bedding intersection lineations Conjugate wrench and wedge faults and associated slickensides
C	Flexural-slip slickensides and associated gash veins on fold limbs Slickensides on reactivated Stage A and B faults Bedding orientations around folds Small-scale fold hinges
D	Conjugate extension faults and associated slickensides Late thrust faults and associated slickensides and gash veins Post-folding crenulation cleavages
E	Veins or fractures

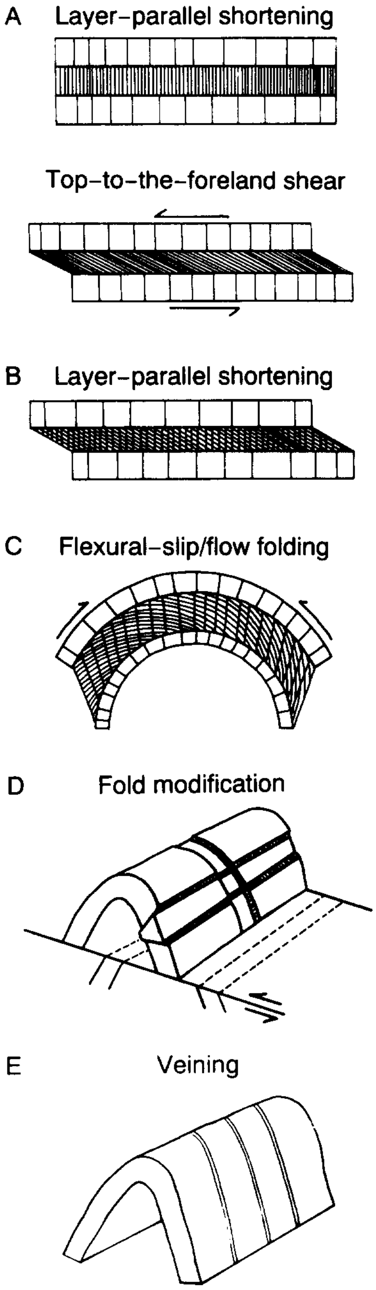

Fig. 2. Schematic diagrams representing the five structural stages of progressive deformation characteristic of the region (see text for explanation).

Stage A

The earliest regionally recognizable stage of deformation is an episode of layer-parallel shortening and top-to-the-foreland (north-northwest), bed-parallel shear when bedding was still at regional dip. Layer-parallel shortening was accomplished by development of a bed-normal pressure solution cleavage and development of conjugate sets of wedge faults (planar acute bisectors parallel to bedding) and wrench faults (planar acute bisectors normal to cleavage and bedding). Although both these types of conjugate faults are found at all stratigraphic levels, wrench faults are most common in thick-bedded, coarse-grained lithologies and wedge faults are commonly found in strata composed of interbedded coarse and fine-grained lithologies. Stage A cleavage is closely spaced to penetrative in shales and spaced in sandstones and conglomerates (Fig. 3a). Quartz and white mica overgrowths on sand-size grains are aligned parallel to the cleavage. Authigenic chlorite, elongate grain shapes and pressure-solution selvages define the cleavage in thin section.

Cleavage–bedding angles vary with lithology and stratigraphic level (Fig. 2). In coarse-grained lithologies, the cleavage is bed-normal and in fine-grained lithologies near the base of the section, the cleavage lies at a low angle to bedding and the angle increases to near bed-normal upsection (Fig. 3a). On restoring bedding to horizontal by rotations on stereonets to remove the effects of later folding, cleavage dips shallowly toward the south-southeast, regardless of position on fold limbs. Cleavage, in some cases, cross-cuts and, in other cases, is cut by slickenfibers on bedding surfaces and gash veins adjacent to bedding surfaces (Fig. 3b). This generation of slickenfibers consistently steps down toward the foreland and gash veins dip moderately to steeply toward the foreland with respect to bedding, indicating a top-to-the-foreland sense of shear. The above relationships suggest that the region experienced an episode of top-to-the-foreland, bed-parallel shear coeval with layer-parallel shortening. After initial development of bed-normal spaced cleavage, cleavage in the fine-grained lithologies was further intensified and reoriented during this layer-parallel top-to-the-foreland shearing.

In areas where only one cleavage is observed (later stages include additional generations of cleavage), Stage A is recognized by the bed-parallel, top-to-the-foreland slickenfibers and early increments of fiber growth at low angles to the medial surface in bed-parallel veins. The effects of Stage A top-to-the-foreland shear are most apparent low in the stratigraphic section and in the eastern half of the region.

Stage B

A second episode of layer-parallel shortening overprints Stage A layer-parallel shortening and top-to-the-foreland, bed-parallel shear structures. This episode of layer-parallel shortening generated another set of conjugate wedge faults and wrench faults and another pressure-solution cleavage. Stage B conjugate wedge faults and wrench faults have similar morphology and mineralogy to those of Stage A and are only possible to classify as Stage B structures in outcrops that also contain Stage A structures (Fig. 3c). In areas where Stage A cleavage is well-developed, Stage B cleavage has a crenulation cleavage morphology (Figs. 3d & e and 5d). Elsewhere, Stage B cleavage is a spaced or primary crenulation (microfolds in a bedding-parallel fabric) pressure solution cleavage. Monocrystalline quartz overgrowths on sand-sized grains are aligned parallel with Stage B cleavage. The orientation of Stage B cleavage varies with lithology and position on folds. Coarse-grained lithologies contain cleavage normal to bedding and finer-grained lithologies contain cleavage at high through low angles to bedding, forming convergent

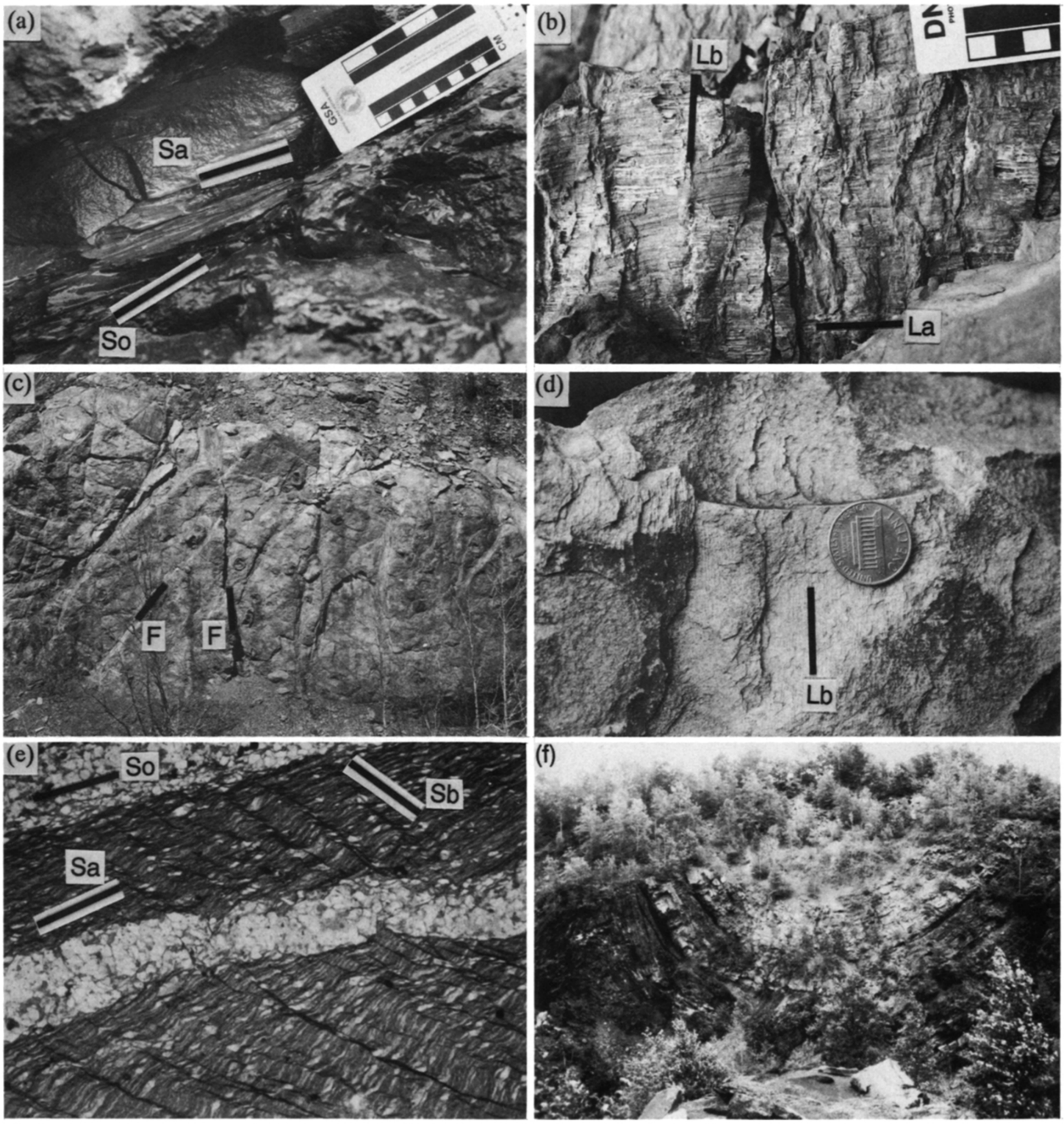

Fig. 3. (a) Outcrop of the Silurian Shawangunk Formation containing Stage A cleavage. Bedding (S_0) dips moderately toward the north-northwest (left). Cleavage (S_a) is at a low angle to bedding and dips shallowly south-southeast after bedding is rotated to horizontal. (b) This steeply-dipping bedding surface in the Devonian Catskill Formation contains Stage A slickenfibers (L_a), indicating top-to-the-foreland slip of the overlying bed (cm scale is directed down-dip of the bedding surface). Slickenfibers are folded and partially truncated by later cleavage (L_b). (c) Numerous Stage B conjugate wrench faults (parallel to black lines, F) reactivated as strike-slip faults during Stage D, causing offset of bedding on the high wall in the abandoned Indian Spring strip mine (Pennsylvanian Llewellyn Formation). Field of view approximately 20 m. (d) This shale bedding plane within the Silurian Shawangunk Formation exhibits WSW–ESE-trending Stage B crenulation cleavage–bedding intersection lineations (L_b). (e) This photomicrograph of the Silurian Shawangunk Formation shows two well-developed cleavages in fine-grained lithologies. The earlier cleavage (S_a) lies at a low angle to bedding (S_0). The second cleavage (S_b), formed during Stage B, is a crenulation cleavage and lies at a high angle to bedding. The orientation of the second cleavage has been modified from bedding-normal due to angular shear on the limb of a flexural-flow fold. Length of photo is approximately 2 mm. (f) A well-exposed example of a syncline in the Pennsylvanian Llewellyn Formation at the Bear Valley strip mine, located in the western Middle Anthracite region. Field of view is approximately 70 m.

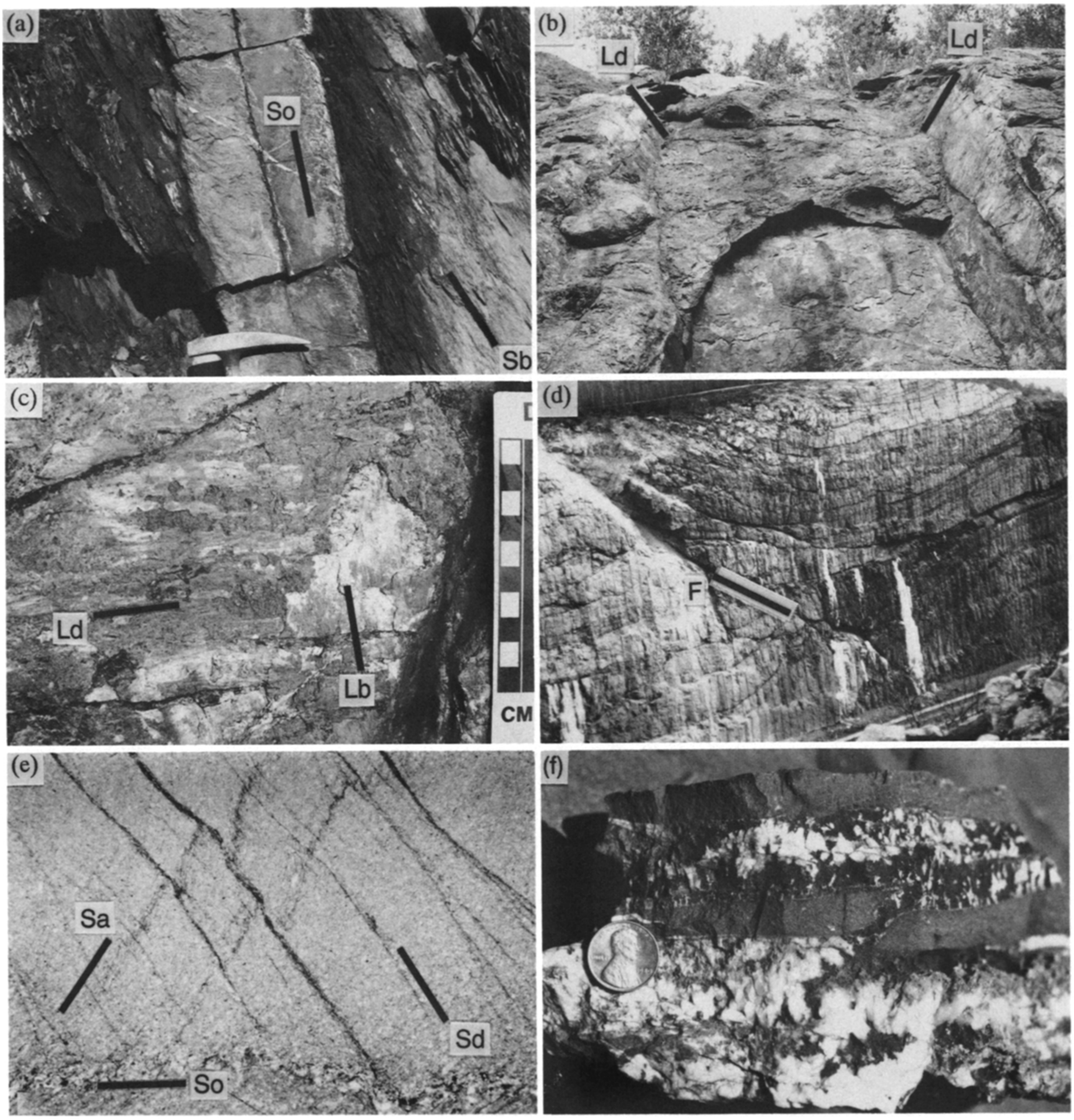

Fig. 4. (a) Bedding (S_0) and cleavage (S_b) relationships in the Devonian Marcellus Formation. The limestone bed in the center of the photograph is overturned and steeply dipping toward the south-southeast (right). Shales above and below are well-cleaved (Stage B) and the cleavage has been modified from bed-normal by flexural-flow folding. Hammer head for scale. (b) The high wall shown in Fig. 3(c) is also transected by Stage D cross-strike conjugate extension faults. Slickenfibers on these faults (parallel to black lines, L_d), drag and offset of bedding indicate that the block bounded by the conjugate extension faults was displaced into the high wall, extending the high wall sub-parallel to the strike of bedding. Field of view is 2 m. (c) Stage D conjugate extension faults often track pre-existing Stage A or in this case, Stage B conjugate contraction faults (wrench faults) seen in Fig. 3(c). The reactivated Stage B fault surface contains two sets of slickensides. The older set (L_b, near vertical) is sub-parallel to the bedding–fault intersection and developed during Stage B fault displacement. The younger set (L_d, sub-horizontal) is sub-normal to the bedding–fault intersection and formed during Stage D strike-parallel extension. (d) This road cut on Interstate Route 81 exposes a syncline (Stage C) transected by a later thrust fault (Stage D) (marked by black line, F). High footwall cutoff angles indicate that the thrust fault propagated through the strata after folding. The thrust fault dips moderately toward the south (right) and carries light-colored Pennsylvanian Pottsville Formation pebble conglomerates and dark-colored Mississippian Mauch Chunk Formation siltstones in the hanging wall and footwall. Guard rail at the base of the photograph for scale. (e) Photomicrograph of Silurian Poxono Island Formation carbonate with multiple cleavages. The earliest cleavage (S_a) may have formed as early as Stage A but continued to develop through Stage C. The later cleavage (S_d) formed during Stage D. Bedding is parallel to the black line marked 'S_0'. Field of view is 0.5 cm. (f) This hand sample from the Devonian Catskill Formation shows the typical mineralogy of the Stage E veins characteristic of the region. The vein contains a thin layer of pyrite at the wall rock–vein contact, void-filling quartz crystals, and latest-stage calcite and siderite mineralization.

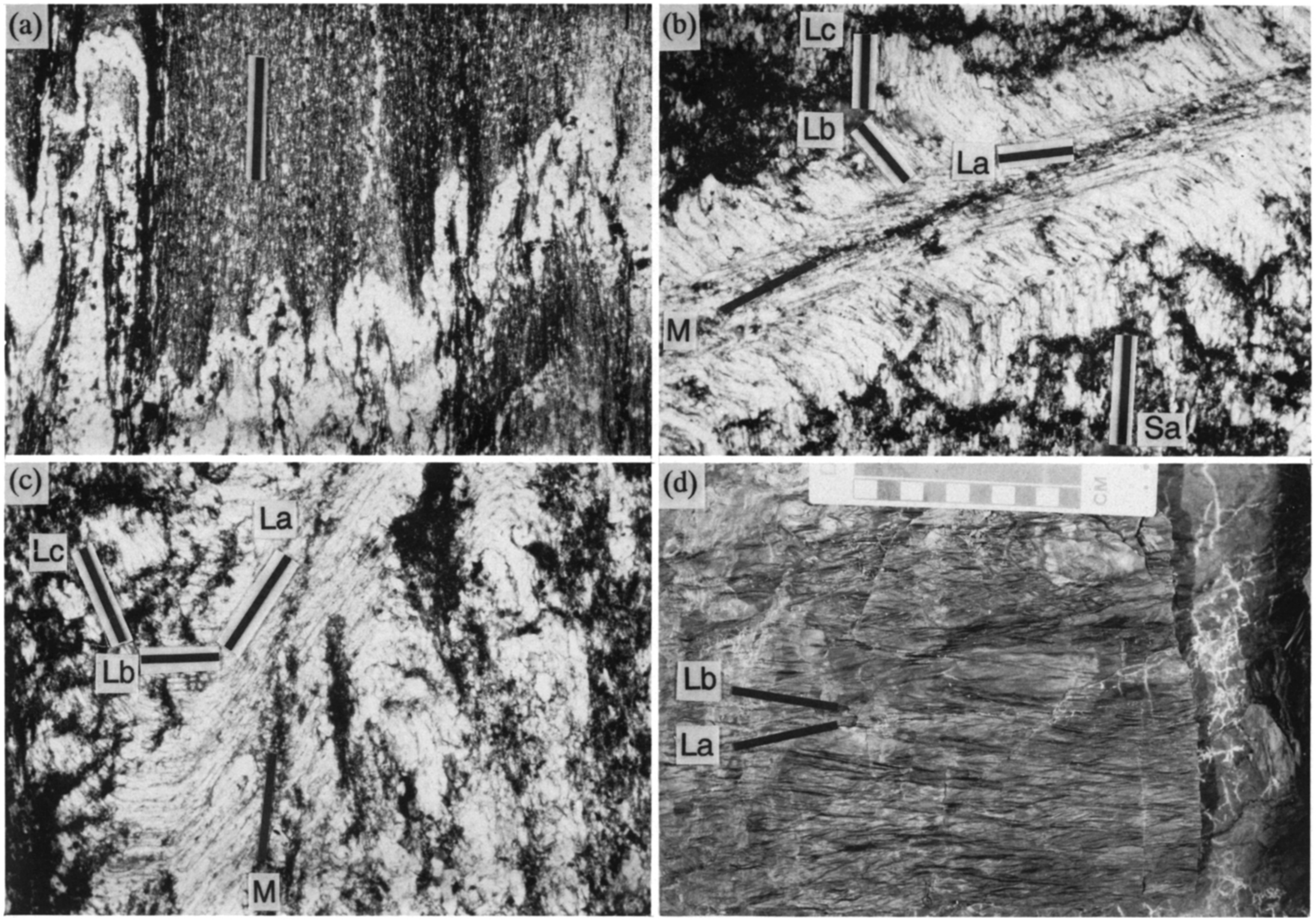

Fig. 5. (a) Folds in microlaminations in the Silurian Poxono Island Formation. Cleavage (parallel to the black line) is axial planar to the isoclinal folds in the microlaminations. Field of view is approximately 0.5 cm. (b) The medial surface (M) of the antitaxial fibrous vein in this photomicrograph of the Silurian Poxono Island Formation is parallel to bedding. The earliest increment of vein growth was nucleation of quartz and calcite crystals along a bed-parallel fracture. Further vein growth was dominated by growth of calcite fibers initially at a low angle to the medial surface (L_a). This stage of vein growth correlates with Stage A cleavage orientations in the adjacent siliciclastic rocks. The calcite fibers incrementally change orientation with distance from the medial surface. A second major increment of growth (L_b) is near bed-normal and corresponds with Stage B incremental extension directions. The final stage of fiber growth (L_c) is parallel to the penetrative cleavage in the surrounding host rock. There is a total of 110° rotation in the orientation of fiber growth in this section of the vein, recording a continuous vein growth history from Stages A–C. Field of view is 0.5 cm. (c) Photomicrograph of Silurian Poxono Island Formation antitaxial fibrous vein with medial surface (M) parallel to bedding. Total rotation in orientation of fiber growth is 140°. Stages of vein growth correspond with those of (c). Field of view is 2 mm wide. (d) This hand sample from the Pennsylvanian Llewellyn Formation contains Stage A and B cleavage–bedding intersection lineations. The Stage A cleavage–bedding intersection lineation (L_a) is counterclockwise of and cut by the more widely spaced, Stage B cleavage–bedding intersection lineation (L_b). North-northwest is toward the top of the page.

fans (Hobbs *et al.* 1976) around folds. Based on these relationships, the second cleavage is interpreted to have formed initially normal to bedding and subsequently to have been reoriented and modified during Stage C, flexural-slip and flow folding (see below).

Stage C

Flexural-slip and flexural-flow folding represents the next structural stage (Fig. 3f). Fold growth modified cleavage–bedding angles in fold limbs, imparted flexural-slip slickenfibers on bedding surfaces, and reactivated favorably-oriented, pre-folding conjugate wedge faults in fold limbs. Flexural-slip folding is indicated by bedding slickensides that have hingeward-directed sense of shear in fold limbs (Tanner 1989). These flexural-slip slickenfibers overprint earlier, Stage A slickenfibers. Stage C slickenfibers can be differentiated from Stage A slickenfibers by their opposite shear sense on the forelimbs of anticlines. Flexural-slip slickenfibers are composed of quartz and calcite, as a function of the composition of the host rock, and generally are less chlorite-rich than Stage A slickenfibers. Cleavage–bedding angles were modified by hingeward-directed angular shear during flexural flow (Fig. 4a) and the amount of reorientation of cleavage with respect to bedding is related to lithology and position on folds (Stamatakos & Kodama 1991a,b).

Stage D

Continued tightening of the smaller-scale folds was accompanied by another generation of conjugate fault sets, late-breaking thrust faults and local cleavages. Earlier, folded structures are cross-cut by later generations of faults: cross-strike and strike-parallel extension faults and late-breaking thrust faults. Cross-strike conjugate extension faults have fault intersections that lie in or close to the plane of bedding (Fig. 4b). Slickenfibers on cross-strike extension faults indicate that motion on these faults was dip-slip in the fold hinges and strike-slip in the vertical or near-vertical fold limbs. These cross-strike faults extended layering sub-parallel to fold hinges and, in several cases, reactivated pre-folding (Stages A and B) wrench faults (Fig. 3c). Strike-slip slickenfibers on reactivated wrench faults clearly overprint the pre-folding slickensides (Fig. 4c). Slickenfibers associated with this stage of deformation are typically composed of quartz.

Strike-parallel conjugate extension faults have fault intersections that are sub-parallel to the strike of bedding and they accomplish down-dip extension of bedding on steeply dipping fold limbs. The development of strike-parallel and cross-strike conjugate extension fault sets at this stage is indicative of sub-horizontal flattening and overtightening of folds.

Other structures characteristic of this stage of deformation are late-breaking (out-of-sequence) thrust faults (Fig. 4d). These faults dip moderately to the south-southeast and cut across previously formed folds. Examples of this stage of faulting are seen at mesoscopic to regional scales. The Blackwood and Sweet Arrow faults, whose traces are shown on Fig. 1, are regional examples of this stage of faulting and they have displacements of up to 3 km (Gray 1991). Exposed Stage D thrust faults contain abundant quartz vein material, quartz slickenfibers and minor chlorite.

Local crenulation cleavages of this structural stage deform and transect earlier Stage A and B cleavages (Fig. 4e). These crenulation cleavages vary in orientation from sub-horizontal to sub-vertical, but the azimuth of shortening direction indicated by the normal to the strike of cleavage is similar to that of the other structures of the same stage at each outcrop.

Stage E

The final regionally-significant, although least well represented, stage of deformation was late veining. This vein set and parallel unfilled fractures cross-cut all earlier structures. These veins have characteristically large surface areas, transect several beds, and can be several cm thick. The veins and fractures are steeply-dipping and strike at large angles to fold axes. In most of the veins, quartz, calcite, pyrite and siderite are present (Fig. 4f). Petrography reveals that vein filling occurred in several stages with pyrite precipitation on the wall rock surface, followed by growth of void-filling quartz crystals. Interstices between quartz crystals were then filled by calcite and siderite.

These five discrete stages were defined by structures in the siliciclastic and pelitic rocks that comprise most of the post-Taconic stratigraphic section. A thin Siluro-Devonian carbonate sequence displays the same stages of progressive deformation but with different structures. The Silurian Poxono Island and Bossardville Formations contain microlaminated limestones and dolomites that have been tightly microfolded (Fig. 5a). Antitaxial (Durney & Ramsay 1973) fibrous veins composed of calcite and minor quartz are parallel to and folded with the microlaminations. The earliest increment of growth adjacent to the medial surface is represented by calcite fibers and small euhedral quartz crystals (Figs. 5b & c). Subsequent stages of vein growth are restricted to calcite fibers alone. These calcite fibers undergo a change in orientation of as much as 140°, recording a continuous, strongly non-coaxial strain history. The earliest stage of fiber growth is uniformly at a low angle (10°) to the medial surface and plunges south-southeast with respect to the medial surface. This incremental extension direction is compatible with that of the Stage A low-angle cleavage found in the nearby pelitic units. An intermediate stage of growth is sub-normal to the medial surface and correlates well with the incremental extension direction associated with Stage B layer-parallel shortening. The final stage of fiber growth is parallel to the penetrative cleavage in the host rock. This cleavage is axial planar to the folded veins and microlaminations and

Table 2. Structures used to determine shortening directions for each structural stage

Stage	Shortening directions
A*	Dip direction of spaced or slaty cleavage Normal to cleavage–bedding intersection lineations Strike of acute bisectors of conjugate wrench faults and trend of associated slickenfibers Dip direction of wedge faults and trend of associated slickenfibers Trend of bedding-parallel slickenfibers and dip direction of associated gash veins
B*	Normal to cleavage–bedding intersection lineations and crenulation lineation Strike of acute bisectors of conjugate wrench faults and trend of associated slickenfibers Dip direction of wedge faults and trend of associated slickenfibers Dip direction of crenulation cleavage
C*	Normal to fold axes Trend of slickenfibers on bedding surfaces Trend of slickenfibers on reactivated Stage A and B faults
D	Parallel to the axis of cross-strike grabens Normal to the axis of strike-parallel grabens Trend of slickenfibers on strike-parallel grabens Normal to trend of slickenfibers on cross-strike grabens Dip direction of late thrust faults and trend of associated slickenfibers Dip direction of post-folding cleavage
E	Strike of late veins and fractures

*Indicates shortening directions determined after bedding was restored to horizontal on stereogram.

forms convergent fans in outcrop-scale folds, implying formation during flexural-flow folding (Stage C).

This fiber growth history suggests that at least Stages A–C were continuous during progressive deformation of the carbonate units. It remains unclear why the neighboring siliciclastic rocks contain multiple cleavages (Figs. 3e and 5d) while the carbonates record a continuous deformation history for the same stages. Perhaps this is a reflection of the fact that carbonates and siliciclastic–pelitic rocks have different thresholds for appropriate deformation mechanisms that depend on such factors as the material properties of their constituent minerals (Groshong 1988).

TEMPORAL VARIATIONS IN REGIONAL SHORTENING DIRECTIONS

The orientations of structures from each structural stage at individual outcrops were measured and plotted on equal-area stereographic projections (Gray 1991). Since folds plunge at angles of only 10° or less in the region, structures formed prior to or during folding were rotated around the strike of bedding on stereograms such that enveloping bedding was restored to horizontal. Best-fitting great circles for different structural elements were chosen by subjective means and by using an algorithm in R. Allmendinger's (1988, unpublished) stereonet program. Great circles and mean vectors defining shortening directions were calculated on each stereogram from the structures listed in Table 2.

The shortening directions for each stage of progressive deformation are shown on maps of the region in Figs. 6(a)–(e). At each outcrop (with rare exceptions), shortening directions for successive structural stages are oriented progressively clockwise of all observed, earlier structural stages. For each structural stage, a regional mean shortening direction was determined (see insets Figs. 6a–e). Each successive regional mean shortening direction is oriented clockwise of previous mean shortening directions. The mean regional shortening directions for each structural stage are, in sequence: AZ 337; AZ 343; AZ 345; AZ 358; and AZ 007 (Fig. 7). These data indicate that a total of 30° clockwise rotation of mean regional shortening direction occurred during progressive Alleghanian deformation.

SPATIAL VARIATIONS IN REGIONAL SHORTENING DIRECTIONS

Stages B and C show a systematic, spatial variation in shortening direction. Graphs of the outcrop shortening directions versus the distance of the outcrops from the hinterland (distance from a datum drawn essentially parallel to the boundary between the Great Valley and Valley and Ridge Provinces) show that, for a given stage, outcrops closer to the foreland record shortening directions clockwise to those at outcrops located closer to the hinterland (Figs. 8a & b). Linear regressions in Figs. 8(a) & (b) grossly indicate that the outcrop shortening directions for Stages B and C rotate clockwise approximately 0.16–0.24° km^{-1} from hinterland to foreland. The difference in orientation is small (approximately 10–20°) and the scatter in the data is relatively large but this is not unreasonable given the size of the region and the heterogeneous nature of rocks.

It is crucial to understand the orientation of the paleostress trajectories prior to interpreting the cause of spatial variations in shortening directions. Spatial variations in shortening directions of individual stages can be the result of instantaneous, non-parallel and/or nonlinear paleostress trajectories caused by diffractions around crustal-scale heterogeneities. The Pennsylvania Middle and Southern Anthracite region is a thin linear belt and major crustal scale heterogeneities that might

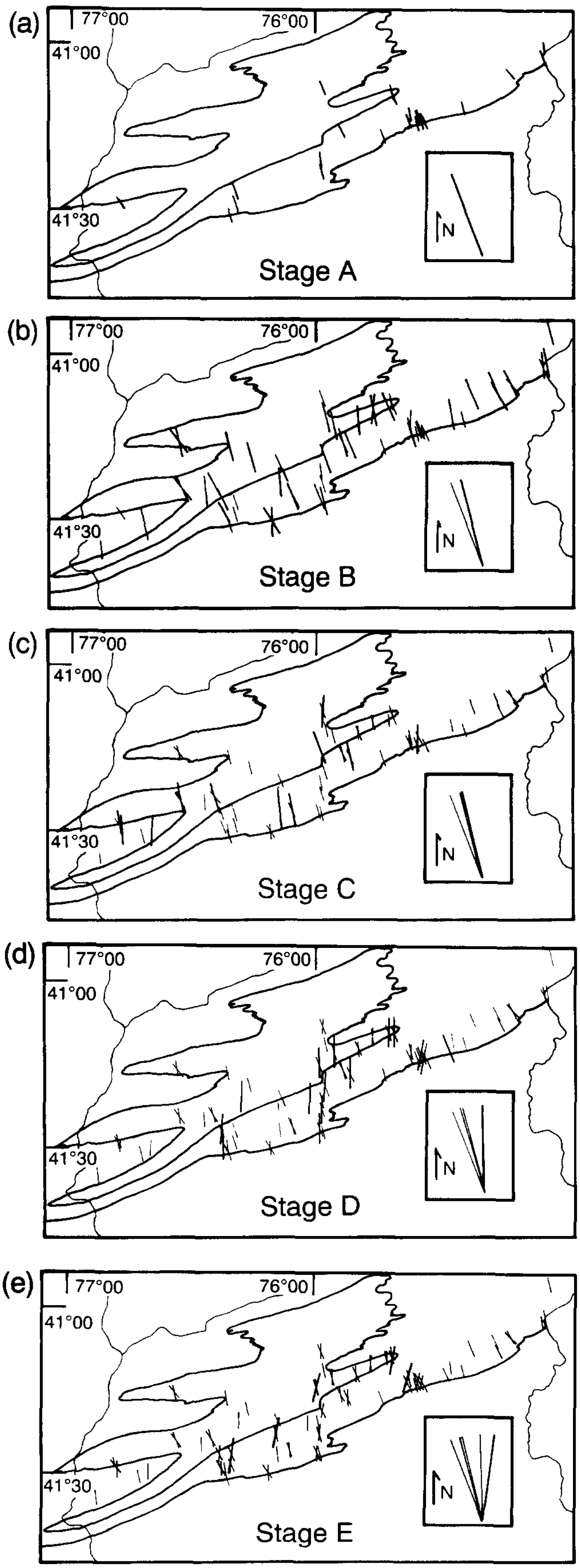

Fig. 6. (a)–(e) Sequential maps of shortening directions of Stages A–E, respectively, at outcrops across the region. Each map is representative of a different stage. Shortening directions of earlier structural stages are shown as smaller lines. Mean regional shortening directions are shown in the inset box on the lower right of each map. The contact lines Mp–Mm (Pocono and Mauch Chunk Formations) and S–O (Silurian and Ordovician strata) are drawn on the maps for reference.

have caused diffraction of paleostress fields are not obvious, based on the available geophysical data. In addition, Alleghanian paleostress trajectories determined from joint orientations in the Appalachian Plateau (directly forelandward of the Anthracite region) are straight with a 10–15° variation in orientation from east to west (Engelder & Geiser 1980). Given the above constraints, the paleostress trajectories across the Southern and Middle Anthracite region were probably near parallel and linear.

A more satisfactory hypothesis for the cause of spatial variations in shortening directions in the Anthracite region is that stages of deformation migrated from one area to another during relative rotation of paleostress trajectories. In an area such as the Anthracite region, where near-parallel and linear paleostress trajectories rotated relative to the deforming mountain belt, structures sharing similar shortening directions can be assumed to have formed at the same time during the same regional shortening event. These structures may be associated with different structural stages, indicating that the deformation had progressed further in one part of the region compared to another.

Maps of shortening directions for structural stages B and C show that structures formed in the same structural stage did not form at the same time throughout the region because the outcrops closest to the foreland yield shortening directions clockwise of similar structures at outcrops closer to the hinterland. Since there was a temporal clockwise rotation in mean regional shortening directions, the spatial clockwise rotation in shortening directions from hinterland to foreland (Figs. 8a & b) indicates that these stages of deformation were diachronous and migrated from hinterland to foreland.

A recent study by Stamatakos *et al.* (1991) examined the absolute age and relative timing of the secondary magnetization with respect to folds in the Anthracite region. The absolute age of the secondary magnetization is the same throughout the region. In the hindward portion of the fold and thrust belt, the secondary magnetization was found to post-date the folds. In the central portion of the belt, the magnetization is partially folded and in the forward portion, the secondary magnetization was acquired prior to folding. These relationships indicate that the folding stage of progressive deformation (Stage C) youngs toward the foreland.

Single- or two-phased Alleghanian orogeny?

Our data generally agree with Nickelsen's (1979) and Geiser & Engelder's (1983) observation that Alleghanian shortening directions rotated clockwise with time in the eastern half of the Pennsylvania salient. Nickelsen (1979) first noted a clockwise rotation in the acute bisectors of wrench faults prior to folding at the Bear Valley strip mine. Geiser & Engelder (1983) documented two layer-parallel shortening events responsible for two dominant joint trends and layer-parallel shortening fabrics in the Appalachian Plateau. Their earlier layer-parallel shortening phase, named the "Lackaw-

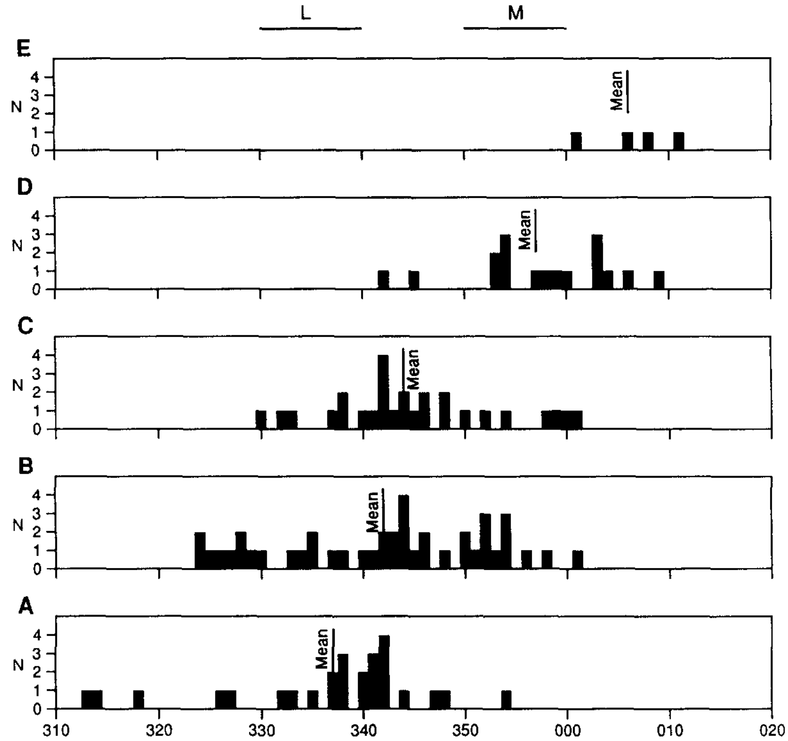

Fig. 7. Histograms for the distribution of shortening directions and mean regional shortening directions for each structural stage. Shortening directions representative of Geiser & Engelder's (1983) Lackawanna and Main phase, (L) and (M), respectively, are shown for reference. These data indicate a clockwise rotation in mean regional shortening directions with progressive deformation.

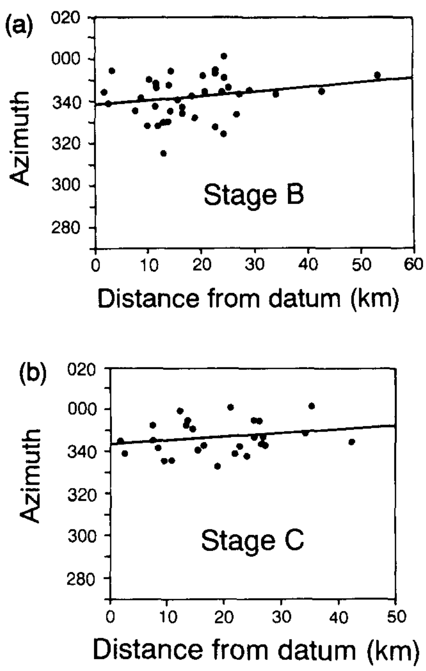

Fig. 8. (a) & (b) The azimuth of shortening directions from Stages B and C, respectively, are plotted against distance of each outcrop from a datum adjacent and parallel to the Taconic unconformity (the south-eastern boundary of the region). Linear regressions through these data have positive slopes, indicating a clockwise rotation in the orientation of shortening directions from hinterland to foreland for structural stages B and C.

anna" phase and the later phase, named the "Main" phase, occurred along different shortening trends, approximately 330–340° and 350–360°, respectively (Fig. 7). The orientations of the "Lackawanna" and "Main" phase shortening directions defined by Geiser & Engelder (1983) in the Appalachian Plateau roughly correlate with Stage A and Stage D regional mean shortening directions, respectively, in the Anthracite region. If the same assumptions hold for the Appalachian Plateau as for the Valley and Ridge Province, structures with similar shortening directions can be assumed to have formed at roughly the same time during the orogeny. Therefore, since Geiser & Engelder's (1983) Main phase layer-parallel shortening episode in the Appalachian Plateau and the orientation of Stage D structures in the Anthracite region are the same, these structures may be of the same age. If this is true, this is another indication that deformation may have proceeded from hinterland to foreland in time.

The orientation of Stage A structures is constant within the Southern Anthracite region (Fig. 6a) and is parallel to the orientations of "Lackawanna" phase structures found in the Plateau. These layer-parallel shortening structures are representative of the earliest recognized stages in both areas. This constant orientation of structures over such a large region may indicate either (1) that this deformation progressed from hinterland to foreland very rapidly (faster than regional stress trajectories changed orientation) or (2) that the regional stress trajectories did not begin to change orientation until some later time during the orogeny (timecorrelative with the onset of Stage B). Since Stage A is fundamentally the same type of deformation (and involves the same types of rate-controlling deformation mechanisms) as Stage B and stress field rotations are recorded by spatial variations in the orientation of Stage B structures, the second explanation appears more likely.

Geiser & Engelder (1983) postulated that the "Lackawanna" and "Main" phases were discrete tectonic episodes, perhaps separated by millions of years. Although we can demonstrate that Stages A–C of the Anthracite region were continuous, we cannot prove that Stages D and E were also continuous. Since Stage D of the Pennsylvania Anthracite region may correlate in time with the "Main" phase of Geiser & Engelder (1983) in the Plateau, we cannot rule out their two-phased model for the Alleghanian orogeny. We contend however, that the evidence for two layer-parallel shortening events in the Appalachian Plateau does not preclude continuous deformation, as demonstrated in the Anthracite region (see previous section). The overall implication of this discussion is that the Alleghanian orogeny was probably continuous, rather than two-phase as suggested by Geiser & Engelder (1983).

DEFORMATION FRONTS

Many studies have mapped the limit of deformation in a mountain belt (e.g. "tectonite frontier" of Fellows 1943, "tectonite front" of Cloos 1971) and/or mapped the boundary between rocks that have undergone a particular style or mechanism of deformation (e.g. "cleavage front" of Cloos 1947, "deformation front" of Groshong 1988 or "tectonite front" of Evans & Dunne 1991). As defined by previous workers, these fronts represent finite states, yet these fronts need not be representative of the position and/or orientation of instantaneous fronts during deformation.

A deformation front as defined in this paper is a conceptual *instantaneous* spatial boundary between rocks undergoing different stages of deformation or between undeformed rocks and those undergoing the earliest stage of deformation. This study documents that in fact, deformation fronts are not fixed in space during the formation of a mountain belt. During Alleghanian deformation in the Pennsylvania Anthracite region, individual deformation fronts migrated progressively and perhaps continuously from hinterland to foreland with time.

Figures 9(a) & (b) schematically show the migration of deformation fronts in sections parallel to the transport direction. These figures imply that deformation fronts dip forward. This would be the case if pressure and temperature, for example, increased with depth and proximity to the internal portions of the belt, thereby causing initiation of deformation mechanisms that control the onset of each new structural stage (Barr & Dahlen 1989). Indeed, Evans & Dunne (1991) mapped a present-day, gently forward-dipping 'tectonite front' in

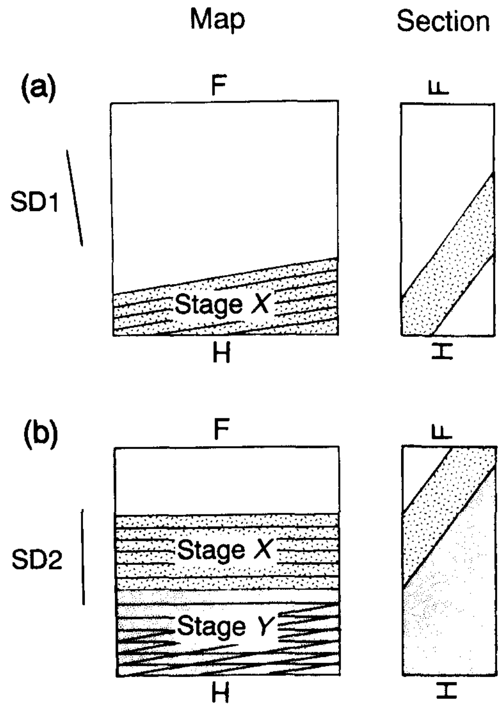

Fig. 9. (a) & (b) This schematic diagram illustrates migration of deformation fronts with time. (a) At some time early in the orogeny, $t = 1$, the hindward part of the belt undergoes Stage A deformation (represented by the heavy stipple pattern), while rocks further toward the foreland remain undeformed (unshaded). (b) At some later time, $t = 2$, the rocks farther out in the foreland are experiencing Stage A of deformation while rocks closer to the hinterland are being overprinted by Stage B structures (represented by the light stipple pattern). This is because the deformation fronts for Stage A and Stage B structures have migrated from hinterland to foreland with time. These schematic diagrams also show the structural relationships expected to develop in a region where the regional shortening directions have changed wth time. In (a), at $t = 1$, the rocks closest to the hinterland undergo the first stage of deformation and their orientation is representative of the earliest shortening direction, SD1. In (b), at $t = 2$, the deformation fronts have migrated forward and rocks closer to the foreland experience Stage A of progressive deformation while Stage B structures overprint the Stage A structures formed closer to the hinterland. The shortening direction for $t = 2$, SD2, is clockwise of SD1 and is the same for both Stage A and Stage B structures developing during this time.

the West Virginia Valley and Ridge Province, perhaps indicating that instantaneous deformation fronts may also have been similarly oriented. It is possible, however, to envision alternative structural scenarios where deformation fronts might be otherwise oriented.

Figures 9(a) & (b) also demonstrate structural patterns (in map view) that arise from migration of deformation fronts in a region where the shortening directions have changed with time. The figures shows that different portions of a region may undergo different structural stages of deformation at the same instant in time. This is borne out in the shortening direction profiles for Stages B and C (Figs. 8a & b). Stage C structures in the hindward segment of the belt have similar orientations as Stage B structures found in the forward segment, indicating that these structures of different stages formed in different areas at the same general time.

Do deformation fronts also migrate laterally with time? It is conceptually possible but not evident in the Anthracite region. The earliest stage of deformation

(Stage A) was largely restricted to the eastern part of the belt and the entire region underwent subsequent stages indicating that deformation migrated laterally between Stages A and B. No demonstrable change in orientation of Stages B, C, D and E occurs along strike, as might be expected if these later stages formed first in the east and the deformation front migrated westward with time; this suggests that the successive onset of each of Stages B, C, D and E occurred at the same general time along strike in the region.

CONCLUSIONS

The Southern Anthracite region has a detailed record of a complex Alleghanian deformation history in the preserved mesoscopic and microscopic structures. This regional structural study has led to the recognition of at least five regionally significant structural stages of progressive deformation: A—layer-parallel shortening and top-to-the-foreland shear; B—a second episode of layer-parallel shortening; C—flexural-slip and flexural-flow folding; D—fold modification and late-breaking thrusts; and E—vein and fracture development. Each successive structural stage developed along a mean shortening direction clockwise of those prior to it. A total of 30° clockwise rotation of mean shortening directions occurred during progressive deformation.

Systematic spatial variations in shortening directions of individual structural stages indicate that some structural stages are time transgressive. Deformation fronts migrated from hinterland to foreland during development of this thrust belt. With attention given to the principal assumptions, this method of study can be applied to other deformed regions, low or high grade, where the shortening directions can be shown to have changed orientation with time or, alternatively, where an orogen can be shown to have changed orientations with time.

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