Pergamon

Journal of Structural Geology, Vol. 19, No. 6, pp. 817 to 834, 1997
Published by Elsevier Science Ltd
Printed in Great Britain
0191-8141/97 $17.00 + 0.00

PII: S0191-8141(97)00009-6

Formation of regional cross-fold joints in the northern Appalachian Plateau

MENG ZHAO and ROBERT D. JACOBI

Department of Geology, 876 NSM Complex, State University of New York at Buffalo, Buffalo,
NY 14260, U.S.A.

(*Received* 21 *June* 1996; *accepted in revised form* 17 *December* 1996)

Abstract—Fold-axis-parallel elongation associated with the development of arcuate fold and thrust belts is proposed as a causal mechanism for syn-orogenic cross-fold joints. Such a mechanism can be coupled with other joint-propagation models, providing a widely applicable resolution to the enigmatic origin of regional systematic joints. The fold-axis-parallel elongation model is compatible with kinematic indicators as recorded by a sequence of cross-fold joints and related deformational fabrics in the central and northern Appalachian Plateau.

Modeling of an arcuate tectonic boundary subjected to normal compressive loading demonstrates that tangential tensile stress can be large enough to initiate cross-fold joints on the convex side of the tectonic boundary. Simulated stress trajectories from boundary element modeling bear a strong resemblance to the stress trajectories inferred from the regional cross-fold joint patterns in the central and northern Appalachian Plateau. Modeling also displays a cratonward decrease in both the tangential stress and the tangential strain. Such a decrease is consistent with the deformation styles observed in the central and northern Appalachian Plateau. Published by Elsevier Science Ltd

INTRODUCTION

Joints in the Appalachian Plateau have been the subject of a number of studies during the past 150 years (e.g. Hall, 1843; Sheldon, 1912; Parker, 1942; Nickelsen and Hough, 1967; Engelder and Geiser, 1980; Engelder, 1985). In each of these well-documented joint systems, one set strikes transversely to regional fold axes ('cross-fold joints', Fig. 1). Cross-fold joints in the Appalachian Plateau typically occur as multiple, non-parallel sets. Parker (1942) suggested that the two most common cross-fold joint sets, which intersect at a small acute angle, occur as a set of 'conjugate shear'; he argued that σ_1 was oriented roughly orthogonal to the orogen, but not parallel to individual joint sets. But evidence for fracture initiation in shear on vertical planes does not exist (Engelder, 1982). In contrast, Nickelsen and Hough (1967) concluded that cross-fold joints are of extensional origin, and are characterized by opening displacement perpendicular to the joint surfaces. Assuming these joints formed perpendicular to σ_3 and assuming joint dilation can accommodate extensional strain of about 10^{-4}, then the joints are highly sensitive indicators of the trajectories of the paleostress field (e.g. Engelder and Geiser, 1980; Segall and Pollard, 1983; Dyer, 1988; Pollard and Aydin, 1988; Engelder and Gross, 1993; Dunne and Hancock, 1994). Thus, multiple sets of cross-fold joints imply a change in the orientation of regional stress over time, with each joint set representing a distinct episode of jointing and a different stress field.

In the Appalachian Plateau of central New York, an Alleghanian clockwise rotation of principal stress trajectories has been proposed based on a temporal sequence of cross-fold joints, pencil cleavages and solution cleavages (Geiser and Engelder, 1983; Bahat and Engelder, 1984; Engelder, 1985) (Fig. 2). The early phase of tectonic shortening in central New York and eastern Pennsylvania was NNW-directed and was named the Lackawanna Phase; the later phase was N-directed and was named the Main Phase (Geiser and Engelder, 1983). This clockwise rotation through time of stress trajectories is compatible with the Alleghanian deformation sequence established in the central Appalachian Valley and Ridge of eastern Pennsylvania (Nickelsen, 1979; Orkan and Voight, 1985; Gray and Mitra, 1991, 1993). In contrast, in the Appalachian Plateau of western Pennsylvania, the fracturing sequence reflects a counterclockwise rotation of the maximum compressive stress direction (Evans, 1994) (Fig. 2). Counterclockwise rotation has also been documented in the Appalachians of central Pennsylvania (Nickelsen, 1988) and southern West Virginia (Dean *et al.*, 1988). Conciliation of these two seemingly contradictory rotations of stress trajectory is crucial to the understanding of the kinematic history of the Alleghanian orogeny.

The mapped extent of the rotation sense of Alleghanian stresses suggest a spatial correlation with the Pennsylvania salient: the counterclockwise rotation occurs in the southwestern section, and the clockwise rotation occurs in the northeastern section of the Pennsylvania salient (Fig. 2). This spatial change in the temporal sequence of various Alleghanian stress orientations may be correlated with the development of the regional 'arcuate' fold and thrust belt.

Arcuate orogens are common around the world (e.g. Bucher, 1924). In a number of arcuate orogens, fold-axis-parallel elongation has been recorded (e.g. Melton, 1929; Laubscher, 1972; Ries and Shackleton, 1976; Coward and Potts, 1983; Ellis, 1986; Bossart *et al.*, 1988; Marshak, 1988; Dietrich, 1989; Sani, 1990; Ferrill and Groshong, 1993; Kirkwood *et al.*, 1995; Morley, 1996). Such elongation provides a likely driving mechan-

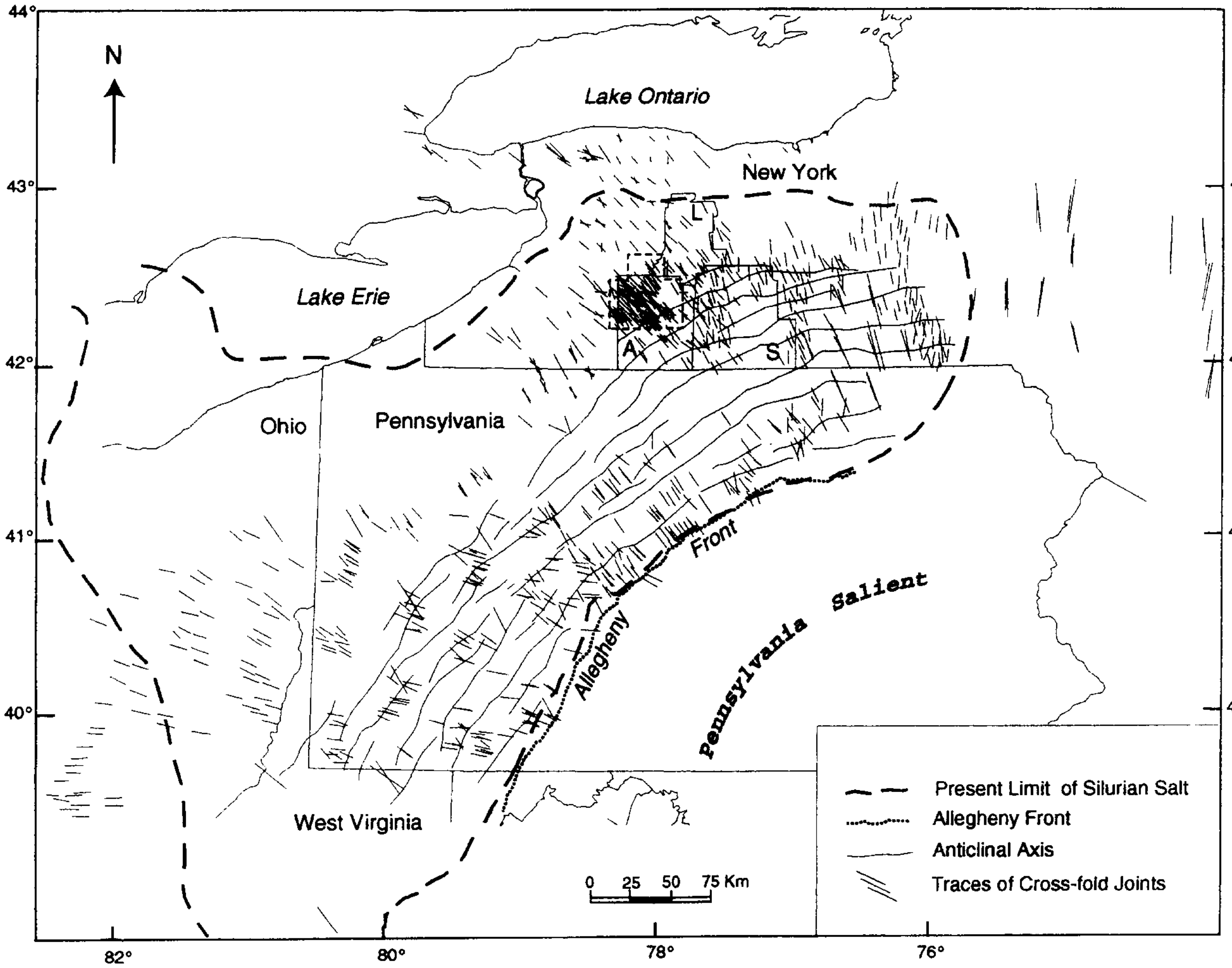

Fig. 1. Map of the central Appalachian Plateau displaying general orientations of cross-fold joints. Data sources include Wedel (1932), Parker (1942), Ver Steeg (1944), Nickelsen and Hough (1967), Overbey and Rough (1968), Fakundiny *et al.* (1978), Engelder and Geiser (1980), Gross and Engelder (1991), Evans (1994) and this study. The area outlined by thin dashed lines indicates the area of detailed mapping and Fig. 3. A, Allegany County; L, Livingston County; S, Steuben County. Modified from Engelder (1985).

ism for the generation of the syn-orogenic cross-fold joints.

Fold-axis-parallel elongation has been proposed for the central Appalachian fold and thrust belt by several researchers. Cloos (1947) described fold-axis-parallel elongation recorded by deformed ooids, microjoints and conjugate microshear fractures from the South Mountain fold of Maryland. Faill (1977, 1979) suggested that in the Pennsylvania salient, fold-axis-parallel elongation was manifested by deformed fossils and conjugate strike-slip faults and resulted from the northwestward radial movement on the Alleghanian décollements; the radial kinematic directions were indicated by the slickenlines on bedding and fault surfaces which were perpendicular to local fold axes. Srivastava and Engelder (1990) proposed that two sets of cross-fold veins and associated fluid inclusions in the Appalachian fold and thrust belt of Pennsylvania provided evidence for strike-parallel stretching associated with either the arcuate shape of the thrust belt or the presence of lateral ramps. Microfracture analyses from the central Appalachian Great Valley (Onasch, 1990) yielded further evidence of fold-axis-parallel elongations up to 11.1%.

Within the Appalachian Plateau, Parker (1942) speculated on the existence of fold-axis-parallel elongation in association with the curvature development of fold belts as outlined by Cloos (1940) in the central and northern Appalachians. Tectonic stresses within the orogenic bend or along the plate boundary impose profound control on the horizontal stresses in regions far beyond the foreland fold and thrust belt (e.g. Engelder, 1979b; Craddock and van der Pluijm, 1989; Zoback *et al.*, 1989). Thus, the recognition of fold-axis-parallel elongation in the central Appalachian fold and thrust belt, especially along the Allegheny front (Faill, 1979), suggests that such elongation may be present in the Appalachian Plateau, which is cratonward of the arcuate Appalachian fold and thrust belt. Indeed, Nickelsen (1966) estimated 4–5% fold-axis-parallel elongation in the Appalachian Plateau of Pennsylvania. However, the finite strain analysis of deformed crinoid columnals (Engelder and Engelder, 1977), and the measurement of preferred orientations of

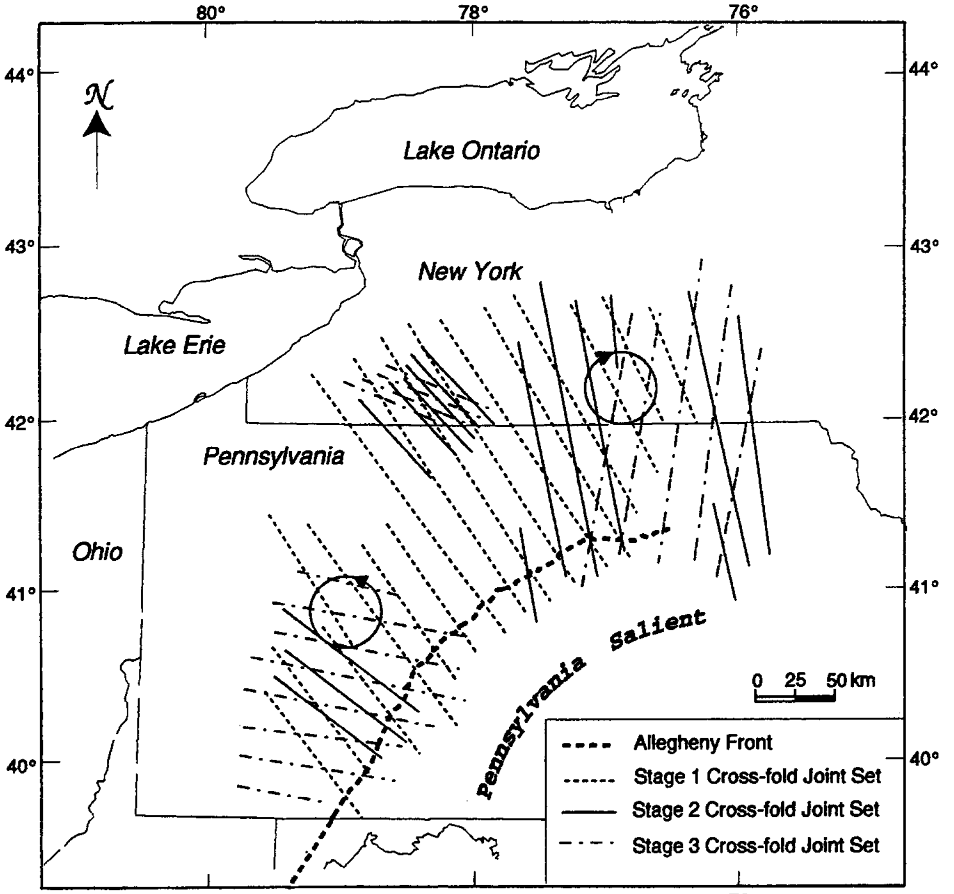

Fig. 2. Rotation directions of the maximum compressive stresses during the Alleghanian orogeny (circles indicate sense of rotation). The different rotation directions of stress trajectories were inferred from the strikes and temporal sequences of cross-fold joints in the central Appalachian Plateau and the adjacent region of the Valley and Ridge province of Pennsylvania (generalized from Fig. 1 and Orkan and Voight, 1985).

the basal plane of chlorite in Devonian shales (Evans *et al.*, 1989b; Oertel *et al.*, 1989), suggested that elongation along the fold axes was either completely absent or of minor importance in the New York Appalachian Plateau. However, the extensional strain accommodated by joint dilation is much less than 1%. For example, the measured extensional strain accommodated by joint dilation in granitic rock of the Sierra Nevada is on the order of 0.01–0.05% (Segall and Pollard, 1983). Therefore, the magnitude of fold-axis-parallel elongation necessary for propagation of cross-fold joints may be too small to be recognized in the finite strain measurements by Engelder and Engelder (1977), Evans *et al.* (1989b) and Oertel *et al.* (1989). Nevertheless, observations made by Engelder (1979a) suggested that extensional strain was recorded by calcite mechanical twins and sparse overgrowths in the pressure shadow of crinoid ossicles.

In this study, we employ both conventional structural analysis and stress modeling to demonstrate that the Alleghanian stress history recorded by the multiple cross-fold joint sets and other related deformational fabrics in the central and northern Appalachian Plateau is compatible with the development of the regional arcuate fold and thrust belt. Fold-axis-parallel elongation associated with the arcuate geometry of the fold and thrust belt is proposed as one of the major mechanisms for the formation of regional cross-fold joints.

STRUCTURAL ANALYSIS

In order to determine the fracturing sequence and to examine the potential relationships among joints, folds, faults, pencil cleavages and deformed fossils, we conducted high-resolution field mapping at over 1000 sites in Allegany County, southwestern New York. The mapping area is located in a transition zone between the region to the east characterized by clockwise rotation of the Alleghanian stress trajectories, and the region to the southwest characterized by counterclockwise rotation of the Alleghanian stress trajectories (Fig. 1).

Detailed mapping in Allegany County revealed eight systematic joint sets in the Upper Devonian interbedded shales, siltstones and sandstones. The strikes of joints in these sets are NNW (322–340°), NW (312–320°), WNW (280–305°), ~E–W (80–95°), ENE (60–75°), NE (45–59°), NNE (25–40°) and ~N–S. Although outcrops commonly show more than one joint set, each of the systematic sets can be the only dominant set at certain localities. Among those eight systematic sets, the NNW, NW and WNW sets can be considered as cross-fold sets.

Relative age of cross-fold joints in Allegany County

The relative age of cross-fold joints can be determined from their abutting relationships and cracking-path interactions (e.g. Dyer, 1988; Cruikshank and Aydin, 1995), or may be inferred from their extent in different lithologies and relation to other structural elements.

Curving-parallel and curving-angular intersections (types 'y' and curved 'y') occur among the cross-fold joint sets. Abutting relationships consistently indicate that the NNW (322–340°) and the NW (312–320°) sets pre-date the WNW (280–305°) set. We emphasize that distinguishing the non-systematic joints from the systematic joints of similar orientation is a prerequisite for using the abutting relationships to determine the relative ages of joints. Non-systematic joints, such as cross-joints (Engelder and Gross, 1993) are excluded from this discussion.

Lithology has a strong effect on the stress distribution and, therefore, on the sequential development of joints. Field observations in central New York indicate that the cross-fold joints in siltstones generally pre-date the cross-fold joints in shales (Bahat and Engelder, 1984; Helgeson and Aydin, 1991). This fact appears to be compatible with the results of *in situ* stress measurements that demonstrate stiffer units generally host higher stress levels (e.g. Evans *et al.*, 1989b). According to the distribution of cross-fold joint sets, the mapped area was divided into two subareas (Fig. 3). In subarea I, the NW joint set is the dominant cross-fold joint set in all types of lithologies. In subarea II, the NNW-striking (322–340°) and NW-striking (312–320°) joints are restricted to competent units (sandstone and siltstone), whereas the WNW-striking (280–305°) joints are the dominant cross-fold joints in shales. Such lithological control of fracture extent is consistent with the abutting relationships that indicate the NNW and NW joint sets (312–320°) pre-date the WNW set. The NNW set is possibly older than the NW set because, in subarea I, the NNW set is more commonly observed in competent units (sandstone and siltstone), whereas the NW joints have been found in the interbedded incompetent units (shale). As will be shown in a later section, this inferred fracturing sequence for the NNW and NW sets is consistent with the age relationship deduced from the structural association between the cross-fold joints and other structure elements.

Thus, abutting relationships and lithological control of joints demonstrate a sequential development (from oldest to youngest) of the NNW, NW and WNW sets. This sequence indicates an overall counterclockwise rotation of paleostress trajectory through time. Further evidence for this rotation can be drawn from the left-lateral subsequent movement along the NW joint set (Fig. 3), and the detailed trace geometry of the NW set. We found a consistent right-step pattern of NW-trending stepped joints and joint-tip en échelon cracks (Fig. 4). The traces of the joint-tip en échelon cracks and stepped joint segments are misoriented from a few degrees up to 10° counterclockwise relative to the trend of the parent joint and joint zone, indicating a sequential mixed-mode rupture when the maximum principal compressive stress rotated from its original orientation of 312–320° to an orientation of 302–310° which is nearly parallel to the younger WNW joint set.

In contrast to this general counterclockwise rotation of stress trajectories, in the southeastern corner of the mapping area, a clockwise rotation is indicated. There, the NNW set can be divided into two subsets, the more northerly striking (~345°) joints are primarily restricted to shales, whereas the more westerly striking (322–330°) joints are more common in competent units. Assuming that cross-fold joints restricted to competent units generally pre-date the joints in incompetent units, the sequential development of the two NNW subsets in east-central Allegany County appears to be consistent with a clockwise rotation of shortening proposed by Bahat and Engelder (1984) for central New York. This clockwise rotation may: (1) mark the regional transition from counterclockwise to clockwise; or (2) be the result of local change in Alleghanian fold and/or thrust geometry.

Other related structural elements in Allegany County

Observations. Since the overprinting of different systematic joint sets is attributed to the multiple deformational events, the structural association among joints and other mesoscopic structures is helpful to determine the temporal sequence of the cross-fold joints. In addition to the subsequent faulting along the NW-striking (312–320°) joint set, three other deformation features are observed at the outcrop scale: deformed fossils, cleavages and small-scale thrusts (Table 1).

A series of small-scale, shallow-dipping thrust faults (with 0.5–8 cm offsets) occur in the thin-layer sandstones of the shale-dominant Caneadea Formation (Fig. 3). Carbonate fibers and slickenlines on the thrust fault surfaces indicate NNW–SSE (~330°) directed shortening (Fig. 5a), which is consistent with the shortening direction recorded by deformed fossils (Engelder and Engelder, 1977), and is roughly parallel to the NNW-striking master joint set at the same sites.

Detailed mapping in Allegany County revealed two types of cleavages in the Machias, Rushford, and the uppermost part of the Caneadea Formations. One type is a regular pencil cleavage developed in thick sections of grey shales. These pencil cleavages were first reported by Engelder and Geiser (1979) as a set of closely-spaced vertical partings that break the shales into elongate pieces with their long edges parallel to the fold axes. We found

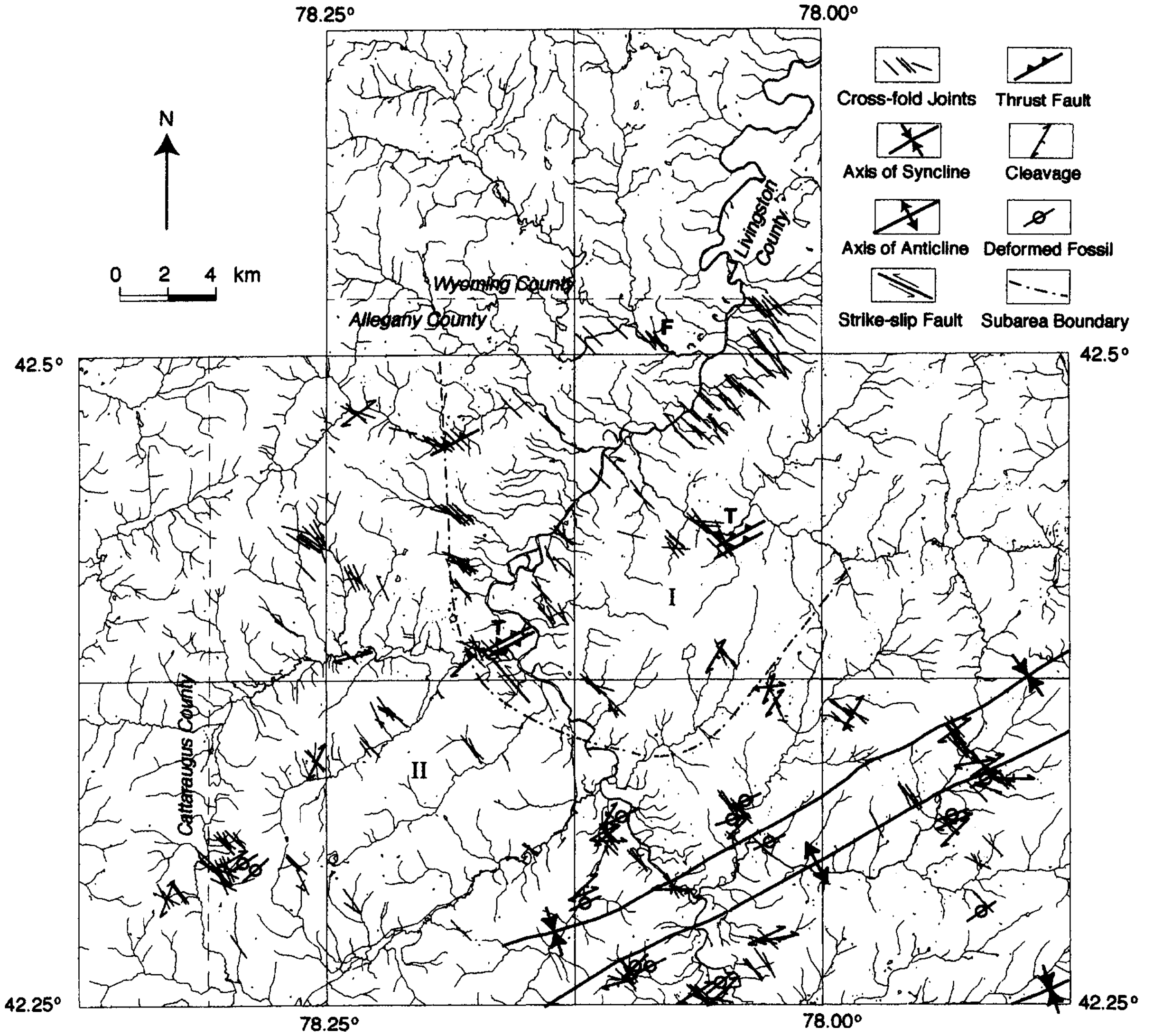

Fig. 3. Map showing fold axes (Wedel, 1932), thrust faults, representative orientations of cleavage, long axes of deformed fossils, strikes of cross-fold joints and stream networks in the area of detailed mapping, southwestern New York. For the purpose of clarity, joint-orientation data from closely-spaced sites are grouped together and displayed as a single joint symbol. Cross-fold joint symbols represent 7238 fracture measurements along scan-lines and 8913 measurements in scan-grids. Roman numerals and dot–dash lines indicate the two subareas based on the preferential orientation of cross-fold joints. F, location for the joint trace pattern shown in Fig. 4; T, data locations for small-scale thrusts in Fig. 5.

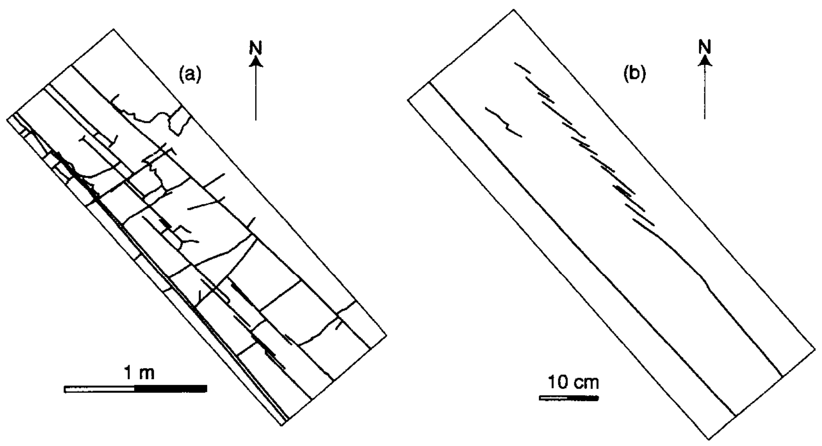

Fig. 4. Joint traces on bedding surfaces of the Wiscoy Formation dolomitic siltstone in northern Allegany County, New York, showing stepped joints (a) and en échelon cracks at a joint tip (b), which may indicate a mixed-mode loading condition (opening and minor left-lateral shearing) due to subsequent counterclockwise rotation of the maximum compressive stress direction.

Table 1. Structural association of cross-fold joints

Deformation sequence	Shortening direction indicated by (structure elements):			
	Cross-fold joints	Deformed fossils	Pencil cleavages	Slickenlines
1	322–340°	~330°	330–350°	~330°
2	310–320°	~320° in Rawson Quadrangle	310–320°	~320°?
3	280–310°	N/A	295–310°	N/A

that in contrast to the 'true' pencils that are bounded by irregular non-planar surfaces (Ramsay and Huber, 1983; Mazzoli and Carnemolla, 1993), pencils in the map area have a relatively regular morphology with a rectangular cross-section that is well defined by the vertical parting and bedding fissility. In terms of their morphology and relation to solution-cleavage (Engelder and Geiser, 1979), they are similar to the weak pressure-solution pencil cleavage defined by Reks and Gray (1982), but different to the pencil cleavage formed by independent grain rotation (Ramsay and Huber, 1983) or by domainal grain rotation in microfold limbs (primary crenulation pencil cleavage of Ferrill, 1989).

The other type of cleavage in the map area is a planar cleavage in silty shales interbedded with very thin shaly silts and silts. This cleavage is characterized by closely-spaced and well-developed planar fissility at low to moderate angles to bedding. In contrast to the pencil cleavage (which represents a layer-parallel shortening), the relatively shallow-dipping planar cleavage may indicate layer-parallel shearing or the superposition of a pure shear with a simple shear (Mazzoli and Carnemolla, 1993).

Although the strike of the cleavages varies by as much as 40° in the map area, previous workers (e.g. Geiser and Engelder, 1983) concluded that the pencils were roughly coeval and consistent with the strain recorded by deformed fossils, all of which resulted from pre-folding, layer-parallel shortening. However, our detailed mapping revealed that the cleavages show three preferential orientations and, thus, can be grouped into distinct sets (Fig. 5b): NNE (25–40°), NE (40–55°) and ENE to E–W (55–80°) sets.

At many sites, the shortening direction represented by the preferred orientation of cleavages (Fig. 5b) is different to the shortening direction indicated by deformed fossils at the same or nearby sites. For example, at Belmont, New York, the deformed fossils in the Machias Siltstone indicate a 330° layer-parallel shortening (Engelder and Engelder, 1977), whereas, in the interbedded shales, cleavages strike from N30°E to N40°E, indicating a WNW (300–310°) shortening direction. At a nearby site, pencil cleavages trending from N40°E to N50°E were also found. These data indicate that at least two stages of shortening were associated with the reorientation of the maximum principal stresses in Allegany County.

Discussion on implications for joint development. Cleavage and the long axes of deformed crinoid columnals are perpendicular to the *Z*-axis of finite strain, whereas each cross-fold joint set is parallel to the σ_1 direction in a distinct stress episode. The orthogonal relationship between cross-fold joints and syn-orogenic fabrics (e.g. cleavage) has been described by several workers (e.g. Cloos, 1947; Engelder and Geiser, 1980; Oertel *et al.*, 1989; Dunne and North, 1990). Thus, the relationships among these features should provide evidence for: (1) stress rotation among multiple stages

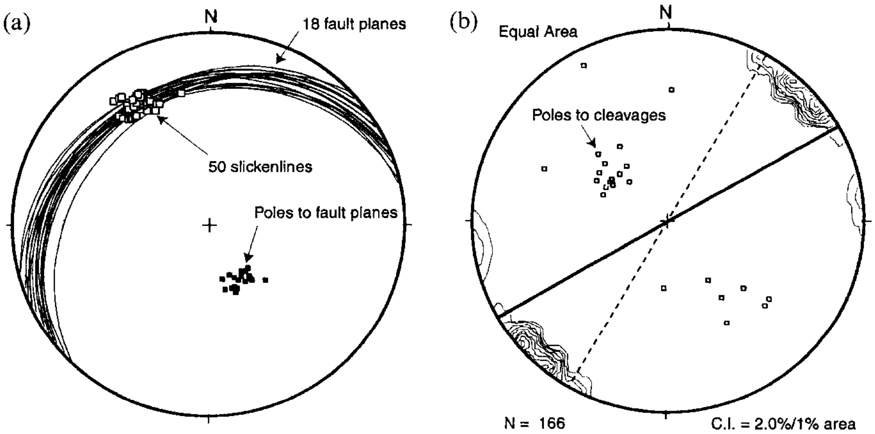

Fig. 5. (a) Orientations of observed thrust faults and slickenlines on fault surfaces in thin bedded sandstone of the Caneadea Formation (plotted on a lower-hemisphere, equal-area stereonet); data from locations labeled with a T in Fig. 3. (b) Geometric relationships among: (1) orientations of cleavages in shales of the Rushford and Machias Formations; (2) the maximum elongation of deformed fossils at Belmont, New York (bold line) (Engelder and Engelder, 1977); and (3) the maximum extensional residual strain (thin dashed line) inferred from the *in situ* strain relaxation experiments at Belmont (Engelder and Geiser, 1980). Plot in (b) is a lower-hemisphere, equal-area stereonet contoured in 1% grids.

of deformation in Allegany County; and (2) a tectonic origin for the cross-fold joints.

The shortening with a consistent NNW–SSE direction as recorded by deformed fossils and slickenlines on small-scale thrust faults may represent pre-folding layer-parallel shortening, which is also parallel to the NNW-striking joints. Because the three sets of cleavages are commonly observed in different units or at different localities, the three sets could indicate either a spatial or a temporal change in paleostress field. However, the fact that each of the cleavage sets (in shale) is approximately orthogonal to a different, regional cross-fold joint set (usually in the interbedded competent units) suggests a temporal change in paleostress, rather than a change in local stress trajectory, and reflects three distinct stages of a non-coaxial deformation history. We emphasize that the strain reflected by the cleavages in the *weakly* deformed shales may be quite small; such 'incipient' cleavages can be a sensitive paleostress marker, with each set of cleavages approximately orthogonal to the maximum compression of a stress episode. If the three cleavages were indeed formed in the same stress fields as the three related cross-fold joint sets, then the sequence of cross-fold joint sets established in the preceding section can be used to determine the sequence of cleavages: from oldest to youngest they are ENE-, NE- and NNE-striking.

However, such a geometric relationship alone is not sufficient to draw conclusions about the genetic (structural) association between the cross-fold joints and the cleavages, since the cross-fold joints might have formed during post-orogenic uplift and might have been controlled by the residual stress 'locked' in these deformed units (Engelder and Geiser, 1980; Engelder, 1985). The following lines of evidence, however, suggest that the 'locked in' stress hypothesis cannot be applicable to all the cross-fold joint sets.

(1) Within the same stratigraphic units in the same area, there may have been an unique post-orogenic residual stress state which was controlled by the latest stage of tectonism. Therefore, in rocks that display several sets of cross-fold joints, at least the earlier jointing stages are unlikely to be post-orogenic. Engelder (1979b) and Engelder and Geiser (1980) suggested that in western New York the residual strain measured from the *in situ* strain relaxation experiments was caused by the tectonic deformation during the Alleghanian orogeny. At Belmont, New York, nine of the 14 strain measurements in the Machias Siltstone yielded a WNW shortening direction ranging from 284° to 313° (Engelder and Geiser, 1980). If this result reflects the shortening direction at the latest stage of the Alleghanian orogeny, the orthogonal pencil cleavages (trending N30°–40°E) observed in the interbedded shales at the site of the *in situ* strain measurements may represent the latest event of the Alleghanian orogeny. This WNW shortening direction is also subparallel to the WNW (280–305°) cross-fold joint set, which we established as younger than the NNW (322–340°) and NW (312–320°) cross-fold joint sets. Thus, even if the youngest joint set is post-orogenic, the older NNW and NW joint sets are probably syn-orogenic.

(2) The NW-striking (312–320°) joints are the most persistent cross-fold joints in the map area, and exhibit a remarkably straight trace pattern; even in zones of relatively closely-spaced joints, neighboring crack paths of the NW-trending joints display little appreciable interaction. The NW joints commonly pass through cross-bedding in sandstones and siltstones without deviation. In subarea I, they cut cleanly through concretions in shales, and the interface between different lithologies. The NW set thus represents a distinctive deformation episode with a relatively high differential stress (cf. Olson and Pollard, 1989; Helgeson and Aydin, 1991), consistent with a tectonic origin.

(3) The abutting relationships between the NW cross-fold joint set and 'strike' joint sets (NE and the ENE sets) provide indirect evidence for the timing and the origin of the NW joint set. Engelder and Geiser (1980) proposed that the 'strike' joint sets (the NE and the ENE sets) are developed during buckling. However, further analysis by Engelder (1982) found conflicting abutting relationships between the NW cross-fold joint set and the 'strike' joint set; such relationships suggested to Engelder (1982, 1985) that both NW-striking joints and strike joints are post-orogenic.

The early joint mapping in Allegany County conducted by Engelder and his coworker was restricted to the more competent siltstones (Engelder, personal communication 1996). Our detailed mapping revealed that the conflicting abutting relationships occur only in competent units, such as the thick Rushford Sandstone. In contrast, in subarea I, a consistent abutting relationship is present in shales: the NW set pre-dates the 'strike' joints. Because multilayer folding generally initiates within the competent units, strike joints first develop in competent units. If the NW set developed during the amplification of the regional folds, then the NW joint set could post-date the strike joints formed during the incipient buckling in the most competent units, but pre-date younger strike joints in relatively incompetent units. This scenario is consistent with the observed abutting relationships between the NW set and the 'strike' joints, and the observed patterns of 'strike' joints. Thus, the NW joint set is probably syn-folding.

In summary: (1) the cleavages associated with the cross-fold joints suggest at least three different stress trajectories; (2) at least the earlier two stress trajectories developed during the Alleghanian orogeny; and (3) the temporal sequence of the Alleghanian stress trajectories in Allegany County, as delineated by joints and other related structural elements, describe a counterclockwise rotation through time.

Regional comparison of cross-fold joints

The tectonic jointing defined in Allegany County may be extrapolated to nearby Steuben and Livingston Counties, New York (i.e. to the east and northeast, respectively; Fig. 1), based on the relationships observed in these areas among: (1) the cross-fold joints; (2) deformed fossils (Engelder and Engelder, 1977); (3) pencil cleavages (Engelder and Geiser, 1979); (4) slickensided small-scale thrusts in thin-layer competent units; (5) left-lateral strike-slip faulted joints (along the NW set); and (6) the lithological dependence of cross-fold joints. NNW-striking (322–335°) joints are present in relatively competent lithologies, whereas the NW-trending (310–320°) joints are mostly restricted to black shales of the Middlesex, West River, and Geneseo Formations.

In central New York, the more westerly striking (330–335°) cross-fold joints (set Ib of Engelder, 1985) are comparable to the NNW set within the competent units in Allegany County in terms of orientation, relative timing, characteristics of host lithologies and orthogonal relation to the long axes of strain in siltstones (cf. Bahat and Engelder, 1984; Engelder, 1985; Oertel *et al.*, 1989); they are consistent with the earliest recognized stages of shortening in western and central New York and even in eastern Pennsylvania (Gray and Mitra, 1993). Younger cross-fold joints in central New York and eastern Pennsylvania trend nearly N–S, suggesting a clockwise rotation which may be comparable in timing to the counterclockwise rotation evidenced in Allegany County.

Southwest of Allegany County, cross-fold joints have been documented in much of the central Appalachian Plateau (e.g. Nickelsen and Hough, 1967; Overbey and Rough, 1968) (Fig. 1). Evans (1994) defined a temporal sequence of cross-fold joints in the west-central Appalachian Plateau. He proposed that the shortening direction associated with the 'main phase' of tectonic jointing, folding and detachment in this region was oriented 300–335°; joints and veins filled with equigranular ferroan calcite, both striking 320–335°, represent the first stage of the 'Main Phase' tectonic jointing. These first-stage 'Main Phase' joints are similar to the NNW joint set defined in Allegany County with respect to relative timing and relationship with slickenlines. Accordingly, the NW set in Allegany County may be correlated with other younger (syn-folding) 'main phase' tectonic joints striking 300–320° defined by Evans (1994).

In summary, the sequential development of NNW- (322–340°), NW- (312–320°) and WNW-striking (295–310°) joint sets in the Appalachian Plateau of western New York and western Pennsylvania, and the sequential development of NNW, ~N–S and NNE joint sets in the Appalachian Plateau of central New York and eastern Pennsylvania, may be correlated in terms of their relative timing and structural association. Such a tentative correlation suggests that the earliest cross-fold joints across the central and northern Appalachian Plateau are oriented relatively consistently at NNW; in contrast, later cross-fold sets show a prominent radial pattern with an increasing radian through time (i.e. the angle between the easternmost cross-fold joints and the westernmost cross-fold joints increases through time) (Fig. 2).

Most previous workers have noted some degrees of consistency in regional joint pattern and the geometric relationship between the cross-fold joints and the general shape of the first-order Appalachian fold belt (e.g. Wedel, 1932; Fettke, 1938; Parker, 1942). Cross-fold joints observed from various depths (0–2442 m) (e.g. Evans, 1994) also show remarkable coherence over very large areas in the Appalachian Plateau and may be traceable in the adjacent region of the Valley and Ridge province (e.g. Orkan and Voight, 1985). Although these joints may not be contemporaneous everywhere, it is possible that they are basically produced by the same stress system (e.g. Gray and Mitra, 1993), if there is no significant change in tectonic setting and stress boundary configuration.

Along the Appalachian orogen there is a remarkable change in structure trend (traces of fold axes and thrusts) (e.g. Marshak, 1988). As the tectonic loading is roughly normal to the fold axes and thrust front (e.g. Chamberlin, 1928; Cloos, 1940), a radial thrusting model, similar to that proposed by Faill (1979) and Ferrill and Groshong (1993), may be considered as a first-order approximation.

Even though the generally 'arcuate' Appalachian fold belts may be better described as a number of linear fold belts and sharp bends (e.g. Faill, 1973), we propose that, to the first-order approximation, fold-axis-parallel elongation did develop as the quasi-radial thrusting (and folding) progressed in the Appalachians of Pennsylvania and New York. This elongation, which includes cross-fold joints, results from tensile stress tangential to the 'arcuate' fold and thrust belts.

The key issue is to determine if 'arcuate' fold belts are capable of producing sufficient fold-axis-parallel elongation to induce the propagation of cross-fold joints. In the following section, we first modeled the stresses in the Appalachian Plateau by means of the analytical solution for an elastic prototype, a thick-walled cylinder, to illustrate the stress distribution and the potential for joint propagation within an ideal radial thrusting model. Then, we utilized a more realistic boundary element stress analysis to test the pertinence of the radial thrusting model and the validity of the fold-axis-parallel elongation model for the formation of regional cross-fold joints. Finally, we employed the available finite strain data to estimate the fold-axis-parallel elongation in the Appalachian Plateau from a kinematic model.

MODEL ANALYSES

The regularly varying regional pattern of the Alleghanian stresses, as inferred from cross-fold joints, suggests that modeling of such a stress system is not only feasible but also meaningful, especially for the Appalachian

Plateau where the strata are essentially flat lying. We emphasize that although in numerical modeling the paleostress state, rock material properties and model geometry cannot be assumed with certainty, numerical stress analysis can be conducted over a range of boundary conditions to develop a conceptual model which is consistent with the field observation. In this context, the main purpose of stress calculation is to obtain the physical insight, and the approach is a qualitative modeling rather than quantitative analysis (Starfield and Cundall, 1988).

Thick-walled cylinder

The simplest elastic stress analysis we performed considered a model wherein a thick-walled cylinder is subjected to an internal pressure p_i and an outside pressure p_o (Fig. 6). The analytical solutions for the radial stress (σ_r) and tangential stress (σ_t) along the circle with the radius r are given by Coates (1981):

$$\sigma_r = \frac{r_o^2 p_o - r_i^2 p_i}{r_o^2 - r_i^2} - \frac{(p_o - p_i) r_i^2 r_o^2}{(r_o^2 - r_i^2) r^2} \tag{1}$$

$$\sigma_t = \frac{r_o^2 p_o - r_i^2 p_i}{r_o^2 - r_i^2} + \frac{(p_o - p_i) r_i^2 r_o^2}{(r_o^2 - r_i^2) r^2}, \tag{2}$$

where r_i is the radius of inner arc and r_o is the radius of outer arc. In the case of a cylinder with an infinite external radius, r_o, the equations become:

$$\sigma_r = p_o - (p_o - p_i) r_i^2 / r^2 \tag{3}$$

$$\sigma_t = p_o + (p_o - p_i) r_i^2 / r^2. \tag{4}$$

Throughout this paper, we follow the engineering sign convention: compressive stress is negative and the tensile stress is positive.

We assume the internal pressure p_i represents the horizontal loading along the tectonic boundary (in this case the modeled boundary is the Allegheny front) and equals the maximum horizontal stress at the tectonic boundary, whereas the outside pressure p_o equals the far-field horizontal stress beyond the limit of the tectonic compression, where it may be assumed to be in a lithostatic stress state (McGarr, 1988):

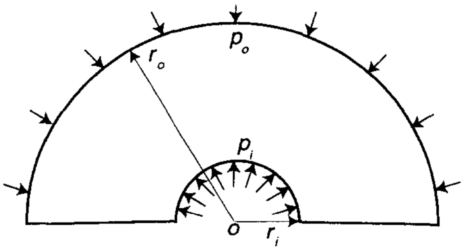

Fig. 6. A thick-walled cylinder model used for the simplest stress analysis of the Appalachian Plateau; p_o is the outside pressure, i.e. the far-field horizontal stress in the absence of tectonic forces, and p_i is the internal pressure which is considered to be the tectonic compression applied normal to the arcuate stress boundary (Allegheny front).

$$p_o = \rho g h. \tag{5}$$

The internal pressure (p_i) may be assumed to be close to the critical value for shear rupture (e.g. Price and Cosgrove, 1990):

$$p_i \geq 4T + \rho g h, \tag{6}$$

where ρ is the density of the overburden, g is the gravitational acceleration, h is the depth and T is the tensile strength with values ranging from 3.2 to 13.1 MPa for Upper Devonian rocks (Evans *et al.*, 1989a).

Figure 7 shows the tangential stress distributions in a cylinder with an infinite external radius and an internal radius $r_i = 250$ km, for a range of values of T and p_i. This model displays a cratonward decrease in the tangential stress and indicates that increasing internal pressure and/or decreasing external pressure will result in an increase in the tangential stress. A significant implication is that tangential extension (fold-axis-parallel extension in this case) induced by the horizontal compressive loading normal to an arcuate tectonic boundary can effectively counteract the compressive stress and facilitate the propagation of cross-fold joints. It can be shown from equation (4) that if the tectonic loading (p_i) is at least twice that of the far-field stress (p_o), extensional stress conditions will occur at shallower depth, within a band 'cratonward' of the arcuate boundary.

Boundary element analysis

A two-dimensional (plane strain) boundary element model is developed assuming an infinite region subjected to a horizontal loading σ_o^{∞} at infinity and a distributed or uniform compression applied normal to a finite

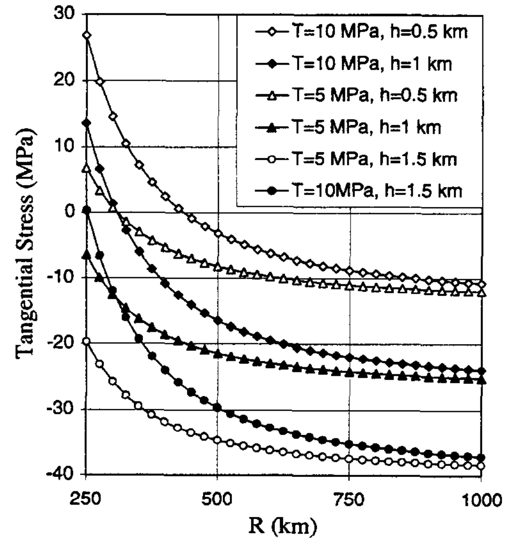

Fig. 7. Tangential stress distributions within the thick-walled cylinder model illustrated in Fig. 6, where r_o is infinitely large, $r_i = 250$ km, h is depth and T is the tensile strength of rocks used for the estimation of the internal pressure (p_i) or the tectonic loading, which is assumed to be close to the critical value for shear rupture.

boundary C (Fig. 8). This model uses the actual trace of the Allegheny front as the stress boundary, so this model is considered to be more 'realistic' than the thick-walled cylinder. The elastic stresses for this model can be solved by the boundary element displacement discontinuity method of Crouch and Starfield (1983). In order to minimize the effect of the singularity at the two ends of the boundary, the Allegheny front was extended along strike from the arc terminations by assigning similar stress boundary conditions on the extended boundaries (Fig. 8). In the boundary element model, the stress boundary is simulated with 152 equal-length linear elements.

An example of the distribution of tangential stresses cratonward of the Allegheny front, calculated with the boundary element method, is illustrated in Fig. 9. In this model, the remote loading, $\sigma_o{}^{\infty} = 0$, and the normal stress at the arcuate boundary equals 50 MPa. Four observations can be made from this example: (1) the calculated trajectories of tangential stress are compatible with the orientations of cross-fold joints (Fig. 9); (2) the tangential stress exhibits a general decrease toward the craton (Fig. 10); (3) tangential stress also displays a dependence on the boundary geometry, the highest value occurring near the portion of the boundary with the greatest curvature (sharp bend or kink), where the tangential stress is amplified; and (4) the overall tangential stress distribution (Fig. 10) represents the composite effect of the loading applied on each portion of the boundary with a different geometry; for example due to the local 'concave' boundary geometry, the position with highest tangential stress along the stress profile III–III′ is at about 80 km away from the boundary.

The more important implications to be drawn from the boundary element modeling are: (i) observations (1) and (2) demonstrate the applicability of a very simple radial thrusting model to the paleostress field recorded by the regional cross-fold joints; (ii) observation (3) indicates that the occurrence of an extensional stress condition is not only possible for a certain range of realistic boundary stress values, but the boundary irregularities (sharp bends) can also cause local tensile stress intensification; and (iii) the overall stress distribution is controlled primarily by the general shape of the stress boundary, indicating that the fold-axis-parallel elongation can occur cratonward of arcuate fold belts.

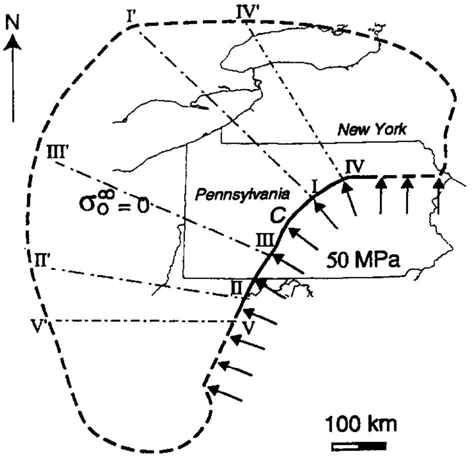

Fig. 8. The boundary element model in which an infinite region is subjected to an arbitrary remote loading, and an uniform compression applied normal to a finite arcuate boundary C. The arcuate boundary considered in the model represents the Allegheny front which divides the Appalachian Plateau from the Appalachian Valley and Ridge province (Engelder, 1985). Dashed lines labeled with roman numerals indicate locations of stress profiles shown in Fig. 10.

Tangential strain deduced from a kinematic model

Following Ferrill and Groshong (1993), fold-axis-parallel elongation can be estimated from a kinematic radial thrusting model (Fig. 11):

$$e_t = \frac{(R_n - R_i)e_r}{R_i - R_n e_r}, \tag{7}$$

where e_t is the tangential extension, e_r is the radial shortening, R_n is the radius of the frontal arc of zero horizontal strain (neutral arc) and R_i is the radius of the inner arc. Although the arcuate fold belts in the central Appalachians are not concentric in detail, we may estimate the curvature center using the roughly concentric arcs that match the general shapes of the Allegheny front and the nearby fold belts in the Pennsylvania Valley and Ridge province. Available finite strain data (e.g. Engelder and Engelder, 1977) impose a crucial constraint for hypotheses of the kinematic model. Because finite strains measured from different indicators reflect different deformation mechanisms operating under various conditions, here we only used the calcite twinning data (Engelder, 1979a,b; Craddock and van der Pluijm, 1989; Craddock *et al.*, 1993), which provide a three-dimensional measurement for intragranular strain at low temperatures. Since the kinematic model is a two-dimensional model, we computed the finite strains in the horizontal plane by determining the horizontal strain-ellipse section of the observed strain ellipsoid (Table 2). The principal strains in the horizontal plane can be considered to be the *observed* radial and tangential strains, respectively.

The radius of the neutral arc (R_n) should be consistent with the deformation front determined from finite strain data. However, positions of the deformation front as defined by different authors are quite different. For example, the deformation front proposed by Geiser (1988) is at a distance of about 220 km from the Allegheny front. In contrast, Craddock *et al.* (1993) concluded that Alleghanian compressive stresses were transmitted over distances up to 1700 km away from the active plate margin. But the finite strain data of Craddock *et al.* (1993) from Phanerozoic rocks pertinent to the central Appalachians are within 300 km of the Allegheny front.

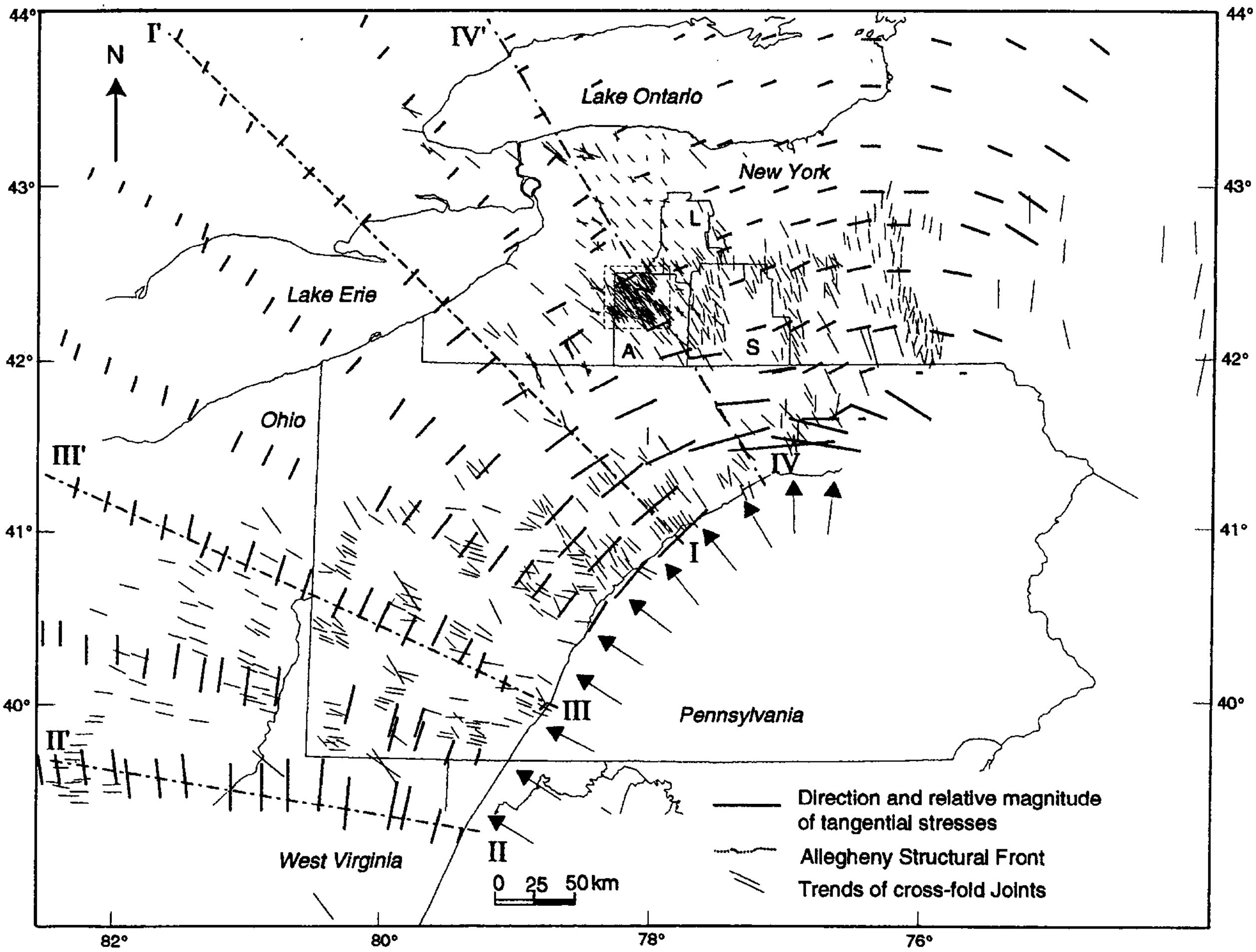

Fig. 9. Distribution of tangential stress cratonward of the Allegheny front, calculated with the boundary element method. Dash–dot lines labeled with roman numerals indicate locations of stress profiles shown in Fig. 10.

Given the uncertainty in determining R_n, we input a series of different values of R_n into equation (7) and calculated different estimates of tangential strain (Table 3). We then compared these results with the observed strains exhibited by calcite twins to test and calibrate the kinematic radial thrusting model. The sum of the squares of the difference between the observed and estimated values of tangential strains (SSM) can be used to quantify the errors of the estimated values from equation (7). The SSM is determined as:

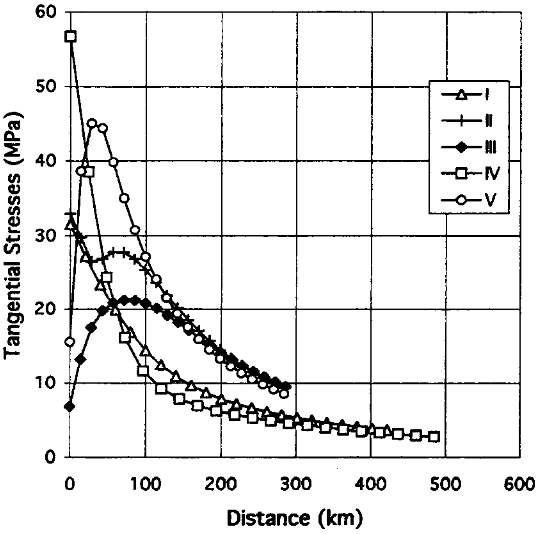

Fig. 10. Distribution of tangential stresses along profiles across the central Appalachian Plateau. Locations of stress profiles are shown in Figs 9 and 10, the prescribed remote loading equals 0 and normal horizontal stress at the arcuate boundary equals 50 MPa.

$$\mathrm{SSM} = \sum_i (e_t(i) - e_{to}(i))^2, \tag{8}$$

where $e_t(i)$ and $e_{to}(i)$ are the estimated and observed tangential strains, respectively.

As shown in Table 3, the computed tangential strains show an obvious linear correlation with the observed values. This relationship suggests that the measured tangential strains, to large extent, can be interpreted by a very simple radial thrusting model. Since the smallest value of SSM occurs with $R_n = 480$ km (Fig. 12a and Table 3), the 480 km value can be used as an estimate for the deformation front in equation (7). Although this estimate depends solely on the calcite twinning data, it is very close to the value for the deformation front proposed by Geiser (1988), based on the overall finite strain data in the Appalachian Plateau of New York. In the vicinity of our proposed deformation front, the elastic strain locked in quartz grains of the Grimsby Sandstone,

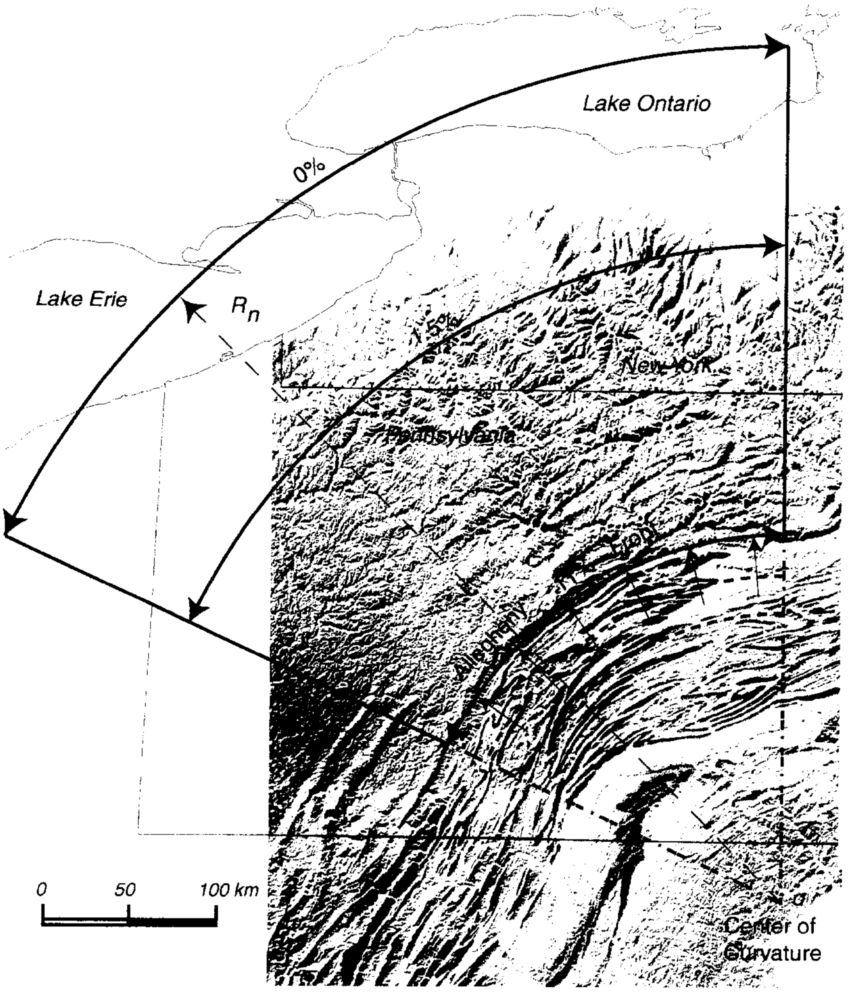

Fig. 11. Map plan of the proposed kinematic radial thrusting model for the Appalachian Plateau of New York and Pennsylvania. The physiography image edited by Cuff *et al.* (1989) is used (with the permission of the Temple University Press) to estimate the curvature center by matching the traces of the Allegheny front and nearby fold axes (thick dashed arcs) in the Valley and Ridge province with concentric arcs. Using the calcite twinning data (Engelder, 1979a,b; Craddock and van der Pluijm, 1989; Craddock *et al.*, 1993), R_n (the radius of neutral arc with 0% elongation) is estimated to be 480 km. The fold-axis-parallel elongations predicted by the radial thrusting model are given as percentages, e.g. 11% along the Allegheny front and 1.5% along an arc across the area of this study. These predicted values are comparable to the elongations recorded by calcite twins.

Table 2. Finite strains in the horizontal plane calculated from the calcite twinning data of Engelder (1979a,b) and Craddock *et al.* (1993)

$R_i\backslash R_n$ (km)	440	450	460	470	480	490	500	550	600	700	800	900	1000	Observed
297.4	2.362	2.532	2.703	2.874	3.045	3.217	3.390	4.262	5.150	6.970	8.855	10.807	12.830	2.10
313	3316	3.587	3.858	4.132	4.407	4.683	4.960	6.371	7.821	10.841	14.035	17.419	21.010	3.27
325	2.044	2.226	2.408	2.591	2.775	2.959	3.144	4.079	5.031	6.989	9.021	11.131	13.325	4.37
327	0.343	0.373	0.403	0.434	0.464	0.495	0.525	0.678	0.832	1.140	1.450	1.762	2.076	0.58
327	0.525	0.572	0.619	0.666	0.713	0.760	0.807	1.042	1.279	1.756	2.237	2.723	3.213	−0.12
353	0.410	0.457	0.505	0.552	0.600	0.647	0.695	0.933	1.173	1.656	2.143	2.635	3.132	0.84
379	0.221	0.257	0.293	0.330	0.366	0.402	0.439	0.621	0.804	1.172	1.543	1.917	2.293	1.24
383.5	0.150	0.177	0.203	0.230	0.257	0.283	0.310	0.444	0.577	0.846	1.117	1.389	1.662	1.11
396	0.631	0.775	0.920	1.065	1.211	1.357	1.504	2.243	2.993	4.527	6.107	7.735	9.414	1.90
400.7	0.074	0.093	0.111	0.130	0.149	0.168	0.187	0.281	0.376	0.565	0.755	0.9461	1.138	−0.01
403	0.017	0.022	0.027	0.032	0.036	0.041	0.046	0.069	0.093	0.140	0.188	0.235	0.283	0.07
410.4	0.064	0.085	0.107	0.128	0.150	0.171	0.193	0.301	0.409	0.627	0.845	1.064	1.284	1.01
418.1	0.004	0.006	0.007	0.009	0.011	0.012	0.014	0.023	0.032	0.049	0.066	0.084	0.101	0.05
418.8	0.004	0.005	0.007	0.009	0.010	0.012	0.014	0.022	0.030	0.047	0.064	0.081	0.097	0.06
438.6	0.001	0.008	0.014	0.021	0.027	0.034	0.041	0.074	0.107	0.174	0.240	0.307	0.374	0.14
R^2	0.8415	0.8475	0.8521	0.8557	0.8584	0.8605	0.8622	0.8662	0.8669	0.8657	0.8637	0.8616	0.8597	
SSM	10.65	9.555	8.789	8.354	8.254	8.494	9.078	17.3	34.77	99.865	209.6	370	588	

The smallest value of SSM occurs with $R_n = 480$ km.

Table 3. Comparison between the values of observed elongation and the values predicted from the radial thrusting model for different radii of neutral arc

Site*	Negative expected value (%)	Principal strains (%)	Estimated error	Bearing (°)	Plunge (°)	Reference	Strain in horizontal plane		
							e_1	e_2	Bearing e_1 (°)
ADI	47	4.03	1.41	234	49	†	2.097	−4.592	74.952
		1.29		91	35				
		−5.32		347	19				
CAM	34	5.22	2.62	70	60	†	3.272	−7.330	79.114
		2.15		261	29				
		−7.37		168	5				
AND	20	5.35	1.37	54	32	†	4.370	−5.358	63.137
		0.52		262	54				
		−5.88		152	13				
VAN I	23	0.88	0.62	180	68	†	0.582	−0.978	33.044
		0.44		48	15				
		−1.32		314	15				
VAN II	11	1.75	1.97	11	84	†	−0.125	−1.490	23.408
		−0.26		211	5				
		−1.49		121	2				
RAW	40	1.53	0.76	221	64	†	0.844	−1.630	65.057
		0.09		53	25				
		−1.63		320	4				
MED	40	1.4	0.25	241	52	‡	0.140	−0.519	85.810
		−0.29		142	7				
		−1.1		47	37				
AVN	43	0.82	0.24	229	75	‡	−0.015	−0.747	32.741
		−0.15		53	15				
		−0.66		323	1				
SFD	37	0.7	0.08	70	55	‡	1.013	−0.875	51.547
		0.11		262	34				
		−0.59		169	5				
LRY	45	0.25	0.05	272	63	‡	0.072	−0.190	93.761
		0.03		51	21				
		−0.22		147	16				
LAN	20	0.2	0.04	56	58	‡	0.053	−0.073	44.592
		0.03		284	23				
		−0.18		184	22				
EVS	29	0.19	0.05	64	42	‡	0.060	−0.070	47.647
		−0.08		305	28				
		−0.11		193	34				
OAK	25	1.8	0.57	264	17	‡	1.110	−1.007	74.481
		−0.45		44	67				
		−1.35		170	13				
SYR	32	1.48	0.42	135	58	‡	1.237	−1.349	92.819
		0.68		254	16				
		−2.16		352	26				
HON	40	4.16	1.81	51	33	‡	1.899	0.670	77.716
		1.18		314	11				
		−5.34		208	54				
2	0	−0.7	0.27	167		§			
3	0	−0.67	0.07	1		§			
4	5	−0.18	0.17	30		§			
5	0	−0.16	0.04	38		§			
6	12	−0.45	0.33	160		§			
7	10	−0.22	0.21	160		§			

*ADI, Addison; CAM, Cameron Mills; AND, Andover; VAN, Vandermark Creek; RAW, Rawson; MED, Medina; AVN, Avon; SFD, Stafford; LRY, Leroy; LAN, Lancaster; EVS, North Evans; OAK, Oaks Corners; SYR, Syracus; HON, Honeoye Falls. Sites 2–7 are given in Craddock *et al.* (1993).

†Engelder (1979a).

‡Engelder (1979b).

§Craddock *et al.* (1993).

as indicated by X-ray analysis, is characterized by a NE principal extension of 0.006% and a 0.001–0.003% NW compression (Engelder, 1979b). These observed values are consistent with our calculated values, using an R_n value of 480 km. If this estimate is correct, then the distribution of fold-axis-parallel elongation may be further expressed by an exponential function (Fig. 12b):

$$e_t(i) = 249003 \exp(-0.0371 R_i). \qquad (9)$$

Such a strain distribution is compatible with the stress distribution obtained from the elastic stress analyses. Therefore, as suggested by the kinematic model, the fold-axis-parallel elongation is of the order of 5–0.01% in the Appalachian Plateau of western New York. This magnitude of elongation is large

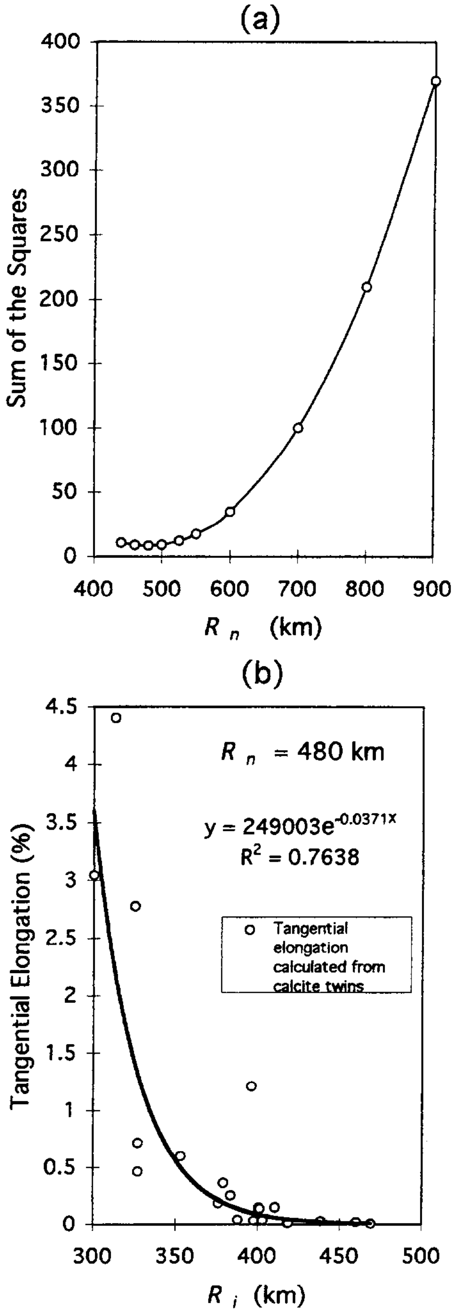

Fig. 12. (a) Sum of the squares of the difference between the tangential strain deduced from the calcite twinning data (Engelder, 1979a,b) and that calculated from the kinematic radial thrust model for various values of R_n (radius of neutral arc). Smallest residual is for $R_n = 480$ km. (b) Distribution of tangential elongation for $R_n = 480$ km: the calculated elongation is of the order of 0.01–5% in the Appalachian Plateau of western New York.

enough to induce the propagation of the regional cross-fold joints.

DISCUSSION

It is generally agreed that joints are opening-mode tensile fractures (e.g. Engelder and Geiser, 1980; Segall and Pollard, 1983; Pollard and Aydin, 1988). Faced with the paradox of how joints propagate in the shallow crust, where *in situ* stress measurements suggest the stresses are commonly compressive, different mechanisms have been proposed for the origins of the 'tensile' stresses. Perhaps the most widely invoked mechanisms are based on concepts of pore pressure and effective stress (e.g. Secor, 1965). Engelder and Lacazette (1990) used the cross-fold joints in the Ithaca Siltstone at Watkins Glen, New York, to show that natural hydraulic fracturing (NHF) is theoretically possible, and that the crack-driving force may arise from the fluid pressure interacting with the poro-elastic behavior of the rock. It has been suggested that large volumes of fluids may have been expelled from deep burial of foreland basin sediments during plate collisions along the margins of the North American craton (e.g. Hearn *et al.*, 1989); this fluid drive could facilitate the joint propagation. However, considerable ambiguity remains concerning the origin of the regional *vertical* joints because the role of pore-pressure in the reduction of effective stress, as well as the anisotropy in fracture toughness of sedimentary rocks, actually favors the propagation of horizontal cracks, rather than the vertical joints. Thus, a different mechanism is required to further reduce the horizontal effective stress to favor vertical crack propagation (Engelder and Lacazette, 1990). As suggested by Engelder and Fischer (1996), multiple end-member joint-driving mechanisms may act in concert in order to initiate crack propagation in nature.

We propose the fold-axis-parallel elongation as one of the major mechanisms for the formation of syn-tectonic cross-fold joints. Although this mechanism is most probably coupled with the pore pressure, our modeling suggests that extensional stress may occur if the tensile stress induced by compression on a pre-existing 'arcuate' tectonic boundary exceeds the compressive stress produced by the overburden loading. Such extensional stress conditions exist in regions north of the Himalayan continental-collision zone, where the crust is stretched in a direction generally orthogonal to the convergence direction, and the maximum compressive stress trajectories exhibit a quasi-radial pattern in response to the curvature geometry of the orogenic belt (e.g. Tapponnier *et al.*, 1981; Ma and Wu, 1987; Zoback *et al.*, 1989).

During the Laurentia–Gondwana continental collision (Alleghanian orogeny), the irregular plate boundaries (e.g. Rankin, 1976; Thomas, 1977) may have placed the central Appalachians in a tectonic setting similar to the Himalayan continental-collision zone, if the Pennsylvania salient collided with a promontory on the African continent, such as the Reguibat rigid indenter (e.g. Lefort and Van der Voo, 1981; Hatcher, 1989; Sacks and Secor, 1990). A system of strike-slip faults extending from southern Europe to Alabama have been interpreted to be a consequence of indenter and escape tectonic processes (e.g. Lefort and Van der Voo, 1981; Hatcher, 1989; Sacks and Secor, 1990). Movements along these fault systems are constrained to between 315 and 260 Ma (e.g. Ziegler, 1986; Zartman and Hermes, 1987; Reck and Mosher, 1988; Gates and Glover, 1989; Snoke and Mosher, 1989; Sacks and Secor, 1990). These collisional tectonics are consistent in timing with the up to 27° relative rotation between the two limbs of Pennsylvania salient, as evidenced by paleo-magnetic data; this rotation occurred before a 255–275 Ma remagnetization event (Kent, 1988; Stamatakos and Hirt, 1994: Stamatakos *et al.*, 1996). Evolution of the regional cross-fold joints and the associated stress field thus can be interpreted as consequences of this Laurentia–Gondwana continental collision.

(1) The earliest stage of tectonic jointing, which displays a small spatial variation in the orientation of σ_1 (NNW) over large areas, is consistent with the 'fold-axis'-parallel elongation induced by the initial compression applied on the tectonic boundaries with a small pre-existing curvature.

(2) The rotation of stress trajectories as inferred from subsequent jointing may have resulted from the penetration of the Reguibat rigid indenter, which caused the cratonward migration of the arcuate boundary of tectonic loading (Fig. 13a) and/or the increase in the curvature of the tectonic boundary (Fig. 13b). Both phenomena caused by the penetration of the rigid indenter can result in opposite rotation directions of Alleghanian stress trajectories cratonward of different parts of the orogenic bends: counterclockwise in southwest-central Appalachian Plateau and clockwise in northeast Appalachian Plateau. In addition, joint propagation may provide a likely explanation for the rapid remagnetization caused by brine mobilization along fractures (cf. Stamatakos *et al.*, 1996).

CONCLUSIONS

Our detailed field mapping in the Appalachian Plateau of western New York provides critical information concerning regional joint patterns in terms of fracturing sequence, tectonic association and regional correlation of the cross-fold joints. The sequential development of NNW (322–340°), NW (312–320°) and WNW (295–310°) joint sets in the west-central Appalachian Plateau and the sequential development of NNW-, ~N–S- and NNE-trending sets in the Appalachian Plateau of central New York and eastern Pennsylvania may be correlated in terms of their relative timing, structural association and their spatial extent in different lithologies. Such correlations suggest that the earliest cross-fold joints across the central and northern Appalachian Plateau strike relatively consistently NNW. In contrast, later cross-fold sets show a prominent radial pattern across the central and northern Appalachian Plateau. The clockwise rotation of joints through time in eastern New York, and the counterclockwise rotation in western New York and further southwest, suggest that this radial pattern evolved through time by increasing the radian (i.e. the angle between the easternmost cross-fold joints and the westernmost cross-fold joints) through time. This regionally evolving joint pattern generally records a counterclockwise rotation of principal stress trajectories in west-central Appalachian Plateau and a clockwise rotation of stress trajectories in easternmost Appalachian Plateau. Such a change in paleostress may be attributed to the tectonism of the Laurentia–Gondwana continental collision.

The pattern of regional cross-fold joints in the central and northern Appalachian Plateau, as revealed by extensive fracture studies, bears a strong resemblance to the simulated stress trajectories from boundary element numerical modeling. Modeling indicates that tensile stresses for the initiation and propagation of cross-fold joints can arise from normal compressive loading along an arcuate tectonic boundary. We have also shown that the fold-axis-parallel elongation in front of the arcuate boundary can be large enough to induce the cross-fold joints. The fold-axis-parallel elongation in the central

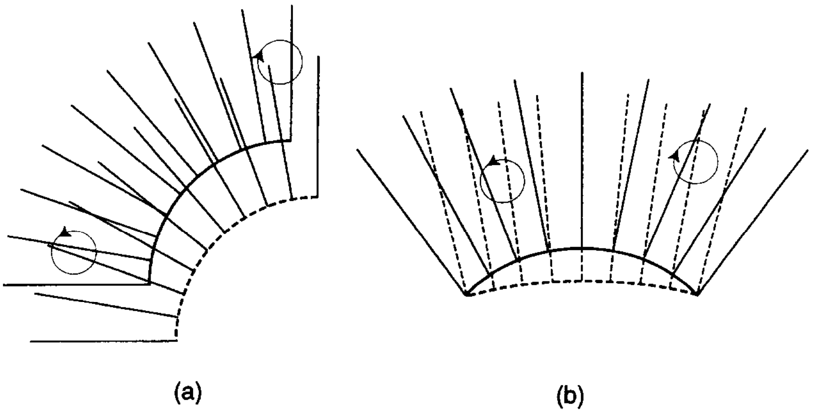

Fig. 13. Two hypothetical interpretations of the Alleghanian stress history; both models result in similar changes in the stress field that have the opposite sense of rotation on the two limbs of the orogenic bend. Model (a) assumes that the acting tectonic boundary maintains a constant curvature when it propagates toward the craton. Note, the results from this model apply to two different conditions: the inner tectonic loading boundary moves outward through a relatively stationary rock system (e.g. Appalachian Plateau), or the tectonic boundary and rocks both move outward. Model (b) assumes that curvature of the leading edge of thrusts or tectonic boundary increases with the cratonward propagation of the thrusts.

and northern Appalachian Plateau can be approximated by a radial thrusting kinematic model; this model has been tested and calibrated against calcite twinning strain data. Our modeling indicates a cratonward decrease in both the tangential stress and fold-axis-parallel elongation, which is consistent with the observed changes in deformation styles from the central Appalachian fold and thrust belt to the Appalachian Plateau.

Tectonic stresses within orogenic bends or along a plate boundary impose profound control on the horizontal stresses in foreland regions beyond the fold and thrust belt. Thus, fold-axis-parallel elongation associated with the development of orogenic curvature can explain the development of cross-fold joints cratonward of arcuate fold and thrust belts. Because arcuate fold and thrust belts are a common feature of orogens around the world, the fold-axis-parallel elongation model, coupled with other joint-propagation models, may provide a widely applicable resolution to the enigmatic origin of regional systematic joints.

Acknowledgements—Field work in Allegany County was supported by grant 1782-LLRW-92, administered by New York Energy Research and Development Agency. We thank the field assistants who helped us gather the structural data in Allegany County, western New York. Discussions with Gerry Smith contributed to our understanding of the lithology and stratigraphy of the area. Discussions with Dr Fountain were always helpful, and Dr Renshaw provided useful comments in his review of an earlier version of the manuscript. We thank Drs Terry Engelder, David A. Ferrill, Mark Evans and S. F. Wojtal for careful reviews. Their efforts greatly improved the quality of this manuscript.

REFERENCES

Bahat, D. and Engelder, T. (1984) Surface morphology on cross-fold joints of the Appalachian Plateau, New York and Pennsylvania. *Tectonophysics* **104**, 299–313.

Bossart, P., Dietrich, D., Ottiger, R. and Ramsay, J.G. (1988) The tectonic structure of the Hazara–Kashmir Syntaxis, Southern Himalayas, Pakistan. *Tectonics* **7**, 273–297.

Bucher, W.H. (1924) The pattern of the Earth's mobile belts. *Journal of Geology* **32**, 265–290.

Chamberlin, R.T. (1928) The strain ellipsoid and Appalachian structures. *Journal of Geology* **36**, 85–90.

Cloos, E. (1940) Crustal shortening and axial divergence in the Appalachians of southeastern Pennsylvania and Maryland. *Bulletin of the Geological Society of America* **51**, 845–872.

Cloos, E. (1947) Oolite deformation in the South Mountain fold, Maryland. *Bulletin of the Geological Society of America* **58**, 843–918.

Coates, D. F. (1981) *Rock Mechanics Principles.* CANNMET Monograph **874**.

Coward, M.P. and Potts, G.J. (1983) Complex strain patterns developed at the frontal and lateral tips to shear zones and thrust zones. *Journal of Structural Geology* **5**, 383–399.

Craddock, J.P., Jackson, M., van der Pluijm, B.A. and Versical, R.T. (1993) Regional shortening fabrics in eastern North America: far-field stress transmission from the Appalachian–Ouachita orogenic belt. *Tectonics* **12**, 257–264.

Craddock, J.P. and van der Pluijm, B.A. (1989) Late Paleozoic deformation of the cratonic carbonate cover of eastern North America. *Geology* **17**, 416–419.

Crouch, S. L. and Starfield, A. M. (1983) *Boundary Element Methods in Solid Mechanics.* Allen and Unwin, London.

Cruikshank, K.M. and Aydin, A. (1995) Unweaving the joints in Entrada Sandstone, Arches National Park, Utah, U.S.A. *Journal of Structural Geology* **17**, 409–421.

Cuff, D. J., Young, W. J., Muller, E. K., Zelinsky, W. and Abler, R. D. (1989) *The Atlas of Pennsylvania.* Temple University Press, Philadelphia.

Dean, S.L., Kulander, B.R. and Skinner, J.M. (1988) Structural chronology of the Alleghanian Orogeny in southeastern West Virginia. *Bulletin of the Geological Society of America* **100**, 299–310.

Dietrich, D. (1989) Fold-axis parallel extension in an arcuate fold-and-thrust belt: the case of the Helvetic nappes. *Tectonophysics* **170**, 183–212.

Dunne, W. M. and Hancock, P. L. (1994) Paleostress analysis of small-scale brittle structures. In *Continental Deformation*, ed. P. L. Hancock. Pergamon, Oxford.

Dunne, W. M. and North, C. P. (1990) Orthogonal fracture systems at the limits of thrusting: an example from southwestern Wales. *Journal of Structural Geology* **12**, 207–215.

Dyer, R. (1988) Using joint interactions to estimate paleostress ratios. *Journal of Structural Geology* **10**, 685–699.

Ellis, M.A. (1986) Structural morphology and associated strain in the central Cordillera (British Columbia and Washington): evidence for oblique tectonics. *Geology* **14**, 647–650.

Engelder, T. (1979) Mechanisms for strain within the Upper Devonian clastic sequence of the Appalachian Plateau, western New York. *American Journal of Science* **279**, 527–542.

Engelder, T. (1979) The nature of deformation within the outer limits of the central Appalachian foreland fold and thrust belt in New York state. *Tectonophysics* **55**, 289–310.

Engelder, T. (1982) Is there a genetic relationship between selected regional joints and contemporary stress within the lithosphere of North America? *Tectonics* **1**, 161–177.

Engelder, T. (1985) Loading paths to joint propagation during a tectonic cycle: an example from the Appalachian Plateau, U.S.A. *Journal of Structural Geology* **7**, 459–476.

Engelder, T. and Engelder, R. (1977) Fossil distortion and decollement tectonics on the Appalachian Plateau. *Geology* **5**, 457–460.

Engelder, T. and Fischer, M.P. (1996) Loading configurations and driving mechanisms for joints based on the Griffith energy-balance concept. *Tectonophysics* **256**, 253–277.

Engelder, T. and Geiser, P.A. (1979) The relationship between pencil cleavage and lateral shortening within the Devonian section of the Appalachian Plateau, New York. *Geology* **7**, 460–464.

Engelder, T. and Geiser, P.A. (1980) On the use of regional joint sets as trajectories of paleostress fields during the development of the Appalachian Plateau, New York. *Journal of Geophysical Research* **85**, 6319–6341.

Engelder, T. and Gross, M.R. (1993) Curving cross joints and the lithospheric stress field in eastern North America. *Geology* **21**, 817–820.

Engelder, T. and Lacazette, A. (1990) Natural hydraulic fracturing. In *Rock Joints*, ed. N. Barton and O. Stephansson. A. A. Balkema, Rotterdam.

Evans, K.F., Engelder, T. and Plumb, R.A. (1989) Appalachian stress study 1. A detailed description of *in situ* stress variations in Devonian shales of the Appalachian Plateau. *Journal of Geophysical Research* **94**, 1729–1754.

Evans, K.F., Oertel, G. and Engelder, T. (1989) Appalachian stress study 2. Analysis of Devonian shale core: some implications for the nature of contemporary stress variations and Alleghanian deformation in Devonian rocks. *Journal of Geophysical Research* **94**, 7155–7170.

Evans, M.A. (1994) Joints and decollement zones in Middle Devonian shales: Evidence for multiple deformation events in the central Appalachian Plateau. *Bulletin of the Geological Society of America* **106**, 447–460.

Faill, R.T. (1973) Kink band folding, Valley and Ridge province, Pennsylvania. *Bulletin of the Geological Society of America* **84**, 1289–1314.

Faill, R.T. (1977) Fossil distortion, Valley and Ridge province, Pennsylvania. *Geological Society of America Abstracts with Programs* **9**, 262–263.

Faill, R.T. (1979) Deformation pattern in the Pennsylvania salient of the central Appalachians. *Geological Society of America Abstracts with Programs* **11**, 11–12.

Fakundiny, R. H., Pomeroy, P. W., Pferd, J. W. and Nowak, T. A. (1978) *Structural Instability Features in the Vicinity of the Clarendon–Linden Fault System, Western New York and Lake Ontario.* University of Waterloo Press, SM Study No. 13, Paper 4.

Ferrill, D.A. (1989) Primary crenulation pencil cleavage. *Journal of Structural Geology* **11**, 457–461.

Ferrill, D.A. and Groshong, R.H. (1993) Kinematic model for the curvature of the northern Subalpine Chain, France. *Journal of Structural Geology* **15**, 523–541.

Fettke, C. R. (1938) *The Bradford Oil Field, Pennsylvania and New York.* Pennsylvania Geological Survey 4th Series Bulletin **M21**.

Gates, A.E. and Glover, L. (1989) Alleghanian tectono-thermal evolution of the dextral transcurrent Hylas zone, Virginia Piedmont, U.S.A. *Journal of Structural Geology* **11**, 407–419.

Geiser, P.A. (1988) Mechanisms of thrust propagation: some examples and implications for the analysis of overthrust terranes. *Journal of Structural Geology* **10**, 829–846.

Geiser, P.A. and Engelder, T. (1983) The distribution of layer parallel shortening fabrics in the Appalachian foreland of New York and Pennsylvania: Evidence for two non-coaxial phases of the Alleghanian Orogeny. *Memoirs of the Geological Society of of America* **158**, 161–175.

Gray, M.B. and Mitra, G. (1991) The relationship between progressive deformation and large scale structural evolution in a blind fold and thrust belt, eastern Pennsylvania Valley and Ridge province. *Geological Society of America Abstracts with Programs* **23**, 37.

Gray, M.B. and Mitra, G. (1993) Migration of deformation fronts during progressive deformation: Evidence from detailed structural studies in the Pennsylvania Anthracite region, U.S.A. *Journal of Structural Geology* **15**, 435–449.

Gross, M.R. and Engelder, T. (1991) A case for neotectonic joints along the Niagara Escarpment. *Tectonics* **10**, 631–641.

Hall, J. (1843) *Natural History of New York: Part IV Geology Comprising the Survey of the Fourth Geological District.* Carroll and Cook, Albany, New York.

Hatcher, R. D., Jr (1989) Tectonic synthesis of the U.S. Appalachians. In *The Appalachian–Ouachita Orogen in the United States. The Decade of North American Geology*, eds R. D. Hatcher, Jr, W. A. Thomas and G. W. Viele, Vol. F-2, pp. 511–535. Geological Society of America.

Hearn, P. P., Jr, Belkin, H. E. and Sutter, J. F. (1989) Tectonically induced fluid migration in sedimentary basins: a new factor to be considered in the assessment of thermal history. In *Appalachian Basin Symposium—Program and Extended Abstracts*, ed. A. P. Schultz. *United States Geological Survey Circular* **1028**, 1.

Helgeson, D.E. and Aydin, A. (1991) Characteristics of joint propagation across layer interfaces in sedimentary rocks. *Journal of Structural Geology* **13**, 4897–4911.

Kent, D.V. (1988) Further paleomagnetic evidence for oroclinal rotation in the central folded Appalachians from the Bloomsburg and the Mauch Chunk formations. *Tectonics* **7**, 749–759.

Kirkwood, D., Malo, M., St-Julien, P. and Therrien, P. (1995) Vertical and fold-axis parallel extension within a slate belt in a transpressive setting, northern Appalachians. *Journal of Structural Geology* **17**, 329–343.

Lacazette, A. and Engelder, T. (1987) Reducing fluids and the origin of natural fractures in the Bald Eagle Sandstone, Pennsylvania. *Geological Society of America Abstracts with Programs* **19**, 737.

Laubscher, H.P. (1972) Some overall aspects of Jura dynamics. *American Journal of Science* **272**, 293–304.

Lefort, J.P. and Van der Voo, R. (1981) A kinematic model for the collision and complete suturing between Gondwanaland and Laurussia in the Carboniferous. *Journal of Geology* **89**, 537–550.

Ma, X. and Wu, D. (1987) Cenozoic extensional tectonics in China. *Tectonophysics* **133**, 243–255.

Marshak, S. (1988) Kinematics of orocline and arc formation in thin-skinned orogens. *Tectonics* **7**, 73–86.

Mazzoli, S. and Carnemolla, S. (1993) Effects of the superposition of compaction and tectonic strain during folding of multilayer sequence—model and observations. *Journal of Structural Geology* **15**, 277–291.

McGarr, A. (1988) On the state of lithospheric stress in the absence of applied tectonic forces. *Journal of Geophysical Research* **93**, 13609–13618.

Melton, F.A. (1929) A reconnaissance of the joint systems in the Ouachita Mountains and central plains of Oklahoma. *Journal of Geology* **37**, 729–746.

Merle, O., Cobbold, P. R. and Schmid, S. (1989) Tertiary kinematics in the Lepontine dome. In *Alpine Tectonics*, ed. M. P. Coward, D. Dietrich and R. G. Parker, pp. 113–134. Special Publication of the Geological Society of London **45**.

Morley, C.K. (1996) Models for relative motion of crustal blocks within the Carpathian region, based on restorations of the outer Carpathian thrust sheets. *Tectonics* **15**, 885–904.

Nickelsen, R.P. (1966) Fossil distortion and penetrative rock deformation in the Appalachian Plateau, Pennsylvania. *Journal of Geology* **74**, 924–931.

Nickelsen, R.P. (1979) Sequence of structural stages of the Alleghany Orogeny at the Bear Valley Strip Mine, Shamokin, Pennsylvania. *American Journal of Science* **279**, 225–271.

Nickelsen, R. P. (1988) Structural evolution of folded thrusts and duplexes on a first-order anticlinorium in the Valley and Ridge province of Pennsylvania. In *Geometries and Mechanisms of Thrusting with Special Reference to the Appalachians*, eds G. Mitra and S. Wojtal, pp. 89–106. Geological Society of America Special Paper **222**.

Nickelsen, R.P. and Hough, V.D. (1967) Jointing in the Appalachian Plateau of Pennsylvania. *Bulletin of the Geological Society of America* **78**, 609–630.

Oertel, G., Engelder, T. and Evans, K. (1989) A comparison of the strain of crinoid columnals with that of their enclosing silly and shaly matrix on the Appalachian Plateau, New York. *Journal of Structural Geology* **11**, 975–993.

Olson, J. and Pollard, D.D. (1989) Inferring paleostresses from natural fracture patterns: A new method. *Geology* **17**, 345–348.

Onasch, C.M. (1990) Microfractures and their role in deformation of a quartz arenite from the central Appalachian foreland. *Journal of Structural Geology* **12**, 883–894.

Orkan, N. and Voight, B. (1985) Regional joint evolution in the Valley and Ridge province of Pennsylvania in relation to the Alleghanian Orogeny. In *Guidebook for the 50th Annual Field Conference of Pennsylvania Geologists*, pp. 144–164. Bureau of Topographic and Geological Survey, Harrisburg, Pennsylvania.

Overbey, W.K. and Rough, R.L. (1968) Surface studies predict well-bore orientation. *Oil and Gas Journal* **66**, 84–86.

Parker, J.M. (1942) Regional systematic jointing in slightly deformed sedimentary rocks. *Bulletin of the Geological Society of America* **53**, 381–408.

Pollard, D.D. and Aydin, A. (1988) Progress in understanding jointing over the past century. *Bulletin of the Geological Society of America* **100**, 1181–1204.

Price, N. J. and Cosgrove, J. W. (1990) *Analysis of Geological Structures.* Cambridge University Press, Cambridge.

Ramsay, J. G. and Huber, M. I. (1983) *The Techniques of Modern Structural Geology. Volume 1: Strain Analysis.* Academic Press, London.

Rankin, D.W. (1976) Appalachian salients and recesses: Late Precambrian continental breakup and opening of the Iapetus Ocean. *Journal of Geophysical Research* **81**, 5605–5619.

Reck, B.H. and Mosher, S. (1988) Timing of intrusion of the Narragansett Pier Granite relative to deformation in the southwestern Narragansett Basin, Rhode Island. *Journal of Geology* **96**, 677–692.

Reks, I.J. and Gray, D.R. (1982) Pencil structure and strain in weakly deformed mudstone and siltstone. *Journal of Structural Geology* **4**, 161–176.

Ries, A.C. and Shackleton, R.M. (1976) Patterns of strain variation in arcuate fold belts. *Philosophical Transactions of the Royal Society of London* **A283**, 281–288.

Sacks, P.E. and Secor, D.T. (1990) Kinematics of the late Paleozoic continental collision between Laurentia and Gondwana. *Science* **250**, 1702–1705.

Sani, F. (1990) Extensional veins and shear joint development in a thrust-fold zone (Northern Apennines, Italy). In *Deformation Mechanisms, Rheology and Tectonics*, ed R. J. Knipe and E. H. Rutter, pp. 483–490. Special Publication of the Geological Society of London **54**.

Secor, D.T. (1965) Role of fluid pressure in jointing. *American Journal of Science* **263**, 633–646.

Segall, P. and Pollard, D.D. (1983) Joint formation in granitic rock of the Sierra Nevada. *Bulletin of the Geological Society of America* **94**, 563–575.

Sheldon, P. (1912) Some observations and experiments on joint planes. *Journal of Geology* **20**, 53–79.

Snoke, A. W. and Mosher, S. (1989) The Alleghanian Orogeny as manifested in the Appalachian Internides. In *The Appalachian—Ouachita Orogen in the United States. The Decade of North American Geology*, eds R. D. Hatcher, Jr, W. A. Thomas and G. W. Viele, Vol. F-2, pp. 288–318. Geological Society of America.

Srivastava, D.C. and Engelder, T. (1990) Crack-propagation sequence and pore-fluid conditions during fault-bend folding in the Appalachian Valley and Ridge, central Pennsylvania. *Bulletin of the Geological Society of America* **102**, 116–128.

Stamatakos, J. and Hirt, A.M. (1994) Paleomagnetic consideration of the development of the Pennsylvania salient in the central Appalachians. *Tectonophysics* **231**, 237–255.

Stamatakos, J., Hirt, A.M. and Lowrie, W. (1996) The age and timing of folding in the central Appalachians from paleomagnetic results. *Bulletin of the Geological Society of America* **108**, 815–829.

Starfield, A.M. and Cundall, P.A. (1988) Towards a methodology for rock mechanics modeling. *International Journal of Rock Mechanics & Mining Science and Geomechanics Abstracts* **25**, 99–106.

Tapponnier, P., Mercier, J. L., Armijo, R., Han, T. and Zhou, J. (1981) Field evidence for active normal faulting in Tibet. *Nature* **294**, 410–414.

Thomas, W.A. (1977) Evolution of Appalachian–Ouachita salients and recesses from reentrants and promontories in the continental margin. *American Journal of Science* **277**, 1233–1278.

Ver Steeg, K. (1944) Some structural features of Ohio. *Journal of Geology* **52**, 131–138.

Wedel, A. A. (1932) Geologic structure of the Devonian strata of south-central New York. *New York State Museum Bulletin* **294**.

Zartman, R.E. and Hermes, O.D. (1987) Archean inheritance in zircon from late Paleozoic granites from the Avalon zone of southeastern New England: an African connection. *Earth and Planetary Science Letters* **82**, 305–315.

Ziegler, P.A. (1986) Geodynamic model for the Paleozoic crustal consolidation of Western and Central Europe. *Tectonophysics* **126**, 303–328.

Zoback, M.L. and Zoback, M.D. (1989) Global patterns of tectonic stress. *Nature* **341**, 291–298.