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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

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ABSTRACT

This paper presents a structural interpretation of a part of the central and northern Appalachian foreland using the correlation in orientation of such deformation features as mechanical twins, solution cleavage, crenulation cleavage, pencils, joints, and deformed fossils. Such a correlation suggests that, within the central Appalachians, the Alleghanian orogeny consists of two major phases: a deformation possibly as old as Pennsylvanian, herein called the Lackawanna phase, and a second deformation, termed the Main phase of Permian or younger age. Effects of the Lackawanna phase deformation are found mainly in the Hudson River Valley and Pocono plateau, while effects in the Main phase deformation are found throughout the Valley and Ridge and Alleghany Plateau. The Lackawanna phase is interpreted as the product of strike-slip motion, possibly between the Avalon microcontinent and North America. The Main phase may record the final convergence of Africa against North America and accreted terranes.

INTRODUCTION

The discovery of abundant evidence (deformed fossils) for layer parallel shortening in western New York (Engelder and Engelder, 1977) led us to analyze the kinematics and dynamics of the Alleghanian Orogeny in the central Appalachians (Engelder, 1979a, 1979b; Engelder and Geiser, 1979; Engelder and Geiser, 1980). In this paper, we present a compilation, correlation, and interpretation of structures indicative of layer parallel shortening in the central Appalachian structures. This compilation further supports Engelder and Geiser's (1980) interpretation that each of two separate and major Alleghanian orogenic events are recorded by structures in the central Appalachian foreland.

The region covered in our study includes the eastern portion of the Pennsylvania salient and the Delaware and Hudson Valleys from Stroudsburg, Pennsylvania, to Albany, New York (Figure 1). Detailed regional studies have concentrated on the New York and Pennsylvania plateaus, the Lackawanna syncline, and the Great Valley–Valley and Ridge transition of the Helderberg escarpment, New York. Reconnaissance work has been done throughout the Valley and Ridge of Pennsylvania and Maryland and in

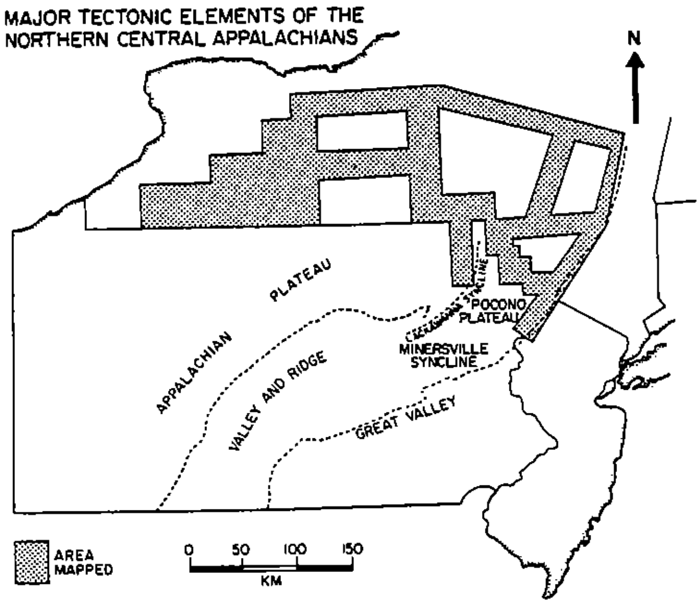


Figure 1. Major structural provinces of the northern Central Appalachians. Hatched areas are regions in which we have done detailed structuram mapping.

the Hudson River Valley from Newburgh to Albany, New York. Regional mapping utilized strips one to three quadrangles wide, with 5-10 stations per 7.5-minute quadrangle, at which structural data were gathered. The data were plotted using the existing geologic base provided by the state maps of New York (Fisher and others, 1970) and Pennsylvania (Gray and Sheps, 1964).

LAYER PARALLEL SHORTENING FABRIC

We use the term layer parallel shortening fabric (LPS fabric) to refer to the assemblage of structures produced during the process of layer parallel shortening. In the central Appalachians, these structures have been described by Nickelsen (1966, deformed fossils), Geiser (1970, 1974, solution cleavage, deformed fossils), Groshong (1971, 1975, mechanical twins, solution cleavage), Engelder and Engelder (1977, deformed fossils), Engelder (1979a, 1979b, mechanical twins, solution cleavage), and Engelder and Geiser (1979, pencils, solution cleavage, deformed fossils). Finite strain associated with layer parallel shortening is partitioned among these structures. Pressure solution is the dominant strain mechanism in many cases (Engelder, 1979a; Slaughter, 1980; Mitra, 1978) but not all (Spang and Groshong, 1981). Although Mitra (1978) has shown that partitioning in quartz between pressure solution and dislocation creep is a function of temperature, no such relationship has yet been found for strain partitioning between calcite twinning and pressure solution in limestones and calcareous siltstones of the New York plateau (Engelder, 1979a; Slaughter, 1980; Geiser, 1980). We also distinguish two types of crenulations: fold crenulations (Nickelsen, 1979, and Figure 2a) and cleavage crenulations (Figure 2b). Fold crenulations seem to be solely the product of microbuckles without any associated pressure solution, whereas cleavage crenulations are created by solution induced offsets of bedding or by the dissolution and removal of pre-existing fold limbs as described by Gray (1978).

The key structures related to the development of the LPS fabric in the central Appalachians are the major detachment faults associated with thin-skinned tectonics as described by Rich (1934), Rodgers (1953, 1970), Gwinn (1964, 1970), Harris and Milici (1977), and Perry (1978). The geometry of these faults consists of a series of ramps and flats with associated splays, duplexes, and zones of imbrication. In most instances, the major ramps and splays become progressively younger in the direction of propagation, with ramps climbing section in the direction of tectonic transport (Bally and others, 1966; Dahlstrom, 1970; Price and Mountjoy, 1970). In the central Appalachians, thrust faults ramp to the surface along portions of the Allegheny front and the Great Valley-Valley and Ridge transition (Rodgers, 1970). Otherwise, the detachments are buried, and the central Appalachians show little evidence of faulting at the surface (Rodgers, 1953; Gwinn, 1964, 1970; Wiltschko and Chapple, 1977; Perry, 1978).

Geiser (1977, 1980, 1982) has proposed that the regional development of LPS fabrics is related to movement on blind detachment faults by differential LPS. Thrusts formed by this mechanism have been termed LPS thrusts by Geiser (1982). LPS fabrics at the surface thus reflect the presence of deeper hidden or "blind" detachments, and, hence, these hidden detachments may be mapped from the distribution of the LPS fabrics. Successive deformations may cause the overprinting of structures formed during the propagation of an initial LPS thrust. An example of suchoverprinting is shown by Mitra and Elliott (1980) in their study of the deformation of the Blue Ridge, where cleavage overprinting is attributed to the progressive migration of a series of thrust sheets within the Blue Ridge. Tracing the fabrics to their highest stratigraphic level permits determination of the maximum age of the detachments and episodes of tectonic overprinting. The recognition of LPS fabrics associated with successive detachments is fundamental to our structural analysis and permits us to unravel the time and space history of the central and northern Appalachians.

Joints are also linked to a progressive deformation scheme for the development of detachments (Geiser, 1982). Some cross-strike joints may predate lithification and be part of an early lateral compaction of the sediments (Faill and Nickelsen, 1973; Nickelsen, 1979). Jointing is also closely associated with the formation of solution cleavage, as indicated by the cross-cutting rela-

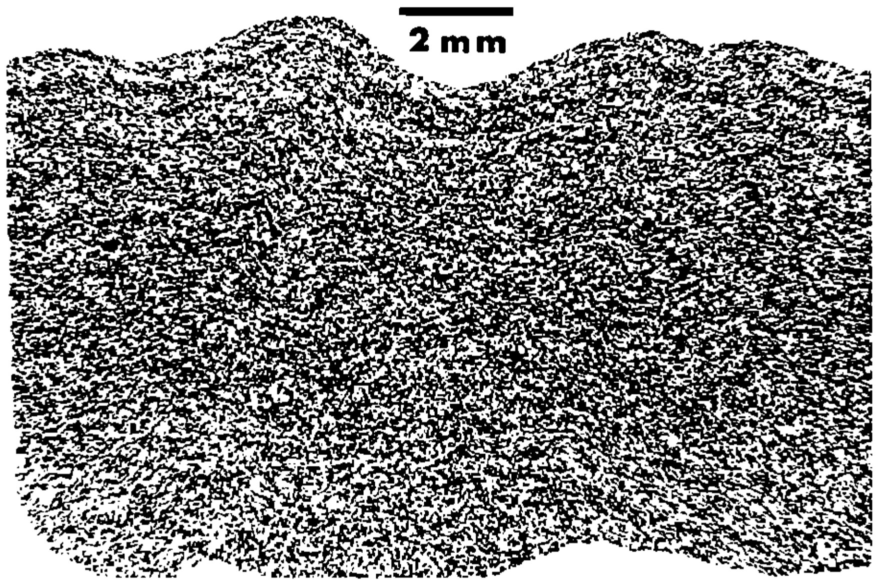


Figure 2a. Fold crenulations.

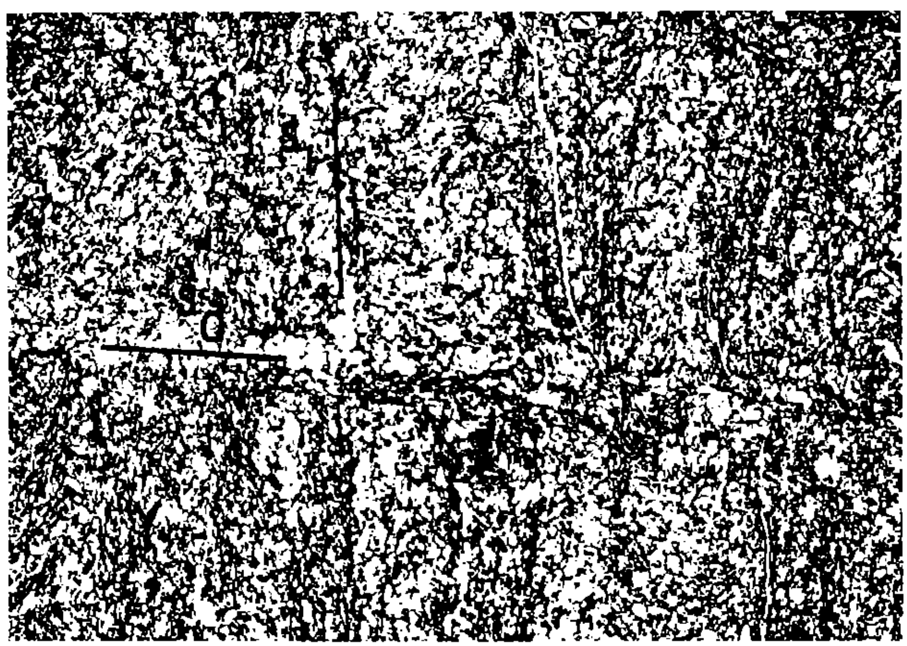


Figure 2b. Cleavage crenulations.

tionships between solution cleavage and calcite filled joints (Engelder and Geiser, 1980). Other cross-strike joints postdate lithification, as indicated by the presence of filled extension joints which break through grains and shell fragments (Engelder and Geiser, 1980). The synchronous development of LPS fabric and jointing indicates that some cross-strike jointing occurred during the thrust propagation process. Thus, the distribution of the jointing as well as LPS fabrics may both be used to delineate the extent and timing of movement on detachments and, hence, orogenic pulses.

COMPILATIONS

Distribution of Layer Parallel Shortening Fabric

LPS fabric data, collected by ourselves and students during seven field seasons from 1975 to 1981, cover the areas of New York and Pennsylvania as shown in Figure 1. A compilation of this data is shown on a trend-line map constructed by plotting the strike of either pencils, solution cleavage, crenulation planes, or the long axes of de-

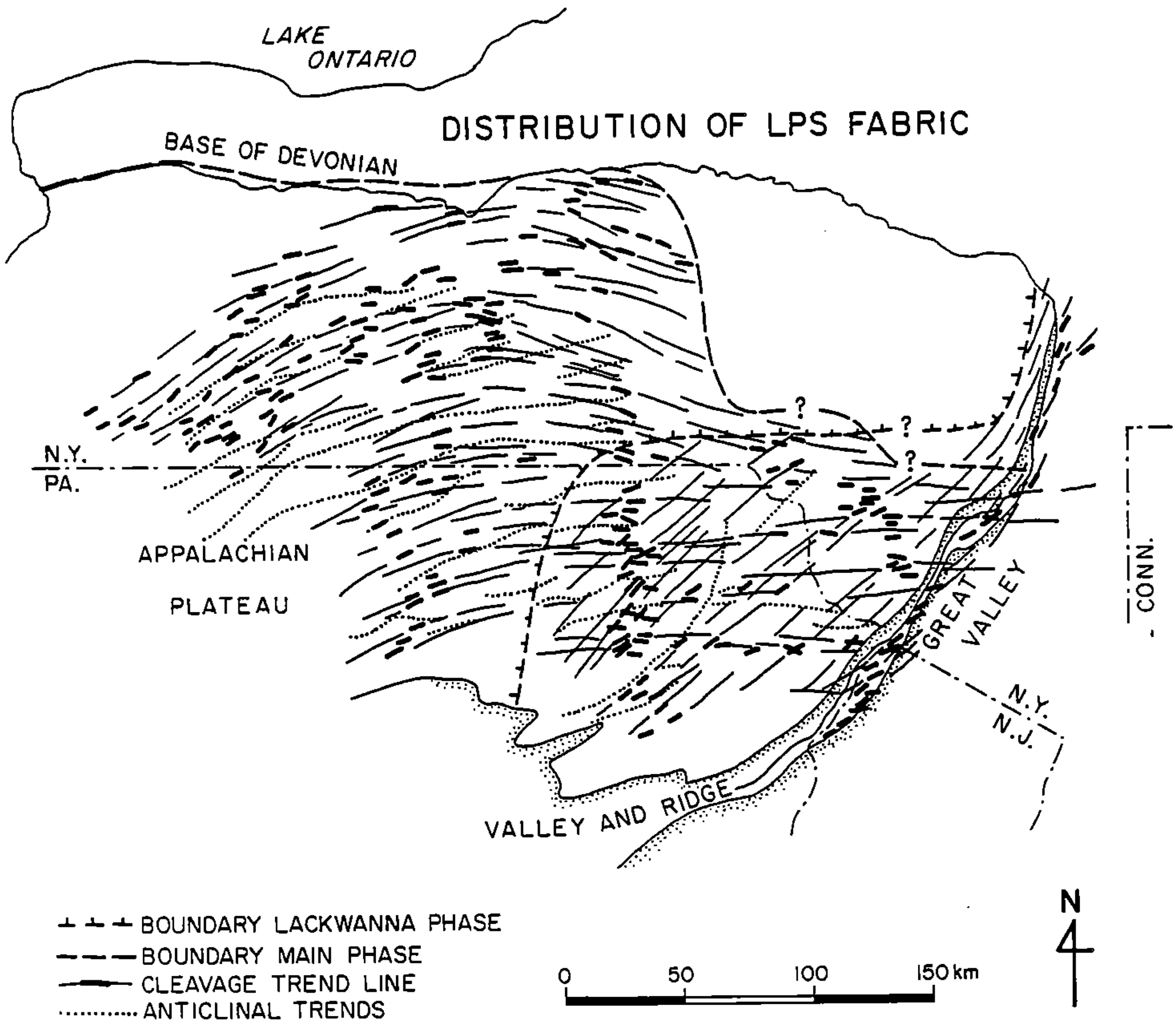


Figure 3. The distribution of layer parallel shortening fabrics across the Appalachian plateau to the Hudson Valley. The trend-line map was prepared by connecting data points (thick lines) with nearly parallel cleavage planes. The orientation of the cleavage planes is shown by a plot of the strike of cleavage planes.

formed fossils as measured in outcrop (Figure 3). Each outcrop where LPS fabrics were observed is represented by a short, thick line on Figure 3. Trend lines are then drawn to extrapolate between outcrop data. Part of the data shown on Figure 3 was published by Engelder and Engelder (1977) and Engelder and Geiser (1979) and reported by Geiser (1980), Slaughter (1980), and Washington (1980).

There exist two dominant sets of LPS fabrics, one with trend lines oriented at 080°-090° and the second with trend lines oriented at 060°-070°, which intersect in outcrops within the region roughly defined by the Lackawanna syncline and the Pocono plateau (Figures 1 and 3). If the fabrics developed sequentially, the later fabric should overprint the earlier. Overprinting relations, however, in outcrop and thin section are ambiguous (Figures 4 and 5). Although the two cleavage sets are found almost everywhere throughout the overprint region, they are not equally developed. On the Pocono plateau, the 080°-090° set seems most obvious in outcrop, while the 060°-070° set tends to stand out in outcrops in the Lackawanna syncline and Delaware Valley. This latter set, which parallels the

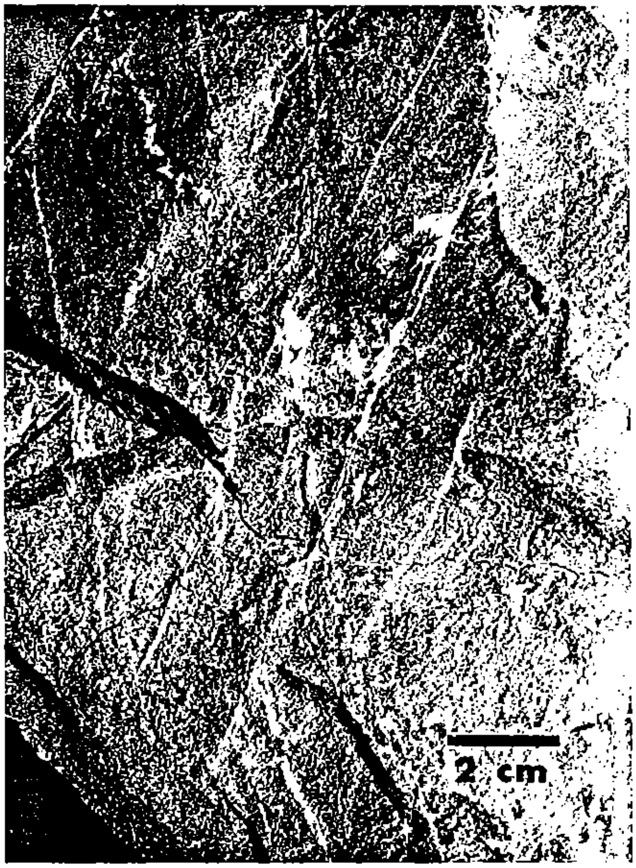


Figure 4. Photo of crossing crenulations, Route I-84 at intersection of Route PA-507, Pocono plateau. Scale is shown.

Figure 5. Photo micrograph of crossing sets of cleavage, same locality as Figure 4.

trend of the southern two-thirds of the Lackawanna syncline, is associated with the deformation we name the *Lackawanna phase,* while the 080°-090° set, which parallels the main fold trains of the Pennsylvania Appalachians, we name the *Main phase.* We have used a geographic name for the Lackawanna phase because it is geographically restricted relative to the Main phase. The overprinting takes the form of crossing sets of crenulations (Figure 4) or cleavages (Figure 5) or, in some cases, microfold interference patterns.

In addition to the two sets of LPS fabrics which are frequently found, three additional sets are sporadically developed and found from the eastern edge of the Pocono plateau westward. Members of each set (000°-010°, 320°-330°, and 350°) have been determined by using our trendline correlation. These sets appear in the form of crenulations (fold and cleavage) or solution cleavage. Where multiple sets overprint on the Pocono plateau, the rocks show a pronounced "sheen" in all argillaceous lithologies. The "sheen" is presumably due to the recrystallization of clays and micas, although it may also be related to the effects of multiple deformation (Beutner, 1982, personal communication). The 000°-010° set has been found from the northern Pocono plateau to the central Pennsylvania plateau. Although fairly common on the Pocono plateau in central Pennsylvania, it seems to be restricted to north-south striking valleys (Pone, 1981). The 320°-330° set is restricted to the region extending from the central Pennsylvania plateau to the Lackawanna syncline. The 350° set occurs in a narrow belt extending from the western side of the Pocono plateau to the eastern limb of the Lackawanna syncline.

Distribution of Joints

Compilations of regional joint patterns in the Appalachian foreland include Parker (1942) in New York, Nickelsen and Hough (1967) in Pennsylvania, Dean and Kulander (1978) in West Virginia, and Engelder and Geiser (1980) in New York. Some general comments can be made about all the compilations from these regions.

1) All the major regional joint sets are mode I cracks propagating either at depth or near the surface. Hypothesized regionally developed shear joints, as, for example, discussed by Parker (1942), have not been supported by more recent studies (Nickelsen and Hough, 1967; Nickelsen, 1979; Kulander and Dean, 1978; and Engelder and Geiser, 1980).

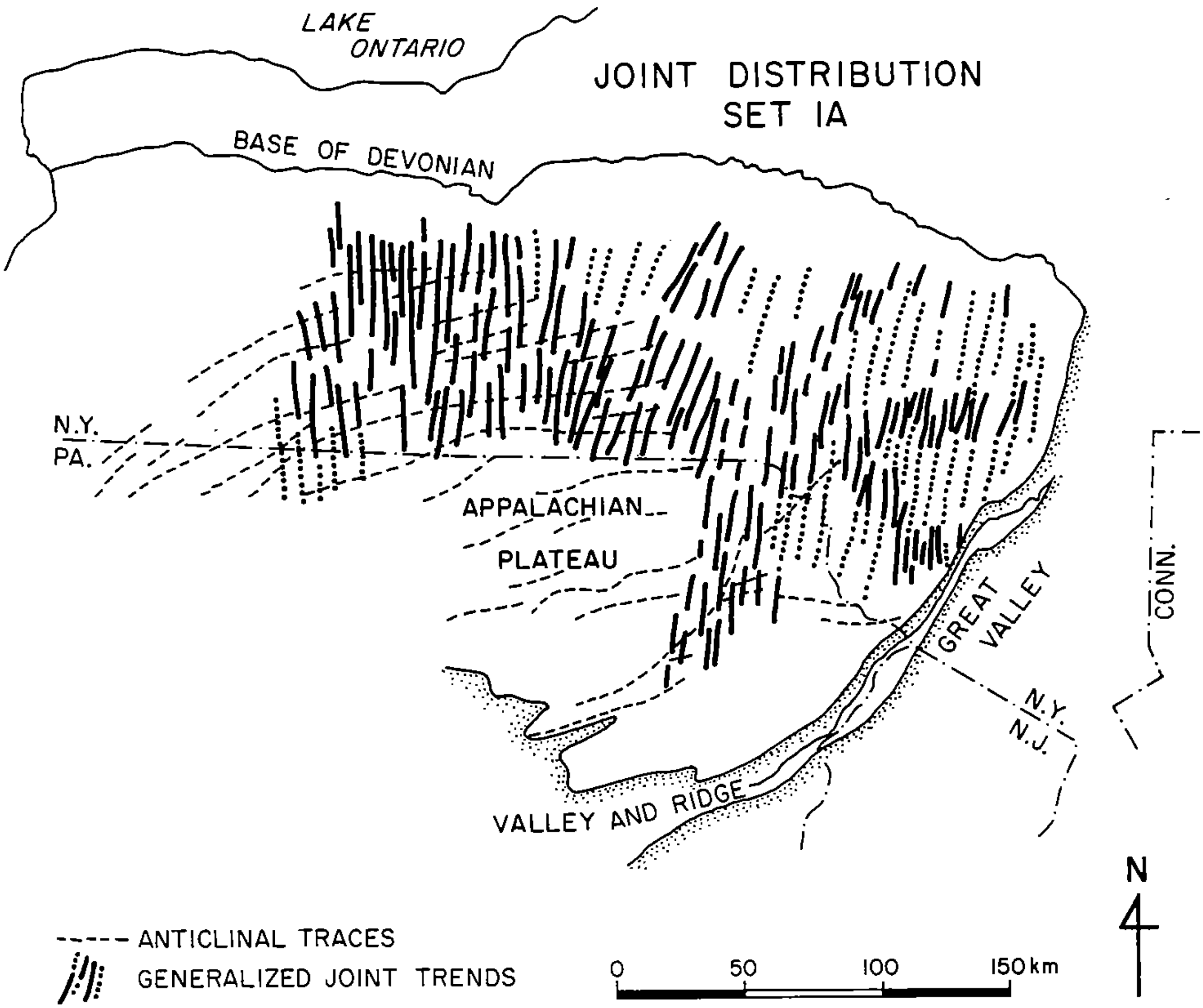


Figure 6b. Plot of trajectories drawn parallel to the strike of set Ia joints shown in Fig. 6a.

possible soft-sediment deformation and set Ib joints are the only structural elements which have an orientation compatible with the Lackawanna phase deformation. There is suggestive evidence for other folds on the Lackawanna trend in both the en echelon fold pattern in the Minersville synclinorium and the presence of low amplitude folds to the northeast of the Lackawanna syncline (Fletcher and Woodrow, 1970) (Figure 1). Other deformations overprint the Lackawanna trend throughout this region. Towards the north, the LPS fabric decreases in intensity and has not been found in the northern part, where the trend of the syncline bends around to about 020°. Presently, we have no explanation for the change in orientation of the northern tip of the Lackawanna syncline.

In the Bear Valley strip mine, located about 50 kms south of the Lackawanna syncline, Nickelsen (1979) has identified a set of structures almost identical to those we have described. In this region, Nickelsen recognizes six stages of deformation, the last five of which are associated with the Alleghanian Orogeny. Nickelsen's stages II (extension jointing), III (cleavage, small-scale folding), and IV (conjugate wrench and thrust faulting) are all associated with an early LPS event. The mean trend of bedding cleavage intersections is 068°, with associated extension joints at 337° (Nickelsen, 1979, Figure 4). The mean acute bisection of the conjugate wrench system is at 327°. This system of structures correlates almost precisely with our set Ib joints and the Lackawanna phase LPS fabric, which trends at 070°. Thus, the orientation of structures

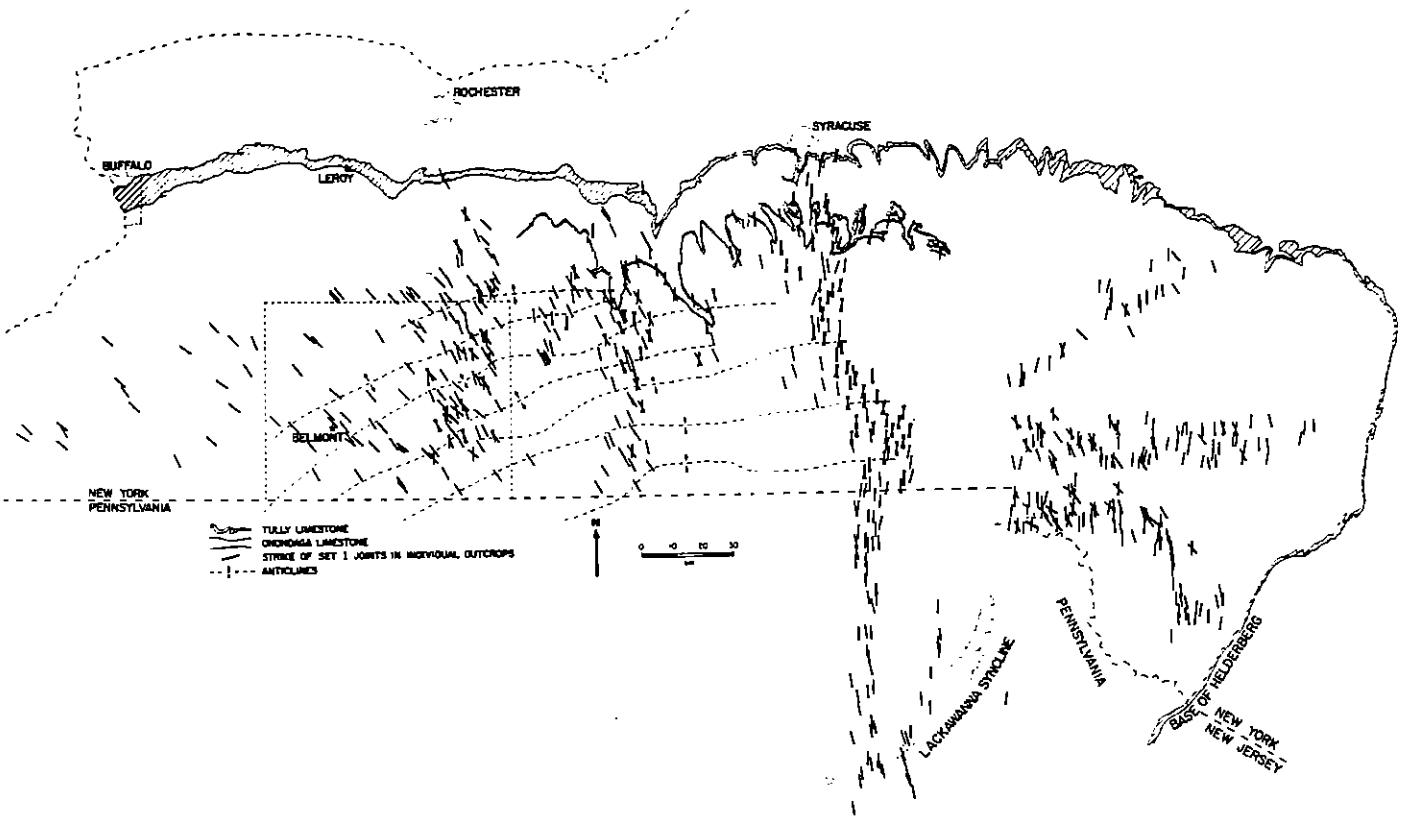


Figure 6a. Plot of strike of set I joints on Appalachian plateau. Each datum represents one or more set I joints within outcrops visited during our study.

2) The earliest joint sets predate finite amplitude folding and generally do not correlate with later Alleghanian deformations; these joints are found primarily as "cleating" in coal (Nickelsen and Hough, 1967; Nickensen, 1979; Kulander and Dean, 1978) and have been tied to the tectonic development of the Appalachian basin by Kulander and Dean (1978).

3) The presence of two or more joint sets is almost ubiquitous. Although the most common sets are approximately normal and parallel to the fold trends, some of these sets are not directly related to the folding process (Nickelsen and Hough, 1967; Kulander and others, 1979; Engelder and Geiser, 1980); however, others can be related (Nickelsen, 1979).

4) The Appalachian plateau of New York State has two well-developed cross-strike joint sets named set Ia and set Ib by Engelder and Geiser (1980) (Figure 6a). Set Ia is characterized by occasional calcite filling and has a marked western limit (Figure 6b), whereas set Ib has never been observed to be filled (Figure 6c). In the area between Binghamton and Syracuse, New York, set Ia parallels the compression direction indicated by finite strain and is contemporaneous with the development of solution cleavage, as indicated by the cross-cutting relationship between the cleavage and calcite-filled joints. To the east and west of this area, set Ia strikes about 10° clockwise from the compression direction indicated by the finite strain. The difference in strike between set Ia and Ib is 15° to 30°, with set Ib counter-clockwise from Ia and never parallel to the compression direction indicated by the post-lithification solution cleavage. Engelder and Geiser (1980) conclude that set Ia and set Ib joints reflect different tectonic events for which joint set Ia formed after lithification and contemporaneously with the Main phase LPS fabrics. Engelder and Geiser (1980) hypothesize that the orientation of set Ib may be controlled by a prelithification tectonic event despite presenting evidence that formation of joint set Ib post dates joint set Ia.

ALLEGHANIAN DEFORMATIONS

Lackawanna Phase

The Lackawanna phase is the earliest of two major deformations that we have identified. The area affected by this deformation is recognized by an assemblage of structures including LPS fabrics, folds, thrusts, set Ib joints, and zones of fold terminations. The LPS fabrics associated with this event extend eastward from the area immediately west of the Lackawanna syncline where it is found as weakly developed cleavage and/or crenulation. Northwest of our boundary for the Lackawanna phase, a

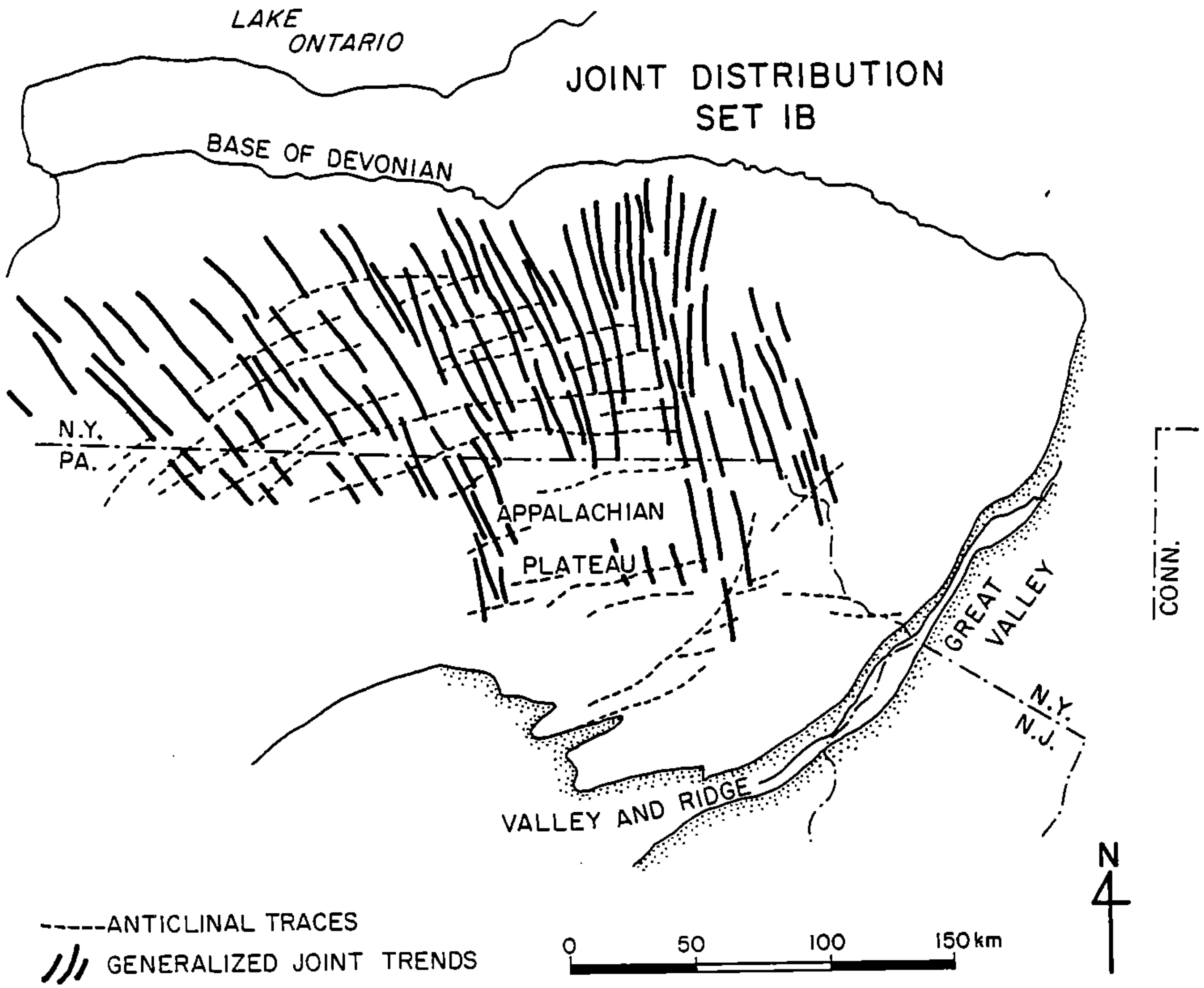


Figure 6c. Plot of trajectories drawn parallel to the strike of set Ib joints shown in Fig. 6a.

associated with Nickelsen's stages II-IV, the earliest Aleghanian events he finds, seems to be in agreement with the orientation of structures of proposed Lackawanna phase.

In the Lackawanna syncline, LPS fabrics parallel the 070° trend of the southern part of the Lackawanna syncline axis and become so well developed that they are the most obvious LPS fabric in this area. East of the Lackawanna syncline, the intensity of the 070° trend also diminishes, occurring only as scattered cleavage and fold crenulations. This relationship is found across the entire plateau to within 3-4 kilometers of the eastern edge of the plateau. As progressively lower parts of the section are exposed in crossing the Pocono plâteau, the Lackawanna phase LPS fabrics become increasingly better developed so that, in the lower part of the Hamilton group, the Lackawanna LPS fabrics are again the most strongly developed, with overprinting only sporadically and weakly developed.

The Lackawanna LPS fabrics can be mapped northward in the Helderberg and lower Hamilton Groups from the Delaware Valley into the Rondout and Hudson River Valleys. The LPS fabric in this region is almost exclusively a well developed solution cleavage. North of Orange County, New York, the solution cleavage is restricted to the interval between the Rondout Limestone and Ulster Group.

From Port Jervis northward, the trend of the Lackawanna phase cleavage gradually swings from 060°-070° to the 010° trends of the Helderberg escarpment. The cleavage can be traced continuously along the escarpment to the latitude of Albany, where the escarpment turns west.

From Albany, the cleavage can only be mapped along the escarpment 10 km to the west, where it dies out. As can be seen along the Rondout Valley and the Helderberg escarpment in Figure 3, the belt containing Lackawanna trends reflects the very narrow zone of foreland deformation which characterizes this region.

We recognize that the correlation of cleavage in the Hudson Valley with Alleghanian structures in the Lackawanna syncline is controversial. Our argument is based on the correlation of cleavage outcrop by outcrop southward down the Hudson and Delaware Valleys and across the Pocono plateau. Ratcliffe and others (1975) recognize the same cleavage and correlate it with an Acadian dynamothermal metamorphism to the east of the Hudson Valley. Their argument is that cleavage structures in the Hudson Valley, when traced eastward, can be shown by metamorphic inclusion textures to be syn- or pre-metamorphic with respect to probable Acadian metamorphism. However, at the present state of knowledge, our interpretation of an Alleghanian age for this change is based on our regional mapping and represents a more complete data base than that of Ratcliffe and others (1975), who only present structural data for the post-Taconic cleavage from the immediate vicinity of Mt. Ida. Moreover, we note that there is abundant evidence, in the form of post-metamorphic faulting, which suggests that both the Taconic and Acadian deformations to the east of the Hudson River Valley are themselves allochthonous.

Relationship among Lackawanna Phase LPS Fabrics, Thrusting, and Folding

A critical relationship among the various tectonic structures is seen along the Helderberg escarpment. This escarpment is characterized by a zone of imbricate thrusting involving all units from the Normanskill shale through the Helderberg group. The presence of cleavage in these structures, which predates thrusting and folding, indicates that the deformation initiated as an LPS thrust, was later broken into a series of imbricates (Geiser, 1980). It is this cleavage that we correlate with cleavage across the Pocono plateau and cleavage in the Lackawanna syncline. The relationship between cleavage and thrusting along the Helderberg escarpment is considered to support our interpretation that the Pocono plateau is a region of layer parallel shortening during the Lackawanna phase.

We suggest that the Lackawanna syncline is the surface manifestation of blind thrusting, with displacement approximately normal to the 070° trends of the Lackawanna phase LPS fabric and the Lackawanna syncline. Although Rodgers (1970) has hypothesized that basement must be involved in the formation of the Lackawanna synclines, as the Carboniferous rocks are almost a kilometer below the level they should be relative to the surrounding Devonian section, recent evidence from structure sections across this region fails to support this hypothesis (Elliott, 1980, personal communication).

The western border of the Lackawanna phase deformation is tentatively placed along the north-south trending zone of fold terminations and hinge trace offsets found to the west of the Lackawanna syncline (Figure 3). Cleavages parallel to the Lackawanna trend are only weakly and sporadically developed throughout this area and to the northwest. Consequently, the boundary of this deformation was drawn on the basis of the fold data rather than cleavages or jointing to the northwest.

Main Phase

The Main phase of the Alleghanian Orogeny in the central Appalachians is developed within both the New York and Pocono plateaus (Figure 3). Presently, its eastward extent is unknown. This event is the most widespread of the two phases which collectively form the Alleghanian Orogeny and is associated with the maximum deformation of the Appalachian foreland. LPS fabric for this phase extends northward at least to the zero isopach of the Silurian salts on the New York plateau and consists of deformed fossils, calcite twins, cleavage, and pencils (Engelder, 1979b). In Carboniferous rocks about 50 km north of the Allegheny front, pressure solution becomes a less important deformation mechanism, and finite strain is accommodated by folding crenulations with wavelengths of 1-2 cm (Figure 2a). The fold crenulations are apparently restricted to the upper Devonian and lower Mississippian units. South of the Allegheny front, where lower stratigraphic units are exposed again, solution cleavage reappears (Faill and Nickelsen, 1973; Geiser, 1974; Faill, 1979). On the Pocono plateau, solution cleavage sporadically appears in the Mississippian and Devonian sections where the best developed fabric in both Main and Lackawanna phases is a cleavage crenulation (Figure 2b).

Folding associated with the Main phase is most prominent west of the Lackawanna syncline. A few low amplitude, east-west trending folds have been recognized on the Pocono plateau (Fletcher and Woodrow, 1970). In addition Main phase folds refold the east limb of the Lackawanna syncline, thus unambiguously establishing that the Lackawanna phase pre-dates the Main phase.

Evidence for tectonic overprinting during the Alleghanian Orogeny has also been documented by Nickelsen's (1979) work. The last two structural stages (V and VI) at the Bear Valley strip mine, consisting of large scale folding and tightening of folds, deforms pre-existing structures along an 080° trend. This orientation correlates well with the Main phase structures to the north. An important question, not entirely resolved by Nickelsen's (1979) work, is whether the Bear Valley strip mine was affected by two separate and distinct tectonic events or by a simple, continuous event in which the associated stress field rotated incrementally 20° clockwise.

We believe that there are two factors that support the concept of two separate events rather than a single continuous event. Both our data and Nickelsen's (1979) show two distinct structural trends. Although Nickelsen has some evidence which suggests that the deformation associated with the wrench faulting can be interpreted in terms of a rotation, he concludes that the different orientations are due to local geometric effects on the stress field rather than a rotation in time. A second consideration arises from recent work by Pfiffner and Ramsey (1982), who point out that finite strain accumulations are nonlinear in behavior, thus leading rapidly to the accumulations of large strains. Consequently, the time required to produce the regionally developed strains of orogenic belts at strain rates between 10^{-13} and 10^{-15}/sec is quite small. For finite strain ratios associated with the deformation of the Appalachian orogen, $1.1 < 1+e_1/1+e_3 < 1.414$, the time required for deformation is less than 10 my and probably closer to 1 my. For example, Engelder and Geiser (1983) present evidence from *in situ* strain measurements that the deformation of the New York Plateau took an aggregate of 1 my. The implication of this is that the response of the orogen to stress loading is very rapid. Consequently, if the stress field was continuously rotating throughout the Alleghanian Orogeny, a rapid response time should generate sets of structures showing the entire range interval of orientations between the two major structural sets. This assumes that successive pulses were of roughly equivalent magnitude as would be required under the concept of a single orogenic event, and that the length of the Alleghanian (variously estimated to be between 60 and 120 my) is reasonably correct. These arguments, based on the data presented by Nickelsen (1979) and Engelder and Geiser (1983) and supported by the timing constraints indicated from the work of Pfiffner and Ramsey (1982), lead us to conclude that the Alleghanian Orogeny in the central Appalachians occurred as two separate events, each being associated with the development of blind thrusts at depth.

The initial deformation, the Lackawanna phase, is expressed by a northwest-directed detachment beneath the Pocono plateau. The age of this deformation is lower Upper Pennsylvanian or younger, as indicated by the youngest rocks affected by the deformation in the Lackawanna syncline (the Llewellyn Formation). The Main phase deformation is the product of a detachment whose displacement is directed north-south in eastern Pennsylvania but swings about the bend of the Pennsylvania salient. Its age, based on folded rocks on the Pennsylvania plateau, is early Permian or younger.

The origin of the three sporadically developed cleavage sets is presently not understood. There is some suggestion from *in situ* strain data that the region was subject to a late E-W compression which might have generated the 000°-010° set (Engelder, 1980). However, this is speculative as we have not been able to relate these fabric directions to any other large-scale tectonic feature. Since we have been unable to determine the ages of the three sporadic sets relative to the principal deformations, the possibility remains that these fabrics represent minor Alleghanian deformational phases.

Other Evidence for Multiple Alleghanian Deformation

Scattered evidence for multiple tectonic events associated with the Alleghanian deformation has been found from as far north as the Narragansett Basin (Murray and Skehan, 1979; McMaster et al., 1981; Mosher, 1981) and as far south as southern West Virginia (Dean and Kulander, 1978). In the north, work on the Narragansett Basin indicates that throughout much of the Carboniferous the Narranganssett basin was the site of rapid deposition of non-marine clastics associated with a release type bend in a system of left-lateral strike slip faults. During the Permian, the basin was subjected to a major dynamothermal metamorphism which, according to McMaster et al. (1981) and Mosher (1981), is associated with a reversal of the strike slip motion so that the former release type bend became a restraining bend, resulting in a compressional event in the former basin.

In the Reading Prong of New Jersey, Drake and Lyttle (1980) have identified what they regard as two distinct episodes of Alleghanian deformation. Only a single Alleghanian event has so far been recognized in the region immediately south of the Reading Prong. Dean and Kulander (1977), however, have documented important evidence for at least two Alleghanian events on the folded Plateau of southern West Virginia. Here they find an early LPS event reflected in the formation of stylo-joints in which the axes of the stylolitic columns indicate that they were formed by a compression directed normal to southern Appalachian trends. This system of stylotized joints was subsequently folded about central Appalachian trends, thus clearly indicating two separate and distinct events. The region of overprinting extends for more than 100 kms along the margin of the plateau. In our interpretation, the change in the orogenic trends of the Roanoke Recess is the product of overprinting of Main phase structures on the Lackawanna trends, rather than either oroclinal bending or a relict of the original boundaries of the North American plate. Such an interpretation is consistent with the sedimentary history of the Roanoke region as discussed by Arkle (1974).

TECTONIC RECONSTRUCTION

In both the central and southern Appalachians, the

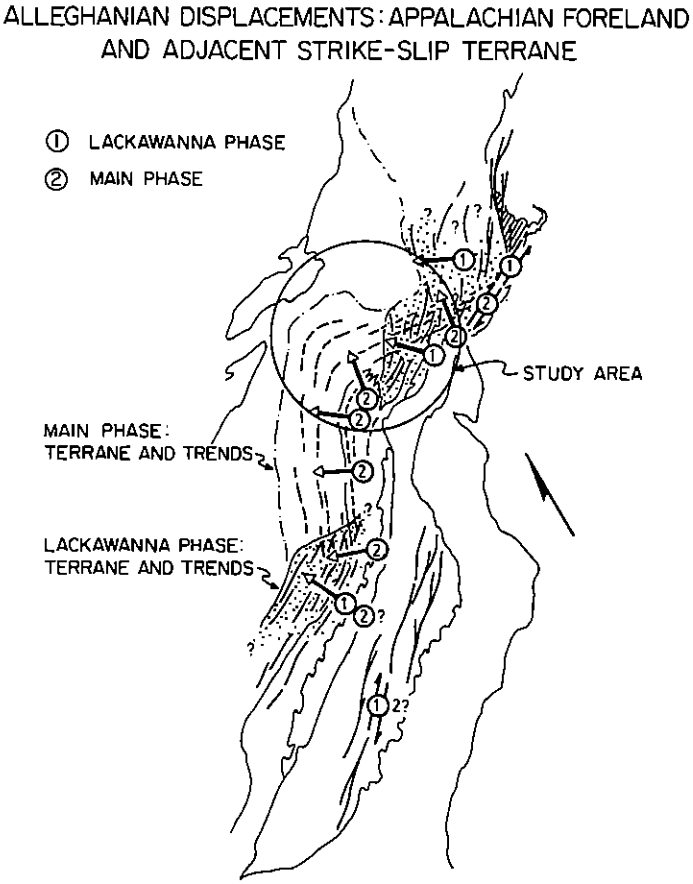


Figure 7. Trends of the Lackawanna and Main phase deformations currently known from the U.S. Appalachians.

foreland contains evidence for LPS fabrics from two phases of Alleghanian deformation (Figure. 7). We note that the evidence shown in Figure 7 has two characteristics: 1) Transport directions indicated for the Lackawanna phase are uniformly oriented NNW and independent of variation in the structural trends of the Appalachian Orogen and, therefore, presumably of the former boundaries of the North America Craton (Thomas, 1977). On the other hand, transport directions for the Main phase closely reflect the structural trends of the orogen. 2) Although the data are sparse, the sequence of overprinting is the same in all areas.

The two phases of Alleghanian deformation can be related to the sequence of events suggested by the paleomagnetic data of Kent and Opdyke (1978), as well as the more detailed tectonic synthesis suggested by LeFort and Van der Voo (1981) for the terminal Paleozoic orogeny of the Appalachian-Caledonide system. The data of Kent and Opdyke (1978) indicate in the Devonian that the Avalon Platform, consisting of the Canadian Maritime Provinces, eastern New England, and the British Isles, was about 15 degrees further south relative to its present position on the North American plate. In their view, during the Carboniferous the Avalon Platform moved some 1500 km northward along a system of shear zones, finally "docking" some time in the Permian or later. LeFort and Van der Voo (1981), in a more elaborate synthesis, suggest a series of events analogous to the current collision between India and central Asia, in which a series of island arcs and microcontinents is collapsing between two older, more rigid plates (the Siberian and Indian platforms), the resulting deformation producing large-scale lateral motions within

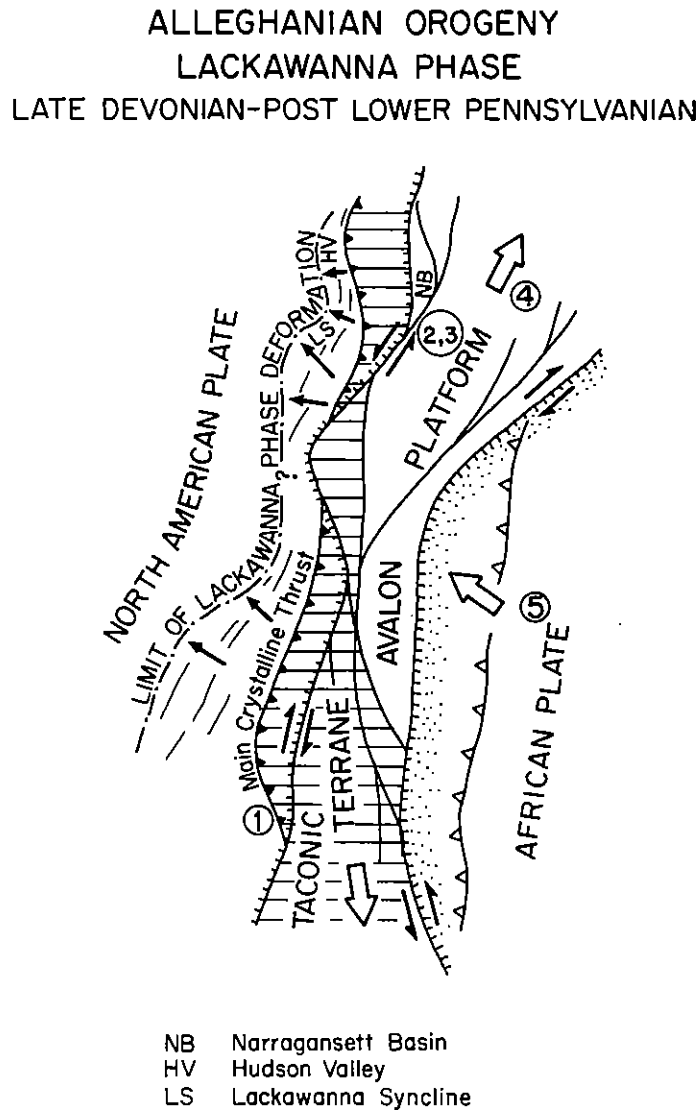


Figure 8a. Tectonic sketch of Lackawanna phase of the Alleghanian Orogeny, showing relative displacement directions for the African plate and deforming Taconic and Avalon terrane. Displacement directions on the foreland are taken from compression directions as indicated by folds, faults, and LPS fabrics. Note that foreland displacements are independent of shape of North American plate margin. The numbers 1 to 5 indicate data from: (1) Cook et al. (1980); (2) Mosher (1981); (3) McMaster et al. (1980); (4) Kent and Opdyke (1978); (5) Le Fort and Van der Voo (1982).

the constricted terrane, as suggested by Molnar and Tapponnier (1978).

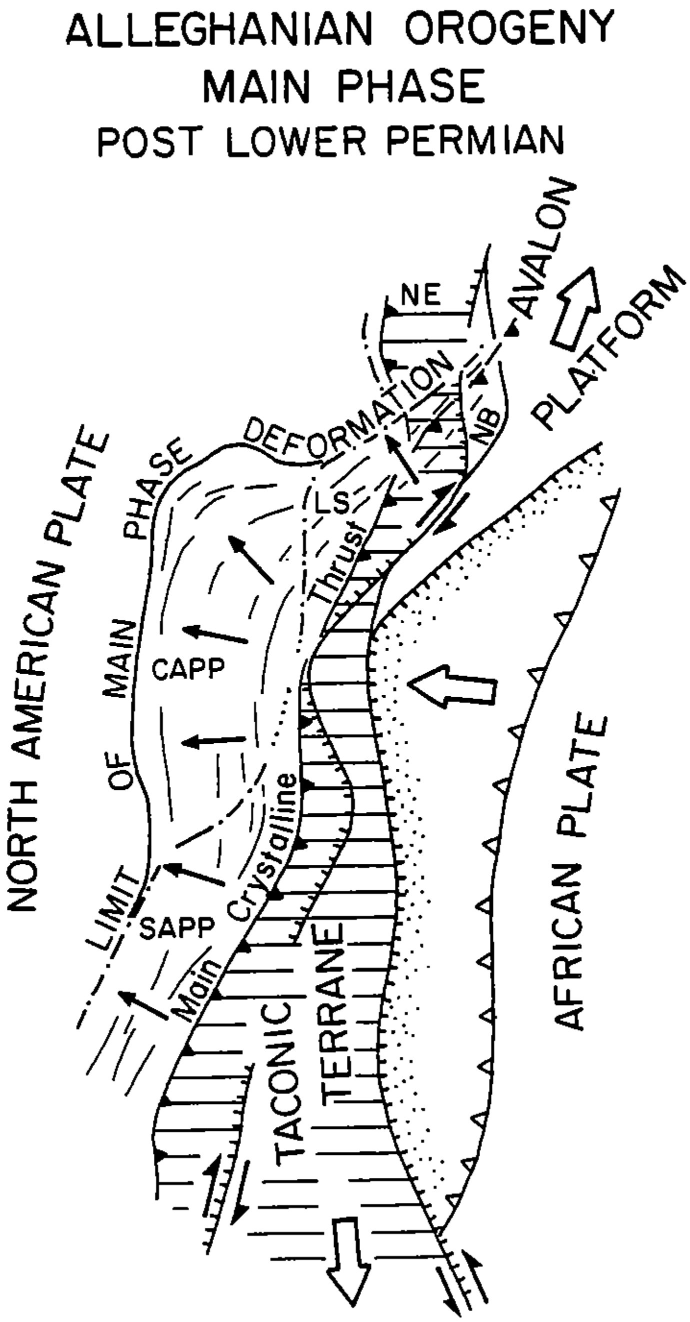
It is our hypothesis that the Lackawanna phase may be the product of either a similar initial period of lateral motion or one possibly associated with oblique subduction, during the Carboniferous. We envision the deformation to be similar to that presently occurring along the Naga-Arakan fold belt of Burma and the Sulaiman Range of Pakistan, where oblique convergence between India and Asia is forming a system of foreland fold-thrust belts on the same scale as the Appalachian foreland (Sarawar and DeJong, 1979).

For the initial Lackawanna phase of the Alleghanian orogeny, we follow the rigid indenter model of Lefort and Vander Voo (1981). In this model, the Avalon Platform is driven northward between the converging African and North American plates, producing the early left lateral motion and associated release bend formation of the Narragansett basin (McMaster et al., 1980). During this phase, a foreland fold thrust belt developed, driven by uniformly northwestward directed compression. Our present data suggest that much of the material within the Pennsylvania reentrant was little affected at this time.

Although a rigid indenter model can provide the necessary kinematics, an alternative to this which seems equally valid in light of present knowledge is a model involving oblique subduction and a form of large scale transpression (Dickinson and Yarborough, 1977). Such an interaction would not require a collision between the two rigid plates in the early phases of deformation; it would, however, seem to require that early stages of strike slip motion in the southern Appalachians be left lateral.

The Main phase of the Alleghanian is interpreted as the final closing and possible contact between the two rigid plates. One of the effects of this closure is to change the zone of faulting south of the Narragansett basin from a zone of simple strike slip motion into a transform between the African and North American plates, resulting in a reversal of the motion on these faults as the edges of the two plates make contact. In the foreland, the expulsion of material from the Pennsylvania reentrant provides the mass to form the body of the central Appalachians. The present curvature of the central Appalachians simply reflects the pre-existing geometry of the old North American plate, which established the geometric boundary conditions for this stage of the deformation. Deformation in the southern Appalachians presumably continues into and through this phase, during which the final assemblage of this part of the chain is completed.

1) Although we lack any sort of precise data on the original width of the Piedmont terrane, based on estimates of shortening within the Appalachians, it is reasonable to postulate that the total shortening is on the order of 100% or more. Given this width and a prograding suture



NB Narragansett Basin
NE New England
CAPP Central Appalachians
SAPP Southern Appalachians
LS Lackawanna Syncline

Figure 8b. Tectonic sketch of Main phase of the Alleghanian Orogeny showing relative displacement directions for the African plate and deforming Taconic and Avalon terrane. Displacement directions on the foreland are taken from compression directions as indicated by folds, faults, and LPS fabrics. Note that, in contrast to Lackawanna phase, foreland displacement directions follow the shape of the North American plate margins.

(Roeder, 1979), the initial deformation would begin outboard and earlier than the events recorded by the foreland.

2) The rate at which thrusts are emplaced is clearly critical to questions of timing of the deformations. Here we note the evidence given by Pfiffner and Ramsey (1982), as well as our own data from the New York plateau [Engelder and Geiser, 1983], that the response of the upper crust to tectonic loadings is geologically instantaneous. Moreover, we note that the geometric requirements induced by a plate driven foreland deformation require that the displacement rates of thrust sheets be of the same order of magnitude as plate convergence (on the order of cms/yr).

3) The maximum age of the arrival of a deformation at any point is given by the youngest rocks affected by that event.

4) The Allegheny plateau in southwestern West Virginia shows two separate tectonic events recorded in the upper Mississippian Greenbrier limestone. An early LPS recorded by stylotized joints which parallel southern Appalachian trends is followed by a later refolding on central Appalachian trends (Dean and Kulander, 1978).

These observations and data suggest to us that, at a maximum, the Lackawanna phase may have begun no earlier than the late Mississippian in the southern part of the central Appalachians, reaching the Lackawanna area no earlier than early Pennsylvanian time. If these dates are correct, the initiation of the Alleghanian is somewhat older than is suggested by radiometric dates from the Narragansett basin, which indicate that the Alleghanian was a rather brief event in the Permian (Murray and Skehan, 1979).

However, the Mississippian to Pennsylvanian age for the deformation is more consistent with the 313-254 my age suggested by Snoke and others (1980) for the Kiokee belt. On the other hand, our suggestion that the Lackawanna phase represents a period of oblique subduction associated with large-scale strike-slip motion along the Appalachian orogen is also consistent with the Carboniferous history of rift type sedimentation of the Narragansett basin, which McMaster and others (1981) interpret as the product of a release type bend initiated as part of a strike-slip fault system.

The Main phase deformation then would represent the final closing between Africa with South America and North America. The complete suturing of continents drives the crystalline core zone westward along the entire length of the central Appalachians. The Lackawanna phase appears to have been restricted rather than distributed along the entire length with displacements whose orientation remains more or less uniformly directed toward the northwest. The age of the Main phase, which is the one originally associated with the Alleghanian and has displacements whose orientation changes along strike (e.g., Rodgers, 1970), we interpret as early Permian or younger, and it may correlate with the early Permian deformation dated by the Narragansett Pier granite (Skehan and Murray, 1980).

Our current data indicate two discrete pulses during a sustained period of plate interactions. The pulses themselves are probably diachronous. Although we do see scattered evidence for other directions of translation, at this stage of investigation we cannot determine whether they are part of a continuous rotation of movement directions in which the Lackawanna phase and the Main phase were major pulses or whether they represent unique translations.

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